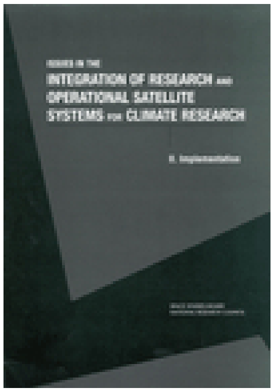

Issues in the Integration of Research and Operational Satellite Systems for Climate Research: Part II. Implementation

Committee on Earth Studies, Space Studies Board,
National Research Council

ISBN: 0-309-55820-4, 98 pages, 8.5 x 11, (2000)

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

ISSUES IN THE INTEGRATION OF RESEARCH AND OPERATIONAL SATELLITE SYSTEMS FOR CLIMATE RESEARCH

II. IMPLEMENTATION

Committee on Earth Studies
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by National Aeronautics and Space Administration contract NASW-96013 and National Oceanic and Atmospheric Administration contracts 50-DGNE-5-00210 and 50-DKNA-6-90040. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

International Standard Book Number 0-309-06994-7

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418

Printed in the United States of America

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Foreword

This is the second of two Space Studies Board reports that address the complex issue of incorporating the needs of climate research into the National Polar-orbiting Operational Environmental Satellite System (NPOESS). NPOESS, which has been driven by the imperative of reliably providing short-term weather information, is itself a union of heretofore separate civilian and military programs. It is a marriage of convenience to eliminate needless duplication and reduce cost, one that appears to be working.

The same considerations of expediency and economy motivate the present attempts to add to NPOESS the goals of climate research. The technical complexities of combining seemingly disparate requirements are accompanied by the programmatic complexities of forging further connections among three different agencies, with different mandates, cultures, and congressional appropriators. Yet the stakes are very high, and each agency gains significantly by finding ways to cooperate, as do the taxpayers. Beyond cost savings, benefits include the possibility that long-term climate observations will reveal new phenomena of interest to weather forecasters, as happened with the El Niño/Southern Oscillation. Conversely, climate researchers can often make good use of operational data.

Necessity is the mother of invention, and the needs of all the parties involved in NPOESS should conspire to foster creative solutions to make this effort work. Although it has often been said that research and operational requirements are incommensurate, this report and the phase one report (*Science and Design*) accentuate the degree to which they are complementary and could be made compatible. The reports provide guidelines for achieving the desired integration to the mutual benefit of all parties. Although a significant level of commitment will be needed to surmount the very real technical and programmatic impediments, the public interest would be well served by a positive outcome.

Claude R. Canizares, *Chair*
Space Studies Board

Preface

This report is the final product of a Committee on Earth Studies (CES) examination of technical and programmatic issues related to the integration of research and operational Earth observation satellite systems in the support of climate research (see Appendix A for the statement of task). In a brief letter report ("On Climate Change Research Measurements from NPOESS," May 27, 1998), the committee provided an overview of the many scientific, technical, and programmatic issues associated with integrating the measurement responsibilities of research agencies with those of operational agencies. These issues are analyzed in detail in the committee's two-part report, *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design*[1] and *II. Implementation,* this volume. In both parts of this study, the committee uses the framework of requirements for climate research—monitoring climate change as well as understanding climate processes and impacts—as the basis for its investigation.

In *Science and Design*, the committee examined whether climate research requirements could be met with the planned National Polar-orbiting Operational Environmental Satellite System (NPOESS) that is being developed by the Integrated Program Office (IPO), a triagency office reporting through the National Oceanic and Atmospheric Administration (NOAA) to an executive committee composed of under secretary and administrator level officials of the Departments of Commerce and Defense and the National Aeronautics and Space Administration (NASA). The report also examined programmatic issues related to the inclusion of climate research requirements in NPOESS. To accomplish this, the committee selected, as case studies, eight measurement sets that are (1) of interest to the operational user community and (2) illustrative of the range of implementation strategies that might be considered in integrating NASA Earth Science Enterprise (ESE) and the NPOESS programs. The committee found that the operational and research systems being developed in the ESE and NPOESS programs can together potentially meet the need for long-term measurements for data continuity as well as the need for a flexible observing system that can take advantage of emerging scientific insights and technical advances.

The current volume, *Implementation*, focuses on approaches that will ensure interoperability between research and operational sensors and allow the infusion of new technology. The committee was particularly

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[1] National Research Council, Space Studies Board. 2000. *Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design*. National Academy Press, Washington, D.C.

interested in comparatively low-cost investments that could be made in planned satellite programs such as NPOESS that would increase its utility to the global change research community. Accordingly, the committee devoted much of its effort to an analysis of issues related to sensor calibration and validation (Chapter 2 and Appendix C). The committee also offers strategies for ensuring continuity across successive sensors and briefly discusses issues related to data systems for NPOESS.[2]

To support its work, the committee organized a 2-day workshop in July 1999, "Workshop on the Integration of IPO/NPOESS and NASA/ESE Capabilities for Climate Research" (see Appendix B for a summary of the discussions and a list of participants). Participants at the workshop—members of the committee, scientists involved in climate and related research areas, and officials from NASA and NOAA—considered opportunities in the near term to make incremental investments that would improve the suitability of operational missions for climate research.

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[2] Partly as a result of this work, NOAA and NASA asked the committee to undertake a short-duration study of climate data processing and archive strategies for the NPOESS Preparatory Project (NPP) and NPOESS. See National Research Council, Space Studies Board. 2000. *Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites*, National Academy Press, Washington, D.C.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their review of this report: Peter Cornillon, University of Rhode Island; Dennis L. Hartmann, University of Washington; Allan Sherman, Lockheed Martin; Roy W. Spencer, NASA Marshall Space Flight Center; William E. Stoney, Mitretek Systems; John Townshend, University of Maryland; and Zhengming Wan, University of California, Santa Barbara.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Wesley T. Huntress, Jr., Carnegie Institution, appointed by the Commission on Physical Sciences, Mathematics, and Applications, and Eugene M. Rasmusson, University of Maryland, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests solely with the authoring committee and the institution.

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Executive Summary

A key objective of climate research and monitoring programs is to deliver scientifically valid knowledge that can be used by the public and by policymakers to make informed decisions about large-scale environmental issues. Because Earth's climate involves a complex interplay among the atmosphere, oceans, cryosphere, and biosphere, meeting this objective will require a comprehensive strategy that includes observations, data analysis, technology development, modeling, and data archiving and distribution. Satellite observations are an essential part of this strategy as they can record global-scale phenomena and collect information on many critical physical, chemical, and biological processes. However, there are challenges in utilizing current satellite observation programs to support climate research and monitoring. The requirements of the climate research community are sometimes at odds with the capabilities of both the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). Further, both agencies are likely to continue to operate in a highly constrained fiscal environment. For these reasons, this report and its phase one companion, *Science and Design* (NRC, 2000), focus on approaches to leverage existing and planned operational and research satellite assets to meet the needs of climate research.

Operational satellite missions are designed primarily to provide observations to support short-term environmental forecasts, while research satellite missions are often designed primarily to study specific processes of scientific interest or to test new observing technologies. Obtaining long-term, well-calibrated measurements from space often falls between these agency objectives. Yet the Committee on Earth Studies believes that, while challenging, the integration of operational and research missions to advance the objectives of climate research is possible and that a unique opportunity to demonstrate such integration is presented by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and the redesigned NASA/Earth Science Enterprise (ESE) missions.

NPOESS and the NPOESS Preparatory Project (NPP) offer significant improvements over the capabilities of the two existing separate operational polar-orbiting systems: NOAA's Polar-orbiting Operational Environmental Satellites (POES) and the Department of Defense's Defense Meteorological Satellite Program (DMSP). Moreover, the redesigned NASA/ESE missions focus on critical science questions in the area of climate research, and NASA's new strategy of employing a larger number of smaller spacecraft provides a high level of flexibility.

NPOESS will collect critical data sets on variables that are not currently included in operational measurements (such as radiation budget, total ozone, wind speed and direction, ocean topography, and ocean color) and will offer improved quality for some variables now being measured (such as atmospheric moisture and temperature profiles, all-weather sea surface temperature, and vegetation indices). Moreover, the orbits of NPOESS satellites will have stable equator-crossing times, which will significantly improve the utility of the data for climate research. The next set of NASA/ESE missions will not be based on copies of the first Earth Observing System (EOS) series. Instead, they will be divided into systematic missions (i.e., emphasizing measurements of processes dominated by long-term variability) and exploratory missions (i.e., focused on specific scientific questions that can be answered with a single mission). Because systematic measurements are an essential element of the NASA/ESE strategy, special attention is being given to NPOESS. In this context, NPP is important as a testbed for the incorporation of NASA/ESE science requirements into an operational mission.

The present report emphasizes two themes. First, data stability—enabled by long-term, consistent data sets—is a critical requirement for climate research. Second, system flexibility is necessary to enable pursuit of new science objectives as well as new technology and to respond to surprises that will emerge in the Earth system. Further discussion of both themes can be found in the "Pathways" report (NRC, 1998).

DATA STABILITY

Because natural signals are often small, it is difficult to ascribe particular events or processes to climate change. This is especially true in the area of anthropogenic forcing, or global warming. Natural events such as the El Niño/Southern Oscillation represent enormous, global-scale perturbations in a variety of Earth system variables, such as ocean winds and sea surface temperature, precipitation, and atmospheric carbon dioxide. For this reason, long-term, high-quality measurements are needed to discern subtle shifts in Earth's climate. Such measurements require an observing strategy emphasizing a strong commitment to maintaining data quality and minimizing gaps in coverage. Operational satellites represent a unique asset that could produce long time series with sufficient quality, although their primary mission is not climate research. NPOESS officials appear to be making significant progress toward facilitating such data records, particularly in their attempts to set stability requirements for some of the critical data sets. Currently, however, some NPOESS environmental data records do not have stability requirements, while others have incomplete or insufficient requirements. In addition, no strategy to test the stability requirements for NPOESS measurements has been defined or developed.

The committee considered data stability from three perspectives:

- Sensor calibration and data product validation,
- Requirements for and approaches to data continuity, and
- Data systems.

Calibration and Validation

Findings

Long-term studies such as those needed for documenting and understanding global climate change require not only that a remote sensing instrument be accurately characterized and calibrated but also that its characteristics and calibration be stable over the life of the mission. Calibration and validation should be considered as a process that encompasses the entire system, from the sensor performance to the derivation of the data products. The process can be considered to consist of five steps. In the approximate order of performance they are (1) instrument characterization, (2) sensor calibration, (3) calibration verification, (4) data quality assessment, and (5) data product validation.

Recommendations

The committee makes the following recommendations with regard to calibration and validation:

- A continuous and effective on-board reference system is needed to verify the stability of the calibration and sensor characteristics from the launch through the life of the mission.

- Radiometric characterization of the Moon should be continued and possibly expanded to include measurements made at multiple institutions in order to verify the NASA results. If the new reflectance calibration paradigm is adopted (see Appendix C), then the objective of the lunar characterization program should be to measure changes in the relative reflectance as a function of the phase and position of Earth, the Sun, and the Moon rather than absolute spectral radiance.
- The establishment of traceability by national measurement institutions in addition to the National Institute of Standards and Technology should be considered to determine if improved accuracy, reduced uncertainty in the measurement chain, and/or better documentation might be achieved, perhaps even at a lower cost.
- The results of sensitivity studies on the parameters in the data product algorithms should be summarized in a requirements document that specifies the characterization measurements for each channel in the sensor. Blanket specifications covering all channels should be avoided unless justified by the sensitivity studies.
- Quality assessment should be an intrinsic part of operational data production and should be provided in the form of metadata with the data product.
- Validation, an essential part of the information system, should be undertaken for each data product or data record to provide a quantitative estimate of the accuracy of the product over the range of environmental conditions for which the product is provided.
- Wavelengths and bandwidths of channels in the solar spectral region should be selected to avoid absorption features of the atmosphere, if possible.
- Calibration of thermal sensing instruments such as CERES (Clouds and the Earth's Radiation Energy System) and the thermal bands of MODIS (Moderate-resolution Imaging Spectroradiometer) should continue to be traceable to the SI unit of temperature via the Planckian radiator, blackbody technology.

Data Continuity

Findings

Continuity is concerned with more than the presence or absence of data. It includes the continuous and accurate characterization of the properties that affect the construction of the time series. The most useful data for climate research purposes are time series that are continuous and for which the characterization of error, in terms of precision and bias, is known. Such errors should be minimized as much as possible in order to detect the often small, climate-related signal.

Recommendations

The committee recommends taking the following steps to ensure data continuity:

- A policy that ensures overlapping observations of at least 1 year (more for solar instruments) should be adopted. The IPO should examine the relation between this requirement and the launch-on-failure strategy and should include a clear definition of spacecraft or instrument failure and an assessment of still-functioning instruments.
- Competitive selection of instrument science teams should be adopted to follow the progress of the instrument from design and fabrication through integration, launch, operation, and finally, data archiving, thereby promoting more thorough instrument characterization.
- As instruments are developed for future missions, the IPO should make a determination of threats to the continuity of currently monitored radiances in the design requirements.
- Out-year funding should be provided to maximize the investment made in climate and operational observing instruments.[1]

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[1] For climate studies, there is a need for continuing investment in sensor studies and tests—programs for operational instruments typically do not fund such activities beyond initial checkout.

- Free-flier status should be evaluated for key climate parameters such as solar radiance and sea-level altimetry whose measurement appears to be endangered by the NPOESS single-platform configuration.
- Proven active microwave sensors should be considered for ocean vector winds, another key climate (and operational) parameter.

Data Systems

Findings

The development of an NPOESS climate data system (NCDS) represents a significant challenge. Care will be needed to ensure that the design and specifications for the data system are given a broad review prior to their implementation. In addition, special attention will be needed in areas including calibration and validation, data product continuity, data archiving, archive access, reprocessing, and cost. The NPP will serve for the early testing of instruments and data systems. It will be a joint activity between NASA and the Integrated Program Office (IPO) and as such will provide an opportunity for NPOESS to benefit from the progress NASA is making in data system development.

The development of an NCDS can clearly benefit from adopting the best elements of the current NASA and NOAA data systems. However, it will not be enough to simply expand existing facilities. A successful NCDS will also require a new vision in which innovation and competition play a central role. Observations of Earth will increase by an order of magnitude when NPOESS begins operation, which could lead to an enormous increase in our understanding of Earth. To realize this potential, the huge volumes of raw data must be converted to usable products and information. The responsibility for doing this should be given to those groups and organizations that demonstrate the vision, innovation, and expertise needed to meet the NPOESS challenge.

Recommendations

The committee recommends meeting the following basic data-systems requirements in addition to what is needed for operational processing:

- A long-term archiving system is needed that provides easy and affordable access for a large number of scientists in many different fields.
- Data should be supported by metadata that carefully document sensor performance history and data processing algorithms.
- The system should have the ability to reprocess large data sets as understanding of sensor performance, algorithms, and Earth science improves. Examples of sources of new information that would warrant data reprocessing include the discovery of processing errors, the detection of sensor calibration drift, the availability of better ancillary data sets, and better geophysical models.
- Science teams responsible for algorithm development, data set continuity, and calibration and validation should be selected via an open, peer-reviewed process (in contrast to the approach taken with the operational integrated data processing system (IDPS) and algorithms, which are being developed by sensor contractors for NPOESS).
- The research community and government agencies should take the initiative and begin planning for a research-oriented NCDS and the associated science participation.

SYSTEM FLEXIBILITY

Because the forcing and response of Earth's climate to natural and anthropogenic variability is a complex, nonlinear process, it can be anticipated that unforeseen properties will emerge. These are the "surprises" discussed in the "Pathways" report (NRC, 1998). Scientific advances will require new observing tools. Moreover, technological advances may reduce costs or improve system performance. A rigid plan of flying exact copies of sensors will not accommodate such changes. Therefore, a way will have to be found to infuse new technology into the system while maintaining data continuity and without driving up costs. Technology insertion is defined as introduction of any new and/or improved capability (either through hardware or software innovations) into an established operational system. NASA/ESE will play an especially important role in this regard, given its experience in technology development. The committee considered the issue of system flexibility primarily from this vantage point.

Technology Insertion

Qualifying technological innovations span a wide range of implied changes and, thus, impose a wide range of risk levels on the operational performance of the system. For example, replacing a computer with a faster model that preserves the form, fit, and function of the earlier model is quite different from changing the computer's operating system or data processing algorithm. There is risk in any change to the design, but some changes may ripple throughout the system, forcing additional changes to accommodate the first. Additional risk is anathema for an operational system, for which reliability and continuity are the prime considerations. Any potential change must be examined carefully and conservatively, no matter how well justified the augmented capabilities may be from a scientific point of view.

Findings

The committee's findings are as follows:

- Operational agencies exhibit a natural tendency to resist change; any candidate technology enhancement to increase the science content of data products must satisfy rigorous prequalification before being accepted into an operational payload.
- The challenge for an operational system such as NPOESS is to accommodate technological change in a timely manner, while ensuring that the modified system will sustain operational functionality.
- In general, the means of technology insertion into operational missions is not well determined. Indeed, there appears to be a gap between the development of instruments in the science stream and their adoption in the operational stream.
- If the NPOESS program is to be used to support the science community as well as the operational weather agency, then a careful assessment of the pertinent science requirements must be made in the early phases of the program.
- Technology insertion always will be subject to limitations. Any downstream change in the on-board technology must fit within the spacecraft resources (mass, power, data bandwidth, data volume, etc.) that may remain over and above the requirements of the baseline system.
- It is likely that the development and qualification of any new measurement capability that might be required for scientific purposes would have to be funded from non-IPO sources, unless that instrument were deemed to be critical to the NPOESS operational mission. Clearly, vision and well-coordinated interagency planning are needed to sustain the development of suitable instruments in synchronization with NPOESS flight opportunities.
- Unlike the relatively short design lifetimes of their predecessors, the NPOESS satellites are meant to have a 7-year lifetime. Although a 7-year design life is laudable for an ongoing operational facility, it adds further roadblocks to the process of technology insertion.
- Under current policy, whether an instrument provides data that are important to a climate science record has no bearing on the criteria for launch of an NPOESS replacement spacecraft. Partial failure, even of a mission-critical instrument, may have such a small impact for operational weather purposes that it does not trigger a replacement launch. However, the same fault could induce degradations that would be far more significant for scientific purposes.
- An opportunity to prove in practice the value of a candidate instrument is often a pivotal step in the effort

to transform a scientific measurement into an operational tool. A satellite program such as NPP could provide such opportunities.

- It is noteworthy that NASA's ESE Technology Development Plan does not provide for the transitioning of technology from scientific status to operational status. This fact is central to the question of technology insertion into NPOESS in support of climate or other scientific objectives. Even if a new technological innovation is proven to offer unique scientific value and is shown to be technically feasible, there are no firm plans to guide its transition onto NPOESS.

Recommendations

The IPO and NASA should strive to accommodate technological change in a timely manner, while ensuring that the modified system will sustain operational functionality. The committee's recommendations with regard to technology insertion are as follows:

- The IPO should identify a person or group to review the system requirements and the design to ensure that both the Integrated Operational Requirements Document (IORD; IPO, 1996) and the contractor approaches will support flexibility and change.
- NASA should provide a list of science requirements (ostensibly from the Science Plan) and climate requirements that are candidates for implementation on NPOESS.
- The IPO should plan for the insertion of new or enhanced measurement capabilities into NPOESS that would likely have to be funded from non-IPO sources.
- NASA ESE should implement its Technology Development Plan with firm plans linked to missions and ensure that any necessary NPOESS enabling technologies are covered in the plan.
- NASA and the IPO should devise an approach to support announcing and accepting additional experiments on NPOESS.
- It is essential that the process of incorporating research requirements into NPOESS be started now and be allowed to influence the program development and risk reduction phase that is in progress, without disrupting the primary NPOESS mission. Opportunities for change after the launch are limited by the longer satellite life and longer time between launches.

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1

Introduction

CHARACTERISTICS AND REQUIREMENTS OF RESEARCH AND OPERATIONAL MISSIONS

When completed, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) will meet the combined operational needs of the Department of Commerce and the Department of Defense (DOD) for data that are currently supplied by the National Oceanic and Atmospheric Administration's (NOAA's) Polar Orbiting Environmental Satellites (POES) and the DOD's Defense Meteorological Satellite Program (DMSP). With the longer planned lifetime of its satellites and more stringent requirements for performance and stability relative to POES and DMSP, the NPOESS system offers an opportunity to begin the development of an operational component of an integrated satellite observing system for climate research and monitoring.

Operational satellite systems have clearly defined missions and observation requirements. The POES satellites, for example, supply environmental information to support short-term weather forecasts for the protection of life and property. This information must be delivered in a timely fashion and in well-defined formats to serve the needs of the forecast models and users who require near-real-time data. NPOESS is being designed to met these needs as well as requirements particular to the Department of Defense for forecasts and imagery that support military operations. Scientific research missions, such as those operated by NASA's Earth Science Enterprise (ESE), generally are more flexible in terms of observing requirements but more stringent in terms of data quality, emphasizing data stability and the use of leading-edge technology. In contrast to operational missions, research missions are usually designed to answer specific scientific questions within a fixed time frame (generally 3 to 5 years).

The requirement for timely data drives the design and implementation of operational sensor and ground systems, which emphasize data reliability and accessibility on short time scales. If a critical sensor fails, the system must be able to launch a replacement within a short period of time to ensure data continuity. Similarly, ground systems must be designed to process and deliver data rapidly in a nearly automated fashion. The operational nature of missions means that NPOESS must accomplish these tasks in a cost-constrained environment: new requirements and capabilities are investigated carefully and weighed in terms of how they might improve services, and sensors are generally acquired in blocks, rather than one at a time, to obtain volume discounts from the manufacturers.

For research missions as for operational systems, observational requirements and considerations of data accessibility drive sensor and ground systems to a particular implementation that emphasizes innovation, data quality, and long-term accessibility. Rather than fly copies of specific sensors, the science research community generally prefers to fly new technology, and its missions are usually designed and implemented with strong scientific oversight. Sensor calibration and data product validation are critical elements of each mission. Ground systems focus on providing long-term access to low-level data to support reprocessing. Although there are cost constraints for research missions, these constraints are not applied to the system as a whole. Compelling new missions can be developed and funded somewhat independently of other elements of the NASA/ESE budget.

Although the operational and the research approaches can appear to conflict, there are features of both that are essential for climate research and monitoring. However, the operational agencies are necessarily wary of assuming responsibility for new requirements that may be open ended in an environment that is cost constrained. The research agencies are similarly concerned about requirements for long-term, operational-style measuring systems that might inhibit their ability to pursue new technologies and new scientific directions. Despite their need for long-term commitments to measure many critical variables, they wonder about relying on operational programs that might decrease the level of scientific oversight as well as opportunities for innovation.

Long-term, consistent time series are essential for the study of many critical climate processes, which vary over inherently long time scales. That said, many of the variables of interest for climate research have analogs in observing systems for short-term forecasting, although the performance requirements may differ significantly. For example, one of the fundamental attributes of operational observing systems—long-term commitment to data availability—is especially appealing to the climate research community. However, climate research also requires the ability to insert new observing capabilities to ensure that data remain at the state of the art as well as to respond to new science opportunities. Thus, the fundamental challenge is not the transitioning of research capabilities into the operational systems but rather the integration of the two capabilities in a rational manner. Both climate research and climate monitoring require a long-term commitment to consistent data sets and short-term flexibility to pursue new science and technology directions.

The integration of research and operational capabilities for climate research will require continuing cooperation between NASA and NOAA. Eventually, a single federal agency may be responsible for the overall climate observing strategy, but for the foreseeable future, the committee expects that the expertise from multiple agencies will be required. Its recommendations, therefore, are directed to NASA, NOAA, and the IPO.

KEY IMPLEMENTATION ISSUES

The following are the key implementation issues:

- Long-term comparability of data sets such that sensor performance and other technical performance issues are not mistaken for natural variability in Earth's system (the committee prefers the term "comparability" rather than "consistency" because, in its view, the long-term objective is to develop data records that can be compared and the basis quantified—it is difficult to develop consistent data sets even with identical sensors);
- Data product validation, including quantitative assessments of the temporal and spatial accuracy of the data;
- Data continuity and strategies to launch replacement sensors to maintain the quality of the long-term data record;
- Long-term archiving of data sets and capabilities for reprocessing and analysis;
- Accessibility and availability of data, including pricing; and
- Planning for technology insertion.

The committee organized these issues into four areas, in each of which operational and research systems differ significantly:

1. Sensor calibration and data product validation,
2. Data continuity,
3. Data systems and ground systems, and
4. Technology insertion.

Each is discussed in turn in Chapters 2 through 5, respectively. For each area, the committee analyzes the approach planned by NASA/ESE and the IPO and recommends how the approaches might be integrated.

CLIMATE DATA RECORDS

This report introduces the concept of a climate data record (CDR), which is a data set designed to enable study and assessment of long-term climate change, with "long-term" meaning year-to-year and decade-to-decade change. Climate research often involves the detection of small changes against a background of intense, short-term variations. In contrast to the environmental data records (EDRs) that are planned for NPOESS, CDRs enable errors in the data to be analyzed and quantified in both space and time. The production of CDRs requires repeated analysis and refinement of long-term data sets, usually from multiple data sources. For example, global temperature measurements from the Microwave Sounding Unit have been assembled from multiple copies of the sensor over the past 20 years (NRC, 2000). Intercalibration and data continuity are critical components of CDRs. Ancillary data, such as orbit parameters and other geophysical fields, are generally used to produce CDRs with minimal biases over time and space. In contrast, an EDR is the best product that can be produced in near-real time. Figure 1.1 compares NOAA/National Environmental Satellite Data and Information Service (NESDIS) sea surface temperature (SST) and the corrected SST derived by Reynolds (1993). Both data sets were estimated using the Advanced Very High Resolution Radiometer on the NOAA POES. The standard NOAA/NESDIS product is equivalent to an EDR, and the Reynolds product is equivalent to a CDR. The SST EDR shows the short-term impacts of an unpredictable event (the Mt. Pinatubo eruption), greatly reducing its suitability for climate research.

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Reynolds, R.W. 1993. "Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures," *J. Climate* 6:768-774.

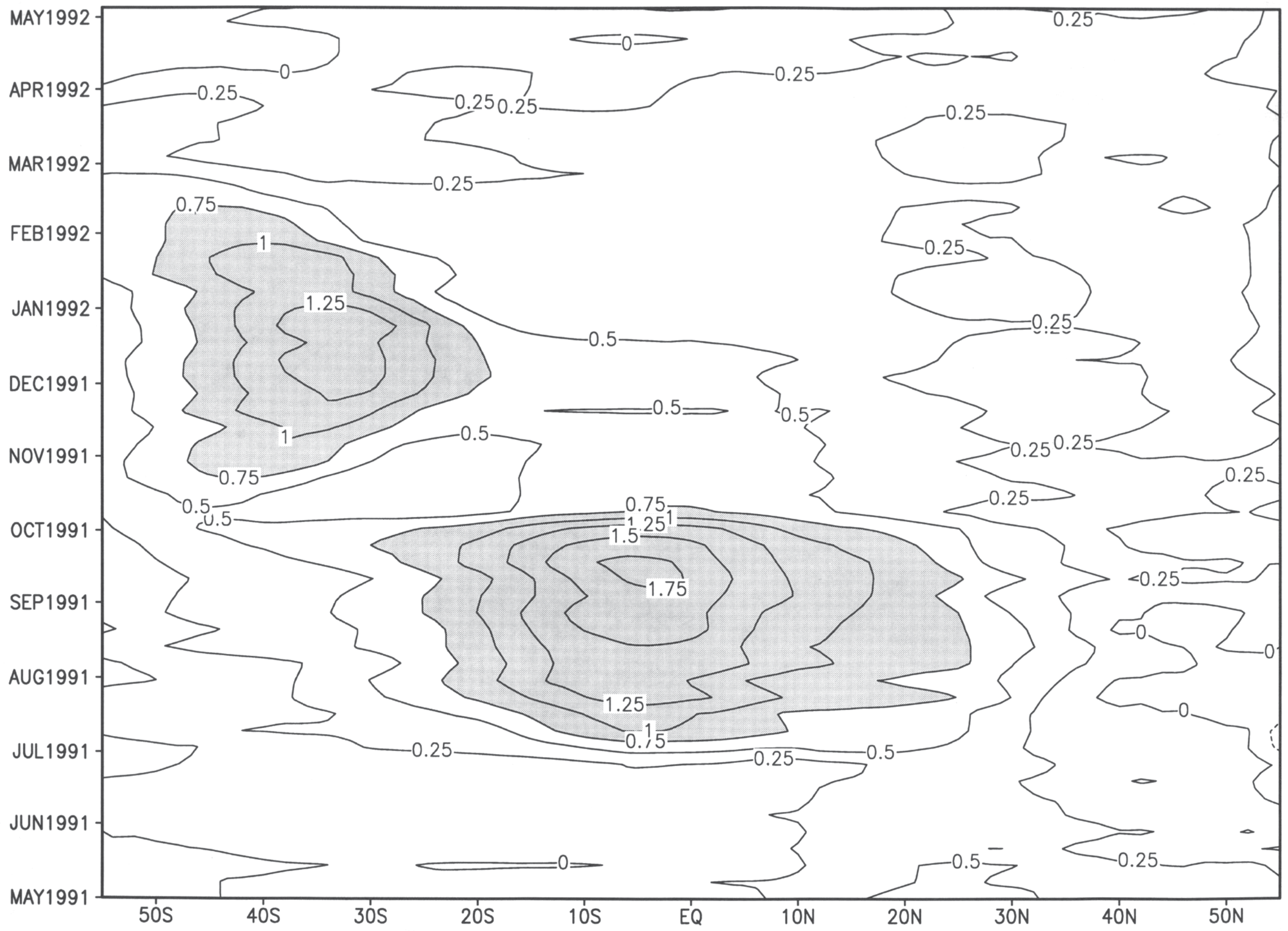

FIGURE 1.1 Zonally averaged difference between the optimum interpolation with and without satellite bias correction for 55 weeks. The first week is April 28 to May 4, 1991; the last week is May 10 to May 16, 1992. The sign of the difference is "with-without" satellite correction. SOURCE: Reynolds (1993).

2

Calibration and Validation

INTRODUCTION

Calibration and validation should be considered as a process that encompasses the entire system, from sensor performance to the derivation of the data products. Long-term studies for documenting and understanding global climate change require not only that the remote sensing instrument be accurately characterized and calibrated, but also that the stability of the instrument characteristics and calibration be well monitored and evaluated over the life of the mission through independent measurements. Calibration has a critical role in measurements that involve several sensors in orbit either simultaneously or sequentially and perhaps not even contiguously. Finally, there is the need to validate the data products that are the raison d'etre for the sensor. As illustrated in Figure 2.1, five steps are involved in the process of calibration and validation: instrument characterization, instrument calibration, calibration verification, data quality assessment, and data product validation.[1] All five steps are necessary to add value to the data, permitting an accurate, quantitative picture rather than a merely qualitative one.

1. *Instrument characterization* is the measurement of various specific properties of a sensor. Most characterizations are performed before launch. They can be performed at the component or subassembly level, or at the system level. For critical characteristics the measurements should be performed before and after final assembly to reveal unpredicted sources of error. Characteristics that are expected to change owing to the rigors of launch must be remeasured on orbit unless it can be shown that the expected changes will be within the error budget allocated according to the data product requirements.
2. *Sensor calibration* is carried out to determine the equivalent physical quantity—for example, radiant temperature—that stimulates the sensor to produce a specific output signal, for example, digital counts. This process determines a set of calibration coefficients, kelvin per digital count in this example. The calibration coefficients transform sensor output into physically meaningful units. The accuracy of the transformation to physical units depends on the accumulated uncertainty in the chain of measurements leading back to one of the

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[1] In this chapter, the term "data" refers to what the NPOESS Integrated Program Office (IPO) characterizes as "raw data records" (RDRs), and the term "data products" refers to the IPO-defined "environmental data records" (EDRs). Note that RDRs are also frequently referred to as "level 0 data."

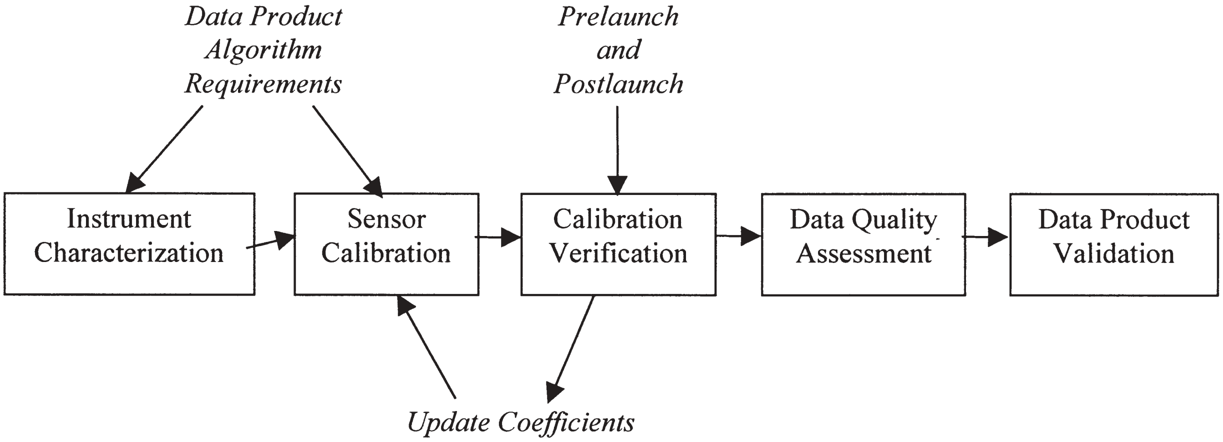

FIGURE 2.1 Calibration and validation are considered in five key steps from prelaunch sensor characterization and calibration to on-orbit data product validation.

internationally accepted units of physical measurement, the SI units.[2] For optimum accuracy and the long-term stability of an absolute calibration, it is necessary to establish traceability to an SI unit.

However, it is more important to determine to which SI unit the measurement must be traceable and whether traceability to an SI unit is even necessary. This can be done by examining the requirements of the data product algorithm. The question of which SI unit to use is answered by determining which chain of measurements has the lowest accumulated uncertainty. Often it is the shortest measurement chain and sometimes the most convenient one. In the case of a relative measurement, that is, in the measurement of a ratio (for example, reflectance), traceability to an SI unit is meaningless. The accuracy in this case will be a function of all the uncertainties accumulated in determining the ratio of the outgoing to the incoming radiation.

The specific characterization and calibration requirements and the needed accuracy are determined by the needs of the algorithms for each data product—that is, the parameters that must be measured and the accuracy to which they must be known. This list of requirements is usually presented as a list of specifications in the contract to build the sensor. It is obvious that if the accuracy requirements are set too high, needless expense will be incurred. If they are set too low, the algorithm will not produce an acceptable data product. The optimum range should be set by sensitivity analyses of the algorithms of several key data products.

3. *Calibration verification* is the process that verifies the estimated accuracy of the calibration before launch and the stability of the calibration after launch. Prelaunch calibration verification could take the form of documentation of accumulated uncertainty or it could be determined by comparisons with other, similar, well-calibrated and well-documented systems. The latter method of calibration verification is preferred since one or more sources of

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[2] The General Conference on Weights and Measures, Conférence Générale des Poids et Mesures (CGPM), recommended the establishment of a practical system of units of measurement that was adopted by all signatories to the Treaty of the Meter (Convention du Metre). The name Système International d'Unités, abbreviated SI, was given to the system by the 11th session of the CGPM in 1960. In 1970 at the 14th CGPM, the current version of the SI was completed by adding a seventh base unit, the mole. The other six base units are the ampere, kelvin, kilogram, meter, second, and candela. These well-defined units (by internationally agreed upon experimental methods for realization) are by convention considered to be dimensionally independent and are to be used to establish the quantities for the measurement of electricity, temperature, mass, length, time, luminous intensity, and amount of substance. All other quantities are derived from the SI units and are defined by the International Organization for Standardization. At the end of the chain of measurements needed to establish a derived quantity is the standard, or measurement artifact, to which has been assigned a value in one of the units derived from the SI. In principle, similar standards obtained from two different national measurement laboratories should be equivalent within the combined uncertainty accumulated in their respective chain of measurements.

uncertainty may have been overlooked in the calibration documentation assembled by a single laboratory. Post-launch calibration verification refers to measurements using the on-board calibration monitoring system and vicarious calibrations. Vicarious calibrations are those obtained from on-ground measurements (ground truth), from on-orbit, nearly simultaneous comparisons to other, similar, well-calibrated sensors or, in the case of bands in the solar reflectance region, from measurements of sunlight reflected from the Moon.

4. *Data quality assessment* is the process of determining whether the sensor performance is impaired or whether the measurement conditions are less than optimal. Data quality assessment ensures that the algorithm will perform as expected; it is a way of identifying the impacts of changes in instrument performance on algorithm performance. Instrument degradation or a partial malfunction will affect data quality. Less-than-ideal atmospheric and/or surface conditions, and the uncertainties in decoupling atmosphere-surface interactions, will also degrade the quality of a surface or atmospheric data product. It is necessary to publish the estimated quality of the data products so that the data user will be able to reach well-informed conclusions.

5. *Data product validation* is the process of determining the accuracy of the data product, including quantifying the various sources of errors and bias. It may consist of comparison with other data products of known accuracy or with independent measurement of the geophysical variable represented by the product. Data product validation provides a quantitative estimate of product accuracy, facilitating the use of the products in numerical modeling and comparison of similar products from different sensors.

Another key issue for calibration and validation is consideration of mission operations factors such as orbit parameters, orbit maintenance, and launch schedules. These items, which are often as important to calibration and validation as the properties of the instruments and software, are not further elaborated on in this report, but the committee considers them important to include in developing plans for calibration and validation in integrating climate research into NPOESS operations.

The five steps leading to a fully calibrated and validated system are discussed in more detail below.

INSTRUMENT CHARACTERIZATION

Instrument characterization must be carried out before a launch, at either the component or the system level, or sometimes both, depending on how critical a specific characteristic is to the data product algorithm as determined by a sensitivity analysis. When summarized in a requirements document that specifies characterization measurements, the results of the sensitivity studies should prove to be a systematic way of accomplishing this work. Blanket specifications covering all channels lead to wasted effort, and important parameters are often overlooked. The time spent in deriving and listing characterization specifications for the parameters for individual channels will result in more efficient design, fabrication, and testing, better sensor performance, and reduced cost.

In addition, an effort should be made to address the interdependency of various instrument characteristics and to ensure balance by determining the sensitivities of the data product algorithms to combinations of instrument characteristics.

The following short list of some of the parameters that might have to be measured is presented as a guide to specifying the characterization requirements for each channel:

- *Spectral response*, both in band and out of band, is the relative spectral shape of the sensor response as a function of wavelength. This is usually a critical parameter, and the out-of-band response is often poorly measured, if it is measured at all. Spectral response is normally measured at the component level, that is, by measuring the transmittance of the filters, and the out-of-band response should be measured at that stage also. Because spectral shifts may arise as a result of temperature changes or beam angle, the in-band spectral response should be measured at the end-to-end system level and at the expected operating temperature(s). The spectral transmission of interference filters has been known to be unstable (and subject to on-orbit vacuum shifts in response), so that it may be necessary to remeasure the spectral response on orbit. An example of instrumentation to measure on-orbit response measurements is the spectroradiometric calibration assembly (SRCA) on board the Moderate-resolution Imaging Spectroradiometer (MODIS) now flying on the Earth Observing System (EOS) Terra spacecraft. Such a complex and expensive instrument may not be necessary if reflectance-based rather than radiance-based calibration is used. In this case the precise spectral shape of the band will be less critical (see Appendix C, "Solar Reflection Region Measurements").

- *Detector and electronics linearity* is the ability of the sensor to accurately scale up or down from the level at which it was calibrated. This feature could be checked at the subassembly level, but it is best measured in the full system. It should be noted that it is presently common practice to check linearity by varying the calibration source output. In the case of a blackbody standard source, care must be taken to avoid the effects of spectral changes due to changes in temperature. In the case of integrating sphere sources employing multiple incandescent lamps, it is common practice to check linearity by varying the number of lamps illuminating the sphere. This is not an accurate method. A linearity-verified detector-amplifier should be used to monitor the sphere output. The linearity characterization is then based on a detector of known linearity characteristics rather than on the assumption that the several incandescent lamps have equal radiant outputs.
- *Detector and electronics noise* should be measured at the end-to-end system level and over the expected range of operating temperatures of the sensor on orbit.
- *Polarization sensitivity* should be measured at the end-to-end system level. It is critical for the short wavelength bands, where the scene is often highly polarized. In systems where a scanning mirror is employed, the reflectance of the scanning mirror may be polarization sensitive, which would change the system polarization response as a function of scan angle.
- *Out-of-field-of-view sensitivity* is the sensitivity of the sensor to scattered radiation. This should be tested at the end-to-end system level.
- *Optical performance* is the measure of the system modulation transfer function (MTF) or, equivalently, the point spread function. This function should be tested at the end-to-end system level. Measures of individual MTFs are rarely useful. Also, since optical performance may be severely affected by launch and may degrade, it should be tested again on orbit. This can be done by the MODIS SRCA, or it can be done using ground scenes. The characterization of MTF was first demonstrated for the Landsat-4 Thematic Mapper under the NASA Landsat Instrument Data Quality Assessment (LIDQA) program in 1984.
- *Detector array uniformity*, often called flat-field correction, will also include measurement of the out-of-specification (bad) pixels and should be measured on the end-to-end system. The detector array can be expected to degrade, so the characterization should be repeated on orbit. Characterization of detector array uniformity can be done by averaging many cloud-filled scenes in both the solar reflective and thermal spectral regions.
- *Pointing accuracy* should be measured on the end-to-end system. Pointing accuracy could degrade during launch, so the instrument alignment should be characterized by the use of a library of ground control points once the sensor is in orbit.
- *Band-to-band registration* measurements should be done on the full system. As in the case of pointing, band-to-band registration accuracy could degrade during launch, so the measurement should be repeated once the sensor is in orbit. Again, the MODIS SRCA can do this, but the check can be made using ground data, as was demonstrated by the LIDQA project (Wrigley et al., 1984).

SENSOR CALIBRATION

It is usually through the tie-in to SI units that measurements made with different instruments and at different times can be related. As noted above, it is important to determine which type of calibration is truly needed for both short- and long-term studies. This determination, that is, which SI unit to use, is not a semantic argument. It has consequences that will affect the cost and performance of an instrument.

It should also be noted that there is a widespread misconception in the United States that traceability to reference standards of the National Institute of Standards and Technology (NIST) is the only way to ensure accuracy. The accuracy of an absolute measurement can be assessed only via a documented chain of measurements traceable to an SI unit, as described above. Often this is accomplished by utilizing an artifact standard from NIST, but this is not strictly necessary. Other national measurement institutions may have more accurate and better-documented standards to meet the same need. Other avenues to verifying accuracy should be examined to determine if reduced cost and perhaps improved performance could be achieved.

Specific calibration requirements for particular sensor types and their data products—energy balance, scene temperature, and scene content—are examined below.

Energy Balance Measurements

Energy balance sensors are the radiation balance sensors, such as Clouds and the Earth's Radiation Energy System (CERES), and the solar irradiance sensors, such as the Active Cavity Radiometer Irradiance Monitor (ACRIM). Each type of sensor is conceptually traceable to the fundamental unit of either electricity or temperature, respectively. The traceability presently in use for these sensors, temperature for radiation balance and electricity for solar irradiance, appears to be state of the art. Their respective measurement chains also appear to be optimal within the limits of present technology.

There has been some recent discussion, however, advocating a change in the traceability of the radiation balance sensors, from temperature to electricity, using an electrical substitution radiometer operated in a cryogenic environment at NIST. The accumulated uncertainty of the measurement chain for the proposed alternative approach, at its present state of development, is much larger than that of the traceability method now being used. If the radiation balance sensors are redesigned and improved, then changing the method of traceability should be considered. A radiation balance sensor on orbit based on the electrical substitution method, the method used in ACRIM, is now technically feasible since the advent of portable, mechanically cooled, cryogenic electrical substitution radiometers (Fox et al., 1996) and superconducting, high-sensitivity temperature sensors (Rice et al., 1998).

Thermal Region Measurements

Remote sensing instruments to determine scene temperature and scene reflectance are normally considered together since they are often functions within the same sensor; two examples are the Landsat Enhanced Thematic Mapper and MODIS. The calibration of these sensors is typically a conversion from digital counts to units of absolute radiance (radiant power per area per solid angle, within a specified spectral band). The calibration traceability is to the SI unit of temperature. The same calibration units are used in both the thermal spectral range, at wavelengths longer than about 2.5 μm, and the solar reflective range, at wavelengths shorter than 2.5 μm. Earth is the dominant radiant source in the thermal spectral range; however, it is not a significant radiant source in the solar reflective range. For a sensor operating in the thermal range, Earth is a radiant emitter, so a calibration in units of radiance traceable to the SI unit of temperature is reasonable. However, in the solar reflective spectral region, Earth is not a radiant emitter, so the basis of the calibration of those channels should be examined more closely. Since reflectance-based calibrations are not typical, the theoretical basis for this type of calibration is discussed in some detail in the next section.

For thermal spectral region sensors such as MODIS, the present method of traceability (that is, via the radiance of a near-Planckian emitter—a blackbody), which is traceable to the SI unit of temperature, is state of the art. It should be mentioned again that changing the method of traceability to the SI unit of electricity by using a cryogenic electrical substitution radiometer could result in a larger uncertainty unless significant improvements are made in this technology.

Similarly, microwave radiation sensor calibrations for active and passive systems are traceable to the SI unit of temperature, the kelvin. Microwave backscatter can be used to deduce roughness or the elevation of properties of the surface rather the radiometric properties. The on-orbit calibration procedure for microwave sensors for measuring scatter or altitude makes use of conventional comparisons of microwave brightness temperatures of near-Planckian sources.

Backscattered microwave radiation sensors on orbit (both active and passive) are calibrated against a hot and a cold brightness temperature source. At the low end, deep space (2.7 K) is the cold brightness temperature source.

At the high end, an on-board blackbody simulator with a calibrated temperature sensor is used as the hot brightness temperature source. The calibration of the temperature sensor is traceable to the kelvin.

CALIBRATION VERIFICATION

As is noted above, prelaunch calibration verification is done by documenting the train of measurements leading to the calibration from the SI unit or from the initial ratio measurement; the uncertainties accumulated in the chain of measurements are the measure of the accuracy of the calibration. The best method of verifying prelaunch calibration accuracy is a comparison between independent paths leading up to the same calibration. The only way for national laboratories to verify accuracy is to conduct interlaboratory measurement comparisons or to compare two different measurement methods.

The on-board calibration monitoring system, often referred to (incorrectly) as the on-board calibrators, should perhaps be called the on-board stability references. It is the function of the on-board references to maintain calibration accuracy through launch and throughout the life of the sensor on orbit. Another role of the on-board reference comes into play if a sensor fails before its replacement is launched. With stable references included in the sensors, there is still the possibility of connecting the two time series.

The stability of microwave radiation sensors, both active and passive, is tested against the on-board hot and cold brightness temperature sources. The greatest uncertainty in backscattered microwave measurements arises from the assumption of sensor linearity in scaling between the hot and cold sources and not from calibrating the temperature of the radiation sources.

If the paradigm for calibrations in the solar reflective spectral region is shifted from radiance- to reflectance-based measurements, there will be no need to maintain the calibration via an incandescent lamp, as is the current practice. Furthermore, as indicated above, wavelength and bandwidth stability will be less critical. Future sensors will not need complex and expensive lamp-based on-board calibrators such as the MODIS SRCA. Only an on-board reflectance standard will be needed, and its stability will have to be assured. The on-board calibrator system for MODIS includes a diffuser stability monitor that is referenced to the Sun and should be able to fulfill the reflectance stability monitoring role, but it has yet to be demonstrated. What has been demonstrated is the use of the Moon to monitor the stability of the diffusers on board the Sea Viewing Wide Field of View Sensor (SeaWiFS) (Barnes et al., 1999) and the Visible and Infrared Scanner (VIRS) (Lyu et al., 2000).

Like Earth, the Moon is not a radiant emitter. It is the ultimately stable reflectance reference, having been undisturbed for eons by the forces that alter the reflectance of Earth. However, it is a less-than-ideal reference because its reflectance is very nonuniform and changes with its position relative to that of the Sun and Earth. The current NASA-supported project to measure the Moon in all the three-body positions will eventually solve the problems associated with its nonuniformity and variability (Kieffer and Wildey, 1996). It is important that this work continue to be supported and possibly verified by measurements made at other institutions. In addition, the impact of the change in calibration paradigm from radiance to reflectance should be examined in regard to the lunar study. Certainly, one immediate result will be to eliminate the need for an absolute spectral radiance calibration, substituting a stable reflectance reference.

Vicarious calibration should be used as one of the methods to assure the long-term stability of a sensor and the comparability of measurements between sensors. Vicarious calibrations involve measuring the radiometric properties of a nearly ideal (i.e., uniform and spectrally unstructured) scene to verify the sensor's characteristics and its calibration factors. Of course there are no truly ideal scenes, so a variety of near-ideal locations are needed to achieve this objective.

Independent measurements are taken for surface targets considered to be nearly uniform and spectrally unstructured targets. For optical systems, well-instrumented, high-reflectance targets such as White Sands (Gellman et al., 1993) or the Railroad Valley Playa (Scott et al., 1996) are commonly used vicarious calibration sites. For thermal systems, investigators use high-altitude lakes or ocean buoys as thermal vicarious calibration targets (Wan et al., 1999). Another approach for optical systems is to use cloud-top radiance statistics (Vermote and Kaufman, 1995). Present methods for vicarious calibrations report the results as absolute spectral radiance at the top of the atmosphere. However, the actual basis for the measurements on the ground is usually the reflectance of the surface (Slater et al., 1987). Since absolute radiance is obtained using the absolute values of solar spectral irradiance, little change in the methods of vicarious calibration would be needed to adapt to a reflectance-based calibration paradigm.

DATA QUALITY ASSESSMENT

The objective of data quality assessment is to identify data that are suspect or of poor quality relative to expected instrument and algorithm performance. Automated data quality assessment is undertaken during data production, and post-run-time quality assessment is done shortly after production, usually on a sample of the data. This latter activity usually involves applying various software tools to analyze sample statistics or time series in order to find anomalies or unexpected trends in the data. Information on product quality should be appended to the product as metadata alerting the user to potential problems with the data. Quality assessment is part of the data production system and continues for the life of the instrument. Along with postlaunch calibration and characterization, it provides an understanding of changes in instrument performance and the impact on algorithm performance.

An example of data quality assessment in the EOS era is provided by the MODIS Land Group (information is available online at <http://modland.nascom.nasa.gov/QAA_WWW/qahome.html>). Most of the quality assessment will be performed automatically by the processing software during production (run time quality assessment). Operators will set production quality assessment when the product is generated; the science team and quality assessment support staff will then set quality flags based on an evaluation of a sample of the data product (science quality assessment). User feedback will be solicited as an additional and important source of quality assessment.

Following the guidelines for the EOS Core System quality assessment, information will be stored as metadata in all products. The various quality assessment flags will enable product users to identify data problems within the MODIS time series. A Web site will provide up-to-date information on data problems and remedial action being taken.

Product quality assessment provides an important input for algorithm refinement and identification of problems with instrument performance. The stored quality assessment metadata will be of considerable help in identifying data product records that are in error as a result of problem data.

DATA PRODUCT VALIDATION

Data product validation answers the critical question, What is the accuracy of the geophysical product over the range of environmental conditions for which it is provided? Conceptually, data product validation is simple, but in practice it is often a complex and difficult task to compare the result of independent measurements of a geophysical variable with the result obtained from the sensor on orbit. However, such comparisons need to be done for each data product or record.

Data product validation must involve more than just comparing measurements of the same quantity made in situ (at the surface) and by a satellite-borne sensor. A complete data product validation should include both field and airborne measurements. These must be backed up by laboratory measurements to ensure their validity and then compared with satellite measurements. Data product validation should begin before launch with the laboratory, field, and airborne measurements. After launch, the data product validations cannot be a one-time exercise but must be repeated periodically to ensure continued validity and to test any improvements to the algorithms. Several different groups should participate in the data product validation exercises, preferably with international representation. Finally, the data must be archived with the same attention paid to the continuous data stream from the satellite.

Data product validation can be difficult and expensive, especially when determining the data product's accuracy over a wide range of conditions. The comparison of surface measurements with satellite measurements requires paying attention to scaling up surface point measurements to the satellite spatial resolution and taking into account the impacts of the atmosphere on the satellite measurement at the time of overpass. Quantifying the temporal and spatial error fields associated with a data product is especially important in the modeling and analysis of long time series for climate research. These assessments require a commitment to sustained field measurements over the life of the sensor.

Preliminary estimates of accuracy can be obtained for a particular algorithm before launch using simulation or modeling. Such estimates provide a guide to what can be expected; however, accuracy is assessed primarily after launch, once the instrument and algorithm have stabilized.

Validation of higher-order data products for parameters such as snow cover, leaf area index, aerosol optical thickness, and water vapor requires different approaches. A useful distinction can be made between continuous and discrete data products and the methods for their validation. The International Geosphere-Biosphere Program 1-km land cover validation activity represents an important pathfinding activity for validating global land cover. The land community for EOS has developed a series of validation test sites representing a broad range of land surface conditions (Justice et al., 1998), including surface reflectance, vegetation index, leaf area index, and primary productivity. These sites provide a focus for the development and testing of validation instrumentation and satellite data acquisition. Data products from MODIS such as changes in snow and ice cover, fire, and land cover/change will be validated at locations suited to specific product validation. Validation efforts will also include information collected by higher-resolution sensors (Justice et al., 1998). Protocols for validation are being developed and tested for suites of land products. The NASA-funded BigFoot program is addressing some of the problems of scaling from field measurements to satellite resolutions. The land community is starting to coordinate its international validation activities under the Committee on Earth Observation Satellites Calibration and Validation sub-working group on validation (Dowman et al., 1999). The Fluxnet program provides a coordination activity contributing to the validation of data on land productivity.

The oceans community is coordinating much of its validation activity through the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) program (McClain and Fargion, 1999). SIMBIOS is focused on reducing measurement errors by quantifying the uncertainties in the ocean color algorithms, with the aim of blending the data streams from ocean color missions such as SeaWiFS, MODIS, and the Ocean Color Temperature Scanner. There are considerable advantages in international cooperation for the collection of validation data. An important consideration is that validation data be made available to the broader community.

In the past many of the assessments of error in satellite data sets were largely anecdotal. For example, it is known that the Coastal Zone Color Scanner delivered poor retrievals in coastal waters and high-latitude oceans. However, as researchers begin to accumulate long data records and as these data sets begin to influence environmental policy, it will be necessary to move from describing the errors to quantifying them. For data assimilation models, quantitative estimates of the temporal and spatial errors are essential. This level of data product validation will require sustained observations: a one-time data product validation exercise at the beginning of the mission is not sufficient.

CONCLUSIONS AND RECOMMENDATIONS

Following are the committee's conclusions and recommendations with regard to calibration and validation:

- A continuous and effective on-board reference system is needed to verify the stability of the calibration and sensor characteristics from launch through the life of a mission. In the case of thermal sensors, there should be an on-board source that is designed for optimum stability. For the solar reflective spectral range, there should be an on-board solar diffuser. The system should be designed to allow for periodic measurements of the Moon. Data product validation and vicarious calibrations should be implemented periodically to verify the stability of the calibration and sensor characteristics.
- Radiometric characterization of the Moon should be continued and possibly expanded to include measurements made at multiple institutions in order to verify the results. If the new reflectance calibration paradigm is adopted (see Appendix C), then the objective of the lunar characterization program could be changed from measurement of the absolute spectral radiance of the Moon to measurement of the changes in the relative reflectance as a function of the phase and position of Earth, the Sun, and the Moon.

- The establishment of traceability by national measurement institutions in addition to NIST should be considered to determine if improved accuracy, reduced uncertainty in the measurement chain, and/or better documentation might be achieved, perhaps even at a lower cost.
- The results of sensitivity studies on the parameters in data product algorithms should be summarized in a requirements document that specifies the characterization measurements for each channel in a sensor. Blanket specifications covering all channels should be avoided unless justified by the sensitivity studies.
- Quality assessment should be an intrinsic part of operational data production. It involves providing metadata on product quality along with the data product so as to give the user an indication of deviations from expected instrument and algorithm performance and the long-term stability of the data product.
- Validation should be undertaken for each data product or data record to provide a quantitative estimate of the accuracy of the product over the range of environmental conditions for which the product is provided. It should involve independent correlative measurement of the geophysical variable derived from the satellite data. The guidelines and protocols that are being developed for validation will lead to more standardized measurements and will make comparing the accuracy of similar products from different instruments possible. Undertaking validation both once the instrument calibration is established and following significant changes to the algorithm will contribute to establishing product continuity.
- Wavelengths and bandwidths of channels in the solar spectral region should be selected to avoid absorption features of the atmosphere, if possible.
- The calibration of thermal sensing instruments such as CERES and the thermal bands of MODIS should continue to be traceable to the SI unit of temperature via Planckian radiator, blackbody technology. The accumulated uncertainty of calibrations traceable to the fundamental unit of electricity via a cryogenic electrical substitution radiometer is at present much larger than that of calibrations traceable to temperature.

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3

Data Continuity

KEY ISSUES AND LESSONS LEARNED

The most useful data for climate purposes are time series that are continuous and for which the characterization of errors, in terms of precision and bias, is known. Time series that are overwhelmed by data gaps or instabilities in the error properties are far less useful because the magnitude of such errors is often of the same order as the small climate signal being sought. Continuity, therefore, is concerned with more than the presence or absence of data: it includes the continuous and accurate characterization of the error properties of the time series. The following sections summarize the lessons that have emerged, lessons that, if learned from, would enhance the generation of climate data records.

Overlapping Observations Are Required (Data Gaps Should Not Occur)

From the perspective of climate research, temporal data gaps in satellite observations introduce uncertainties in time series construction that are usually greater than the climate signal under investigation and, therefore, are intolerable. Not only do gaps create noncontinuous time series, but they also prevent the performance of a key climate analysis function, that is, the calculation of relative instrument bias from data collected simultaneously when a new spacecraft replaces an old. In other words, overlapping observations give an opportunity for old and new spacecraft to be simultaneously calibrated against a common target (Earth). Without a proper knowledge of instrument bias, the continuity of the time series is jeopardized.

Instrument biases tend to develop during the long period between instrument characterization, spacecraft integration, launch (with its associated vibration and forces), and commissioning. By the time it is in space, the instrument has many opportunities to undergo a response change in the radiometer itself or in its calibration system. For example, laboratory tests for channel 2 of the Microwave Sounding Unit (MSU) on NOAA-12 indicated that the instrument view of cold space would produce about 700 digital counts. Once in space, however, the cold view reported about 1,800 cold counts, significantly altering the dynamic range and gain and requiring empirically based adjustments to the original laboratory calibration coefficients (Mo, 1995).

Although the intersatellite instrument biases may be minuscule from the operational standpoint (for temperature they are usually about 0.5 K), they are probably much larger than the magnitude of the climate signal scientists generally require (e.g., a decadal trend of only 0.1 K). Experience has shown that overlapping space observations of virtually every instrument are necessary to empirically determine the magnitude of these climatically large and unpredictable intersatellite biases. The overlapping observations should last at least 1 year as some biases depend on season.

The present two-orbit configuration (nominal northbound equatorial crossing times of 1330 and 1930) is manageable for bias calculations for certain climate data sets. Overlapping observations from a 1330 spacecraft may be used to determine the bias of the 1930 instrument as long as their respective biases relative to the diurnal component are known. This is possible for quantities such as stratospheric temperature, which is fairly coherent in space and time. However, quantities with substantial diurnal variations, such as cloudiness or surface properties, will require overlapping observations between old and new spacecraft in the same orbit node. (The shift from 0730/1930 to 0530/1730 in the AM node, as has been proposed for the National Polar-orbiting Operational Environmental Satellite System (NPOESS), will probably cause some discontinuity. Additionally, some instruments will fly on only one node, again requiring overlapping observations of the old and new spacecraft in each node.) The following two examples demonstrate the critical value of overlapping observations.

A time series of total solar irradiance (TSI) solar variations was pieced together by Willson (1997) using data from two consecutively flown Active Cavity Radiometer Irradiance Monitor instruments (ACRIM I and II). A gap of about 2 years in the ACRIM data was bridged by using mutually overlapping observations from two other TSI instruments, the Nimbus-7 Earth Radiation Budget (ERB) and the Earth Radiation Budget Satellite (ERBS). The results from the ERB and ERBS were less precise than those from ACRIM I and II and the absolute irradiance values differed by 0.5 percent (Figure 3.1). However, the extent of the overlap in the data made possible a sufficient reduction of noise in the bias calculations, allowing for the production of a time series with a trend of 0.032 (±0.0009) percent per decade.

Christy et al. (1998, 2000) utilized the MSUs on National Oceanic and Atmospheric Administration (NOAA) polar orbiters in both 1330 and 1930 orbits, alternating between the two nodes, to merge data from nine satellites into a time series of daily global atmospheric temperatures. The duration of most overlapping periods was 1 to 3 years; however, two periods were less than 7 months long. Biases, which could be as large as 0.5 K, were determined to be globally accurate to a precision of 0.01 to 0.02 K (as estimated through a variety of subsampling experiments) only because data from overlapping observations were available.

Flexible strategies for providing overlapping data should be investigated because data from the older spacecraft are not required in real time for climate purposes. Thus, information from instruments for which overlapping observations are necessary may be stored on board for downloading at more convenient times. Additionally, though an overlap period of 1 year is a requirement, the sampling during this year may be less than continuous, being whatever is sufficient to characterize the annual cycle of the bias. Most instruments will need overlapping observational periods for each orbit node (e.g., from an old 0530 to a new 0530 spacecraft).

Spacecraft Orbit Should Be Stable

The past generation of polar-orbiting satellites was injected into orbits that included slow longitudinal (east-west) drifting relative to local equatorial crossing time (LECT), to prevent the spacecraft from approaching local solar noon. The rate of the drift was up to 15 degrees per year in some cases, representing up to an hour drift per year in terms of LECT. Two consequences of this drift conspire to corrupt the observations from the standpoint of their stability.

Because these spacecraft drifted to earlier or later LECTs, observations were influenced by the local diurnal cycle (e.g., afternoon temperatures are warmer than morning temperatures) in the quantity measured. Trend calculations are thus skewed by the local time at which observations are taken and may be misinterpreted as a trend in the absolute instrument bias. This is particularly important for most surface quantities, atmospheric temperature, and cloud observations, where diurnal signals and solar angle changes, which might affect the upwelling radiance, are substantial relative to decadal trends.

One method of dealing with this problem was developed by Waliser and Zhou (1997) for outgoing longwave radiation (OLR) and highly reflective cloud (HRC) data sets. Because the spatial variation of the changes in OLR and HRC is substantial as a satellite drifts through the diurnal cycle, Waliser and Zhou based their corrections on

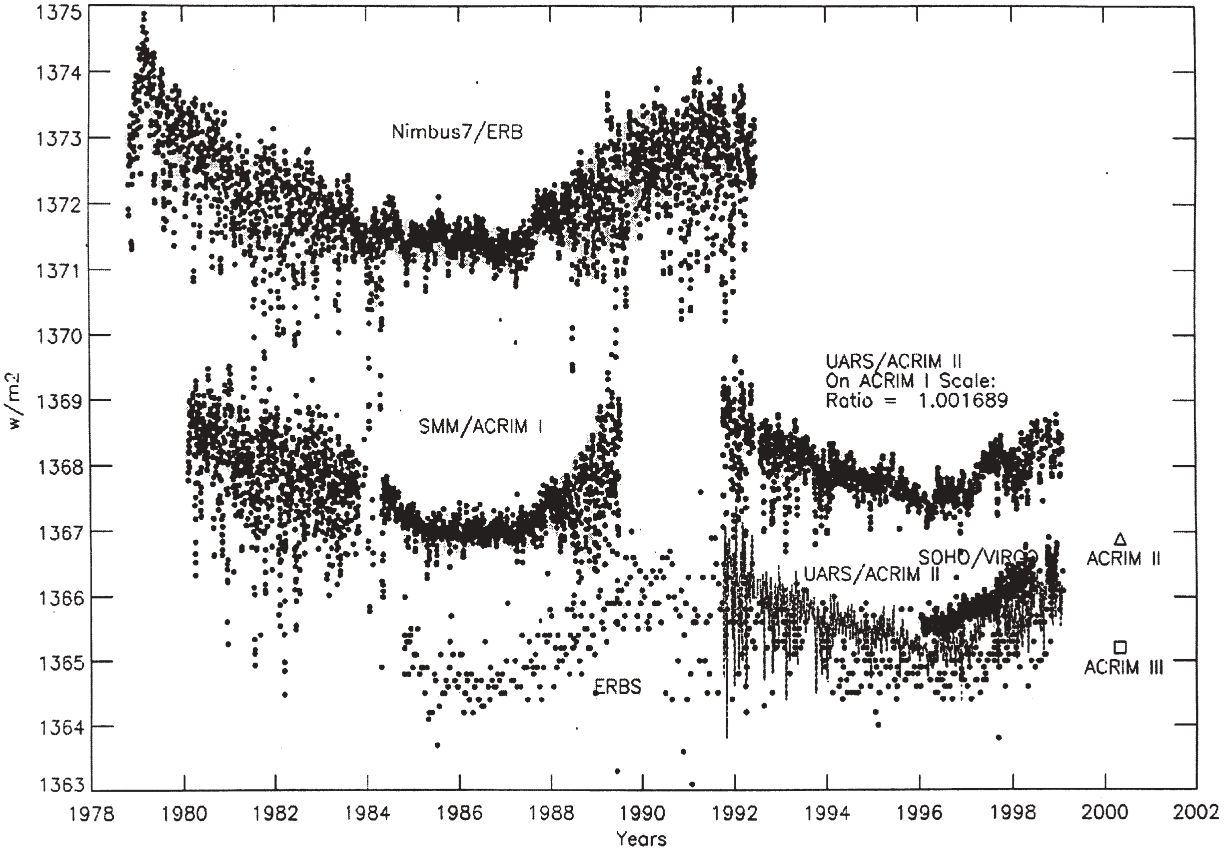

FIGURE 3.1 Total solar irradiance measurements (daily means and uncertainties) obtained during solar cycles 21 through 23 from space-based sensors. See discussion in Willson (1997). Courtesy of Richard C. Willson.

empirical orthogonal functional analyses of the patterns of change whose time series correlated with LECT variations. However, there remains some uncertainty owing to the possible convolution of real interannual changes in OLR or HRC during a drifting period and changes caused by the diurnal cycle alone.

As mentioned earlier, instruments on board Sun-synchronous polar-orbiting spacecraft undergo substantial variations in incident solar radiation. If station-keeping is rigorous and the spacecraft positioning is maintained at a consistent LECT, these effects are systematic on a latitudinal basis. As the spacecraft drifts relative to a fixed LECT, there are changes in the shadowing effects on the various instruments, and this in turn induces considerable changes in instrument body temperatures. Precise laboratory characterization of the instrument responses apparently has not provided enough information to determine the effects due to variational solar heating. The magnitude of the error introduced by these effects, at least in the case of the MSU temperatures, is as large as the signal of climate change.

One way to compensate for this effect of spurious instrument response to varying instrument body temperatures relies on simultaneous observations of Earth from two orbiting instruments. Comparing the Earth observations from each with the instrument body temperatures of each allows for estimating the error. In this case, the intersatellite differences in Earth-viewed temperatures might be highly correlated with the individual instrument body temperatures, so that adjustments might be applied (Christy et al., 2000). This effect could be better dealt with by requiring a more thorough characterization of the instrument response in the calibration chamber tests. For example, simulated solar radiation could be made to strike the instrument from all angles in a simulated orbit cycle to determine the effect on instrument response.

A further source of orbit variability relates to changes in the altitude of the Sun-synchronous satellites (~840 km). This orbit is occupied by a rarified atmosphere that nevertheless is dense enough to exert a drag on the orbiting spacecraft. This drag is accentuated during solar maxima as the upper atmosphere expands from below, causing an increase in the atmospheric density at orbit altitude. The increased drag results in a loss of altitude for the spacecraft, which in the case of the TIROS-N family of polar orbiters accumulated to about 20 km. Measurements that require a fixed altitude are thus affected, and corrections are required (Wentz and Schabel, 1998).

The current intention of the Integrated Program Office (IPO) to require a fixed orbit node to within ±10 minutes (±2.5 degrees longitude at the equator) has been greeted with particular satisfaction by the climate community.

Thorough Instrument Characterization Is a Requirement

Once in space, the instrument's behavior and response may be quite different from its laboratory behavior and response. In thermal/vacuum testing, the instruments are tested (characterized) individually as isolated pieces of equipment, without the impact of changing solar illumination and often without all their components (e.g., mirrors removed where small emissivity adjustments may not be properly accounted for). Later, each instrument is integrated into the spacecraft along with other instruments, all of which compete for space and power. The instrument configurations generate complex shadowing effects, and after enduring the forces of a launch into orbit, the instruments can experience changes in the very components that were designed for measurement and calibration. Ideally, to anticipate the impact of these on-orbit effects, the instrument should be tested after all the spacecraft components have been fully integrated to document potential anomalies arising from variations in sunlight and thermal loads. However, the environmental chambers used in characterization are not large enough to accommodate a complete spacecraft. An alternative approach would be to enhance the on-board monitoring devices, which would allow for a higher degree of on-board characterization (see Chapter 2).

Data Sets Should Be Uniformly Archived and Continuously Available

A significant impediment to the construction of continuous, space-based climate data sets is the lack of attention given to the archiving methodology. Often, investigators must piece together observational data sets held at various locations, written in various formats, and residing on various media before work can begin. For example, in the case of the MSU archive (part of TIROS-N operational vertical sounders (TOVS)), pre-1985 data were stored on terabit memory (TBM) reels (5-cm-wide videotape weighing 7 kg each) at the National Center for Atmospheric Research (NCAR), which housed the last operating TBM reader in the world. Post-1984 data were available on IBM cartridges from the National Environmental Satellite Data and Information Service in Washington, D.C. Knowing the TBM reader was to be decommissioned, NCAR personnel copied the data to a newer medium in 1989. The TOVS orbit files were complex with many duplicate orbits, so various checks were employed to ensure that only the proper data were extracted and copied. One such check was the satellite identifier number, which if not recognized as one of the operational spacecraft would cause those orbit files to be skipped. Unknown to NCAR personnel, NOAA-6's identifier number was changed after its third commissioning in space, when NOAA-8 failed for the second time. The identifier change was not discovered until after the copying had been completed and the TBM reader scrapped. Several months of operational data from NOAA-6 were lost as a result. The lesson here is that as new devices become available for data storage, all previously archived data should be copied to the new media and archived in one place. Thus, the archive itself will have uniformity and continuity.

The delivery of these data sets conveniently to researchers is the first part of this overall issue. The second is that agencies must be prepared to provide continued funding to researchers to allow them to study the data and get the most out of the substantial investment. Budget cuts tend to fall disproportionately on the end-researcher, preventing the mission from achieving its full results. This is especially the case for climate issues, as they are often not apparent until years after the spacecraft and instruments have been decommissioned and (unfortunately) long after agency interest has peaked. The NASA and NOAA Enhanced Data Set Project states as its central theme "producing new and/or enhanced climate or global change data sets for analysis, applications, assessments, or climate impact studies." Satellite data are included in this project. However, this is a fairly small program in which investigators must compete against those who study nonsatellite data sets.

Compared with the excitement of instrument design and fabrication and of spacecraft integration, launch, and operation, the issues of accessible archives and out-year science funding are rather unglamorous. Yet for any mission to be considered a success, these two issues must be considered as equally important requirements when the mission is defined. This argues for assigning funds for these tasks when the mission is planned, either from the agency in charge of the instrument or from a program whose priority is climate data and research. Because climate date records cross multiple satellite missions, this particular funding is crucial to the generation of long, continuous data records.

Backward Compatibility Is Highly Recommended

Many space-based measurements go back at least 20 years. As new technology is developed, there is always a chance that continuity will be lost in the time series of radiances (the fundamental observation). Most requirements for space-based measurements are stated in terms of geophysical parameters (e.g., atmospheric temperature at height corresponding to pressure of 500 hPa). These measurements may be delivered using new technology and instrumentation and, therefore, with different fundamental radiance observations (e.g., frequency or bandwidth). Many climate data sets are produced from reanalyzed radiance-based data, so new technology may become a threat to the continuity of these level 1 time series. In cases where operational quality is not compromised, it is recommended that the backward compatibility of proposed radiances with currently archived radiances be considered as a climate requirement.

NPOESS REPLENISHMENT STRATEGY

The first lesson listed above (overlapping observations) is fundamentally related to the NPOESS replenishment strategy.

Launch-on-Failure Versus Launch-on-Schedule

The decision to launch a replacement spacecraft depends on many factors, not the least of which is budgetary constraint. Accordingly, for NPOESS missions, a launch-on-failure strategy has apparently been adopted. By this strategy, the decision to launch a replacement spacecraft is based on the failure or anticipated failure of one of the critical instruments (which are indicated in Table 3.1). The key driver is the data stream that supports the operational mission.

Depending on the readiness of the next spacecraft, a launch-on-failure strategy might take up to 12 months to execute from the moment an unanticipated failure occurs. The launch-on-failure strategy virtually guarantees discontinuities in the radiance time series and thus will create considerable difficulties for climate research. By this strategy, overlapping periods of observations will not be possible in cases of instrument failure.

In the case of incremental failure of an instrument, such as increasing noise, the launch decision is more difficult. The guidelines are unknown and perhaps impossible to set because a multitude of minor problems might occur. As a problem develops, assessments would presumably be made as to when the accumulated effect of the increased noise would prevent accurate weather monitoring.

With the launch-on-failure strategy, measurements that have little value for operations but great value for research will be allowed to expire so that the associated time series would become discontinuous. Data sets for solar radiance and altimetry, for example, would become discontinuous if either instrument failed and all other operationally critical instruments maintained nominal performance. This raises the question of the use of still-working assets on board decommissioned spacecraft.

TABLE 3.1 NPOESS Notional Payloads to Satisfy IORD-1

NPOESS Instruments	0530	1330	METOP 0930	NPP 1030
IPO Developed:				
Visible/Infrared Imager Radiometer Suite (VIIRS)*	x	x	x (AVHRR)	x
Cross-track IR Sounder (CrIS)*		x	x (IASI/HIRS)	x
Conical Scanning Microwave Imager/Sounder (CMIS)*	x	x		
Ozone Mapping and Profiler Suite (OMPS)		x	x (GOME)	
GPS Occultation Sensor (GPSOS)	x	x	x (GRAS)	
Space Environmental Sensor Suite (SESS)	x	x	x (SEM)	
Leveraged:				
Advanced Technology MW Sounder (ATMS)*		x	x (AMSU/MHS)	x
Data Collection System (DCS)	x	x	x	
Search and Rescue (SARSAT)	x		x	
Earth Radiation Budget Sensor (ERBS)			x	
Total Solar Irradiance Sensor (TSIS)	x			
Radar altimeter (ALT)	x			
Advanced Scatterometer (ASCAT)			x	

NOTE: "IORD-1" is the shorthand term for the *Integrated Operational Requirements Document* issued in 1996 by the Integrated Program Office and since updated.
*Critical instrument—failure constitutes need to replace satellite.
SOURCE: NPOESS IPO.

From the perspective of climate research, a launch-on-schedule strategy is preferred. Launching a new spacecraft while a fully functional one is operating allows for the necessary period of overlap. This aids the operational mission, which also needs some overlapping observations for intersatellite calibration. Too, if the new spacecraft develops serious problems, the old, still-functional spacecraft could continue to fulfill its operational mission until the next spacecraft is launched. NOAA-6, for example, was recommissioned twice (May 1985 and November 1985) when problems developed with its replacement (NOAA-8), and it performed the operational mission until NOAA-10 was launched.

Specific Concerns Related to Continuity

Many space-based data sets are in some sense threatened by loss of continuity. For example, measurements of oceanic chlorophyll and dissolved organic material from the Moderate-resolution Imaging Spectrometer have no continuing commitment after the Earth Observing System (EOS) mission. Four other measurements viewed as critical to climate research and global change that at this time appear threatened with loss of continuity are discussed below. At present, policymakers are demanding to know which are the required long-term, precise time series of geophysical parameters and, of these, which are plagued by uncertainties (NRC, 1999). Fifty years and more from now, policymakers will still be asking scientists to provide societally relevant information, some of which will be based on observations discussed here. From the perspective of future generations, the points addressed below become necessary considerations because having useful long-term time series in the future is dependent on obtaining good data from monitoring that is accomplished now. The points discussed in the following four sections speak directly to the requirements for climate quality records stated in NRC (1999).

Solar Irradiance

Within the climate research community, there is substantial support to make solar irradiance missions independent of the operational constraints of NPOESS. Few issues in the area of climate and global change research have sparked more uncertainty and controversy than the characterization of solar irradiance and its influence on climate, yet variations in solar irradiance are not considered a critical factor in supporting the operational task of NPOESS.

A particular concern centers on the consequences of a gap in solar irradiance measurements between the planned NASA SORCE (Solar Radiation and Climate Experiment) mission in mid-2002 and follow-ons in the NPP/NPOESS era. Designers plan to operate and obtain data from the SORCE spacecraft for a period of 5 years (with a goal of 6 years), which would nominally extend solar irradiance data sets through mid 2007. However, the first NPOESS satellite might not be launched until 2009 or later. Since 1978, a total solar irradiance (TSI) data set has been continued through a strategy of overlapping satellite-based measurements and multiple redundant instruments in orbit at one time. The committee considers solar irradiance to be a key climate forcing parameter that should be monitored precisely during the NPP/NPOESS time frame for purposes of climate change detection and attribution.

The committee believes free-flying satellites should be evaluated as an additional platform option for planned solar irradiance measurements. Sensors to monitor solar irradiance are relatively small and lightweight, making them particularly suited for small satellites (notional payloads of only approximately 40 kg would be necessary). In this way:

1. The orbit selected gives the highest-quality observations;
2. The NPOESS operational spacecraft would benefit from a reduction in the mechanical components required for Sun-pointing; and
3. A discontinuity in measurements would become less likely because replenishment of a "noncritical" sensor would not be dependent on launching a new NPOESS multisensor spacecraft.

However, the committee also notes the concern among some in the scientific community that executing the solar irradiance mission on a free-flier would make the program more vulnerable to the vagaries of the budgetary process versus execution of the mission as a secondary payload on an operational weather satellite.

Ocean Altimetry

The success of the present observations of sea-level height from the TOPEX satellite is due in large part to its non-Sun-synchronous orbit (~1,300 km). Such an inclined orbit is required to determine and eliminate the unknown spatial variations in random tidal components, which at present are poorly known. Placing the altimetry instrument on a Sun-synchronous spacecraft (~800 km) would degrade the operational and climate effectiveness of this data set. Improvements in seasonal forecasts of El Niño/Southern Oscillation have been demonstrated as a result of the more precise characterization of the ocean height (and thus temperature and circulation) brought about by TOPEX. The potential for understanding more of the causes of interannual, decadal, and climate-change time-scale fluctuations will be limited unless this data set continues with its present (or an enhanced) level of precision.

The altimeter is not considered a critical measurement for NPOESS launch decisions should failure occur (see Table 3.1). Thus, as in the case of solar irradiance, this measurement would be in jeopardy of complete discontinuity should problems develop.

Jason-1 is intended to extend the TOPEX-type measurements until about 2005, but there is no assurance of continued high-precision surveillance in the NPOESS Preparatory Project and NPOESS periods. Present attempts to produce high-precision ocean height measurements from other sources (e.g., Earth Resources Satellite (ERS-1 and -2)) are successful only because TOPEX data serve as a standard. A further requirement put forth by Mitchum et al. (forthcoming) points to the need for very long overlapping observations from the old and new instruments and for the spacecraft to be in very similar orbits. Precise ocean altimetry after Jason-1 is considered a critical issue that must be resolved.

Ocean Vector Winds

The recent success of QuikSCAT, developed and launched following the failure of the Japanese Advanced Earth Observing Satellite (ADEOS), which contained the NASA scatterometer, NSCAT, has demonstrated the utility and limitations of a single broad-swath, Ku-band, active scatterometer system in the retrieval of surface vector winds (speed and direction) over the ice-free global ocean. Based on experience with ERS-1, ERS-2, NSCAT, and QuikSCAT, the case for tandem scatterometer missions in support of climate research and predictions has been made (Milliff et al., forthcoming). A roadmap for international cooperation to achieve the climate science requirements for surface vector winds awaits multiagency approval and support (see Milliff et al., forthcoming). The surface vector wind is the critical climate measurement, as opposed to surface wind speed alone.

Further research and development of passive microwave methods for vector wind retrieval are encouraged. However, this technology is unproven in space, and satisfactory performance in a wide variety of environmental conditions (e.g., under cloudy conditions) has yet to be demonstrated. It is premature to regard the NPOESS/CMIS instrument as sufficient to meet the needs of the climate community for surface vector winds.

CERES

The infrared measurements provided by the Clouds and the Earth's Radiation Energy System (CERES) are especially sensitive to the diurnal cycle, the magnitude of which is easily comparable to the small changes sought in the detection of climate change. The placement of CERES on Tropical Rainfall Measuring Mission (TRMM) (inclined), EOS-AM (1030), and EOS-PM (1330) provides the opportunity to study problems requiring relatively high Sun angles, low cloud amounts (AM), and high cloud amounts (PM). However, because many useful quantities are surface or surface-related, a morning orbit is preferred because cloudiness is less prevalent. At present, NPP will provide a bridge for atmospheric correction and moderate resolution in the 1030 measurements (VIIRS, Cross-track IR Sounder (CrIS)), but these will end with the anticipated European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) Operational Polar Orbiter (METOP) missions designed to fill the 1030 (at 0930) slot with a less useful Advanced Very High Resolution Radiometer (AVHRR)-class instrument. Thus, the continuity of the climate-change quantities measured to high precision (e.g., broadband, top-of-the-atmosphere Earth radiation budget) at a specific point in the diurnal cycle will be compromised. High-resolution visible and infrared measurements in the mid-morning orbit will become discontinuous under the present plan.

RECOMMENDATIONS

The committee's recommendations on data continuity are as follows:

- A policy that ensures overlapping observations of at least 1 year (more for solar instruments) should be adopted. The IPO should examine the relation between this requirement and the launch-on-failure strategy. It should include a clear definition of spacecraft or instrument failure and an assessment of still-functioning instruments.
- Competitive selection of instrument science teams should be adopted to follow the progress of the instrument from design and fabrication through integration, launch, operation, and finally, data archiving, thereby promoting more thorough instrument characterization.
- As instruments are developed for future missions, the IPO should make a determination of threats to the continuity of currently monitored radiances in the design requirements.
- Out-year funding should be provided to maximize the investment made in climate and operational observing instruments.[1]

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[1] For climate studies, there is a need for continuing investment in sensor studies and tests—programs for operational instruments typically do not fund such activities beyond initial checkout.

- Free-flier status should be evaluated for key climate parameters such as solar radiance and sea-level altimetry whose measurement appears to be endangered by the NPOESS single-platform configuration.
- Proven active microwave sensors should be considered for ocean vector winds, another key climate (and operational) parameter.

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4

Data Systems

INTRODUCTION

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) offers unique opportunities for the climate research community. The next-generation sensors flying on a continuous series of NPOESS orbiting platforms for some 20 years beginning in approximately 2000 are expected to produce data of unprecedented quality and coverage. However, to capitalize on this opportunity, the research community and government agencies will need to develop data processing and archiving systems that can enable the huge volumes of raw data (approximately 1 terabyte/day) coming from NPOESS to be stored and converted into useful scientific products and information (see NRC, 2000a).

Currently the NPOESS procurement process is focusing on operational needs. The NPOESS system contractor is being asked to provide a data system that will produce raw data records, sensor data records, and environmental data records for all NPOESS sensors (see Table 4.1). This operational data system will be installed at various Department of Defense and National Oceanic and Atmospheric Administration (NOAA) centers. An important requirement for the data system is timeliness (processing the data from one orbit of data in 20 minutes). Archiving the various products is not a requirement; neither are the many other attributes associated with a research data system. For example, in its phase one report (NRC, 2000b), this committee concluded that the operational environmental data records will not meet all the needs for climate research and that access to the unprocessed sensor-level data will be required. The current focus of NPOESS on operational needs is certainly prudent from a programmatic standpoint, given the enormity of the space hardware segment and the very high data rates, and to impose the many additional requirements associated with climate research onto the current NPOESS operational system is probably impractical. Instead the committee sees the need for an autonomous infrastructure of data systems focusing on climate research rather than operational needs.

The development of an NPOESS climate data system (NCDS) represents a significant challenge requiring planning, revision, hard work, and adequate funding. Care will be needed to ensure that the design and specifications for the data system are given a broad review prior to their implementation. Calibration and validation, data provision, data product continuity, data archiving, archive access, reprocessing, and cost will need to be given special attention for the climate research community. The NPOESS Preparatory Project (NPP) will provide an early test of the instruments and data system. A joint activity of the National Aeronautics and Space Administration

TABLE 4.1 Data Set Processing Levels

Data Level NASA/NOAA	Description
Level 1A: Raw data records	Reconstructed unprocessed instrument or payload data at full resolution, time referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (i.e., platform ephemeris and orientation) computed and appended but not applied to the level 0 data
Level 1B: Sensor data records	Level 1A data that have been processed to sensor units
Level 2: Environmental data records	Derived geophysical variables at the same resolution and location as the Level 1 source data

(NASA) and the Integrated Program Office (IPO), the NPP will provide an opportunity to benefit from the progress NASA is making in data system development.

In this chapter, the committee first establishes the need for an NCDS separate from the operational system. Some essential elements of an NCDS are then discussed. These elements include a long-term archive for the lowest-level NPOESS data (raw data records or sensor data records) and a system architecture in which science teams are primarily responsible for the development of the algorithms needed to generate geophysical products, which are then archived and distributed by innovative data centers. The need for the NCDS to accommodate algorithm and sensor evolution, reprocessing, and multiple versions of data sets is also described. Finally, the importance of innovation and competition in the emerging NCDS is stressed.

OPERATIONAL VERSUS RESEARCH NEEDS

Operational processing and research have different requirements. Operational processing, as it is now envisioned for NPOESS, will be done at a number of centralized sites, with each site using a common data processing system provided by the NPOESS prime contractor. The emphasis will be on generating products very quickly for weather applications. The centralized, no-archiving, one-time-processing architecture of the operation centers is totally different from that required by the research community, in which scientific algorithms are continuously evolving and reprocessing is routine. For research, the requirement of timeliness can be relaxed, thereby allowing for the implementation of complex algorithms using diverse ancillary data. As understanding of sensor calibration issues and radiative transfer from Earth improves, algorithms can be improved, and better products can be generated via reprocessing.

To be more specific, NCDS has the following basic requirements over and above what is needed for operational processing:

- *A long-term archiving system that can fully support the needs of the climate research community.* This entails easy, affordable, and timely access for a large number of scientists in many different fields. The data must be supported by metadata that carefully document sensor performance history and data processing algorithms.
- *The ability to reprocess large data sets as understanding of sensor performance, algorithms, and Earth science improves.* Examples of new information that would warrant reprocessing are detection of sensor calibration drift and the availability of better ancillary data sets, better geophysical models, and errors in previous processing.
- *Use of standard formats and interfaces, so that researchers, data producers, and archives can be closely linked.* Research data systems tend to be less centralized and more distributed than operational processing systems.

Another element of an NCDS that is missing from the operational system is the selection of science teams by an open, peer-reviewed process. Good science is the key to generating reliable climate products, and peer-reviewed science teams are essential in this endeavor. In contrast, the operational algorithms for NPOESS are being developed by the sensor contractors. This may ensure that operational algorithms are ready at launch, but there is no assurance that the algorithms will enjoy the consensus of the scientific community.

Daily weather prediction and long-term climate monitoring have different requirements, and from both a cost and research perspective, the committee thinks it would be a mistake to burden the NPOESS operational weather prediction system with all the additional requirements associated with climate research. Rather, it encourages the research community and government agencies to take the initiative and begin planning for an NCDS. To begin this planning exercise, some of the essential elements of an NCDS are pointed out, along with some of the more important issues that need addressing.

A recurring theme in the committee's phase one report was the need to facilitate comparisons among data sets from different instruments and different time periods, to (1) permit periodic reprocessing of data sets, (2) preserve long-term data collections for climate monitoring, and (3) allow examination of issues not always anticipated at the time the data were acquired (NRC, 2000b).

LONG-TERM ARCHIVING OF RAW DATA RECORDS

It is in the national interest to have a climate data system to improve the likelihood of achieving a scientific understanding of climate change. One essential element of an NCDS is a long-term archive of the raw data records. (A possible alternative would be to archive the sensor data records if the sensor data records are reversible to raw data records.) As mentioned above, data archiving is currently not part of the operational NPOESS data system. Given the extremely high data rates (~1 terabyte per day) anticipated for NPP/NPOESS and the large number of diverse users that will be accessing the data, a raw data records archive is in itself an enormous undertaking. It is essential that archiving the raw data records be addressed and responsibilities assigned as soon as possible.

A U.S. Global Change Research Program report (USGCRP, 1999) discussed the elements required for the long-term archive component of the data system and emphasized the following:

- A long-term archive should be established and operated in the simplest way possible to meet user needs and program goals.
- A long-term archive is not only for today's generation of users but also for the next generation of scientists and citizens whose needs have yet to be expressed but must be provided for.

Specifically, the report states that the long-term archive must ensure that archived data sets and products are accompanied by complete, comprehensive, and accurate documentation. Its recommendation for simplicity and longevity is particularly pertinent to the NPOESS raw data records archive. Because the raw data records archive will be a major interface between the operational and research communities, early discussions are needed between NASA, NOAA, and the IPO to ensure that the NPOESS operational data system meets the archiving requirements of the research community.

A conceptual study of the raw data records long-term archive should be initiated in the near future. This study should address issues such as the following:

- What government agency (or agencies) will be responsible for funding the long-term archive?
- Which agencies or organizations will maintain the long-term archive (existing NOAA and NASA data centers or industry via a request-for-proposals procurement like NPOESS)?
- Will the long-term archive be located at one central site or will it be distributed (different products at different sites)?
- What data and metadata need to be saved for climate research? How long will the data be saved and maintained? What is the procedure for deciding when a data set is no longer useful?

- How will users access the data? Will users be charged for data access? Will the costs impede the development and analysis of long-time-series data sets?
- Should the long-term archive have advanced features such as subsetting and data mining or should it be kept as simple as possible? Should it be designed to accommodate advanced features later on (e.g., by using formats that can later support subsetting and data mining)?
- What innovative software solutions are available to reduce cost and increase functionality (e.g., no-loss compression, geolocation computed on demand, elimination of redundancy, etc.)? What innovative hardware solutions are available to reduce cost and increase functionality (e.g., data storage devices in 2010)?

ARCHITECTURE FOR THE NPOESS CLIMATE DATA SYSTEM

The two basic tasks of an NCDS are (1) data production (i.e., converting the raw data records or sensor data records to science products) and (2) archiving and distribution of these science products. Defining an optimum architecture for performing these two tasks for a system as large as NPOESS will be difficult. NASA has been struggling with this problem for a number of years. Early on, NASA's Earth Observing System Data and Information System (EOSDIS) concept involved a small number of centralized distributed active archive centers (DAACs) that would in effect be all things to all people. The EOSDIS architecture consisted of a relatively small number of physically distributed sites that were organized and run in a centrally controlled, hierarchical manner. EOSDIS was designed to manage data from NASA's Earth science research satellites and field measurement programs, providing data archiving, distribution, and information management services. Through the EOSDIS Core System contractor, EOSDIS provided the necessary hardware and software to the DAACs to capture, process, and distribute data from the EOS satellites. Each DAAC was responsible for archiving and managing data in a given scientific discipline (Table 4.2).

Site visit reports of the seven DAACs by National Research Council (NRC) review panels concluded that most DAACs are serving the user community quite well, although several DAACs have management problems and poor records with the user community (NRC, 1998). Although individual DAACs support their discipline scientists, the objective of an overall seamless coordination of the DAACs into the EOSDIS has not been realized. The heavily centralized architecture of EOSDIS proved difficult to manage and built an unnecessarily high wall between the Earth scientists and computer scientists so that operating within the original time lines became impossible.

In reaction to these and other problems coming from EOSDIS (see NRC, 1998), NASA began experimenting with a much more distributed architecture, called the Earth Science Information Partnerships (ESIPs). This was an

TABLE 4.2 NASA's Distributed Active Archive Centers

DAAC	Host Institution	Scientific Specialty / Terra Instruments
ASF	Alaska SAR Facility, University of Alaska	Sea ice, polar processes / none
EDC	EROS Data Center, U.S. Geological Survey	Land processes / ASTER MODIS
GSFC	Goddard Space Flight Center, NASA	Upper atmosphere, atmospheric dynamics, global biosphere, hydrologic processes / TRMM, MODIS
LaRC	Langley Research Center, NASA	Radiation budget, aerosols, tropospheric chemistry / CERES, TRMM, MISER MOPITT
NSIDC	National Snow and Ice Data Center, University of Colorado	Snow and ice, cryosphere / MODIS
ORNL	Oak Ridge National Laboratory, Department of Energy	Biochemical fluxes and processes / none
PO.DAAC	Jet Propulsion Laboratory, NASA-Caltech	Ocean circulation, air-sea interactions / none
SEDAC	CIESIN, Columbia University	Socioeconomic data and applications / none

experiment to develop a federated approach to the provision of data and data services. In the federated concept, data processing responsibilities were given back to the principal investigators (PIs). This PI-driven model involves a large number of loosely related groups. The advantage of this model is that smaller organizations are more easily managed, and the PI has more control over the generation, distribution, and quality of the science products. The disadvantage is that the architecture of many independent groups generating various products may lack the cohesion necessary to provide the Earth science community with an integrated and consistent set of Earth science products (Matt Schwaller, NASA, personal communication, 1999). It is too early to assess the success of the ESIPs. Meanwhile, NASA is currently studying the trade-offs between centralized and PI-driven data systems models and is moving toward a new data system architecture called NewDISS.

An important lesson to be learned from this experience is that the production of research climate data sets from the raw data records is mostly a scientific problem. The scientists best understand the problems associated with the retrieval process. They are the ones who develop the methods, techniques, and algorithms for processing the data, and they should be an integral part of the data production if it is to be successful. Accordingly, the committee recommends that science teams, selected by peer review, play the central role in producing climate data records. A good paradigm for the NPOESS science teams is the NASA science team model that uses NASA research announcements to solicit proposals from the community at large. In this way, climate data sets will be produced in a peer-reviewed, competitive environment. In many cases, the science team will have the capacity to do its own data processing. In addition, the quality and consistency of climate data records can be further ensured by setting up some type of oversight mechanism that routinely reviews the status and progress of the climate research teams. In other scenarios, the data processing can be turned over to a data center, but the science team will still be the responsible entity.

One potential problem with having the science team be responsible for the generation of climate data records is that the team may be reluctant to release the data until they feel the quality is sufficient for general release. In so doing, the team can maintain exclusive use of the data for an extended period. To alleviate such a concern, the raw data records data should be made available to any interested investigator, who may then implement his or her own approach to generating climate data records. The committee notes that raw data records are produced on a near-real-time basis (3 hours) as part of the NPOESS operational processing. Therefore, it should be possible to make them available to investigators (through the raw data records long-term archive) within 1 or 2 days after the observation. A further safeguard is the opportunity during a peer review cycle to change the membership of a science team that is not fulfilling its obligations to provide algorithms and produce data. However, the committee doubts that data hoarding will be a problem in this very competitive age. Most scientists are more than eager to have others use their data products, and near-real-time access is becoming the norm.

Archiving and distribution of climate data records are distinctively different from data product generation. Optimum archiving and distribution are related more to computer science than to physical science. Many of the comments above about a raw data records archive apply to archiving the climate data records, except that the climate data records encompass a much more diverse set of data than do the raw data records. Climate data records will be used throughout the world for a large variety of Earth science applications. In view of this, advanced archival features will be highly desirable, including capabilities for data mining, subsetting, and provision of products on demand. Many of these archival functions are dependent on the type of data sets and applications being considered. This suggests that a distributed set of government, university, and commercial data centers, both large and small, each specializing in a particular type of geophysical product and application, may be advantageous. To facilitate interoperability among the various data centers and users, standards relating to formats, interfaces, and protocols need to be established. In addition, the climate data products have to be provided in a timely manner with no unnecessary delays. Again, innovation will be critical to success. These data centers should be selected in a competitive environment to encourage innovative and cost-effective solutions.

EVOLUTION, REPROCESSING, AND MULTIPLE VERSIONS OF DATA SETS

An NCDS should be designed to fully accommodate our ever-increasing understanding of Earth as well as the satellite sensors used to observe it. Geophysical retrieval algorithms are in a constant state of evolution: incorporating more realistic radiative transfer models, relying on more ancillary data sets (perhaps from non-NOAA or even non-U.S. data centers), and using more complex and accurate retrieval techniques. The ability to detect small sensor drifts and other systematic measurement errors is improving dramatically as researchers learn the subtleties of the sensor response functions and perform on-orbit intersensor comparisons. Numerous reprocessings are unavoidable and in fact desirable in that they improve the quality of the data products. Multiple versions of the same data sets, coming from different investigators using competitive algorithms, are extremely valuable in understanding the errors and uncertainties associated with retrieval.

Incorporation into an NCDS of these requirements for evolution, reprocessing, and multiple versions is another significant challenge. These requirements are completely different from those imposed on an operational system that relies on stability and rigid control of change. One obvious aspect of an evolving data system is the necessity for ample metadata. All data sets need to be accompanied by comprehensive metadata precisely describing the algorithms used to process the data, the relevant sensor characteristics, and all the ancillary data sets used in successive data generation. Other aspects of an NCDS are not as obvious. If reprocessing is done too frequently or there are too many versions of a particular data set, then the NCDS will be overburdened and the users will be confused. The trade-off between improving data quality and producing too many versions can be a difficult one. There could also be competing interests among the science teams, the data producer (if different from the science team), and the data archive and distribution center. For example, the science team may want to do a reprocessing but the data producer or archive may not have the resources to support it. Such issues are particularly problematic because it is difficult to predict beforehand the amount of reprocessing that will be required. Nonetheless, they will have to be resolved if an NCDS is to have adequate flexibility and adaptability.

EXISTING NASA AND NOAA DATA CENTERS

The NCDS can be built in part on the existing NASA DAACs and ESIPSs and the NOAA data centers (see Tables 4.2 and 4.3). The two approaches taken by NASA and NOAA to data management and archiving are in many ways complementary. The focus of NASA has been on providing data for scientific research. In the NASA nonoperational environment, evolving algorithms and retrospective reprocessing are common, and the data archives often contain multiple versions of the same products coming from different investigators. In contrast, the NOAA data centers have a wider array of responsibilities, ranging from delivery of operational weather data to the National Weather Service, to the analysis and archiving of weather and climate data, physical oceanography data collected by ships and satellites, coastal observations, solar-terrestrial observations, and data related to glaciology, and even to marine geology and geophysics. However, rather than simply expanding and continuing the present modes of operation at the NASA and NOAA data centers, it is necessary to review the strengths and weaknesses of past performance with the objective of developing better approaches for handling the NPOESS data.

CONCLUSION

The planned NPOESS climate data system would benefit from adopting the best elements of the current NASA and NOAA data systems. However, it will not be enough to simply expand existing facilities. A successful NCDS will also require a new vision in which innovation and competition play a central role. Observations of Earth will increase by an order of magnitude when NPOESS begins operation. Realizing the potential increase in scientific understanding will require converting the huge volumes of raw data to usable products and information. The responsibility for doing this should be given to those groups and organizations that demonstrate the vision, innovation, and expertise needed to meet the NPOESS challenge.

TABLE 4.3 NOAA Data Centers

Data Center	Host Institution and Location	Specialty
NCDC	National Climatic Data Center, Asheville, NC	Climate of United States Archive of weather data
NGCD	National Geophysical Data Center, Boulder, CO	DMSP satellite archive Glaciology World Data Center-A for marine geology and geophysics Paleoclimatology Solar-terrestrial physics Solid Earth geophysics
NODC	National Ocean Data Center, Silver Spring, MD	Coastal oceanography Ocean climate Biological oceanography
NSIDC	National Snow and Ice Data Center, University of Colorado	Snow and ice, cryosphere World Data Center-A for glaciology

RECOMMENDATIONS

The committee recommends meeting the following data-systems requirements in addition to what is planned for operational data processing:

- A long-term archiving system is needed that provides easy and affordable access for a large number of scientists in many different fields.
- Data should be supported by metadata that carefully document sensor performance history and data processing algorithms.
- The system should have the ability to reprocess large data sets as understanding of sensor performance, algorithms, and Earth science improves.
- Science teams responsible for algorithm development, data set continuity, and calibration and validation should be selected via an open, peer-reviewed process (in contrast to the operational integrated data processing system and algorithms, which are being developed by sensor contractors for NPOESS).
- The research community and government agencies should take the initiative and begin planning for a research-oriented NCDS and the associated science participation.

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5

Technology Insertion

INTRODUCTION

Preceding chapters in this report discuss how the utility of operational spacecraft to the climate research community can be improved through attention to instrument calibration and characterization as well as to continuity of certain time series of data. The need for an adequate data infrastructure to support processing, archiving, and analysis activities is also explored. This chapter discusses another opportunity to improve the utility of National Polar-orbiting Operational Environmental Satellite System (NPOESS) data for climate researchers—augmentation of planned sensor or system capabilities. In particular, this chapter examines some of the unique challenges associated with the insertion of new technology into operational systems that are conservative by design and whose foremost objective is to provide unbroken service to the primary user communities.

The phase one report of the committee (NRC, 2000a) forms the basis for the present discussion. That report reinforces the findings of several other studies and identifies the programmatic and technological issues to be addressed if an operational system such as NPOESS is to be more responsive to climate research needs. The main impediments are the following:

- Lack of a NASA program to facilitate the development of instruments for NPOESS;
- Reliance on the use of operational weather data products (as stipulated in the Integrated Operational Requirements Document (First Version) (IORD-1; IPO, 1996) environmental data records) to meet long-term climate monitoring and climate research requirements (which are different from weather-monitoring requirements), adding cost and requirements to the operational system;
- Insufficient provision for temporal overlap between replacement instruments, which is necessary to validate and cross-calibrate measurements that span more than one satellite; and
- No requirement or specification for long-term instrument stability.

Among other responses to these issues, the phase one report (NRC, 2000a) makes the following recommendations [paraphrased]:

- There should be a continuing program for operational satellite improvement that can support joint research and operational activities.

- Space should be provided on the NPOESS platforms for research payloads.

These recommendations are discussed further in this chapter.[1]

BASIC CONSIDERATIONS

In the present context, technology insertion is defined as the introduction of any new and/or improved hardware or software capabilities into an established operational system. Qualifying innovations span a wide range of potential changes and pose varying levels of risk for the operational performance of the system. For example, replacing a computer with a faster model that preserves the form, fit, and function of the earlier model is quite different from changing the operating system of the computer or the data processing algorithm. Any change in design involves risk, but some changes may ripple throughout a system, forcing additional changes to accommodate the first. Additional risk is anathema for an operational system, whose reliability and continuity are the prime considerations. No matter how well justified the augmented capabilities may be from a scientific point of view, any potential change must be examined carefully and conservatively.

Any program with a long time line must face the issue of technology insertion. In past decades, the relatively long lifetime of many of the operational weather satellites and the relative stability of their instrumentation frequently led to obsolescence, and the need for change became a dominant consideration.

The National Oceanic and Atmospheric Administration (NOAA) Polar-Orbiting Environmental Satellites (POES) program essentially began with TIROS in April 1960 and, proceeding through several generations, will fly through 2009 (2011 for the Defense Meteorological Satellite Program (DMSP)). Although there have been several block changes that modified the spacecraft design or exchanged existing instruments for improved or enhanced versions, the POES and DMSP series have been characterized by long periods during which they operated with essentially fixed configurations. Occasionally, these programs made changes and flew special instruments between block changes. These changes included permanent additions as well as one-of-a-kind instrument flights. However, the sponsoring agencies have learned that even apparently simple changes can lead to setbacks.

The Advanced Very High Resolution Radiometer (AVHRR) and the Solar Backscatter Ultraviolet (SBUV) sensor provide examples of the kinds of difficulties that may be encountered. Both instruments were built as a set of several identical flight units. The 3.7 μm band on the first AVHRR was discovered soon after launch to be contaminated with noise, which gave a herringbone pattern in the imagery. Subsequent analyses suggested that there was a design flaw in an amplifier, but funds were no longer available to redesign and rebuild the remaining AVHRRs for future flights. A similar problem occurred with the SBUV. A simple design flaw diminished the scientific utility of the data set for analysis of low-frequency processes (Mark Schoeberl, NASA Goddard Space Flight Center, personal communication, 1998). However, NOAA was unable to provide funding to rectify the problem for future SBUV sensors. These and similar experiences have reinforced the operational agencies' natural tendency to resist change, and they underscore the need for thorough prequalification of any candidate instrument before it is accepted into an operational payload.

Introducing new technology through block changes is a direct approach to enhancement that avoids the problems caused by introducing new components into an older design. When a block change is associated with recompetition for the program, it also addresses the programmatic and contract issues. However, it does not directly address the issue of continuity of data products and the ability to put a long time series of data on a standardized scale. For short-term weather prediction, new and improved systems may be acceptable if they provide forecasts with higher accuracy. However, for climate research it is necessary to be able to relate the old measurements to the new quantitatively if small trends in critical variables are to be observed over time. Thus,

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[1] The committee notes that accommodation of "leveraged payloads" was included in the request for proposals (RFP) for the NPOESS system definition and risk reduction phase (IPO, 1999). Leveraged payloads are those provided by NASA or other agencies and presumably are not necessary to satisfy the core NPOESS requirements. However, they could eventually become part of the operational payload. The RFP also includes the accommodation of the NPOESS Preparatory Project (NPP) mission as a single flight before the NPOESS spacecraft are launched. Implications of the NPP are also discussed in this chapter.

BOX 5.1
Operational Satellite Improvement Program

The history of the Operational Satellite Improvement Program (OSIP) was reviewed in a 1993 publication by the U.S. Congress, Office of Technology Assessment (U.S. Congress, OTA, 1993):

> NASA and NOAA have a long history of cooperation in developing spacecraft. An agreement between the two agencies, originally signed in 1973, gives the Department of Commerce and NOAA responsibility for operating the environmental systems and requires NASA to fund development of new systems, and fund and manage research satellites. This NASA line item is known as the Operational Satellite Improvement Program, and was usually funded at an average level of about $15 million per year. Prior to initiating the Geostationary Operational Environmental Satellite (GOES)-Next development, this division of labor seemed to work well. NASA had developed the TIROS and Nimbus research satellites, which carry instruments that were eventually transferred to NOAA operational satellite systems. NASA and NOAA budgets and organizational structure were based to an extent on the agreed-upon division of responsibility.

In the polar-orbiting part of this approach, NASA's Nimbus spacecraft was used as a science platform (Eden et al., 1993) on which new instruments could be developed and flown as a research or demonstration mission. NOAA's TIROS (followed by the TIROS Operational System, the Improved TIROS Operational System, and POES) was the corresponding operational spacecraft, whose technology and instrumentation naturally evolved more slowly. The dual path central to the OSIP concept was deemed to be too expensive at the time, and the approach was abandoned in 1985. Nimbus continued to fly for several years as a science program in its own right, but it no longer served as the development platform for the operational system.

technology insertion poses a dilemma: system change is necessary, yet in certain respects it may be undesirable. Any enhancement that appears to be desirable from a science point of view must also be well understood, well qualified, and well documented to qualify as a proposed change. The challenge for NPOESS is to find a way to accommodate technological change in a timely manner, while ensuring that the modified system will sustain operational functionality.

An early strategy of NASA and NOAA was the Operational Satellite Improvement Program (OSIP; Box 5.1). While Congress has questioned the loss of OSIP,[2] it has not been reinstated.

The National Research Council (NRC) has addressed the issue of technology development at NASA in several reports.[3] These reports generally have expressed concern about NASA's commitment to technology development and to technology insertion into NOAA programs.

NOAA itself has always taken a conservative approach to flying new instruments, and the process of introducing new instrumentation has been slow and rigorous by design. This conservatism has a reasonable basis, because instrument changes usually imply subsequent changes in the information products used throughout the weather services and the secondary data processors (commercial users). Any change in the original data may also require a different data processing algorithm, which could disrupt the continuity of corresponding climatology records. (One means of insuring against this risk is to preserve the original data.)

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[2] For example, the hearings held for Fiscal Year 1998 Budget Authorization Request: National Oceanic and Atmospheric Administration (NOAA) and H.R. 437, the Marine Revitalization Act of 1997, Thursday, March 13, 1997, U.S. House of Representatives, Committee on Science, Subcommittee on Energy and Environment, Washington, D.C. At that hearing, the GAO responded to a congressional suggestion that OSIP should be reinstated.

[3] See, for example, National Research Council (1993; 1995a,b; 1996; 1997a,b,c; 1998a,b,c).

NOAA is not a space agency; in the past it has relied on NASA to develop instruments and spacecraft. In recent years, NOAA's alliance with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) has added an international dimension to the technology insertion question. Economics, reduced budgets, and increased awareness of the global nature of the issues has engendered more international cooperation, both scientifically and programmatically, with European and Asian countries. However, the means of technology insertion for these operational missions is still not well determined. Indeed, there appears to be a gap between the development of instruments in the science stream and the application of instrumentation in the operational stream. For example, the NASA Earth Science Enterprise has expressed its intention to rely on international partners to fulfill certain of its NASA science goals (P. Morel, NASA presentation, 1999). Such international exchange may be sound financial policy in this age of reduced budgets, but it does not necessarily lead to enhanced instrumentation on the operational satellites of either Europe or the United States. For example, it was originally agreed that the Meteorological Operational satellite (METOP; supplied by EUMETSAT) would provide morning coverage for NPOESS, and in exchange there was meant to be shared instrumentation between METOP and NPOESS. At this time, however, planned METOP flights through 2017 will not include NPOESS operational instruments. There have been no substantive discussions between the pertinent agencies regarding the insertion of new instrument capabilities that might follow from the international scientific cooperative programs.

Without making a major block change, how can new instruments be introduced directly on the operational platforms? Technological insertion of a new instrument outside a block change has a precedent on POES with SBUV and the Earth Radiation Budget Experiment (ERBE). However, the policy that would determine the future of such new instruments is not clear. Are they to be adopted as part of the operational program, or are they to be replaced by a different experiment on the next flight? Resources for the operational platforms are limited and usually committed well in advance; there does not seem to be enough excess capacity ("margin") to support many concurrent experiments. There are lessons to be learned from the POES experience. If the NPOESS program is to be used to support the science community as well as the operational weather agency, then a careful assessment of the pertinent science requirements must be made in the early phases of development. A possible solution to this dilemma is a continuing program of missions where "preoperational" measurements and technologies can be tested without disrupting the operational programs. This approach is in the spirit of the OSIP or Nimbus model.

TECHNICAL ISSUES[4]

The insertion of technology raises issues of hardware and software capability and capacity. Once a major system design such as NPOESS has been finalized, it is increasingly difficult to accommodate change. Hence, advance planning that anticipates change and technology insertion over the life of the program is essential. Such planning should be part of the NPOESS system definition and risk reduction (SDRR) phase and continue into the subsequent stages of design. To the extent that instrumentation innovations from NASA science programs might become candidates for NPOESS, NASA and the Integrated Program Office (IPO) must incorporate planning for technology insertion in the near term. Highlights of the technical issues to be considered are described in the following sections.

Defining Available Program Resources

Technology insertion always will be subject to limitations. Any downstream change in the on-board technology must fit within the spacecraft resources (mass, power, data bandwidth, data volume, etc.) that may remain over and above the requirements of the baseline system. To estimate resource availability, it will be necessary to

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[4] NPOESS was just entering the system definition and risk reduction (SDRR) phase (the RFP was released September 16, 1999) as this section was being written, so that the potential contractors for NPOESS were not able to respond freely to requests for information. As a result, the questions considered in this section are directed to the engineering, manufacturing, deployment, and operational phases. However, it would be valuable for these questions to be readdressed during the execution of the SDRR phase.

consider all system elements from the program level through the space segment down to the individual instruments. For the introduction of enhancements, it may even be necessary to consider sensor subsystem attributes, such as frequency bands and data streams. For example, the AVHRR on the current POES was enhanced (over the VHRR instrument) by adding a new channel. Even this change, as simple as it might appear to have been, encountered a resource limitation in the downlink data rate that restricted the data flow from the AVHRR to the same number of channels as the older version. For the satellite and payload combination, it is difficult to increase resource demand within the design envelope of the spacecraft and launch vehicle. Because the spacecraft liftoff mass usually is matched to launch vehicle capacity, it may take a major redesign of either the spacecraft or the launch vehicle to accommodate an increase in mass or volume. For the ground segment, usually it is possible to add capacity during the operational life of the mission, but even this may require difficult choices, such as changes to remote site antennas and processing equipment. Ground segment changes are to be avoided because, in general, many facilities worldwide would be affected.

Characteristics of the Available Spacecraft

Just as the measurement characteristics of instruments must satisfy the requirements imposed by meeting science objectives, so must the host spacecraft be able to support the requirements of the instrument payload. The science community, through its participation in the NPOESS science team, should provide guidance to the IPO on the magnitude of the spacecraft resource margins necessary to support planned or potential new instruments. This will require that the IPO and its contractor maintain a status report on the resource margins for use in the technology insertion process.

For any innovation being considered, the resource needs and requirements of the candidate technology insertion, measurement enhancement, or new instrumentation must be compared with the margins and limitations determined by the spacecraft characteristics. For an existing operational design—such as that for NPOESS—there will be virtually no possibility of substantive changes to the spacecraft and its standard payload. An additional constraint is that NPOESS is being designed for a relatively long (7-year) lifetime.[5] Indeed, if the design has little room built in for enhancement, many potentially interesting innovations can be ruled out. Clearly, NPOESS and its payload should be designed from the outset with sufficient margin in its critical parameters to support the insertion of new or enhanced measurement capabilities.

Potential Instruments

The committee anticipates calls from the scientific community, and perhaps also tangible interest from the operational community, for the addition of new, enhanced, or more reliable measurement capabilities over the lifetime of the NPOESS system. In anticipation of these events, a process and infrastructure should be defined now to review proposed technological or measurement innovations and oversee their acceptance when warranted. The IPO was responsible for the generation of the original NPOESS operational requirements (IPO, 1996), so there is already in place a process that should provide for multiservice approvals and signoffs of revisions to those requirements. Requirements for enhanced measurement capabilities that would respond to the needs of the climate science community would have to be developed and approved through that process.

The NPOESS RFP for the SDRR phase (IPO, 1999) provides for leveraged instruments, which are to be developed by other (non-IPO) organizations and then offered to the IPO at zero (or nominal) cost. The RFP specifies that the contractor develop a process to accommodate the leveraged instruments that are accepted for flight. The IPO's inclusion of this task in the SDRR statement of work, an effort that the committee supports, indicates that the IPO recognizes the need to incorporate additional instruments, and it sets a precedent that could help in the formulation of a review and selection process for future technology insertion. Leveraged instruments

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[5] The IORD specifies a mission lifetime of 7 years, but how this translates into spacecraft reliability is to be determined by the development contractor.

can be developed by either domestic or international agencies. If successful, NASA's Instrument Incubator Program (IIP), which is designed to prove the value of new measurement concepts by aircraft or suborbital implementation, could be followed by a satellite-based mission, selected, for example, through Earth science flight programs such as the Earth System Science Pathfinder. Another possibility for a leveraged instrument is the radar altimeter, which appears in the straw-man manifest for the 0530 satellite and which the IPO has said it favors being contributed by the French, in contrast to its strategy for facility instruments such as the atmospheric sounder, whose development it funded directly.[6] A lesson that could be drawn from the IPO's position in this instance is that the development and qualification of any new measurement capability for scientific purposes would have to be funded from non-IPO sources, unless that instrument were deemed to be critical to the NPOESS mission. Because important science issues may not be addressed by this approach, vision and well-coordinated interagency planning are needed to sustain suitable instrument development in synchronization with NPOESS flight opportunities.

PROGRAMMATIC ISSUES

Programmatic issues for an explicit technology insertion element include those related to cost and schedule. There will be direct costs associated with planning for and accommodating system contingencies (margins), staffing in the IPO for the science dimensions of NPOESS, and associated schedule impacts and indirect costs. If NPOESS is to be successfully extended from an operational system to a system that can encompass climate research objectives, then the partners in the IPO, primarily NASA and NOAA, must allocate (or reallocate) funds accordingly. The SDRR contractor's costs will probably have to increase to accomplish these future tasks, an increase that the government would have to factor into the overall costs and funding or find other ways to accommodate. The time required to develop, select, and qualify potential research payloads cannot be allowed to compromise operational needs.

Unlike its predecessors, which have relatively short design lifetimes, the NPOESS satellites are meant to have a 7-year lifetime. While a 7-year design life is a laudable objective for an ongoing operational facility, the launch and replacement schedule as well as the physical resources of the spacecraft will inhibit technology insertion. Having longer intervals between launches implies also a larger number of instrumentation innovations worthy of flight, yet there will be fewer opportunities to insert them.

Management of the Process

If the NPOESS satellite series is to be enhanced in response to climate science requirements, the leadership and management responsible for doing so need to be identified. The IPO, on behalf of its three principal stakeholders (NOAA, the Department of Defense (DOD), and NASA), is coordinating convergence toward an operational polar-orbiting weather satellite system, but the climate and research requirements are outside its primary mission. No single organization represents the needs of climatology.[7] If such an organization were created, it could provide insight and oversight, but the responsibility for NPOESS would, with good reason, remain with the IPO. Therefore, the science and operational mandates of NPOESS would have to be coordinated at the highest levels of the three sponsoring agencies.

NASA's Earth Science Enterprise is committed to continue funding small, short-duration missions to study Earth, including climate-related variables of its ocean and atmospheric environments. However, such missions are ill-suited to long-term climate studies (NRC, 2000b). As noted in a number of places in this report and elsewhere, polar-orbiting operational weather satellites (no matter how long their missions) are not equipped to meet the needs of climate science. These two themes could be harmonized if suitable and coordinated leadership were exercised.

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[6] Note that to date, there is no agreement between the IPO and the French for the NPOESS altimeter.
[7] See the "Organizational Issues" section in Appendix B of this report.

Coordination of Instrument and Spacecraft Development Schedules

Consider a situation where the NPOESS spacecraft have spare on-board resources that have been identified for scientific use. If no additional Earth observation satellites are identified for demonstration of new instrumentation, the only opportunities to insert the new technology into the NPOESS program would be during routine replacement flights. Once the NPOESS system is fully in place,[8] the replacement cycle for each of the two IPO satellites will be at nominal 7-year intervals, with an average launch frequency of one every 5 years. If historical trends continue,[9] spacecraft will probably last longer than their design lifetime, so that replenishment opportunities will be further delayed. Instrument development and procurement must be synchronized with the spacecraft procurement cycle, which in general is paced by the scheduled ready-to-launch date. The actual launch date may be delayed by several years because of the continued operation of the on-orbit spacecraft.

Replenishment Cycles

Technology insertion into the space segment is a discrete process that culminates only when a spacecraft is launched. As discussed above, the expected time between launches is likely to lengthen as the program matures and early-life design problems are eliminated. The IPO has stated that failure of one of the NPOESS mission-critical instruments (see Table 3.1 in Chapter 3) will require a replenishment launch.[10] Experience has shown that instruments frequently degrade gradually, perhaps losing a channel rather than failing completely. NOAA, as the cost-conscious operator of POES, has been tolerant of instrument degradation and has a complex, and not explicitly stated, decision process for deployment of a replacement spacecraft. The decision factors include the availability of alternative data sets, the specific data loss, the weather parameters affected, and the availability of a replacement spacecraft ready for launch. Under current policy, the fact that an instrument provides data that are important to a climate science record has no bearing on the replacement launch criteria. Partial failure may have only a small impact for operational weather purposes but may induce degradations that are far more significant for scientific purposes. Thus, the IPO's replacement strategy could have a serious impact on the science community.

In general the IPO has not announced a formal replacement policy in response to the failure of a non-mission-critical payload instrument. The committee has expressed concern about the loss of continuity in data collected from such secondary instruments, which may play a more significant role for climate and other science studies than they do for weather. It seems that the current IPO policy is to not order a launch if a secondary instrument fails, as long as the mission-critical instruments remain viable.

The complementary question is what happens when the spacecraft is replaced early (in response to the failure of one instrument) and the other instruments are still performing satisfactorily. The histories of POES and DMSP indicate that it is difficult to maintain operational status for spacecraft that have failed partially at the same time as their replacements are also in orbit. The main problems are conflicts at the downlink data readout and command and control stations, and the additional burden on all ground facilities and personnel. If additional NPOESS spacecraft are to be operated after a replacement launch, additional resources (including funds) will be necessary.

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[8] The complete configuration (nominal) consists of one NPOESS spacecraft at 0530 equator crossing and the second one at 1330, and Europe's METOP at 0930.

[9] Records show that POES and DMSP spacecraft have had consistently longer lives than the a priori expected life based on design specifications (NASA, 1995). The initial launches in a new series have shorter operational lives, probably due to early-life problems with the new design, but the operator also tends to replace that first unit early. Launch failures and a few early-life failures bias the statistics toward shorter life expectancy. Data compiled by the Aerospace Corporation show that sequences of most operational spacecraft are better than the design predictions when early failures are discounted.

[10] The IORD specifies the measurements (environmental data records) deemed to be of critical importance to the mission, and by implication, the corresponding instruments become mission critical, according to information provided to the committee by representatives of the IPO. There appear to be no simple criteria by which to assess the import of partial or gradual deterioration of a mission-critical instrument. The IORD-1 stipulates six key parameters for measurement: (1) atmospheric vertical moisture profile, (2) atmospheric vertical temperature profile, (3) cloud and ice imagery, (4) sea surface temperature, (5) sea surface winds, and (6) soil moisture.

A CONTINUING NPOESS SYSTEM AUGMENTATION PROJECT

NASA and the NPOESS IPO are formulating final plans to build, launch, and operate an NPP satellite as a bridge mission between the current POES/DMSP and the future NPOESS series. The goals and objectives of the NPP mission are to validate critical and new instruments, algorithms, and processing for NPOESS, as well as to provide continuity for selected science and climate measurements. The NPP was conceived as a bridge between science and operations. Experience has shown that proving in practice the value of a candidate research instrument is often the crucial step in developing it for operational use. A satellite program such as NPP can provide just such an opportunity.

The dichotomy between operational and research systems suggests that a separate and continuing series of spacecraft would be a useful adjunct to NPOESS. Such a program could support short-term studies, serve as a technology development testbed for instruments and spacecraft, and help to ensure continuity of noncritical measurements. Unfortunately, NPP may be only a one-time opportunity, as NASA has no plans to continue it. Nevertheless, the concept of an ongoing bridging capability between the scientific and operational arenas is very appealing. This should be closely tied to the IPO.

NASA views the NPP as a means of continuing certain EOS measurements and as a demonstration platform for selected NPOESS instruments. The mission is in the concept-development stage, and not all the requirements are fixed. The next stage, in which the level 2 and level 3 requirements will be developed, will provide more detail. The timing of the mission is important for the continuity of data. EOS-AM (Terra) and EOS-PM (Aqua) will complete their expected mission lives in 2006 and 2007, respectively. NPOESS does not launch until 2009, and this could be delayed if the POES system survives beyond its predicted lifetime (which is probable, based on past performance). METOP-1 launches in 2003, but it does not include new NPOESS instruments.

The flight of NPP is planned for 2005 (IPO, 1999) with the Advanced Technology Microwave Sounder (ATMS), CrIS, VIIRS, and possibly a fourth instrument. The NPOESS program development and risk reduction (PDRR) phase calls for a study of system enhancements to ensure the system's readiness to accept NPP data. The NPP data will not be processed exactly like the NPOESS data, although the front-end processing will be similar. There will be a best-effort attempt to produce environmental data records (EDRs). The EDR algorithms produced from the NPP are expected to converge to production quality, but the time required for the products may be greater than the 3 hours required for NPOESS products. This approach is being taken by the IPO to facilitate and speed the development of the Integrated Data Processing Segment that is planned to process data from NPOESS satellites.

The NPP system architecture also incorporates a science data system that will produce science data records (SDRs) and climate data records (CDRs). This research side of the NPP data system is expected to support a number of science projects through the announcement-of-opportunity process. This is the bridge from EOS to NPOESS. The CDRs and the SDRs will need to be defined as the program matures.

The details of NPP data processing will be developed in the next few years as the NPP and NewDISS (New Data and Information System and Services) designs mature. The committee is in favor of this early proof of concept and validation of the instruments, algorithms, and processing systems. With a flight planned for 2005, NPP precedes NPOESS by a sufficient margin to allow correcting any problems in the ground system before NPOESS becomes operational.

NASA STRATEGIES AND PLANS FOR TECHNOLOGY DEVELOPMENT

Earth Science Enterprise Technology Development Plan

Goals and Themes

In 1999, NASA's Earth Science Enterprise (ESE) published its technology strategy (NASA, 1999). A summary provided in the Introductory Letter states as follows: "To insure timely technology availability, the Enterprise has established a strategically driven technology development program with two primary objectives.

The first is to accomplish the defined ESE missions more efficiently and effectively, and the second is to enable new fundamental and applied research programs essential for meeting the long-term Enterprise goals."

These goals are to be accomplished through the Technology Development Plan, which includes both near- and long-term projects with a flow of promising developments into ESE missions. The Instrument Incubator Program and the ESE core technology initiatives are also being developed to meet ESE needs. The New Millennium Program (NMP) is the space demonstration segment of the approach. It was originally conceived as a technology improvement program for deep-space missions but has been expanded to include Earth observation.[11] The NMP includes six areas of technology (listed below), which can be applied to any type of spacecraft if the projects are chosen correctly. It is the choice of demonstration projects that makes the results more or less specific to a class of systems (e.g., deep space or near Earth observation).

- Autonomy,
- Telecommunications,
- Microelectronics,
- In situ instruments and microelectromechanical systems,
- Instrument technology and architecture, and
- Modular multifunctional systems.

The goal statement[12] for the instrument technology and architecture (IT&A) group promises as follows:

> The Instrument Technologies and Architectures IPFT is focusing on the identification, development, and validation of revolutionary technologies that will enable new science measurement capabilities in the 21st century, or that will provide current capabilities at a significantly lower life-cycle cost. The emphasis on reducing overall science mission cost, while increasing the science return through increased mission frequency, results in a strategy of miniature microspacecraft and instrument systems. Consequently, technologies that contribute to system requirements of lower power, mass, and volume while maintaining or enhancing performance and reliability are of particular interest. Special attention will be given to technologies that enable the development of highly integrated, multifunction observational systems.
>
> The New Millennium Science Working Group has identified and defined science measurement capabilities in support of the programs of Mission to Planet Earth, Solar System Exploration, Origins, Structure and Evolution of the Universe, and the Sun-Earth Connection. These capabilities are used as a guide for identifying and selecting IT&A technology candidates for flight validation by the NMP.

However, concerns have been raised about the direction of the NMP, specifically that there has been an overemphasis on microsatellites, and the related technologies may not be applicable to NPOESS-type missions, which are concerned with more conventional Earth observation. The committee does recommend that technology development should continue and, specifically, that part of the effort should be focused on reducing cost. Both nonrecurring and recurring costs need to be addressed, but in a long-term operational program recurring costs are most important because of the number of copies that will be procured. Additional effort is needed to develop instrument technologies that reduce the costs and development times. Larger instruments, such as those in the EOS program, have a development time of about 10 years. It takes about 60 months to go from a phase B concept to a flight instrument, but the time from initial concept to flight can be highly variable and quite long. Shortening this time would greatly reduce the costs and provide a faster return of science data, which is the goal of all the new NASA initiatives.

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[11] The overall goals were discussed by the Jet Propulsion Laboratory program manager, E. Kane Casani, in an interview for Space News (Space News, 1996).

[12] This information was available in November 1999 from the Jet Propulsion Laboratory Web site at <http://npm.jpl.nasa.gov/tec/index>. The site provides information about NMP, but the information is subject to change.

NASA's ESE has generated three interlinked themes (NASA, 1999), which are captured as ESE's level I requirements:

1. Development of instruments and information systems to support coupled Earth systems studies;
2. Development of information system architectures to greatly increase the number of users to tens of thousands over 5 to 7 years; and
3. Development of partnerships with industry and operational organizations.

There are also concerns about both the schedule and the decision process in the NMP. The present schedule does not suit NPOESS needs and it is not clear if it can be shortened to have an impact on NPOESS. It is also not clear who makes the decisions on what technology will be pursued. A technology subcommittee of the ESE Earth System Science and Applications Advisory Committee is said to be the guiding body, but as this report was written its membership was not known and it was not clear how the subcommittee would interact with the operational programs. The NASA contribution to NPOESS is technology, and the needs of NPOESS must be addressed by the goals of the ESE program.

Schedules

The ESE plan is to have demonstration instruments and other technologies ready in the 2003 to 2009 time frame. This is rather late if the aim is to get them into the first NPOESS flight cycle. However, this schedule does depend on when the first flight actually occurs. Although economics may favor a delay, that is, use of the POES/DMSP spacecraft for as long as they are available (potentially to 2014), it will be necessary to start developing NPOESS early to be prepared in case it must fly as early as 2007. This reduces the probability that the ESE initiatives will have an impact on NPOESS. The climatology community favors earlier flight of NPOESS to ensure overlap with the long-term POES data sets (AVHRR, Microwave Sounding Unit, etc.).

The ESE Technology Development Plan appears to be coherent and to make sense for ESE's mission types. However, the committee is concerned that missions have not been fully defined in terms of the interaction between science objectives and enabling technology. Furthermore, as of February 2000, mission funding had not been clearly delineated, nor had the Technology Development Plan been implemented.

The committee is concerned that NASA/ESE's current approach to mission implementation is too ad hoc and could lead to a fragmented collection of small missions.[13] The committee makes a distinction between small missions and small satellites, because a larger mission can use several small satellites (or one). A system consisting of many small satellites flying in formation and using data fusion may not be a small mission. The general position of the committee is that a mix of mission sizes and satellite sizes is required and that each mission must be addressed on its own merits (NRC, 2000c).

Integration with NPOESS

It is noteworthy that the ESE Technology Development Plan does not provide for transitioning the technology from scientific status to operational status. This fact is central to the question of technology insertion into NPOESS in support of climate or other scientific objectives. Even if a new technological innovation is proven to be feasible, there are currently no plans to carry it forward once NASA's scientific missions have ended. One of the three divisions of the IPO, the Technology Transition Division, is led by NASA. There is little linkage between that office and the NASA office that drafted the ESE technology strategy. In spite of its name, the Technology Transition Division is responsible mainly for contractor oversight of the operational instruments now being developed for NPOESS.

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[13] The NRC has addressed this question in a separate report (see NRC, 2000a).

Flight Systems

The NASA plan also addresses spacecraft hardware and operations. It gives a general impression of the direction ESE expects spacecraft systems to take. A heavy emphasis on formation flying of small spacecraft, including instrument calibration and data fusion considerations, portends the use of smaller spacecraft, but not necessarily single-spacecraft small missions. Although smaller spacecraft can reduce certain costs, they do not necessarily reduce overall mission cost, a point discussed in the report *The Role of Small Satellites in NASA and NOAA Earth Observation Programs* (NRC, 2000b), which recommended that NASA continue to use a mix of mission and spacecraft sizes to maintain a balanced approach.

NASA's ESE will also support research into ways to simplify the methodology for the design and building of spacecraft. This is a commendable goal that has been neglected somewhat in the past. Previous attempts to use modular systems did not fare well and the costs were often higher than those for conventional methods.

In addition, ESE is looking into how to greatly reduce resource requirements (mass, power, etc.), a necessary condition if smaller spacecraft are to be used and the payload fraction increased. The committee believes that instrument development must also be part of this effort. While there are lower limits on the size of instruments to achieve a certain resolution and signal gathering, other aspects of instruments are amenable to size reduction.[14]

Other areas of development include increased autonomy, on-board data fusion and inter-instrument data comparisons with autonomous and adaptive strategies, and advanced communications. On-board data fusion is an area that will require cooperation from the science community. Past efforts to perform data processing on the spacecraft have met with resistance from the science community. The science community in general and the climate research community specifically require the raw data records so that retrospective processing can be performed as knowledge of the sensor, models, or physics improves over time. With on-board processing there is concern over loss of data and loss of ability to reprocess the data when better algorithms are developed. In the interplanetary missions, data compression and processing have been accepted, because the difficulty of transmitting large volumes of data overrides the other issues.

FINDINGS

The committee recognizes the consequences and risks of technology insertion on the operational performance of the system. Its findings on technology insertion are as follows:

- Operational agencies naturally tend to resist change; any candidate technology enhancement to increase the science content of data products must satisfy rigorous prequalification before being accepted into an operational payload.
- The challenge for an operational meteorological satellite system such as NPOESS is to find a way to accommodate technological change in a timely manner while ensuring that the modified system sustains operational functionality.
- In general, the means for insertion of technology into operational missions is not well determined. Indeed, there appears to be a gap between the development of instruments in the science stream and their adoption in the operational stream.
- If the NPOESS program is to be used to support the science community as well as the operational weather agency, the pertinent science requirements must be carefully assessed in the early phases of the program.
- Technology insertion always will be subject to limitations. Any downstream change in the on-board technology must fit within the spacecraft resources (mass, power, data bandwidth, data volume, etc.) that may remain over and above the requirements of the baseline system.
- It is likely that the development and qualification of any new measurement capability that might be required for scientific purposes would have to be funded from non-IPO sources, unless that instrument were

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[14] See Chapter 3, "Payload Sensor Characteristics," and Appendix B, "Effects of Technology on Sensor Size and Design," in NRC (2000c).

deemed to be critical to the NPOESS operational mission. Clearly, vision and well-coordinated interagency planning are needed to sustain the development of suitable instruments in synchronization with NPOESS flight opportunities.

- Unlike the relatively short design lifetimes of their predecessors, the NPOESS satellites will have a 10-year design lifetime. While such a long life is laudable for an ongoing operational facility, it impedes the process of technology insertion.
- If an instrument provides data that are important to a climate science record, under current policy this fact has no bearing on the launch of an NPOESS replacement spacecraft. Partial failure, even of a mission-critical instrument, may have such a small impact for operational weather purposes that it does not trigger a replacement launch. However, the same small fault could induce degradations that would be far more significant for scientific purposes.
- An opportunity to prove in practice the value of a candidate instrument is often a pivotal step in the effort to translate a scientific measurement into an operational tool. A satellite program such as NPP could provide such opportunities.
- It is noteworthy that the ESE Technology Development Plan does not provide for transitioning the technology from scientific status to operational status. This fact is central to the question of technology insertion into NPOESS in support of climate or other scientific objectives. Even if a new technological innovation is proven to offer unique scientific value and is shown to be technically feasible, there are no current plans that would guide its transition to NPOESS.
- A study of the use of small satellites (NRC, 2000b) noted the advantages of using a mixed fleet of missions, rather than trying to achieve all operational, research, and technological objectives with one type of spacecraft. Although there are resources for additional sensors on the NPOESS spacecraft, opportunities to include small spacecraft with one or two sensors should also be pursued. Such spacecraft could even be placed in nonpolar orbits to maximize their contribution to both weather and climate measurements.

RECOMMENDATIONS

The committee's findings all point to the need to maintain an open and flexible system that can accept new technology, which includes new instruments. The desire to use the operational meteorological system for research places demands on both the IPO (for the operational use) and NASA and NOAA (for climatology research use). Because of the ongoing competition for the NPOESS total system performance requirements contract, it was not obvious to the committee which issues are being addressed, and the following more specific recommendations are intended to provide guidance. On the climate research side there is no designated agency, but NASA and NOAA are the stakeholders. NASA has a vested interest in using NPOESS to satisfy some of its plans, and NOAA has responsibility for the long-term archiving of data to support the needs of the climatology community.

- The IPO should identify a person or group to review the NPOESS system requirements and the design to ensure that both the IORD and the contractor approaches will support flexibility and change.
- NASA should provide a list of science requirements (presumably from the Science Plan) and climate requirements that are candidates for implementation on NPOESS.
- The IPO should plan for the insertion of new or enhanced measurement capabilities into NPOESS that would likely have to be funded from non-IPO sources.
- NASA ESE should implement its Technology Development Plan with firm plans linked to missions and ensure that any necessary NPOESS enabling technologies are covered in the plan.
- NASA and the IPO should devise an approach to support accepting additional experiments on NPOESS.
- It is essential that the process of incorporating research requirements into NPOESS be started now and be allowed to influence the program development and risk reduction phase that is in progress, without disrupting the primary NPOESS mission. Opportunities for change after the launch will be limited by the longer satellite lifetime and longer intervals between launches.

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Appendixes

A

Statement of Task

INTEGRATION OF RESEARCH AND OPERATIONAL SATELLITE SYSTEMS

Background NASA officials have long envisioned developing operational versions of some of the advanced climate and weather monitoring instruments planned for the Earth Observing System (EOS) afternoon (PM) satellite. In the 1995 EOS "Reshape" exercise, NASA adopted the assumption that some of the measurements in the second PM series would be supplied by the Department of Commerce (NOAA) and Department of Defense (Air Force) National Polar-orbiting Operational Environmental Satellite System (NPOESS). NASA is about to begin intensive planning for the EOS-PM mission. NASA is also examining the potential for advanced instruments on future versions of the NOAA GOES (Geostationary Operational Environmental Satellite) satellites to be integrated into the EOS program.

Integrating NOAA-DOD operational weather satellites into NASA's Earth Observing System program poses numerous interrelated technical and organizational challenges. By definition, the "operational" weather programs of NOAA and DOD must meet the needs of users who require unbroken data streams. Historically, development of operational instrumentation has been successful when managed with a disciplined, conservative approach towards the introduction of new technology. In addition to minimizing technical risk, minimizing cost has been an important factor in the success of operational programs, especially for NOAA.

Achieving NASA research aims on a satellite designed to meet the operational needs of the civil and defense communities will require agreement on joint agency requirements, and coordination of instrument development activities, launch schedules, and precursor flight activities. The proposed study will include an analysis of these issues, especially those related to (1) sensor design and development, (2) program synchronization, and (3) data continuity and interoperability.

Plan The proposed study will analyze generic issues related to the transition of NASA research satellite instrumentation for NOAA operational use. The study will focus in particular on observational priorities and technical issues related to the potential integration of the NOAA-DOD NPOESS satellite with the NASA EOS "PM" series of satellites. Among the key questions to be addressed are:

1. Sensors and Measurements

- How well do current NPOESS IORD requirements match NASA research requirements for the EOS PM-2 satellite series? Are there any overlaps with AM-2 or CHEM requirements?
- If additional capability is needed for climate monitoring goals, what is this capability and what are technical and programmatic implications?
- Are there instruments that could be added to the operational suite, e.g., a scatterometer or SAR? What issues must be addressed in adding capabilities of this kind?
- What are the requirements for on-orbit or ready-to-launch replacement instrumentation for research and operational goals? Are there common spares strategies that could serve both research and operational needs satisfactorily?
- What issues might arise should NPOESS be tasked to undertake new missions such as long-term climate monitoring?

2. Program Synchronization

- What are the critical milestones in integrating research and operational space systems? Are any disjoints apparent?
- What are possible approaches to establishing program flexibility to ensure that both research and operational missions are achieved in the face of inevitable schedule changes?

3. Data Continuity and Interoperability

- What are the highest priorities for continuous/interoperable research datasets?
- What are technical approaches to ensuring data (a) interoperability between research and operational sensors and (b) continuity in the face of evolving sensor technology?
- What is the status of data storage, retrieval, and access planning for research use of NOAA operational data or possible NPOESS-obtained climate data?

A report summarizing the findings and recommendations that address technical items (1) and (2) ('Sensors and Measurements') and 'Program Synchronization') will be the Phase 1 report. Item (3) 'Data Continuity and Interoperability' will be addressed in the Phase 2 report.

B

Workshop Discussion and Participants

WORKSHOP ELEMENTS

Context

When completed, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) will provide operational support for a wide variety of Earth remote sensing measurements. With the longer planned lifetime of its satellites and the more stringent performance and stability requirements (relative to Polar Orbiting Environmental Satellites (POES) and the Defense Meteorological Satellite Program (DMSP), the current operational weather systems NPOESS is to replace), the NPOESS system offers an opportunity to begin developing an *operational component* of an integrated satellite observing system for climate research and climate monitoring. This was the subject of a workshop hosted by the committee on July 26-27, 1999. This appendix summarizes the committee's discussions at the workshop along with the committee's perspective on the views of workshop participants.

Differences in agency history and culture and the distinctions that characterize the operating philosophy of a "research" agency such as the National Aeronautics and Space Administration (NASA) and an "operational" agency such as the National Oceanic and Atmospheric Administration (NOAA) formed the backdrop for many of the workshop's discussions. In general, NOAA approaches climate research as an outgrowth of its primary mission, which is weather prediction and warning, while NASA's Earth Science Enterprise (ESE) carries out its climate-related research in connection with a program to answer specific science questions. Despite these differences, both agencies frequently require access to long-term, systematic observations to support their missions. However, while the particular observations may have considerable overlap, there are often significant differences in the measurement requirements. These similarities and differences underlie the challenge in crafting a strategy to meet the needs of climate researchers. They also account for the belief among members of the Committee on Earth Studies that long-term (or systematic) observations in support of climate research require a comprehensive strategy, not simply modified requirements.

Because climate variability occurs on a wide range of time and space scales and involves complex interactions between atmosphere, ocean, and land, researchers can completely specify with certainty neither the types of variables that need to be measured nor the appropriate sampling strategy. However, according to workshop participants, it is possible to define the key elements of a strategy that would facilitate climate research. They suggested the following elements:

- Scientific insight into sensor requirements and implementation;
- Calibration and validation of the sensor and its data products as well as comprehensive sensor characterization;
- Data analysis to assess data quality and develop new data products;
- Reprocessing of data to incorporate new knowledge;
- Ground networks for validation;
- Multiple approaches to variables to increase confidence;
- Assessment of temporal and spatial sampling strategies; and
- Technology development to lower costs and improve performance.

Workshop participants said that execution of this strategy was beyond the capabilities of any single agency. They also noted that the strategy required more than just observations—its components also include data analysis and technology development. Workshop participants viewed NPOESS as a critical element in executing a climate research strategy as it provides a platform for the long-term, continuous observations that will be required for the study of many climate-related variables. Programs sponsored by NASA ESE were also thought to be a critical element of a climate research technology development strategy. Currently, the ESE plans to rely heavily on NPOESS for the systematic observations that are required to meet its climate research objectives. Workshop participants saw the challenge for developing a NASA-NOAA climate research and monitoring program as being one of integrating the operational stability of NPOESS with the research flexibility of NASA/ESE. At present, no agency is charged, nor is there a formal process in place, to assess climate requirements and the overall approach and balance of a climate observational system.

In advance of the workshop, the committee distributed materials, including the following questions, for discussion:

- How can research-quality data sets be obtained that are suitable for study of decadal-scale processes?
- How can agencies implement the required program of long-term measurements to support climate research in a constrained fiscal environment?

A number of workshop participants concluded that the answers to these questions included both operational satellite platforms and research satellite platforms. Moreover, they believed it would involve a new category of missions in which both research and operations work together on data sets of mutual interest. Such preoperational missions could be used to bridge the needs of research and operational users as well as forge links between the observational and satellite sensor communities. An integrated approach to climate research is needed, according to workshop participants, because of the critical need for continuous high-quality data, the size of the national investment involved, and the need to demonstrate scientific progress upon which to base sound national policies regarding climate.

Goals

As noted, participants at the workshop were asked to consider opportunities in the near term to make incremental investments that would improve the suitability of operational missions for climate research. Further, participants were asked to be sensitive to the need for climate research to be carried out in a way that blends the flexibility provided by research missions with the long-term stability provided by operational missions.

The workshop focused on the following two questions:

1. In the near-term (the next 2 to 3 years), what marginal investments can be made by the Integrated Program Office (IPO) to improve the climate capabilities of the NPOESS Preparatory Program (NPP) and NPOESS? What

marginal investments can be made by NASA and NOAA to improve the climate capabilities of NPP and NPOESS, as well as other missions?

2. What activities are needed on a longer time scale to increase the likelihood that NPOESS will have the capability to be responsive to both currently anticipated needs and those needs that might arise in response to new scientific or technical developments?

Workshop participants developed their opinions on what can be done now to ensure a reasonable record of critical climate variables for the study of key climate processes. The objective was not to develop the "best" system but to develop one that might make significant contributions to climate research within the fiscal, technical, and programmatic constraints of existing and planned programs.

Approach

A variety of intra- and interagency actions appear necessary to address the issues outlined above. Many participants saw the need for a national policy regarding climate and long-term environmental variability, particularly to direct interagency efforts. Others focused on issues regarding the integration of NASA and NOAA research and operational observing systems. Looking in more detail, some participants commented on the need for national policy objectives regarding the collection and analysis of decadal-scale observations. Finally, some participants focused on comparatively narrow issues regarding the development of NPOESS and the NASA/ESE missions. *At the workshop, attention was focused on making interim progress on specific issues of integration of the NPOESS and EOS programs.* It was anticipated that this approach would also inform policymaking discussions that might occur at higher levels of government.

The workshop was organized as follows: Prior to the meeting, the committee selected a small set of critical satellite-based data sets for discussion. These data sets, chosen in part based on previous Intergovernmental Panel on Climate Change (IPCC), National Research Council (NRC), and NASA reports, were thought to be representative of those needed to study decadal-scale climate variability. The workshop addressed the structures (including policy, agency, and observing systems) that might be needed to obtain these data sets with sufficient overall quality to meet climate research requirements. These needs were then examined in light of the plans of the NPOESS IPO and NASA/ESE.

Workshop participants were asked to focus their discussions on approaches to meet climate observational priorities within the technical, fiscal, schedule, and programmatic constraints of agency programs. Specific attention was paid to those variables where realistic changes could be made within existing NPOESS plans. This implied, for example, a consideration of improved sensor performance or better sensor characterization versus consideration of a sensor that was not already in the baseline plan. Systematic measurements that had been identified by NASA/ESE as candidates for continued measurement by NPOESS were examined in detail.

Workshop participants also discussed a strategy to acquire or continue measurements of high-priority climate variables that are not part of the NPOESS framework. Elements of the strategy included measurements by NASA/ESE, bridging missions between research and operational programs, technology development, or international partnerships. Participants recognized that scientific understanding and technology will evolve, and that the needs of policymakers may change. Therefore, they also considered ways agencies might formalize a process to reassess their observation strategies.

Climate Variables Discussed

The variables chosen for discussion at the workshop are listed below:

- Atmospheric and forcing variables
  —Atmospheric temperature and moisture profiles
  —Cloud properties
  —Stratospheric ozone and aerosols

  —Precipitation
  —Earth radiation budget
  —Solar irradiance

- Ocean variables
  —Ocean topography
  —Ocean winds
  —Sea surface temperature (SST)
  —Sea ice
  —Phytoplankton biomass

- Land variables
  —Land cover.

While all of these variables have a demonstrated or anticipated importance to climate research, it should be recognized that only a subset have a long heritage in satellite remote sensing. They are atmospheric temperature and moisture, stratospheric ozone, solar irradiance, SST, sea ice, Earth radiation budget, and land cover.

To be useful in climate research, these variables require measurement nearly continuously over multidecadal time scales (essentially indefinitely), that is, data acquisition in an operational manner. The committee recognized that there were other variables that needed such long-term records; however, budgetary and programmatic constraints at NASA and NOAA suggested that the initial focus of the workshop should be on a comparatively smaller set of variables.

The connection between these variables, the key scientific questions identified in the Draft NASA Earth Science Implementation Plan (which in turn draws on the "Pathways" report (NRC, 1998)), and a measurement strategy is shown below. Workshop discussions did not consider all of the critical measurements that are necessary to address these questions. Instead, participants deliberately selected a small number of measurements where long-term continuity was thought to be essential and where expectations of marginal investments in the present measurement strategy were thought to have a reasonable chance to yield data records suitable for climate research.

Biology and Biogeochemistry of Ecosystems and the Global Carbon Cycle

Key Questions

- How do ecosystems respond to and affect global environmental change?
- How are land cover and land use changing? What are the causes and consequences?

Required Measurements

- Systematic measurements at moderate spatial resolution of land cover
- Systematic measurements at moderate spatial resolution of phytoplankton biomass

Global Water and Energy Cycle

Key Questions

- Is the global water cycle accelerating?
- Can weather systems, precipitation, and the hydrologic processes that control water resources be related to observed or predicted large-scale climate anomalies?
- Can the integrated effect of fast atmospheric and surface processes be accurately represented in large-scale model predictions of climate change?

Required Measurements

- Systematic measurements of global temperature and water vapor
- Systematic measurements of global precipitation
- Systematic measurements of the components of Earth's radiation budget
- Systematic measurements of cloud properties

Climate Variability and Prediction

Key Questions

- Is climate varying in ways that we can understand and predict?
- What causal relationships can be established between observed climate changes and specific forcing factors?

Required Measurements

- Systematic measurements of solar irradiance
- Systematic measurements of the components of Earth's radiation budget
- Systematic measurements of global stratospheric aerosols
- Systematic measurements of global ocean topography
- Systematic measurements of ocean surface vector winds
- Systematic measurements of sea surface temperature
- Systematic measurements of sea ice

Atmospheric Chemistry

Key Questions

- Is the Montreal Protocol working as expected to stop stratospheric ozone depletion by industrially produced chemicals?
- How are meteorological and chemical processes in the atmosphere affecting the distribution of trace constituents?
- How much will industrial and urban pollution expand globally and with what consequences?

Required Measurements

- Systematic measurements of stratospheric ozone and aerosols

Emerging Requirements for Climate Data Products

The requirements for climate observations to meet the needs of scientific research were recently considered in connection with the decadal review of the U.S. Global Change Research Program (USGCRP) (NRC, 1999). In addition, national assessments[1] reflect the growing interest in climate changes on both the interannual and decadal scales by business, governmental planners, and the general public. Interest in the economic impact of climate change is evident, for example, in business decisions regarding investment in the energy sector of the economy, an area sensitive to both climate trends and anomalies. Further, the impact of climate change on the energy sector is

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[1] Information on the USGCRP-initiated "U.S. National Assessment of the Potential Consequences of Climate Variability and Change for the Nation" is available online at <http://www.nacc.usgcrp.gov/>.

expected to grow as the nation expands its energy use during the coming years. Planning to meet that growing demand requires climate projections concerning decadal time scales, whereas generating scenarios for dealing with seasonal peaks requires interannual climate products.

At the moment, important climate products are being prepared on an operational basis. The newly developed market for weather futures is placing demands on timeliness, which differ from the needs of the research community. The potential for increasing these observing capabilities with the advent of NPOESS is great. Realizing that potential, however, is neither an easy nor a well-defined process.

Strategies

To date, the climate research community has had only a limited involvement in the process that determines the NPOESS requirements (NOAA, 1997). Further, there is substantial concern that the NPOESS data products will be only marginally useful for climate purposes. As noted earlier in this report, the needs of the climate research community were not a driving part of the process for determining the NPOESS environmental data records (EDRs), which reflect the joint *operational* needs of NOAA and the Department of Defense (DOD).

Workshop participants highlighted key issues and identified several actions for consideration by the IPO that they believed would greatly improve the suitability of NPOESS data for climate studies. At the moment, for example, there is no provision for archiving the metadata concerning the sensor calibrations, housekeeping information, or prelaunch characterizations of the sensors, which are critical to the ability to construct climate applications based on the NPOESS data, especially when attempting to identify trends.

Another concern of workshop participants is related to continuity of the NPOESS data. Data continuity might not appear to be an issue as the NPOESS satellites have a 7-year life expectancy and are planned for launch on a 5-year cycle. However, it is expected that the launch cycle will be driven by cost considerations and launches of replacement systems will be made on a “demand” basis, that is, when systems critical to operational weather services begin to fail. There is a 9 to 12 month period between the time the decision is made to make a replacement launch and the actual operational service of the new satellite. A gap in the record of that magnitude, where there is no overlap with the then-current satellite, cannot be bridged for the investigation of climatic trends. (An example is the interannual variability associated with El Niño/Southern Oscillation (ENSO) events.)

Workshop participants also had concerns related to the actual production of climate data products. For example, the IPO does not have a requirement to provide a data archive and retrieval capability. That responsibility is currently left to the operational agencies, namely NOAA. There has been only preliminary planning within NOAA to address this responsibility. If climate applications require affordable and relatively easy access to raw radiances, the storage capacity needs to be larger than present NOAA capabilities. Other concerns relate to data formats, access procedures, media obsolescence, and provision for reprocessing when errors are detected in the original data sets. In fact, workshop participants discussed the need to design a climate processing system that would operate in parallel with the operational one.

The impact of tight budgets on agency capabilities to serve the climate community was another concern of workshop participants. Present plans call for transition from the research-demonstration mode of NPP to the operational mode of NPOESS. However, the budget implications of a complete operational end-to-end NPOESS that are sustainable are greater than the totality of all other operational observing programs in NOAA. The disparity appears to be so large that it will not be possible to make traditional trade-offs between one or the other operational observing system to pay for the infrastructure to support the operational NPOESS. Eliminating the entire rawinsonde program, for example, would net only some $6 million per year. Supporting the operational NPOESS would require significantly more funding.

In summary, workshop participants believed that the process of realizing major climate benefits from NPOESS was incomplete—scientific understanding needs to be enhanced and the infrastructure for embedding NPOESS into existing operational programs needs to be defined and established along with the organizational structures for making that process work. As the actions required are very complex, participants suggested that agencies consider testing concepts in “real time” to gain experience and inform decisions on how the operational program should function. Important parts of such a process already exist and workshop participants thought they could be modified at modest cost to provide a basis for generating the capability to use NPOESS effectively for climate applications. In particular, workshop participants focused on the NPP as a key element in their suggested plans.

Workshop participants saw the NPP as an excellent vehicle to test more than the functioning of the satellite systems and their application to weather forecasting. Participants expected the NPP to provide hard information on the operational costs likely to be involved with NPOESS. In addition, they believed experience with the NPP would provide a basis for identifying the support required from the in-situ observing system, as well as the efforts required to transition that system into the NPOESS era. Finally, they expected the data stream from the NPP to provide the basis for designing an effective archival and retrieval system.

Another existing resource of interest to participants was the North American Atmospheric Observing System (NAOS).[2] NAOS is a cooperative program supported by governmental organizations and universities in Canada, Mexico, and the United States. Its purpose is to make recommendations on the configuration of the upper air observing program, in those three countries and adjacent water areas, that would meet societal needs in the coming few decades. The main thrusts are (1) a scientific evaluation program focused on, but not limited to, the value of various combinations of observing systems to numerical weather prediction, and (2) an assessment of the operational, financial, and organizational implications of configurations based on the results of the scientific evaluations.

NAOS supports network design and scientific studies of the impact of current observing systems, including the potential impact of future systems on the ability of the weather services to provide both weather and climate services. A fundamental concern of NAOS members is the mix of satellite and surface-based observations. This established activity provides a vehicle for building a consensus of the relative roles of satellites and other observations in the future observing system.

Organizational Issues

Any climate observing system will be based on a complex combination of elements that are often perceived to be in opposition. These include short-term, focused satellite missions versus long-term, continuous missions; research-driven measurements versus operation-driven measurements; systematic versus process studies; frequent technology insertion versus tried and true systems; "facility-class" instruments versus those developed in "principal investigator mode"; and in situ versus satellite remote sensing. All of these elements are needed because climate research requires both an understanding of complex, interrelated processes and systematic measurements to detect subtle changes in the Earth system.

Many workshop participants thought the present organizational structure within the federal government was not adequate to manage this complicated arsenal of observing systems in a coherent manner. Responsibilities cross agency boundaries, and many organizations are tasked with specific components without sufficient infrastructure or expertise to manage these components. There is no forum in which to balance the responsibilities or to set scientific or policy priorities. Thus, the present U.S. strategy for climate observations relies on a set of largely ad hoc agreements as well as on missions whose primary purpose is not climate research and monitoring.

NPOESS will be an enormous asset for observing Earth. Its stable orbit and commitment to the continuous observation of a broad range of climate-related geophysical variables are its most notable features from a climate research and monitoring perspective. However, NPOESS is organized primarily to deliver data products for use in short-term environmental prediction. Its mission does not include further exploitation of these products, although it is expected that they will be used by both civilian and military forecast systems. For NPOESS to realize its full potential for climate observation, agencies with different missions and cultures will need to work together effectively. Workshop participants were concerned about the adequacy of existing organizational structures to meet this challenge.

Participants at the workshop also detailed the functional requirements for an organization that would support a climate observing system:

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[2] Information about NAOS is available online at <http://is1715.nws.noaa.gov/naos/>.

- *Promoting the necessary insight into sensor characterization and performance.* This includes involvement in the development of the sensor and the prelaunch tests. The goal is not to direct these activities but rather to gain insight into the process. Additional testing might be suggested to enhance the suitability of the sensors in climate research.
- *Promoting access to sensor data, including operational data.* The climate research community requires easy, affordable access to low-level sensor data to develop long-term consistent data records, as well as new data products. In most cases, climate data sets will be based on specific processing algorithms rather than on the operational algorithms necessary to meet the NPOESS objectives. Metadata describing the sensor and its operational history are also required.
- *Promoting continuing data analysis and product validation.* Subtle errors in algorithms or sensors often appear only in long time series. A vigorous data analysis program is necessary to ensure the long-term viability of the data records. Moreover, data product validation means more than just comparisons with ground truth for algorithm tuning; it also involves continuing assessments of temporal and spatial errors in the data.
- *Supporting data reprocessing and long-term archiving.* Data should be reprocessed to ensure a consistent data record in light of improved knowledge of sensor performance, as well as improved understanding of the physics underlying the algorithms. To study decadal-scale trends requires that the data and metadata be preserved and made accessible far into the future.
- *Supporting the development of algorithms for climate data records (CDRs).* NPOESS will be delivering data products primarily for use in near-real time. However, CDRs will be based on extensive analysis as well as ancillary data that may not be available until long after the data are collected. Such algorithm development is an essential component of climate research to ensure that the data records remain viable for studies of long-term trends. This also includes aggregation of data in time and in space at scales that are not part of the EDR specifications. Such development requires long lead times, perhaps as long as 10 years.
- *Developing long-term data records suitable for climate research based on data from existing operational data streams, research missions, NPP, and NPOESS.* For many critical data sets, there exist multiyear to decadal-scale records from operational satellites such as POES and DMSP as research systems such as TOPEX/Poseidon, SeaWiFS, UARS, and EOS. Specific attention should be given to bridging between these data records and NPOESS (including the various pre-NPOESS missions such as NPP and Windsat).

Participants noted that the suggestions above would result in only a small percentage increase in the overall cost of NPOESS; however, they recognized that in absolute dollar terms the increase would be significant.

Workshop participants considered the creation of three organizational units they thought would assist the NPOESS program in meeting the needs of climate researchers: climate science teams, a climate research working group, and a joint steering council. These ideas would require further consideration if the NPOESS agencies decided to pursue them.

Climate Science Teams

NASA and NOAA would select climate science teams through a peer-reviewed, competitive process. They would provide support for these teams to develop selected CDRs based on NPOESS measurements (including the pre-NPOESS missions) rather than simply on specific sensors. The composition and focus of the teams would change over time as the satellite systems move from definition to launch to postlaunch. The teams would provide advice to NASA, NOAA, and the IPO on sensor characterization, data product validation, and algorithm development and would also conduct research. In the near term, attention would be paid to the transition from existing satellite-based data records to data from the new satellite systems. The teams would be formed soon after the contractors are selected for the NPOESS sensors to ensure that scientific insight is provided into the sensor development and testing process.

Climate Research Working Group

The working group would consist of representatives from each of the climate science teams as well as additional representatives from NASA, NOAA, and the IPO. The participation of still other scientists might be sought to ensure that all areas of climate research (especially modeling and interdisciplinary research) are represented. The working group would focus on broad issues of importance for all of the climate science teams (e.g., data systems and archiving) and would advise agencies on these issues, as well as in areas where there are competing demands for limited funds, such as the reprocessing of data sets, overlap strategies for operational missions, and the definition of requirements for system replenishment from a climate research perspective.

Issues to be studied might range from continuity of current research and operational missions to those that are still in the planning and development stage (such as NPOESS). The NPP could chart the way through the definition of agency responsibilities and relationships, the setting of priorities, and the development of an advice and decision-making process. The NPOESS total system performance requirements (TSPR) contractor would have to ensure that pre-NPOESS missions such as NPP and Windsat are a part of its activities.

Joint Steering Council

The joint steering council would be composed of agency managers and researchers from government and academia. It would define and evaluate the government's strategy for long-term observations for climate research and monitoring. Relying on various national and international assessments, the council would identify key uncertainties and develop priorities for the observing strategy necessary to reduce these uncertainties. The joint steering council would work closely with NAOS to ensure that its recommendations were compatible with operational plans. The council would report to NASA and NOAA, as well as to other USGCRP agencies. It would consider both the satellite and nonsatellite components of the observing systems.

Summary

Although there are significant technical challenges in developing a climate observing system, workshop participants thought that the organizational issues were the most difficult because of the (1) substantial cultural differences from one agency to another and even within the agencies, (2) complexities of a multiagency budget process, (3) balance of civil and military interests that must be achieved and maintained within NPOESS, and (4) need for climate research to balance resources to enable the continuation of long-term data sets (operational programs) versus embarking on new scientific paths or employing new observational techniques (research programs).

NASA and NOAA have both acknowledged these issues in letters (unpublished) to Neal Lane, the head of the Office of Science and Technology Policy. Workshop participants generally believed that interagency issues related to the roles and responsibilities for climate research would be resolved only with direction from higher levels within the executive branch. This belief was reinforced by the perception that agencies are already taxed in responding to changing budgets and programmatic directions.

Workshop participants stressed the importance of having the climate research community both in the government and in academia play an active role in the design, implementation, operation, and evolution of the climate observing strategy. Although missions such as NPOESS initially were focused on requirements other than climate, workshop participants believed that climate requirements could also be included without disrupting the primary mission requirements. In this regard, they believed that pre-NPOESS missions such as NPP could play an important role in addressing both the science and programmatic issues associated with the transition (or, more accurately, the integration) of research systems to operational missions.

Although NPOESS and its precursors are not ideal platforms for collecting every critical data set for climate research and monitoring, in many respects they are an adequate and, in some cases, a significant step in building a climate observing system. Stable orbit crossing times, data stability requirements (for some of the variables), and longer sensor/platform lifetimes are some of the NPOESS capabilities that represent a significant improvement from the present generation of operational satellite missions in terms of climate research needs. Workshop participants thought that an organizational structure that provided the necessary oversight and leadership should be able to meet the primary objective of the climate research community—developing viable data sets for research and monitoring.

Workshop participants thought the three agencies involved with NPOESS—NASA, DOD, and NOAA—could create the infrastructure needed to use NPP as a platform for designing, testing, and evaluating an end-to-end capability that would allow using the NPOESS data stream for climate applications. Participants acknowledged the likely need to fine-tune existing NPOESS requirements but did not believe substantive revisions would be necessary to achieve much enhanced utility to climate researchers. Indeed, most agreed that the emphasis should be on establishing appropriate organizational relationships and responsibilities, setting in place processes for determining priorities, creating and using scientific bases for making decisions, and developing a processing system attuned to climate needs and the generation of climate products.

SYNOPSIS OF DISCIPLINE GROUP DISCUSSIONS[3]

Report of the Atmospheres Discipline Group

General Issues

Following are summary comments of the atmospheres discipline group as compiled by its chair, Dennis Hartmann:

- The NPOESS program, if properly executed, has the potential to provide critical data for climate monitoring and research. It is perhaps the only program that can provide long time series of calibrated measurements for climate purposes.
- Every EDR to be used for climate purposes should specify stability in its definition. In the 1996 IORD (IPO, 1996), stability is included for many variables. In the recent update that the discipline group received from the IPO, long-term stability had too often been deleted. Accuracy and precision were sometimes replaced with a variable called uncertainty. The discussion of the specific EDRs below suggests stability requirements that are thought to be both useful and achievable.
- A data system is needed for taking the observations from the NPOESS data stream and putting them into an efficient, accessible, affordable archive and retrieval system that will allow for science investigations and reprocessing. This system should be capable of retaining the information necessary to reproduce the EDRs and to understand the calibration, validation, and processing. The required information is as follows:
  —The raw radiances (RDR),
  —Metadata on the NPOESS data,
  —All calibration algorithms and data,
  —The data processing algorithms, and
  —Validation and calibration data.
- A data validation plan is needed for each variable of importance.
- Overlap between each succeeding instrument in each orbit is critical. It would be best to have 1 year of overlap to adequately sample EDR differences through all the seasons, although during periods of high solar activity, it might be necessary to have 2 years for measurements of solar irradiance. Insufficient overlap will lead

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[3] Three discipline groups met during the course of the workshop to consider the particular data needs for climate researchers studying processes occurring within and among the atmosphere, the oceans, and land. Synopses of the discipline groups' views were prepared by their chairs for consideration by the Committee on Earth Studies. The committee is including these summaries in its report because they contain valuable ideas and suggestions. However, these summaries did not undergo the NRC review process; therefore, they should be interpreted only as the opinions of individual participants at the workshop.

to a loss of data continuity needed for measuring variability on time scales ranging from interannual (for instance, for ENSO monitoring and prediction) to decadal (for global change studies).

- The stable orbits (i.e., fixed altitude and fixed equator crossing time) will be of great benefit to climate monitoring and research.
- Active research programs intimately related to the data production process are needed, particularly programs that focus on topics that will lead to the discovery and documentation of systematic errors in the NPOESS data stream.
- A thorough, well-documented instrument characterization should be performed before launch and retained for later use by researchers.
- If it can be accomplished without compromising data quality, some NPOESS channels should overlap the channels from heritage instruments that NPOESS will replace, such as AVHRR, SSMI, and MSU. Such an overlap would be helpful in resolving continuity-of-data issues.

NPP General Issues

- A CERES-like instrument is needed on NPP to provide a continuous set of broadband Earth radiation budget measurements across the gap between EOS-PM and planned broadband measurements on NPOESS. The broadband measurement data set begins in 1978 with the Nimbus-7 ERB.
- There could be a gap between solar irradiance measurements from the the Solar Radiation and Climate Experiment (SORCE) mission and the NPOESS mission. SORCE is scheduled for 2002 to 2007 and NPOESS from 2009 onward. A total solar irradiance (TSI) data set has been continued since 1978 through a strategy of overlapping measurements and multiple redundant instruments in orbit at one time. Solar irradiance is a central climate forcing parameter, and it needs to be monitored precisely for climate detection and attribution purposes. Solar irradiance needs to be measured in the NPP/NPOESS time frame, which might be accomplished on an independent small satellite.
- From the perspective of atmospheric measurements for weather prediction and climate, it would be better for a number of reasons if the NPP were in a 1330 local time orbit rather than a 1030 orbit:[4]

—NPP will provide a new, more capable interferometer sounding instrument. For sampling longitude and the diurnal cycle, it would be better to have the 0930 METOP interferometer and a 1330 NPP interferometer rather than a 0930 and 1030 configuration.

—In a 1330 orbit the NPP instruments would measure at the same local time and within 45 minutes of the heritage instruments on POES and EOS-PM and would also overlap the first NPOESS 1330 orbiter, providing a link between NPOESS and its predecessor instruments. This would allow NPP to provide inter-instrument calibration for the infrared sounders HIRS → AIRS → CrIS and the microwave sounders MSU → AMSU → ATMS, AVHRR → MODIS → VIIRS and also tie together broadband radiation measurements that may be taken from EOS-PM, NPP, and NPOESS. The POES and EOS instruments will not be available in a morning orbit at the time NPP is planned to be in orbit (2006 to 2011).

Environmental Data Records

The EDRs to be provided by NPOESS could be extremely important for climate monitoring and research. Because its operational missions require it to be up and operating continuously, NPOESS is particularly important for data continuity. The stable orbits are good for climate monitoring, and the three-satellite system gives adequate diurnal sampling of key variables.

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[4] The land-surface community would use the relatively low resolution global data from VIIRS to extend high-resolution data from other sources. They prefer the morning because cloud coverage over land is less in the morning than in the afternoon. Perhaps the planned Japanese instrument Global Imager might be used for this purpose.

The discipline group had three specification documents available for its use in making suggestions for changes in the specifications of the EDRs: the original 1996 IORD (IPO, 1996), the draft IORD-IA, which is available on the World Wide Web, and the Climate Measurements Workshop report from 1995 (NOAA, 1997). The discipline group worked mostly from the draft IORD but found that all three documents had errors and omissions of various kinds. Some key climate variables in the IORD document did not appear in the IPO draft document (e.g., cloud ice and broadband radiation budget quantities). Below, the discipline group provides a list of potential changes to the IPO draft or IORD documents, along with a brief justification for each change. The list is given in the order that appeared in the IPO draft document obtained from the Web. Also included are some atmospheric climate EDRs omitted from that list.

The EDRs are specified for instantaneous measurements at the finest scale of observation, but, for climate purposes, accuracy, precision, and stability requirements are often better specified for averages over space and time. The discipline group tried to extrapolate to the instantaneous observation scale used in the draft IORD, but there is a need for a data analysis system to convert the data to space and time averages for use in many climate investigations.

Definitions

Long-term stability: The mean calibrated and retrieved value for the EDR derived from a uniform and unchanging scene should not vary more than the specified amount during the lifetime of a mission (nominally 7 years). This could also be interpreted as an upper limit on the temporal change of the difference between the true and the observed value after random errors are removed by averaging.

K40.2.1 Atmospheric Vertical Moisture Profiles

Add a long-term stability requirement for mixing ratio (g/kg) of 2 percent over the life of a mission (nominally 7 years).

Justification: Water vapor is the most important greenhouse gas and is involved in the most important climate feedback processes. Latent heat of condensation provides the energy for tropical storms. Humidity needs to be accurately measured over long periods of time. A change in humidity of 2 percent can have an effect on the energy balance of Earth comparable to that associated with carbon dioxide changes expected in the future.

K40.2.2 Atmospheric Temperature Profiles

The 1 K over 1 km altitude uncertainty requirement is very important and will be a significant improvement for weather forecasting and climate.

Add a long-term stability requirement of $< \pm 0.05$ K/decade in the troposphere, and $< \pm 0.1$ K/decade in the stratosphere.

Justification: These stability requirements are necessary for purposes of detecting climate trends. Note, too, that the requirement to directly measure long-term trends in temperature from satellites implies similar demands on the lifetime of NPOESS instruments. This may or may not be feasible but would be a desirable objective.

V40.2.3.2 Cloud Cover

Add a long-term stability requirement of 2 percent of the average cloud fraction, or about 0.01.

Justification: This would allow changes in the effect of clouds on the energy balance of Earth to be measured to an accuracy of about 1 Wm^{-2}, assuming a mean cloud albedo of 40 percent. Clouds have a large direct effect on the radiation balance of Earth and could be important in determining the amplitude of future climate changes.

V40.4.1 Cloud Base Height

Data from future missions using radar and lidar should help with this important variable. Inferences of cloud base height from microwave or other passive measurements involve a large amount of modeling and, therefore, are of limited use for climate monitoring or climate model validation.

V40.4.3 Cloud Effective Particle Size

Meets climate requirements; the 2 percent stability requirement is good.

V40.4.6 Cloud Optical Depth

The range should be at least 0 to 50, not 0 to 10. The variation from 10 to 50 is observable and important.

Add a long-term stability requirement of 2 percent.

Justification: Cloud optical depth is an important climate forcing parameter, and stable long-term measurements of it are needed.

V40.4.7 Cloud Top Height

Satisfies important climate requirements.

V40.4.8 Cloud Top Pressure

Satisfies important climate requirements.

V40.4.9 Cloud Top Temperature

Satisfies important climate requirements.

4.1.6.4.3 Cloud Ice Water Path

The EDR described in the IORD satisfies important climate requirements.

C40.3.4 Precipitation

Change range to 0 to 75 mm/h rather than 0-50 mm/h.

Add a stability requirement of the greater of 0.5 mm/h or 2 percent.

Change the accuracy to threshold: 2 mm/h or 10 percent; objective: 1 mm/h or 5 percent.

Change the precision to threshold: 1 mm/h or 5 percent; objective: 0.5 mm/h or 2 percent.

Justification: Precipitation is a critical constraint on the hydrological and energy budgets of Earth and it needs to be known to these levels of precision, accuracy, and stability. A precipitation rate of 0.5 mm/h corresponds to a latent heat release rate of 350 Wm^{-2}.

4.1.6.3.5 Cloud Liquid Water

In the IORD the accuracy specifications are too large, and land and ocean are reversed. The table in the NPOESS climate workshop report (NOAA, 1997) is good.

Change the accuracy to the greater of 0.025 mm or 10 percent over ocean; greater of 0.05 mm or 20 percent over land.

Add a stability requirement of 2 percent.

SRD3.2.1.1 Stratospheric Ozone

The EDR described in the IPO draft satisfies important climate requirements.

Tropospheric ozone is extremely important for health and climate. The discipline group suggests that a precision requirement of 10 percent be added.

V40.3.1 Stratospheric Aerosols

This category should be relabeled “Total Aerosol Burden.” Since it is derived from VIIRS, it will likely be dominated by tropospheric aerosols in most cases, but it will be difficult to distinguish tropospheric and stratospheric aerosols from solar reflection measurements.

For measurement accuracy over land, the discipline group recommends changing the formula given in row V40.3.1.1-12 to a straight 0.2. This should be more realistic and easier to achieve.

V40.3.1.2 Aerosol Size

The EDR described in the IPO draft satisfies important climate requirements.

The requirements should be relaxed over land, where the measurement is more difficult.

4.1.6.4.1 Albedo Surface Visible

The product is useful, but for climate purposes a broadband albedo would also be useful.

4.1.6.4.2. Downward Longwave Radiation at the Surface

The precision and accuracy thresholds should be relaxed to 10 Wm^{-2} and 15 Wm^{-2}, respectively; the discipline group believes that values given in the IORD are unachievable.

4.1.6.4.3. Downward Shortwave Radiation at the Surface

The precision and accuracy thresholds should be relaxed to 10 Wm^{-2}. This is a modeled parameter and cannot be measured directly from space.

4.1.6.4.6 Outgoing Longwave Radiation

Thresholds for broadband measurements should be precision, 5 Wm^{-2}; accuracy, 2 Wm^{-2}; and stability, 1 Wm^{-2}.

Justification: These are useful levels and are what the CERES team says it can produce.

4.1.6.4.6 Absorbed Solar Radiation

Since these are given as instantaneous measurements within a range of 0 to 1400 Wm^{-2}, the limits should be given in percentages.

Thresholds for broadband measurements should be precision, 5 percent; accuracy, 1 percent; and stability 0.5 percent.

Justification: These are useful levels and are what the CERES team says it can produce.

4.1.6.4.5 Solar Irradiance

Solar irradiance is the radiated power incident on a radiometer aperture whose surface is orthogonal to the radiometer's optical axis, which is aligned to the line of sight to the Sun from the aperture's center. The total irradiance (i.e., the integral over all wavelengths) and the spectral irradiance from 0.2 to 2 µm are to be reported. This EDR supports monitoring of the total and spectral irradiance for determining solar influences on global change. These influences involve the entire radiation spectrum via varying mechanisms and are known to have strong wavelength dependencies.

Solar variability can influence global surface temperatures directly because the visible and infrared radiation (longward of 0.3 µm) that constitutes the bulk of the total irradiance penetrates to Earth's lower atmosphere and heats the surface, atmosphere, and upper ocean layers. Proper attribution of climate change thus requires reliable characterization of direct solar forcing by solar visible and near-infrared radiation. Variations in solar ultraviolet irradiance in the 0.2 to 0.3 µm range, which is absorbed by ozone in Earth's atmosphere, is necessary to assess long-term ozone variations and for reliable detection of ozone depletion and recovery. As well, the measured total irradiance variability must be adjusted to account for variability of this radiation, which varies by an order of magnitude more than does the visible spectrum but does not reach Earth's surface. Because of this, monitoring the ultraviolet spectral interval (0.2 to 0.3 µm) is a high priority for spectral irradiance monitoring.

Also of high priority is monitoring the near-infrared band centered near 1.6 microns. This radiation emerges from the deepest layers of the Sun's atmosphere, is thought to be the least variable part of the spectrum, and provides a measure of sunspot modulation of irradiance for interpreting the solar irradiance measurements. The Total Solar Irradiance Monitor is the sensor for this EDR (Table B.1).

TABLE B.1 Solar Irradiance

Systems Capability	Threshold	Objective
Measurement range		
Total	1310-1420 Wm^{-2}	1310-1420 Wm^{-2}
Spectral (0.2-2 µm, bandpass 2-20 nm)	0-100 Wm^{-2}	0-100 Wm^{-2}
Measurement precision		
Total	0.002% (20 ppm)	0.001% (10 ppm)
Spectral (0.2-2 µm)	0.02%	0.01%
Measurement Accuracy		
Total	1.5 Wm^{-2} (0.1%)	0.15 Wm^{-2} (0.01%)
Spectral (0.2-2 µm)	1%	0.1%
Refresh	20 min stare, each orbit 2 satellites	50 min stare, each orbit 3 satellites
Long-term stability		
Total	0.002%/yr (20 ppm/yr)	0.0005%/yr (5 ppm/yr)
Spectral (0.2-2 µm)	0.02%/yr	0.01%/yr

Report of the Ocean Discipline Group

Following are summary comments by the ocean discipline group as compiled by its chair, Frank Wentz.

Data System

Archive

All of the RDRs should be placed in a long-term archive with sufficient metadata so that future investigators can fully understand the characteristics of the data sets. The archive should be easily accessible at no cost (or minimal cost) for scientific research. Basic archival features, such as data subsetting, should be implemented.

Climate Data System

The requirements for high-quality research and climate products differ greatly from those for operational data products. Climate-specific algorithms may require ancillary data not available in real time. Furthermore, algorithm evolution and satellite intercalibation require continual reprocessing and refinement. Accordingly, a data system designed specifically for producing climate data records (CDRs) needs to be developed. In designing this data system, the NASA ESSIPs model should be considered as one possible prototype.

Integrated Data Processing System

The integrated data processing system (IDPS) for NPOESS should be sized so that it has the processing power to handle data from nonoperational spacecraft that may still have functioning sensors providing valuable data. These nonoperational data should not be discarded, but should be processed to RDRs for archiving. In this case, the IDPS only needs to produce the RDRs.

Science Teams

The NPOESS data products will be of a considerable benefit to the research and climate communities. To fully realize the benefit of these observations, science teams need to be formed. These teams will have responsibility for producing the CDRs, calibration and validation, and subsequent research. They should be selected via an open competition with peer review, similar to that associated with a NASA research announcement.

Calibration and Validation

Prelaunch

There should be more scientific involvement in the prelaunch calibration and characterization of the NPOESS sensors. Oversight by the science teams of these critical measurements (antenna pattern and thermal-vacuum) will benefit both the NPOESS program and the research community. All engineering data from these prelaunch tests should be archived for future reference.

Postlaunch Calibration

Discussions should be held with the IPO about the possibility of doing on-orbit maneuvers so that the sensors can be calibrated to cold space and to the Moon. The stability of the Moon's emissivity may allow calibration of out-instrument drift, thereby providing reliable long-term trends on climate variability. On the other hand, calibration maneuvers may negatively affect orbit stability, and their impact with respect to ocean altimetry measurements should be studied. The science teams should be responsible for intersatellite calibration after launch.

TABLE B.2 Stability Requirements for Climate Data Records

Parameter	Trend Accuracy	Spatial Resolution (km)	Intersatellite Overlap (yr)
Sea surface temperature	0.1 °C/decade	100	1
Ocean color (443 nm)	0.5 $mW/cm^2 sr\ \mu m$/decade	100	1
Ocean color (555 nm)	0.25 $mW/cm^2 sr\ \mu m$/decade	100	1
Ocean color (865 nm)	0.08 $mW/cm^2 sr\ \mu m$/decade	100	1
Ocean topography	5 mm/decade	100	See altimetry
Ocean wind speed	0.5 m/s/decade	50	1
Ocean wind stress curl	10^{-9} N/m^3/decade	50	1
Sea ice concentration	1%/decade	50	1

Stability Requirements for Climate Data Records

Table B.2 gives the stability requirements for CDRs. The trend accuracy refers to the slope of a least-squares regression to the particular CDR over a long time baseline (> 5 years) at the specified spatial resolution. The intersatellite overlap is the minimum overlap time between successive satellites required to remove intersatellite biases.

Altimetry

The NPOESS Sun-synchronous orbit presents serious problems for doing climate research with altimetry. The fixed local time for the equator crossings will alias the tidal signal into the time series. Perhaps more serious, the NPOESS ground track is not the same as the TOPEX/Jason ground track, effectively breaking the 20-year time series for sea-level height. In addition, it is not clear if the NPOESS altimeter will meet the climate requirements of 3 cm radial orbit accuracy with a 1 km repeat cycle. For these reasons, the option of flying the altimeter for NPOESS on a separate, dedicated spacecraft, following the TOPEX/Jason ground track, should remain open until these technical and tidal aliasing issues are settled. Also, NASA should continue to sponsor technology development for the altimeter, as well as the work of the science teams.

The requirement for an overlap between successive satellites is of particular concern for the altimeter. The Jason-2 mission will end in 2010, and the first NPOESS altimeter is not scheduled until 2011. In the discipline group's view, a disconnect at 2010 would have devastating consequences for the long-term monitoring of sea-level variability. Furthermore, if the NPOESS altimeter does not repeat the TOPEX/Jason ground track, then a 3 to 5 year overlap would be required to intercalibrate the two altimeters. An overlap of only 0.5 years would be required if the NPOESS altimeter has the same ground track as TOPEX/Jason. In the discipline group's view, these serious questions on the continuity of the altimeter climate mission need to be addressed jointly by NASA and the NPOESS IPO.

Advantages of the NPOESS Preparatory Project (NPP) and NPOESS

Continuity of Data Sets

Many critical ocean data records that were begun as research missions will be continued with NPP and NPOESS. This includes phytoplankton chlorophyll (started with SeaWiFS and MODIS and to be continued with VIIRS on NPP) and combined microwave/infrared measurements of SST (begun on TRMM and to be continued with CMIS and VIIRS on NPOESS). These geophysical variables are characterized by low-frequency variability; multiyear gaps, which would likely occur if NPP and NPOESS were not to fly, would greatly inhibit the ability to study these climate-related processes.

Improved Sensors

CMIS is likely to be a significant improvement over the present operational passive microwave radiometer, SSM/I, which is on board the DMSP series. With its additional frequencies and improved sensor performance, CMIS will probably provide higher-quality data products. Similarly, VIIRS will likely have better capabilities than the AVHRR. However, all of these improvements are based on the discipline group's assessment of the EDRs derived from these sensors. Until the details of the sensor designs are known, it will not be possible to make definitive statements.

Equator Crossing Time

Both the NPOESS and NPP platforms will maintain a constant equator crossing time. This capability greatly simplifies sensor calibration and improves long-term data continuity. The present generation of POES satellites does not maintain crossing times, and the orbits drift over the life of the platform such that missions that began with morning crossing times eventually have afternoon crossing times. Many apparent long-term trends in geophysical data sets derived from the POES sensors can be attributed to orbit drift.

Colocation of Sensors

Simultaneity has sometimes been used to justify the need for large platforms, such as the early plan for the Earth Observing System. However, except for rapidly changing phenomena such as clouds, there are few requirements for strict simultaneity of observations. Climate research does require contemporaneous observations, and because the processes and trends are often subtle, the combination of different measurement approaches to observe the same geophysical variable is advantageous. For example, the combination of passive microwave and infrared measurements improves SST retrievals. Moreover, climate research often focuses on the coupling of Earth system components. Thus, measurements of winds, SST, and ocean color are essential for understanding ocean productivity and its relationship to ocean mixing.

The facility approach of NPP (and eventually NPOESS) to platform configuration means that many critical sensors will be in orbit at the same time. This not only simplifies program and platform management, but also ensures that critical data sets will be collected together to study coupled Earth system processes.

Early Test of Programmatic Relationships

NPOESS will eventually become an important element of the climate observing system. However, there is much to be done to define the roles and responsibilities of the various agencies if the integration of operational and research missions is to be successful. NPP can serve as a testbed for these activities, as attempts are made to develop climate-quality data products in an operational setting. This goal will require coordination among multiple agencies, and NPP could provide an early test.

In addition to its observing elements, NPP should also serve as a testbed for ground data processing, archiving, and distribution. While the focus of the IPO is on an early test of the ground system capabilities necessary to meet its primary mission of short-term forecasting, NASA and NOAA should use NPP to develop methods to integrate climate science requirements into the ground system. This may mean the development of a parallel system that branches off from the main IPO system, which is focused on short-term forecasts.

Report of the Land Discipline Group

Following are summary comments of the land discipline group as compiled by its chair, Chris Justice.

The NPOESS Preparatory Project mission is an important step forward in the transition from satellite missions whose primary purpose is scientific research on the evolution of Earth processes and the climate system and missions whose primary purpose is to monitor parameters necessary for short-term numerical weather prediction.

The NPP should provide both scientifically interesting and useful data sets, as well as a base of experience for the operation of NPOESS that will serve to reduce risk in the final NPOESS configuration.

Like NOAA and DOD, NASA has an important role to play in this transition, particularly in the identification and provision of systematic measurements for understanding the state and dynamics of climate. The three agencies, but perhaps especially NASA, need to create a management philosophy that is robust in the face of the inevitable peregrinations of their individual budgets, that can balance the sometimes competing demands of operational and climate users, and that can deliver and operate a series of missions that address long-term scientific needs without compromising the primary operational needs. NPP is the first mission in which these management philosophies, as well as the instruments and spacecraft themselves, can be tested.

The VIIRS instrument will be the culmination of the sequence, AVHRR→MODIS→VIIRS (NPP)→VIIRS (NPOESS). These multispectral instruments have the general characteristics of relatively coarse spatial resolution, broad swath widths, and relatively fine temporal resolution. Careful calibration and periods of overlap of these instruments will be required for climate science. Measurements with these characteristics have been identified several times, most recently by the NASA science community in the Easton process,[5] as crucial for understanding biological productivity and its underlying processes on both land and ocean. However, two other types of measurements have also been consistently identified as either crucial or important for terrestrial processes: a Landsat-class imager (but not an Enhanced Thematic Mapper (ETM+)), and a hyperspatial resolution sampler. The latter instrument, which has the potential to be important scientifically, clearly is being pursued by commercial vendors, but the former, while scientifically critical, does not appear for consideration in the NPOESS suite of instruments. These issues are examined in more detail below.

Landsat and Instrument Synergies

The Landsat class of polar-orbiting multispectral measurements is crucial for climate and global change research, especially that part related to the carbon budget, land-use change, and ecosystem impacts. Many of the changes in land cover occur on spatial scales that are small relative to the coarse pixel sizes of AVHRR, MODIS, and VIIRS, and, while those instruments should be able to identify where areas of rapid change are taking place, only Landsat-class imagers will be able to quantify the changes. These changes are important for climate: approximately 20 percent of the net addition of carbon to the atmosphere comes from land-use change, particularly deforestation in the tropics, and the putative "missing sink" is thought to be in part a land-use issue as well.

The discipline group found strong arguments for making Landsat-class measurements more nearly operational. There exists a good data record dating back to 1972, and there is increasing awareness of the importance of capturing interannual variability in land-cover changes. Such an instrument could logically be included in the NPOESS suite for providing systematic environmental measurements. No agency has made a long-term commitment to providing Landsat-class measurements since Landsat-7 (however, NASA has identified the Landsat measurement as a high priority). The discipline group noted with interest the potential to fly "instruments of opportunity" on NPP and NPOESS utilizing spacecraft volume, weight, and power margins. From a terrestrial science perspective, this may be an opportunity to fly a lightweight, multispectral resolution imager with spatial resolution of about 30 m, that is, a Landsat-class imager. Colocation of a Landsat-class instrument with a moderate resolution imager like VIRRS is scientifically desirable but not crucial.

Orbit Crossing Time

AVHRR has flown in both 0730 and 1430 orbits. The land data record (1981 to the present) uses the 1430 overpass time based on availability of the data, rather than on what was scientifically optimal for the measurements themselves. The 1430 overpass will continue through NPOESS C1.

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[5] The Easton process refers to NASA's post-2002 mission planning exercise, which culminated in an August 1998 meeting at Easton, Maryland. A link to the full report from the Easton Workshop is available online at <http://eospso.gsfc.nasa.gov/eos_homepage/misc_html/intro_kennel.html>.

MODIS is slated to fly in both 1030 orbits on EOS-AM-1 (Terra) and a 1330 orbit on EOS-PM (Aqua). The land research community prefers the earlier crossing time for reduced cloud cover and more usable data sets. NPP is currently carrying a nominal 1030 crossing time, which would be very good for the land community interested in VIIRS. However, the NPOESS VIIRS is slated for 0530 and 1330 crossing times, neither of which is optimal for terrestrial observations. While METOP is slated for the 0930 crossing time in the final configuration, clarification is needed on its instrument capability. At the time of the workshop (July 1999), the discipline group understood that METOP would not have a VIIRS but would carry an AVHRR or similar instrument until 2018. Because the AVHRR is a much less capable instrument for terrestrial observations than the VIIRS is designed to be, this would clearly be a problem for the land community.

Environmental Data Records

There is an urgent need for the climate science community to evaluate the actual instrument specifications and proposed design. This need arises because the environmental data records for the VIIRS, as they are presented now, do not allow an understanding of the quality of the actual measurements. Needed for a more complete scientific understanding are comprehensive specifications for radiances (brightness temperatures). In addition, there need to be strict specifications for geolocation and band-to-band registration and for long-term stability of the measurements.

While the discipline group recognizes that the 500 m spatial resolution threshold for land products is an improvement over earlier versions of the VIIRS documentation, the discipline group would have preferred a 250 m spatial resolution threshold and a specification for repeat cycle that nominally provides daily coverage of Earth at 1 km resolution or better.

With respect to particular EDRs, the discipline group emphasizes that the fire detection capability that is part of the MODIS suite of measurements is necessary for climate science and should be part of the VIIRS suite. Improvements are needed for the proposed vegetation index and land-cover specifications from the standpoint of climate science and the long-term scientific record.

While it is clear that the climate science community will want to make use of the operational EDRs to the maximum extent possible, other land products are also needed. Among these are leaf area index, albedo, percent green vegetation, and percent tree cover. These are unlikely to be of immediate operational use in the NPP time frame but are considered essential scientifically by the land discipline group.

The IPO organizes EDRs by instrument. The discipline group found that this organization made it difficult to ascertain whether there are significant gaps or overlaps (from the standpoint of climate science) within the current complement of instruments. The discipline group suggests that NASA and NOAA examine the EDRs by cross-cutting scientific issues (e.g. carbon cycle, land-atmosphere interactions, clouds, aerosols, and radiation) to ensure that there are no major inconsistencies.

Calibration and Characterization

One of the thorniest problems inherent in the NPOESS mission is the degree of instrument characterization and calibration that will be required for climate science. The discipline group recognizes that a fair degree of instrument characterization and calibration will be done, but what is required is a full plan for each activity from the standpoint of the needs for long-term data sets required for climate science.

For example, discipline group members thought it essential that there be stability specifications for radiances from VIIRS. It would be very desirable to obtain periodically a lunar view or deep-space view for calibration purposes, and it was unclear from the briefings and available material whether this is in the plans for NPP and ultimately for NPOESS. A calibration plan should include the means of doing on-board calibration utilizing a solar diffuser and vicarious calibration through ground programs and field campaigns. Geolocation and post-launch geolocation validation are critical elements. A science team could provide valuable advice to NASA, NOAA, and the IPO on these elements.

Instrument characterization is equally important. The experience with the ETM+ on Landsat-7 and with MODIS on the NASA Terra mission is that the full participation of a science team in instrument characterization is crucial for ensuring that the measurements ultimately derived are maximally useful for scientific purposes. With respect to VIIRS, the land discipline group stresses the importance of allowing sufficient time to correct problems that may be identified after the analysis and interpretation of test results.

Climate Data System

The land discipline group finds the data system envisioned by the IPO deficient in several respects in terms of providing the services needed for climate science. In particular, the discipline group believes that the lack of plans for a long-term archive or the capability to reprocess data as algorithms mature would impede the ability of NPP or NPOESS to serve the needs of climate science. Discussions focused on a separate data stream for climate products that would be linked closely to a science team responsible for analysis. Such a data stream would originate at level 1a/1b of the existing data stream, so it would be necessary for these data to be of climate quality.

In addition to the land surface measurements themselves, the climate data stream would need to be combined with comprehensive data on the instrument itself in order for anomalies due to variations in instrument and spacecraft characteristics to be identified. The discipline group believes that the design for such a data system should be initiated as soon as possible and involve both NASA and NOAA at a minimum. The discipline group does not envision a data system as ambitious as that originally designed for EOS and believes that design of the data system would benefit from study of earlier experiences with EOSDIS and the Earth System Science Information Partnerships, as well as from study of the planned NewDIS.

Validation

Validation of data products is as important to the climate science community as the calibration of the VIIRS instrument itself. There is an enormous opportunity for NPP/VIIRS to build on existing EOS validation activities and also on activities that are under way elsewhere in NASA, NOAA, and DOD. In addition, the calibration/validation working group of the Committee on Earth Observation Satellites (CEOS)[6] provides a crucial forum for international cooperation. The discipline group notes that part of the reason that cooperation on validation activities is so important is that they can be, and arguably should be, a large budget item. The discipline group suggests that opportunities to leverage both government and private-sector efforts be investigated to support validation efforts for NPP/VIIRS.

Need for a Climate Science Team

In the discipline group's view, the development of VIIRS would clearly benefit from having a science team. Such a team could stand alone or be part of an overall science team for the NPP mission. Roles for the science team include the following:

- Providing guidance for instrument characterization and calibration efforts;
- Providing a climate science review of level 1 data;
- Assessing the EDRs for climate use and suggesting improvements;
- Providing algorithms for additional products that are necessary for climate;
- Undertaking climate product validation; and
- Assisting in the planning and implementation of the climate data system.

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[6] CEOS was created in 1984 as a result of the international Economic Summit of Industrialized Nations and serves as the focal point for international coordination of space-related Earth observation activities. Information about CEOS is available online at <http://www2.ncdc.noaa.gov/CEOS/ceospg1.html>.

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C

Solar Reflection Region Measurements

This appendix presents a potentially new data processing and calibration paradigm for solar reflection measurements. Since the paradigm is a departure from the traditional calibration methodology based on radiance, this discussion of it is somewhat tutorial. A calibration of reflectance involves measurement of the incoming and the outgoing radiation and then calculating the ratio (Hsia and Weidner, 1981). For a diffusely reflecting material (radiation scatter), the incident radiation is in units of irradiance (radiant power per area, within a specified spectral band) and the outgoing radiation is in units of radiance (radiant power per area per solid angle, within the same band). Reflectance is a relative, not absolute, calibration since it is the ratio of the radiance to the irradiance. The units of radiant power and area cancel out. The units of bidirectional reflectance are 1/steradians and therefore are not traceable to any of the seven fundamental units of measurement. Calibrations of reflectance are much simpler to perform than calibrations of absolute spectral radiance. Reflectance-based calibrations could provide considerable savings in cost and instrument complexity over present methods. A sensor on orbit does not measure a radiant source but a reflector of the radiant energy from the Sun. This is illustrated in Figure C.1. The reflectance of a diffuser depends upon the directions of the incident and the exiting radiation and is usually called bidirectional reflectance. A complete set of measurements over all directions of incoming and outgoing radiation is called the bidirectional reflectance distribution function. Since, for most remote sensing instruments, reflectance measurements will be made over a limited set of incoming and outgoing angles, a full distribution function calibration is not necessary.

For a remote sensing instrument operating in the solar reflective spectral region, the radiation incident at the aperture is the product of the bidirectional reflectance of Earth (surface plus atmosphere), $\rho_E(\lambda, \theta, \phi)$, times the solar irradiance, $E_S(\lambda, \theta)$. The incident angle is θ and the view angle is represented by ϕ. (Out of plane, bidirectional reflectance is covered by these same arguments.) For the i^{th} channel that has a relative spectral response $r_i(\lambda)$, the sensor output, DN_i, is the calibration factor, K_i, times the integration over the wavelength:

$$DN_i = K_i \int \rho_E(\lambda, \theta, \phi) E_S(\lambda) \cos(\theta) r_i(\lambda) d\lambda.$$

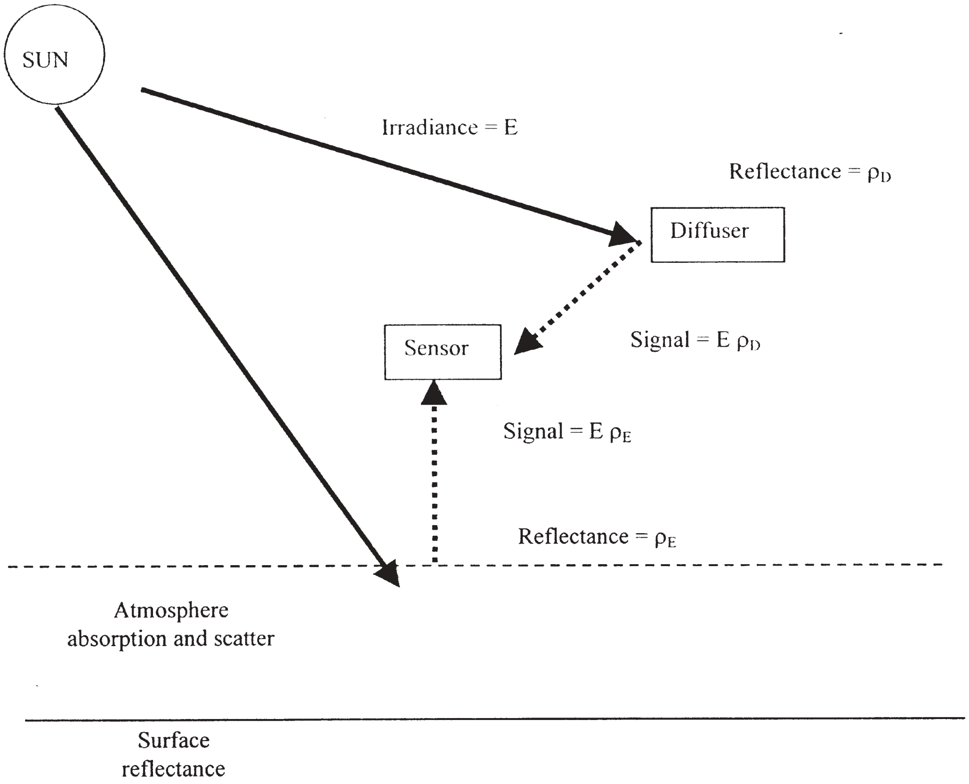

FIGURE C.1 Calibration shown in terms of the reflectance of an on-board diffuser.

For sensors that have an on-board diffuser, such as SeaWiFS and MODIS, the sensor output when viewing the diffuser would be

$$DN_{i,c} = K_i \int \rho_D(\lambda, \theta_c, \phi_c) E_S(\lambda) \cos(\theta_c) r_i(\lambda) d\lambda.$$

Taking the ratio of these two equations yields the following equation,

$$\frac{\int \rho_E(\lambda, \theta, \phi) e_{S,i}(\lambda) r_i(\lambda) d\lambda}{\int e_{S,i}(\lambda) r_i(\lambda) d\lambda} = \frac{DN_i \cos(\theta_c) \rho_D(\lambda_i, \theta_c, \phi_c)}{DN_{i,c} \cos(\theta)}.$$

Here we have normalized the solar spectral irradiance function at the wavelength λ_i,

$$e_{S,i}(\lambda) = \frac{E_S(\lambda)}{E_S(\lambda_i)}.$$

This shows explicitly the independence of Earth reflectance on the absolute value of the solar spectral irradiance. The bidirectional reflectance of the diffuser is nearly spectrally flat. In almost all cases it can be assumed constant within the bandwidth of the channel and equal to its value at λ_i. The bidirectional reflectance of Earth is the combined effect of the atmosphere transmission and scattering, and the bidirectional reflectance of the surface. If these functions are constant over the bandwidth of the channel, then the bidirectional reflectance of Earth is

$$\rho_E(\lambda,\theta,\phi) = \frac{DN_i \cos(\phi_c)\rho_D(\lambda_i,\theta_c,\phi_c)}{DN_{i,c}\cos(\theta)}$$

One is still left with the problem of extracting the surface reflectance term from the overall reflectance, that is, separating the surface reflectance from the effects of the atmosphere. Characterization of the atmosphere and the problem of solving for the surface reflectance will remain the objective of much research. However, what has been gained is a result that is independent of the absolute value of the solar irradiance and a calibration accomplished simply in terms of the bidirectional reflectance of an on-board diffuser. Many of the existing models of atmospheric effects and surface reflectance may require as input the value of the radiance at the top of the atmosphere. For these cases one simply needs to multiply the combined absorption, scattering, and reflectance operator, $\rho_E(\lambda_i)$, by the values of solar irradiance to obtain absolute radiance (Gordon, 1981; Kaufmann, 1989).

Recall that bidirectional reflectance is a relative, not an absolute, calibration and as such does not require traceability to an SI unit. Gordon (1981, p. 209) in the case of the Coastal Zone Color Scanner recognized this conclusion. At that time he did not pursue this line of reasoning. Perhaps he did not see a way to guarantee the stability of the diffuser. Recent developments, however, have overcome this difficulty.

The assumption of constancy over the bandwidth of most channels is certainly true for molecular and aerosol scattering. It is usually true as well as for the surface reflectance, since the bandwidth of the channels is normally selected to satisfy this condition. However, absorption of the atmosphere's molecular constituents results in sharp spectral features and, if occurring within a band, will not satisfy the constant-value assumption; see, for example, band 7 of SeaWiFS (Mueller et al., 1995, Chapter 2). In this case the equation becomes more difficult to solve. However, effective use can be made of the fact that the relative solar irradiance function appears in both the numerator and denominator. Also, the surface reflectance and atmospheric scattering functions can be made to appear as multiplicative operators within the integral. Both considerations should lead to a simplification of the problem. The lesson to be learned here is to select bandwidths that avoid the atmosphere absorption features, if at all possible, for bands used to measure surface or low-cloud features.

Another simplification that accrues from using a reflectance-based calibration is that bandwidth and wavelength stability on orbit become less critical. One of the major problems in this regard is due to the highly structured solar spectrum. If the bandwidth of a channel includes a Fraunhofer line or is very close to one, then shifts in the band wavelength or shape could significantly affect the calibration of that channel (Flittner and Slater, 1991). A portion of the problem arises from the fact that the laboratory calibration uses an artificial light source, an incandescent lamp, whose spectral output is radically different from that of the Sun. Since incandescent sources would not be required in a reflectance calibration, spectral band inaccuracy and instability should be less of a problem.

It should be noted that there is one data product in the solar reflective region that relies on an absolute radiance calibration, the measurement of chlorophyll fluorescence. Chlorophyll is a reflective measurement (the backscatter of sunlight from phytoplankton after absorption by chlorophyll), whereas fluorescence is emitted by phytoplankton (Letelier and Abbott, 1996). In this case once the reflectance of the surface has been determined and multiplication by the atmosphere corrected, absolute solar irradiance will yield the absolute radiance.

Backscattered microwave radiation is also a reflectance measurement; however, the calibration methodology described above does not carry over into the microwave region simply because the radiation source is not the Sun but rather a microwave source aboard the satellite.

The committee believes that NASA should evaluate the merits of this possible new approach.

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D

Acronyms and Abbreviations

ACRIM	Active Cavity Radiometer Irradiance Monitor
ADEOS	Advanced Earth Observing Satellite
AMSU	Advanced Microwave Sounding Unit
ATD	advanced technology development
ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
BigFoot	A NASA Earth Observing System mapping project
CDR	climate data record
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and the Earth's Radiation Energy System
CES	Committee on Earth Studies
CGPM	Conférence Générale des Poids et Mesures
CMIS	Conical Scanning Microwave Imager/Sounder
CrIS	Cross-track Infrared Sounder
DAAC	distributed active archive center
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
EDR	environmental data record
ENSO	El Niño/Southern Oscillation
EOF	empirical orthogonal function
EOS	Earth Observing System
EOS AM	Earth Orbiting System Morning Satellite
EOS PM	Earth Orbiting System Afternoon Satellite
EOSDIS	Earth Observing System Data and Information System
ERB	Earth Radiation Budget

ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
ERS	Earth Resources Satellite
ESE	Earth Science Enterprise
ESSIPs	Earth System Science Information Partnerships
ESSP	Earth System Science Pathfinder
ETM+	Enhanced Thematic Mapper
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GOES	Geostationary Operational Environmental Satellite
HRC	highly reflective cloud
IDPS	integrated data processing system
IGBP	International Geosphere-Biosphere Program
IIP	Instrument Incubator Program
IORD-1	Integrated Operational Requirements Document (First Version)
IPFT	Integrated Product Formulation Team
IPO	Integrated Program Office
ISO	International Organization for Standardization
LECT	local equatorial crossing time
LIDQA	Landsat Instrument Data Quality Assessment
LTA	long-term archive
METOP	Meteorological Operational satellite
METOP-3	EUMETSAT Operational Polar Orbiter 3
MODIS	Moderate-resolution Imaging Spectroradiometer
MODLAND	MODIS Land Group
MSU	Microwave Sounding Unit
MTF	modulation transfer function
NAOS	North American Atmospheric Observing System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDS	NPOESS Climate Data System
NESDIS	National Environmental Satellite Data and Information Service
NewDISS	New Data and Information System and Services
Nimbus-7	NASA Environmental Research Satellite Series, 7
NIST	National Institute of Standards and Technology
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRA	NASA research announcement
NRC	National Research Council
OCTS	Ocean Color and Temperature Scanner
OI	optimum interpolation
OLR	outgoing longwave radiation

OMPS	Ozone Mapping and Profiler Suite
OSIP	Operational Satellite Improvement Program
OSS	Office of Space Science
PDRR	program development and risk reduction (phase)
PI	principal investigator
POES	Polar-orbiting Operational Environmental Satellite
QuikSCAT	Quick Scatterometer
RDR	raw data record
RFP	request for proposal
SBUV	Solar Backscatter Ultraviolet
SDR	sensor data record
SDRR	system definition and risk reduction (phase)
SDS	Science Data System
SeaWiFS	Sea Viewing Wide-Field-of-View Sensor
SI units	Système International d'Unités
SIMBIOS	Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SORCE	Solar Radiation and Climate Experiment
SRCA	Spectroradiometric Calibration Assembly
SSM/I	Special Sensor Microwave/Imager
SST	sea surface temperature
TBM	terabit memory
TDP	Technology Development Plan
TIROS	Television Infrared Observation Satellite
TOA	top of the atmosphere
TOPEX	Ocean Surface Topography Experiment
TOVS	TIROS-N operational vertical sounder
TRMM	Tropical Rainfall Measuring Mission
TSI	total solar irradiance
TSIM	Total Solar Irradiance Monitor
TSPR	total system performance requirements
USGCRP	U.S. Global Change Research Program
VIIRS	Visible/Infrared Imager and Radiometer Suite
VIRS	Visible and Infrared Scanner