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NIST ROLE IN RADIOMETRIC CALIBRATIONS FOR REMOTE SENSING PROGRAMS AT NASA, NOAA, DOE AND DOD

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ABSTRACT

The Optical Technology Division (OTD) at the National Institute of Standards and Technology (NIST) has been actively involved in providing calibration support to establish SI traceable measurement support for the National Aeronautic and Space Administration (NASA) Earth Observing System (EOS) radiometric sensors. Specialized transfer standard radiometers traceable to the NIST spectroradiometric scales were built; they cover the visible and infrared spectral range up to 10 μm. An example of this effort has been the calibration support provided for the NASA's SeaWiFS program. The OTD has also developed the Thermal Infrared Transfer Radiometer (TXR) for NASA's EOS program, and measurements are planned at the calibration facilities for the High Resolution Dynamics Limb Sounder (HIRDLS) and the Tropospheric Emission Spectrometer (TES) that will fly on the Aura spacecraft. The TXR was used for the end-to-end radiometric calibration of a chamber at Los Alamos in support of DOE remote sensing programs. Plans also call for the TXR to be used in a feasibility test of calibration support for the National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) program. The need to calibrate the performance of sensors for missile defense prompted the Ballistic Missile Defense Organization (BMDO) of the Department of Defense (DOD) to sponsor the development of the Low Background Infrared Calibration Facility (LBIR) at NIST. The LBIR facility has been providing calibration of blackbodies and detectors to BMDO/DOD missile test facilities for over ten years. Internationally, OTD has been actively participating in the intercomparisons with other national standard laboratories in the measurement of SI traceable radiometric quantities. The requirements for global warming and climate change studies show the need for high accuracy data from remote sensing platforms. This translates into the need for long term radiometric calibration support for space-based sensors during the course of the mission. As a possibility to provide real time radiometric calibration support for a variety of missions, we will explore the future prospects of deploying SI traceable transfer standard radiometers on the International Space Station or other such platforms. Such a program would allow for recoverable instruments that could be periodically intercompared with the absolute radiometric standards in the laboratory and thereby provide long term measurement assurance for space based radiometry.

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INTRODUCTION

The Optical Technology Division (OTD) at the National Institute of Technology (NIST), as a part of its responsibilities to provide primary optical standards for the US, is actively involved with developing radiometric standards to ensure SI traceability and to promote the accuracy of radiometric measurements in US government sponsored remote sensing programs undertaken by NASA, NOAA, DOE and DOD. The strategic goal of a series of satellites being launched by these agencies is to expand the scientific, climatic, and strategic knowledge of the Earth system and its environment through remote sensing from space. Space provides a unique advantage as the remote sensor can make global measurements and truly complement the earth based measurements. In order for these measurements be useful for meaningful interpretation, the earth borne or space borne instruments should be calibrated with respect to SI traceable standards. For this purpose (as well as other applications), the OTD developed the High Accuracy Cryogenic Radiometer (HACR) as the Nation's primary radiometric standard. A brief description of HACR as the primary standard and its planned improvements will be given in the next section. Several radiometers, described in this paper, were built to transfer radiometric measurements from NIST to the various remote sensing calibration laboratories. Plans call for all of these instruments to be calibrated on a new tunable laser-based facility that is directly tied to the HACR. This facility will be described in this paper. Portable stable sources were built by NIST to assess the stability and absolute calibration of field radiometers used in remote sensing programs. Also, we will discuss the Low Background Infrared (LBIR) Calibration Facility at NIST that was established to support the calibration requirements for the Ballistic Missile Defense Organization (BMDO). The future needs in improving accuracy of remote sensing measurements are discussed further in the last section with a possible scenario of using the International Space station (ISS) with retrievable radiometric standards maintained in space to provide calibration support for other satellite sensor platforms.

HIGH ACCURACY CRYOGENIC RADIOMETER (HACR) FACILITY

Irradiance and radiance are the main radiometric quantities that are measured by any sensor, whether located in the laboratory or in a terrestrial or space-based remote sensing application. Most applications require the spectral responsivity of the sensor be fully characterized so that the sensor output voltage can be interpreted in terms of the spectral content of the target source. The chain of calibrations that enables the measurement of the spectral responsivity of the sensor starts with an absolute detector in a National Measurement Institute (NMI) like NIST, where measurements of the optical power are made directly, without the reliance upon other calibration artifacts. During the last twenty years, electrical substitution radiometers operated at cryogenic temperatures have become the standard method in most NMIs for the determination of the quantity of optical power in SI units. The basic principle of electrical-substitution radiometers (ESRs) is that an optical watt is the same as an electrical watt (Hengstberger, 1989). An ESR measures optical power by comparison to electrical power by equating the rise in temperature of an absorber from both optical and electrical power. ESRs have been developed extensively in the past few decades, and are now the primary standard for measuring optical power at NMIs. Cryogenic ESRs achieve the lowest uncertainty in radiant power measurements, since most of the adverse effects on the measurement (e.g. systematic effects) have less impact in vacuum and at cryogenic temperatures.

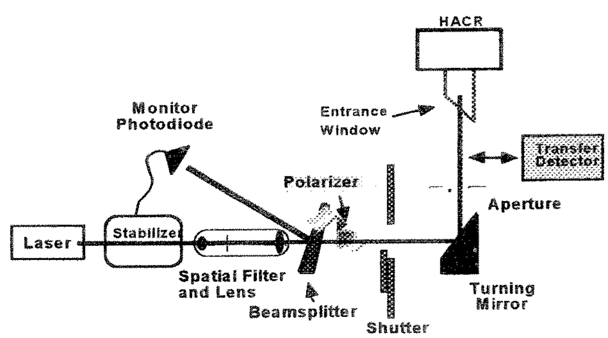

Fig. 1. Detector calibrations using HACR as Primary Standard

The primary ESR at NIST is the HACR and it is described in detail by Gentile et al. (1996). The scheme to calibrate transfer detectors for optical power measurements with respect to the HACR is shown in Figure 1. Collimated light from a mode-locked, intensity-stabilized laser is the source of optical power measured by the HACR. Once the power in the laser beam is determined, the detector or sensor under test is placed in the laser beam with same power and thus its power responsivity is determined. Currently, lasers for this experiment exist to cover the visible and the most of UV and IR. The HACR performs measurements of optical power of about 1mW with a combined relative standard uncertainty of 0.021%. The dominant uncertainty component (of 0.019%) is due to uncertainties in the window transmittance. To minimize these errors and to extend the operating range to lower power levels, a new instrument called HACR 2 is being built. The cavity in HACR 2 is designed to be horizontal as shown in Figure 2. HACR 2 will have an enhanced capability of calibrating the detector under test in vacuum. The uncertainty component from the window transmittance will no longer contribute to the error budget, and comparisons of the in-air or in-vacuum detector responsivity will be possible.

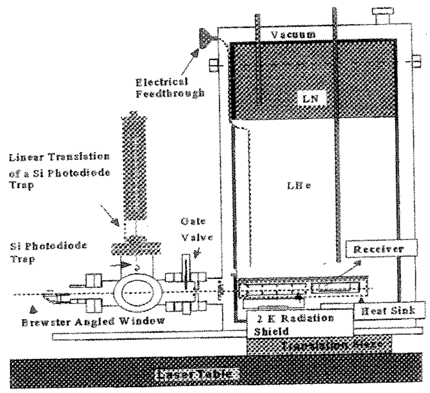

Fig. 2. Schematic of HACR 2 Radiometer

Calibrations at the HACR facility yield the power responsivity for collimated beams at the highest accuracy possible. Therefore this facility is primarily used to calibrate secondary standard detectors for general use in a variety of laboratories and for a wide range of purposes.

SIRCUS Facility

In a typical user application, the spectral radiance and irradiance responsivity of radiometers for measurement of Lambertian sources is needed. This requires a source of known spectral content and uniform lambertian distribution with sufficient radiance to operate in the useful range of the sensor system. In traditional calibration facilities, based on broadband sources and monochromators, one or more of these requirements is impossible to satisfy. Addressing this need, OTD has developed a Spectral Irradiance and Radiance Calibration with Uniform Sources (SIRCUS) facility. The SIRCUS facility (Figure 3) incorporates custom laser-illuminated

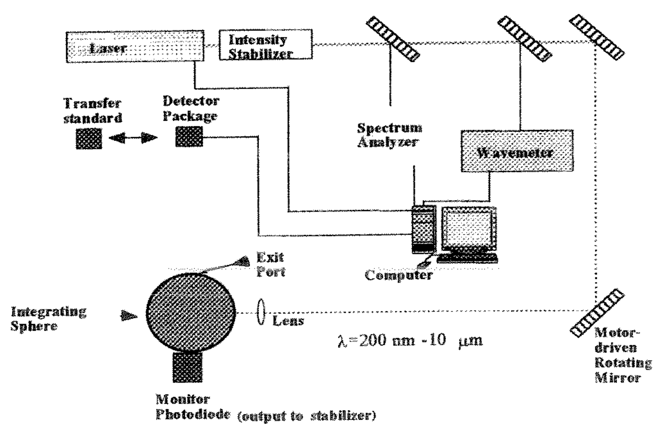

Fig. 3. SIRCUS Facility

integrating spheres to produce uniform, Lambertian sources with variable area. The tunable laser sources provide high spectral resolution, excellent wavelength accuracy, and high flux levels. The laser systems include Ti-sapphire lasers and Nd:Yag pumped and Ti-sapphire pumped optical parametric oscillators, which cover the spectral region from 0.2 μm to 12 μm. The input laser powers to the various integrating spheres for different parts of the spectrum are sufficient to produce the required radiance level of about 1 $\mu W/(cm^2\ sr)$ at the exit aperture of the integrating sphere (Brown et al., 2000).

In radiance-responsivity calibrations, a large area Lambertian monochromatic source is needed. This is realized with a large exit aperture on the integrating sphere sources at the SIRCUS facility. In irradiance-mode calibrations, a small aperture is placed at the integrating sphere exit port and this produces a uniform field for overfilling the sensor aperture. For both irradiance and radiance response calibrations, the reference detectors are unfiltered, broadband irradiance detectors that are calibrated against HACR. Test irradiance detectors from users are calibrated with respect to the transfer standard detectors. The radiance of the SIRCUS sphere source exit port is calibrated against the transfer standard irradiance detector. User radiance detectors are calibrated at SIRCUS as the ratio of the electrical output signal to the known input radiance.

TRANSFER STANDARD RADIOMETERS

The OTD has developed various transfer standard radiometers to provide NIST-traceable calibrations at various contractor and user test facilities for NASA, NOAA and DOD. For example, in the Earth Observing System (EOS) program at NASA, in the pre-flight timeframe, the EOS calibration facilities use large area calibrated sources i.e. integrating spheres or blackbodies to determine the radiometric response of satellite sensors operating from ultraviolet to short wave infrared. It is extremely important that the calibration of the EOS laboratory standard sources be consistent between various EOS calibration facilities and traceable to SI units. For this purpose, the OTD developed and built stable, portable, well characterized radiometers. These radiometers were extensively characterized and calibrated using NIST facilities. The characterization and calibration involves measurement of the linearity, temporal, spatial, spectral, and polarization response functions as well as the overall radiometric calibration. The overall EOS calibration scheme involving OTD provides measurement assurance and data quality assessment for EOS instruments over the life time of the 18 year program (Butler et al., 1999).

SXR for SeaWiFS

The goal of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) project at NASA is to collect ocean color data that are critical for studying ocean phytoplankton concentrations, the carbon cycle, and biogeochemistry (Hooker et al., 1998). From orbit, the combined standard uncertainty requirement for the SeaWiFS determination of the water-leaving radiance is 5%. The combined standard uncertainty requirement for the *in situ* measurements of water-leaving radiance with various field instruments is 1%. To provide the measurement assurance to meet these challenging requirements, the OTD developed the SeaWiFS transfer radiometer (SXR). In addition, the SeaWiFS sensor was calibrated and characterized at the spacecraft integrator's facility with NIST-traceable standards. The performance of SeaWiFS is being assessed, monitored and verified using solar and lunar observations and *in situ* measurements of the Earth's radiance (Barnes and McClain, 1999).

The SXR is a multichannel imaging radiometer with interference filters for spectral selection. Johnson et al. (1998) describes it in detail; a schematic is shown in Figure 4. The SXR a portable, stable radiometer that derives its calibration from relative spectral response measurements on the NIST Visible Spectral Comparator Facility and measurements of NIST-calibrated lamp-illuminated integrating sphere sources. Two channels were also calibrated on SIRCUS and plans call for additional measurements in the fall of 2000. The agreement between the two techniques was good (Johnson et al., 2000). The measurement uncertainty is better using SIRCUS, partly because

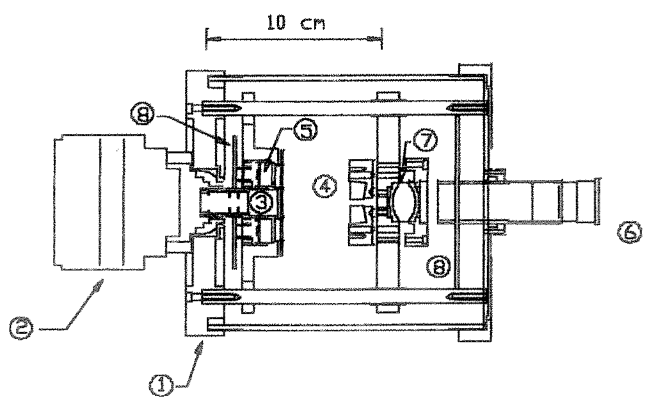

Fig. 4. The SeaWiFS Transfer Radiometer (SXR).(Johnson et al., 1999; reprinted with permission from the SeaWiFS project office at GSFC).

the experimental chain relating radiance responsivity to the HACR is simpler compared to the previous approach (Johnson et al., 2000). The SXR is operated by the SeaWiFS Project and it provides spectral radiance measurements of integrating sphere sources and various diffuse plaques used to calibrate various field instruments. Based on the extensive characterization effort at OTD, the relative standard uncertainty of the calibration is estimated to be about 1% for any of the six channels. As an example of utilizing the SXR for tracking temporal changes in sources of interest to the SeaWiFS project, Figure 5 shows the relative change in the spectral radiance of a Goddard Space Flight Center (GSFC) sphere source as measured in 1997 during the calibration of SeaWiFS normalized by the 1995 measurements (Johnson et al., 1998). Thus the SXR measurements established traceability of SeaWiFS to national standards. The SeaWiFS radiance responsivity was determined with standard uncertainties of 1.2% to 3.3%, depending on the instrument channel. The calibration approach used by the SeaWiFS program, in particular the direct traceability to NIST established by the SXR, resulted in a good agreement between the pre-launch calibration and on-orbit measurements (Barnes and McClain, 1999).

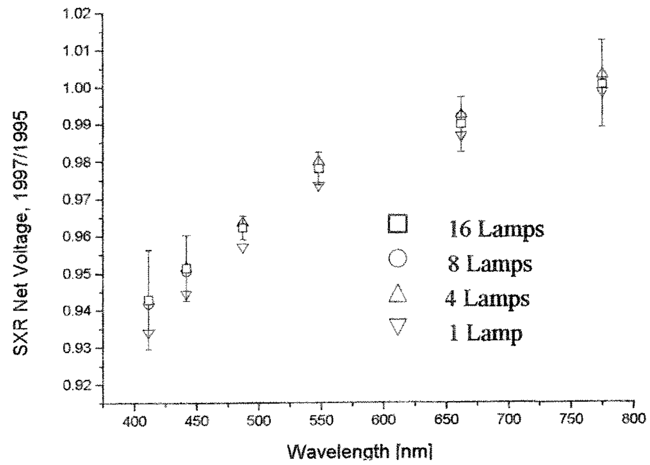

Fig. 5. SXR-determined temporal stability of the GSFC sphere source used to calibrate SeaWiFS. (Johnson et al., 1999; reprinted with permission from the SeaWiFS project office at GSFC).

VXR, SWIXR and TXR for EOS

As part of the overall NIST/NASA calibration program for EOS, the Visible Transfer Radiometer (VXR), the Short-Wave Infrared Transfer Radiometer (SWIXR), and the Thermal-infrared Transfer Radiometer (TXR) were designed and built by the OTD to cover the wave length of 0.4 µm to 10 µm. The VXR similar to the SXR with slight modifications to serve the needs of the EOS program. The VXR also has 6 channels and covers wavelengths ranging from 411 nm to 870 nm. As with the SXR, the VXR was calibrated using broadband sources, and two channels have been calibrated on SIRCUS to date (Johnson et al., 2000). The agreement was good and a complete characterization on SIRCUS is scheduled for the fall of 2000.

The SWIXR is a double grating monochromator with reflective input optics and a liquid nitrogen cooled indium antimonide (InSb) detector. It is designed for spectral radiance determinations integrating sphere sources from 0.8 µm to 2.5 µm. Based on characterization utilizing conventional sphere sources, the combined relative standard uncertainty for the SWIXR is estimated to be 2%. This will improve with the use of the SIRCUS facility.

The TXR is a two channel radiometer with filters at 5 µm and 10 µm. The 5 µm channel uses an InSb detector and the 10 µm channel uses an Mercury Cadmium Telluride (MCT) detector. Measurements with the TXR of cryogenic large area black body sources in medium background test chambers result in determination of radiance temperatures that can be compared to those predicted for the blackbody based on contact thermometry (Rice et al., 1998). The schematic setup of TXR is shown in Figure 6. The telescope of the TXR, which is focused at infinity, consists of a planar fold mirror and two off-axis parabolic mirrors. Two apertures, one at the entrance of the cryostat and one at the intermediate image define the diameter of the entrance pupil and the 2 degree full angle field of view. The TXR is designed to view the user's standard blackbody sources in the same way that the flight instruments are calibrated in a test chamber. Analogous to the VXR, the relative spectral responsivity of the two TXR channels was determined using the NIST ambient IR Spectral Comparator Facility. The instrument was calibrated using a water-bath blackbody source as the standard radiance source. The overall combined relative standard uncertainty of TXR to measure the radiance temperature of large area blackbody sources is estimated to be 0.05%. The calibration of the TXR will be improved by utilizing the SIRCUS facility and IR lasers.

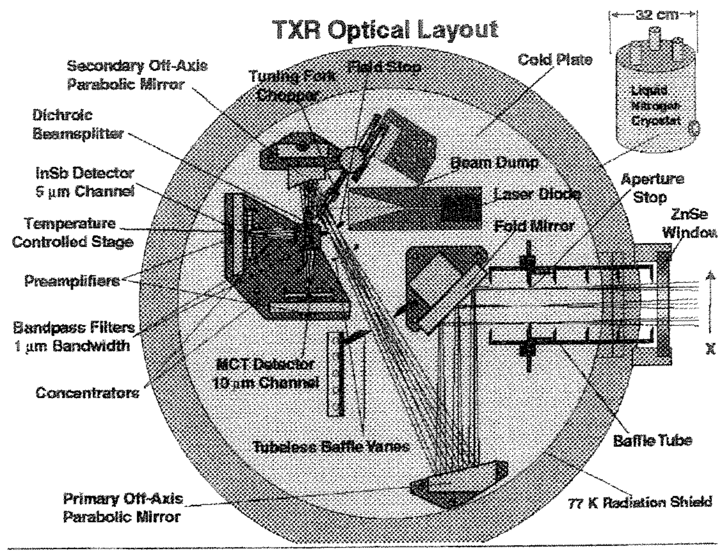

Fig. 6. TXR Radiometer schematic

SQM, UV-IRRADIANCE, AND NPR SOURCES

The SeaWiFS Quality Monitor (SQM) was developed for the SeaWiFS program by the OTD to satisfy the need to have periodic checks on the performance of the radiometers in the field (Johnson et al., 1998). The common

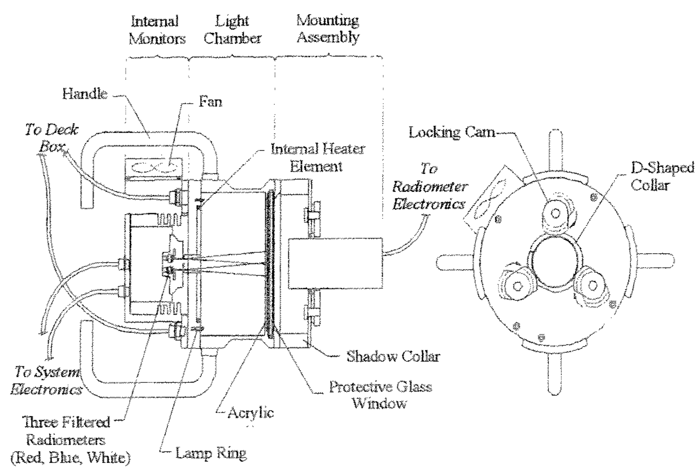

Fig. 7. SeaWiFS Quality Monitor (SQM) ((Johnson et al., JAOT,15 (1998); republished with the courtesy of American Meteorological Society).

practice had been to assign any change in the field radiometer performance between pre- and post- cruise calibrations to the degradation of the instrument. However, this procedure is highly suspect as stresses associated with shipping, handling, and deploying in harsh environments produce effects that are not due to degradation of component performance. The SQM is designed to be portable stable source approximating a Lambertian radiator. Its instability is less than 1% and it has been serving the SeaWiFS community as a stable source to periodically check the on-board radiometers during oceanographic cruises away from the calibration laboratory (Hooker and Aiken, 1998). Figure 7 shows the schematic drawing of SQM. It consists of a white acrylic diffuser illuminated from the back by a ring of two sets of halogen lamps. The stability of the device is monitored from the back of the acrylic diffuser by radiometers equipped to view different wavelengths. The SQM is not designed to be an absolute radiance or irradiance source, but it is designed to be a highly reproducible and repeatable source. The ocean color community has built additional field sources and the device is now commercially available.

The community that performs absolute determinations of downwelling UV spectral irradiance at the surface of the earth began a series of intercomparisons in 1994 that were organized by the OTD. The measurements require an *in situ* absolute spectral irradiance calibration, and the OTD responded with the development of an absolute, portable field calibration unit for UV spectroradiometers (Early, et al., 1998). Implementation of the calibration system resulted in relative standard uncertainties of the spectral irradiance responsivity of a typical Brewer spectroradiometer of 1.5% at 290 nm.

In the EOS program, the OTD built a stable, portable integrating sphere source called the NIST Portable Radiance Source (NPR) (Brown and Johnson, 1999). The NPR is a NIST traceable radiance source. Measurements of this source with transfer radiometers from NIST and other institutions in the EOS program validate their radiance responsivity scales and tie them directly to the national radiance scale maintained at NIST. The NPR integrating sphere is 30.5 cm in diameter with a 10.2 cm exit aperture and it is coated inside with Spectralon (a TM of Labsphere, Inc.). It is illuminated with four, 30 W, quartz-halogen lamps located at 90-degree intervals around the inside of the exit aperture. A Si-photodiode with a photopic filter and a InGaAs photodiode with 200-nm bandpass filter centered at 1400 nm are used to monitor the stability of the source. The change of the sphere radiance over time has been assessed by the VXR radiometer from 440 nm to 780 nm and the maximum variation has been within 0.5%.

BRDF STANDARDS

Accurate determination of the Bi-directional Reflectance Distribution Function (BRDF) of on-board and laboratory diffuse plaques is needed for the visible, near infrared, and shortwave infrared EOS instruments. The diffuse plaques are used on satellite platforms and in calibration laboratories to establish a scale of spectral radiance using NIST-traceable lamp standards of spectral irradiance. The OTD has been involved in accurate measurements of these plaques with the Spectral Tri-function Automated Reference Reflectometer (STARR) facility to support various remote sensing programs (Proctor and Barnes, 1996). An intercomparison among EOS laboratories and the OTD was held in 1998 and 1999 (Early et al., 2000); the results were within the combined uncertainties.

FIELD DEPLOYMENT OF RADIOMETERS AND SOURCES

The deployment of the NIST radiometers and sources establishes uniform measurement practices and traceability to SI units for various US government programs. Unaccounted discrepancies in the calibrations performed in the field may be identified, followed by suitable corrections. For example, at the third SeaWiFS Intercalibration Round-Robin Experiment (SIRREX-3), SXR measurements demonstrated an unacceptable level of temporal stability in one of the participants integrating sphere sources (Mueller et al., 1996).

Another recent radiometric comparison experiment was conducted at the NASA's Ames Research Center. Ames supports aircraft-borne optical sensors that are used to ground truth the satellite measurements. A total of five radiometers and three sources from five institutions participated. NIST deployed the VXR and the SWIXR radiometers and the NPR source. The preliminary results reported show that the radiometers agreed to better than ± 3.1% relative to the average when measuring the NPR sphere source, whereas the differences were higher when measuring other sources. This effort resulted in improvements in the calibration procedures at Ames that removed the differences up to 30% in previous radiance measurements using the Ames radiometer (Butler, 2000).

The TXR was used to make *in-situ* measurements of the radiance from the calibration sources in the Los Alamos National Laboratory (LANL) test chamber that was designed for remote sensing instrument calibrations for the Department of Energy (DOE) (Rice et al., 2000). These measurements were used to verify the LANL chamber radiance scale that was used during space-flight instrument calibration. The calibration set up at LANL chamber with TXR is shown in Figure 8.

The results from the TXR measurements showed that the LANL radiance scale agreed with the NIST scale to within combined uncertainties. The measured discrepancy corresponded to a brightness temperature difference of 50 mK at 5 um and a 300 K LANL blackbody temperature. The TXR demonstrated its ability to provide an economical end-to-end system-level verification of the component-level radiometric scale assigned to a calibration facility such as at LANL. This success resulted in increased demand for TXR type measurements at other chambers such as at NOAA contractor facilities.

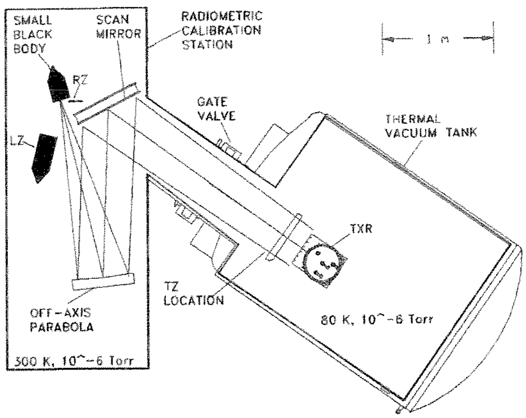

Fig. 8. TXR deployed at the LANL Calibration Chamber

LOW BACKGROUND INFRARED CALIBRATION FACILITY

The remote sensing effort in the Department of Defense has been largely focused on having sufficient sensitivity and discrimination in the infrared to detect incoming missiles to be intercepted in space. The Ballistic Defense organization (BMDO) of US Department of Defense has been actively pursuing various scenarios in this regard for more than a decade. In order to test the sensors developed by contractors at BMDO facilities, standards and methodologies for measurements have been developed at the OTD at NIST. The calibration problem in missile defense is different compared to the civilian programs which are primarily satellites viewing the earth. In missile defense, the goal is to detect point sources against the very low radiance background of space. Simulation of these environments in the laboratory requires cryogenically cooled chambers which can simulate the background the sensors observe when deployed. At OTD, the Low Background Infrared Calibration Facility was built with two cryogenic chambers that maintain a 20 K thermal background. The cryoshields are cooled by closed cycle He refrigeration system at 15 K. Fig 9 shows the broadband chamber which is equipped with an absolute cryogenic radiometer (ACR) as an absolute detector.

The ACR is an electrical substitution radiometer with a cavity receiver and is capable of measuring optical power from 5 nW to 200 μW with less than 1% combined standard uncertainty. It is designed to measure irradiance of point sources in an absolute fashion with respect to electrical quantities. This allows the determination of the radiometric temperature of the blackbody using the Stefan Boltzmann law. These cryogenic blackbodies are brought from user facilities to the LBIR facility for calibration and once calibrated, they provide NIST-traceable standards at their facilities. The broadband chamber does not have spectral selection whereas the second chamber has a cryogenic grating monochromator for calibrations requiring spectral characterization. The spectral chamber is also equipped with a cryogenic radiometer (ACR ii) as an absolute detector and provides the opportunity to calibrate cryogenic detectors from user community. The ACR ii is similar to ACR, but has 10 times the sensitivity. These radiometers have been compared to HACR and their performance is well characterized.

There are challenging new requirements for the LBIR facility. These fall in to two categories. One category is to develop transfer standard radiometers to calibrate the collimated output of sources in space chambers that are designed to test the BMDO sensors. This challenge is being addressed by the OTD by developing transfer standard radiometers like the TXR that enable end-to-end characterization of cryogenic test chambers. The BMDO transfer standard radiometer, BXR, is currently being developed for this purpose. The other category is the need to measure the bulk optical properties of materials under the conditions of usage in space to help design the sensors and viewing optics. This challenge is being met at NIST by improving the state-of-the-art optical properties of materials measurements in the infrared. This new capability will also benefit the remote sensing science objectives in the future.

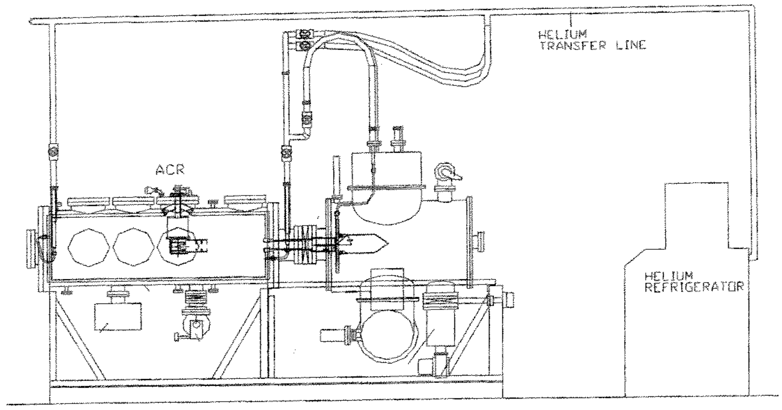

Fig. 9. LBIR Facility

LONG TERM MEASUREMENT ASSURANCE PROGRAM

Long term measurement assurance depends on stability of standards which are to be internationally validated by verification in terms of SI units. Towards achieving uniform metrology across the world for optical measurements, the OTD at NIST had been actively participating with other NMIs around the world in key international intercomparisons of selected radiometric quantities. In this regard intercomparisons in spectral radiance (Saunders et al.,1995/96)) and spectral responsivity measurements (Kohler et al.,1995/96) have been performed. Such intercomparisons assess the accuracy of radiometric calibrations at the NMIs and represent the present state of art around the world in making these measurements.

Many global issues with high economic impact such as global warming, ozone depletion, or trace gas pollution in the atmosphere require very accurate radiometric data over a long time series and a global scale to elucidate incremental changes. Experience has shown that remote sensing could provide such comprehensive data, but the accuracy has to be improved. A Space Based Radiometry Colloquium was held the NIST OTD and which led to the publication of a document titled "High Accuracy Space-Based Remote Sensing Calibration Requirements" (Murdock, 1998). As an example of the conclusions of the colloquium, the uncertainty recommendations of the attendees was that the total solar spectral irradiance needed to be determined to within 0.01%, traceable to SI units, in order to accurately track the known solar variability of 0.1% per 11 year solar cycle. This means the external and internal standards used for onboard calibration of sensors have to be known to a higher absolute accuracy than presently available in order that degradation of sensor performance in space could be very accurately accounted and corrected. As noted by attendees at the meeting, the required accuracy for remote sensing radiometric data equals or exceeds the accuracy available on current absolute standards in national laboratories. One possible way this demand could be met is to use the International Space Station (ISS) as a staging platform to deploy high accuracy transfer standard radiometers for the purpose of providing calibration data on the radiance of the Sun, Moon and various sites on earth selected for that purpose. The great advantage in this endeavor is that the ISS radiometers can be manned and maintained through periodically bringing them to ground and intercomparing them with laboratory standards that are traceable to SI units. Also, vicarious calibrations can be planned with other sensors in space or on ground after properly matching observation scenarios. Thus effects of sensor degradation and atmospheric absorption, where applicable, can be systematically studied in a manner that has never been possible thus far. Also, as ISS is planned to be in space for a decade or longer, for the first time we would have an independent method to obtain calibrated data on long term variability of such important parameters of interest such as the solar constant.

CONCLUSION

The OTD at NIST has assumed the important role of building measurement assurance for remote sensing programs at NASA, NOAA, DOE and DOD. For this purpose, it has been involved in calibrations, developing transfer standards, and reviewing measurement methodologies to advance the state of the art for remote sensing radiometry.

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