IMPACTS OF NPOESS

NUNN-McCURDY CERTIFICATION

ON JOINT NASA-NOAA

CLIMATE GOALS

December 11, 2006

A Joint Document of
The National Aeronautics and Space Administration (NASA)
And
The National Oceanic and Atmospheric Administration (NOAA)

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NASA Headquarters
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EXECUTIVE SUMMARY

This report describes the impacts of the Nunn-McCurdy Certification of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) on the climate program goals of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). It was developed at the direction of the Office of Science and Technology Policy (OSTP) as a result of a meeting on June 26, 2006. The report contains joint NASA-NOAA recommendations as to how the impacted climate-related observations and related science might be recovered.

This document narrowly focuses on the impacts of the NPOESS Nunn-McCurdy Certification on two climate-related objectives within the context of the U.S. Climate Change Science Program (CCSP). These two objectives are: (1) to fly critical climate sensors that had been planned for NPOESS which represent the continuation of NASA's Earth Observing System (EOS) capabilities, and (2) to fly those sensors that represent a fundamental contribution to NOAA's Climate Mission, which includes both heritage satellite and in-situ observing systems. It does not consider the agencies' broader mandates and it does not consider international contributions beyond those already identified in the EUropean Organisation for the Exploitation of METeorological SATellites' (EUMETSAT) METeorological OPerational satellite (METOP) program. A Decadal Survey prepared by the National Academy of Sciences, expected in December 2006, will provide a science strategy and recommended missions for the next decade. The National Academy of Sciences is also developing a companion study addressing the loss of the climate sensors due to the NPOESS Nunn-McCurdy Certification that will be completed in July 2007. The Decadal Survey and the companion study as well as other available information will form the foundation of a NASA/NOAA mission roadmap to be completed later in the summer of 2007.

Detecting climate change, understanding the associated shifts in specific climate processes, and then projecting the impacts of these changes on the Earth system requires a comprehensive set of consistent measurements made over many decades. Many climate trends are small and require careful analysis of long time series of sufficient length, consistency, and continuity to distinguish between the natural long-term climate variability and any small, persistent climate changes. *Interruptions in the climate data records make the resolution of small differences uncertain or even impossible to detect*. To confidently detect small climate shifts requires instrument accuracy and stability better than is generally required for weather research and most other scientific uses. For more than thirty years, NASA research-driven missions, such as the EOS, have pioneered remote sensing observations of the Earth's climate, including parameters such as solar irradiance, the Earth's radiation budget, ozone vertical profiles, and sea surface height. Maintaining these measurements in an operational environment provides the best opportunity for maintaining the long-term, consistent, and continuous data records needed to understand, monitor, and predict climate variability and change.

NPOESS was created by Presidential Decision Directive/NSTC-2 of May 5, 1994 wherein the military and civil meteorological programs were merged into a single program. Within NPOESS, NOAA is responsible for satellite operations, the Department of Defense (DoD) is responsible for major acquisitions, and NASA is responsible for the development and infusion of new technologies. The history of the NPOESS Program and the path to the Nunn-McCurdy violation are provided in Appendix A.

To continue climate-quality measurements beyond the first series of EOS satellites, NASA and the NPOESS Integrated Program Office (IPO) entered into an understanding in 1999 to develop the NPOESS Preparatory Project (NPP) – a satellite mission to bridge a potential climate data gap between the existing EOS and the beginning of the future NPOESS. This understanding assumed that the NPOESS system would continue the mature EOS measurements in an operational environment, many of which addressed the nation's climate monitoring needs. For NASA, NPOESS was not only a converged civilian and military weather observing system but also the cornerstone of the nation's future climate research program. For NOAA, NPOESS represented a key component of its operational climate observing program and a cornerstone of its Climate Goal.

NPOESS, as originally configured, would have represented a significant step forward in the nation's ability to deploy a comprehensive climate observing system. Many key climate variables would be measured for decades. The revised Interagency Operational Requirements Document (IORD-2) defined the requirements for the NPOESS geophysical products, or Environmental Data Records (EDRs), which represented a more expansive calibration/validation program than was in place for the Polar Operational Environmental Satellites (POES). In the context of an overall climate observing system, the original NPOESS was an enormous advance over the existing operational systems of POES and the Defense Meteorological Satellite Program (DMSP), and it sustained many of the new capabilities demonstrated by NASA research missions.

Unfortunately, the recent loss of climate sensors due to the NPOESS Nunn-McCurdy Certification places the overall climate program in serious jeopardy. These shortfalls are characterized in a recent letter from the Chair of the Joint Science Committee from the World Climate Research Programme (WCRP) and from the Chair of the Steering Committee from the Global Climate Observing System (GCOS) to the Chair of the Committee on Earth Observation Satellites (CEOS). The Chairs from WCRP and GCOS state, "*Some of the difficulties in establishing and maintaining climate observations from space are currently being highlighted by the de-scoping of NPOESS, in which climate observations have been seriously compromised.*" They add, "*…unless revised plans compensate for the anticipated shortcomings in climate observations, gaps in several key climate data records (some that go back almost 30 years) are highly likely.*" They further state, "*WCRP and GCOS assert that our ability to address critical climate issues, with profound societal implications, will be strongly limited unless observation of climate variables is given higher priority. We urge that this be done*."

The Nunn-McCurdy Certification defines four possible dispositions for the original sensors:

1. De-manifested: sensor flown only if developed outside of NPOESS program
2. Reduced Coverage: sensor flown on one less flight per day (i.e., one less orbit)
3. Reduced Capability: sensor to be redesigned at lower cost and less capability
4. No Change: sensor is built and flown as specified before certification.

Findings and Recommendations:

NASA and NOAA have established the following priorities for the recovery of losses in NPOESS climate capabilities, ranked from most critical (1) to least critical (8). The prioritization is based exclusively on the agencies' climate objectives and it does not consider the broader mandates of the agencies or the costs of the mitigation options. Greater detail is provided in the body of the report.

1. **Total Solar Irradiance Sensor (TSIS)**, a de-manifested sensor:

   Science Impact: These measurements monitor the energy of the sun incident on Earth. They are crucial measurements that can be accurately determined only above the atmosphere. Any interruption of the 28-year data record of Total Solar Irradiance jeopardizes our ability to confidently resolve small changes in this most fundamental variable.

   Recommendation: We recommend that three TSIS instruments be built; the first to bridge a probable data gap between Glory and NPOESS and the next two for integration onto the NPOESS C2 Mission (2016) and the C4 Mission (2020).

2. **Earth Radiation Budget Sensor (ERBS)**, a de-manifested sensor:

   Science Impact: This measurement monitors the energy that maintains climate and it can be accurately determined only above the atmosphere. Overlap among space-based sensors is critical to confidently detect and monitor the small changes in the Earth's radiation balance capable of affecting climate.

   Recommendation: We recommend that the remaining CERES instrument should be moved to the NPP Mission. The ERBS instrument should be developed for integration onto the NPOESS C1 and C3 missions. NPOESS supports the integration of ERBS onto C1 and C3, including the ground system.

3. **OCEAN Altimeter (ALT)**, a de-manifested sensor:

   Science Impact: Ocean topographical data are vital to study the role of ocean circulation and the associated thermal transport in the climate system, sea level rise, assessing the severity of hurricanes, tracking costal ocean currents, and aiding in the forecasting of natural disasters. Sea level measurements are the climate change indicators of most direct concern for a substantial proportion of the U.S. and the world's population, most of whom live near the coast.

Recommendation: For the near-term, we recommend that support be provided for either an operational Ocean Surface Topography Mission (OSTM) follow-on mission (i.e., Jason-3) as a NOAA-EUMETSAT effort, or for the development of a next generation altimeter (i.e., wide swath, higher resolution) as a research and development mission between NASA and the U.S. Navy. The best option should be selected in a time frame that allows the required overlap with OSTM. In the longer-term, continuity in measurements throughout the NPOESS era will require successive flights of missions of comparable characteristics at an interval to provide the required overlap.

4. **Ozone Mapping and Profiler Suite Limb Subsystem (OMPS-Limb)**, a de-manifested sensor**:**

   Science Impact: Stratospheric ozone absorbs incoming solar ultraviolet radiation that can be harmful to humans and other organisms. Anthropogenic emissions of halogen-containing gases (e.g. Freon) are now known to destroy stratospheric ozone. The Montreal Protocol on Substances Depleting the Ozone Layer has resulted in successful international actions to reduce atmospheric concentrations of halogen-containing gases. The continuation of stratospheric ozone observations is crucial to monitor and evaluate the recovery of the ozone layer.

   Recommendation: The first OMPS-Limb for NPP is already built and we recommend calibration, testing, and integration of this instrument onto the NPP Mission. This will enable continuity with existing EOS Aura satellite measurements. Additional OMPS-Limb units should be built and integrated onto the two NPOESS missions flying the OMPS –nadir units (C1 and C3).

5. **Conical Scanning Microwave Imager (CMIS)** a reduced sensor capability:

   Science Impact: Microwave observations from satellites have allowed sea surface temperatures, sea ice and snow cover extents, vegetation, ocean surface wind speed, water vapor, precipitation rates, and other surface variables to be analyzed even in the presence of heavy cloud cover and have consequently made microwave radiometers particularly applicable for climate studies.

   Recommendation: We recommend that the rescoped CMIS requirements should be carefully monitored. If the resulting instrument is not adequate for climate quality measurements of precipitation, soil moisture, and sea surface temperature, then alternative instruments must be identified. The imager/sounder combination should stay on the C2 Mission as planned. A capability to continue the eight-year QuickScat ocean vector wind measurements is also needed.

6. **Aerosol Polarimetry Sensor (APS)**, a de-manifested sensor:

Science Impact: Aerosol properties are a high priority in the U.S. Climate Change Science Program. The effects of aerosols on global temperature are significant and may be comparable in importance to the role played by “greenhouse” gases, such as carbon dioxide and methane, which contribute to the warming of the Earth’s surface.

Recommendation: The APS instrument should be flown on the NASA Glory Mission as planned. The support of future polarimetry observations should be based on the Glory results. If favorable, accommodations exist on the NPOESS C1 (2013) and C3 (2018) Missions.

7. **Visible Infrared Imaging Radiometer Suite (VIIRS)**, a reduced coverage sensor:

   Science Impact: VIIRS is a moderate resolution, wide swath, multispectral radiometer covering the visible to thermal infrared spectral range. For more than three decades, scientists have depended on such imagery for a wide variety of societal applications, including weather and climate analysis, monitoring agriculture, and disaster prediction and assessment.

   Recommendation: We should fly a VIRS-like instrument on one or more platforms in the mid-AM orbit to provide a continuous data record throughout the initial METOP era (A, B, C). For sustained continuity beyond METOP-C, work with EUMETSAT to define the requirements for a VIIRS-like imager to fly on the METOP follow-on series.

8. **Cross-track Infrared Sounder (CrIS)**, a reduced coverage sensor:

   Science Impact: The CrIS is designed to work with the ATMS to produce daily vertical profiles of atmospheric temperature and moisture.

   Recommendation: No additional mitigation is recommended.

1.0 Introduction

This report responds to a request from the Office of Science and Technology Policy (OSTP) following a meeting with NOAA and NASA held on June 26, 2006. At that time, it was agreed that NASA would characterize the substantial climate science impacts attributable to the instrument deletions and scope reductions contained in the recent certification of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Program. The history of the NPOESS program and the path to the Nunn-McCurdy Certification are provided in Appendix A. NOAA has since incorporated its requirements and recommendations into this white paper.

There is an emphasis in this report on two climate-related objectives. In the first instance, NASA and the NPOESS Integrated Program Office (IPO) entered into an agreement in 1999 to develop the NPOESS Preparatory Project (NPP) in lieu of extending the EOS Program assuming that the NPOESS system would continue the mature EOS measurements in an operational environment. For NASA, NPOESS is not only a converged civilian and military weather system but the cornerstone of the nation's climate research program. For NOAA, NPOESS represents a critical component of its operational climate observing program and a cornerstone of its Climate Goal.

This paper is narrowly focused on the impacts of the NPOESS Nunn-McCurdy Certification on climate observations within the context of the U.S. Climate Change Science Program (CCSP). To that end, it associates key variables from the Global Climate Observing System (GCOS) Essential Climate Variables (ECVs) and CCSP climate system observations (Appendix B) with the sensors affected by NPOESS Certification. We expect the National Academy of Sciences' Decadal Survey, expected in December 2006, to provide additional guidance and the prioritization of U.S. climate observing systems.

This report contains recommendations as to how the impacted measurements could be recovered. These recommendations follow the Nunn-McCurdy Certification, which is to say, that the de-manifested instruments are developed outside of the NPOESS Program, subsequently delivered to it, and integrated onto one or more of the four remaining NPOESS spacecraft according to the current schedules. Some mitigation strategies consider various observing systems other than NPOESS. Furthermore, the co-location of complementary sensors to improve the quality and/or interpretation of sensor records is also discussed. A summary of the sensor co-location recommendations is provided in Appendix C.

Once the National Academy of Sciences' Decadal Survey is available, NASA and NOAA will prepare a mission roadmap responsive to that survey. NASA and NOAA will explore alternative approaches including the "scarring" (i.e. provide accommodation) of NASA or partners' spacecraft to fly the same instruments should the NPOESS Program experience future difficulties. International partnerships will also play a significant role in the mission roadmap. They are also extremely important in developing in-situ benchmark observing networks, a key international observing strategy for climate that has been highlighted by various GCOS planning documents and supported by the Global Earth Observing System of Systems (GEOSS) and the World Meteorological Organization (WMO).

The significant shortfalls reflected in the NPOESS Nunn-McCurdy Certification were characterized in a recent letter from the Chair of the Joint Science Committee of the World Climate Research Programme (WCRP) and the Chair of the Steering Committee from the Global Climate Observing System (GCOS) to the Chair of the Committee on Earth Observation Satellites (CEOS). The Chairs from WCRP and GCOS state, *"Some of the difficulties in establishing and maintaining climate observations from space are currently being highlighted by the de-scoping of NPOESS, in which climate observations have been seriously compromised."* They add, *"…unless revised plans compensate for the anticipated shortcomings in climate observations, gaps in several key climate data records (some that go back almost 30 years) are highly likely."* They further state, ***"WCRP and GCOS assert that our ability to address critical climate issues, with profound societal implications, will be strongly limited unless observation of climate variables is given higher priority. We urge that this be done."*** (Emphasis was added by the WCRP and GCOS Chairs). By planning a contingent approach independent of NPOESS, the likelihood of achieving these critical climate observations is much improved. This information will be incorporated into the NASA and NOAA mission roadmap to be completed late in the summer of 2007.

If these instruments are to be developed outside of the NPOESS Program, there are potential issues dealing with instrument performance. Understanding and predicting climate variability involves the ability to detect small changes over a long period of time. The diurnal, day-to-day, seasonal, and interannual variance will likely be larger than the decadal climate change we seek to detect. To confidently detect such small climate shifts requires accuracy and stability better than generally required for weather research and most operational applications. Where such accuracy and stability is not yet technologically possible, it is essential that one instrument overlap the other to make direct inter-instrument comparisons. Without such comparisons, the resulting data gap represents an uncertainty that is often larger than the postulated climate change we seek to measure. Other performance considerations include the rigor and timeliness of algorithm development, the depth and breadth of instrument characterization prior to flight, the robustness of on-orbit characterization, the nature of the calibration and validation program once aloft, the ability to periodically reprocess the data to incorporate improved knowledge of instrument behavior and retrieval algorithms, and the data policies providing the data to all interested investigators.

During the Nunn-McCurdy process, ground rules endorsed by the NPOESS Executive Committee (EXCOM) stipulated that a higher priority would be placed on the continuity of legacy operational capabilities in support of weather measurements, which resulted in a lower priority for climate-focused measurements. The Office of the Secretary of Defense (OSD) led a tri-agency process culminating in the certification of a restructured NPOESS Program on June 5, 2006. The certified program is described in the following language taken from the Acquisition Decision Memorandum:

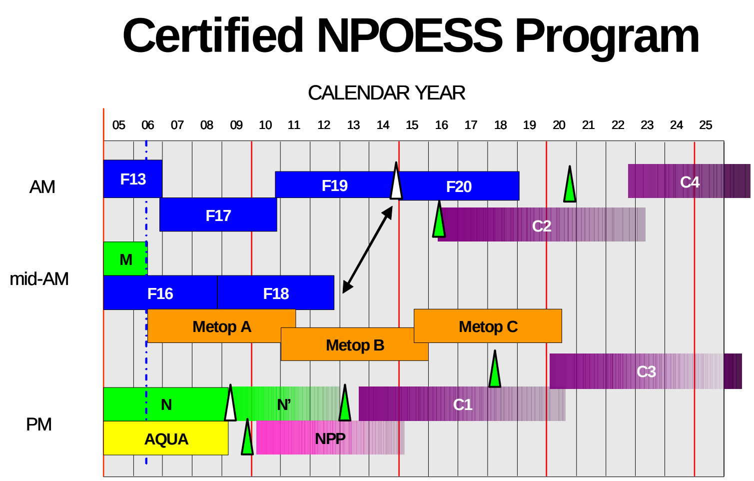
- The NPOESS Certified Program now includes the following sensors: Visible/Infrared Imager/Radiometer Suite (VIIRS); Microwave Imager/Sounder; Search and Rescue Satellite Aided Tracking (SARSAT); Cross-track Infrared Sounder (CrIS); Advanced Technology Microwave Sounder (ATMS); Advanced Data Collection System (ADCS); Cloud's and Earth's Radiant Energy System (CERES); Ozone Mapping and Profiling Suite (OMPS) Nadir; and the Space Environment Monitor (SEM);

- It does not include funding for the following sensors: Aerosol Polarimetry Sensor (APS), Total Solar Irradiance Sensor (TSIS); OMPS-limb; Earth Radiant Budget Suite (ERBS); Altimeter (Alt); Survivability Sensor (SuS); and Full Space Environment Sensors (SESS); however, the program will plan and fund for the integration of these sensors onto the satellite buses, if the sensors are provided from outside the program;

- It also terminates the Conical Scanning Microwave Imager/Sounder (CMIS), while developing a competition for a new, less expensive Microwave Imager/Sounder starting with the second EMD satellite; and

- It is now a two-orbit rather than three-orbit program that uses data from the European Meteorological Operational (METOP) satellites provided by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) for the mid-morning orbit, while providing flexibility to deploy Defense Meteorological Satellite Program (DMSP) satellites depending on the health of the constellation in either early-morning or mid-morning orbits.

The current NPOESS certification mission baseline schedules and the corresponding sensor assignments are displayed in Figure 1.



	NPP	Early AM C2	Early AM C4	Mid AM MetOp	PM C1	PM C3
• VIIRS	x	x	x	AVHRR	x	x
• CMIS*		x	x			x
• CrIS/ATMS	x			IASI/ATMS	x	x
• SESS (SEM)**				x	x	x
• OMPS (nadir)***	x				x	x
• APS						
• TSIS						
• CERES/ERBS					x	
• ALT						
• Survivability						
• SARSAT		x	x	x	x	x
• ADCS		x	x	x	x	x

* CMIS is revised microwave imager/sounder

** SEM will fly in place of full SESS suite

*** OMPS nadir sensor only

Figure 1: Mission schedules and sensor assignments for the Nunn-McCurdy Certified NPOESS Program

NASA and NOAA have established measurement priorities based on the following criteria: 1) Continuation of NASA's Earth Observation Systems (EOS) capabilities and observations that allow for the monitoring, understanding, and prediction of climate variability and change, and 2) Extension of existing Climate Data Records (CDRs) – developed to address GCOS and CCSP measurement priorities -- rather than the initiation of new CDRs.

Detailed descriptions of each affected sensor's climate objective, disposition, impacts of the disposition, and mitigation options for recovery are provided in the body of this document. The sensors are listed in order from most critical to least critical common to

NASA's and NOAA's climate objectives. The prioritization is based exclusively on the agencies' climate objectives. These include:

- Societal relevance of the sensor loss or degradation,
- Relevancy of the measurement to better understanding of the causes of climate change or the sensitivity of the climate system to external or internal forcing,
- Importance of sensor to measuring one or more Essential Climate Variables, that are not being adequately measured by other satellite or in-situ systems,
- Historical heritage of the sensor and the related Climate Data Records,
- Likelihood of a gap in measurement if not flown, and
- Maturity of the measurements from the sensor in question.

It does not consider the broader mandates of the agencies or the costs of the mitigation options. The prioritization is as follows:

1. Total Solar Irradiance Sensor (TSIS; de-manifested)
2. Earth Radiation Budget Sensor (ERBS; de-manifested)
3. OCEAN Altimeter (ALT; de-manifested)
4. Ozone Mapping and Profiler Suite Limb (OMPS-Limb; de-manifested)
5. Conical Scanning Microwave Imager (CMIS; reduced capability planned)
6. Aerosol Polarimetry Sensor (APS; de-manifested)
7. Visible Infrared Imaging Radiometer Suite (VIIRS; reduced coverage planned)
8. Cross-track Infrared Sounder (CrIS; reduced coverage planned)

The Survivability Sensor (SuS) and the Space Environment Sensor Suite (SESS) are not directly pertinent to climate research and are not considered here. The Advanced Data Collection System (ACDS) is a change of no consequence since the METOP platform will have a similar capability in the mid-morning orbit and, for this reason; it is not considered in this report.

Additional details are contained in Appendix D.

2.0 Impacts and Mitigation of Nunn-McCurdy Certification on Climate Sensors

2.1 De-manifested Sensors

2.1.1 Total Solar Irradiance Sensor (TSIS)

Summary of Findings:

Essential Climate Variable(s): Total solar irradiance (TSI)

Societal applications and impacts: Precise, long-term observations of the total energy output by the sun are required to identify and isolate natural solar variations that impact climate in contrast to other factors, such as human influences on climate. Long-term records are needed to capture multiple instances of the 11-year solar cycle. The spectral dependence of solar output is also required to determine changes in ultraviolet solar output which affects stratospheric temperature, structure, composition, and dynamics. These effects impact long-term climate predictions, particularly ozone and human health. Without TSIS, we cannot definitively discriminate and quantify natural versus anthropogenic drivers of climate change. Further, we cannot assess how solar variability is affecting different components of the Earth system. This represents an irrevocable end of a 30-year TSI record. Spectral measurements stop at end of SORCE mission after ~ 9 years.

Maturity, continuity and science: Satellite observations of total solar irradiance are well established and considered mature, but still require overlap among differing sensors for inter-satellite calibration.

Sensor Complements: TSIS need not fly with other sensors.

NPOESS Certified Program: No provision for TSIS, but the Program will plan for the integration of TSIS-like sensors onto the satellite buses, if the sensors are provided from outside the NPOESS Program. Total solar irradiance (~ 30 year record) and spectrally resolved solar irradiance records terminate with the likely end of Glory and SORCE missions in ~2014 and ~ 2011, respectively.

Mitigation Option 1: We recommend that two TSIS instruments be built and that the NPOESS IPO supports integration onto NPOESS C2 (2016) and C4 (2020) platforms. Total Solar Irradiance (TSI) observations end with Glory mission in ~ 2014; spectral observations end with SORCE mission in ~2011. Both restart with TSIS on C2.

> *Pros:* Long-term observations of the total energy output from the sun are continued through 2013 using the Joint Agency Program planned ground segment and processing.
>
> *Cons:* It is unlikely that Glory TIM will survive beyond ~2014 to overlap with C2 launch in 2016 and may thus result in a critical gap in the TSI record. Loss of

spectrally resolved irradiance is even more likely, given anticipated end of SORCE in ~ 2011.

Mitigation Option 2: We recommend three TSIS instruments be built and that a joint NASA/NOAA/Commercial/international satellite platform be solicited with a launch scheduled to overlap the Glory mission before its anticipated end in ~ 2014 for the first of the three instruments. The second and third instruments should be flown on flights of opportunity (these could be NPOESS flights but do not need to be).

Pros: Greater likelihood of continuous observations of total energy output from the sun including required overlap periods for intersatellite calibration.

Cons: Some fraction (up to all) of communications, ground systems, and processing costs must be borne by this alternative. If relying on non-NPOESS missions, risk of data gap in future exists if no suitable flight opportunities can be identified.

Background: The sun is the only significant external source of energy to the Earth system. Thus, Total Solar Irradiance (TSI) has a major impact on Earth's average temperature. Furthermore, solar radiation is the dominant, direct energy input into terrestrial ecosystems and, thus, it affects all physical, chemical, and biological processes – many of which impact human health and well being. *Precise observations of the total solar output are therefore essential to determine the influence of natural variability in climate and climate change.*

About 20 % of the TSI is absorbed by atmospheric water vapor, clouds, and ozone, by processes that are strongly wavelength dependent. Ultraviolet radiation at wavelengths below 300 nm is mostly absorbed by the Earth's atmosphere and contributes the dominant energy source in the stratosphere and thermosphere, establishing the upper atmosphere's temperature, structure, composition, and dynamics. Even small variations in the Sun’s radiation at these short wavelengths will lead to corresponding changes in atmospheric chemistry. These processes, in turn, control the small fraction of ultraviolet radiation that leaks through to the Earth’s surface and potentially impacts human health.

Radiation at the longer visible and infrared wavelengths penetrates into the lower atmosphere, where the portion not reflected is partitioned between the troposphere and the Earth's surface, and becomes the dominant term in the global energy balance and an essential determinant of atmospheric stability and convection. Some recent studies suggest that the cloudy lower atmosphere absorbs more visible and near infrared radiation than previously thought, which impacts atmospheric dynamics and cloud formation.

Variability in TSI occurs over most time scales, from day-to-day variations up to and including variations over the 11-year solar cycle. Precise space measurements obtained during the past 28 years imply that TSI varies on the order of 0.1% over the solar cycle (see Figure 2), but with greater variations on a short-term basis. *Due to the complex and* *variable absorption of the atmosphere, this measurement can be made only from space to achieve the accuracy necessary to support climate research.*

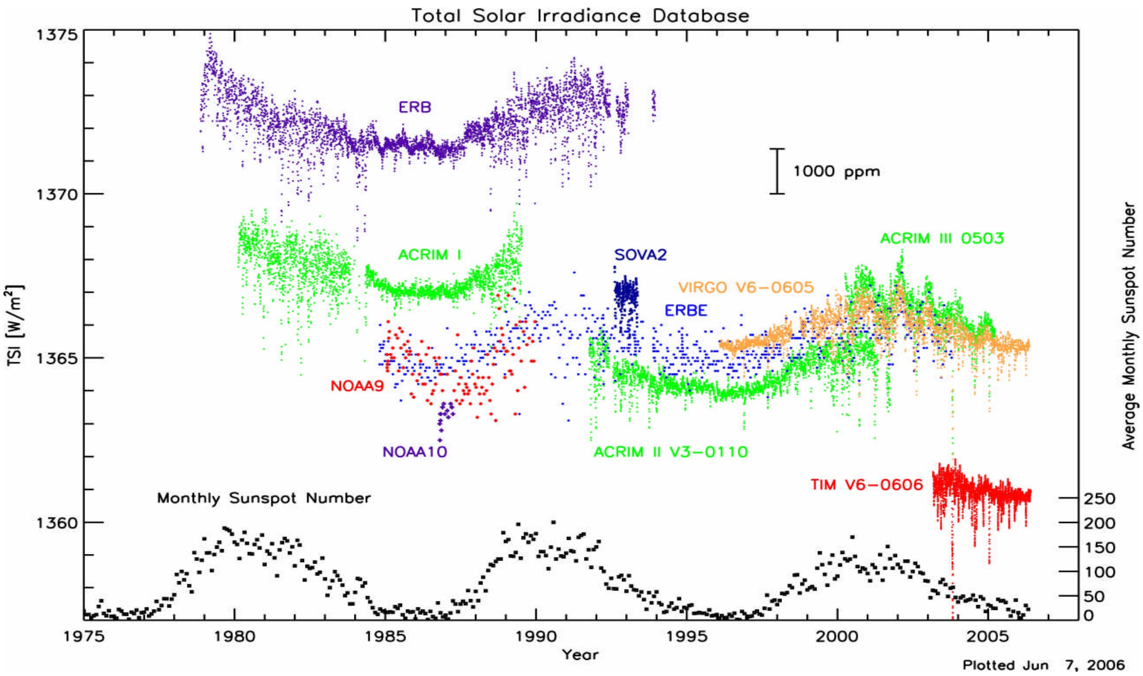


Figure 2: Total Solar Irradiance over 30 years (See the website: lasp.colorado.edu.sorce)

How solar output variability is distributed in wavelength (Solar Spectral Irradiance, or SSI) is still poorly understood. The largest relative solar variations are factors of two or more at ultraviolet and shorter wavelengths, but the greater total energy available at visible and longer wavelengths makes their small variations (far less than 1%) of potential importance (see Figure 3). Such precise measurements can only be achieved from space.

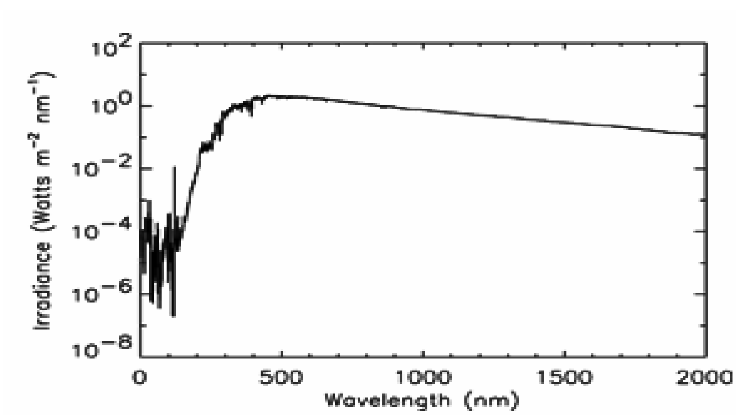


Figure 3: Spectral distribution of solar energy incident at the top of the atmosphere (See the Website: lasp.colorado.edu/sorce).

The solar ultraviolet, which varies far more than the TSI, influences stratospheric chemistry and dynamics, which in turn controls the small fraction of ultraviolet radiation that leaks through to the surface, and may provide dynamical forcing of the troposphere (the principle of "downward control").

Intended Science: TSIS measurements specifically address long-term climate change, natural variability and enhanced climate prediction, and atmospheric ozone and UV-B radiation. UV-B radiation is within the bandwidth 290-320 nm; it is readily absorbed by DNA and causes significant bond damage to the DNA. Solar radiation is the dominant, direct energy input into the terrestrial ecosystem; and it affects all physical, chemical, and biological processes. The Sun provides a natural influence on the Earth's atmosphere and climate and is critical to understanding climate change.

Precise, long-term observations of the total energy output by the sun are required to identify and isolate natural solar variations that impact climate in contrast to other factors, such as human influences on climate. Long-term records are needed to capture multiple instances of the 11-year solar cycle. The spectral dependence of solar output is also required to determine changes in ultraviolet solar output which affects stratospheric temperature, structure, composition, and dynamics. These effects impact long-term climate predictions, particularly ozone and human health. Without TSIS, we cannot definitively discriminate and quantify natural versus anthropogenic drivers of climate change. Further, we cannot assess how solar variability is affecting different components of the Earth system.

The Sun's broadband radiative input to the Earth's atmosphere varies by 0.1% over a solar cycle and by approximately 0.2% on shorter time scales (days to weeks). Climate change may depend on yet smaller changes over greater periods of time, making the required measurements of solar variability extremely difficult. To detect small but long-term changes in TSI, instruments require either:

1. Uncertainties of <0.01% in absolute accuracy – This level of absolute accuracy, with measurements spanning decades to centuries, helps mitigate potential gaps in the data record and maintain a link to the existing TSI record.

2. Uncertainties of <0.001%/year in relative accuracy and continual, overlapping measurements – Overlapping measurements with instruments able to correct for on-orbit sensitivity degradation can determine relative changes in solar irradiance. The simpler of the two approaches, this method is susceptible to loss of data continuity.

The latter has been achieved; the former has not, with reported absolute accuracies ranging from 0.35% to 0.5%.

Data Heritage: Long-term data records are needed in part because of the 11-year solar cycle; measurements spanning two or three solar cycles at a minimum are needed to ascertain the inherent variability. Long-term data records are needed because changes in solar irradiance have been linked to past climate changes. They are critical in any strategy for attributing the proportion of human influence on global climate change (IPCC, 2001). NASA's measurement of TSI extends to nearly three decades so far. Precise measurements of TSI began with the ERB instrument in 1979 and have continued to the present with the ACRIM and SORCE series of measurements. Experience with such instruments has demonstrated the need for overlap between successive instruments in order to understand systematic biases between them. The solar irradiance instrument suite on the SORCE mission, part of NASA's EOS, also provides the measurements of the solar spectral irradiance from 1 nm to 2000 nm, accounting for 95% of the spectral contribution to TSI. The total irradiance observations will be succeeded by the Total Irradiance Monitor (TIM) on the Glory mission, with no planned successor. Solar spectral monitoring will terminate at the end of the SORCE mission (~2011).

Critical Performance Parameters:

Total Irradiance Monitor (TIM) Requirements:

TSI Continuity: To measure the Total Solar Irradiance consistent with the continuity of this measurement with respect to the Glory mission.

Accuracy: The TIM instrument shall measure TSI to an absolute accuracy of 100 parts per million (1σ) with noise less than 4 ppm (1σ).

Stability: The TIM instrument shall have relative stability not greater than 10 ppm (1σ) per year after data corrections in post-processing.

Lifetime: At least 3 years of continuous observations

Spectral Irradiance Monitor (SIM) Requirements:

Wavelength Range: 300-2000 primary, 200-300 secondary

Wavelength Resolution: 0.25-33 nm

Absolute Accuracy: 300 ppm (1 sigma)

Long-term Accuracy: 100 ppm/5-years

Redundancy: 2 redundant spectrometers

***NPOESS Original Flights*:** Originally the NPOESS Program planned to fly the TSIS on the early AM flights, C2 and C5. C2 would launch in 2015 and C5 would launch in 2021.

NPOESS Proposed Flights: In the NPOESS certification, the opportunity to fly on the early AM missions, C2 and C4 would be available if the instruments could be made available by 2014. The C2 Mission launches in 2016 and the C4 Mission launches in 2020.

Proposed Alternative Approach: A research/operations/commercial/international partnership that would include development of three TSIS sensors should be planned as soon as possible to be hosted on flights-of-opportunity. *The first flight would need to be planned to overlap the Glory mission before its anticipated end in ~ 2014*. Particular concerns for such flights of opportunity are accurate pointing and sufficient solar viewing.

Specific Performance Deficit: A data gap in the space-based TSI measurement cannot be mitigated without continuous satellite measurements for two reasons:

1) The absolute accuracy of the measurement is not sufficient to meet the science requirements, and

2) *In situ* Earth-based measurements are not adequate due to the large absorption by the atmosphere of the solar energy, thus making the satellite measurements unique.

Nevertheless, relying on instrument stability and data continuity has risk. The existing TSI data record that is currently almost 30 years long and likely the beginning of a record that will become centuries long is still susceptible to a break in measurement continuity, which would make connection to future TSI measurements extremely difficult or impossible at the accuracies needed to detect small solar variability. The longer – and thus more valuable – the current data record becomes, the more critical data continuity and absolute accuracy become.

Specific Climate Research Deficits:

Data Continuity Deficits: The current TSI record relies on continuity of measurements with overlap between successive TSI instruments. SORCE data measuring TSI will be provided through 2008, possibly extendable to 2011. Prior to the NPOESS Nunn-McCurdy Certification, NASA committed to fly a TSI instrument on its Glory Mission to ensure data continuity between SORCE and the first flight of TSIS on NPOESS. As a result, TSI data will be provided by Glory starting late in 2008 and extending through 2011 and possibly through 2014. SSI will not be measured on Glory. Therefore, there will be a data gap in SSI starting in 2009 at the end of the SORCE Mission and a data gap of TSI at the anticipated end of the Glory Mission in 2014. Until absolute accuracy at the 0.01% level is achieved with a direct link to the existing nearly 30-year data record, any gap in TSI measurements risks the loss of connectivity with this established data record. ***This is a significant climate program shortfall.***

Measurement Overlap Deficits: Experience with such instruments has demonstrated the critical need for overlap between successive instruments to understand systematic biases between instruments.

Science Deficits: The existing 28-year TSI record is the result of several overlapping TSI instruments on different missions (see Figure 1 above). Offsets are due to inconsistent absolute accuracies, although each instrument precisely monitors short-term TSI changes. None of these instruments is calibrated end-to-end for irradiance at the desired absolute accuracy levels, as no such capability currently exists. The error bar shown indicates 0.1% variation. This data record currently relies on instrument stability and continuity, whereby successive instruments are linked to the existing TSI data record despite offsets between instruments on an absolute scale. The TSI record clearly shows the Sun's variability over the 11-year solar cycle and on shorter time scales. The accuracy of the measurements and the length of the TSI data record are currently insufficient to definitively indicate multi-decadal variations in the solar irradiance; with current instrument sensitivities and levels of solar variability, this will require a longer record.

Climate simulations of solar forcing, such as the Maunder minimum (a period from 1645-1715 AD when sunspots were exceedingly rare), have so far assumed that SSI varies without changing spectral shape, which has been shown to be incorrect. Consequently, the SSI measurements will be crucial to making more accurate simulations of pre-industrial climate, which are required to separate natural forcings (solar and volcanic) from anthropogenic forcings (greenhouse gases and manmade aerosols). Unlike the nearly three-decade long record of TSI, the continuous record of SSI, which began with the SORCE Mission in 2002, is in its infancy and its total duration is less than one-half of a single solar cycle.

SIM measurements were proposed before three-dimensional global models were capable of chemistry-climate coupling. With the advent of such models, we may now assess climate sensitivity to solar energy deposited in the atmosphere at different altitudes, with different wavelength-dependent solar cycle variability.

Recommendations: We recommend that three instruments be built to continue TSIS as originally planned to ensure no data gap in TSI beyond the Glory mission. This first TSIS instrument could fly on a flight-of-opportunity in a time frame to overlap with the Glory mission before its anticipated end-of-life in ~ 2014. Additional TSIS instruments should be built and integrated on NPOESS C2 and C4 Missions, consistent with the NPOESS Nunn-McCurdy Certification.

Based on SOURCE results, we recommend that solar spectral irradiance be considered for incorporation into subsequent TSIS instruments.

TSIS data processing and analysis do not require that any other NPOESS sensors fly on the same platform or in the same orbit.

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2.1.2 Earth Radiation Budget Sensor (ERBS)

Summary of Findings:

Essential Climate Variables: Net shortwave and longwave radiation at the top of the atmosphere.

Societal applications and impacts: The Earth-atmosphere system equilibrium temperature is determined by the balance between the incoming solar radiation, the amount of that incoming radiation reflected back to space by the Earth's surface and clouds, and the longwave Earth emitted radiation. The Earth's emitted radiation is regulated by clouds and greenhouse gases. Accurate observations of the Earth's radiation are essential to accurately determine the causes of climate change and important internal climate feedback effects, which over decades can substantially alter climate.

Maturity, continuity and science: Accurate Earth radiation budget observations can only be made from space. They were the first Earth scientific observations ever from space in 1960 and ongoing observations have been made for over 20 years. As the measurement understanding has matured, it has become clear that a variety of synchronous research quality observations, extending beyond the spectrum observed by operational satellites and operational observations, are needed to meet climate observation requirements.

Sensor Complements: Coordinated ERBS/CERES data collection with a wide-swath imager like VIIRS is required, and coordination with MIS, CrIS/ATMS and APS adds substantial value to the measurements.

NPOESS Certified Program: As a cost saving action, NPOESS IPO asked NASA to make available the last copy of the CERES instrument that is part of the TRMM, Terra, and Aqua EOS satellites. Since the instrument already exists, the flight of CERES on NPOESS C1 remains a part of the certified NPOESS.

> *Pros:* Cost saving achieved and Earth radiation budget record will be obtained during the period of operation of C1.
>
> *Cons:* Given the Aqua launch of the last CERES in 2002, and the planned launch of C1 now in 2013, a gap in Earth radiation data is highly likely. In addition, there are no long-term plans to fly Earth Radiation budget instruments beyond C1. Verification of climate feedback by clouds is significantly reduced, leading to large uncertainties in future climate change projections.

Mitigation: Move remaining CERES instrument to NPP to ensure continuity of Aqua CERES record. Develop ERBS for flights on C1 and C3 outside of NPOESS but have the NPOESS IPO support the integration of ERBS on to C1 and C3 including ground system.

Pros: Continues continuity of Earth radiation budget observations. Flights on NPOESS provide required synergy with the VIIRS high resolution cloud data.

Cons: Integration on NPP may be prohibitive. Funding required outside of NPOESS program for development of new ERBS instruments and for science data processing and transition to operations.

Background: Along with incoming solar radiation, outgoing radiation helps establish the Earth's radiant energy balance; the difference between the two corresponds to "climate forcing", which is exhibited in part by rising global average tropospheric temperatures.

The radiant energy from the sun provides the energy that maintains climate. Approximately two thirds of the solar radiant energy incident on the Earth is absorbed, heating it until it radiates as much energy back to space as it absorbs from the sun. The remaining one third of the incident solar energy is reflected back into space. Both the absorbed and reflected solar radiation are in the shortwave part of the electromagnetic spectrum (mostly visible light), while the Earth's radiation emitted back to space is longwave or thermal infrared radiation. The balance between the solar input and the thermal output is known as the Earth's radiation budget. The radiation budget is most affected by the nature of the Earth's surface and its atmosphere including clouds.

Clouds affect the radiation budget in different ways and understanding the characteristics of clouds may be the key to understanding climate change. Optically dense low clouds, such as the oceanic stratus decks, reflect more of the incoming solar energy than the darker surface of the Earth and, in this situation, the surface under the clouds will be cooled. High clouds with tops considerably colder than the Earth's surface reduce the longwave emission into space. This "trapped" thermal emission warms the surface. This trapping by high clouds enhances the "greenhouse effect." Other clouds, such as those associated with thunderstorms, are as effective at reflecting solar radiation as they are at trapping longwave radiation; these clouds neither warm nor cool the surface beneath them. *While NASA's Earth Radiation Budget Experiment observationally demonstrated that clouds act to cool the current climate, the impact of clouds on the radiation budget as the climate responds to natural and anthropogenic forcing remains one of the largest uncertainties in climate science.*

Intended Science: Persistent climate changes are small and difficult to detect within the diurnal, regional, and seasonal variance of the reflected shortwave and emitted longwave energy. To identify and study these changes requires measurements of high accuracy and precision extending over a time period of at least 30 years based on systematic sampling studies.

One challenge is that the current absolute accuracy of satellite-borne radiation budget instruments is inadequate to reliably observe the small climate signals representative of decadal climate change if there is insufficient overlap between radiation budget instruments. In particular, the CERES one percent absolute accuracy in shortwave radiance is insufficient by a factor of four to assure better than 0.3% per decade consistency between non-overlapped observations of cloud radiative forcing (Ohring et al., 2005, IPCC, 2001). The CERES record does appear sufficiently stable to meet the climate requirement if given six to twelve months overlap with the previous mission in the same orbit (Loeb et al., 2006). Achieving highly accurate satellite calibration for solar reflected energy is much more difficult than for thermal infrared, where blackbodies can be used (Ohring et al., 2005). Even for thermal infrared, with the most accurate broadband radiation budget data of the past at 1% accuracy (ERBE), and currently at 0.5% accuracy (CERES), the expected differences with non-overlapped data can reach 1.5% of the mean longwave flux or $240*0.015 = 3.6\ Wm^{-2}$.

A second challenge lies in assuring that clouds modulating the radiation fields are properly associated with the radiation budget measurements and that their effects on the measurements are consistently taken into account. Observing cloud characteristics is performed well from satellites viewing the top of the atmosphere where it is possible to measure the solar shortwave energy reflected back to space from cloud tops and the Earth's surface while also measuring the longwave emission from the atmosphere, clouds, and the Earth's surface. To obtain its current accuracy, CERES uses spectral radiances from MODIS to identify cloud properties within each field of view and then uses these properties to select a measured Angular Distribution Model that relates the observed radiance to the outgoing shortwave and longwave fluxes. In building a long-term record of consistent radiation budget and cloud properties, it will be critical to avoid "algorithm shock," in which algorithm modifications produce changes in the record that make it difficult or impossible to distinguish between physical changes in the Earth-atmosphere system and artifacts in the algorithm.

A third challenge is how to deal with the temporal variations that need to be taken into account in interpolating between the individual satellite measurements. Some of the systematic time variability arises from heating of the Earth's surface during the day. The Sahara, for example has large, systematic variations in longwave flux, while the large expanse of ocean exhibits very small variations. More important in temporal interpolation are the variations associated with clouds. In the shortwave, reflection from clouds has a smaller dependence on the solar zenith angle than does reflection from clear land or ocean. In the longwave, the emitted energy is modulated by clouds and the current algorithms provide an interpolation that depends on the observations of cloud properties.

Data Heritage: NASA and NOAA have long cooperated in providing Earth Radiation Budget measurements, although it has proven difficult to provide measurement continuity and to transfer from proven research-based instruments to operationally funded ones. The earliest contributions to the current measurement history are those from the NOAA-provided Nimbus-7 Earth Radiation Budget measurements that provided critical measurements of the angular distribution of radiances, categorized by a rough cloud fraction. The NASA Earth Radiation Budget Experiment (ERBE) used scanning narrow field-of- view (NFOV) broad spectral band measurements similar to the Nimbus-7 scanner starting in 1984. Identical ERBE instruments also flew aboard NOAA-9 in 1984 and NOAA-10 in 1986. An improved instrument, known as the Clouds and Earth's Radiant Energy System (CERES) was included on the Tropical Rainfall Measuring Mission launched in 1997, the Terra Mission launched in 1999 and the Aqua Mission launched in 2002. In addition to the scanning radiometers, there have been longer-lived non-scanning instruments on Nimbus-6 and Nimbus-7.

Critical Performance Parameters:

ERBS is considered a follow-on instrument to CERES with the following performance parameters.

Spectral Range: 3 Broadband channels:
Total radiance (0.3 to 100 µm)
Shortwave (0.3 to 5 µm)
Window (8 to 12 µm)

Swath:
Limb to Limb

Spatial Resolution:
20 km at nadir

Climate Data Record Accuracy Requirements:
Absolute: 1% Shortwave and 0.5% Longwave
Stability: ~0.1%/yr for Shortwave and ~0.05%/yr for Longwave

***NPOESS Original Flights*:** Prior to the Nunn-McCurdy Certification, the NPOESS IPO asked NASA to make available a CERES flight spare (FM-5) as a cost savings action. This instrument is identical to the CERES instruments flying on TRMM, Terra, and Aqua. NASA agreed and it was planned to fly on the NPOESS C1 Mission.

NPOESS Proposed Flights: With the de-manifesting of ERBS, there are no current plans for an Earth radiation instrument beyond the remaining CERES planned for the NPOESS C1 Mission.

Proposed Alternative Approach: Given the Aqua launch in 2002, and the planned launch of C1 now in 2013, a gap in CERES data is likely. Given the present necessity to overlap the sensors, it makes more sense in the near term to move the remaining CERES instrument from C1 back to NPP to ensure the continuity of this measurement.

Specific Climate Research Deficits:

Operational Monitoring Deficits: The loss of NPOESS ERBS threatens the broadband radiation budget data record that began in 1984. This record was continued by EOS CERES missions (TRMM, Terra, and Aqua).

The flight of CERES on NPOESS C1 remains a part of the post-Nunn-McCurdy Plan. Given the Aqua launch in 2002, and the planned launch of C1 now in 2013, a gap in CERES data is likely. Moreover, with the loss of ERBS, there are no current plans for an Earth radiation instrument beyond the remaining CERES.

Measurement Overlap Deficits: *Measurement overlap is critical for earth radiation budget sensors.* Persistent climate changes are small and difficult to detect within the diurnal, regional, and seasonal variance of the radiation parameters. To identify and study them requires measurements of high accuracy and precision spread over decades of time. The challenge is that the current absolute accuracy is inadequate to reliably observe the small climate signals representative of climate change. Figure 4 (below) shows the variability of absolute calibration of broadband LW flux radiation budget data sets currently available for the 1980s and 1990s, and confirms the critical need for overlapping observations. This time series shows the jumps that can occur without sufficient overlap of sensors. Therefore, it is crucial to have an overlap of satellites for a period of six to twelve months in order to maintain an accurate record of radiation budget data sets from which changes in the earth's radiation balance can be detected and monitored reliably.

Science Deficits: As stated in Chapter 12 of the Strategic Plan of the U.S. Climate Change Science Program (CCSP), independent methods and observations are crucial in achieving confidence of true climate change. The CCSP concluded that a rigorous climate observing system should contain independent observations as well as independent analyses of all key climate components. High confidence in observed decadal change in cloud feedback will ultimately require climate accuracy in both cloud property and radiation budget observations to provide independent bottom-up (cloud property plus theory) and top-down (broadband radiation balance) observations of climate change.

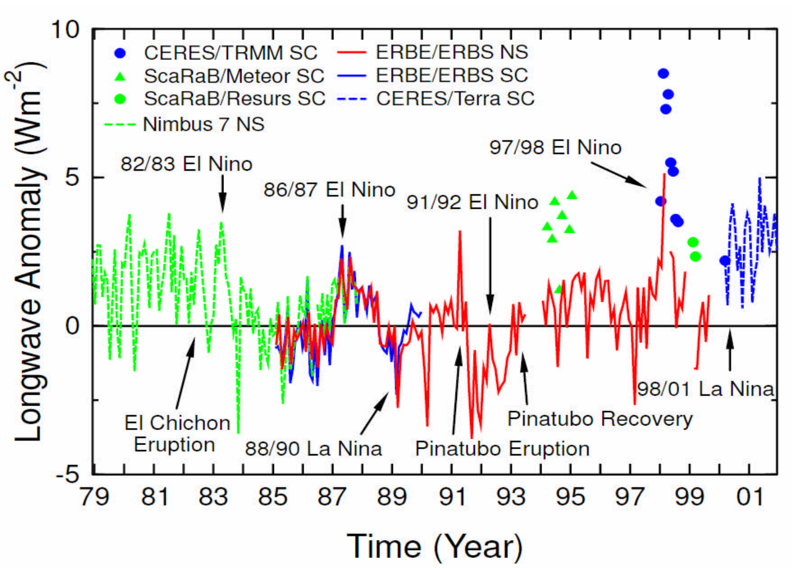

Figure 4: Satellite record of tropical mean (20°S to 20°N latitude) anomalies in broadband thermal emitted LW flux. Anomalies are referenced to the ERBS scanner baseline period of 1985 through 1989.

Recommendation: The immediate concern is the potential data gap following the Aqua Mission. We recommend that the remaining CERES instrument from the NPOESS C1 Mission be moved to the NPP Mission to provide for the necessary overlap with the present CERES instrument on the Aqua Mission and to ensure the continuity of this measurement. For missions after the planned end of NPP (2014), ERBS should be developed as an instrument fully responsive to the present science requirements for accuracy, broadband design, and adequacy of area monitored. To preserve some overlap of instruments and to achieve data continuity, ERBS should be considered for the NPOESS C1 Mission (2013 launch) and for the NPOESS C3 Mission (2018 launch).

ERBS (or CERES) data processing and analysis require sub-pixel cloud, atmospheric state, and surface information that is acquired from other sensors. Therefore, orbital co-location of ERBS/CERES with VIIRS is necessary and co-location with MIS, CrIS/ATMS, and APS adds substantial value to the measurements that are summarized in Appendix C.

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2.1.3 Ocean Altimeter (ALT)

Summary of Findings:

Essential Climate Variables: Sea level height, regional ocean currents, basin-scale variability such as El Niño.

Societal applications and impacts: Satellite altimeters are the only means to monitor spatially continuous fields of changes in global and regional sea level, as well as basin-scale and regional ocean circulations. Sea level rise is of growing concern in the coastal zone and air-sea interactions are responsible for persistent climate flood and drought anomalies such as El Niño and the Pacific Decadal Oscillation. Altimeter data are required for initializing and validating seasonal to interannual climate forecast models. Without ALT, we cannot comprehensively assess and predict rates of ocean expansion due to ice-melt and temperature change. Continued ocean expansion will likely inundate some coastal areas. Furthermore, we cannot adequately assess ocean storm intensification.

Maturity, continuity and science: Altimeter observations are planned for transition from research to operations with international partners in the Ocean Surface Topography Mission (OSTM) scheduled to fly from 2008-2011 with a possible two-year extension. Altimeter techniques are well established and considered mature, but still require overlap among missions for inter-satellite calibration.

Sensor Complements: ALT need not fly with other sensors.

NPOESS Certified Program: No Altimeter is planned

> *Pros:* Reduced costs for NPOESS Program of record.
>
> *Cons:* Loss of the ability to monitor global and regional changes in sea level. Additionally we will be unable to monitor basin-wide sea level changes and will have an inability to contribute required initialization and validation of ocean climate models.

Mitigation (Near-term): Support planning of either an operational OSTM follow-on mission (i.e., Jason-3) as a NOAA-EUMETSAT effort, or the development of a next generation altimeter (i.e., wide swath, higher resolution) as a research and development mission between NASA and the Navy.

> *Pros:* Continuity of sea level rise monitoring and seasonal to interannual forecasting and validation.
>
> *Cons*: None identified.

Mitigation (Longer-term): After the planning period, select the best option (from above) in a time frame that allows the required overlap with OSTM. Implement successive flights of missions of comparable characteristics at an interval to provide the required overlap.

> *Pros:* Allows option to choose best value after adequate planning period.
>
> *Cons:* If research sensor option chosen, technology is higher risk and Navy use will be experimental. There is the potential for a gap in coverage if the new development is delayed.

Background: The Earth's oceans, covering 70% of its surface, exert great influence on global climate. Only from space can we observe our vast oceans on a global scale and monitor critical changes in them. Continuous ocean dynamic height data from satellites like TOPEX/Poseidon and JASON help us understand the effects of the changing oceans on our climate and on significant cyclical climate events such as El Niño and La Niña. The Earth's oceans are a major sink for solar energy. The oceans transport this solar energy as heat through ocean currents and release it back into the atmosphere as water vapor and sensible heat, which is then returned back to the oceans and land as heat and precipitation. This is a major part of the water and energy cycles. In addition, global climate variability (El Niño and La Niña, the Pacific Decadal Oscillation and the North Atlantic Oscillation) affects regional ocean circulation patterns, which transport heat and other materials and change regional climate, fisheries, water quality, CO_2 uptake, etc. *Global warming is increasing sea level height through both increases in ocean volume (warming effects) and the addition of water to the oceans due to the melting ice sheets.*

Altimeters allow us to monitor changes in global and regional sea level, as well as basin-scale and regional circulation. There are a number of societal impacts that result from sea level changes. On the global and regional scales, altimetric data tracks the rate of sea level rise, which affects the people living in coastal regions and who constitute an ever increasing percentage of the human population. With a long enough record, we will be able to detect not only the rate of this rise but any acceleration in that rate. Altimeters also monitor changes in the locations of major currents, such as the Gulf Stream and Kuroshio Current, which play a critical role in oceanic heat transport. In addition, changes in basin-scale and regional currents result in changes in the nutrients and other properties of water in coastal areas, which, in turn, affect their highly productive fisheries.

***Intended Science*:** In climate science, regularly updated ocean topographical data from space-based altimetry are vital to study the role of ocean circulation and the associated thermal transport. Additionally, sea level rise determinations, assessment of the severity of hurricanes, tracking costal ocean currents, and the forecasting of natural disasters all use ocean topographical data. Direct applications of ocean topographical data can be found in operational uses as diverse as ship routing, commercial fisheries, planning offshore installations, tracking marine debris, studies of migration patterns in large marine mammals, and assessment of the health of coral reefs. For the numerical prediction of the El Niño and La Niña phenomena and their global consequences, topographical data, along with *in situ* data, provide the means for establishing the initial ocean state that is critical for such forecasts. *Besides these societal benefits, it can be argued that sea level measurements, in particular, are the climate change indicators of most direct concern for a substantial proportion of the U.S. and the world's population, most of who live near the coast.*

The assessment of present and future climate change is accomplished using coupled models of the oceanic and atmospheric circulation. These models require validation, which is accomplished by "hindcasting" the changing ocean-atmosphere system for periods in the past when we have adequate observations. The global altimetric time series of sea surface height provides the most comprehensive data set to use in these validation exercises. To forecast future changes in climate, the present state of the ocean and atmosphere must be used as initial conditions. Only the altimeter gives us the global coverage of the ocean needed for model initialization. Thus, besides monitoring and assessing the present rate of sea level rise and changes in ocean circulation, altimeter data are needed for operational forecasts of the ocean's future response to climate variability and change.

Data Heritage: After several proof-of-concept efforts, the first useful ocean altimeter was flown on the Seasat Mission in 1978. To further our understanding of ocean dynamics and marine geophysics, the U.S. Navy developed the Geosat Mission that was launched in 1985. The first mission designed for precision altimetry, TOPEX/Poseidon, was launched in 1992. It established an overall measurement accuracy of about four centimeters that proved enabling to many scientific endeavors including the study of climate variables. TOPEX/Poseidon monitored sea level rise, large-scale ocean features like Rossby and Kelvin waves, tracked the great El Niño of 1997-1998 and the subsequent La Niña, and has begun to allow exploration of possible long-term climatic trends such as the Pacific Decadal Oscillation, the North Atlantic Oscillation, and other basin-scale patterns of change. The TOPEX/Poseidon data set was continued with the JASON-1 Mission that was launched in 2001 and a follow-on mission, known as the Ocean Surface Topography Mission (OSTM), is presently in development and will be launched in 2008.

NASA has been working with European agencies (including its TOPEX and JASON partner) and NOAA to transition JASON-1 measurements to an operational status. OSTM is intended to provide an initial operational capability, with responsibility for U.S. operations handed off from NASA to NOAA after launch and on-orbit checkout. In parallel, the NPOESS IPO was working to define an operational ocean altimeter as part of NPOESS. These two approaches have different optimal orbits and the question of one system or two had not been resolved at the time of the Nunn-McCurdy Certification.

The ALT instrument in the NPOESS Program was planned as follow-on to OSTM, albeit in a different orbit. ALT was to be an operational instrument to continue OSTM quality resolution of sea surface height for Navy and NOAA operational use. However, sun-synchronous orbits, such as NPOESS uses, are not ideal for ocean altimetry because they alias tidal activity.

Critical Performance Parameters: The ALT instrument was to have the same performance as the OSTM altimeter:

- Maintain the same measurement accuracy of JASON (3.4 cm) with a goal of achieving 2.5 cm;

- Maintain the stability of the global mean sea level measurement with a drift less than 1 mm/year over the life of the mission, and

- Maintain the accuracy of significant wave height to 50 cm or 10% of the value (whichever is greater)

The more restrictive OSTM requirement for sea surface height accuracy is equal to the JASON performance of 3.4 cm. The ALT instrument (or its replacement) must maintain this same accuracy in order to continue to track the apparent acceleration of sea level rise. To achieve these levels of measurement accuracy and precision requires a non sun-synchronous orbit, a high degree of precision orbit determination using a combination of onboard instrumentation including GPS, and ground-based techniques such as laser ranging.

NPOESS Original Flights: The ALT instrument was originally planned to fly on the C2 and C5 Missions.

NPOESS Proposed Flights: There is no alternative to ALT within the NPOESS Program. The OSTM Mission will be launched in June 2008 and will provide at least three years of ocean topographical data. Without ALT, there is no planned ocean altimetry mission after OSTM.

Proposed Alternative Approaches: The primary concern of the climate community is to preserve data continuity and accuracy which requires six to twelve months overlap between comparable missions. We have identified two approaches.

To preserve data continuity, NOAA, in coordination with the Committee on Earth Observations (CEOS), is pursuing in partnership with EUMETSAT to develop an OSTM follow-on mission. A NOAA/EUMETSAT mission would use flight-tested technology to minimize cost and increase reliability and benefit from the leveraging of international cooperation between two operational agencies to produce a true example of transitioning research to operations.

From NASA's perspective, precision altimetry data, dealing with the various aspects of ocean circulation and the associated thermal transport, are critical variables in studying climate and climate change mechanisms. An advanced altimeter, capable of mapping out a wider swath on the ocean surface, and providing a significant improvement in spatial resolution, would yield important information on energy flux in the ocean through mesoscale eddies, and on coastal processes (Figure 5). An OSTM follow-on mission would only partially address these problems. Current NASA climate research requires an advanced altimeter capable of 2 km spatial resolution (about 3 times better than the OSTM nadir resolution). Such a mission could also be "backward compatible" with OSTM and, thereby, meet the Navy's operational needs and those of NOAA. Presently, NASA and the Navy are beginning the definition of such a mission and initial funding needs to be available in 2008 to initiate work on a mission that could be launched early enough to ensure no data gap after OSTM. NASA proposes that such a mission will be capable of providing Jason-type observations along track, in addition to the wider swath coverage.

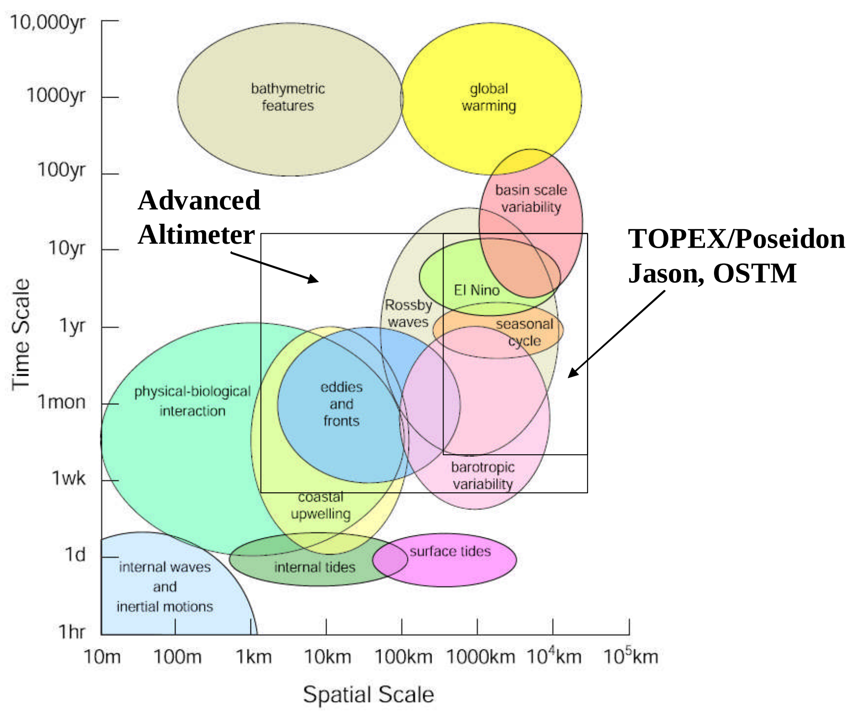


Figure 5: Capabilities of the Advanced Altimeter

Specific Performance Deficits: The certified NPOESS Program has no capability to perform sea surface height measurements.

Specific Climate Research Deficits: Ocean altimetry provides climate variables such as sea surface height, ocean circulation, ocean heat content, and sea level change.

Figure 6 shows how our present measurement capability allows sea level rise to be divided into two

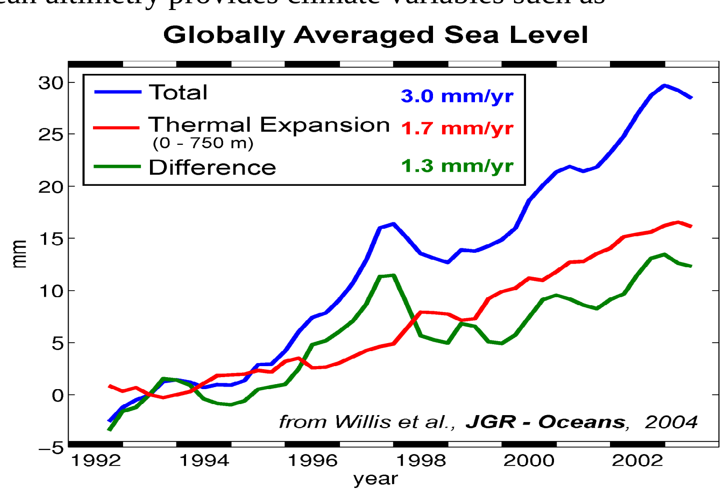


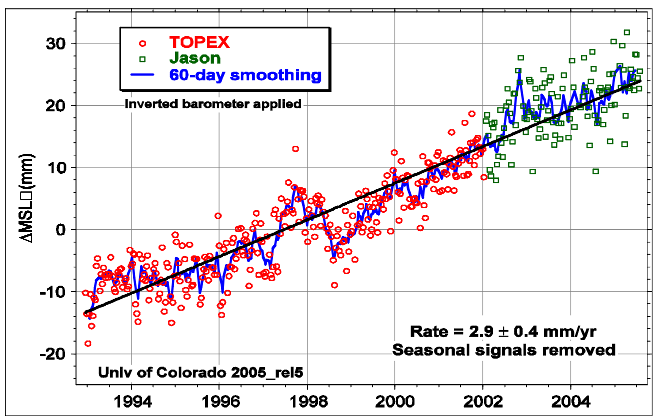
Figure 6: Sea Level Change Components

components: thermal expansion and runoff from land and ice masses. By accurately knowing sea level rise (from radar altimetry) and the component caused by thermal expansion (from measurements of the Earth's gravitational field), we can accurately estimate the magnitude of melting ice masses.

The loss of these data is unacceptable to any comprehensive program to study climate change. The study of climate variability in the oceans requires better accuracy than was planned for ALT, with precision orbit determination and the use of non-sun synchronous orbits to identify the tidal contribution to sea surface height.

Figure 7 summarizes TOPEX/Poseidon and JASON data indicating a persistent, obvious rise of the mean sea level of about 3.0 mm/year. This type of climate data record is only possible with successive, overlapping missions. OSTM will provide continuation of these data through 2011 or possibly 2012. *To avoid a gap in this critical data record, planning for a new mission with an OSTM-class altimeter needs to be started as soon as possible.*

Figure 7: Mean Sea Level Changes



Recommendation: We recommend that the continuity of ocean surface topography data be provided at levels of accuracy consistent with previous missions. The next mission should be launched in time to provide for six to twelve months overlap with the OSTM planed for launch in 2008. NOAA is exploring a partnership with EUMETSAT to extend the OSTM capability while NASA and the Navy are exploring an advanced ocean altimeter mission. Thus, the recommended near-term mitigation is to support the planning for an OSTM follow-on mission (i.e., JASON-3) as either a joint operational NOAA-Eumetsat effort or to support the development of the next generation altimeter (i.e., wide swath, higher resolution) as a research mission between NASA and the Navy. After this planning period, a decision needs to be made selecting the best option in a time frame that can allow for the required overlap with OSTM. In the longer-term, continuity in measurements throughout the NPOESS era will require successive flights of missions of comparable characteristics at an interval to provide the required overlap. Co-location of the altimeter mission with other NPOESS sensors in space provides no substantial benefit to data processing and analysis.

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2.1.4 Ozone Mapping and Profiler Suite (OMPS) Limb Instrument

Summary of Findings:

Essential Climate Variables: Global ozone observations at high vertical resolution.

Societal applications and impacts: Stratospheric ozone absorbs incoming solar ultraviolet radiation that can be harmful to humans and other organisms. The Montreal Protocol, ratified by the U.S., requires ongoing monitoring of ozone recovery. Changes in stratospheric ozone have a radiative impact on climate. The detailed vertical structure of stratospheric ozone has been shown to be a useful contributor to extended range (beyond one week) forecast in global models. *Without OMPS-Limb, we cannot assess the rate of ozone recovery and adequately inform climate models on atmospheric structure and stability, resulting in less accurate climate predictions.*

Maturity, continuity and science: Ozone limb soundings have a record of over 15 years and this specific limb sounding technology is currently deployed on the European Space Agency Envisat.

Sensor Complements: Coordinated OMPS data collection with CrIS/ATMS and VIIRS adds significant value to measurements.

NPOESS Certified Program: No limb sounder, but an ozone ultraviolet backscatter instrument to measure total column ozone and profiles remains.

> *Pros*: Cost savings from NPOESS program of record.
>
> *Cons:* Less capability to observe and predict ozone changes important for extended climate prediction and understanding and tracking the ozone hole recovery.

Mitigation Option: OMPS Limb for NPP is built but there is a need to provide for calibration, testing, and integration of this instrument on NPP enabling continuity with existing Aura measurements. We recommend building and flying additional OMPS Limb for all NPOESS platforms flying OMPS nadir.

> *Pros:* May be more cost effective to fund the currently built OMPS instrument than to cancel it. Ozone limb soundings critical to monitoring the ozone recovery and initializing extended range climate models are maintained.
>
> *Cons:* Additional funding is required to complete this mitigation.

Background: Stratospheric ozone absorbs incoming solar ultraviolet radiation that can be harmful to humans and other organisms. Anthropogenic emissions of halogen-containing gases (e.g. Freons) are now known to lead to the destruction of stratospheric ozone. The amount of global ozone has declined in recent decades with the largest losses observed in the 1980s and 1990s. The continuous satellite ozone record dating back to 1979 has been an essential element in determining stratospheric ozone trends. The Montreal Protocol on Substances That Deplete the Ozone Layer has resulted in successful international actions to reduce atmospheric concentrations of halogen-containing gases. Based on the long atmospheric lifetime of these gases, the recovery of the ozone layer should occur around 2050 in the low and mid-latitudes and 2070 over Antarctica (WMO, 2006). See Figure 8 below.

Since the onset of ozone depletion, increasing anthropogenic greenhouse gas emissions have further modified the atmosphere's composition and thereby increased climate forcing. These changing conditions have heightened the need to understand how ozone will be influenced during its recovery phase and beyond. The understanding of the ozone layer and its fate are periodically evaluated by the Scientific Assessment Panel of the Montreal Protocol via the WMO/UNEP Scientific Assessments of Ozone Depletion. *The planned continuation of stratospheric ozone observations via NPOESS is an essential component of the ongoing monitoring and evaluation of the recovery of the ozone layer.*

Intended Science: The OMPS Limb instrument provides a vertical profile of ozone that is critical to addressing our understanding of the stratospheric ozone located in the 12-30 km altitude region where most of the halogen related depletion occurs. The OMPS Limb vertical resolution (< 3 km) for ozone profiles allows the ozone structure in this region to be detected. The full global and seasonal coverage provided by the OMPS Limb instrument is essential to quantify trends in ozone and to understand the large number of factors that influence ozone amounts, which are changing in the short term (days) to long term (years) time scales. Specifically, OMPS Limb ozone measurements will document the onset of ozone recovery in mid-latitude and polar regions. Evidence of recovery is already detectable at some altitudes. The progress in recovery will be different between mid-latitudes and polar regions because of the contrasting conditions underlying ozone depletion in these regions. In addition, current climate models predict that stratospheric cooling due to greenhouse gases may hasten the return of global column ozone to pre-1980 values at lower altitudes. However, WMO (2006) cautions this would not be considered a "recovery" of stratospheric ozone from ozone-depleting gases, because perceptible depletion due to anthropogenic ozone-depleting substances will still be contributing to the ozone levels. *The global high-resolution OMPS Limb measurements are an essential component of interpreting the ozone recovery process.*

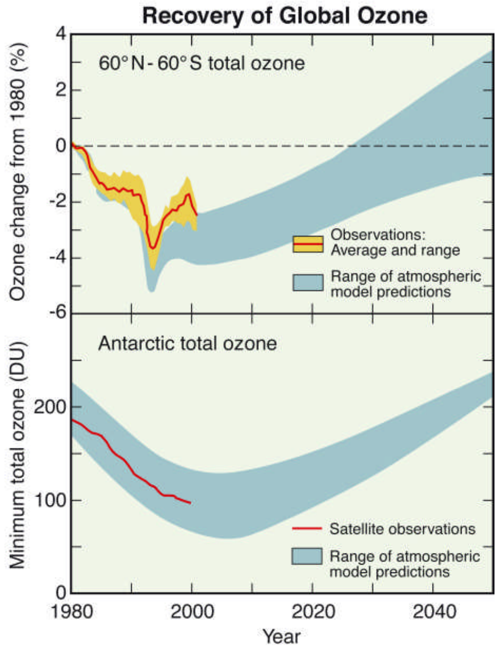

Figure 8. Observed values of global total ozone (top panel) and minimum total ozone over Antarctica (bottom panel) have decreased beginning in the early 1980s. As halogen source gas emissions decrease, ozone values are expected to increase and recover toward pre-1980 values. Model results show that recovery is expected to be significant by 2050. This figure is from the UNEP/WMO Scientific Assessment of Ozone Depletion: 2002 (WMO, 2003). The more recent assessment (WMO, 2006) indicates that Antarctic ozone recovery may not occur until 2070.

Data Heritage: Previous high-vertical-resolution ozone profile measurements were made with the Stratospheric Aerosol and Gas Experiment (SAGE I) starting in 1979, SAGE II starting in 1984, the Halogen Occultation Experiment (HALOE) starting in 1991, and SAGE III in 2001. However, all of these missions have ended. Since 2004, the Microwave Limb Sounder (MLS) and the High Resolution Dynamics Limb Sounder (HIRDLS) have been making ozone profile observations on the Earth Observing System (EOS) Aura Mission. These sensors have the potential of continuing trend quality ozone profile observations throughout the anticipated six-year mission and potentially beyond. For this potential to be realized, we must understand the long-term calibration of these sensors, which is needed to produce global trend-quality data. Beyond the completion of the Aura Mission in 2010, the NPOESS OMPS Limb Instrument was to provide the trend-quality profile observations.

OMPS Limb Instrument: The current OMPS contains two ozone measuring components: a nadir-viewing ultraviolet backscatter module and an ultraviolet/visible/near-IR limb scattering instrument. This approach was chosen as a cost-effective compromise: it provides the traditional total column and profile ozone measurements comparable to NASA's Total Ozone Mapping Spectrometer (TOMS) and the Solar Backscatter Ultraviolet/2 (SBUV-2) on NOAA's Polar Operational Environmental Satellite (POES) in the nadir module. The second instrument was designed and has been built to meet the Integrated Operational Requirements Document (IORD2) vertical resolution requirement of 3 km for the ozone profile retrievals and uses a limb scattering technique. This technique has been proven (e.g. *McPeters, et al., 2000, Rault, 2005*) and is being successfully employed on ESA's ENVISAT (SCIAMACHY) and Sweden's ODIN (OSIRIS) satellites launched in 2002 and 2001, respectively. The OMPS is being built by the Ball Aerospace & Technology Corporation in Boulder, Colorado. The first flight unit of the OMPS Limb is fabricated but, due to funding limitations, the testing and final integration will not be completed. In the Nunn-McCurdy Certification, the nadir-viewing instrument is maintained but the limb scattering instrument was de-manifested.

Critical Performance Parameters (OMPS Limb):

Spectral Range: 290-1000 nm
Spectral Sampling Interval: 2.0 pixels per FWHM (Full Width Half Maximum)
Spectral Resolution (FWHM):1.5-40 nm
Spatial Vertical Resolution (FWHM of MTF): 2.3 km
Field-of-View: 8.5 x 2.7 deg (3 slits)
Revisit time: 4 days average

Ozone Profile Environmental Data Record (EDR)

Vertical Coverage: Tropopause – 60 km
Vertical Cell Size: 3 km
Horizontal Cell Size: 250 km
Measurement Range: 0.1-16 pp mv
Accuracy: 10% (15-60km) 20% (Trop – 15)
Precision: 3% (15-50km) 10% (Trop – 15, 50-60km)
Long-term Stability: 2% over 7 yrs

NPOESS Original Fights: The OMPS Limb Instrument was originally planned to fly on the NPP Mission as well as the PM missions, C1 and C4.

NPOESS Proposed Flights: No alternative flights have been identified for the OMPS Limb Instrument. The OMPS Nadir Instrument will be retained on the NPP Mission and the new PM missions, C1 to be launched in January 2013 and C3 to be launched in January 2018.

Proposed Alternative Approach: Lower vertical resolution data are available from SBUV-2 on the Polar-orbiting Environmental Satellite (POES) and from GOME-2 on METOP. In the middle stratosphere, SBUV-2 provides 8 km vertical resolution while GOME provides 6-8 km resolution; both have poorer resolution in the lower stratosphere. Therefore, their performance is poorer than the 3 km resolution required to address the ozone structure in the lower stratosphere. The MLS and HIRDLS on Aura presently provide ozone profile estimates with 3.5 and 1.2 km vertical resolution respectively. However they are not expected to produce climate-quality data sets over the long term. OSIRIS on ODIN and SCIAMACY on ENVISAT are also research instruments and they too are not expected to produce climate-quality data sets. Figure 9 displays the ozone structure that is to be monitored and the capabilities of these instrument types.

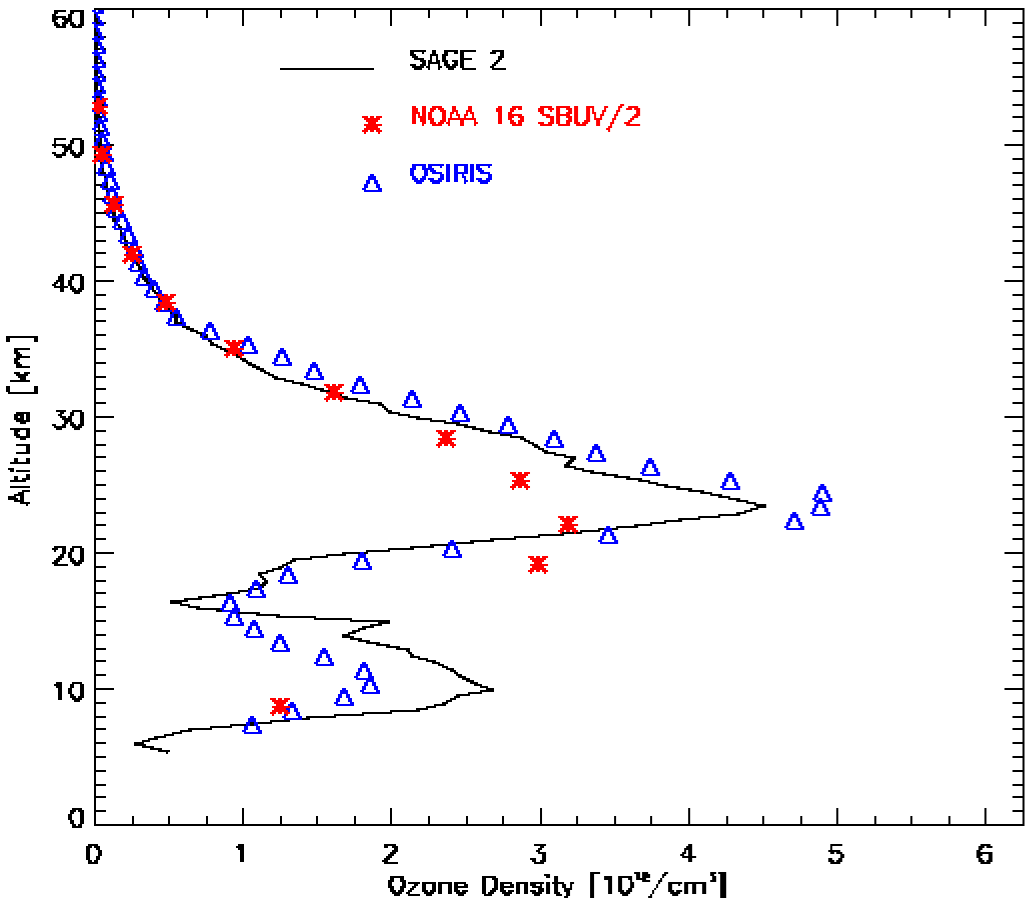

Figure 9: Near simultaneous measurements of ozone profiles inside the Antarctic Ozone hole demonstrates the vertical resolution of three observing techniques. SAGE II (occultation) has a resolution of about 1 km. SBUV-2 (nadir UV backscatter) has resolution of about 8 km with little response (i.e. missing data) in the lower stratosphere, and OSIRIS (limb scattering) has resolution of about 3 km similar to OMPS limb scattering. Differences near 10 km are due to non-simultaneity. (Data for this figure compliments of David Flittner, NASA Langley Research Center, 2006).

Specific Performance Deficit: Characterizing the structure of the ozone in the lower stratosphere requires a vertical resolution of 3 km or less and the proposed alternatives, SBUV-2, GOME-2, and the OMPS Nadir Instrument, all provide substantially poorer resolution in this region and in other regions of the stratosphere. The current MLS and HIRDLS instruments on the EOS Aura Mission provide adequate vertical resolution and they are projected to last through ~2010 but are not planned to produce climate quality data sets. After 2010 there is no identified ozone profiling instrument capable of providing the required vertical resolution.

***Specific Climate Research Deficits**:*

Science Deficit: Data from the OMPS Limb Instrument provide a vertical profile of ozone and address our understanding of the ozone in the lower to middle stratosphere, typically 12-30 km in altitude. Most of the halogen related ozone depletion occurs in the lower stratosphere and the ozone measurements need to be made with sufficient resolution to resolve the ozone structure in that region. In addition, the sign and magnitude of forcing due to stratospheric ozone loss are governed by the vertical profile change. This requires a vertical resolution of three kilometers or better that is critical for both assessing the recovery of the ozone layer due to the results of the Montreal Protocol and characterizing the further impact of a changing climate on the ozone layer recovery. Current climate change models predict upper tropospheric warming which paradoxically leads to lower stratospheric cooling that leads to even more ozone depletion in the lower stratosphere in the polar regions. Current models indicate that the ozone layer recovery will be slowed by several decades because of climate change effects. The effect is altitude dependent and most pronounced in the lower stratosphere, where nadir-viewing instruments (POES/SBUV-2 and METOP/GOME-2) lack vertical resolution and sensitivity. *Without the OMPS Limb Instrument, the vertical structure of this critical region cannot be resolved beyond the end of the Aura Mission (~2010) and this will limit our understanding of the ozone recovery progress and processes controlled by climate change.*

Data Continuity Deficits: After 2010, there is no available instrument presently identified that will provide data continuity with the Aura data set. The instrument intended to preserve data continuity with Aura was the OMPS Limb Instrument. Should this instrument or an equivalent instrument not be developed, then there will be a gap in global observations for high resolution ozone profiles that will make it difficult, if not impossible, to understand the ozone structure in the lower stratosphere in sufficient detail and, consequently, an inability to track the impact of climate change on the ozone recovery resulting from the Montreal Protocol. Some limited ground and balloon-based data will be available with high vertical resolution but these data will be sufficiently limited in spatial and temporal coverage that they cannot be used to extend global trend measurements without adding appreciably to the uncertainty, especially in poorly sampled regions.

Measurement Overlap Deficits: Measurement overlap with Aura (MLS) is critical to assess limb instrument performance and to achieve global trend-quality data. Calibration and validation using ground and balloon-based datasets are necessary but insufficient for producing global trend-quality data.

Recommendation: The OMPS Limb instrument with 3 km vertical resolution is required to address the NOAA-NASA climate goals. We recommend that including the OMPS Limb capability as a part of the overall OMPS instrument is cost-effective compared to alternative approaches.

The OMPS Limb subsystem for the NPP Mission is already built and is awaiting calibration and testing. Consistent with the Climate Change Science Program, we recommend the calibration, testing and integration of the OMPS Limb subsystem for NPP. The OMPS Limb subsystem should be included in future OMPS instruments that will be developed for NPOESS satellites C1 and C3.

The OMPS performs well in a 1:30 PM equator crossing time. The OMPS Limb measurement retrieval algorithm employs data from the OMPS Nadir instrument. Collocation of total ozone from OMPS and CrIS for intercomparisons during daylight will provide improved ozone products. This combination will also allow for continuation of the merged IR/UV ozone products currently produced from a SBUV-2 and HIRS combination. Cloud and aerosol information from VIIRS, will also improve OMPS ozone retrieval accuracy. Therefore, the OMPS Limb instrument should fly on the same platform as the OMPS Nadir, CrIS, and VIIRS instruments.

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2.1.5 Aerosol Polarimetry Sensor (APS)

Summary of Findings:

Essential Climate Variable: Aerosol type and species

Societal applications and impacts: Aerosols have a major impact on climate and climate change. The reason for the interest in aerosols is that they may be offsetting the warming by carbon dioxide and other anthropogenic greenhouse gases. Aerosols are relatively short lived in the atmosphere, so any change in emissions will have a rapid impact on climate. There are reasons other than climate that will influence human control on aerosols such as human health and ecological impacts. *Without APS, we may not be able to identify the most effective strategy to mitigate the human contribution to future climate impacts*.

Maturity, continuity and science: Global satellite monitoring of aerosols is relatively new and does not have a climate record.

Sensor Complements: Coordinated APS data collection with a wide-swath imager such as VIIRS adds substantial value to the measurements

NPOESS Certified Program: There is no aerosol polarimetry sensor.

> *Pros:* Reduces cost from NPOESS program of record.
>
> *Cons:* Impact of aerosols on climate change projections and understanding remains highly uncertain.

Mitigation: Fly APS instrument on the NASA Glory Mission. Support future aerosol research as dictated by the Glory results. Provide an additional APS on a future research mission prior to the NPOESS C3 Mission

> *Pros* – Risk of new instrument on an operational satellite is mitigated by flying it on Glory. Leaves option for platforms of opportunity to ensure a continuous measurement record.
>
> *Cons* – Additional funding is required if platform-of-opportunity option prevails.

Background: The Earth's climate is driven by the absorption, scattering, and thermal re-radiation of the incident solar energy by the Earth's surface and atmosphere (including clouds and aerosols). Diurnal and seasonal changes in the radiative properties of the atmosphere and surface affect weather. Persistent long term changes in these radiative properties, brought about in part by long-term changes in aerosol amounts, characteristics and distribution, can cause the climate to change. *Thus aerosol properties are a high priority in the U.S. Climate Change Science Program.*

Intended Science: Atmospheric aerosols are created by both natural processes and human activities. *The effects of aerosols on global temperature are significant and may be comparable in importance to the role played by "greenhouse" gases, such as carbon dioxide and methane, which contribute to the warming of the Earth's surface.* The role of atmospheric aerosols remains both poorly understood and inadequately quantified and, as such, represents a large uncertainty in attributing various possible causes of global warming (Ramaswamy et al. 2001, Schwartz 2004, Yu et al. 2006, and Penner et al. 2006). Although other space-based instruments have been used to study aerosols, the APS is the first satellite instrument dedicated to characterizing atmospheric aerosols with the requisite accuracy (Figure 10) to explore the role they play in the regulation of climate both in terms of how they affect the radiative properties of the atmosphere and how they affect clouds and precipitation. The APS is based on a successful aircraft instrument known as the Research Scanning Polarimeter (RSP) (Cairns et al. 1999) which achieved an accuracy of better than 0.2% in polarization. This represents a tenfold increase in accuracy over any previous operational remote sensing approach.

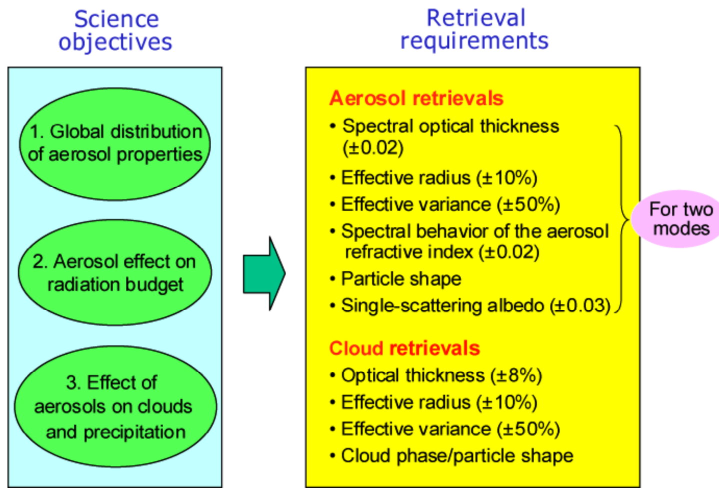

Figure 10. APS Science Objectives and Requirements

Data Heritage: The precise aerosol measurements produced by the APS have no precedents in operational satellite records. NASA's Glory Mission (planned for a 2008 launch) will carry the first Aerosol Polarimetry Sensor

***Critical Performance Parameters*:** The APS is a spectrophotopolarimeter with an IFOV of 8 mrad, swath of 6.6 km cross track and 2200 km along track, spatial resolution of 6.6 km (nadir), and a spectral range of 0.4 through 2.4 µm. The right hand side of Figure 1 defines the critical performance requirements relative to aerosol and cloud retrievals (Mischenko et al 2004) and Figure 11 (below) depicts the APS band structure. These requirements reflect the capability to characterize the physical properties of both aerosols and clouds to compare and contrast how they contribute to the regulation of climate.

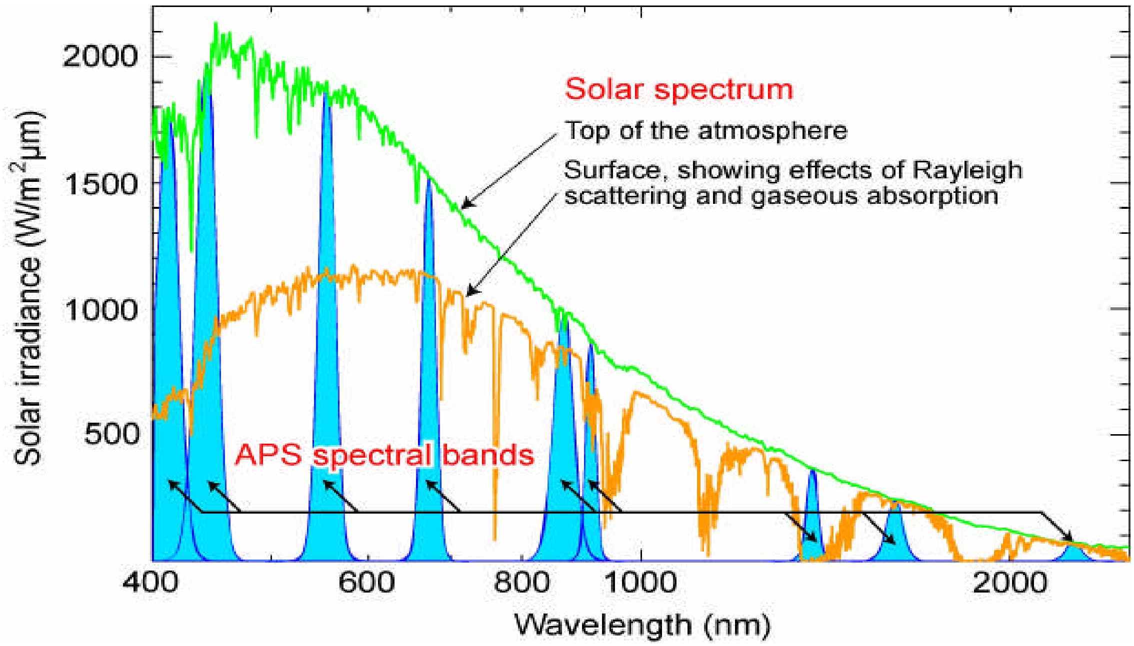

Figure 11. APS spectral channels, superimposed upon top-of-the-atmosphere and surface solar spectra.

NPOESS Original Flights: Prior to the Nunn-McCurdy Certification the APS instrument was proposed as a NASA flight demonstration to reduce the risk of subsequently flying similar instruments on NPOESS. The APS is currently planned to be flown on the NASA Glory Mission scheduled for launch in December 2008. The required life of the mission is three years with a five-year goal which would extend the aerosol measurements until 2011 as a minimum and 2013 at a maximum. Within the NPOESS Program it was originally scheduled for the C1 and C4 missions to be launched in FY 12 and FY 19, respectively.

NPOESS Proposed Flights: With the NPOESS Certification, the APS instrument was de-manifested but the capability to include it on the C3 flight would be available if the instrument could be developed outside of the NPOESS Program. The NPOESS C3 mission launches in January 2018.

Proposed Alternative Approach: No global alternative is proposed. Tests of aerosol models for some properties such as single scattering albedo could be attained by using VIIRS to provide global coverage of aerosol optical depth and a network of non-satellite measurements to provide additional point-scale information. These non-satellite measurements would include sun photometer networks such as AERONET, regular in-situ aircraft measurements, and other surface and aircraft based in-situ and remote sensing.

Alternative Instruments: No suitable alternatives exist. Other individual sensors such as MODIS, MISR, POLDER and the planned VIIRS cannot comprehensively address the aerosol problem with the requisite capability or accuracy. See Figure 10 above.

Specific Performance Deficits: All instrument performance parameters are unsatisfied since the APS is no longer within the certified NPOESS Program and no completely suitable alternative exists. The data record to be started with the Glory Mission will be interrupted or discontinued. *This is alarming in that aerosols play a significant role in climate regulation and presently represent an area of substantial uncertainty.* Moreover, what we learn about aerosols will likely complement our understanding of the physics of clouds.

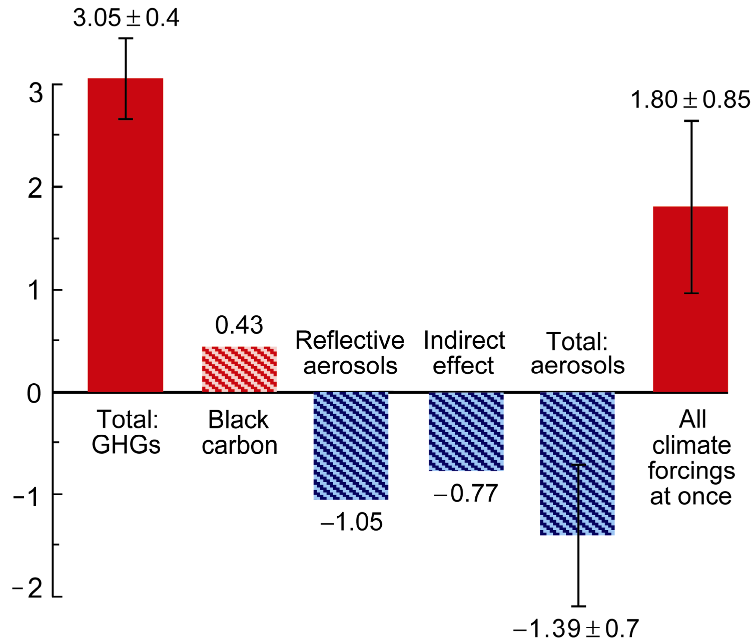

Figure 12: Estimated changes in climate forcing (W/m^2) during the period 1880-2003. A positive change means a contribution towards warming; a negative change means a contribution towards climate cooling. The crosshatched bars represent forcings addressed by the APS.

Specific Climate Research Deficits:

Science Deficits: Aerosols play an important role in establishing the energy balance for the Earth's climate system. Figure 12 depicts the components of the energy balance that the APS will investigate. Without a global assessment of the role of aerosols in the Earth's climate, significant uncertainty will remain regarding the overall effects of aerosols including the relative importance of anthropogenic and natural occurring atmospheric aerosols.

There is no alternative presently available. The experience gained with the previous satellite instruments (AVHRR, MODIS, MISR, POLDER), as well as with the aircraft prototype, RSP, indicate unequivocally that multi-angle, multi-wavelength photopolarimetry is the best remote-sensing technique available to address the aerosol uncertainty. *The APS is the first instrument designed to comprehensively explore atmospheric aerosols with the accuracy necessary to resolve the small changes representative of decadal climate change.*

Data Continuity Deficits: The data record for this type of measurement will begin with the Glory Mission in 2008. The termination or interruption of the Glory APS measurements will prevent a climatological reference record of sufficient duration from being established, and therefore prevent discovery of semi-decadal and longer cycles, trends, and patterns that cannot be resolved with a single mission.

Measurement Overlap Deficits: Measurement overlap is highly desirable and it is critical to avoid data gaps exceeding two years to achieve the climate research objectives.

Recommendation*:* Once the performance of the APS instrument has been demonstrated with the Glory Mission, we recommend that future support be given for aerosol research as dictated by the Glory results. *To avoid a lengthy data gap, one should fly the APS instrument on Glory as planned and provide an additional APS on a future research mission prior to the NPOESS C3 Mission*. APS data collections, coordinated with a wide-swath imager such as VIIRS, add substantial value to the measurements.

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2.2 Reduced Capability

2.2.1 Conical Microwave Imaging Scanner (CMIS)

Summary of Findings:

Essential Climate Variables: Sea surface temperatures, sea ice and snow cover extents, vegetation, ocean surface wind speed (and more recently wind direction), integrated atmospheric liquid water, water vapor, precipitation rates, and other surface variables to be analyzed even in the presence of heavy cloud cover.

Societal applications and impacts – The ability to observe many essential climate variables even in the presence of heavy cloud cover has been particularly important in monitoring of the polar regions where rapid climate change is taking place. Pending the new sensor design definition, we may lose the ability to assess sea surface temperature in cloudy conditions which would significantly impact climate analysis – especially as related to storm intensification. We may also lose the ability to monitor soil moisture which would diminish the potential for monitoring droughts, crop irrigation, and wildfire conditions.

Maturity, continuity and science – Microwave observations have evolved from the DMSP SSMI through the AMSR-E and Windsat/Coriolis missions. The technological challenge for CMIS was related to a large antenna and integrating so many capabilities into one instrument.

Sensor Complements: Coordinated CMIS data collections with a wide-swath imager, such as VIIRS, adds significant value to the measurement.

NPOESS Certification: The Program will seek to develop a less capable replacement for CMIS likely based on the SSMIS. No microwave instrument will fly on NPOESS C1. No microwave instruments will fly on the mid-morning orbit, although METOP will fly a narrow width scatterometer in that slot.

> *Pros:* Reduce costs for the NPOESS program of record. Certified program concentrates on already mature and demonstrated capabilities
>
> *Cons:* No microwave imager on C1 means a loss of continuity of products from AMSR-E and other potential losses, such as soil moisture and all-weather sea surface temperature measurements.

Mitigation: Monitor rescoped CMIS (MIS) requirements development. If MIS is not adequate for climate-quality measurements of precipitation, soil moisture, and sea surface temperature, identify and fund alternative instruments. Ensure imager/sounder stays on C2 as planned. Also, provide capability to continue eight-year QuikSCAT ocean vector wind measurements as soon as possible.

Pros: Potential for Climate Goals to influence MIS requirements. Allows option to diverge from MIS if it will not provide key climate-quality products and provides for continuity of QuikSCAT vector wind data.

Cons: Climate may not impact the new MIS requirements. If MIS is inadequate, then significant costs for a different microwave imager and accompanying support services will be realized.

Background: Microwave observations from satellites have allowed sea surface temperatures, sea ice and snow cover extents, vegetation, ocean surface wind speed (and more recently wind direction), integrated atmospheric liquid water, water vapor, precipitation rates, and other surface variables to be analyzed even in the presence of heavy cloud cover. The ability to obtain day and night measurements independently of cloud cover (although not in heavy precipitation), along with the coverage afforded by simultaneous flights of multiple broad-swath instruments in coordinated orbits (e.g., three SSM/I instruments are flown routinely on DMSP), are enabling global records with moderately high temporal frequency. A few of these records extend back to the late 1970s but continuous, consistent, high-quality data sets for some variables are available only since 1987. Although the spatial resolution (e.g., on the order of 25 km for 37 GHz channels at altitudes of about 700 km) is coarser than for many visible and infrared observations from space, the fact that useful measurements can be obtained under all but heavy rain conditions has made microwave radiometers particularly applicable for climate studies.

Intended Science: CMIS was intended to provide science/climate data products that will continue and enhance those mature data sets presently produced by the Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E) on the EOS Aqua Mission, the SeaWinds scatterometer on the QuikSCAT Mission, and the experimental surface vector wind data produced by the Naval Research Laboratory's Windsat/Coriolis Mission. A radiometer of CMIS-like capabilities is critical to multiple climate variables identified by CCSP and GCOS (see Appendix B), including precipitation, soil moisture, sea surface temperature (under cloudy skies), sea surface vector winds, and integrated column atmospheric properties (e.g., water vapor).

Data Heritage: The first geophysically useful space borne microwave radiometer was the Scanning Multichannel Microwave Radiometer (SMMR) that flew on the Seasat and Nimbus-7 satellites launched in 1978. They collected vertical and horizontal polarized measurements at wavelengths of 6.6 GHz, 10.7 GHz, 18.0 GHz, 21.0 GHz, and 37.0 GHz; while the SeaSat mission failed after 90 days, the Nimbus-7 instrument collected data on an every-other-day basis for most of the period from November 1978 through mid-August 1987.

NASA's SMMRs were succeeded by the Special Sensor Microwave Imager (SSM/I) instruments on satellites of the Defense Meteorological Satellite Program (DMSP), with (horizontal and vertical polarized) channels at 19.35 GHz, 22.23 GHz, 37.0 GHz, and 85.5 GHz. Note that the SSM/I instruments lack the low frequency channels of SMMR, while including the 85.5 GHz channel useful for detecting atmospheric ice particles. The first SSM/I was launched in June 1987, and the series of subsequent SSM/Is have maintained frequent passive-microwave data coverage for most of the period since June 1987. A constellation of three SSM/I instruments in coordinated orbits (ascending nodes of 1830, 1908, and 2105) has been maintained since the early 1990s.

The TRMM Microwave Imager (TMI) was launched in late November 1997 as a NASA-contributed instrument on the joint U.S./Japanese Tropical Rainfall Mapping Mission. The 350-km altitude orbit and low inclination (non-sun-synchronous) TRMM orbit provide more frequent sampling at low latitudes (between ~40 S and 40 N) than is possible from a limited constellation of sun-synchronous polar orbiting instruments. In addition, while the TRMM antenna size is similar to that of SSM/I, the lower orbital altitude results in greater spatial resolution (16 km for TMI) than was possible with SSM/I. TMI measures a 795 km wide swath. Similar to SSM/I, TMI measures at 19.4, 21.3, 37, 85.5 GHz. However, TMI also acquires horizontal and vertical polarization data at 10.7 GHz, thus allowing the estimation of sea-surface temperature that was not possible with SSM/I.

The Advanced Microwave Scanning Radiometer instrument (AMSR-E) was provided by the Japanese Space Agency NASDA (now JAXA) for flight on NASA's Earth Observing System Aqua satellite in May 2002. The AMSR-E provides horizontal and vertical polarization measurements at frequencies of 6.9 GHz, 10.6 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz, and 89.0 GHz. Its large antenna (1.6 m) allows higher resolution than previous passive-microwave instruments, and its inclusion of the 6.9 GHz and 10.7 GHz channels allows determination of sea surface temperatures, ice temperatures, and an indication of soil moisture, all also obtainable from SMMR data (at considerably lower spatial resolution) but not at all from SSM/I data.

Most recently, the Windsat instrument was launched in January 2003 onboard the Naval Research Laboratory's Coriolis Mission in an 830 km, sun-synchronous near-polar orbit. In addition to horizontal and vertical polarization measurements at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz, Windsat also acquires fully polarimetric ($\pm 45^0$ linearly polarized data and right- and left-hand circular polarized) measurements at the 10.7, 18.7, and 37.0 GHz frequencies. In principle Windsat has the ability to make accurate sea-surface temperature measurements owing to the 6.8 and 10.7 GHz channels, as well as measurements of ocean surface wind direction based on the polarimetric channels. Indeed, the primary Windsat objective was to quantify the ability of space borne polarimetric microwave radiometers to measure ocean surface wind velocity. A summary of the involved frequencies is reflected in Table 1 below.

Table 1: Satellite Microwave Radiometer Frequency Range Coverage

	Frequency Range (GHz)					
Sensor	**6.5-7.0**	**10.5-11**	**18.5-19**	**21-24**	**36-37**	**85-89**
SMMR	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**	
SSM/I			**V,H**	**V,H**	**V,H**	**V,H**
TMI			**V,H**	**V,H**	**V,H**	**V,H**
AMSR	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**
Coriolis	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**	
CMIS	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**	**V,H**

V = Vertical Polarization and H = Horizontal Polarization

NPOESS Original Flights: CMIS was originally planned to fly on all six NPOESS missions. Any gap in climate records between Aqua and NPOESS would have been somewhat mitigated by the SSM/I measurements from the ongoing DMSP sensors.

NPOESS Proposed Flights*:* The NPOESS certification will cancel the current CMIS effort and then develop new requirements for a subsequent competition. The intent of this action is to build a less expensive, less capable instrument of the same type. It is not likely that the newly defined CMIS could be made ready for the new C1 flight but it might be available for the subsequent C2-C4 flights.

Proposed Alternative Approach: The remaining DMSP missions will fly SSM/I sensors, which do not include 6 or 10 GHz channels. The DMSP missions are expected to provide coverage through at least 2017. Without a microwave imaging capability on NPOESS, climate records from microwave imagers, such as sea ice coverage, imagers will end with the DMSP missions. These measurements will provide the transition at less capability between the Aqua AMSR-E measurements and the recertified and recompeted CMIS instruments starting on C-2 in 2016.

METOP flies a scatterometer which will provide some all-weather ocean surface wind speed and direction measurements in the mid-morning. This approach covers 2006 through 2020. However, the single METOP scatterometer instrument with its two 550 km wide swaths separated by a 720 km wide nadir gap provides only 70% of the daily coverage presently obtained by the NASA QuikSCAT scatterometer mission. This would be less than 50% of the coverage originally planned for the 1700 km wide CMIS swath. The METOP vector wind spatial resolution of 50 km (with a 25 km resolution experimental product) is 2-4 times worse than that of QuikSCAT, and even worse when compared with the IORD-II and more recently developed NOAA operational requirements.

Specific Performance Deficits: A reduced capability CMIS will be procured in the future but the requirements for that sensor have not yet been defined. The value of passive microwave instruments depends on the particular frequencies included. Channels measuring at frequencies of approximately 6 GHz and 10 GHz are particularly useful for sea surface temperature and soil moisture; frequencies of 18/19 GHz, 36/37 GHz, and, to a lesser extent, 89 GHz are more useful for sea ice and snow cover; frequencies of 23/24 GHz are more useful for atmospheric measurements. The lower frequencies, 18/19 GHz and below, are particularly useful in estimating precipitation over the oceans. Frequencies of 10, 18/19, and 36/37 GHz need to be polarametric to enable the retrieval of the wind vector measurement. From a cost perspective, the 6 and 10 GHz channels, as well as the polarametric capability are more expensive to implement and, therefore, may be the most likely to be deleted in the new instrument.

Specific Climate Research Deficits:

Science Deficits: Since the specifications for the new CMIS instrument are not presently known, one can only speculate as to all of the impacts on climate research. Current studies involve critical climate variables, such as sea surface temperatures, precipitation, sea ice, ice concentration, snow water, surface wetness, wind speed and direction, atmospheric cloud cover, and water vapor. These variables must be in the requirements for the rescoped sensor. For example, the higher resolution of AMSR-E, as compared to SSM/I, has greatly benefited sea ice climate work, an area of particular concern given the rapid changes now being observed in the Arctic and northern high latitudes in general.

The GPM Mission planned to take advantage of the original NPOESS configuration to facilitate the measurement of global precipitation using CMIS. Since precipitation varies strongly in time and space, the reduced frequency of observations will have considerable negative impacts on observations of precipitation. In particular, because precipitation is a primary modulator of ocean-atmosphere interactions, degradation in precipitation observations is likely to lead to reduced accuracy in coupled ocean-atmosphere model forecasts, resulting in less accurate weather and climate forecasts.

Since the underlying wind forcing varies on short time and space scales, sampling issues for ocean surface vector wind measurements are of particular importance to NOAA for climate, as well as operational, applications and science. The low-resolution, infrequent sampling afforded by a single METOP scatterometer cannot capture the important wind forcing over the ocean; as with the present DMSP constellation, which only measures wind speed not direction. Ultimately, multiple high-resolution, broad-swath instruments in coordinated orbits are necessary to achieve the necessary coverage. Insufficient sampling will inevitably result in irretrievable, erroneous aliasing of higher frequency variability into seasonal, annual, and interannual climate time scales. Similarly, the diurnal cycle of ocean vector winds can only be resolved with four passes (AM and PM orbits). This sampling is needed to detect climatic changes in diurnal cycles, especially over the coastal ocean.

Data Continuity Deficits: *No microwave imager on C1 means a loss of continuity of products from AMSR-E and other potential losses, such as soil moisture, ocean vector winds, and all-weather sea surface temperature measurements.* It is imperative that the new imager be aboard C2, C3, and C4 as planned, to overlap with DMSP and maintain the continuity of passive microwave observations at the quality introduced in mid-1987 by SSM/I and maintained by the SSM/Is. *No gap in passive microwave observations can be tolerated.*

Recommendation: NASA and NOAA climate goals are best addressed by a new NPOESS instrument comparable to the AMSR-E on the current Aqua Mission and overlapping it in time to facilitate cross-calibration measurements. This would enable the continuation of the science supported by the AMSR-E. We recommend careful monitoring of the development of requirements for the new microwave imager. If climate-quality retrieval of soil moisture, precipitation, and sea surface temperature are removed from the rescoped CMIS, then alternative capabilities must be identified and funded. It is likely that the current Decadal Survey presently in preparation by the National Academy of Sciences will contain a soil moisture mission that could be enhanced to include sea surface temperature. When combined with an SSM/I capability either through DMSP or the rescoped CMIS on C2, the combination would approach the capabilities of the current AMSR-E. It is also important that a wide-swath imager accompany this instrument and overlap the DMSP SSM/I measurements.

Similarly, to continue the eight-year ocean vector wind record from the QuikSCAT Mission, we recommend the development of a comparable capability, probably on missions independent from NPOESS, as soon as possible. Such a capability might be added to the Advanced Altimetry Mission mentioned as a part of the ALT instrument discussion in an earlier section of this report.

2.3 Reduced Coverage, Loss of Mid-Morning Orbit

2.3.1 Visible Infrared Imaging Radiometer Suite (VIIRS)

Summary of Findings:

Essential Climate Variable: Land cover type, snow cover, leaf area, land surface temperature, fires, cloud optical thickness, cloud top pressure, cloud top temperature, cloud effective radius, aerosol optical depth, precipitable water, ocean color, and sea surface temperature

Societal applications and impacts: VIIRS provides a variety of essential climate variables that directly contribute to monitoring and prediction of climate variability and change related to land and ocean interactions with the atmosphere, climate and ecosystem interactions, and cloud feedback processes and aerosols. *Without VIIRS in the mid-morning orbit, we cannot adequately resolve fine scale phenomena, such as clouds, wildfires and sea surface temperature structure, at the spatial and temporal resolution needed for certain climate applications and models. This particularly affects areas where afternoon convective clouds are common, such as the central and western U.S.*

Maturity, continuity and science – VIIRS is an evolution of the AVHRR and OLS and similar to the MODIS on the NASA Terra and Aqua spacecraft. Although these technologies are mature, the combination of these on VIIRS is new and has been technologically challenging. The climate data records from the legacy systems however have proved invaluable to both NASA research and the NOAA Climate Mission.

Sensor Complements: VIIRS requires no other NPOESS sensors. However, co-location of VIIRS with CMIS, CrIS/ATMS, ERBS, OMPS and APS (when possible) adds significant value to measurements from those sensors.

NPOESS Certification: Relies on the METOP spacecraft with only an AVHRR in the morning orbit.

> *Pros:* Reduced costs from NPOESS Program of record.
>
> *Cons:* The loss of a VIIRS in the morning orbit will end the climate record begun by the Terra MODIS instrument which has been critical for ocean color in particular.

Mitigation: Throughout the initial METOP (A, B, C) era, we recommend flying a VIIRS-like instrument on one or more platforms in the mid-AM orbit to provide a continuous data record. For continuity beyond METOP-C, we recommend working with EUMETSAT to define requirements for a VIIRS-like imager to fly on the METOP follow-on series.

Pros: Will continue the record of MODIS in the morning orbit and help mitigate the loss of APS for aerosols.

Cons: VIIRS is a large instrument and flights of opportunity on another Earth remote sensing spacecraft are limited and there will be some added uncertainty in the confidence of the time series of several of the essential climate variables.

Background: Unique scattering and absorption of solar radiation by components of the land-ocean-atmosphere system lead to spectral signatures detectable by satellite. The spectral, temporal and angular variations of these signatures can allow both identification and monitoring of environmental features. Multispectral imagers are designed to sample the signatures in key spectral intervals. For more than three decades, scientists have depended on such imagery and derivative products for a wide variety of societal applications, including weather and climate analysis, monitoring agriculture, and disaster prediction and assessment (Justice et al., 1998).

The NASA MODerate Resolution Imaging Spectroradiometer (MODIS; Justice et al., 1998) is a moderate resolution, width-swath imaging radiometer covering the visible through thermal infrared bands. Two MODIS instruments are presently aloft: one on the Terra Mission launched in 1999 and the second on the Aqua Mission launched in 2002. Terra has a descending node at 0930 and Aqua has an ascending node at 1330 mean local time. The MODIS instruments sample most areas of Earth each day and night, and all areas of Earth within two days. These instruments have been very productive and have validated the usefulness of the measurements. They have also contributed much to the application support and algorithm development for VIIRS, a new instrument that builds on the heritage of the earlier MODIS technology. The VIIRS instrument is planned to maintain the systematic Earth observations currently being obtained by MODIS.

***Intended Science*:** Like MODIS**,** VIIRS is also a moderate resolution, wide swath, multispectral radiometer covering the visible to thermal infrared spectral range (Murphy et al., 2001). As such it will have many uses, including the detection and monitoring of finer scale features (below one km) for which it will be the only available sensor during the NPOESS era. It will also be the only NPOESS sensor capable of simultaneously measuring the spectral signature of fires, land cover type, snow cover, cloud characteristics, vegetation health and productivity, aerosols, ocean color, and sea surface temperature over the visible through the thermal infrared range.

Data Heritage: The primary multispectral image record from polar-orbiting satellites began in 1978 with NOAA's AVHRR (Stowe et al., 2002). AVHRR has five spectral bands extending from the visible to thermal infrared wavelengths. The global AVHRR data have a spatial resolution of about 4 km (1 km over the U.S. and other select regions). AVHRR has flown on all morning and afternoon orbits used by NOAA operational satellites, and is currently operational via NOAA-17 and NOAA-18.

The DoD's multispectral imager is the Operational Line Scanner (OLS). It has been in service since the 1970s; however the relevant digital data archive begins in 1992. It has only two spectral bands (one visible, one thermal infrared), and has a nominal resolution of 2.7 km. It flies in two orbits: a morning orbit and an early morning, dawn/dusk "terminator" orbit. Although it provides the operational imager heritage for the DoD, OLS was primarily designed for cloud and nighttime imagery, and therefore is of limited use to the NASA-NOAA climate goals.

The 36-band MODIS data record began in 2000 with flight on the mid-morning Terra mission. In 2002, the afternoon-pass Aqua Mission was added. Currently, both sensors are still in service and performing nominally. More than 60 geophysical products are systematically produced and archived from MODIS as part of NASA's Earth Observing System.

VIIRS Instrument: The 22-band VIIRS features a rotating telescope design to minimize stray light from the sun (Murphy et al., 2001). Each band has a nadir resolution of either 375 or 750 m at nadir. Unlike AVHRR and MODIS, VIIRS will have constrained pixel growth with view angle, potentially providing a more useful data record for climate studies. Its 3000 km swath provides a measurement of every Earth location at least once each day and night. VIIRS has onboard calibration systems for both the solar reflective and thermal infrared bands, including a deep-space port. The sensor is built by Raytheon's Santa Barbara Remote Sensing Division in California. Challenges in its development have significantly impacted the NPP/NPOESS schedule and budget.

Critical Performance Parameters:

Spectral Range: 0.3 through 14 microns

Spectral Bands:
- 22 Total:
  - Visible/ Near IR: 9 plus Day/Night Band
  - Mid-Wave IR: 8
  - Long-Wave IR: 4

Imagery Spatial Resolution: ~375m or ~750m @ nadir

Swath Width: 3000 km

VIIRS Environmental Data Records (EDRs): VIIRS contributes to 23 EDRs and is the primary instrument for 18 EDRs; these EDRs are critical to developing necessary climate data records. This product suite is the most extensive of the NPOESS sensors. VIIRS data products do not depend on measurements from other sensors but they are used synergistically with other sensors such as CMIS, CrIS/ATMS, and OMPS. VIIRS data are also used in the production of data products of other NPOESS instruments.

NPOESS Original Flights**:** A VIIRS instrument was planned for each of the three orbits in the pre-Nunn-McCurdy NPOESS Program: one on the early morning (5:30 AM local), mid-morning (9:30 AM local), and afternoon (1:30 PM local) missions. The first of these missions would be launched in 2010. Two missions were planned for each orbit with an anticipated lifetime of six years apiece, extending the VIIRS measurements beyond 2025. To minimize any data gap with Terra and Aqua, a VIIRS instrument was also included on the NPOESS Preparatory Program (NPP) Mission to be launched into the mid-morning orbit, originally planned for 2006 and subsequently planned for 2009. Although this approach meant that Terra would have to last a total of nearly ten years to achieve data continuity with NPP, this assumption was not considered unreasonable.

NPOESS Proposed Flights: In the certified NPOESS Program there are only two orbits in place of the original three. A VIIRS instrument is included on the satellites in the 5:30 AM orbit and the 1:30 PM orbit. In the 5:30 AM orbit, the NPOESS C2 launches in 2016 and the NPOESS C4 launchers in 2020. In the 1:30 PM orbit, NPP launches in 2009, the NPOESS C1 launches in 2013, and the NPOESS C3 launches in 2018. The European METOP program will provide data from the 9:30 AM orbit via the less capable AVHRR. The METOP A launched in 2006 and the B, and C missions are planned to launch in 2010, and 2015 respectively.

A VIIRS instrument on NPP was originally to fly in the mid-morning to continue the MODIS observations on Terra. NPP was subsequently moved to the afternoon orbit to serve as a back-up to NOAA N'. The mid-morning MODIS data would have been succeeded by VIIRS data from the NPOESS C2 Mission. In the new arrangement, the VIIRS instrument on NPP in the 1:30 PM orbit follows the MODIS on Aqua and this, in turn, is followed by the VIIRS on the NPOESS C1 Mission. Consequently, most studies started with the MODIS on Aqua should be continued unless unexpected data gaps occur.

Specific Performance Deficits: VIIRS appears comparable in performance to MODIS but it is not yet proven (Murphy et al., 2001). However, the AVHRR is much less capable than either MODIS or VIIRS. Consequently, the MODIS on Terra in the 9:30 AM orbit has no useful follow-on instrument because the AVHRR on METOP cannot continue most of the studies and climate data records started with the MODIS on Terra.

One notable shortcoming of the baseline VIIRS design is the absence of a 6.7 micron band. This band has proven to be highly valuable for MODIS cloud detection in the polar night and polar wind determinations, and thus leads to significant improvements in forecasting skill for polar areas. Prior to the Nunn-McCurdy Certification, this band was being considered for inclusion beginning with VIIRS instrument on the NPOESS C3 Mission.

Specific Climate Research Deficits:

Science Deficits. Although most of the scientific problems studied in the mid-AM orbit (Terra) can also be studied in the PM orbit (Aqua), many important science investigations require comparable mid-morning and afternoon observations. Comparisons of Terra and Aqua data indicate that aerosol properties and global cloud cover do not vary substantially between the mid-AM and PM orbits but cloud thickness does vary significantly and cloud particle size varies with thickness. For those scientific problems and geographical areas where afternoon clouds represent a serious interfering factor, the PM orbit may prove to be less effective than the mid-AM orbit. The mid-morning AVHRR lacks the band structure, signal-to-noise ratio, and the spatial resolution to fully compensate for the loss of the mid-morning VIIRS.

Additional gaps in ocean color measurements are caused by sun glint. These gaps can be filled with both mid-morning and afternoon VIIRS data. The Nunn-McCurdy Certification depends on the AVHRR instrument to provide mid-morning data. However, its spectral band structure is inadequate for ocean color.

Some MODIS algorithms (e.g., surface albedo) use data from both the AM and PM orbits; in those cases, algorithm performance will degrade with only PM data. Historically, scientific uses of MODIS data have focused on land cover, vegetation, surface albedo, land imagery, fire monitoring, aerosol and cloud properties, ocean color, and sea surface temperature. *The AVHRR can continue some of these studies, but most cannot continue given the major technology gap between AVHRR and MODIS. This represents the most serious shortfall of the NPOESS certification relative to VIIRS.*

Data Continuity Deficits: The NPOESS certification continues the PM record, however program delays have put the quality of the record at risk since the nominal 6-year lifetime of Aqua MODIS expires in 2008. Should the Aqua MODIS fail before the NPP launch (~late 2009), the inferior AVHRR data cannot be used to fill the data gap for all of the important climate data records. A complementary climate data record effectively began with the AM orbit of Terra MODIS in 2000. The nominal Terra mission ended in late 2005; however MODIS continues to provide climate-quality data. Once Terra MODIS ceases operations, the AM data record would degrade significantly under the certified NPOESS program since METOP's AVHRR, rather than VIIRS, would be used.

Measurement Overlap Deficits: Given the requirements for data continuity and the large number of products generated from these sensors, overlap is strongly desired when a new sensor design is flown since product intercomparisons facilitate development of seamless multisensor climate data records.

Recommendation: Throughout the initial METOP era (METOP A, B, and C), we recommend that a VIIRS-like instrument should fly on one or more Earth remote sensing spacecraft in the mid-morning orbit to provide a continuous data record. For data continuity after METOP C, we should work with Eumetsat to define the requirements for a VIIRS-like imager to fly on the METOP follow-on series.

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2.3.2 Cross-track Infrared Sounder (CrIS) used in conjunction with the Advanced Technology Microwave Sounder (ATMS)

Summary of Findings:

Essential Climate Variables: Vertical temperature and moisture profiles in clear (CrIS) and cloudy (ATMS) conditions, greenhouse gas amounts, cloud properties, outgoing longwave radiation, and precipitation (scattering signature).

Societal applications and impacts: ATMS heritage instruments (MSU, AMSU) have been key contributors to the global warming debate. Satellite measurements from these instruments have been used to test the validity of human-induced warming. ATMS ensure this climate record will continue. CrIS provides a means to assess outgoing longwave radiation, the longest climate data record used to assess trends in the global hydrologic cycle.

Maturity, continuity and science – Hyperspectral sounders have flown on research satellites and will be the basis of all future infrared sounders. Microwave technology has been used to calculate many climate data records including the tropospheric and stratospheric temperatures which have been extensively cited in climate change detection and attribution.

Sensor Complements: Coordinated CrIS/ATMS data collection with a wide-swath imager such as VIIRS adds significant value to the measurements.

NPOESS Certification: The CrIS/ATMS is not flown in the early morning orbit.

> *Pros:* The early morning orbit has only flown DMSP with the SSM (I, T, T2) and SSMIS microwave imager/sounder. A reconfigured MIS instrument should preserve this continuity.
>
> *Cons:* The loss of the hyperspectral infrared sounder (CrIS) in the early morning will limit diurnal sampling of the atmosphere. As a sensor package providing a Key Performance Parameter, a failure on CrIS or ATMS in theory triggers the launch of a new satellite. In practice, nominal performance by all other sensors on the same platform may make a new launch cost-prohibitive. In that case, no nominally-operating CrIS/ATMS suite would be in space.

No additional mitigation is proposed.

***Background*:** The CrIS is designed to work with the ATMS to produce daily vertical profiles of atmospheric temperature and moisture. CrIS is functionally a continuation of the NASA EOS Atmospheric Infrared Sounder (AIRS) instrument and follows the application heritage of the High-resolution Infrared Radiation Sounder (HIRS) instrument on the NOAA polar orbiting series satellites. ATMS is a microwave sounder that is a continuation of the present-day AMSU instrument from which vertical temperature profiles in cloudy and clear conditions, cloud characteristics, precipitation, and snow cover are derived. Following the NOAA heritage of HIRS, the CrIS can be used to produce estimates of outgoing longwave radiation.

Intended Science: Thermal and microwave sounder suites collect atmospheric data to permit the retrieval of temperature and moisture profiles on a global scale. Climate modal re-analyses require temperature and moisture sounding data to reconstruct global and regional weather patterns, storm tracks, and precipitation. The current HIRS instrument on the NOAA POES missions provides about 20 infrared channels of information and is able to characterize atmospheric temperature profiles to an accuracy of 2 to 3 degrees Kelvin. Precision re-constructions of the climate in order to examine trends and variability demand higher accuracy observations.

CrIS will provide improved measurements of the temperature and moisture profiles in the atmosphere. CrIS will provide over one thousand spectral channels of information in the infrared at an improved horizontal spatial resolution and will be able to measure temperature profiles with improved vertical resolution to an accuracy approaching one degree Kelvin per each layer of the atmosphere of one kilometer depth.

In addition, CrIS observations can accurately estimate cloud top heights, monitor the concentration and distribution of various trace gases, and be used to estimate outgoing longwave radiation which can affect climatic change, and obtain a more accurate retrieval of sea surface temperatures. The high spectral resolution can also be used to cross-calibrate the IR channels on geostationary satellites.

ATMS will have 22 channels which include all of the channels of the present-day AMSU (A and B) and MHS sensors. With the cancellation of the CMIS on C1, microwave observations from the ATMS will take on increased importance. The ATMS can retrieve surface information under most cloud conditions. Therefore, ATMS alone on C1 will be able to provide atmospheric layer temperature measurements, cloud information, precipitation, and snow cover information, albeit at a lower resolution than the CrIS or VIIRS.

Data Heritage: The CrIS and ATMS build on a long and strong heritage of NOAA sounder instruments. The ATMS will continue the microwave measurements begun by NOAA's MSU in 1979 and continued with the newer AMSU sensor. These data have been critical for improved understanding, detection, and attribution of climate trends (Karl et al., 2006). The first High Resolution Infrared Radiation Sounder (HIRS) flew on Nimbus-6 in 1975. Climate records derived from the HIRS go back to the late 1970s and will continue through 2010 as HIRS is scheduled to fly on METOP. While HIRS-3 is still operated by NOAA, the Japanese IMG, EOS AIRS, and the METOP IASI are setting the foundation for the CrIS instrument.

Critical Performance Parameters:

CrIS Specifications:

Spectral Range: 3.9 to 15.4 microns
Temperature profile: 1K per 1-km layers
Moisture profile: 20% per 2-km mean layers
1 Kelvin / 1 km layers

ATMS Specifications: Provides 22 microwave sounding channels in two frequency ranges; fifteen channels between 23 and 57 GHz and seven channels between 87 and 183 GHz.

NPOESS Original Flights: The CrIS and ATMS sensors were originally planned for the early AM (5:30) and afternoon (1:30 PM) orbits. It was understood that METOP would have a similar capability available in the mid-morning orbit (9:30 AM).

NPOESS Proposed Flights: In the NPOESS Certification, CrIS and ATMS are deleted from the early AM orbit but maintained on the afternoon orbit (NPOESS Certification Missions C1 and C3). AM data for profiles could be attained from METOP IASI instrument.

Specific Performance Deficits**:** Loss of CrIS/ATMS moisture and temperature profiles in early AM (5:30) orbit.

Specific Climate Research Deficits:

Science Deficits: The NPOESS certification removes CrIS and ATMS from the early morning orbit. Having a sounder capability in the early AM orbit would help characterize diurnal variation in moisture and temperature profiles but this is not presently considered to be a high priority for climate research.

Data Continuity Deficits: Historically, the early-morning orbit has been used by DMSP with limited microwave sounder capability supplied by the SSMT, SSMT2 and now the SSMIS. The CrIS/ATMS sounder will now be in the afternoon orbit (same as Aqua), which should provide data continuity and actually enhance the quality of the climate observations between Aqua and NPP. Moreover, METOP also provides mid-morning sounding data using the AISI/AMSU instrument suite.

Recommendation: The loss of the CrIS and ATMS from the early morning orbit has minimal impact on climate research. The additional temperature and moisture information associated with these instruments in the early morning orbit is not considered a high climate priority.

CrIS/ATMS data processing and analysis require sub-pixel cloud information as provided by a multispectral imager. Therefore, coordinated CrIS/ATMS data collection with a wide-swath imager such as VIIRS adds substantial value to the measurements.

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3.0 The Impact of Nunn-McCurdy Certification on Transforming satellite sensor measurements into climate data records

The Nunn-McCurdy Certification will significantly decrease our ability to detect climate variability versus change and our ability to understand the causes of change. The Nunn-McCurdy Certification results in the termination of critical data records and causes a number of climate data gaps. In coping with this situation, scientists need to rely on a variety of alternative and usually inferior data sets to extend and provide the missing data. In many cases, the procedures necessary to use alternative data require extraordinary efforts, especially in those cases where the alternative data are very different in character and/or quality from the data they are replacing. In spite of these efforts, the resulting data sets will have greater uncertainty than would be available from a continuous, homogeneous data set, and also have the potential to introduce larger errors into the interpretation of climate variability and change.

Numerous examples exist of our past difficulties encountered in trying to piece together a climate data record across multiple sensors and platforms. These include

- Global temperature records from MSU and AMSU data resulting from short overlaps between successive satellites [CCSP, 2006],

- Total solar irradiance across solar cycles 21 and 22 resulting from different interpretations of how to connect across satellites, and

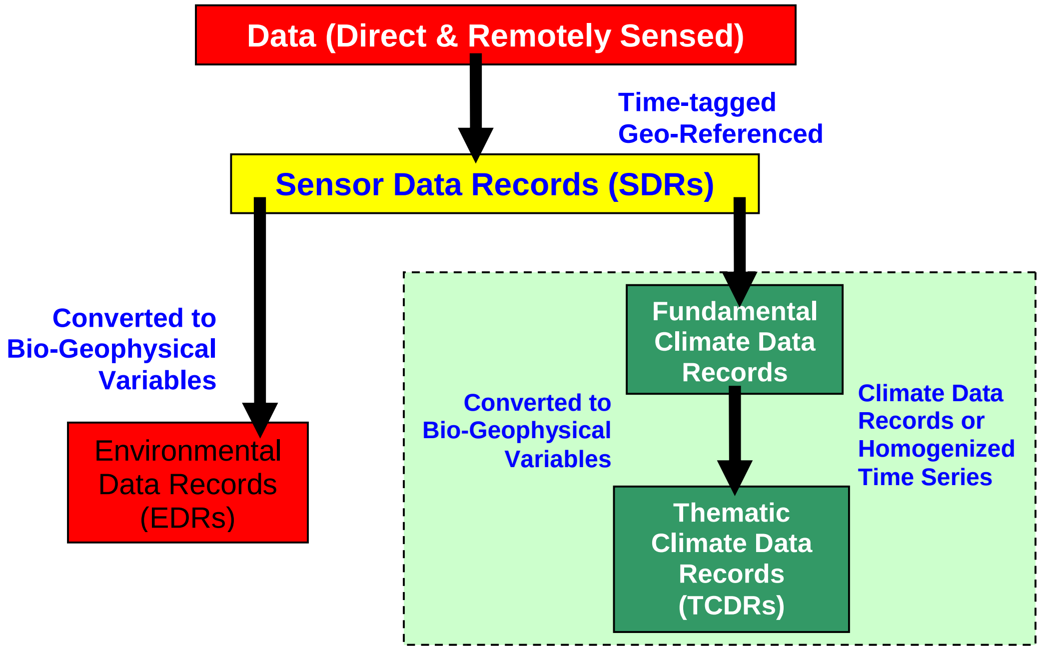
- Ozone vertical profile resulting from the ~three year gap between the first and second Stratospheric Aerosol and Gas Experiment (SAGE) instruments.

Under ideal circumstances, transforming and seamlessly merging huge volumes of satellite sensor radiances from multiple instruments flown on various satellites into Climate Data Records (CDRs)* follows well established practices. A number of these basic practices have been documented by the National Research Council (2005) along with a complementary set of principles (GCOS, 2003) that address our ability to develop, deliver, and preserve long-term data sets. The situation is made that much more difficult when there is insufficient overlap between successive measurements. Moreover, in those cases where alternative data sources are able to contribute to a CDR, scientists need to be able to critically assess their quality (including their validation and calibration procedures), have the ability to reprocess those data, and have data systems that can integrate data from multiple sources into a unified whole. All of these challenges exacerbate those present in attempting to create CDRs from less homogeneous data sets.

* A Climate Data Record is a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change [NRC, 2005]

A framework for the development of CDRs is depicted below.

Figure 13: CLIMATE DATA RECORDS



The development and maintenance of CDRs often requires the blending of an appropriate combination of satellite measurements, in-situ data, and model output. The basic principles required to deliver and maintain CDRs were laid out by NRC (2005) and GCOS (2003). The capability to construct high quality CDRs must be considered in evaluating potential approaches to recover climate data as a consequence of the NPOESS Nunn-McCurdy Certification.

References

Global Climate Observing System, The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC, GCOS-82, April 2003 (WMO/TD No. 1143).

National Research Council, 2005: Review of NOAA's Plan for the Scientific Data Stewardship Program. Committee on Climate Data Records from NOAA Operational Satellites. National Research Council of the National Academies, The National Academies Press, Washington, D.C.

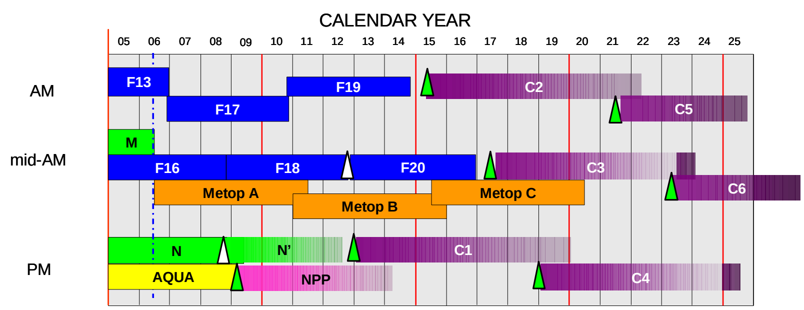
Appendix A. History of NPOESS Program

Presidential Decision Directive/NSTC-2 of May 5, 1994 established the NPOESS. This directive merged the military and civil meteorological programs into a single program. NOAA is responsible for satellite operations, the DoD is responsible for major acquisitions, and NASA is responsible for the development and infusion of new technologies.

The NPOESS Integrated Program Office (IPO) was established in late 1994. In 1999 the IPO started awarding contracts to develop the necessary instruments. In 2000 a contract was awarded to Santa Barbara Remote Sensing to develop the Visible/Infrared Imager/Radiometer Suite (VIIRS), a critical instrument within the NPOESS. In August 2002 the IPO awarded the prime NPOESS contract to Northrop Grumman (then TRW) and transitioned the sensor development efforts from government contracts to Northrop Grumman subcontracts. NPOESS is being developed under a shared system performance responsibility (SSPR) contract in which the government and contractor share both program risk and the associated decisions.

The pre-Nunn-McCurdy NPOESS missions and the sensor assignments are shown below.

Pre-Nunn-McCurdy NPOESS Program



	NPP	Early AM		Mid AM		PM	
		C2	C5	C3	C6	C1	C4
• VIIRS	x	x	x	x	x	x	x
• CMIS		x	x	x	x	x	x
• CrIS/ATMS	x	x	x			x	x
• SESS		x	x	x	x		x
• OMPS	x					x	x
• APS						x	x
• TSIS		x	x				
• CERES/ERBS						CERES	ERBS
• ALT		x	x				
• Survivability		x	x	x	x	x	x
• SARSAT		x	x	x	x	x	x
• ADCS		x	x	MetOp	MetOp	x	x

In late 2004, the IPO announced a delay in the delivery of the first VIIRS flight unit due to technical and managerial issues. The delay threatened the NPOESS Preparatory

Project (NPP) mission scheduled at that time for a launch late in 2006. NPP is a dual-purpose mission: it represents a risk-reducing pathfinder mission for NPOESS and for NASA it represents a "bridge" mission between Earth Observing System capabilities and the continuation of similar capabilities in NPOESS. As a result of the VIIRS problems, the NPOESS Program Executive Committee (EXCOM) established an Independent Review Team (IRT) for the NPP. As the IRT was completing its work in the spring of 2005, the NPOESS IPO announced further developmental issues and cost growth with the VIIRS instrument that threatened to delay the launch of the first NPOESS spacecraft known as "C1" from its targeted 2009 date to sometime as late as 2013. It also impacted the launch date of NPP that is now scheduled for launch in September 2009.

Due to the additional developmental difficulties with the VIIRS instrument, the EXCOM then established an Independent Program Assessment (IPA) for the entire NPOESS Program with cost estimates developed by the Cost Analysis Improvement Group (CAIG) within the Office of the Secretary of Defense (OSD). After an initial assessment by the IPA, DoD submitted a Nunn-McCurdy notification on September 28, 2005 indicating an estimated unit cost increase of greater then 15%. The IPA provided its final report in December of 2005 that included CAIG estimates indicating a unit cost increase of now greater than 25% that required a Nunn-McCurdy Certification.

The NPOESS System Program Director notified Congress of the breach in December 2005 initiating the six-month certification process.

During the Nunn-McCurdy certification process, ground rules endorsed by the NPOESS Executive Committee (EXCOM) stipulated that a higher priority would be placed on the continuity of legacy operational capabilities in support of weather measurements, which resulted in a lower priority for climate-focused measurements. The Office of the Secretary of Defense (OSD) led a tri-agency process culminating in the certification of a restructured NPOESS Program on June 5, 2006. The certified program is described in the following language taken from the Acquisition Decision Memorandum:

- The NPOESS Certified Program now includes the following sensors: Visible/Infrared Imager/Radiometer Suite (VIIRS); Microwave Imager/Sounder; Search and Rescue Satellite Aided Tracking (SARSAT); Cross-track Infrared Sounder (CrIS); Advanced Technology Microwave Sounder (ATMS); Advanced Data Collection System (ADCS); Cloud's and Earth's Radiant Energy System (CERES); Ozone Mapping and Profiling Suite (OMPS) Nadir; and the Space Environment Monitor (SEM);

- It does not include funding for the following sensors: Aerosol Polarimetry Sensor (APS), Total Solar Irradiance Sensor (TSIS); OMPS-limb; Earth Radiant Budget Suite (ERBS); Altimeter (Alt); Survivability Sensor (SuS); and Full Space Environment Sensors (SESS); however, the program will plan and fund for the integration of these sensors onto the satellite buses, if the sensors are provided from outside the program;

- It also terminates the Conical Scanning Microwave Imager/Sounder (CMIS), while developing a competition for a new, less expensive Microwave Imager/Sounder starting with the second EMD satellite; and

- It is now a two-orbit rather than three-orbit program that uses data from the European Meteorological Operational (METOP) satellites provided by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) for the mid-morning orbit, while providing flexibility to deploy Defense Meteorological Satellite Program (DMSP) satellites depending on the health of the constellation in either early-morning or mid-morning orbits.

Appendix B. CCSP's Earth Climate System Observations

This table provides a summary of "State" and "Forcing/Feedback" variables for the major components of the Earth system for which observations are required. It is adapted from: *Climate Change Science Program Strategic Plan Chapter 12. Observing and Monitoring the Climate System*, published by the U.S. Climate Change Science Program, Washington, DC 20006. Only measurements identified for space-based instruments are shown here. Many of these ECVs require in situ observational networks to ensure reliable and validated retrievals from space-based sensors.

(1) Atmosphere

STATE VARIABLES	EXTERNAL FORCING OR FEEDBACK VARIABLES
• wind • upper air temperature • surface air temperature • sea-level pressure (I) • upper air water vapor • surface air humidity/water vapor • precipitation • clouds • liquid water content	• sea surface temperature • land surface soil moisture/temperature • land surface structure and topography • land surface vegetation • CO_2 and other greenhouse gases, ozone and chemistry, aerosols • evaporation and evapotranspiration • snow/ice cover • shortwave and longwave surface radiation budget • solar irradiance and shortwave/longwave radiation budget

(2) Ocean

STATE VARIABLES	EXTERNAL FORCING OR FEEDBACK VARIABLES
• upper ocean currents • sea surface temperature • sea-level/surface topography • sea surface salinity • sea ice • wave characteristics • ocean biomass/phytoplankton	• ocean surface wind and wind stress • incoming surface shortwave radiation • downwelling longwave radiation • surface air temperature/humidity • precipitation (freshwater/salinity flux) • evaporation • freshwater flux from rivers and ice melt • organic and inorganic effluents (into ocean) • biomass and standing stock • coastal zones/margins

(3) Terrestrial

STATE VARIABLES	EXTERNAL FORCING OR FEEDBACK VARIABLES
• topography/elevation • land cover • leaf area index • soil moisture/wetness • soil structure/type • vegetation/biomass vigor • water runoff • surface ground temperature • snow/ice cover • subsurface temperature and moisture • land use • lakes and reservoirs • rivers and river flow • glaciers and ice sheets • water turbidity, nitrogen, phosphorus, dissolved oxygen	• incoming shortwave radiation • net downwelling longwave radiation • fraction of absorbed photosynthetically active radiation • surface air temperature and humidity • albedo • evaporation and evapotranspiration • precipitation • land use and land-use practices • deforestation • human impacts—land degradation • erosion, sediment transport • fire occurrence • volcanic effects (on surface) • biodiversity • earthquakes, tectonic motions • coastal zones/margins

GCOS' Essential Climate Variables (ECVs)

The Global Climate Observing System recently found that there remain serious deficiencies in the ability of the current global climate observing systems to meet the observational needs of the UNFCCC. In response, GCOS published a list of Essential Climate Variables (ECVs) – variables that are both currently feasible for global implementation and have a high impact on UNFCCC requirements. It concludes that achieving global coverage and climate-quality observations for ECVs is essential to ensure that the needs of the UNFCCC and the IPCC for systematic climate information are addressed.

Domain	Essential Climate Variables	
Atmospheric (over land, sea and ice)	**Surface:**	Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapor.
	Upper-air:	Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties.
	Composition:	Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[1], Aerosol properties.
Oceanic	**Surface:**	Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure.
	Sub-surface:	Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.

[1] Including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs).

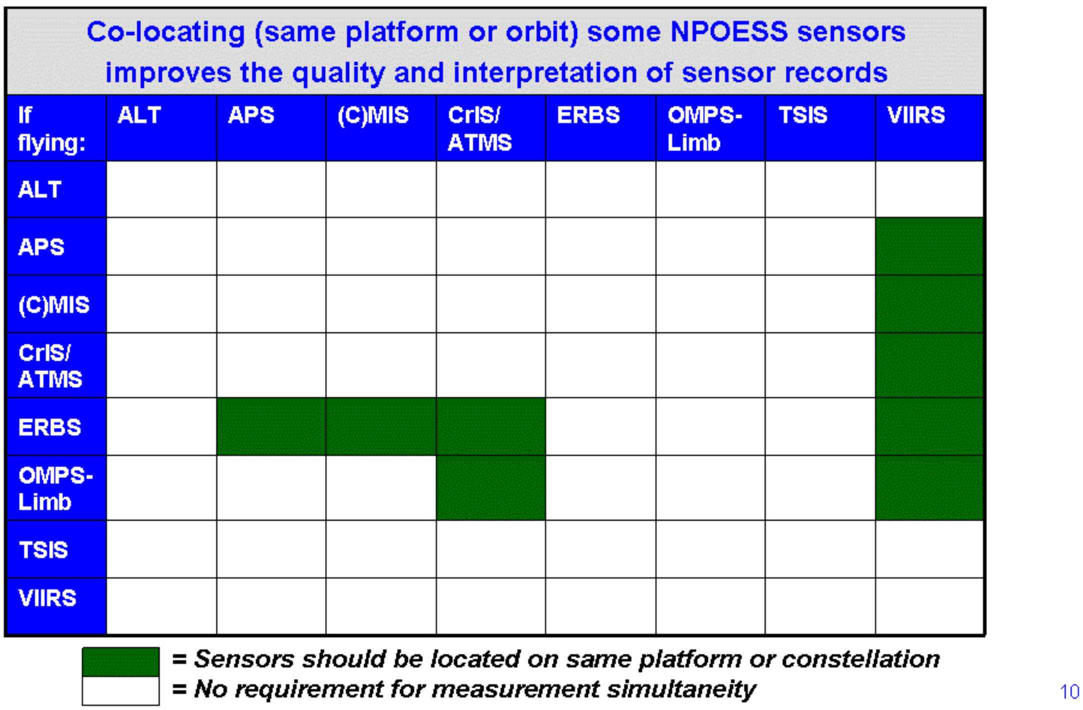
Terrestrial[2]	River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI), Biomass, Fire disturbance.

From: *The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC, GCOS-82, April 2003 (WMO/TD No. 1143).*

[2] Includes runoff ($m^3 s^{-1}$), ground water extraction rates ($m^3 yr^{-1}$) and location, snow cover extent (km^2) and duration, snow depth (cm), glacier/ice cap inventory and mass balance (kg $m^{-2} yr^{-1}$), glacier length (m), ice sheet mass balance (kg $m^{-2} yr^{-1}$) and extent (km^2), permafrost extent (km^2), temperature profiles and active layer thickness, above ground biomass (t/ha), burnt area (ha), date and location of active fire, burn efficiency (%vegetation burned/unit area).

Appendix C. NPOESS Complementary Measurements

To maximize the quality of the data records and the usefulness of the climate information, the mitigation strategies for certain NPOESS instruments can exploit sensor co-location. In this context, co-location is defined as two sensors manifested on the same satellite platform, or coordinated through flight formation (satellite constellations). The objective is near-simultaneous observations of the same geographical area. If the sensor in the leftmost column of the table (Column 1) is to be flown, its measurements should be coordinated with data collection by sensors of similar capability to those marked with green boxes to the right.



Instrument: Advanced Data Collection System (ADCS)

Societal applications and impacts: Used to transmit in-situ observations in remote areas. Critical part of the in-situ data transmission.

Maturity, continuity, and science: Mature and reliable

Sensor Complements: ADCS need not fly with other sensors.

NPOESS Certification: No impact.

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ACRONYM LIST

ACRIM	Active Cavity Radiometer Irradiance Monitor
ADCS	Advanced Data Collection System
AIRS	Atmospheric Infrared Sounder
ALT	OCEAN Altimeter
AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System
APS	Aerosol Polarimeter Sensor
ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
CAIG	Cost Analysis Improvement Group
CCSP	Climate Change Science Plan
CEOS	Committee on Earth Observation Satellites
CERES	Clouds and Earth's Radiant Energy System
CMIS	Conical Scanning Microwave Imager
CNES	Centre National d'Etudes Spatiales (French Space Agency)
CrIS	Cross-track Infrared Sounder
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
EMD	Engineering Model Development
EOS	Earth Observing System
ERB	Earth Radiation Budget
ERBS	Earth Radiation Budget Sensor
ESA	European Space Agency
ESR	Electrical Substitution Radiometer
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EXCOM	Executive Committee
FWHM	Full Width Half Maximum
GEOS	Geodynamics Experimental Ocean Satellite
Geosat	Navy mission to measure sea height launched in 1986
GOME-2	Global Ozone Monitoring Experiment-2
GPS	Global Positioning System
HALOE	Halogen Occultation Experiment
HIRDLS	High Resolution Dynamics Limb Sounder
HIRS	High-resolution Infrared Radiation Sounder
HYDROS	Hydrosphere State Mission
IFOV	Instantaneous Field-of-View
InGaAs	Indium-Gallium-Arsenide
IORD	Integrated Operational Requirements Document
IPA	Independent Program Assessment
IPO	Integrated Program Office
IRT	Independent Review Team

LW	Longwave
METOP	Meteorological Operational Satellite (European)
MISR	Multiangle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MODIS	MODerate resolution Imaging Spectroradiometer
NFOV	Narrow Field-of-View
Nimbus -7	NOAA satellite launched in October 1978
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
OMPS	Ozone Mapping and Profiler Suite
OSD	Office of the Secretary of Defense
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
POES	Polar Operational Environmental Satellite
POLDER	POLarization and Directionality of the Earth's Reflectances
RSP	Research Scanning Polarimeter
SAGE	Stratospheric Aerosol and Gas Experiment
SARSAT	Search and Rescue Satellite Aided Tracking
SBUV	Solar Backscatter Ultraviolet
Seasat	First Synthetic Aperture Radar Earth-observing Mission launched in 1978
SeaWiFS	Sea-viewing WIde Field-of-view Sensor
SEM	Space Environment Monitor
SESS	Space Environment Sensors Suite
SIM	Spectral Irradiance Monitor
SMMR	Scanning Multichannel Microwave Radiometer
SORCE	Solar Radiation and Climate Experiment
SSI	Solar Spectral Irradiance
SSMI	Special Sensor Microwave Imager
SSPR	Shared System Performance Responsibility
SuS	Survivability Sensor
SW	Shortwave
TOMS	Total Ozone Mapping Spectrometer
TOPEX/Poseidon	Ocean TOPography Experiment
TRMM	Tropical Rainfall Measuring Mission
TRW	Thompson-Ramo-Wooldridge
TSI	Total Solar Irradiance
TSIS	Total Solar Irradiance Sensor
VIIRS	Visible Infrared Imaging Radiometer Suite
WFOV	Wide Field-of-View
WMO	World Meteorological Organization

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