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Title: VISIBLE/INFRARED RADIOMETRIC CALIBRATION STATION

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Abstract

Visible/Infrared Radiometric Calibration Station

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Los Alamos National Laboratories has begun construction of a visible/infrared radiometric calibration station that will allow for absolute calibration of optical and IR remote sensing instruments with clear apertures less than 16 inches in diameter in a vacuum environment. The calibration station broadband sources will be calibrated at the National Institute of Standards and Technology (NIST) and allow for traceable absolute radiometric calibration to within $\pm 3\%$ in the visible and near IR (0.4-2.5 μm), and less than $\pm 1\%$ in the infrared, up to 12 μm . Capabilities for placing diffraction limited images or for sensor full-field flooding will exist. The facility will also include the calibration of polarization and spectral effects, spatial resolution, field of view performance, and wavefront characterization.

The configuration of the vacuum calibration station consists of an off-axis 21 inch, f/3.2, parabolic collimator with a scanning fold flat in collimated space. The sources are placed, via mechanisms to be described, at the focal plane of the off-axis parabola. Vacuum system pressure will be in the 10^{-6} Torr range.

The broadband white-light source is a custom design by LANL with guidance from Labsphere Inc. The continuous operating radiance of the integrating sphere will be from 0.0-0.006 $\text{W}/\text{cm}^2/\text{Sr}/\mu\text{m}$ (upper level quoted for ~ 500 nm wavelength). The blackbody source is also custom designed at LANL with guidance from NIST. The blackbody temperature will be controllable between 250-350 $^{\circ}\text{K}$. Both of the above sources have 4.1 inch apertures with estimated radiometric instability at less than 1%. The designs of each of these units will be described.

The monochromator and interferometer light sources are outside the vacuum, but all optical relay and beam shaping optics are enclosed within the vacuum calibration station. These sources are to be described, as well as the methodology for alignment and characterization.

Visible/Infrared Radiometric Calibration Station

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Introduction

Los Alamos National Laboratories (LANL) has undertaken a role in the radiometric calibration community to produce a calibration station¹ that is to be directly traceable to the National Institute of Standards and Technology (NIST). The expected radiometric accuracy of these sources, with their associated optical systems, is to be $\pm 3\%$ in the near infrared (NIR), between 0.9-2.5 μm , and $\pm 1\%$ elsewhere in the visible (VIS) and infrared (IR) spectrums to be included in this instrument, currently between 0.4-12 μm . The calibration station is being designed to accommodate sensors within its vacuum environment, with apertures up to 16 inches in diameter. Sources within the station include a blackbody source, a second blackbody source utilized specifically for minimal contrast feature testing, a visible integrating sphere, a grating monochromator input, and laser input allowing for interferometric qualification and polarization sensitivity characterization. To allow for projection of spatial resolution features, apertures can be placed in front of the sources to allow for detailed feature response characterization at the sensor focal plane. A set of apertures will be cryogenically cooled for the IR wavelengths and will be at room temperature for the visible. The apertured sources can be scanned across the sensor focal plane utilizing the scanning fold flat directly in front of the sensor input port. The entire vacuum system will be housed in a thermally controlled environment, stable to 1 $^{\circ}\text{F}$. Cryo-pumps and a large turbo pump will provide for rapid evacuation of the calibration station as well as the sensor enclosure vessel. Ion pumps are to be utilized during data collection to maintain the 10^{-6} Torr vacuum level, without vibration, during testing.

The facility is still largely under design at this time. A layout of the radiometric calibration station (RCS) is shown in Figure 1. Many thanks should go to the design/drafting efforts of Bill Horn, Ralph Ricketts, and George Jordan, all from LANL. The sources are all nested at the focal point of a large f/3.13 off-axis parabolic collimation mirror fabricated by SORL. The source movements and monitoring are done from outside the vacuum tank enclosure. The motion within the tank is provided in part by devices supplied by Daedal Inc., NRC, and Burleigh. The large lightweight optical scan-flat was fabricated by Zygo Corp. The spectral relay optics were fabricated by OCA ($\lambda/10$) and CVI Corp (West). The interferometer optics were procured from Special Optics, CVI Corp., and NRC. The blackbody sources were designed and fabricated at LANL with NIST collaboration. Thermal control of the blackbodies is to be provided by one of three possible flexible kapton resistive-heater vendors. The integrating sphere was designed at LANL with guidance from Labsphere Inc., who also fabricated the interior sphere. Vacuum apparatus was accumulated from Varion Assoc., APD Cryo, MDC, Norcal, and VAT.

Although the vendors are chosen for their known as well as demonstrated capabilities, LANL is not endorsing them as being the premier companies in their fields. Credits aside, I will describe the individual sources and their functions and capabilities.

Radiometric Calibration Station Component Description

Vacuum-compatible Extended Standard Diffuse Source (VESDS) (Integrating Sphere):

The VESDS integrating sphere² (white-body) is enclosed within a vacuum shroud that allows the unit to reside within the main calibration vacuum tank. The inner sphere illumination, $0.4 < \lambda < 2.5 \mu\text{m}$,

exits from the 21 cm diameter integrating sphere into the main vacuum chamber through a 7.4 cm square perforation in the inner sphere housing and a 10.4 cm diameter Fused Silica window in the outer jacket. The unit is shown in Figure 2. The three 20 W lamps within the main sphere housing and the two 20 W bulbs inside of the satellite sphere are color matched with the additional 10 W bulb in the main sphere. The heat from the lamps is dissipated convectively through controlled flow of cooled gaseous Nitrogen (GN_2) around and through the inner sphere. This transfer of internal heat allows the unit to operate at a predefined temperature dependent on the amount of flow and initial temperature of the gas. The gas flow is directed across the inside of the output window in order to force any heat-induced contaminants to exit through the gas flow port at the back of the sphere housing. The gas source is expected to come from liquid Nitrogen (LN_2) boil-off to insure cleanliness. This arrangement is expected to allow for extended calibration lifetime of the white-body unit.

The white-body output window is oriented perpendicular the parent axis of the off-axis parabolic collimator in order to allow for close placement relative to the focal plane apertures. The expected Lambertian output of the device allows for uniform radiance from the unit at well beyond the 140° angle about which it is pointed with respect to the chief ray of the collimator system. All sources and detectors within the sphere are internally positioned to allow for this offset angular orientation without being directly in the field of view (FOV) of the collimator assembly. The orientation of the focal plane targets themselves are perpendicular to the parent parabolic axis, giving best symmetric performance for extended target patterns. Targets will be placed at the focal point of the collimator system using encoded stepper-motor-driven stages to ensure repeatability. The targets will either be opaque patterns on transmissive substrates or patterns milled into thin metallic substrates, whichever will allow for the most accurate target shapes over the broad spectrum of interest.

The output level of the white body is controlled by powering the bulbs in the main sphere independently. This coarse power regulation, coupled with the stepper-motor-controlled slide between the main and satellite spheres, allows for precise adjustment of luminance output of the unit from 0 up to about $0.29 \text{ W/cm}^2/\text{sr}$ at $0.9 \mu\text{m}$ (the location of the peak spectral radiance). Spectral monitoring of the internal luminance is accomplished by sending a small portion of the light within the inner sphere to a linear array spectrometer, outside of the main vacuum chamber, via a fiber optic which will be calibrated for spectral losses. The color temperature of the bulbs in use, up to about $1 \mu\text{m}$ wavelength due to the use of Silicon detectors in the linear array, would be adjusted by controlling the current to the bulbs. The correction of the internal integrated luminance would then be accomplished by a small adjustment of the slide between the main and satellite spheres. The integrated signal for this internal luminance would then be detected within the integrating sphere using both Silicon and Germanium detectors, allowing for controlled use of this unit through the VIS and NIR wavelengths.

The enclosure of the white body in a vacuum environment will cause the output window to bow outward during use. This effect will not be present when the unit's emissivity is calibrated at NIST, but is expected to cause immeasurable differences in the output characteristics. The integrating sphere will be operated from within a small vacuum enclosure during calibration, to ensure that the cooling effects are considered, but the window will encounter an air-vacuum pressure differential across the window only when in use at LANL. A NIST characterized detector outside of the white body, positioned at a prescribed distance along the chief ray of the collimator system (calibration detector position 1), will give yet another periodic check on source radiometric output.

Vacuum-compatible Cryogenically-cooled Blackbody:

The LANL/NIST blackbody design utilizes the high emissivity of a special anodization process developed by Martin Marietta Corp., Enhanced Martin Black (diffusivity ≈ 0.5 at grazing incidence and ≈ 0.9 at normal incidence, emissivity ≈ 0.96), which allows for integrated effective emissivity of the unit, over a $\pm 90^\circ$ FOV and from $0.4\text{-}14 \mu\text{m}$ wavelengths, to lie at about 0.999 when the thermal uniformity is within $30\text{-}600\text{mK}$. Experimentation is currently in progress, utilizing a higher pressure and temperature in the process, to improve on the performance of this type of coating.

area of the calibration station. Figure 5 shows the source carousel area where the two radiometric sources (white body and small blackbody) reside. The optics for the interferometer and spectral sources, as well as many other local devices, have been removed from the carousel area for clarity.

Calibration of the emissivity for the smaller blackbody source will occur at the NIST Low Background Infrared Radiometer (LBIR) facility, within a vacuum environment, over the full FOV and the range of wavelengths from 2.5-12 μm . The present NIST facility may not be large enough for the larger of the two blackbody units, in which case an alternative method of calibration will need to be devised. The radiometric calibration of the output through the targets is expected to be performed by placement of a NIST characterized infrared detector at calibration detector position 1, interchangeable with the aforementioned visible detector.

Spectral Source (monochromator):

A double-grating monochromator will be used as an input source to the collimator system to allow for monochromatic input across our full spectrum of VIS, NIR, and IR wavelengths. Different sources, including a 3000°C blackbody, are planned at the input to the monochromator, which lies outside the vacuum chamber. Several available double grating designs spectrally filter the input light to result in a spectrally narrow source with wavelength dispersion of $\approx 1.6 \text{ nm/mm}$ over the exit slit in the VIS wavelengths and $\approx 26 \text{ nm/mm}$ at the longest IR wavelengths. The monochromator source will be filtered to suppress stray light in unwanted orders and chopped for the infrared signal detection. The exit slit of the unit is positioned at the focal point of an 18 inch focal length off-axis parabola. The off-axis distance was chosen to just allow for placement of a fold flat to redirect the 4 inch diameter collimated beam away from the source, without obscuration. The entry of the monochromatic illumination diverging from the exit slit into the vacuum chamber, is accomplished through a BaF₂ window. The thickness was chosen to provide for the standard 4x safety factor to accommodate the one atmosphere pressure differential across the window. The effect of the window-bowing on the imaged slit is being investigated.

The collimated beam is further redirected, by two periscope flats, to another off-axis parabola which shares a common parent axis with the main collimator mirror of the calibration station. These latter three optics lie on the source carousel. The off-axis distance of this refocusing parabola is again kept to the minimum that will allow for the collimated beam to remain unvignetted as well as allowing for matching the chief ray angle of the main collimator parabola. The 12 inch focal length parabolic mirror, with the 4 inch propagated beam diameter, allows for slight overfilling of the main collimator parabola clear aperture. The magnification factor of this pair of parabolas results in a small extended width source at the focal plane of the main collimator optical system, which is 2/3 the size of the exit slit. Raytrace analysis will predict the expected uniformity of the intensity across the slit presented to the main parabola. The portion of the resultant image that is to be used for any one test will be determined by the sensor detector pixel size and pitch. The aperture wheel will position the required pattern at the focal point of the main collimator system and the spectral relay will back illuminate this pattern. Radiometric output through the pattern can again be measured by the calibration detectors at position 1.

The monochromator position is expected to shift somewhat due to vacuum chamber contraction when the system is brought under vacuum. The best focal position for the monochromator can be re-identified, assuming that all mirrors were initially aligned and that they reside on a platform that is isolated from this effect, by placing a small interferometer on the platform which will support the monochromator and then, after propagation through the spectral relay optical train, retro-reflecting off of a small reference tooling ball attached to the aperture wheel which would identify the main collimator focal point. This aperture wheel position would be used as the global system reference by utilizing absolute encoders to guarantee repeatability. The schematic of the spectral relay optical train from the monochromator to the main collimator system focus is broken out from the remaining optical sources on the carousel in Figure 6.

The variable spectral input is to be used for integrating under the transmission curve of any filters that may be placed onto the sensor detector plane. With the expected dispersions stated above, the worst

case (in the IR) would allow between 8-10 individual integration steps across typical transmission filters. Complete characterization of this transmission curve will be coupled with the broadband transmission of the calibrated radiometric sources through the sensor filters, allowing for wavelength weighting of sensor detector signals.

Interferometer Source:

An interferometer was included in the calibration system in order to allow for periodic maintenance of the collimator system alignment, at least until the long term stability can be judged, and also for the judgment of state-of-health of the sensor optical train. An NA 0.17, or greater, objective would be required to allow for overfilling of the main collimator parabola. This objective, as well as a pair of periscope mirrors, reside on the source carousel. The beam that is focused by the sensor, at least in the first of the sensors that is planned to be tested by this calibration station, will have instrumentation at the focal plane to allow for retro-reflection of the entire transmitted beam back through the full optical train to return to the interferometer. This double path is to be the test arm of the modified Twyman Green interferometer arrangement. The laser source was positioned outside of the vacuum chamber in order to ease the cooling problems associated with keeping it inside the vacuum environment. The entrance port in the tank wall is exactly the same as for the spectral source, except with a FuSi substrate. The effect of the window bowing is expected to be minimal due to the beam size. Some analysis will precede the actual implementation of this unit in order to minimize any effects this may have on the resultant quality of the interferometer beam expander optics. If the laser beam is diverged by the window, the beam expander can be adjusted to compensate for this primarily defocus-type of aberration.

The main collimator fold flat will have to be manually turned toward the collimator parabola to allow for a collimator path calibration, which will need to be performed under vacuum in order to take into account the chamber effects. This type of calibration check will be done only rarely once the chamber is fully outgassed, since the manual manipulation of the large flat requires that vacuum be broken and personnel enter the chamber. More frequent checks will be performed by remotely placing a small 6 inch diameter optical flat into the 20.5 inch diameter collimated beam and returning that portion to the interferometer. Several sub-aperture checks, guided by positioning stages within the vacuum tank, should allow for state-of-health checks on the main collimator parabola alignment whenever desired. This same set of stages will also be used for positioning of a second set of calibration detectors (calibration detector position 2) that will be used to calibrate the spatial intensity distribution of the collimated beam. The placement of these periodic-calibration devices within the tank has not yet been incorporated into the design, although real estate has been reserved.

The reference arm of the interferometer will require basically two different adjustment positions, to produce maximum contrast fringes for the main collimator assembly check and for the sensor optics check. These positions will need to be identified and remote adjustments incorporated into the trombone leg of the interferometer reference arm. Tilt control of the reference beam is controlled remotely to allow for fringe orientation adjustment. Remote alignment of the source-carousel-mounted periscope optics and objective lens allows for pointing and placement of the interferometer focus. The reference for these adjustments will again be the tooling ball on the aperture wheel. The imaging of the different scenarios for the interferometer's use are accommodated by remote placement of various lens combinations between the beam splitter cube and the CCD detector. Polarization of the expanded interferometer beam is cleansed by passing the beam through a high quality polarization cube, dumping the unpolarized portion of the beam, and then remotely orienting to the desired angle by rotation of a half-wave plate. The polarized beam is split in a non-polarization sensitive cube into the test and reference arms. The design is described in Figure 7, which also shows the optical path to the objective without the other sources on the source carousel.

Source Carousel:

The source carousel/lift mechanism is a method by which four different sources can be placed at the focal plane of the collimator parabolic focus. The sources and their associated optics are located on two different levels of the carousel, requiring a specialized stepper-motor-driven lift mechanism designed at LANL. The placement of the four sources requires only two rotation and two height positions. The

rotation axis is encoded for repeatable placement while the lift mechanism is kinematically located at its two different extremes. The weight of the carousel, the optical apparatus on the carousel, as well as the rotation stage and encoder are estimated to weigh about 80-100 lbs. This weight is off-loaded using a spring motor, allowing the stepper motor to see loads well below what would be required to lift the entire weight of the source carousel. The 7 inch height difference between the sources was dictated by the volume of the source and mount packages required to produce a stable alignment scenario for this densely packed design. This amount of required lift forced the location of the entire optical centerline within the vacuum chamber. As can be seen in Figure 1, the clearance between the bottom of the lift mechanism and the tank is minimal. Had further height been required, an alternate motor configuration would have been required, since we are limited by other constraints in the vertical direction. Currently, an overdrive accommodation will allow for the stepper motor drive to raise the lift mechanism beyond the point where the kinematic landing comes into contact at the top of travel. This accommodation spring will allow a substantial load to be placed onto the kinematic mount and provide more positive seating. In the lower position, the load for positive seating of the kinematic landing is provided by gravity on the remaining portion of the weight that is not off-loaded by the spring motor.

The remote movement of these sources, especially in the rotation axis, causes concern for the torque that will be imparted to the cryogenic lines that are required for the operation of the blackbody. There are also cooled gas lines, electrical leads, and fiber optics that must be accounted for when moving the source carousel. Adequate room exists above the source carousel to allow for coiling of these lines to accommodate the expected movements of the source package. The design and routing of these lines to their respective vacuum bulkhead interfaces is being considered, but will probably not be fully addressed until later in this design phase of the program.

Sensor Enclosure Tank:

The beam that is created by a point source placed at the focal point of the parabola would create a collimated beam output through a 20 inch diameter output port into a sensor enclosure tank. The output of the calibration chamber will possess an intensity wedge in the off-axis direction of the collimator mirror. This is due to the off-axis optical configuration itself and currently being modeled in the laboratory as well as in various codes to allow for the elimination of the effect of this anomaly. The capability will exist for remotely scanning the fold flat $\pm 1.25^\circ$ in both axes, thereby setting the limit of the testable field of the sensor. This field, the limits of source diameters at the focal plane, the clear apertures of the collimator system, as well as the distance through the exit port of the system to the expected position of the sensor under test, result in a sensor aperture limit of about 16 inches diameter.

We expect that over time, the calibration tank will approach a 'clean' state where outgassing has been allowed to cleanse the contaminants from the many components enclosed within the tank. Sensors that will be tested will probably be in a much more rudimentary phase of outgassing. The sensor tank is vacuum isolated from the main calibration station enclosure by a large (20 inch open diameter) gate valve. An independent pump and cold trap will be utilized to try and keep the contaminants contained within the sensor enclosure. The sensor enclosure will have resistive heaters balanced against cryogenic transfer lines attached to an internal shroud, similar in theory to the blackbody design, that will allow for radiative heat control of the sensor under test. The temperature range of the sensor under test will be adjusted by varying the amount of cryogenic flow and heater current to the inner shroud of this vessel.

Summary

The design difficulties for assembling the RCS for customer use in the near future (late 1996) are proving to be every bit as complex as we had expected. The state-of-the-art is being pushed out in both of the radiometric sources as well as the remote sensing and control areas. The RCS chamber, once completed, will undoubtedly host sensors that will ultimately be able to detect visible and infrared sources at accuracies that have been unachievable across a broad spectrum, until this time. Innovative solutions to complex calibration concerns continue to be required through this design effort.

The vacuum chamber, with the associated pumping units, is expected to be placed into the laboratory and operated by the end of fiscal 1994. The sources, currently being fabricated, will be fully calibrated at NIST by early fiscal 1995. The remainder of the operational apparatus will be built during the balance of that fiscal year. A major portion of 1996 is expected to be required to arrive at a fully operational radiometric calibration station at Los Alamos National Laboratory.

Optical alignment of the various components that are included in this calibration station, is expected to be performed in a completely traceable manner providing a comprehensive understanding of any signal that is presented for calibration purposes. Optical surface characteristics will be modeled in several of the available software codes, allowing for versatile configuration changes when desired by sensor specifications. Routine re-calibration of the radiometric sources is scheduled to insure NIST traceability throughout the lives of the sources. Target patterns will also be designed to allow for ease of replacement with this versatility in mind.

Multi-spectral thermal imaging in the next decade is expected to be a primary emphasis of many space-born platforms. Los Alamos hopes to be able to provide a unique capability within this growing science community.

References:

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- 2) W.B. Maier II, R. Holland, S. Bender, D. Byrd, F.D. Michaud, S. Moore, and T.R. O'Brian; "Radiometric Sources for the Los Alamos National Laboratory Calibration Laboratory"; 4th Infrared Radiometric Sensor Calibration Symposium, 1994

Figure Captions:

Figure 1

The RCS enclosure houses a large off-axis collimator with the output direction controlled by a large scanning fold flat. The sources at the focal plane of the collimator include two blackbodies, an integrating sphere, a monochromator, and an interferometer. Four of the sources are positioned using a unique rotation/lift mechanism. Apertures are available for visible and infrared sources. The expected absolute accuracy of the RCS output is $\pm 1\%$ in the visible and IR, and $\pm 3\%$ in the NIR wavelengths.

Figure 2

The VESDS unit allows the internal integrating sphere to reside within a vacuum environment. The unit has output capability through the visible to about $2.5\mu\text{m}$ wavelength. The output radiance will be fully calibrated at NIST. Silicon and Germanium detectors will monitor the internal integrated radiance. Fiber optics will send internal illumination to a spectrometer for color temperature monitoring of the four sources within the main sphere and the two sources within the satellite sphere. A stepper motor driven slide separates the two spheres.

Figure 3

Two blackbody units will reside within the vacuum tank. Their relative sizes are shown. The internal cavity is resistively heated and radiatively cooled to a cryogenic bath that surrounds the cavity. A cryogenic reservoir will reside on the tops of the units. Electrical/sensor leads will exit the cryogenic enclosures at the front edge. Calibration of the smaller unit will occur at the NIST-LBIR facility. The large unit will be calibrated in an as yet undetermined manner.

Figure 4

The large blackbody will be used in conjunction with an infrared contrast disk composed of copper with differing emissivity coatings on its surface. The disk is located at the focal plane of the large RCS collimation mirror. The disk is thermo-electrically controlled to the blackbody temperatures. Differing from this temperature creates changes in the amount of contrast desired in the surface patterns.

Figure 5

The two radiometric sources, blackbody and whitebody, are situated on a source carousel (the remainder of the optics have been removed for clarity). The visible aperture wheel is shown slightly displaced from the focal plane of the main collimator. An IR cryogenically cooled aperture plate and field block are also shown at the RCS focal plane in conjunction with the small blackbody. The whitebody is rotated out of its in-use position.

Figure 6

The monochromator is located outside the RCS vacuum chamber. Its output enters the chamber through a BaF_2 window, is collimated and redirected to a focusing mirror which fills the main RCS collimator mirror. The spectral relay optics that reside on the source carousel, are located above the small blackbody and are attached to an upper plate (not shown). The visible aperture wheel and IR aperture plate are both expected to be used with this source.

Figure 7

The interferometer assembly is nested inside the RCS vacuum chamber next to the source carousel. The laser resides outside the chamber and enters through a FuSi window. An adjustable periscope mirror set directs the interferometer test beam into an adjustable objective lens. The reference for these adjustments will be a retro-sphere attached to the aperture wheel. A waveplate between the polarization dump and the reference beam-splitter allows for polarization orientation experiments.

VESDS INTEGRATING SPHERE

LANL CRYO COOLED/RESISTIVELY HEATED
BLACK BODY UNITS

VARIABLE IR CONTRAST CALIBRATION PATH

RADIOMETRIC SOURCES/APERTURES

INTERFEROMETER OPTICAL PATH

MONOCHROMATOR OPTICAL PATH

DATE

FILMED

8/17/94

END