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Report to Congressional Requesters

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# WEATHER FORECASTING

## Systems Architecture Needed for National Weather Service Modernization

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The Honorable Ernest F. Hollings
Chairman, Committee on Commerce,
Science, and Transportation
United States Senate

The Honorable George E. Brown, Jr.
Chairman
The Honorable Robert S. Walker
Ranking Minority Member
Committee on Science, Space,
and Technology
House of Representatives

This report responds to your request that we review the National Weather Service's (NWS) modernization program. As agreed, we focused on whether NWS is using a systems architecture and has clearly assigned responsibility for development and management of the modernization.

We will provide copies of this report to the Secretary of Commerce; the Director, Office of Management and Budget; and interested congressional committees. Copies will also be made available to others upon request.

Please call me at (202) 512-6253 if you or your staff have any questions concerning the report. Other contributors to this report are listed in appendix IV.

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# Executive Summary

## Purpose

The National Weather Service's (NWS) ability to forecast the weather impacts not only the lives and property of every American but also our nation's commercial interests. Catastrophic disasters such as hurricane Andrew and the "great flood of 1993" demonstrate the importance of providing timely weather forecasts and warnings. To improve the accuracy, timeliness, and efficiency of its weather forecasts and warnings, the National Oceanic and Atmospheric Administration (NOAA), of which NWS is a part, is spending over $4 billion to modernize NWS weather observing, information processing, and communication systems.

Given the risks inherent in such a large and complex undertaking, the Chairman of the Senate Commerce, Science, and Transportation and the Chairman and Ranking Minority Member of the House Science, Space, and Technology Committees requested that GAO review the NWS modernization effort to determine (1) whether NOAA has a systems architecture to guide the development and evolution of the many interrelated subsystems under the modernization, (2) whether there are architectural differences among these subsystems and the impact of any such differences, and (3) whether responsibility for managing the modernization has been clearly assigned.

## Background

The modernization program includes four new major subsystem developments, subsystem hardware and software upgrades at three NOAA organizations, and the development of a number of other smaller subsystems. Collectively, these subsystems will comprise a single weather forecasting and warning system that must work together as an integrated set to meet NWS requirements.

These subsystems will evolve as forecasting methods improve and operational requirements change. Improvements are already being developed for subsystems still under development, and other changes are likely to occur as research results are incorporated.

## Results in Brief

NOAA lacks a systems architecture, or overall blueprint, to guide the design, development, and evolution of the many subsystems comprising the modernization because NOAA officials have not managed the multiple subsystem initiatives as interrelated parts of a single system. This lack of a systems architecture has led to incompatibilities among the subsystems, such as different communication protocols (sets of rules that govern communications among computer systems) and application languages. To address the protocol differences, special interfaces have to be developed and maintained to interconnect the subsystems. Furthermore, multiple application languages are problematic because software written in different languages is more difficult and expensive to maintain and share among subsystems. Sharing application software is especially important because NWS is considering reallocating forecasting functions among the subsystems to provide better support to each weather office, and subsystem incompatibilities make such functional transfers difficult.

The modernization has also never had a central manager or chief architect. As a result, the subsystems continue to be developed and managed in largely the same manner as they were started—as individual systems that must be interconnected after development to meet NWS mission requirements. Unless a single management entity is designated and an architecture is developed and enforced, the integration of these and potentially other new weather forecasting subsystems in the future will continue to require more time, effort, and money than is necessary.

# Principal Findings

## NWS Does Not Have a Systems Architecture

A systems architecture is widely recognized as an essential element in guiding system development, operation, and maintenance because it promotes commonality among subsystem components, thereby increasing efficiency and minimizing maintenance. NWS does not have a systems architecture for the modernization. The subsystems were started at different times, some as early as 1980, when the state of technology for interconnecting systems was not as mature as it is today. Thus, it is somewhat understandable why the subsystems' genesis and early development were not guided by an overall systems architecture. However, the subsystems continue to be developed today independent of one another. NOAA's Systems Program Office, in realizing the importance of a systems architecture to assist in managing and guiding future systems development and evolution, recently initiated an effort to define an architecture for the four subsystems under its purview. However, this effort does not encompass all subsystems comprising the entire modernization.

## Lack of Systems Architecture Impacts Modernization's Cost and Performance

Developing the modernization subsystems independently, without an architecture, has resulted in incompatibilities that require additional resources to acquire, interconnect, and maintain hardware and software. For example, the modernization subsystems use a number of differing protocols. This can best be seen in the Advanced Weather Interactive Processing System (AWIPS), which, as the integrating component of the many subsystems, requires extra hardware and software to accept data from other subsystems that use their own communication protocols. Not only do these multiple protocols require the purchase and maintenance of additional hardware and software, but they also complicate interconnection of the subsystems.

NWS is considering reallocating functions among subsystems to use weather data more efficiently, as well as migrating certain subsystems to vendor-independent environments.[1] However, because of existing and potential incompatibilities among the subsystems, this will be more difficult than necessary. A systems architecture would facilitate the transfer of functions among subsystems and the migration to compatible, vendor-independent operating environments.

## No One in NWS Is Responsible for the Modernization

In order for the modernized subsystems to be designed, built, operated, and evolved as a system of interconnected subsystems, someone within NOAA must have the responsibility and authority to do so. However, other than the head of NOAA, there is no such designated individual. Instead, the management of the modernization is diffused. For example, the NOAA Systems Program Office is managing four new major subsystems, while existing subsystems are managed independently by various NOAA and NWS organizations. As a result, systemwide architectural standards have not been formulated.

# Recommendations

To help ensure the success of the NWS modernization, GAO recommends that the Secretary of Commerce direct the Deputy Under Secretary for Oceans and Atmosphere to designate a single manager or chief architect for the modernization with the responsibility and authority to define and enforce adherence to an overall systems architecture. GAO further recommends that the Deputy Under Secretary direct this individual to develop a systems architecture and that the architecture include all

[1] A vendor-independent environment uses hardware and software with characteristics that conform to specifications in the public domain (that is, that are not unique to a particular vendor or group of vendors).

weather forecasting and warning subsystems and be used as a guide in current and future subsystems development.

## Agency Comments

In its written comments on a draft of this report, the Department of Commerce stated that the report's focus is appropriate and timely and that the report thoughtfully addressed important technical and organizational considerations facing NOAA from a modern systems point of view. In addition, the Department agreed that NOAA lacks a single, complete, and unified systems architecture that encompasses all the various subsystems used to create and disseminate weather information and services. The Department added that NOAA accepts and shares the goal of establishing a comprehensive and unifying architecture that will serve as a guide for current and future development. Accordingly, the Department generally concurred with GAO's findings, conclusions, and recommendations, and it stated that NOAA is currently taking steps to implement the recommendations. The Department also noted several considerations associated with the modernization that it believed GAO's report did not address. GAO agrees with the Department's points, as discussed in chapter 5, and believes that they further strengthen GAO's argument for a comprehensive systems architecture.

# Contents

**Abbreviations**

| | |
|---|---|
| ASOS | Automated Surface Observing System |
| AWIPS | Advanced Weather Interactive Processing System |
| DOD | Department of Defense |
| FAA | Federal Aviation Administration |
| GAO | General Accounting Office |
| GOES-Next | Next Generation Geostationary Operational Environmental Satellite |
| ISO | International Standards Organization |
| NESDIS | National Environmental Satellite, Data, and Information Service |
| NEXRAD | Next Generation Weather Radar |
| NMC | National Meterological Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NWS | National Weather Service |
| NWSTG | National Weather Service Telecommunications Gateway |
| OSI | Open Systems Interconnection |

# Introduction

The National Weather Service's (NWS) basic mission is to provide weather and flood warnings, public forecasts, and advisories primarily for the protection of life and property. NWS' operations also support other agencies' missions and the nation's commercial interests. For example, NWS provides specialized forecasts to support aviation safety and the agricultural and marine industries.

To fulfill its mission, NWS uses a variety of systems and manual processes to collect, process, and disseminate weather data to and among its network of field offices and national centers. Many of these systems are outdated. For example, the current radar equipment dates to 1957, and the one remaining U.S. geostationary weather satellite has exceeded its planned life and will run out of fuel prior to the planned April 1994 deployment of its replacement.[1]

Since the early 1980s, NWS has been modernizing its observing and processing systems so it can more accurately and quickly predict the weather. The goals of the modernization are to achieve more uniform weather services across the nation, improve forecasts, provide more reliable detection and prediction of severe weather and flooding, permit more cost-effective operations, and achieve higher productivity. The modernization involves new orbiting and ground-based technology for collecting data on weather phenomena and powerful new information and forecast systems. According to NWS, new technological systems are essential to improve warning and forecast services and to replace obsolete and increasingly unreliable systems. Because of the productivity and efficiency gained from these new systems, NWS expects to reduce the number of weather field offices from 249 to 116 and overall staffing levels by over 17 percent by around the year 2000.

## Description of Modernization Subsystems

As defined by NWS, the modernization program consists of four acquisitions—the Advanced Weather Interactive Processing System (AWIPS), the Next Generation Geostationary Operational Environmental Satellite (GOES-Next), the Next Generation Weather Radar (NEXRAD), and the Automated Surface Observing System (ASOS)—and an upgrade to the National Meteorological Center (NMC) computer system. However, accomplishing the goals of the modernization also requires other new and existing subsystems. These complementary subsystems, with a combined estimated cost of over $4 billion, must work together as an integrated unit

[1]Geostationary satellites maintain a constant view of a single location on the earth from about 22,300 miles in space.

to provide the forecaster with all the information needed to prepare forecasts and weather warnings. The major subsystems that encompass NWS' modernization are described below.

- AWIPS, the centerpiece of the modernization, is an information processing system that acquires, integrates, analyzes, displays, and disseminates weather data from various sources. AWIPS will be deployed to each of the 116 weather forecast offices beginning in April 1996 with full deployment estimated for March 1998. NOAA estimates the cost to develop and deploy AWIPS to be about $475 million.
- GOES-Next measures temperature and moisture levels of the atmosphere, provides visible and infrared images of clouds and the earth's surface, and collects data from remote locations. The GOES-Next program, which includes five satellites and the ground systems to command, control, and communicate with the satellites, is estimated to cost about $2 billion. The satellites are to be launched between 1994 and 2004.
- NEXRAD is a Doppler radar system that measures wind velocity in severe weather, such as thunderstorms, tracks storm movement and intensity, and generates images for use by forecasters and other users.[2] This joint acquisition with NWS, the Federal Aviation Administration (FAA), and the Department of Defense (DOD) will consist of 175 units. As of August 1993, 44 radar units had been delivered to the three agencies. NWS estimates NEXRAD's cost to be about $1.3 billion, with full deployment to occur in January 1996.[3]
- ASOS is a system of sensors that automatically collects and processes data on weather conditions, including temperature, barometric pressure, wind, visibility, clouds, and precipitation. As of August 1993, NWS had deployed approximately 321 of the 868 planned ASOS units at NWS, FAA, and DOD sites. NWS estimates its share of the ASOS program to be about $340 million, with full deployment to occur by May 1996.[4]
- NMC processes weather data through computer models to generate numerous weather products, such as extended and medium-range forecasts and advisories of hazardous weather for aviation interests. NMC plans to upgrade its systems by acquiring a supercomputer at an estimated cost of about $47.5 million. Completion of the upgrade is expected to occur by 1994.

[2]Doppler radar, named for Christian Johann Doppler, is used to determine the speed and direction of rain or snow particles, cloud droplets, or dust moving toward or away from the radar. The radar accomplishes this by sending out a pulse using a stable soundwave frequency and then measuring the changing frequencies as the distances between the radar and the object change.

[3]FAA and DOD are reimbursing NWS $306 million and $281 million, respectively, for NEXRAD units.

[4]FAA and DOD are reimbursing NWS $191 million and $18 million, respectively, for ASOS units.

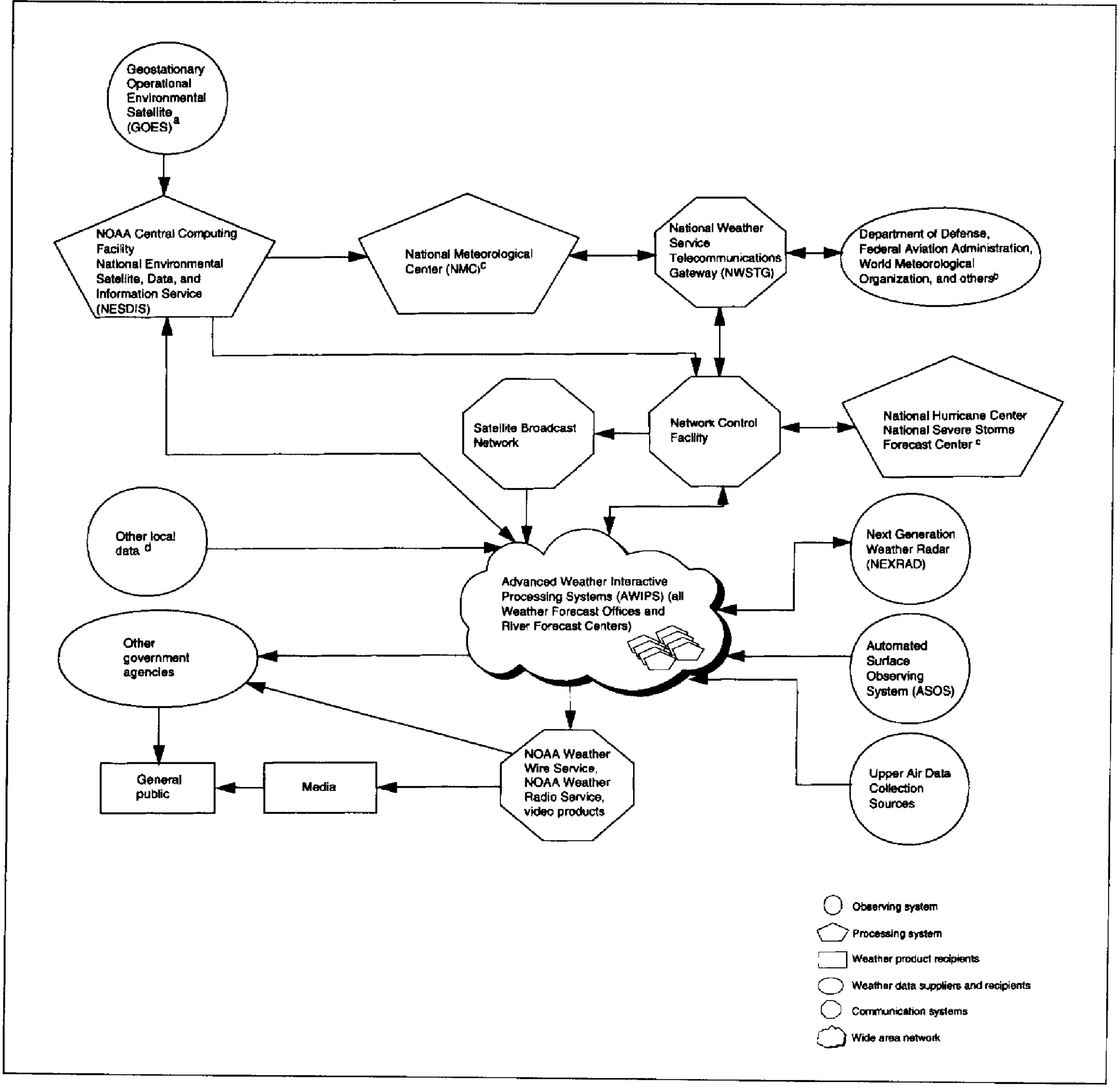
- The National Weather Service Telecommunications Gateway (NWSTG) receives data from NMC for dissemination to AWIPS, other government agencies, other nations, and private users. NWSTG also collects and disseminates weather observations received from such sources as aircraft and ships. To process the much larger traffic volumes that will be required by the modernization, NWSTG plans to upgrade its current computer system at a cost of about $9.5 million. The upgrade is to occur between 1995 and 1996.
- The National Environmental Satellite, Data, and Information Service (NESDIS) collects and processes data from GOES satellites for use by AWIPS and NWS national centers. In October 1992, to accommodate GOES-Next data, NESDIS began upgrading its system at a cost of about $400,000. NWS will continue this effort through June 1994.

In addition to these major acquisitions and upgrades, the modernization also includes other, smaller acquisitions and existing subsystems. For example, NOAA's Office of Oceanic and Atmospheric Research developed a Wind Profiler system that uses Doppler radar to automatically measure upper-atmospheric winds. As of May 1992, NOAA's Office of Oceanic and Atmospheric Research fielded a demonstration network of 32 profilers. NWS plans to acquire a national, operational network consisting of 150 to 250 profiler units. The estimated acquisition cost of this national network is about $250 million. In addition, the Automatic Hydrologic Observing System is an existing network of remote sensors (satellite and ground-based) that automatically collects river and rainfall data. These smaller subsystems are also to be integral components of the modernized weather forecasting and warning system.

## The Modernization Is a System of Subsystems

The multiple subsystems that comprise the NWS modernization must work together to form one integrated system. Collectively, these subsystems comprise a single weather forecasting and warning system, with each component being expected to fulfill its part of the total weather forecasting and warning process. For example, satellite image data from GOES-Next is collected and processed by NESDIS, which then distributes these processed data to NMC. The Center uses these data in computer models to generate products, which are sent through NWS' telecommunications gateway to AWIPS. AWIPS integrates these products with weather information from other sources, including NEXRAD and ASOS, to generate local forecasts and warnings. AWIPS then distributes these forecasts and warnings through various means to the local media and government agencies, which in turn provide this information to the general public. Figure 1.1 depicts the relationships and flow of data among the different subsystems.

**Figure 1.1: Future NWS Weather Forecast System**



[a]Includes data from other observing satellites (for example, Polar Orbiting Environmental Satellites).

[b]Includes data from remote sensors (for example, ground-based Automated Hydrological Observing System), local flood warning system, spotter network, cooperative observers, and government agencies.

[c]The National Meteorological Center, the National Hurricane Center, and the National Severe Storms Forecast Center will also have AWIPS workstations.

[d]Includes Ocean Products Center, private meteorologists and corporations, aircraft and ship reports, lightning network, and Wind Profiler system.

## The Modernization Subsystems Will Continue to Evolve

The systems that comprise the NWS modernization must be flexible enough to meet dynamic operational requirements. Current forecasting methods will be constantly improved, and the subsystems must evolve to accommodate these changes. According to the scientific operations officers at the weather forecast offices we visited, NWS has only begun to think about how to use the wealth of data that their modernized systems will provide.

The evolutionary nature of the modernization system is evidenced by the many changes currently taking place. In addition to the NMC, NESDIS, and NWSTG upgrades, enhancements are also being planned for the subsystems that are under development. For example, NOAA's Forecast Systems Laboratory and NWS' Techniques Development Laboratory are currently developing the AWIPS Forecast Preparation System to be incorporated into AWIPS. The AWIPS Forecast Preparation System will further automate forecast and warning generation and enhance the forecaster's ability to edit graphics on the AWIPS workstation screen. The Forecast Systems Laboratory estimates that this system will consist of at least 250,000 lines of code and will be incorporated into AWIPS in 1999.

The subsystems will also evolve as they are used to conduct meteorological research. This research will then be used to establish new requirements that must be incorporated into each subsystem. For example, forecasters will use AWIPS to develop new forecasting techniques and strategies, from which new applications will be developed to provide weather forecasts and warnings.

## Objectives, Scope, and Methodology

The objectives of our review were to determine (1) whether NOAA has a systems architecture to guide the development and evolution of the many interrelated subsystems under the modernization, (2) whether there are architectural differences among these subsystems and the impact of any such differences, and (3) whether responsibility for managing the modernization has been clearly assigned. To determine whether a systems architecture was used to guide subsystem development and evolution, we met with NOAA and NWS officials responsible for each component of the modernization to determine whether a modernization architecture exists. In addition, we reviewed NWS' data flow diagrams, Office of the Federal Coordinator for Meteorological Services and Supporting Research guidance, and the AWIPS specification to determine if these documents constitute a systems architecture. We also met with NOAA Systems Program Office officials to discuss their efforts to develop a systems architecture for the four subsystems they currently manage (AWIPS, NEXRAD, GOES-Next, and ASOS).

To determine whether architectural differences existed among the subsystems and the impacts of any differences, we (1) acquired information on each subsystem's hardware, operating system, application languages, database management, communications, and security characteristics, (2) reviewed key technical documents, including the AWIPS contractor's best and final offer and the AWIPS specification that described subsystem interfaces and communication protocols, (3) analyzed the impacts of these differences, (4) interviewed NOAA and NWS officials and well-recognized experts in the field of computer technology at the National Institute of Standards and Technology, Massachusetts Institute of Technology's Lincoln Laboratory, and Carnegie Mellon University's Software Engineering Institute, and (5) interviewed National Research Council officials involved in the modernization.

To determine whether responsibility for managing the modernization has been clearly assigned, we reviewed the modernization strategic plan and asked NOAA and NWS officials responsible for each respective component of the modernization who is responsible for the modernization. In addition, we reviewed the subsystems configuration management plans to assess how changes in subsystems are analyzed and ascertain the cross-representation of configuration control board members among subsystems.

We performed our work at the Department of Commerce in Washington, D.C.; NOAA and NWS headquarters in Silver Spring, Maryland; NOAA's Forecast Systems Laboratory in Boulder, Colorado; National Institute of Standards and Technology in Gaithersburg, Maryland; Lincoln Laboratory in Lexington, Massachusetts; and the Software Engineering Institute in

Pittsburgh, Pennsylvania. The Department of Commerce provided written comments on a draft of this report. These comments are presented in appendix I and are addressed in chapter 5. Our work was performed between January 1993 and September 1993, in accordance with generally accepted government auditing standards.

# NOAA Has Not Developed a Systemwide Architecture to Guide the Development of the Modernization

A complete systems architecture is vital in effectively and efficiently guiding the development, operation, and maintenance of any complex system. It promotes compatibility among subsystem interfaces, protocols, hardware, operating systems, application languages, and data formats, thereby increasing system performance and minimizing system development and maintenance costs. NOAA has never had an architecture for its modernization subsystems because each subsystem was historically viewed and managed as a disparate piece.

## An Architecture Is a Fundamental Component of Sound Systems Development, Operation, and Maintenance

A systems architecture describes the functions, elements, and performance requirements of the system, and defines the most effective approach to meet current and future mission needs.[1] Effective architectures are derived from a strategic information systems planning process, which analyzes the system's functional, informational, data, and application requirements. The architecture describes all functional activities to be performed by the system, the elements needed to perform these functions, and the performance requirements for these elements. An architecture further defines the hardware, software, communications, data management, and security subarchitectures of the system; and defines the system's required operational effectiveness, maintainability, and flexibility to adapt to changing missions. Failure to specify an architecture may result in additional development and maintenance costs, additional development time, and systems that do not function as required.

NOAA and NWS officials, as well as officials at Lincoln Laboratory, the Software Engineering Institute, the National Institute for Standards and Technology, and the National Research Council, acknowledge that a systems architecture is valuable in guiding system development and optimizing system operations and maintenance. Also, 9 of the 11 NOAA and NWS officials we spoke with who are directly involved in and responsible for different aspects of the modernization agreed that a systemwide architecture to guide the development and evolution of the subsystems would be valuable. For example, a NOAA program official stated that without an architecture, there are no limitations or constraints on future development, which results in programs being developed using different standards. Also, the mission statement for the System Program Office, the NOAA organization that is responsible for managing AWIPS, NEXRAD, GOES-Next,

[1]Strategic Information Planning: Framework for Designing and Developing System Architectures (GAO/IMTEC-92-51, June 1992).

and ASOS, specifically recognizes the need for a systems architecture to promote interoperability[2] and plan future systems.

## NWS Does Not Have a Systems Architecture for the Modernization

We interviewed 16 NOAA and NWS officials responsible for each component of the modernization, and all but 3 stated that no systems architecture exists for guiding development or integration of the subsystems under and related to the modernization. The principal reasons cited by several of these officials for no architecture were that the subsystems were largely begun and have since been managed separate from one another and that no one has taken a more global view of the modernization. NWS and NOAA officials also emphasized that certain subsystems were begun many years ago and at different times to replace systems that were basically stand-alone. Moreover, the state of technology for interconnecting systems was not as a mature as it is today.

The three officials who said that an architecture existed referred to several documents, including data flow diagrams, interface control documents, program specifications, and Office of the Federal Coordinator for Meteorological Services and Supporting Research documentation. While these different documents represent parts of an architecture, they do not constitute a complete systems architecture. For example, the NWS data flow diagram, although displaying logical data exchange between subsystems, does not provide any specifics concerning how data exchange is to be accomplished, including data formats, data definitions, interfaces, hardware, software, or security features. Further, the Office of the Federal Coordinator for Meteorological Services and Supporting Research documentation regarding automated weather information system programs expressly states that it does not apply to weather data acquisition systems, weather information dissemination systems, operational processing centers, and their associated communications links.

The beginnings of a systems architecture can be found in the NOAA Systems Program Office. This office recently began defining a systems architecture to (1) assist in managing subsystems' interfaces, and (2) guide future systems development, management, and evolution. However, this effort covers only the four subsystems managed by the Systems Program Office—AWIPS, GOES-Next, NEXRAD, and ASOS—and therefore will not result in a complete NWS systems architecture.

[2]Interoperability is the ability to have computers from different vendors work together in a cooperative way over a network.

At the conclusion of our audit work in September 1993, NOAA's Deputy Under Secretary for Oceans and Atmosphere agreed that it would be beneficial to develop an architecture for the modernization. The Deputy Under Secretary stated that she planned to place this matter high on the agenda of a council she recently formed to advise her on a wide range of issues facing NOAA.

# Incompatibilities Among Subsystems Increase Integration and Maintenance Costs and Limit System Flexibility

The lack of a global view of the modernization and a systemwide architecture has caused incompatibilities among the subsystems (for example, differences in communication protocols[1] and application languages) that require additional resources to overcome, and makes transferring functions among subsystems and migrating to vendor-independent operating environments[2] more difficult and expensive.

## Subsystem Architectural Characteristics Differ

The modernization's subsystems are very dissimilar. These differences can be noted by examining the specific architectural characteristics of each subsystem in five areas—hardware, operating systems, application languages, database management systems, and communications. (The specific architectural characteristics for the seven major subsystems are shown in table 3.1, and described in detail in appendix II). The differences among the subsystems are apparent in any one of the five areas. For instance, each subsystem uses a different operating system (for example, AWIPS uses Hewlett-Packard's version of the UNIX operating system, called HP-UX, while NEXRAD uses Concurrent's OS/32 operating system). This means that each subsystem relies on a completely different set of tools and techniques (for example, interfaces between applications and the operating systems, interfaces between the operating systems and peripheral devices, interfaces between the operating systems and communication software, etc.) to control and manage the interaction of its software and hardware.

[1]Sets of rules that govern communications among computer systems.

[2]A vendor-independent environment uses hardware and software with characteristics that conform to specifications in the public domain (that is, that are not unique to a particular vendor or group of vendors).

**Table 3.1: Architectural Characteristics of NWS Subsystems**

| Subsystem | Hardware | Operating System | Application Languages | Database Management System | Communications |
|---|---|---|---|---|---|
| AWIPS | Hewlett-Packard | HP-UX, HP-RT | C, FORTRAN, Pascal, HP Assembly | Informix | X.25, IEEE 802.2 & 3, ISO 8802/5, SNA, ASOS, NEXRAD, Asynchronous, Async. satellite TCP/IP, HP Network File System |
| GOES-Next | VAX, Micro-VAX | DEC VMS, ENCORE MPX, Data General AOS/AOSVS | FORTRAN, MACRO Assembly | custom | X.25, DECnet |
| NEXRAD | Concurrent Microfive | Concurrent OS/32 | FORTRAN | none | custom X.25 |
| ASOS | custom i486-based processor | custom real-time | C, HP Assembly | none, all data reside in RAM | custom |
| NMC | CRAY Y-MP8, Hitachi mainframes | CRAY UNICOS, MVS/SP, MVS/XA | FORTRAN, IBM Assembly, Hitachi Assembly, Cray Assembly, C | none | TCP/IP |
| NWSTG | Amdahl and Hitachi mainframes | IBM MVS, IBM VM/SP, IBM VSE/SP, NCP | IBM Assembly, Amdahl Assembly, Hitachi Assembly, FORTRAN, C | custom | IBM X.25, IBM TCP/IP, IBM FTP, Baudot |
| NESDIS | Force-based processor, Pentek | Microware OS-9 | C | none | Defense protocol suite (TCP/IP, FTP, SMTP, TELNET) |

## Multiple Communication Protocols Complicate the Interconnection of Subsystems

Differing subsystem protocols make exchanging data among the subsystems more difficult and expensive. This can best be seen in AWIPS, which integrates information provided by many subsystems and thus must be able to accommodate the differences among subsystem interfaces. Specifically, AWIPS is required to support 24 communication interfaces.[3] As a result, AWIPS requires extra communication hardware and software to translate among differing sets of protocols. This additional hardware and

[3]These interfaces include five different transport layer protocols, five different network layer protocols, nine different data link layer protocols, and eight different physical layer protocols. See appendix III for a detailed description of the different layers of the Open System Interconnection Reference Model.

software for AWIPS not only involves the added cost of buying it, but also the cost of upgrading and maintaining it. Moreover, 5 of the 24 interfaces are proprietary, meaning that NWS must deal with these vendors on a sole source basis and cannot acquire, upgrade, and maintain these interfaces competitively. Without a systems architecture, subsystem incompatibilities will persist, and NWS will continue having to compensate for them.

## Differing Application Languages Complicate Maintenance

Systems written in multiple application programming languages are more difficult to modify and maintain than systems written in fewer languages. Limiting the number of programming languages results in lower maintenance costs because programming staff require less training and less support software (for example, compilers, debuggers, program libraries)[4] must be maintained.

Software for the modernization's subsystems is written in a variety of programming languages; the choice of which language to use was based solely on what NWS used in the past, rather than on the type of analysis and deliberate decision-making that is needed to define a complete and effective software subarchitecture.

Currently, the seven major subsystems' applications are written in nine programming languages,[5] and no restrictions have been placed on the use of additional languages. For instance, in the absence of any restrictions, NOAA's Forecast Systems Laboratory and NWS' Techniques Development Laboratory have chosen to develop the AWIPS Forecast Preparation System (the new AWIPS user interface) in an additional language (C++) not used previously. According to the concepts document for this system, C++ is being used because it is object oriented[6] and believed to be more flexible, easier to maintain, and needing fewer lines of code to write a given application than the C programming language. However, none of the NWS subsystems provide compilers for this language. Therefore, NWS will either have to convert the code or purchase additional compilers and translators

[4]A compiler is a program that translates the source code written by the programmer into object code that can be executed. A debugger is a program that aids in identifying and correcting program errors. A program library is a collection of routines that a programmer can use, as needed, without having to write them anew.

[5]Includes six assembly languages.

[6]Object orientation is a new paradigm for software construction. Historically, writing programs involved defining procedures that act on a separate set of data. Object oriented languages, like C++, permit the creation of programs using collections of self-sufficient objects (modules that contain data and the procedures that act on the data) that act upon, request, and interact with each other by passing messages back and forth.

to incorporate the code into AWIPS. A software subarchitecture, based on careful and systematic analysis of the needs of current and planned operating environments, would define the languages to be used and thus help to avoid the unnecessary costs and difficulties associated with language proliferation.

## Heterogenous Subsystems Hinder Reallocation of Subsystem Functions

The interdependence between and among the modernization's many subsystems demands that architectural incompatibilities be minimized. Such incompatibilities lead not only to increased costs, as discussed earlier, but they can also restrict flexibility in deciding which systems will perform which weather forecasting and warning functions. A systems architecture that defines critical standards (for example, communication protocol standards, application language standards) promotes architectural compatibility and thus facilitates reallocation of functions between and among subsystems.

NWS is currently planning to transfer some subsystem functions to better meet user needs, and more transfers are being considered. For example, NMC will transfer its graphics generation function to the AWIPS workstation to allow forecasters to better manipulate graphics to their specific geographical area. Also, certain NEXRAD functions, such as generating storm tracks or tornado position information, may be transferred to the AWIPS workstation, according to a senior NOAA Forecast Systems Laboratory official. In addition, the AWIPS program manager stated that some functions now performed by the Wind Profiler subsystem may also transfer to the AWIPS workstation. How difficult these and other transfers prove to be will depend on the extent of inherent architectural differences among the subsystems.

## Lack of Guidance for Migrating Subsystems to an Open Environment May Perpetuate Architectural Incompatibilities

NWS is also considering migrating subsystem applications to open operating environments. An open environment is one that is based on vendor-independent, publicly available standards. Implementation of these standards allows applications to (1) run on any vendor's hardware, (2) use any vendor's operating system, (3) access any vendor's database, and (4) communicate and interoperate over any vendor's networks. An open system environment supports portable and interoperable applications through standard services, interfaces, data formats, and protocols. Such an open system environment would facilitate NWS' efforts to transfer functionality between subsystems by eliminating reliance on vendor-specific products. Moreover, an open environment would allow NOAA to competitively acquire, upgrade, and maintain equipment.

The NOAA System Program Office is considering migrating from NEXRAD's proprietary hardware and operating system environment to an open environment. In addition, NWSTG is converting existing software from nonstandard assembly languages to the C programming language, which Lincoln Laboratory officials described as the language of choice for open systems development.[7]

There are still choices to be made, however, in moving to an open environment because different open system options may be selected. If each subsystem moves to open systems independently, different open system options may be selected, perpetuating architectural incompatibilities and continuing to incur additional expenses to interconnect the subsystems and reallocate functions among them. Moreover, ensuring that the appropriate standards for the subsystems as a whole are selected requires careful and thorough analysis of systemwide requirements. The rigor associated with developing a systems architecture can ensure such analysis.

[7]The C programming language is the preferred language for open systems because it is (1) considered to be a machine-independent language, (2) closely associated with the UNIX operating system, (3) widely used, and (4) standardized by the American National Standards Institute.

# Overall Responsibility Not Assigned for the Modernization Effort

NOAA's management structure for the modernization is a reflection of it viewing the modernization as a collection of autonomous subsystems. Specifically, responsibility and authority for the modernization are shared by several NOAA organizations, leaving no one entity in charge. Without a designated chief architect or engineer for the modernization, no one other than the head of NOAA has the authority to develop a systemwide architecture. To NOAA's credit, it is managing individual subsystem changes through change control groups that bring together representatives for the multiple subsystems. However, this process, which focuses on individual subsystem changes, is not an effective alternative to having a systems architecture and a chief engineer or single manager because it does not focus on the design, development, management, and evolution of the total weather forecasting and warning system.

## Lack of a Single Manager Limits Ability to Enforce Architecture

The management of the modernization is diffused—no single manager or entity has the responsibility and authority to manage all aspects of the modernization or the evolution of the various subsystems comprising or associated with it. Instead, autonomous organizations are managing the subsystems. For example, the Systems Program Office is responsible for AWIPS, GOES-Next, NEXRAD, and ASOS. NOAA created this office in 1991 to manage these four subsystems' acquisitions to control cost overruns and schedule delays on each. In addition, NMC, NWSTG, and other subsystems (for example, the Automated Hydrological Observing System) are each independently managed within NWS. NESDIS is managed independently within NOAA.

The use of a guiding architecture and the designation of a single manager are concepts that go hand-in-hand. Because accountability and responsibility for the entire modernization have not been assigned to a single manager, key officials directly associated with the modernization stated that they do not have the organizational authority to develop a total systems architecture. In the absence of someone having been assigned such authority, the only individual currently having purview over the entire modernization is the Deputy Under Secretary for Oceans and Atmosphere. Consequently, subsystems have been, and without appropriate changes will continue to be, developed and modified independent of one another, with incompatibilities that will require additional time, effort, and money to overcome.

At the conclusion of our audit work, the Deputy Under Secretary for Oceans and Atmosphere agreed that central leadership of the modernization would be beneficial. The Deputy Under Secretary stated that clearly fixing responsibility and authority for the entire modernization with a chief architect or single manager would be high on the agenda of a council she recently formed to advise her on a variety of issues facing NOAA.

## Change Control Process Is No Substitute for Systems Architecture and Single Manager

To NOAA's credit, it is managing individual subsystem changes in a manner that considers the systemwide impact of such changes. Specifically, all subsystems have their own configuration control board to (1) review requests for change and engineering change proposals, (2) determine if the change is needed, (3) evaluate the total effect of the change, and (4) issue changes to the subsystems' individual configuration baselines. These boards consist of multiple subsystems representatives. According to the AWIPS program manager, board members use technical documentation (for example, software specifications, interface control documents, etc.) and their knowledge about the subsystems as the means of (1) determining what impact hardware, software, and communication changes made to a subsystem may have on their's or others' subsystems, and (2) deciding whether the benefits of the change justify its cost. The program manager for AWIPS, which is the integrating component of the modernization and thus the subsystem most affected by changes, stated that a systems architecture would facilitate the change control process by limiting the scope of subsystem change and providing a systematic basis for determining the systemwide impact of individual changes.

Relying on a change control board process to guide and control systemwide evolution is not an effective alternative to a systems architecture for two primary reasons. First, it provides no single point of reference that members can turn to for clarification and guidance in objectively evaluating the effects of changes on the system as a whole. A systems architecture, particularly one that has been modeled in an automated form, can be this point of reference and thus establish criteria for optimizing the entire system rather than merely its parts. Second, the change control board process manages specific subsystem changes on a change-by-change basis. It is not a mechanism for planning or implementing the collection of changes needed to evolve the system as a whole to effectively meet future weather forecasting and warning mission needs. That is, it does not provide an effective means for directing and limiting change in the sense that a globally-oriented, systemwide blueprint can.

# Conclusions, Recommendations, and Agency Comments and Our Evaluation

## Conclusions

The benefits of developing an architecture and fixing accountability and responsibility for the entire modernization are numerous. The lack of a guiding systems architecture and a single manager or chief architect has resulted in the largely independent development and upgrade of subsystems that will need to be adapted later to permit subsystem integration and interoperability. Such an approach has proven to be unnecessarily costly because subsystem incompatibilities that result must be overcome through additional hardware, software, and the associated maintenance. Moreover, these incompatibilities limit NWS' flexibility in moving functions to the subsystems where their execution makes the most sense.

It is somewhat understandable that NOAA and NWS have not had a systems architecture from the modernization's inception, since (1) some of the subsystems were developed to replace systems that relied on outdated technology and were largely stand-alone and (2) the technology and standards now available to permit system integration and interoperability did not exist or were only emerging at the time. However, continuing to evolve the subsystems without the benefit of an architecture and the designation of chief architect or single manager who is below the Deputy Under Secretary level is unwise. In particular, the absence of an architecture will likely continue to result in incompatibilities among subsystems, and the breadth and technological complexity of the modernization calls for a chief architect or manager whose full attention is devoted to the modernization and all its subsystems.

NWS' observational and information processing systems will not remain inert; they will evolve, incorporating new computer technology and emerging science. Without an architecture and a single system manager, existing incompatibilities will continue and new ones will occur, limiting NWS' ability to migrate the subsystems to open environments and reducing the effectiveness and efficiency of the overall weather forecasting and warning systems. Moreover, overcoming these incompatibilities will require NOAA and NWS to expend more time, effort, and money than is necessary.

## Recommendations

We recommend that the Secretary of Commerce direct the Deputy Under Secretary for Oceans and Atmosphere to designate a single manager or chief architect for the modernization with the responsibility and authority to define and enforce adherence to an overall systems architecture. We further recommend that the Deputy Under Secretary direct this individual to develop a systems architecture and that the architecture include all weather forecasting and warning subsystems and be used as a guide in current and future subsystems development.

## Agency Comments and Our Evaluation

In its written comments on a draft of this report, the Department of Commerce generally agreed with our findings, conclusions, and recommendations. The Department stated that the report thoughtfully addresses important technical and organizational considerations facing NOAA from a modern systems point of view and that the report's focus is appropriate and timely. In addition, the Department acknowledged that there is currently no single, complete, and unified systems architecture that encompasses all the various systems used by NOAA in exchanging and disseminating weather information and services.

Accordingly, the Department stated that the Deputy Under Secretary for Oceans and Atmosphere is directing the Assistant Administrator for Weather Services to prepare by September 30, 1994, the plans and schedules for the development, documentation, and promulgation of an overall systems architecture to guide current and future developments for modernized NWS operations. According to the Department, the Assistant Administrator for Weather Services will have both the responsibility and authority to define and direct an overall systems architecture for NOAA systems that are part of the modernization effort. In addition, the Assistant Administrator has established a new position of NWS Modernization Systems Manager responsible for all systems modernization matters.

The Department's comments also noted several considerations associated with the modernization that it believed our report did not address. The Department stated that NWS' infrastructure is complex and involves diverse system interfaces and protocols to permit data exchange with various federal, state, and local agencies, as well as private sector organizations and individuals. It noted that some of the major subsystems serve other missions besides NWS' and that this creates an environment of diverse requirements and formidable integration challenges. Further, the Department commented that fundamental differences among the various weather forecasting subsystems' functions, technologies, life cycles, external interfaces, and operational impact dictate that an overall systems architecture be able to accommodate a range of standards reflecting the various vintages of the subsystems. Finally, the Department stated that the overriding need for continuity of operations and services necessitate that "old" systems must generally overlap with "new" systems to permit successful transition of internal operations and to allow external weather users and collaborators to adapt to the new technologies and products.

We fully agree with each of the Department's points. In fact, we believe that they make our argument for a comprehensive systems architecture even stronger. Given the complexity, diversity, and interdependence of the many weather forecasting subsystems, which both we and the Department have pointed out, the absence of such an architecture increases the risk of subsystem incompatibilities and thus the unnecessary expenditure of time, effort, and money to overcome them.

# Comments From the Department of Commerce

THE SECRETARY OF COMMERCE
Washington, D.C. 20230

January 14, 1994

The Honorable Donald H. Chapin
Assistant Comptroller General of
the United States
General Accounting Office
Accounting and Information
Management Division
Washington, D.C. 20548

Dear Mr. Chapin:

Enclosed is a copy of the Department of Commerce's reply to the General Accounting Office draft report entitled "Weather Forecasting: Systems Architecture Needed for National Weather Service Modernization."

These comments are prepared in accordance with the Office of Management and Budget Circular A-50.

Sincerely,

Ronald H. Brown

Ronald H. Brown

Enclosure

COMMENTS:

The Department of Commerce (DOC) appreciates and welcomes the opportunity to review and comment on the General Accounting Office (GAO) Draft Report.

The Report thoughtfully addresses important technical and organizational considerations from a modern systems point of view. In view of the growing importance of systems in improving both the quality and efficiency of weather services and considering the large investment the Government is making to introduce new systems, this focus is appropriate and timely.

DOC agrees that there is currently no single, complete, and unified systems architecture that encompasses all the various systems used by NOAA and collaborating Federal, state, local, and private sector organizations in creating, exchanging, and disseminating weather information and services. NOAA accepts and shares the goal of establishing a comprehensive and unifying systems architecture that will serve as a guide for current and future development.

DOC also acknowledges that managing the complex modernization and associated restructuring (MAR) of the National Weather Service (NWS) is extremely challenging. DOC and NOAA are considering several organizational adjustments and key appointments to focus responsibility, authority, and accountability for the MAR. The Deputy Under Secretary will take additional steps to ensure that an overall systems architecture for weather service modernization is formally established and used to guide development and acquisition.

While accepting most of the findings and conclusions of the GAO Report, NOAA respectfully notes that the NWS MAR must consider and balance a number of additional mandates and constraints that are not recognized or emphasized in the Report. These considerations also must influence the scope and timing of systems changes and the details of organizational structure and management. Also, technical personnel within NOAA believe that the extent and detail of their commitment to a modern systems approach was not fully appreciated by GAO reviewers.

The GAO Report did acknowledge that the major modernization systems they studied were developed over an extended period of time (at least 1 to 2 decades, in fact,) and that key technologies and standards were not available at the time many design decisions had to be made. Some are not available even today. Nevertheless, the state-of-the-art and the marketplace now make it practical to achieve system integration and interoperability on a very large scale.

2

Some very important considerations not addressed by the GAO Report are summarized as follows. The Nation's weather service infrastructure is a complex, largely voluntary partnership of several Federal, state, and local government agencies and various private sector organizations and individuals. These participants have distinct missions and interests as well as largely independent decision processes and access to resources. Much of the diversity in NWS systems, and particularly in system interfaces and protocols, is driven by the need to exchange weather-related data and products with "external" systems. Fortunately, the evolution of technology, practices, and the marketplace will facilitate the adoption of much more commonality for information exchange.

The various "subsystems" that comprise the NWS weather "system" are not only numerous but quite inhomogeneous in their function, underlying technologies, relationship to the marketplace, life cycle, impact on operations, external considerations, etc. The extent to which the NWS MAR addresses several major subsystems in a consistent, interdependent framework is unprecedented. It is impractical for all important systems to be specified, let alone changed, at the same time. Considering the dynamic evolution of technology and standards, a realistic overall architecture must be able to accommodate a range of standards reflecting the various vintages of the subsystems.

Some major subsystems, such as environmental satellites, ships, and aircraft, directly serve a much broader range of missions than that of NWS, including not only other units of NOAA but also other Federal agencies and external organizations. The diversity of requirements and users and the very long life-cycle of these unique systems preclude complete integration with more rapidly changing components of the "NWS System," which are closely tied to the commercial information systems marketplace. Nevertheless, NOAA devotes great effort to maintaining interoperability through ground systems and interfaces.

The overriding need for continuity of operations and services that are essential to the safety of life and property poses special constraints on system evolution. NWS people and human skills are and will continue to be at least as important as systems. "Old" systems generally must overlap "new" systems in important ways to permit successful transition of internal operations while allowing external users and collaborators to adapt to new technologies and products. This consideration has proven to be one of the most demanding in the NWS MAR.

RECOMMENDATION:

We recommend that the Secretary of Commerce direct the Deputy Under Secretary for Oceans and Atmosphere to designate a single manager or chief architect for the modernization with the responsibility and authority to define and enforce adherence to an overall systems architecture. We further recommend that the Deputy Under Secretary direct this individual to develop a systems architecture and that the architecture include all weather forecasting and warning subsystems and be used as a guide in current and future subsystems development.

RESPONSE:

DOC generally concurs with the recommendation. NWS is establishing a new position of NWS Modernization Systems Manager who will report directly to the Deputy Assistant Administrator for Modernization. This person will coordinate systems issues with the Systems Program Office (SPO).

The Assistant Administrator for Weather Services will have both the responsibility and authority to define and direct an overall system architecture for NOAA systems that are part of the modernization effort. DOC believes this addresses the GAO recommendation in a way that appropriately balances operations and services as well as systems considerations. The Deputy Under Secretary is directing the Assistant Administrator for Weather Services, with the support of the SPO, to prepare by September 30, 1994, the plans and schedules for the development, documentation, and promulgation of an overall systems architecture for modernized NWS operations. This defined architecture will be used to guide current and future system developments.

# Architectural Characteristics of the Major NWS Subsystems

This appendix provides more detail on the subsystem architectural characteristics presented in table 3.1.

Amdahl: A computer manufacturer.

ANSI: American National Standards Institute, an organization of American industry and business groups dedicated to the development of trade and communication standards.

AOS/AOSVS: Operating systems developed by the Data General Corporation.

Assembly: A type of low-level programming language in which each statement corresponds directly to a single machine instruction. Assembly languages are thus specific to a given processor.

ASOS: The Automated Surface Observing System-specific interface.

Asynchronous: A way of transmitting data over a circuit in which time intervals between characters are unequal and thus each character or byte must be controlled by a start and stop bit. In contrast, synchronous transmissions send characters and bits at a fixed rate that both the sending and receiving devices have predetermined and know (i.e., the two devices are in sync with one another).

BAUDOT: Five-bit code, also called five-level code, is named “Baudot code” after Emil Baudot, who invented the first constant length teleprinter code in 1874.

C: A compiled programming language that contains a small set of built-in functions that are machine dependent. The rest of the C functions are machine independent and are contained in libraries that can be accessed from C programs.

CCITT: Comite Consultatif Internationale de Telegraphie et Telephonie, an organinzation based in Geneva, Switzerland, and established as part of the United Nations International Telecommunications Union. The CCITT recommends the use of communications standards that are recognized throughout the world.

Concurrent Microfive: Computer platform that will replace the Concurrent 3200 series platforms that are currently being used by NEXRAD.

Concurrent OS/32: The current operating system for NEXRAD.

CRAY Y-MP8: A specific supercomputer model developed by Cray.

DECnet: Network architecture from Digital Equipment Corporation.

ENCORE: The company that developed the MPX operating system.

Force-based Processor: Processor developed by the Force company.

FORTRAN-77: FORmula TRANslation language, the first high-level, structured and compiled computer language and the progenitor of many high-level concepts, such as variables, expressions, statements, iterative and conditional statements, separately compiled subroutines, and formatted input/output.

FTP: File Transfer Protocol, one of the Department of Defense suite of protocols for transferring files between different makes and models of computers.

Hewlett-Packard: A computer manufacturer.

Hitachi: A computer manufacturer.

HP-RT: Hewlett-Packard's real-time operating system.

HP-UX: Hewlett-Packard version of the UNIX operating system.

i486: An Intel microprocessor introduced in 1989 (also called the 80486 or the 486). Like its 80386 predecessor, the i486 is a processor with 32-bit registers, 32-bit data bus, and 32-bit addressing.

IEEE: Institute of Electrical and Electronics Engineers, an organization of engineering and electronics professionals who developed the IEEE 802 standards for the physical and data-link layers of the local area networks following the ISO Open Systems Interconnection model.

IEEE 802.2: Describes the functions, features, and services of the Logical Link Control sublayer in the ISO 8802 Local Area Network Protocol, including the peer-to-peer protocol procedures that are defined for the transfer of information and control between any pair of Data Link Layer service access points on a local area network.

IEEE 802.3: Describes the Carrier Sense Multiple Access with Collision Detection media access method—the means by which two or more stations share a common bus transmission medium.

INFORMIX: A company that develops software tools that support client/server database management.

ISO: International Organization for Standardization, an international association of member countries, each of which is represented by its leading standard-setting organization (e.g., American National Standards Institute for the United States).

ISO 8802/5: This standard specifies the formats and protocols used by the Token-Passing Ring Medium Access Control Sublayer, the Physical Layer, and the means of attachment to the Token-Passing Ring physical medium.

MACRO: VAX assembly language.

MPX: Mapped Programming Executive operating system from ENCORE.

MVS/SP: Multiple Virtual System/System Product operating system from International Business Machines Corporation.

MVS/XA: Multiple Virtual System/Extended Architecture operating system from Internation Business Machines Corporation.

NCP: Operating system from International Business Machines Corporation.

Network File System: Allows HP 9000 computer systems to share file systems in a multi-vendor network of machines and operating systems.

NEXRAD: The Next Generation Weather Radar-specific interface.

OS-9: UNIX-derivative operating system from Microware Corporation.

Pascal: A compiled, structured language, built upon the Algorithmic Language. It simplifies syntax while adding data types and structures, such as subranges, enumerated data types, files, records, and sets.

Pentek: A digital signal processor manufacturer.

RAM: Random access memory, the semiconductor-based memory that can be read and written by the microprocessor or other hardware devices.

SMTP: Simple Mail Transfer Protocol, one of Defense's suite of protocols for message transfer in electronic mail form between different makes and models of computers.

SNA: Systems Network Architecture from International Business Machines Corporation, a widely used communications framework to define network functions and establish standards for enabling different models of its computers to exchange and process data.

TCP/IP: Transmission Control Protocol/Internet Protocol, two of Defense's suite of protocols that define message handling at layers 3 and 4 of the ISO model.

TELNET: One of Defense's suite of protocols for interfacing terminal devices and terminal-oriented processes to each other.

UNICOS: The UNIX-derivative operating system from Cray.

VAX/MicroVAX: Virtual Address Extension computer architecture from Digital Equipment Corporation.

VMS: Virtual Memory System operating system from Digital Equipment Corporation.

VM/SP: Virtual Machine/System Product operating system from International Business Machines Corporation.

VSE/SP: Virtual Storage Extended/System Product operating system from International Business Machines Corporation.

X.25: A CCITT recommendation for packet switching over a wide area network.

# The OSI Reference Model

The Open System Interconnection (OSI) Reference Model is a seven-layer model based on a proposal developed by the International Standards Organization (ISO) as a first step toward international standardization of the various protocols. The model deals with connecting open systems—systems that communicate using standard protocols in the public domain.

The OSI model describes seven layers of functionality—physical, data, network, transport, session, presentation, and application. It is a hierarchial and peer-to-peer model for communications—hierarchical because each layer above the physical layer is built on top of the services provided by the lower layers and peer-to-peer in that one layer in a system has a protocol by which it communicates with the equivalent or peer layer in another system. ISO has produced standards for each layer. However, the standards are not part of the model and each one has been published as a separate international standard. A description of each of the seven layers follows.

Layer 1: The Physical Layer - This layer handles the mechanical and electrical details of the actual physical transmission of bit sequences over communication lines.

Layer 2: The Data Link Layer - This layer defines station-to-station connections, generates message frames, and detects and possibly corrects errors in the physical layer.

Layer 3: The Network Layer - This layer controls the switching and routing of messages between stations in the network.

Layer 4: The Transport Layer - This layer provides for transfer of messages between end users. The users need not be concerned with the manner in which data transfers are achieved.

Layer 5: The Session Layer - This layer provides the means for cooperating presentation-entities to organize and synchronize their dialogue and manage their data exchange.

Layer 6: The Presentation Layer - This layer resolves differences in formats among the various computers, terminals, databases, and languages used in the network.

Layer 7: The Application Layer - This is the highest layer and provides services directly to users. It deals with data exactly as it is generated by and delivered to user processes.

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