

CHAPTER 2

REPORT OF OPTICAL RADIOMETRIC INSTRUMENTS AND CALIBRATION PANEL

INTRODUCTION

In the Flight Technology Improvement Workshop, 16 panel members made informal presentations of their recent experiences in the calibration and use of flight data from electro-optical remote sensors in a wide range of applications and made recommendations for technology improvements to enhance future applications. These presentations were, in some cases, based on informal papers submitted for review by the panel members prior to the workshop.

A general panel discussion was held which included the measurement and accuracy needs for future missions and how these new requirements would impact the recommendations based on past experience. This discussion surfaced three general problem areas in the field of radiometric instrumentation and calibration which would form the substance of the panel's deliberations. These problem areas included:

- Knowledge of in-orbit radiometric accuracy of current and past measurements is poor even where adequate calibration standards exist
- New program requirements exceed state-of-the-art for components, calibration sources and transfer standards by significant factors
- Problems encountered in past programs have revealed inadequate pre-flight ground simulation, testing, and/or modeling which simulated in-orbit flight conditions

The available standards and techniques (ground based) and required accuracy (ground based and orbital) of remote measurements are summarized in Table 1. From these discussions and considerations a wide range of technology improvement needs were identified which will be addressed in the following sections.

TABLE 1
STANDARDS AND CALIBRATION TECHNIQUES
AVAILABLE AND REQUIRED ACCURACY OF REMOTE MEASUREMENTS

<u>Spectral Range</u> (μm)	<u>Available Accuracy</u> (%)	<u>Required Accuracy</u> (%)	<u>Applications</u>
0.12-0.2	25	1-5	Ozone Monitoring, Solar Variability
0.2 -0.4	10	1	
0.4 -1.6	5	0.5	Earth Resources Monitoring, Meteorology, Air Quality, Ocean Content, Hydrology, Ozone Monitoring
1.6-5.0	5	1	Earth Resources Monitoring, Meteorology, Air Quality, Ocean Content, Hydrology, Sea Surface Temp., Solar Variability
5.0-20	1	0.1-1	Sea Surface Temperature, Earth Resources, Meteorology
<u>Integrated Broad-Band</u>			
0.2-5.0 μm	10	0.5	Climate Monitoring
5-100	5	1	Earth Radiation Budget
0.2-100	0.5	0.1	

TECHNOLOGY DEVELOPMENT PROBLEM AREAS

Interaction with the National Bureau of Standards

Recommendations

The National Bureau of Standards (NBS) should be tasked and supported to establish, when necessary, and maintain national radiometric standards for verification of remotely sensed data applied to environmental monitoring--for at least one 22-year cycle. NBS should be tasked and supported, together with user agencies, e.g., NASA, NOAA, and EPA, to develop highly stable radiometric instruments at user facilities to allow frequent comparison of secondary standards with the primary standard.

NBS should work with user agencies to develop techniques for transfer of calibration from the national radiometric standards to particular radiometric sensors on a consultive fee basis. Application examples include:

- 1) Climate measurements, albedo change, etc.
- 2) Atmospheric constituent changes, e.g., ozone and CO₂.
- 3) Solar total and spectral irradiance monitoring.

Interagency/Intercenter Coordination

Recommendations

Recommendations for upgrading NASA expertise are:

- 1) Maintain radiometric measurement expertise at each NASA center that has radiometric sensor responsibility. Coordinate, using an OAST interagency working group. Manage, using a radiometric measurement Unique Project Number under OAST with individual Research and Technology Operating Plans at each center. Center groups would also be tasked and supported in response to short-term project requirements.
- 2) Establish and maintain NASA standards using NBS consultation. NASA standards would be maintained at selected NASA field centers and used to support NASA projects. Provide "consultation fee" support to NBS to advance the quality of NASA standards and to review as required the application of these standards. A set of national standards for remote sensing established and maintained at NBS would be used to back up these NASA standards.
- 3) Provide low-cost, end-to-end experiment concept and feasibility test opportunities using balloons, rockets, aircraft, and Shuttle. The experiments selected would be those missions where the radiometric performance required pushes the state-of-the-art. Could be used as a "fly-before-buy" competitive selection process for free-flying, long-term missions.

End-to-End System Analysis

Background

To obtain improved remote-sensor calibration, the instrument design must include total end-to-end system, including:

- 1) Flight hardware design including data processing.
- 2) Ground test equipment.
- 3) Calibration equipment and facilities.
- 4) Pre-flight test program and objectives.
- 5) Flight data reduction algorithms.
- 6) Test data reduction algorithms.

Justification

Radiometric accuracies of 3% or better require early identification of critical instrument parameters, of available primary and transfer standards

for calibration, and of the test program requirements and associated test equipment to prevent bad surprises late in development. Also, sensor system and test program outputs must meet needs of flight data algorithm to facilitate efficient and timely flight data reduction.

Recommendation

NASA management should stress early end-to-end systems analysis.

Shuttle Contamination Potential

Background

A number of radiometric instruments flown on past missions have experienced in-orbit performance degradation which is known or believed to have been caused by contamination. These include ITOS, Nimbus, Landsat, CMP, and DMSP missions. Sensors with cooled optical elements and/or detectors, radiative coolers, or thermal control are particularly susceptible, since gaseous contaminants are quickly condensed on the cooled elements. This changes their transmission and/or spectral characteristics or degrades cooler efficiency and detector responsivity. Scattering or emission of energy by particles, whether on optical elements or in the field-of-view, degrades the out-of-field rejection of sensors and introduces erroneous inputs.

Justification

Optical systems not only measure the desired phenomenon but any intervening radiation between the instrument and the desired phenomenon. Therefore, it is vitally important to reduce any corrupting radiation from optics contamination to an absolute minimum. Numerous NASA and DOD experiments such as C System on DMSP, Filter-Wedge Spectrometer on Nimbus 4, Block 5A line scanner on DMSP, Very-High-Resolution Radiometer on ITOS, Surface-Composition Mapping Radiometer on Nimbus 5, and Multispectral Scanner (MSS) on Landsat 1 have been moderately to severely affected due to contamination within the measurement environment. Current NASA and DOD payloads such as Infrared Astronomical Sensor (IRAS), Shuttle Infrared Test Facility (SIRTF), and Satellite Infrared Sensor (SIRS) are all much more susceptible to contamination due to their sensitivity and out-of-field-of-view rejection requirement than any previously flown sensors.

Since most future space missions will use Shuttle as the sensor platform, the cleanliness of Shuttle will be critical to experiment success. Studies by optical-sensor engineers of the Shuttle contamination sources have led to extreme concern about using it as a sensor platform. Incomplete specifications appear to have been placed on surface cleanliness, outgassing of Shuttle materials, and contamination by waste from the onboard systems. An early Shuttle experiment on cleanliness has been planned, but there is considerable apprehension about the ability of this experiment to measure the levels, types, and distances from the Shuttle of the contaminants required by

optical engineers. This has led this Panel to recommend that an immediate review of Shuttle contamination and its effects on optical sensors be accomplished.

Approach

Conduct a study dedicated to inventorying the materials and consumables employed by Shuttle and the contamination buildup likely during fabrication, testing, transportation, etc., and evaluation of the in-orbit environment resulting from this contamination, outgassing, and release of wastes, consumables, etc. The study should address the various payload configurations, be based on other similar studies which have been completed or are underway, and should evaluate the applicability of results from currently planned Shuttle Contamination Experiments for guidance in designing future remote sensors. The contaminants which are identified should be evaluated as to their effects on radiometric systems, components, and in-orbit performance.

Recommendation

A comprehensive evaluation of the Shuttle contamination environment must be made, and its effects on radiometric systems and accuracy assessed. This evaluation must address both particulate and gaseous contamination.

In-Orbit Performance of Previously Flown Remote Sensors

Background

Significant changes in radiometric response and/or calibration have been observed during space missions with several instruments such as BUV, ERB 6 and 7, and MSS, which have flown aboard several spacecraft. While some of the observed changes have been explained (e.g., BUV diffuser contamination) and avoided on subsequent missions, there are no satisfactory explanations for others (e.g., ERB 7 solar channels 6 through 9).

Justification

Measurement requirements for planned Climate and Solar Monitoring related missions impose increasingly more severe accuracy and stability criteria on planned and future radiometric systems. A compilation of past history covering a range of sensors and a correlation of observed changes with wavelength, materials, environment, etc., will be of significant value to radiometric sensor designers and evaluators.

Approach

A study should be commissioned to compile performance and descriptive data on remote sensors flown on past NASA and NOAA spacecraft which have exhibited apparent in-orbit changes of radiometric performance. Scope of the study should include data on pre-launch calibration, and on instrumentation,

auxiliary measurements, etc., used to evaluate in-orbit performance in addition to configuration of the sensor hardware.

Recommendation

A study is needed to compile a history of changes of responsivity/calibration during past flight missions and to attempt classification of observed degradation with environmental exposure and/or optical materials, electronics, detectors, coolers, etc.

Calibration Standards

Justification

A radiometric accuracy 10 times greater than currently achieved is necessary to meet remote sensing requirements, which requires:

- 1) Improved transfer capability from national standards.
- 2) Working standards that are usable in simulated and natural space environment.

This high accuracy is essential for detecting small but significant changes over long periods of time in environmental parameters. Current capabilities vs. requirements as a function of spectral region are shown in Table 1.

Approach

Support establishment and maintenance of improved standards:

- 1) National radiometric standards.
- 2) NASA working standards -- integrating spheres and solar simulators.

Support development of improved calibration transfer techniques and instruments:

- 1) Self-study manual documenting principles and techniques.
- 2) Instruments accommodating large differences in:
 - a) Field-of-view, area, polarization, and spectrum.
 - b) Environmental parameters and vacuum/air.

Recommendations

Develop improved primary standards as required to establish a complete set of National Standards for Remote Sensing at NBS which covers the spectral range from 0.12 micrometers to beyond 50 micrometers.

Develop NASA Calibration Standards to meet NASA program requirements and permit sensor-system calibration to required accuracy under realistic measurement conditions. This activity must include joint NASA/NBS activities to apply existing primary standards to systems test activities without unacceptable loss of accuracy.

In-Flight Calibration References

Background

To verify the calibration in orbit, a number of sensors have incorporated internal radiometric reference sources. The most stable and consistent to date have been sources for thermal IR channels using temperature monitored or controlled blackbodies. Major problems have been encountered with calibration lamps for the shorter wavelengths because of filament aging with use; tendency for heated filaments to creep or move, thus changing the efficiency of the calibration source; and susceptibility of envelope or focusing optics to contamination. Several sensors have employed diffuser plates for indirect solar viewing as an in-orbit calibration. Diffuser-plate coatings have shown changes with time due to solar UV impingements and to contamination, or combinations thereof. Conventional diffuser-plate outputs are also sensitive to illumination and/or viewing angles which introduce additional uncertainties.

Justification

The advent of the Shuttle as a measurement platform presents a critical problem from the standpoint of sensor contamination by the spacecraft environment. Knowledge of the degradation that results from this contamination is vitally important. The magnitude of the degradation is measurable using in-flight calibration sources. However, if the calibration source is not stable, then the amount of performance degradation becomes uncertain. Current in-flight sources are not adequate for monitoring these degradations. Extended mission lifetimes compound the problem and further justify the need for stable sources.

Approach

Suggested measures to improve in-flight calibration are:

- 1) Qualify on-board calibration sources with life tests.
- 2) Investigate contamination, degradation characteristics, and stability of diffuser plates.
- 3) Develop new and improved calibration lamps.
- 4) Investigate new and improved materials and techniques for in-orbit solar reference.

Recommendation

Develop in-flight reference sources to monitor radiometer instrument performance and responsivity in orbit, for use at all wavelengths from the near UV to LWIR.

High-Attenuation Neutral-Density Filters

Background

In the calibration of low-background, high-sensitivity IR radiometers such as IRAS, SIRTf, COBE, and CLIR, standard blackbody sources operating at 500K are typically employed against a room temperature (approximately 300K) background, and the input to the sensor is attenuated by several orders of magnitude, using neutral-density filters to represent the expected space measurement conditions. The uncertainties in knowledge of the spectral flatness and attenuation characteristics of the filter over the required spectral range and in the entrapment of scene energy reflected from the filter face limit calibration accuracy to 20-30% currently.

Justification

The calibration accuracies attainable for low-background, long-wavelength IR sensors are significantly poorer than those achieved for sensors making measurements of average Earth background levels and temperatures. To facilitate laboratory test and calibration of remote sensors for measuring astronomical parameters and diurnal atmospheric-constituent surveys, very low-transmission, neutral-density filters having known characteristics within 1-5% accuracy will be required.

Approach

Develop improved filters which are spectrally flat, with high attenuation across broad ranges of the IR spectrum; and develop improved laboratory facilities to characterize such filters to approximately 1% accuracy.

Recommendation

Develop improved high-attenuation neutral-density filters for use in calibrating low-background, very-high sensitivity radiometric instruments.

Solar Testing Facility

Background

While laboratory procedures using stabilized lasers as stimuli provide valuable complementary information on the properties of instrument components

(e.g., the reflectance of cavity sensors), definitive testing of pyrhemometers must be performed using the Sun as a source. Use of the Sun may be more advantageous for more accurate calibration of solar occultation sensors, such as HALOE and SER, which are now being developed. The advantages are that the spectral distribution, total irradiance level, and solid angular subtense of the irradiance are close to that of the Sun in space, which is the source that the instrument is designed to measure.

Justification

Characterization and comparison of solar measurement instrumentation using the Sun as a source provide a definitive verification of accuracy in realization of SI units; correlation of results from different flight experiments; and demonstration of pre-to-post-flight performance for flight sensors.

Approach

With the addition of vacuum chamber capability, the existing building, structures, and solar tracker at the NASA/JPL facility at Table Mountain, CA will meet the basic requirements.

Recommendations

Develop a solar testing facility for multi-project use to characterize instrumentation and provide systems test capability using the Sun as a radiance source. The facility should be obtained by modification of the existing JPL Table Mountain Test Site in California.

Systems Calibration Facility

Background

NASA has generally provided test equipment, facilities, procedures, etc., as a part of the specific project development, with limited carryover and use of equipment previously developed. DOD has established calibration and test facilities at Arnold, Naval Ocean Systems Center, and at McDonald-Douglas Corporation, which have received wide use with successive generations of flight sensors of a similar type and application. With the repetitive flights required by NASA to obtain climate-type data, it will be more efficient to establish a facility at a selected location to assure "normalized" calibrations.

Justification

To meet the increasingly stringent accuracy requirements for data sets compiled from multiple-flight missions, improved calibration standards and transfer standards and techniques are required. Calibration activities

conducted by experienced personnel supplemented by periodic verification of working standards, etc., can be most efficiently obtained by establishing a common test facility which carries out continuing calibrations and tests, as required.

Approach

A facility capable of providing 1% flight measurement accuracy and having the following characteristics is needed:

- 1) In scope, the facility would be similar to setups available to DOD, expanded to solar spectral range, but scaled down to NASA sensitivity requirements.
- 2) Sized to accommodate entire flight sensors in simulated (static) flight environment.
- 3) Target is of known radiometric characteristics (spatial, spectral, temporal, and polarization).
- 4) Traceability to NBS national standard is established periodically using transfer standard.
- 5) Adaptable to measurement of critical sensor parameters.
- 6) Contamination controlled.
- 7) Permanently and continually maintained; staffed with personnel skilled in critical transfer radiometric techniques.

Recommendations

Establish a dedicated test facility for each of the sensor types, e.g., ERB, Limb-Scanned IR, BUV, Solar Monitoring, etc., planned for repetitive, continuing use on flight missions in order to allow more efficient and more complete testing of flight systems.

Analytical Design Tools for Stray-Light

Background

Currently planned and future space-flight radiometers, such as those for the Earth radiation budget, are required to have absolute accuracies and precisions on the order of 1% and 0.1%. These radiometers are often carried on "bus" satellites which are comprised of several experiments, antennas, solar panels, etc., and consequently constitute potential out-of-field scatterers and/or emitters of energy. Early determination of instrument parameters critical to characterizing sensor field-of-view and out-of-field rejection are necessary to achieve the required accuracies within reasonable cost and schedule. Analytical programs, e.g., GURAP (General Unwanted Radiation Analysis Program), are available; however, they are cumbersome to use and terribly expensive to execute. For these reasons,

a number of sensors have required design modifications during the testing phases to eliminate experimentally detected out-of-field response which had not been predicted during the design phase. Other sensors have exhibited "stray-light" problems during flight missions.

Justification

The Climate and Earth Radiation Budget experiments are currently establishing radiometric requirements an order of magnitude beyond those achieved to date. These requirements include data over long time durations requiring multiple flight missions. The sensors are flown on operational satellites to minimize cost, and these platforms (e.g., TIROS-N) have many sources of stray radiation, such as antennas, which will compromise both precision and accuracy. The use of Shuttle as a measurement platform will pose multiple stray-light problems, both from the airframe structure and other payload elements, and from particle scattering from the contaminated environment. Far infrared astronomical and DOD sensors will be particularly sensitive to these sources as well as to energy from the Earth, Sun, and other bright out-of-field sources. In summary, currently planned missions will require better understanding of, and designs for, rejection of stray radiation.

Approach

Existing analytical unwanted-radiation programs should be validated from an optical standpoint and should be modified to improve computing efficiency and reduce user cost. Their ability to handle diffraction effects must be improved.

Recommendations

Develop improved analytical design tools to assure adequate rejection of out-of-field-of-view energy (stray-light) with electro-optical system designs for use under conditions of strong backgrounds.

Systems Level Stray-Light Test Facilities

Background

The stray-light testing of sensors has historically been handled by each project individually as a part of test and calibration. This limits the funds available for test equipment, etc., and has limited tests and test conditions severely. DOD has attempted to provide a more complete capability for multiple IR sensor use at Arnold. NASA earlier had established a visible, near IR facility at General Electric for the OAO star trackers where severe requirements existed. Increasing accuracy requirements for NASA sensors will require that much improved test facilities again be developed.

Justification

The increasing need for high-accuracy sensors which operate in the presence of out-of-field rejection. (See also recommendation for improved analytical design tools).

Approach

Develop dedicated facilities for multi-project use to determine experimentally sensor-system sensitivity to stray-light. Separate facility may be required for visible near IR spectral regions and another for thermal and longwave IR spectral regions. Facilities will largely use components and techniques currently within state-of-the-art, however, and must be configured to allow efficient testing of remote sensor systems under anticipated viewing conditions. Current capabilities to measure specifically the bidirectional reflectance distribution function of materials, surfaces, cavities, etc., must be extended to small angles both to provide sensor design information and to allow validation of system level test facilities.

Recommendation

Develop facilities for experimental determination of the out-of-field-of-view rejection of remote sensor systems.

Spectrally Flat Detectors

Background

The ERBE program has specific scientific requirements for flight detectors which have the following parameters:

- 1) Spectral response uniform to within $\pm 1\%$ over the range of 0.2 to 50 mm (this can be practically achieved only with an absorptivity of 93% over the spectral range).
- 2) Fields-of-view up to 150 degrees
- 3) Minimum sensitivity to degradation by environmental contamination.
- 4) Sensitivity up to $D^* = 3 \times 10^8 \text{ cm-Hz}^{1/2}\text{-watt}^{-1}$.
- 5) Response time constants as short as 10 milliseconds.

For ERBE and other broadband spectral instruments, the weak link in the calibration chain is the short-wavelength calibration for wide fields-of-view. In the absence of a spectrally flat transfer standard detector, long-wavelength radiation cannot be equated with short wavelength radiation, and we must depend on a long and tenuous radiometric traceability path of transfer standard radiometer measurements of white coated reflective plates

which reflect uncertain tungsten or xenon arc lamp sources, to either the World Radiometric Reference or the International Practical Temperature Scale.

Justification

Previously used flat plate thermopile, thermistor, and pyroelectric sensors have shown deficiencies in all the above-mentioned requirements and probably will not meet ERBE requirements.

Secondly, if an electrically-calibrated, wide-field radiometer, having greater than 98% absorptivity and uniform spectral responsivity from 0.2 to 50 mm could be developed, such a radiometer could accurately characterize the existence of a short-wavelength reflective plate on an absolute basis without requiring long and tenuous radiometric traceability to either the World Radiometric Reference or the International Practical Temperature Scale.

Approach

Develop a family of active and/or passive cavity sensors whose designs are optimized for specific measurement requirements.

This development should yield detectors for ERBE flight instruments as well as transfer standard radiometers for use in absolute radiometric calibration at all wavelengths, thus addressing deficiencies in the general calibration areas.

Recommendation

Develop a family of spectrally flat, high-absorptance, wide field-of-view sensitive detectors having a true cosine response for use in flight sensors and in the laboratory.

Long-Term Stability Sensor Components

Background

Some components degrade with time in an unknown manner resulting in uncertain instrument accuracy. Examples of component degradation include:

- 1) Blue haze on super-polished mirrors.
- 2) Severe degradation in orbit of solar attenuators on BUV and ERB due to solar UV and other environmental factors.
- 3) Suprasil changes on ERBS 6 due to UV.
- 4) Degradation, spectral shifts, out-of-band transmission, and excess scattering for spectral filters and coatings.

Justification

Extended operation in space and some observed degradation have resulted in uncertain instrument accuracy. New planned programs demand even greater accuracy and, in some cases, even longer duration missions. The problem of stability verification of self-calibrating radiometers to the 0.1% relative accuracy level is extremely difficult and requires development of new technology and techniques to realize the total of 1.0% accuracy of data over a 22-year period. The establishment of long-term stability of the radiometers used in the Solar Monitoring Program is critical for the success of the program.

Approach

Investigate changes with widely-used material and components, develop new improved components and materials that match new system requirements, and provide long-term stability in orbital performance. The following Table lists a number of components which need early study and consideration.

TABLE 2 - Required Component Developments

Component	Problem	Recommendation
Onboard calib. source	Long-term stability	Qualify with life tests
Reference solar diffuser	Unknown in-orbit degradation	Investigate contamination and stability
Suprasil optics	In-orbit degradation	Investigate and characterize
Very low scatter mirrors	"Blue haze" phenomenon	Investigate and control
Spectral filters and coatings	Degradation, spectral shifts, out-of-band transmission, and excess scattering	Develop better filters
Detectors and preamplifiers	Stability and linearity over very large dynamic range	Develop for new program requirements

Recommendation

Investigate long-term stability of optical components, spectral filters, detectors, and in-flight reference sources under typical laboratory and space flight environments to increase accuracy and minimize in-orbit degradation of future sensor systems.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

As a result of the workshop, a number of conclusions were reached, some of which assess the current radiometric-sensor state-of-the-art vs. requirements, some that indicate NASA should make changes in policy and procedures to facilitate improved communication and interactions with other government agencies and between NASA centers, and some detailed conclusions and recommendations as to needed improvements in technology. These conclusions are summarized as follows:

NASA Policy and/or Procedural Changes

1) A standing interagency and intercenter committee should be established to maintain cognizance of radiometric calibration requirements, capabilities, and new technology needs within NASA and NBS. DOD and NOAA members may also be desirable.

2) A centralized radiometric measurement and calibration expertise group should be developed and maintained at each NASA center responsible for radiometric sensor development and application. These expertise groups would be individually supported by the Office of Aeronautical and Space Technology (OAST) and would be responsible for assuring the proper application of calibration standards to each remote sensor system. They should each be represented on the interagency standing committee, which would coordinate their activities.

3) NBS should be supported and charged with establishing and maintaining a set of National Standards for Remote Sensing as a primary base for calibrations of all sensors.

4) NASA Calibration Standards should be established at selected NASA centers to support remote measurement projects. These standards would be developed by NBS and/or NASA, with "consultation fee" support provided to NBS for its development, improvement, and periodic verification. Similar NBS support would be required to help establish procedures and techniques for applying NASA Standards to specific systems. For this latter purpose, the committee feels NASA should support further development of the NBS Self-Study Manual on Optical Radiation Measurements (NBS Technical Series) as reference material.

5) NASA should consider a program to provide more accessible "low-cost" flight opportunities for feasibility and "end-to-end" testing of measurement concepts, instrumentation, and software prior to committal to long-term, free-flyer missions. Balloons, aircraft, rockets, or Shuttle would be used to verify performance of systems requiring significant advances in radiometric state-of-the-art before undertaking development of more expensive long-term Class A or B missions.

6) NASA program and project management should stress the use of "end-to-end" system analysis and design early in the design phase of radiometric

system development. This effort would include all measurement aspects from the observed source characteristics and sensor environment through the data reduction requirements for ground-test and flight data. Pre-launch ground testing and calibration should realistically simulate flight measurement conditions and environment for maximum confidence and accuracy.

Needed Improvements in Technology

1) A much-improved knowledge of the Shuttle contamination environment and an evaluation of its potential impact on radiometric sensors is urgently needed.

2) Compilation and analysis of data from past missions which exhibited evidence of in-orbit calibration changes or performance degradation will provide valuable design data and criteria for future development of more accurate radiometric instruments.

3) Primary radiance and irradiance standards currently available for radiometric calibration are not adequate to meet requirements for planned and future missions. Accuracy limitations are most severe in the short-wavelength region ($\leq 5 \mu\text{m}$).

4) Much improved calibration transfer standards and techniques are required to take advantage of existing primary standards and obtain improved calibration accuracy for remote sensor systems.

5) Improved in-flight calibration sources are required to monitor in-orbit performance of remote sensors. As with primary standards, present accuracy is worst in short-wavelength regions.

6) High-attenuation, spectrally-flat, "neutral-density" filter technology is inadequate for calibration of low-background, low radiance-threshold sensors for astronomy and defense measurements.

7) A facility is badly needed to allow ground calibration of pyrheliometers and solar occultation sensors while operating in a vacuum environment and viewing the solar disc.

8) Dedicated calibration facilities should be established for each of the remote-sensor types or categories (e.g., Earth radiation budget or solar monitoring) which are planned for continuing applications. Such facilities would permit more efficient and more complete testing and calibration of each of the sensors while providing traceability of the multiple calibrations to reference standards.

9) More efficient analytical design tools to evaluate the out-of-field-of-view rejection ("stray-light" sensitivity) for remote-sensor optical systems are badly needed. Lack of flexibility and high computer costs limit use of currently available tools during the design phase. This often leads to expensive redesign late in the program and occasionally compromises in-orbit performance.

10) Development of a dedicated facility to permit experimental evaluation of remote-sensor "stray-light" sensitivity would allow more complete testing and probably reduce costs for NASA-wide sensor testing.

11) The development of a family of wide-angle, spectrally-flat, "self-calibrating" detectors is urgently needed for both flight and laboratory applications. They would allow much improved flight measurements for Earth-radiation budget and other climate-related applications. These detectors will also facilitate the development of calibration transfer techniques and standards for laboratory calibrations of sensor systems.

12) The stability of the spectral, transmission, reflection, and scattering characteristics of state-of-the-art optical elements including mirrors, filters, etc., must be investigated to provide design and testing criteria for future remote sensors of higher radiometric accuracy and performance.

Radiometric Needs Versus State-of-the-Art

1) Measurement requirements imposed by the planned climate-related flight missions include radiometric accuracy and stability which is improved more than one order of magnitude over current experience. This is particularly true for Earth radiation budget parameters requiring very high accuracy to relate data obtained over long time spans (> 22 years) and from multiple flight missions.

2) Experience indicates that our knowledge of the in-orbit radiometric accuracy obtained from past missions is poor, even where adequate primary calibration standards are available. A primary contributor to this fact has been inadequate pre-flight ground simulation, testing, and/or modeling of the sensors to represent realistically the in-orbit measurement and environmental conditions. Another factor has been use of inadequate calibration transfer standards and/or techniques to interface the sensors with available primary standards during ground calibration.

3) Requirements for low-radiance threshold measurements for astronomy and for defense-related parameters impose a need for much improved sensor design, calibration, and testing procedures and facilities. Currently, uncertainties in laboratory calibration over large dynamic ranges and low background conditions, and in the knowledge of sensor rejection of unwanted off-axis radiation during flight, are believed to be the limiting factors.

4) In-orbit performance degradation caused by contamination of sensor system optics by space platform environments is a major problem in obtaining high radiometric accuracy over extended mission lifetimes. Current in-flight calibration monitors are not adequate for accurately assessing this degradation. The contamination problem will become particularly severe with the use of Shuttle as a measurement platform, even with its use as a launcher for free-flyer spacecraft. Sensor systems which employ cooled optical components and/or detectors are particularly susceptible, and gaseous contaminants will be rapidly condensed onto the cooled components, thus affecting performance and calibration.

PRIORITIZED RECOMMENDATIONS FOR IMPROVED RADIOMETRIC INSTRUMENTS

The panel obviously felt that all of the needs reflected by the conclusions are real and should be pursued; however, the following recommendations are believed to be of widest and most valuable near-term usefulness:

- 1) Establish the interagency/intercenter committee to coordinate calibration requirements.
- 2) Establish National Standards for Remote Sensing through NBS support.
- 3) Establish NASA Calibration Standards and calibration transfer techniques through joint NASA/NBS developments.
- 4) Conduct a study to define the Shuttle contamination environment.
- 5) Develop a family of wide-angle, spectrally-flat detectors.
- 6) Investigate stability of state-of-the-art radiometric components.