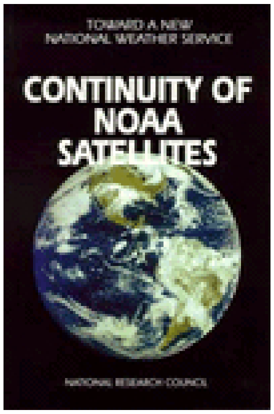

Continuity of NOAA Satellites

National Weather Service Modernization Committee,
National Research Council

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Continuity of NOAA Satellites

Toward a New National Weather Service

National Weather Service Modernization Committee
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

The mission of the National Weather Service (NWS) includes providing up-to-date forecasts of the weather for the United States and the adjacent oceans and providing reports of severe or dangerous weather conditions, both in advance and as they occur. In carrying out these functions, the NWS makes use of data obtained from several satellites operated in various orbits about the Earth by the National Environmental Satellite, Data, and Information Service (NESDIS).

The National Research Council's (NRC) National Weather Service Modernization Committee (NWSMC) has been reviewing the NWS modernization since February 1990 under contracts between the National Oceanic and Atmospheric Administration (NOAA) and the NRC. In January 1995, as part of the extension of the contract, NOAA requested the NWSMC "to assess the adequacy of planned NOAA geostationary and polar-orbiting satellite coverage in terms of system continuity and backup." The NWSMC formed the Satellite Continuity Panel in February 1995 to determine the scope of the issues involved and to develop a study plan. In September 1995, the Executive Committee of the Governing Board of the NRC authorized the NWSMC to conduct a study that accomplished the following tasks:

- Evaluate the records [of past satellite lifetimes] and replenishment plans of current NOAA and Department of Defense meteorological satellite programs.[1]

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[1] The NWSMC did not investigate the Defense Meteorological Satellite Program of the Department of Defense except as it relates to the schedule of the proposed National Polar-orbiting Operational Environmental Satellite System and as a backup to the current Polar-orbiting Operational Environmental Satellite program.

- Examine each meteorological satellite program with respect to requirements for continuity of coverage.
- Determine best estimates of continuity for current meteorological satellite programs, considering strategies for satellite replacement.
- Assess need and timing for satellite programs not presently under contract to provide future replenishment of geostationary and polar-orbiting weather satellites.

Further, the Satellite Continuity Panel of the NWSMC was asked to gather data and to present reports to the full committee for its analysis and for completion of the final report. The panel includes three NWSMC members and a former committee study director serving as an advisor.

The committee appreciates the cooperation and assistance provided by the staff of NOAA; the NWS; several weather forecast offices; the NESDIS; the Storm Prediction Center, Aviation Weather Center, and Environmental Modeling Center of the National Centers for Environmental Prediction; and the National Aeronautics and Space Administration.

I also want to thank the chairman of the Satellite Panel, George J. Gleghorn; member, William E. Gordon; and advisor, David S. Johnson, who worked so diligently with me to obtain and analyze data for this study and to compile drafts for the committee.

On behalf of the committee, I express our appreciation to Mr. Floyd Hauth, study director, and Ms. Mercedes Ilagan, study associate, for their excellent organizational and logistical support and to consultant Robert Katt for his assistance with several reviews of the report.

ROBERT J. SERAFIN, CHAIR
NATIONAL WEATHER SERVICE
MODERNIZATION COMMITTEE

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Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) asked the National Research Council (NRC) to assess the adequacy of planned geostationary and polar meteorological satellite coverages in terms of system continuity and backup. This report, prepared by the NRC's National Weather Service Modernization Committee (NWSMC), responds to that request. The NWSMC has not investigated the Defense Meteorological Satellite Program (DMSP) of the Department of Defense except peripherally, as it relates to the proposed National Polar-Orbiting Operational Environmental Satellite System (NPOESS) program and as a backup to the polar-orbiting operational environmental satellites (POES).

The National Weather Service (NWS) is charged with providing forecasts of the weather for the United States and the adjoining oceans and with providing warnings of severe weather conditions in advance and as they occur. Satellite observations have been essential inputs in the provision of these services for more than 20 years. In addition, satellite data in many forms are used by NOAA, other government agencies, and the private and academic sectors in a broad range of applications, such as monitoring climate, planning land-use, and research. The National Environmental Satellite, Data, and Information Service (NESDIS) operates two satellite systems: the geostationary operational environmental satellite (GOES) system, which observes the same area of the Earth continuously; and the POES system, which observes the full area of the Earth in north-south strips, with the orbit height set so that each strip is observed at the same local time.

The committee's findings and recommendations are summarized in this Executive Summary, and details are provided in the report. In general, the findings show that NOAA's satellite systems are adequate and the strategy for satellite replenishment and scheduling of launches is sound. However, the committee made no attempt to evaluate the impact of incorporating improved sensors and new technology or other factors not presently included in planned programs. The committee does recognize the importance of these other factors, particularly the long lead time required for developing and integrating new sensors and other new technology. This lead time must be taken into account in planning follow-on replenishment programs for environmental satellites.

Reliable and continuous service from the operational satellites remains a dominant national requirement. Completely redundant systems and sensors are not provided aboard each satellite; therefore, a sufficient number of GOES and POES must be launched to provide the necessary redundancy in orbit at all times.

The committee's analysis of NWS requirements for satellite data led to the following findings and recommendations.

Finding 1a. At least one operational POES is needed in orbit at all times to provide data vital to global numerical-prediction models. A backup POES in orbit also is required to ensure that unacceptable degradation of service does not occur when the operational POES fails. The backup satellite may also be operated simultaneously with the first satellite, thus providing global coverage four times a day. A replacement must be available for launch in case either of the orbiting spacecraft fails.

Finding 1b. At least two operating GOES satellites are needed in orbit at all times to provide the necessary coverage from the central Pacific Ocean eastward to the coast of West Africa.

Recommendation 1. To meet NWS high priority requirements for satellite coverage in support of weather forecasts and warnings, NOAA must ensure that the requisite data are available at all times from at least one POES and two GOES in orbit. To ensure this continuity, a backup POES and a backup GOES need to be available in orbit.

Finding 2. The GOES-8 and GOES-9 offer an opportunity to establish the operational utility of deriving soundings and upper air winds from GOES data and implement new operational techniques. Field office staff visited by the committee would like to have access to sounding and wind data from GOES.

Recommendation 2. NWS/NOAA should fully support efforts to develop and demonstrate techniques for using GOES soundings and winds to improve warnings and forecasts. It is essential that the NESDIS and the NWS (particularly the National Centers for Environmental Prediction) devote adequate personnel to processing, evaluating, and applying newly available satellite data as soon as possible. Science operations officers and other field staff could also contribute to this effort.

In response to a presidential decision directive, steps are being taken to merge the present POES system and the DMSP into a single system, the NPOESS. The first NPOESS launch is planned for 2008. Negotiations are under way between the NOAA and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT); the latter will provide a replacement for one of the two POES satellites currently in orbit. The European satellites, called "meteorological operational" (METOP) satellites, will be introduced about 2002. Cooperation between NOAA and EUMETSAT is expected to continue in the NPOESS era, during which two of the nominal three satellites in orbit will be provided by NOAA. EUMETSAT will provide the third.

Examination of the launch and in-orbit performance of the POES and GOES satellites, schedules for future satellites, possible backups to POES and GOES, spacecraft availability, and ground system vulnerabilities led the committee to the following additional findings and recommendations.

Finding 3. The polar program, as presently planned, depends on the availability of European METOP satellites in polar orbit from 2002 to 2010 and the availability of NPOESS beginning about 2008.

Recommendation 3. NOAA should closely coordinate the POES program with the progress of the NPOESS and METOP satellite programs so that "gap-filler" satellites are not needed.

Finding 4. In the longer term, the replenishment strategy depends on the new NPOESS for polar-orbiting satellites and on the procurement of additional GOES satellites. (NOAA plans to procure a new design beginning with GOES-R.) Longer lead times than normal are required when new designs, which are planned for GOES-R, METOP, and NPOESS, are introduced.

Recommendation 4. When considering ways to develop new spacecraft and incorporate major new improvements in technology, NOAA should carefully consider the lead times dictated by the required launch schedules and the very long procurement cycle. NOAA should develop schedules for the transition from current designs to new ones, such as NPOESS and GOES-R, that adequately account for the necessary lead times for funding approval, procurement, design and development, fabrication, and verification.

The POES ground system appears to be adequate for the foreseeable future. However, the Wallops command and data acquisition (CDA) station is a potential single point of failure for the GOES system. Any phenomenon that could shut down the station, such as a hurricane, flooding, major fire, or explosion, would result in a complete cutoff of data from GOES satellites. Minimum prudent backup would require—at a location geographically remote from the Wallops facility—an antenna subsystem and the necessary receiving, transmitting, data formatting, and processing subsystems to command a GOES satellite, receive telemetry, and acquire and distribute data from the sounding and imaging instruments.

Finding 5. The Wallops CDA station is a potential single point of failure for the GOES system. Shutdown of the station would result in a complete cutoff of data from the GOES satellites.

Recommendation 5. NOAA should implement an adequate backup system to the Wallops CDA station to ensure the uninterrupted operation of GOES satellites and the acquisition of sufficient data to generate basic image and sounding products to meet NWS mission requirements.

An agreement exists between NOAA and EUMETSAT whereby, under certain circumstances, one organization may provide backup of the other's operational geostationary meteorological satellite system. At the present time, the agreement appears to offer backup of GOES that is of limited value. This supports the following findings and recommendations.

Finding 6. Although arrangements have been made for a European geostationary meteorological satellite, METEOSAT, to provide backup to GOES under certain conditions, the coverage by METEOSAT or its successor is very limited compared to the coverage provided by GOES.

Recommendation 6. NOAA should ensure that a replacement GOES satellite can be launched and operated as soon as an operational GOES fails to continue the full level of coverage expected of this series of satellites.

Finding 7. One additional GOES is needed in orbit as a ready spare to protect against a dangerous, protracted loss of full, two-satellite coverage if one operational GOES fails. Even more severe, although far less likely, would be an outage of continual, real-time coverage if both satellites in orbit should fail before a replacement could be made operational. Dependence on commercial launches for GOES can lead to delays of well over a year, even if a spacecraft is available for launch.

Recommendation 7. To ensure the continuity of two-GOES coverage, NOAA should store a standby GOES in orbit, rather than on the ground, if this is technically and operationally feasible and cost effective.

Consideration of factors that determine continuity of service has led to a launch-decision process in which a group of senior managers of the NWS and

NESDIS regularly review the status of the satellites in orbit, satellite production, the availability of launch times, the readiness of the next satellite in the short range, and the replenishment strategy in the long range. They also review and update satellite availability prediction studies on a regular basis.

Finding 8a. The launch-decision process used by NWS and NESDIS is appropriate.

Finding 8b. The planned GOES, POES, METOP, and NPOESS procurements are adequate to provide continuity of the NOAA geostationary and polar-orbiting satellites for at least the next 15 years, if they are funded and carried out on the current schedule.

Recommendation 8. To ensure continuity, NOAA should fund and procure the planned block of four GOES-Next spacecraft in a timely fashion and should avoid further delays in the METOP and NPOESS programs.

1

Introduction

The potential benefits of satellite observations for monitoring current weather patterns and for forecasting weather were recognized soon after the first Earth-orbiting satellites were launched in the late 1950s. Several research and operational programs were initiated in the United States by both military and civilian agencies. The TIROS-1 (television and infrared observation satellite) experimental weather satellite was launched on April 1, 1960. As described in Chapter 3, the National Weather Service (NWS) has made daily operational use of satellite data since 1966.

Over the intervening years, improvements in sensing instruments and in processing and disseminating data have expanded the utility and importance of satellites in NWS operations. Today the NWS uses satellite data in a great variety of its products. These range from daily inputs to global forecast models, the near-real-time tracking of hurricanes and severe storms, the mapping of snow cover, and the determination of temperature and water vapor content of the atmosphere to the provision of animated cloud images we have all come to expect on daily television news programs. NOAA, other government agencies, research organizations (including academia), and private organizations also use NOAA satellite data and derived information for many purposes. Some examples are:

- developing specialized forecasts for agriculture, construction, transportation and other applications; developing weather depictions for television broadcasts (mostly private sector)
- measuring sea-surface temperatures for marine activities and monitoring and predicting climate (governments, private sector, research)
- using multispectral imaging of the atmosphere and land surfaces to detect and monitor forest fires (governments, private sector); global drought

watch (governments); global mapping of vegetation, precipitable water, snow and ice coverage, reflectance and brightness temperature to monitor changes in climate (governments, research); land use planning (governments, private sector)

- forecasting sea ice, predicting snow melt, etc., for managing water resources, forecasting floods, improving marine navigation (governments, private sector, research)
- monitoring ozone in the atmosphere for impact on climate and health (governments, research)
- monitoring solar activity to warn of the impact on terrestrial communications, electric power distribution, and high-altitude aircraft and space flights (governments, private sector, research)
- receiving and relaying emergency beacon signals in support of search and rescue services (cooperative program of Canada, France, Russia, and the United States; governments, private sector)
- collecting and relaying ocean, land, and atmospheric data from a wide variety of automatic observing devices to central locations; broadcasting processed satellite data to relatively low cost receivers (governments, private sector, academia, research)

Beginning in 1989 some of these services were threatened when one of the two geostationary operational environmental satellites (GOES-6) failed. Earlier, in 1986, the GOES-G, planned as a replacement, had been lost on launch. The United States was left with a single satellite, GOES-7, to provide imaging until the next replacement was launched. The replacement satellite, the first of a new design, was delayed because of development problems, so no immediate additional satellite was available. Fortunately, the National Oceanic and Atmospheric Administration (NOAA) was able to obtain the use of a European geostationary meteorological satellite (METEOSAT) to provide coverage over the eastern United States and the Atlantic Ocean, and the threatened outage was avoided.

NOAA has planned satellite programs to provide replenishment satellites through about 2010 (see Chapter 4). To provide some confidence that the planning is adequate to preclude future outages, in January 1995 NOAA requested that the National Research Council's (NRC) National Weather Service Modernization Committee (NWSMC) provide a report on “the adequacy of planned NOAA geostationary and polar satellite coverage in terms of system continuity and backup.”

Accordingly, a panel was formed to gather data and prepare a draft report for analysis, review, and development of a final consensus report by the NWSMC. The panel was composed of three members of the NWSMC; the former study director, serving as an advisor; and the current study director, serving *ex officio*. Three of the panelists have extensive experience in various satellite programs; three are meteorologists; three are members of the National Academy of

Engineering; and three are experienced users of satellite sensing data. All four panel members have several years of experience working with NWS programs.

In carrying out its tasks, the panel arranged five formal briefings with NOAA/NWS. They spoke with NOAA personnel involved in the procurement, production, and operational phases of the satellite programs and with NWS personnel who use satellite data for monitoring the weather and for developing numerical models used to produce daily weather forecasts. Lists of topics discussed at these meetings are contained in the Appendix. The panel met several more times to consolidate information, develop conclusions and recommendations, and produce draft reports for consideration by the NWSMC.

In responding to its charge (see Preface), the NWSMC limited its investigation to the evaluation of the NOAA satellite programs as currently planned (see tables 4-3 and 4-4). These programs include the GOES and polar-orbiting operational environmental satellite (POES) programs presently on contract; a planned (but not yet contracted) block of four additional GOES satellites; one or more supplementary polar orbiting satellites provided by the European Space Agency; and the planned National Polar-orbiting Operational Environmental Satellite System (NPOESS) program.[1] NPOESS is a follow-on program to the POES program and is a joint effort of NOAA, the Department of Defense (DOD), and the National Aeronautics and Space Administration (NASA). These programs are expected to provide weather satellite coverage for about a decade following the phase-in of the first NPOESS satellite, which is planned for 2008. Only preliminary plans exist beyond 2008.

The committee made no attempt to evaluate the impact of incorporating improved sensors, new technology, or other factors that are not included in planned programs.[2] However, the committee does recognize the importance of these other factors, particularly the long lead time required for developing and integrating new sensors and other new technology. This lead time must be taken into account when planning follow-on replenishment programs for environmental satellites.

The historical background of the current satellite program, including the history of satellites used by NOAA, is covered in Chapter 2. Chapter 3 discusses the significance of the satellite data and products used by the NWS as a basis for evaluating the number of operational satellites needed. Studies of the availability of satellites to meet the needs of the NWS, the various factors that affect availability, predictions of future satellite performance, and the adequacy of the existing and planned satellites to provide reasonable assurance of continuity of observations are discussed in Chapter 4. References and a list of acronyms follow Chapter 4, and topics discussed during the several briefings are included in the Appendix.

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[1] The NWSMC has not investigated the DOD Defense Meteorological Satellite Program (DMSP), except peripherally as it relates to the proposed NPOESS program and as a backup to POES.

[2] The NWSMC plans to evaluate improved sensors and new technology as part of a future study for NOAA.

2

NOAA Environmental Satellite Programs.

NOAA operates two environmental satellite systems: the POES system and the GOES system. The two-satellite POES system observes the entire Earth at least four times per day; the two spacecraft of the GOES system provide continuous coverage of the contiguous 48 states, the southern part of Alaska, Hawaii, and adjacent ocean areas. These two systems provide data and communications in support of a variety of environmental and related programs, such as meteorology, oceanography, climate, hydrology, land use, and the space environment. The systems also support international search and rescue satellite-aided tracking (SARSAT), the broadcast of processed weather analyses and other environmental information via weather facsimile (WEFAX), and various direct broadcasts of data as they are collected by the satellites.[1] This report focuses on elements of the POES and GOES systems that are of high priority in the current modernization of the NWS:

- multispectral imaging of the Earth's surface and atmosphere (including inferring the three-dimensional wind field where suitable clouds or water vapor patterns exist)
- sounding of the atmosphere to determine the three-dimensional distribution of its temperature and water vapor

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[1] Much of the information in this chapter regarding the history of meteorological satellites through 1988 is based on Rao et al., 1990, published by the American Meteorological Society.

POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM

The current POES evolved from the NASA launch of TIROS-1 on April 1, 1960 (Table 2-1). This first "weather satellite" was very crude compared to weather satellites today. TIROS-1 contained only two television cameras which were quite primitive by today's standards; the sensors, orbit, and stabilization of the spacecraft limited the coverage and utility of the images. TIROS-2 included the first scanning radiometer (SR), with five channels in the visible and infrared portions of the spectrum. TIROS-3 through TIROS-7, launched in 1961, 1962, and 1963, were intended to provide nearly daily observation of the Earth's cloud cover as viewed from space by satellite. The images were valuable in data-sparse areas, particularly for detecting and tracking tropical storms over the oceans. TIROS-8, launched in December 1963, was equipped with a new type of television camera for automatic picture transmission (APT) to relatively inexpensive ground stations within the line of sight of the satellite as it orbited the Earth. A significant advance in technology was implemented with the launch of TIROS-9 in January 1965. Coverage of the Earth was vastly improved by (1) increasing the orbit inclination from 48 to 58 degrees, which was used for earlier TIROS satellites, to 99 degrees (near-polar, sun-synchronous, circular orbit);[2] and (2) introducing the "wheel" configuration, in which the spin axis of the satellite was maintained perpendicular to the orbit plane. The optical axes of the two wide-angle television cameras were oriented perpendicular to the spin axis (i.e., rotating within the orbit plane), and the shutters of the cameras operated only when the cameras were pointing directly at the Earth beneath. Thus, the sunlit part of the entire Earth could be viewed each day, about a fourfold increase in coverage over earlier TIROS satellites. TIROS-10, the last TIROS to be launched (July 1965), assured adequate coverage of tropical storms prior to the launch of the first series of operational weather satellites in 1966.

Beginning in the early 1960s, NASA developed the Nimbus polar-orbiting satellite as a test bed for new technology for possible use in the operational satellite program or for the collection of special observations for environmental

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[2] Sun-synchronous orbit is achieved by launching the satellite into a near polar (about 99 degrees), retrograde orbit so that the orbit will precess eastward at the same rate as the Earth moves around the Sun (0.986 degrees per day). Each spacecraft crosses the equator at the same local time on each of its orbits. The imagers have fields of view on each side of the orbit plane that are wide enough to provide contiguous coverage at the equator between adjacent orbits. (The advanced, very-high-resolution radiometer [AVHRR] and the high-resolution infrared radiation sounder [HIRS], which are the current primary imager and sounder, scan perpendicular to the orbit plane.) Thus, the entire Earth's surface passes beneath each satellite twice a day, once on the daylight side and once on the night side. The current series of NOAA satellites are launched with their orbital planes about 90 degrees apart; one has a southbound equator crossing time of about 0730 local standard time (LST) and the other northbound at about 1330 LST (also called the AM and PM orbits). They also cross the equator northbound at about 1930 and southbound at about 0130 LST.

research. Seven Nimbus satellites were launched from 1964 through 1978; Nimbus-7 operated until 1994. Of major importance to the operational systems was developing the satellite infrared spectrometer (SIRS) flown on Nimbus-3 in 1969 to measure atmospheric temperature and water vapor. Subsequently, the Nimbus series demonstrated smaller, lighter sounders that had higher sensitivity than SIRS and were, therefore, more practical for use in operational spacecraft. These sounders defined the spectral intervals to be sensed with a series of interference filters rather than a grating.

TABLE 2-1 TIROS Satellites

Name	Launch Date	Operating Life (days)[a]	Orbit	Features
TIROS-1	1 Apr 60	89	Inclined	2 TV cameras
TIROS-2	23 Nov 60	376	Inclined	2 TV cameras, SR[b]
TIROS-3	12 Jul 61	230	Inclined	2 TV cameras, SR[b]
TIROS-4	8 Feb 62	161	Inclined	1 TV camera, SR[b]
TIROS-5	19 Jun 62	321	Inclined	2 TV cameras
TIROS-6	18 Sep 62	389	Inclined	2 TV cameras
TIROS-7	19 Jun 63	1,809	Inclined	2 TV cameras, SR[b]
TIROS-8	21 Dec 63	1,287	Inclined	1 TV camera, APT[c]
TIROS-9	22 Jan 65	1,238	Sun Synch[d]	Global coverage, 2 TV cameras
TIROS-10	2 Jul 65	730	Inclined	2 TV cameras

[a] Number of days until satellite was turned off or failed. Various sensors and other units could have degraded or failed before the satellite was turned off.
[b] Scanning radiometer (visible and infrared channels).
[c] Automatic picture transmission for direct readout locally.
[d] Sun-synchronous, see footnote 2 on page 10.

The first operational weather satellite system began with the launch of the first environmental survey satellite (ESSA-1) on February 3, 1966, and ESSA-2 on February 28, 1966.[3] These spacecraft (see Table 2-2) were based on the design of TIROS-9, except for the sensors. Because of the payload limitation of this spacecraft, the sensors were split, with the odd-numbered satellites (ESSA-1, -3, -5, -7, and -9) flying two (redundant) advanced vidicon camera systems (AVCS) to obtain images of the Earth globally for reception by command and data acquisition (CDA) stations in Fairbanks, Alaska, and Wallops, Virginia. The even-numbered satellites (ESSA-2, -4, -6, and -8) were all equipped with two (redundant) APT cameras. The images from these cameras, which respond only to reflected sunlight, were continuously broadcast by the satellites as they orbited around the Earth. They could be received by anyone with a relatively inexpensive receiving and display system.

TABLE 2-2 ESSA Satellites—The First Operational Weather Satellite System

Name	Launch Date[a]	Operating Life (days)[b]	Features
ESSA-1	3 Feb 66	861	2 AVCS[c]
ESSA-2	28 Feb 66	1,692	2 APT[d]
ESSA-3	2 Oct 66	738	2 AVCS
ESSA-4	26 Jan 67	465	2 APT
ESSA-5	20 Apr 67	1,034	2 AVCS
ESSA-6	10 Nov 67	763	2 APT
ESSA-7	16 Aug 68	571	2 AVCS
ESSA-8	15 Dec 68	2,644	2 APT
ESSA-9	26 Feb 69	1,726	2 AVCS

[a] All spacecraft were placed in near-polar, sun-synchronous orbits; see footnote 2 on page 10 for explanation.

[b] Number of days until satellite was turned off or failed. Various sensors and other units could have degraded or failed before the satellite was turned off.

[c] Advanced vidicon camera system with data recorders to obtain cloud pictures globally for central analysis.

[d] Automatic picture transmission vidicon camera for local direct readout over the Earth.

Using pairs of ESSA satellites to carry out the operational mission was a temporary measure until a more suitable spacecraft could be developed and launched. The new spacecraft series was the improved TIROS operational system (ITOS) (see Table 2–3). The NASA prototype spacecraft, ITOS-1, was launched in January 1970. It was equipped with two APT and two AVCS cameras, plus two medium-resolution, two-channel SRs. One channel of the SR responded to visible light; the other operated in the infrared portion of the spectrum. The latter channel allowed full global coverage day and night. The SR data were recorded throughout each orbit for later transmission to a CDA station and relayed to a central processing facility for global analysis. The SR data were also broadcast in the APT mode.

NOAA-1, which followed in December 1970, had the same instrument complement as ITOS-1. However, this was the last time vidicon cameras were used in the operational system. NOAA-2 through NOAA-5, launched from October 1972 through July 1976, continued the use of two SRs, but added two very high resolution radiometers (VHRR) for imaging in place of the APT and AVCS cameras. This series of satellites also used two vertical temperature profile

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[3] In 1961 President Kennedy gave responsibility for the civil operational meteorological satellites in the United States to what was then called the U.S. Weather Bureau of the Department of Commerce. The initial appropriation to establish the system was approved for fiscal year 1962. In 1965, the Weather Bureau and other science agencies in the Department of Commerce were consolidated to form the Environmental Science Services Administration. In 1970, other U.S. agencies involved in marine activities were merged with the Environmental Science Services Administration to form the National Oceanic and Atmospheric Administration of the Department of Commerce (NOAA). The second and subsequent series of operational satellites in polar orbit have been named NOAA.

radiometers (VTPR), the first operational instruments for sounding the atmosphere from space. Reflecting a new mission that the NOAA had inherited, the spacecraft also included a solar proton monitor (SPM) for space environment monitoring and warnings. (ITOS-B and ITOS-E failed to achieve useful orbits on launch in 1971 and 1973.)[4]

TABLE 2-3 ITOS Satellites

Name	Launch Date[a]	Operating Life (days)[b]	Features[c]
ITOS-1[d]	23 Jan 70	510	2 APT,[e] 2 AVCS,[f] 2 SR[g]
NOAA-1	11 Dec 70	252	2 APT, 2 AVCs, 2 SR
ITOS-B	Failure	—	
NOAA-2	15 Oct 72	837	2 SR,[g] 2 VHRR,[h] 2 VTPR[i]
ITOS-E	Failure	—	
NOAA-3	6 Nov 73	1,029	2 SR, 2 VHRR, 2 VTPR
NOAA-4	15 Nov 74	1,463	2 SR, 2 VHRR, 2 VTPR
NOAA-5	29 Jul 76	1,067	2 SR, 2 VHRR, 2 VTPR

[a] All spacecraft were placed in near-polar, sun-synchronous orbits; see footnote 2 on page 10 for explanation.

[b] Number of days until satellite was turned off or failed. Various sensors and other units could have degraded or failed before the satellite was turned off.

[c] Primary sensors of high priority in the current modernization of the NWS, that is, imagers and atmospheric sounders (see p. 9).

[d] ITOS-1, the prototype of this new series of satellites, was funded, named, and operated by NASA. The subsequent operational satellites were funded by NOAA and named by them.

[e] Automatic picture transmission vidicon camera for local direct readout over the Earth.

[f] Advanced vidicon camera system with data recorders to obtain cloud pictures globally for central analysis.

[g] Two-channel (visible and infrared), medium-resolution scanning radiometer providing image data day and night for immediate broadcast (APT function) and stored for later playback to provide global coverage for central analysis.

[h] Very high resolution radiometer (visible and infrared).

[i] Vertical temperature profile radiometer; the first instrument for obtaining temperature soundings of the Earth's atmosphere from the operational satellite system.

TIROS-N, the NASA prototype of the next generation of operational satellites (see Table 2–4), was launched in October 1978, in time to be used in the

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[4] The designation of individual spacecraft varies from one series to the next and among sponsoring agencies. The spacecraft funded by NOAA beginning with the TIROS-N series and the entire GOES series are initially designated by a letter (e.g., NOAA-B, GOES-D). When a spacecraft is successfully launched and placed into the proper orbit, the name changes from the letter to the next appropriate number in the series of operational spacecraft. In an attempt to minimize confusion, this report uses the number designators for all spacecraft successfully orbited or where the number designator was also used before launch. The letter designator is used only for spacecraft that suffered a launch failure or had not yet been launched.

TABLE 2-4 TIROS-N Series of Operational Satellites

Name	Launch Date[a]	End of Useful Life[b]	Orbit[c]	Features[d]
TIROS-N[e]	13 Oct 78	1 Nov 80	PM	AVHRR,[f] HIRS,[g] MSU,[h] SSU,[i] DCS[j]
NOAA-6	27 Jun 79	19 Sep 83	AM	same
NOAA-B	29 May 80	launch failure		
NOAA-7	23 Jun 81	7 Feb 85	PM	same
NOAA-8[k]	28 Mar 83	26 May 84	AM	same
NOAA-9	24 Dec 84	limited use[l]	PM	same
NOAA-10	17 Sep 86	limited use[l]	AM	same, except no SSU
NOAA-11	24 Sep 88	limited use[l]	PM	same, with SSU
NOAA-12	14 May 91	operational	AM	same, except no SSU
NOAA-13	9 Aug 93	21 Aug 93	PM	same, with SSU
NOAA-14	30 Dec 94	operational	PM	same, with SSU

[a] All spacecraft placed in near-polar, sun-synchronous orbits; see footnote 2 on page 10 for explanation.

[b] Various sensors and other units have degraded or failed before the satellite was turned off.

[c] See footnote 2 on page 10.

[d] Primary sensors of high priority in the current modernization of the NWS, that is, imagers and atmospheric sounders (see p. 9).

[e] TIROS-N, the prototype of this new series of satellites, was funded, named, and operated by NASA. The subsequent operational satellites were funded and named by NOAA.

[f] Advanced very high resolution radiometer.

[g] High resolution infrared radiation sounder.

[h] Microwave sounding unit.

[i] Stratospheric sounding unit (provided by the United Kingdom).

[j] Data collection system (provided by France).

[k] First spacecraft "bus" of the Advanced TIROS-N type; larger, with more power than the previous spacecraft in the series in order to accommodate more equipment.

[l] Satellite cannot fully support NWS primary requirements because of component degradation or failures. Satellite may still support other missions such as ozone monitoring and search and rescue.

Global Weather Experiment, a major international endeavor to improve weather forecasting. The key sensors included an AVHRR for day and night imaging as well as providing quantitative measurements from which parameters, such as sea-surface temperature, can be derived; the HIRS-2, a stratospheric sounding unit (SSU), and a microwave sounding unit (MSU) to provide better soundings of the atmosphere than VTPR. TIROS-N also included a data collection system (DCS) to relay environmental data from fixed and moving platforms (such as buoys and balloons) for central processing and distribution and a space environment monitor (SEM) to replace the SPM and measure solar electron and alpha-particle densities in addition to protons. Following the launch of NOAA-6 and NOAA-7 (and the launch failure of NOAA-B in 1980), which were the first operational versions of TIROS-N, the spacecraft was lengthened approximately 0.5 m, and the solar array was enlarged to accommodate additional components. For example, a search and rescue (SAR) capability was added to all spacecraft beginning with NOAA-8, launched in March 1983; a solar backscatter ultraviolet spectrometer (SBUV), which measures ozone distribution, was added to all spacecraft flying in the afternoon orbit beginning with NOAA-9, launched in December 1984; and an Earth radiation budget experiment (ERBE) was flown on NOAA-9 and NOAA-10. The series has continued to the present with the launches of NOAA-10 through NOAA-14. (NOAA-13 failed shortly after launch in August 1993, causing continued degradation in the quality of POES data until check-out of NOAA-14 was completed in January 1995.)

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE SYSTEM

Except over the polar areas of the Earth, where the satellite orbits converge, each polar-orbiting NOAA satellite observes a given point on the Earth's surface and the atmosphere above it only twice a day. However, for rapidly changing severe storms (such as hurricanes and storms that produce flash floods, tornadoes, or hail), much more frequent observations of weather phenomena that produce and guide such storms are essential to provide adequate tracking and warning. The late Professor Verner E. Suomi of the University of Wisconsin-Madison conceived the idea of using geostationary satellites as platforms for this purpose.[5] In the early 1960s, NASA was developing geostationary satellites to test for use in long distance communications. NASA agreed to add the spin scan cloud camera (SSCC) devised by Suomi to its first applications technology satellite (ATS-1), which was launched in 1966 and successfully operated for almost six years.

The spinning of ATS-1 about its axis, which was parallel to the Earth's axis, generated the east-west scan of the camera; stepping the SSCC's optical axis between each east-west scan provided the north-south scan. It took about 20 minutes to obtain one image of the Earth's disk and 10 minutes to reset the camera for the next image. The first SSCC operated only in visible light, so coverage was not available at night. The useful coverage of the Earth's surface from the geostationary satellite's vantage point is the area within a circle on the Earth's surface with a radius of about 55 degrees of great circle arc and centered on the satellite subpoint (the point on the Earth's surface directly below the satellite). Thus, to cover the territory of prime interest to the United States, two satellites with overlapping coverage at the equator are necessary (see Figure 2-1).

The successful development and operation of the camera on ATS-1 and of a similar camera on ATS-3 (launched in 1967) led to the decision to proceed with

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[5] The satellite's nominal orbit plane is coincident with the plane of the Earth's equator, and its altitude of about 36,000 km is adjusted so that the satellite rotates about the Earth's axis at the same speed as the Earth rotates, that is, once a day. Thus, the satellite remains stationary with respect to the Earth.

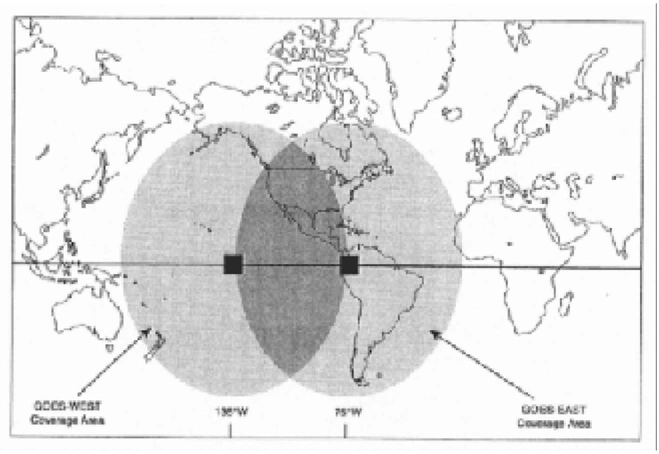

Figure 2-1
Geographic coverage of the two-GOES system.

an operational system for meteorology. NASA developed the new spacecraft system and built two prototypes, called synchronous meteorological satellites, SMS-1 and SMS-2. They were launched in May 1974 and February 1975. Three identical operational versions funded by NOAA, GOES-1, -2, and -3, were launched in October 1975, June 1977, and June 1978 (see Table 2–5). The primary sensor on all five satellites was the visible infrared spin scan radiometer (VISSR). The addition of an infrared channel permitted imaging 24 hours a day. The resolution of the visible channel was 1 km at the satellite subpoint; for the infrared, it was 7 km at the subpoint. Also included was an SEM, the GOES data collection system for gathering and relaying environmental data from remote data platforms, and the WEFAX broadcast service for transmitting processed satellite images and weather maps that could be received by anyone with relatively inexpensive equipment.

TABLE 2-5 SMS and GOES Series Satellites Launched through 1995

Name[a]	Launch Date[b]	End of Useful Life[c]	Features[d]
SMS-1[e]	17 May 74	29 Jan 81	VISSR,[f] GOES DCS,[g] WEFAX[h]
SMS-2	6 Feb 75	5 Aug 81	same
GOES-1	16 Oct 75	3 Feb 85	same
GOES-2	16 Jun 77	26 Jan 79	same
GOES-3	15 Jun 78	5 Mar 81	same
GOES-4	9 Sep 80	26 Nov 82	VAS,[i] GOES DCS, WEFAX
GOES-5	22 May 81	30 Jul 84	same
GOES-6	28 Apr 83	21 Jan 89	same
GOES-G	3 May 86	launch failure	
GOES-7	26 Feb 87	standby	same
GOES-8	13 Apr 94	operational	GOES-I-M imager and sounder, DCS, WEFAX
GOES-9	23 May 95	operational	same

[a] See footnote 4 on page 13 for the convention used in naming satellites.

[b] All spacecraft placed in geostationary orbit. When at least two spacecraft are operational, one is usually located over the Pacific Ocean at about 135 degrees west longitude and the other at about 75 degrees west longitude (see Figure 2-1). When only one spacecraft has been operational, it is usually moved to about 98 degrees to 112 degrees west longitude.

[c] Various sensors and other units may have degraded or failed before the satellite was turned off.

[d] Primary sensors of high priority in the current modernization of the NWS, that is, imagers and atmospheric sounders (see p. 9) plus data collection and relay.

[e] SMS-1 and SMS-2, the prototypes of this new series of satellites, were funded, named, and operated by NASA. The subsequent operational satellites were funded and named by NOAA.

[f] Visible infrared spin scan radiometer, for day and night imaging.

[g] Geostationary operational environmental satellite data collection system

[h] Weather facsimile (for relay of weather maps and satellite images).

[i] Visible infrared spin scan radiometer atmospheric sounder (developed by NASA).

[j] First of the completely new design, GOES-Next, with three-axis stabilization and new sensors for imaging and obtaining soundings of the atmosphere.

Five additional GOES spacecraft were procured to continue geostationary coverage during the 1980s. Four, GOES-4 through GOES-7, were launched from September 1980 to February 1987; however, the fifth, GOES-G, suffered a launch failure in May 1986. The main difference in the sensors on these satellites from the earlier GOES series was the use of 12 infrared channels to obtain soundings of the temperature and humidity of the atmosphere, in addition to imaging the clouds and the Earth's surface. This new sensor was called the VISSR atmospheric sounder. However, images and soundings could not be obtained at the same time. Since the highest operational priority was given to tracking severe weather using geostationary satellite images, the soundings were obtained only on an experimental basis. (The NWS relied on the NOAA series of polar-orbiting satellites for soundings from areas of the Earth where sounding data from surface-based or other systems were limited or not available.)

The GOES spacecraft are normally operated in pairs: one is located at about 75 degrees west longitude, and the other at about 135 degrees. Together they provide coverage of the United States and adjacent oceans. When only one spacecraft was operational, it was positioned at about 100 degrees west, which limited or eliminated coverage of Hawaii and much of the Pacific and Atlantic oceans. Insufficient coverage of these areas is of particular concern during the hurricane season. Extended periods of such limited coverage occurred during July 1984 to March 1987 and January 1989 to February 1993, when only one GOES spacecraft was in operation. The single remaining GOES spacecraft was moved to 98 degrees west longitude during the summer-fall period to enhance coverage of hurricanes in the Atlantic Ocean. In the winter it was moved to 108 degrees west longitude to optimize coverage of storms over the Pacific Ocean.

Five spacecraft, GOES-I through GOES-M, were ordered in the GOES-Next series. The first two, now called GOES-8 and GOES-9, were launched in April 1994 and May 1995, and are currently in operation. GOES-K is scheduled for launch in April 1997. The two remaining spacecraft are in various stages of construction (see Chapter 4).

The design of the GOES-Next spacecraft represents a major step forward from the previous GOES. Most important for the NWS is the use of separate imagers and sounders (so both can operate at the same time) with much higher temporal and spatial resolution, more channels, and more precise measurements than the earlier GOES. The new three-axis stabilization (which replaces the older spinning spacecraft) increases the effective sensitivity of the sensors. Also, the navigational accuracy has been improved, which permits more rapid geographical location of data.

3

National Weather Service Uses of Satellite Data

Satellite data and satellite products have been important elements of NWS operations for more than 20 years. They will become even more critical in the modernized weather service. When one examines the uses of satellite data specific to the internal forecast and warning operations of NWS, two main applications are evident. The first is the use of global data in numerical weather prediction models; the second is the use of satellite imagery for mesoscale and short-range weather warning and prediction. The former application has relied primarily on data from the POES sun-synchronous, polar-orbiting satellites, while the latter depends primarily on data from GOES satellites in geostationary orbit. It must also be noted that satellite data are widely used outside of the NWS. Users include private-sector weather service providers, other government agencies, the media, and educational institutions. Important uses of satellite data, beyond weather forecasting applications, include climate monitoring, climate research, and oceanographic applications (see Box 3-1).

SATELLITE DATA IN NUMERICAL WEATHER PREDICTION

The primary NWS user of POES data is National Centers for Environmental Prediction (NCEP), formerly known as the National Meteorological Center. The NCEP uses the data to initialize numerical weather prediction models (see Box 3-2). Currently NCEP uses POES data, essentially on a global basis.

The data that have traditionally been used are the profiles of temperature and humidity inferred from multispectral radiances measured by the TIROS operational vertical sounder (TOVS).[1] For comparable medium-range forecasts for the

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[1] TOVS includes three components: the HIRS and MSU, and, on some satellites, the SSU.

southern hemisphere, these data have provided about a one-day advantage over forecasts made without satellite data. For example, a forecast that includes POES data will be as accurate for the fifth day as a forecast made without POES data would be for the third or fourth day.

BOX 3-1 ROLE OF SATELLITE DATA IN MONITORING CLIMATE AND OTHER APPLICATIONS

The NRC has previously noted the importance of the NWS modernization in climate monitoring and research (NRC, 1991; NRC, 1992). Satellite data play a unique role because of their systematic and global nature. Estimates of critical variables, such as sea-surface temperatures, snow and ice cover, cloud cover, water vapor distributions, precipitation, and soil moisture are all provided globally from both geostationary and polar-orbiting satellites. Indeed, well-calibrated, space-borne radiometers may be among the most accurate means for measuring global temperature change (Spencer and Christy, 1992a and 1992b). The essential need for satellite data in climate applications is discussed in considerable detail in other NRC reports (NRC, 1988; NRC, 1990). NOAA's operational satellite data contribute significantly to the climate mission.

Another important operational use of satellite observations (from both geostationary and polar-orbiting platforms) is estimating snowpack conditions for hydrologic forecasting of snowmelt and runoff. At the NWS National Operational Hydrologic Remote Sensing Center in Chanhassen, Minnesota, visible and infrared imagery from geostationary satellites is used to map the areal extent of snowpack on the ground. Highly reflective surfaces in the visible spectral range are classified either as clouds or ground snowpack, depending on the physical temperature derived from infrared channels. Under large-scale cloudy conditions, microwave measurements by polar-orbiting satellites replace geostationary satellite observations in estimating snowpack cover.

Estimates of snowpack coverage and liquid water equivalent are made by merging satellite observations, ground measurements, and gammaray sensor aircraft observations. A gridded product has been developed and used at NWS River Forecast Centers to forecast snowmelt and run-off. Many spring floods and flash floods are associated with melting snow-pack caused by rain on snow or rapid changes in air dry-bulb or dew-point temperatures.

New ways are being discovered for more effective, quantitative use of satellite data. In October 1995, NCEP implemented a new method to incorporate POES data. According to their tests, this method demonstrated the single largest improvement in the analysis and forecast system in the past decade. The new method uses spectral radiances from POES directly in the data assimilation cycle, rather than first converting the radiances into vertical profiles of temperature and humidity. By incorporating the radiances directly, the model's temperature, water vapor, and wind fields adjust in a mutually consistent way to all available observations so that the radiances calculated from the model variables match the observed radiances more closely.

POES sounding data (see Box 3-3) are used in the NCEP's regional and global models; direct use of radiances will be operational in the regional systems by the end of 1996. NCEP also uses total precipitable (vertically integrated) water vapor, which is derived from the special sensor microwave/imager (SSM/I) on the DMSP spacecraft. Surface wind speed over the oceans, inferred from SSM/I data, and sea-surface wind speed and direction over the oceans, inferred from scatterometer data obtained by the European remote-sensing satellite ERS-1, are also used.

NWS is concerned that the quality and number of radiosonde observations worldwide are declining, particularly in developing countries. As a result, NWS will have to rely even more heavily in the future on both satellite information and aircraft data and, perhaps, on adaptive observations, for numerical weather prediction cycles. Another important application of POES data is for imagery of weather phenomena in northern latitudes beyond the range of GOES coverage, particularly for aviation forecasting in Alaska and the heavily traveled northern-Pacific commercial air routes.

Data from the PM[2] satellite have historically been of primary importance for numerical models. Data from the AM satellite are used partly as a backup; however, they also contribute to the numerical weather prediction cycles. The AM satellite data will become even more important as the resolution of models increases and they require data with higher temporal and spatial resolution. Both the NCEP and the European Centre for Medium Range Weather Forecasts have already had a positive impact using data from a second POES. In any case, long-term operations with a single polar orbiter would be unacceptable because, if it were to fail, the delay in launching a replacement would lead to an unacceptable degradation of weather forecast skill and reliability in the intervening period.

Finding 1a. At least one operational POES is needed in orbit at all times to provide data vital to global numerical-prediction models. A backup POES in orbit also is required to ensure that unacceptable degradation of service does not occur when the operational POES fails. The backup satellite may also be operated simultaneously with the first satellite, thus providing global coverage four times a day. A replacement must be available for launch in case either of the orbiting spacecraft fails.

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[2] PM and AM refer to the afternoon and morning crossing of the equator by the satellite in a north or south direction, respectively, in the sun-synchronous orbit. See footnote 2 on page 10.

BOX 3-2 NCEP MODELS[1]

The NCEP routinely runs global and regional numerical forecast models in support of operational requirements of the NWS. Models that are run on a daily basis include the mesoscale eta model (named for the Greek letter used as a symbol for the vertical coordinate), the nested grid model (NGM), the rapid update cycle (RUC), the aviation (AVN) model, and the medium range forecast (MRF) model. The hurricane model is run whenever a tropical storm or hurricane develops in the Atlantic, east Pacific, or Caribbean basins (including the Gulf of Mexico).

The suite of production jobs, which ingests meteorological information, analyzes it, and predicts the future state of the atmosphere for world-wide distribution, comprises a number of subsuites, or “runs.” The runs, although they differ in purpose and content, have much in common. Each run includes the establishment of initial conditions and describes the current state of the atmosphere, forecasts the future state, and disseminates the analyses and forecasts to many users. There are six such runs; all but one are repeated twice daily. The six runs are named either for their relative positions within each cycle (early or final) or for their general purpose (regional, aviation, hurricane, or medium-range forecast).

The early (ERL) eta run provides a regional forecast over the United States as soon as possible after 0000 and 1200 Greenwich Mean Time (GMT) synoptic times for early guidance out to 48 hours to the NWS and the meteorological community at large. The ERL is run on a 48-km grid covering all of North America and has 38 layers in the vertical. At the initial and six-hour forecast times, it produces isobaric heights, temperature, and wind fields on standard output grids. Other information provided includes freezing levels, stability parameters, and relative humidity.

The mesoscale (MSO) eta run provides forecasts over the United States at a very high resolution (29 km), from 0300 and 1500 GMT out to 33 hours, for internal distribution to the NWS and to the greater meteorological community via Internet. The MSO model produces weather forecast elements at the initial time and every three hours.

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[1] This information is primarily from the NCEP Annual Numerical Model Research Report, May 1996.

The regional run produces forecasts to two days for the United States, using the regional analysis and forecast system. Sequences of analyses and short-range forecasts from the nested grid model (NGM) are produced every three hours during the 12-hour pre-forecast period. The analysis grid has a resolution of approximately 90 km over North America and 200 km elsewhere. The NGM forecasts are for 16 layers and a two-grid nested system out to 48 hours. The forecast grids have approximate resolution of 170 and 85 km at 45 degrees north latitude and a resolution of 320 km for the hemispheric grid. Model output statistics from the NGM are produced twice a day for more than 700 locations in the United States for a wide range of weather elements, such as maximum/minimum temperature, surface wind speed and direction, probability of precipitation, cloud ceiling height, visibility, and similar data.

The RUC run provides high-frequency, short-term forecasts on a 60-km resolution domain covering the contiguous 48 United States and adjacent areas of Canada, Mexico, and oceans. Every three hours the RUC produces analyses and hourly forecasts out to 12 hours. The prediction system uses a hybrid vertical coordinate of 25 levels. The output from this model includes variables such as temperatures, heights of coordinate surfaces, relative humidity, and wind components.

The AVN run is the first forecast in each cycle that is global in extent. Its primary purpose is to prepare guidance in support of NCEP's international aviation responsibilities. The forecast model and analysis system are identical to the MRF described below. The forecast is run to 72 hours with the production of pressure-level information at six-hour intervals. An array of weather elements similar to those produced in the NGM output are available for 225 locations in the contiguous United States, Alaska, and southern Canada from both the 0000 and 1200 GMT runs.

The MRF run is generated only in the 0000 GMT cycle. Its purpose is to generate a global forecast for the medium-range scale, generally understood to mean the three-to ten-day range. Vertical resolution is 28 levels throughout. Data cutoff time is six hours after the synoptic observation times of 0000, 0600, 1200, or 1800 GMT. Objective guidance is available from this model for a wide range of weather elements for over 225 stations in the contiguous United States, Alaska, and southern Canada.

Other runs, for example, the hurricane run and the ensemble run, are for special operational support or test purposes, respectively, and are not included in this summary.

NCEP global models also use winds estimated from tracking the horizontal motion of clouds and water vapor viewed by GOES. The only GOES-7 sounder data used operationally by NCEP prior to 1996 were gradient winds. However, in 1997 NCEP plans to incorporate precipitable water data from GOES-8 into its regional models. Reasons for not previously using GOES temperature and moisture sounder data include the following:

- The GOES sounder was considerably less accurate than existing TOVS. Because there was no microwave instrument to remove the effects of clouds, sampling of GOES data was confined to clear regions of the atmosphere, which are relatively well predicted by forecast models.
- Experiments with first-generation sounder data from GOES-4 through GOES-7 in numerical weather-prediction models did not demonstrate more accurate forecasts.

Since the introduction of GOES-8 and GOES-9, NCEP has increased its emphasis on the operational use of sounder data. NCEP is evaluating the quality of GOES-8 and GOES-9 sounder products, including temperature and moisture retrievals and radiances within operational numerical models. They are collaborating with NOAA's Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin-Madison and with NESDIS to optimize the use of satellite information by using radiance data directly in NCEP's next generation analysis systems (NOAA, 1995).

USE OF GEOSTATIONARY SATELLITE DATA BY WEATHER FORECAST OFFICES

The GOES data are a fundamental information source for NWS field offices. The first system that provided GOES images to some forecast offices was installed in the late 1970s. This analog facsimile transmission system required about 35 minutes for processing and delivery of a GOES image to the forecaster. The information was qualitative, and the forecaster could not control either the area covered or the resolution of the scenes. Digital data became available on a limited basis in 1982. The staff at the Storm Prediction Center state, without equivocation, that the availability of digital geostationary satellite data in 1982 led to an immediate "quantum improvement" in the accuracy of tornado watches. In 1985, improved analog satellite imagery was made available to 52 NWS field offices. Recently, a digital system that uses personal computers and data from the regional and mesoscale satellite data information system (RAMSDIS) was made available to 25 NWS field offices.[3]

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[3] RAMSDIS was developed, installed, and training was provided through the collaboration of the NWS, NESDIS, and scientists at NOAA's Cooperative Institute for Research in the Atmosphere at Colorado State University.

BOX 3-3 SOUNDING DATA

To be useful for analyses and forecasts, sounding data must be gathered over large portions of the globe within fixed time constraints. Since the polar-orbiting satellites require time to traverse each orbit, and must rely on the rotation of the Earth beneath them to provide global viewing, the data are not gathered simultaneously or “synoptically,” as is desired by current operational numerical analysis models. The numerical models will, however, accept data within ±3 hours of the primary synoptic times of 0000 and 1200 GMT, and of the secondary synoptic times of 0600 and 1800 GMT. The present two-satellite POES system provides data valid (within ±3 hours) for use in numeric models initialized for both primary synoptic times. By international convention, radiosondes are released near 0000 and 1200 GMT each day. The combination of satellite data and radiosonde data is the principal source of data for the primary synoptic analysis periods. Satellite data coverage of data-sparse (no radiosonde data) regions of the world (oceans, southern hemisphere, and polar regions) is critical to the proper analysis of the atmosphere, which in turn forms the basis of the 24-hour to 5-day numerical forecasts of global and regional weather. The POES satellites are the principal source of sounding data that are valid for the “off-time” analysis cycles of 0600 and 1800 GMT. The present orbit of the afternoon satellite provides timely coverage over the eastern Pacific to gather data vital for the analysis and forecast models that are used for 12- to 48-hour forecasts of the weather over the continental United States. The proper analysis of weather systems that originate between 180 degrees west longitude and the west coast of the United States is critical to the accuracy of these models. These are the weather systems that will move eastward and affect U.S. weather in a 12- to 48-hour time period. Source: DOC (1985).

Images of weather phenomena provided by geostationary satellites are essential for field office operations for mesoscale and short-range forecasting because they are continuously available in real time. Forecasters rely heavily on visible and infrared imagery for monitoring the tracks and evolution of severe storms, hurricanes, extra-tropical cyclones, and a host of other weather phenomena. Time-lapse imagery is particularly valuable. Data obtained over the Pacific and Atlantic oceans are critical for aviation and marine forecasts.

In the Weather Service Forecast Office in Honolulu, Hawaii, which has forecast and warning responsibility for areas as far west as Guam, Fiji, and Samoa, satellite data are often the most reliable indicators of changing and significant weather. Indeed, forecasters in this office, as well as at the Aviation Weather Center, also use the Japanese geostationary meteorological satellite; forecasters on the eastern seaboard use the European METEOSAT. In addition to monitoring existing weather systems, the capability of geostationary satellites for detecting water-vapor fields and thin cloud lines and for deriving winds from the motion of clouds and water vapor has improved the accuracy of local weather forecasts.

Reliable and continuous service from the operational satellites remains a dominant national requirement. Since completely redundant systems and sensors are not provided aboard each satellite, sufficient GOES and POES must be launched to provide the necessary redundancy in orbit at all times.

Finding 1b. At least two operating GOES satellites are needed in orbit at all times to provide the necessary coverage from the central Pacific Ocean eastward to the coast of West Africa.[4]

Recommendation 1. To meet NWS high priority requirements for satellite coverage in support of weather forecasts and warnings, NOAA must ensure that the requisite data are available at all times from at least one POES and two GOES in orbit. To ensure this continuity, a backup POES and a backup GOES need to be available in orbit.

Finding 2. The GOES-8 and GOES-9 offer an opportunity to establish the operational utility of deriving soundings and upper air winds from GOES data and implement new operational techniques. Field office staff visited by the committee would like to have access to sounding and wind data from GOES.

Work at the Forecast Systems Laboratory, Aviation Weather Center, Storm Prediction Center, National Center for Atmospheric Research, and universities will also contribute to the recommended research and development effort. This effort is fundamental to improving forecasts and warnings and to providing sufficient information for NOAA's future decisions regarding the North American Atmospheric Observing System and the design of the next generation of satellites for the 21st century.

Recommendation 2. NWS/NOAA should fully support efforts to develop and demonstrate techniques for using GOES soundings and winds to improve warnings and forecasts. It is essential that the NESDIS and the NWS (particularly the NCEP) devote adequate personnel to processing, evaluating, and applying newly available satellite data as soon as possible. Science operations officers and other field staff could also contribute to this effort.

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[4] See Finding 7 on page 39 regarding the need for an additional standby GOES in orbit.

4

Ensuring Continuity

The meteorological requirements for polar and geostationary satellite data were discussed in Chapter 3. Based on these requirements, the committee assessed the number of each type of satellite that is required to be operating in orbit. This chapter examines the launch and in-orbit performance of POES and GOES satellites and uses this information to predict future performance. These predictions are based on Monte Carlo studies, with appropriate assumptions about launch successes, availability of satellites on the ground, delay in the launch and check-out of a replacement for a satellite that fails in orbit, and the expected life of consumable supplies on the satellites.[1] These studies are compared with the schedule of POES and GOES spacecraft in orbit, under contract, and planned to determine whether the NOAA satellite program is on a sound footing regarding the continuity of observations for the NWS. Finally, POES and GOES ground systems are examined for possible vulnerability as well as the possibility of other spacecraft providing some backup to POES and GOES in an emergency.

PAST PERFORMANCE OF GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES AND POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITES

The operational experience for GOES over about two decades is summarized in Table 4-1. Useful life of the U.S.-launched geostationary satellites ranges from

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[1] The Monte Carlo model operates using random numbers to select the probability of events occurring in a large number of simulated scenarios. The resulting ensemble of scenarios is presumed to represent the probability distribution (PD) of the true events. It is analyzed to estimate the PD of key results, such as number of operating satellites versus time. Sensitivity to assumptions about various parameters (launch success, satellite mean-time-to-failure, etc.) can be determined by varying the appropriate parameter, rerunning as a new case, and comparing the results.

TABLE 4-1 SMS/GOES Operational Experience

West Operational Spacecraft (135 degrees west longitude)	Central Operational Spacecraft (98 to 112 degrees west longitude)	East Operational Spacecraft (75 degrees west longitude)
SMS-2 03/10/75 to 04/04/78		SMS-1 11/15/74 to 01/08/76
GOES-1 04/04/78 to 07/13/78		GOES-1 01/08/76 to 08/15/77
GOES-3 07/13/78 to 03/05/81 (fail)		GOES-2 08/15/77 to 01/26/79 (fail)
GOES-4 03/05/81 to 11/26/82 (fail)		SMS-1 01/26/79 to 04/19/79
GOES-1 11/29/82 to 06/01/83; no IR[a]		SMS-2 04/19/79 to 08/05/81 (fail)
GOES-6 06/01/83 to 07/30/84 (Break in west service)	GOES-6 07/30/84 to 03/25/87	GOES-5 08/05/81 to 07/30/84 (fail)
GOES-1 08/27/84 to 02/03/85; no IR[a] (fail) (Break in west service)		(break in east service)
GOES-6 03/25/87 to 01/21/89 to 01/21/89 (fail) (Break in west service)	GOES-7 01/21/89 to 01/20/95	GOES-7 03/25/87 to 01/21/89 (Break in east service)
GOES-7 01/20/95 to 01/11/96		METEOSAT-3 02/28/93 to 01/23/95[b]
GOES-9 01/11/96 to present		GOES-8 01/20/95 to present

[a] Infrared (IR) channel failed 3/24/79, eliminating all night-time images from GOES-1.

[b] A spare METEOSAT was loaned by the European consortium, EUMETSAT. After installation of the necessary ground equipment and communication links of the NESDIS CDA station in Wallops Island, Virginia, METEOSAT-3 was moved to 75 degrees west longitude where it operated until 1/23/95, at which time it was moved to 70 degrees west longitude.

Notes:

1. One SMS/GOES spacecraft, GOES-G, suffered a launch failure in June 1986.
2. When a spacecraft was moved from one location to another, the departure date shown above is also assumed to be the subsequent arrival date at the new location. The actual movement rate is about .5 to 1 degree/day.
3. Low-level satellite winds (picture pair or triplet) have been operational with interruptions as indicated above. They are produced from IR data, with exceptions as noted (that is, when only visible data were available).
4. Regarding the data collection system (DCS), the Satellite Services Division of NESDIS does not believe there has been a major failure since the new DCS automated processing system (DAPS) was established in 1989. Data sets were periodically lost because of problems with ground equipment, especially hard disk failures, starting in August 1993. New disks installed in September 1994 resolved the problem.

1.55 years to 9.30 years (Hernandez, 1994).[2] The breaks in service for a west operational GOES and an east operational GOES are also listed in Table 4-1 and discussed below; the failures are described in the accompanying notes.

From July 1984 to March 1987, and again from January 1989 to February 1993, just one geostationary spacecraft that provided forecast support was in operation.[3] Three factors were responsible:

- The lifetimes of four GOES spacecraft (GOES-2 through GOES-5) were much shorter than expected because of a component problem.
- The launch vehicle for GOES-G failed.
- The development of the new GOES-Next series of geostationary satellites experienced delays.

Generic problems, such as the problems that arose on GOES-2 through GOES-5; launch failures (e.g., GOES-G); and delays in procuring and introducing new technology (GOES-Next) justify the conservative planning of launch schedules. Fortunately, making backup arrangements with a consortium of European nations was possible. One of their geostationary weather satellites, METEOSAT-3, was borrowed from 1993 until the first satellite in the GOES-Next series could be completed, launched, and used operationally in 1995. The METEOSAT-3 was used to provide coverage of the eastern United States and the Atlantic Ocean.

Table 4-2 is a summary of the operational experience for POES, including outages (and degradations) of sensors on the morning POES and afternoon POES. The problems experienced by the POES are described in the accompanying notes.

The useful life of the POESs launched since 1978 has ranged from 12 days to more than eight years. The more recent satellites have lasted longer than expected, with the exception of NOAA-13. Through December 1995, the mean life, defined as the total operating time divided by the number of failures, has been five years (Broadhurst, 1996). Because of the limited number of failures in this series of spacecraft, Broadhurst also calculated an estimated average mission life of 4.3 years with a 70 percent confidence factor. These computations do not include the ITOS series of six satellites, which bear little resemblance to the current satellite or instrument designs.

PREDICTIONS OF FUTURE PERFORMANCE.

NASA commissioned engineering studies to evaluate the probabilities of GOES and POES continuity as the POES program makes the transition to the

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[2] Useful life is the length of time a satellite actually performed its mission.

[3] METEOSAT-3 started operation as the east satellite in February 1993.

TABLE 4-2 POES Operational Experience[a]

Morning Operational Spacecraft—about 0730 local sun time

		Atmospheric Sounding		
Spacecraft	Imaging: AVHRR	HIRS	SSU	MSU
NOAA-6[b]	7/79 to 8/81, 9/81 to 2/82 no AM images 8 to 9/81 and 2/82 to 6/83	7/79 to 6/83	7/79 to 6/83	7/79 to 6/83
NOAA-8[c]	6/83 to 6/84 and 7 to 10/85	6/83 to 6/84	6/83 to 6/84	6/83 to 6/84
NOAA-6[d]	10/85 to 1/87 no AM images 6/84 to 7/85	failed	6/84 to 1/87	6/84 to 11/86
NOAA-10	11/86 to 9/91	11/86 to 9/91	none	11/86 to 9/91
NOAA-12[e]	9/91 to present	9/91 to present	9/91 to present	9/91 to present

Afternoon Operational Spacecraft—about 1330–1430 local sun time

		Atmospheric Sounding		
Spacecraft	Imaging: AVHRR	HIRS	SSU	MSU
TIROS-N[f]	1/79 to 1/20/80	1/79 to 1/20/80	1/79 to 1/20/80	1/79 to 1/20/80
TIROS-N	1/30/80 to 11/30/80	1/80 to 2/81	1/80 to 2/81	1/80 to 2/81
NOAA-B	launch failure, 1980; no PM data 2/81 to 8/81			
NOAA-7	8/81 to 2/85	8/81 to 2/85	8/81 to 2/85	8/81 to 2/85
NOAA-9[g]	2/85 to 11/88	2/85 to 11/88	2/85 to 11/88	2/85 to 11/88
NOAA-11[h]	11/88 to 9/94	11/88 to 1/95	11/88 to 1/95	11/88 to 1/95
NOAA-13[i]	spacecraft failed after 12 days			
NOAA-14	1/95 to present	1/95 to present	1/95 to present	1/95 to present

[a] Only the imaging and sounding instruments, of prime importance to the NWS modernization, are covered in this table. Dates shown are for the provision of operational data, not necessarily component life.

[b] NOAA-6 had no AVHRR 8/81–9/81 due to excessive jitter. Also MSU may have degraded beginning 11/79.

[c] NOAA-8 attitude control system failed 6/84 and recovered later, affecting all sensors.

[d] After NOAA-8 failed, NOAA-6 again provided coverage on a limited basis from June 1984 to January 1987.

[e] NOAA-12 AVHRR degraded periodically by line jitter (11/91, 1/92, 12/92, 3/94).

[f] NASA prototype spacecraft.

[g] NOAA-9 HIRS long-wave channels became noisy, significantly degrading soundings beginning 12/84. MSU lost one channel (of three) 2/87; a second failed 5/87; these failures significantly degraded soundings.

[h] NOAA-11 AVHRR and HIRS degraded from 10/89 due to orbit drift that caused sunlight to periodically enter instrument apertures. No aerosol optical thickness or global vegetation index products 9/14/94 to 3/20/95. The NOAA-11 AVHRR failure on 9/14/94 resulted in loss of aerosol products until NOAA-14 was operational on 3/20/95. Sea surface temperatures were switched to NOAA-12. During this period, radiation budget and coast watch products were produced only from NOAA-12, instead of from both morning and afternoon spacecraft.

[i] The electrical problem that caused a failure of NOAA-13 has been identified. Design modifications were made in subsequent spacecraft to preclude a recurrence.

NPOESS era. Based on stated assumptions, these studies included predictions (based on Monte Carlo techniques) of satellite in-orbit availability for the next decade or so. The results of these studies are not exact, however, because of the uncertainty and dispersion in the reliability data and because of the assumptions used. However, the committee found that the results do provide order of magnitude estimates and indicate their sensitivity to variations of parameters and assumptions.

Four important assumptions were used in the GOES study (Hernandez, 1994):

- Satellite reliability mean-time-to-failure was based on earlier experience.[4].
- Engineering studies of propellant consumption (provided by NASA) were used.
- Failed satellites were assumed to be replaced as needed, with a delay to account for preparation of the replacement satellite for launch, availability of a launch slot, and check-out of the new satellite in orbit.
- Launch vehicle reliability was assumed to be 90 percent, the industry average at that time.

This operating scenario projected ten GOES launches from 1994 through 2009, with six failures during that time, ending with two operational satellites and two backup satellites in orbit (see related discussion on pp. 33–34). Hernandez (1994) includes a figure (presented here, with scale adaptations, as Figure 4-1) showing that, under the assumptions listed above, the probability of two GOES spacecraft operating in orbit from now until 2012 is approximately 95 percent. Allowances have been made for some of the more pessimistic startup conditions used by Hernandez. For example, the committee notes that industry launch reliability as of December 1995 is better than the 90 percent value assumed in the Hernandez study.

The Monte Carlo model of the original POES study (Hernandez, 1995) has been updated and is now called the NASA “Mission Planning Model” (Mazur, 1996). The new set of assumptions reflect an additional year of experience with POES:

- Satellite life is based on TIROS/POES experience through December 1995.
- The availability of POES satellites is based on the current production schedule.
- More precise launch vehicle reliability data are used (e.g., Titan II. 94 percent; Delta, 97 percent; Ariane-5,[5] 90 percent).
- The response time to replace a failed satellite has been updated.

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[4] In this regard, it should be noted that GOES-8 and GOES-9, launched in 1994 and 1995, are of a major new design compared to previous GOES. Thus experience with the new design is very limited.

[5] Ariane-5 reliability was introduced to account for launches of the METOP satellites.

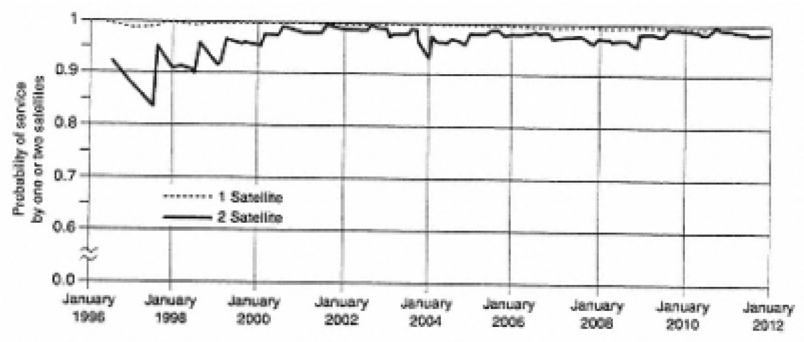

Figure 4-1
Availability of GOES service in a two-satellite constellation. Adapted from Hernandez (1994).

These factors were used to predict the probability of POES satellites operating in orbit. Figure 4-2, derived from the data in Mazur (1996), shows that the probability at any given time of at least one POES operating in orbit from 1996 to 2002 (when METOP-1 is scheduled to be available) is better than 95 percent. If METOP-1 and METOP-2 are included as a part of the operational scenario, the probability of at least one polar satellite operating remains better than 95 percent to at least 2010. Launch of the first NPOESS is currently planned for about 2008, and this time frame was included in the operational scenario.

These models may be used to indicate behavior and approximate levels of availability of the POES and GOES satellites. Sensitivity studies in the referenced reports showed the system to be fairly insensitive to variations in parameters, such as satellite reliability and lifetime (due to expendables). The strongest

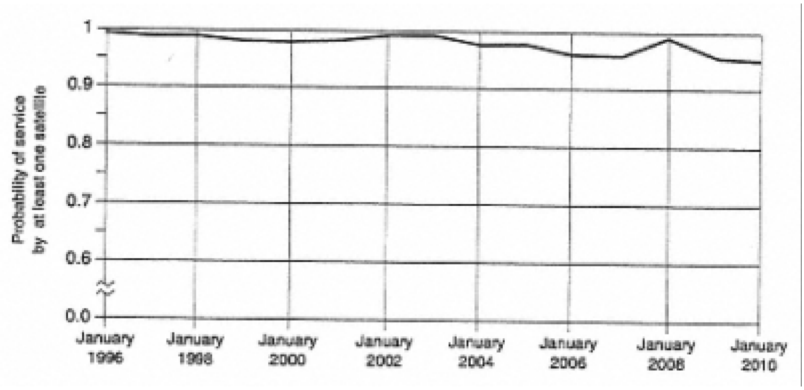

Figure 4-2
Availability of POES service by at least one satellite in a two-satellite (AM and PM) constellation. Derived from data in Mazur (1996).

influences were the programmed delivery dates of satellites and launch vehicles and the long delays between failure of a vehicle in orbit and the launch of a replacement. The models are useful as tools to judge the effect of alternate choices in the replenishment launch-decision process discussed in the section on Satellite Launches later in this chapter.

SCHEDULE OF FUTURE GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITES AND POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITES

The planned launch schedule for GOES is shown in Table 4-3. The actual schedule will depend primarily on the need for replacement satellites, of course, but also on spacecraft and launch availability. NOAA has planned, but has not yet procured, a block of four additional satellites, essentially of the same design, to provide coverage through about 2012. This plan assumes three-year lifetimes for GOES-8 and GOES-9, with one launch failure in the series; a four-year lifetime for GOES-K; and five-year lifetimes for the remaining five spacecraft, following

TABLE 4-3 GOES Schedule

Satellite[a]	Need Date[b]	Satellite Availability Date	Planned Launch Date[c]
GOES-8	Launched Apr 1994		
GOES-9	Launched May 1995		
GOES-K	Apr 1997	Apr 1997	Apr 1997
GOES-M	Apr 1998	Aug 1999[d]	Apr 2000
GOES-L	Apr 2001	Apr 2001	Apr 2002 (failure)
GOES-N	Apr 2001[e]		Apr 2002
GOES-O	Apr 2004		Apr 2005
GOES-P	Apr 2006		Apr 2007
GOES-Q	Apr 2008		Apr 2010
GOES-R	to be determined		

[a] This planning schedule assumes one launch failure (GOES-L), a lifetime of only three years for GOES-8 and GOES-9 (the first of a new design), a four-year lifetime for GOES-K, and five-year lifetimes for subsequent satellites of the same design (through GOES-Q). GOES-R is proposed as an new design with competitive procurement (requiring longer lead time). Spacecraft through GOES-M are under contract. The plan assumes that approval to contract for GOES-N et seq. and necessary funding will be received on schedule.

[b] The earliest date a satellite and launch vehicle are required to ensure mission continuity.

[c] Estimated launch date if no unexpected problems occur.

[d] In some cases, cuts in funding can interrupt the manufacturing schedule and delay the availability of satellites and launch vehicles.

[e] GOES-N through GOES-Q are not yet on contract.

successful launches. The Hernandez (1994) prediction of GOES continuity discussed earlier projected that ten launches in the period 1994 through 2009 would give a probability of approximately 95 percent of having two GOES operating in orbit until 2012. The current schedule (Table 4-3) calls for nine spacecraft to be launched in the same period.

The planning launch schedule for POES is shown in Table 4-4. This table, adapted from Winokur (1996), covers the period in which the POES program will undergo the transition to the NPOESS program. The launch of NOAA-K, scheduled for 1997, will provide some sensor improvements: the AVHRR/2 will have an additional channel (for a total of six) and some adjustments to spectral intervals; HIRS-3 will be introduced; and the MSU and SSU will be replaced by an advanced MSU to improve soundings in cloudy regions. Four additional spacecraft, NOAA-L,-M,-N, and-N', are under contract. Launch dates extend to 2007 (see Table 4-4). Negotiations with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) are under way. If agreement is reached, Europe will launch and operate the METOP mid-morning satellites in lieu of the morning POES now provided by NOAA. The launch schedule for NOAA-M is based on successful conclusion of the European agreement.

In May 1994, President Clinton signed a presidential decision directive to merge the POES system and the DMSP into a single system to “reduce the cost of acquiring and operating polar-orbiting environmental satellite systems, while continuing to satisfy U.S. operational requirements for data from these systems.” In response to this directive, an Integrated Program Office was established within NOAA on October 3, 1994. This office is staffed with DOD, NASA, and NOAA personnel.

TABLE 4-4 Polar Satellite Planning Launch Schedule

Spacecraft	Orbit[a]	Launch Year[b]
NOAA-K	AM	1997
NOAA-L	AM OR PM	2000
NOAA-M	AM OR PM	2001
METOP-1	AM[c]	2002
NOAA-N	PM	2003
METOP-2	AM[c]	2006
NOAA-N'	PM	2007
1st NPOESS	PM	2008[d]

[a] See footnote 2 on page 10.

[b] Planning schedule (calendar years) as of July 1, 1996.

[c] The European METOP satellite are to assume the AM orbit: NOAA and NPOESS satellites will cover the PM orbit.

[d] Subsequently, NPOESS also will replace DMSP in the early morning orbit (about 5:30 a.m. local standard time).

The present schedule calls for the launch by the United States of the first new, merged-system satellite, NPOESS in 2008, with subsequent launches as required to maintain continuity of coverage for the following decade. Studies are under way to develop a detailed definition of the capabilities of the sounders, imagers, and other sensors that will be flown on these new satellites. Present plans call for three NPOESS spacecraft to operate simultaneously, with two U.S. satellites (at the 0530 and 1330 equator-crossing times) and one European satellite, the METOP, at the 0930 equator-crossing time. The first METOP launch is planned for about 2002. It is anticipated that the NOAA POES spacecraft (through-N and-N') and METOP will provide coverage for NOAA until the new NPOESS is operational (see Table 4-4). The need and timing for "gap-fillers" in case of a delay in NPOESS (including METOP) depend on the availability factors discussed here and on the launch-decision process. It should be noted that the DMSP spacecraft can provide only a limited level of backup to the POES (see p. 36).

Finding 3. The polar program, as presently planned, depends on the availability of European METOP satellites in polar orbit from 2002 to 2010 and the availability of NPOESS beginning about 2008.

Recommendation 3. NOAA should closely coordinate the POES program with the progress of the NPOESS and METOP satellite programs so that "gap-filler" satellites are not needed.

Finding 4. In the longer term, the replenishment strategy depends on the new NPOESS for polar-orbiting satellites and on the procurement of additional GOES satellites. (NOAA plans to procure a new design beginning with GOES-R.) Longer lead times than normal are required when new designs, which are planned for GOES-R, METOP, and NPOESS, are introduced.

Recommendation 4. When considering ways to develop new spacecraft and incorporate major new improvements in technology, NOAA should carefully consider the lead times dictated by the required launch schedules and the very long procurement cycle. NOAA should develop schedules for the transition from current designs to new ones, such as NPOESS and GOES-R, that adequately account for the necessary lead times for funding approval, procurement, design and development, fabrication, and verification.

POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE GROUND SYSTEM

Spacecraft programming and commands originate at the Satellite Operations Control Center (SOCC) in Suitland, Maryland. Commands, spacecraft telemetry, and environmental data are relayed between the SOCC and CDA stations by commercial communication satellites.

The current POES ground system consists of two major subsystems: the polar acquisition and control subsystem (PACS) and the central environmental satellite computer system (CEMSCS). The PACS components are located at two CDA stations near Wallops Island, Virginia, and Fairbanks, Alaska; at the SOCC; and at a western European station near Lannion, France. PACS includes all components necessary to command and control the spacecraft, to monitor the health of the spacecraft using housekeeping telemetry, and to retrieve and transmit environmental data to the CEMSCS. The CEMSCS ingests, preprocesses, and stores the raw satellite data along with other information, such as data related to Earth location and quality control. This ground system for POES appears to be adequate for the foreseeable future.

POLAR-ORBITING OPERATIONAL ENVIRONMENTAL SATELLITE BACKUP

Reliable and continuous service from POES is a high priority design criterion. As noted in Chapter 3, at least one operational POES is needed in orbit at all times to meet data requirements for NCEP's global numerical prediction models. NOAA meets this requirement by having two operational POES in orbit at all times and launching another one whenever a primary spacecraft system or sensor fails.

In the event of a catastrophic POES failure, significant launch delay, or launch failure, NOAA and DOD have shared processing arrangements to provide a modest level of backup using sounder data from DMSP satellites. Because the current DMSP satellites are designed to meet military requirements, their sounding capabilities and orbit can provide only limited backup, which does not satisfy NOAA's primary requirements. The planned NPOESS, the follow-on to the current POES and DMSP, will have three operating spacecraft in orbit. One of these will be the European METOP. NPOESS plans reflect both U.S. civil (not only NWS) and military requirements, as well as European needs via their contribution of METOP. This NRC study of the high priority NWS needs for continuity finds that at least one operational POES should be in orbit at all times (p. 21). A backup POES should also be in orbit to prevent unacceptable degradation of service when the operational POES fails. If these plans for NPOESS materialize, there should be adequate spacecraft to meet NWS's backup requirements for polar orbiting satellites. However, it is important to maintain the planned schedules of the METOP and the NPOESS. (See findings and recommendations 3 and 4.)

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE GROUND FACILITIES AND BACKUP SYSTEMS

The operations ground equipment for GOES consists of components located at the CDA station near Wallops Island, Virginia, and the SOCC at Suitland, Maryland. Operational management and planning are performed at the SOCC, where all elements of the system are monitored, evaluated, scheduled, and commanded. Communications links, ground support equipment, and data transmission paths complete the interfaces among the GOES-specific components and other equipment. This network routes broadcast and mission data.

The operations ground equipment at the CDA station receives streams of raw images, sounder information, and other data from the GOES spacecraft. The data are formatted in real time, and this data stream is transmitted from the CDA station via its corresponding GOES spacecraft to primary system users. The data stream relayed by the GOES is also received at the CDA station and at the SOCC for use in other internal operations, such as diagnosing instruments and spacecraft and monitoring the quality of processed sensor data.

The Wallops CDA station is a potential single point of failure for the GOES system. Although the Wallops CDA station is internally redundant and can sustain many subsystem failures without significant effect on system performance, any phenomenon that could shut down the station, such as a hurricane, flooding, major fire, or explosion, would result in a complete cutoff of data from the GOES satellites. Minimum prudent backup would require an antenna subsystem and receiving, transmitting, data formatting, and processing subsystems to command a GOES satellite, receive telemetry, and acquire and distribute data from the sounding and imaging instruments. These backup systems would need to be located in an area geographically remote from the Wallops facility to ensure the continuity of operations.

Finding 5. The Wallops CDA station is a potential single point of failure for the GOES system. Shutdown of the station would result in a complete cutoff of data from the GOES satellites.

Recommendation 5. NOAA should implement an adequate backup system to the Wallops CDA station to ensure the uninterrupted operation of GOES satellites and the acquisition of sufficient data to generate basic image and sounding products to meet NWS mission requirements.

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE BACKUP

From 1993 to 1995, when only one GOES spacecraft was operational, EUMETSAT loaned NOAA a geostationary weather satellite, METEOSAT-3. The satellite was repositioned to 75 degrees west longitude in order to cover the eastern United States and Atlantic Ocean (see Table 4-1). This permitted restoration of U.S. geostationary satellite east-west coverage (imaging only) until the new GOES-8 satellite became operational. Subsequently, EUMETSAT permanently deactivated METEOSAT-3, the necessary ground equipment at NESDIS was removed, and communication satellite channels between NESDIS and EUMETSAT were discontinued.

A formal agreement, "Backup of Operational Geostationary Meteorological Satellite Systems," was consummated between NOAA and EUMETSAT in 1993 (NOAA and EUMETSAT, 1993). The agreement describes the backup EUMETSAT/NOAA will provide and the conditions under which backup will be provided in case of the launch or in-orbit failure of a GOES or METEOSAT. The agreement discusses gridded image data and wind vectors derived from the image data. Geostationary satellite sounding data are not included because METEOSAT does not have a sounding capability. Under the agreement, a satellite will be deemed to have failed if the expected products (images and winds) cannot be provided.

The agreement also specifies conditions under which a backup METEOSAT or GOES satellite would be moved to benefit the other party. Because of communication range, a METEOSAT would not be moved farther west than 50 degrees west longitude (rather than the 75 degrees used with METEOSAT-3). Under the agreement, if NOAA requests the move of an operable METEOSAT westward to a position that ensures U.S. coverage, it would be moved if an operational GOES fails, if no other operable GOES is in orbit, if a GOES launch is not possible within four months, and if at least two operable METEOSATs are in orbit. If EUMETSAT makes the same request for a GOES to be moved to ensure European coverage, but not farther east than 5 degrees west longitude, it would be moved only if the operational METEOSAT fails, if there is no other operable METEOSAT in orbit, if a METEOSAT launch is not possible within four months, and if at least two operable GOES are in orbit.

NESDIS now receives the full suite of processed METEOSAT data (satellite subpoint at zero degrees longitude) covering Europe, Africa, and adjacent oceans. These data are processed by EUMETSAT in Darmstadt, Germany, and rebroadcast through the METEOSAT to users, including NESDIS, via the Wallops CDA station. This data processing and relay system would be used if a METEOSAT were moved to 50 degrees west longitude to take the place of a GOES. (A METEOSAT can only be moved and operated west of 50 degrees west longitude if the communication satellite links are reestablished and the necessary ground equipment is installed at Wallops for command and control of the satellite from the EUMETSAT ground station at Fucino, Italy.)

The METEOSAT-6 backup satellite in orbit today has limited imaging and no sounding capability. Thus, under the current agreement and satellite availability, EUMETSAT can now provide only limited backup to GOES, even at 50 degrees west longitude. If the current METEOSATs fail and only two GOES remain in operational condition in orbit, the agreement could force the U.S. system down to only one GOES. The other GOES would be moved to a position to ensure European coverage (a longitude not specified in the agreement) to replace the METEOSAT. Thus, the backup appears to be of limited value for meeting NOAA's requirements.

Finding 6. Although arrangements have been made for a European geostationary meteorological satellite, METEOSAT, to provide backup to GOES under certain conditions, the coverage by METEOSAT or its successor is very limited compared to the coverage provided by GOES.

Recommendation 6. NOAA should ensure that a replacement GOES satellite can be launched and operated as soon as an operational GOES fails to continue the full level of coverage expected of this series of satellites.

SATELLITE LAUNCHES

As discussed earlier in this chapter and in Chapter 3, the NOAA mission requires at least two operational geostationary satellites in orbit at all times. At least one operational polar-orbiting satellite and an additional backup satellite in orbit are needed at all times to ensure continuous service. The launch-decision process is schedule driven, from call up until a satellite is in orbit and operational. Another satellite must be available to replace one that fails. It now takes nearly two years to call up, launch, and check out a GOES, if one is available on the ground. More than a year of this time is required for scheduling and launching a GOES using current commercial launch services. Thus, it appears that only a standby GOES satellite in orbit can ensure that there is no interruption of coverage. Since the availability of geostationary satellites from EUMETSAT appears to offer backup of limited value, NOAA is examining the merits of storing a GOES in orbit (in a non-operating mode) rather than on the ground.

Finding 7. One additional GOES is needed in orbit as a ready spare to protect against a dangerous, protracted loss of full, two-satellite coverage if one operational GOES fails. Even more severe, although far less likely, would be an outage of continual, real-time coverage if both satellites in orbit should fail before a replacement could be made operational. Dependence on commercial launches for GOES can lead to delays of well over a year, even if a spacecraft is available for launch.

Recommendation 7. To ensure the continuity of two-GOES coverage, NOAA should store a standby GOES in orbit, rather than on the ground, if this is technically and operationally feasible and cost effective.

The time to prepare, launch, and check out a POES is on the order of one year because government launch services are used. Other challenges to the continuity of both POES and GOES service include launch failures, satellite system and sensor failures, delays due to the introduction of new technology into the observing system, budgets, and a ten-year procurement cycle.

The determining factors in continuity of service are the time between a failure in orbit and an operating replacement and the recovery time after a launch failure. Consideration of these factors has led to establishing a launch-decision process in which a group of senior managers of the NWS and NESDIS regularly review the status of satellites in orbit, satellite production, the availability of launch times, the readiness of the next satellite in the short range, and the replenishment strategy in the long range. They also review satellite availability prediction studies and update them regularly. This review process recently led to a decision to delay the launch of GOES-K from May 1996 to April 1997. The review process also led to a decision to change satellite orientation and other steps to extend in-orbit lifetimes, thereby maintaining continuity of coverage.

Finding 8a. The launch-decision process used by NWS and NESDIS is appropriate.

Finding 8b. The planned GOES, POES, METOP, and NPOESS procurements are adequate to provide continuity of the NOAA geostationary and polar-orbiting satellites for at least the next 15 years, if they are funded and carried out on the current schedule.

Recommendation 8. To ensure continuity, NOAA should fund and procure the planned block of four GOES-Next spacecraft in a timely fashion and should avoid further delays in the METOP and NPOESS programs.

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Acronyms.

AM	morning crossing of the equator
APT	automatic picture transmission
ATS	applications technology satellite
AVCS	advanced vidicon camera system
AVN	aviation model
AVHRR	advanced very high resolution radiometer
CDA	command and data acquisition
CEMSCS	central environmental satellite computer system
DAPS	data collection system automated processing system
DCS	data collection system
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
ERBE	Earth radiation budget experiment
ERL	early eta run
ERS	European remote-sensing satellite
ESSA	environmental survey satellite
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GMT	Greenwich Mean Time
GOES	geostationary operational environmental satellite(s)

HIRS	high-resolution infrared radiation sounder
IR	infrared
ITOS	improved TIROS operational system
LST	local standard time
METEOSAT	the European geostationary meteorological satellite
METOP	the European meteorological operational satellite in polar orbit
MRF	medium range forecast
MSO	mesoscale eta run
MSU	microwave sounding unit
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NGM	nested grid model
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRC	National Research Council
NWS	National Weather Service
NWSMC	National Weather Service Modernization Committee
PACS	polar acquisition and control subsystem
PD	probability distribution
PM	evening crossing of the equator
POES	polar-orbiting operational environmental satellite(s)
RAMSDIS	regional and mesoscale satellite data information system
RUC	rapid update cycle
SAO	Systems Acquisition Office
SAR	search and rescue
SARSAT	search and rescue satellite aided tracking
SBUV	solar backscatter ultraviolet spectrometer
SEM	space environment monitor
SIRS	satellite infrared spectrometer
SMS	synchronous meteorological satellite
SOCC	Satellite Operations Control Center
SPM	solar proton monitor
SR	scanning radiometer

SSCC	spin scan cloud camera
SSM/I	special sensor microwave/imager
SSU	stratospheric sounding unit
TIROS	television and infrared observation satellite
TOVS	TIROS operational vertical sounder
VHRR	very high resolution radiometer
VISSR	visible infrared spin scan radiometer
VTPR	vertical temperature profile radiometer
WEFAX	weather facsimile (broadcasts from GOES)

Appendix

Summary of Panel Meetings

The Satellite Continuity Panel of the National Weather Service (NWS) Modernization Committee is composed of the following:

George J. Gleghorn, chair
William E. Gordon
Robert J. Serafin
David S. Johnson, advisor
Floyd F. Hauth, study director

The panel met five times to review the technical and management aspects of satellite continuity and backup. Information was gathered to provide the basis for the committee's analysis of the National Oceanic and Atmospheric Administration (NOAA) satellite program in accordance with the study tasks as approved by the Executive Committee of the Governing Board of the National Research Council. Following are summaries of the five meetings, including date, place, principal participants, and a list of topics.

July 25, 1995, Silver Spring, Maryland

The panel met at the NWS Headquarters for presentations by and discussions with managers and staff members of National Environmental Satellite, Data, and Information Service (NESDIS), Systems Acquisition Office (SAO), NWS, and National Aeronautics and Space Administration (NASA) on technical aspects of plans for NOAA weather satellite coverage, continuity, and backup.

Principal Participants:

NESDIS:	John Hussey, Gerald Dittberner, Greg Mandt
SAO:	Wilfred Mazur
NASA:	Vern Weyers, Marty Davis, Harry McCain
NWS:	Susan Zevin, Louis Uccellini

List of Topics:

1. NOAA's satellite programs
2. NWS satellite requirements
3. Geostationary operational environmental satellite (GOES) program
4. GOES in-orbit availability prediction (1996–2011)
5. Polar-orbiting operational environmental satellite (POES) program
6. Television and infrared observation satellite (TIROS) constellation mission study (1995–2004)
7. Data quality and feedback
8. GOES follow-on schedule

October 25, 1995, Silver Spring, Maryland

The purpose of this meeting was to meet with principal NOAA managers to discuss policy and management issues related to planned NOAA geostationary and polar coverage in terms of system continuity and backup.

Principal Participants:

NESDIS:	Robert Winokur, James Mannen, John Hussey, Jamie Hawkins
NWS:	Elbert J. Friday, Jr., Susan Zevin

List of Topics:

1. NOAA and NWS requirements for satellite data and priorities to meet these requirements within the geostationary and polar programs
2. Strategies in NOAA satellite programs to meet continuity of coverage and backup requirements and priorities
3. Factors governing operational lifetimes of NOAA satellites
4. Plans for sensor improvements
5. Converged polar satellite plans; integrated program office

October 26, 1995, Pleasant Hill, Missouri

The panel visited an NWS forecast office and river forecast center to observe and discuss the use of satellite data in forecast and hydrology operations.

Principal Participants:

NWS: Lynn Maximuk, William Bunting, Peter Browning

List of Topics:

1. Use of satellite data at the NWS forecast office and at the colocated river forecast center
2. Tour of facility and demonstration of satellite data uses

October 26, 1995, Kansas City, Missouri

The purpose of this meeting was to review the use of satellite data at the Storm Prediction Center and the Aviation Weather Center of the National Centers for Environmental Prediction (NCEP).

Principal Participants:

NWS: Fred Ostby, James Henderson, Joseph Schaffer, Fred Mosher, M. Doug Matthews, Terry Schoeni

List of Topics:

1. Use of satellite data at the Storm Prediction Center
2. Use of satellite data at the Aviation Weather Center
3. National and international responsibilities of the centers
4. Availability and capabilities of current and future weather satellites for application at these centers

November 29, 1995, Camp Springs, Maryland

The panel met at the Environmental Modeling Center of the NCEP to gather information and discuss the use of GOES and POES data in numerical models at the NCEP.

Principal Participants:

NWS: Ronald McPherson, Eugenia Kalnay, Stephen Lord, Steven Tracton

List of Topics:

1. NCEP tests on GOES-8 sounder data
2. Results of test evaluations
3. Plans for further assessments of GOES-8/9 sounder data
4. Use of radiance data in models
5. Future sensor development
6. Adequacy of NCEP testing resources