

Facility for optical calibration at low level light (FOCAL³)

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Abstract. This paper presents information on a new optical calibration facility developed specifically for testing and calibrating low light devices, including auroral imagers, star sensors and similar instruments. A combination cleanroom/darkroom is utilized to isolate instruments from airborne particulate and stray light. A key component of the calibration facility is a custom integrating sphere that provides a uniform light source for imager calibration with an intensity range comparable to auroral emissions. Components also include a monochromator, collimator, and high-end optics bench. Current applications using this facility include the ePOP satellite (aurora imagers), ROPA rocket (aurora imagers), and the Star Sensor for the IBEX mission (PMT star sensor).

1 Introduction

With many scientific instruments, the quality and precision of the collected data relates directly to the quality and precision of the instrument's calibration. This is especially true of optical instruments used to measure low level light. As the number of photons being measured decreases, the difficulties in accurately measuring them increases accordingly. However, with the proper instruments and a properly controlled environment, there are techniques that can be used to overcome these difficulties and still obtain high quality scientific data from a low level light phenomenon.

A research goal at the Magnetosphere-Ionosphere Research Laboratory (MIRL) at the University of New Hampshire (UNH), is to collect high quality optical data of the aurora. To help realize this goal, a new optical calibration facility was designed specifically for testing and calibrating low light devices, including auroral imagers, star sensors and

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similar instruments. In August 2006, construction and equipping of the Facility for Optical Calibration at Low Light Levels (FOCAL³) was completed. This paper describes the new facility, its instrumentation, and several calibration projects which use the facility.

2 Facility enclosure

To protect optical equipment from particulate that can cause distortion (e.g., dust on lenses), an optical calibration facility must provide an environment that controls airborne particles. Space-bound instruments also require a clean calibration environment to help prevent electrical problems in space. In addition, to accurately calibrate optical instruments at very low light levels, it is imperative to eliminate as much stray light as possible. Even a small LED power indicator is many times brighter than the aurora the instruments are designed to image.

2.1 Physical characteristics

The facility enclosure for FOCAL³ was specifically designed and constructed to meet the cleanroom and darkroom requirements. (See Fig. 1.) The enclosure is approximately 6.1 m long, 2.4 m wide and 2.1 m tall. The front wall and ceiling of the enclosure are framed with aluminum extrusion beams and sheathed on the inside with 0.6 cm thick plastic sheets. The sheathing is ultra-high molecular weight polyethylene (UHMW PE) with a flat black finish. This material meets the cleanroom and darkroom requirements and proves to be sturdy, relatively inexpensive, and easy to work with. A static-dissipative variation of this plastic provides protection for the static sensitive electronics used in the room. The back and side walls of the enclosure make use of existing laboratory walls which were painted flat black to help absorb stray light and minimize reflections.



Fig. 1. Front wall of FOCAL³ enclosure

Clean, filtered air blows into the enclosure via three ceiling mounted high-efficiency particulate air (HEPA) cleanroom filtering units. The makeup air from the HEPA units blow out of the enclosure through two special light-tight air vents mounted in the front wall. The environment within FOCAL³ is designed to meet “class 10,000” cleanroom specifications, a standard requirement for space-bound equipment. After construction, particle count tests confirmed that this requirement was met and in fact, exceeded.

2.2 Interior

The cleanroom / darkroom enclosure is partitioned internally into two spaces, both clean and dark. The larger space (approximately 4 m long) is called the calibration room and houses the optical instruments being calibrated and the light sources used for calibration. It also contains a large, high-end optics table with a “floating” surface (1.2 m × 1.8 m) which allows for a wide range of optical setups.

The smaller space (approximately 2 m long) is called the control room and houses all “light polluting” support devices. Most of the optical instruments and light sources used during calibration require a variety of computers, power supplies, and other electronic support equipment. Since each of these devices generate unwanted light, they are kept in a separate room from where the low level light calibrations are performed. A light-tight door between the two areas prevents light from the control room from entering the calibration room, but allows the operator to easily move between the two rooms while still in cleanroom attire.

3 Integrating sphere

A key calibration instrument at FOCAL³ is the custom integrating sphere, which is used as a calibrated uniform light

source for low level light applications. The integrating sphere allows precise calibration of optical equipment such as the charge-coupled device (CCD) sensor used in many auroral imagers. A properly calibrated imager yields a significant increase in the precision of the scientific data obtained in the field.

The design of the FOCAL³ integrating sphere was the result of a collaborative partnership between MIRL and SphereOptics LLC of Contoocook, NH. Detailed discussions over many months resulted in a unique design which ultimately provided a sophisticated and flexible instrument for low light calibrations. The sphere was subsequently constructed and calibrated by SphereOptics.

3.1 Definitions

In CCD camera calibration, a *uniform light source* is used to measure intensity readout variations across the pixels (photosites) of the CCD array. During calibration, the camera’s field of view (FOV) is flooded with light having a uniform intensity. Since the light presented to the camera is known to be uniform (a “flat field”), any intensity variations from the CCD readout can be treated as imperfections and recorded as such. When actual images are recorded in the field, the saved pre-recorded flat field information can subsequently be used to correct for the inherent intensity variations found with the camera. An *integrating sphere* is one type of a uniform light source and is often used in CCD camera calibrations.

A uniform light source can provide a means for adjusting the light’s intensity across some specified dynamic range. This intensity selection is typically calibrated by the manufacturer so that precise values may be selected in an appropriate luminance or radiance unit, such as cd/m², W/m² sr, or rayleigh. [See McCluney (1994) for definitions of photometric and radiometric quantities such as luminance, radiance, and spectral radiance. See Trondsen (1998) Chap. 4 for a definition of rayleigh (R), a unit of radiance often used in auroral research.]

In addition, calibration of the light source by its manufacturer may be certified and traceable to a recognized standards organization such as the National Institute of Standards and Technology (NIST) in the USA. The importance of standards traceability cannot be overstated. With a light source that is not traceable to some standard, the accuracy of the light intensity values is unknown. If accuracy of the light source is in question then the accuracy of any scientific instrument calibrated from that source is also in question. As a result, the quality and precision of any data collected by that instrument will suffer.

3.2 Capabilities and specifications

Physically, the FOCAL³ integrating sphere is 60 cm in diameter with a 20 cm circular opening used as the output light port. (See Fig. 2.) This size light port allows calibration of

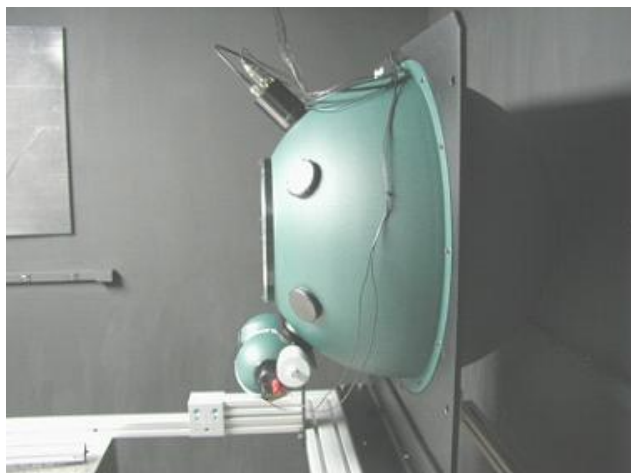


Fig. 2. Integrating sphere

instruments with optical apertures up to 20 cm. The uniformity of intensity across the area of this light port is specified by the manufacturer as $\pm 2\%$.

The integrating sphere supports two overlapping intensity levels to accommodate a wide dynamic range of intensity values. Each intensity level uses a separate 20 watt tungsten filament lamp and each lamp is driven at a specific, regulated current value to produce a constant intensity light source for input into the integrating sphere. A micrometer-driven mechanical “knife edge” is used to attenuate the light passing from one of the lamps into the main part of the sphere. This allows the operator to adjust the light level at the output port of the integrating sphere. A thermo-electrically cooled silicon detector attached to the sphere measures precisely how much light is presented to the output port of the sphere. In luminance units, the full dynamic range of the integrating sphere is approximately 0.0001 to 70 cd/m^2 .

The FOCAL³ sphere was designed to allow calibration of optical instruments across the range of frequencies most often studied in auroral research. This spectral range includes visible light and a portion of the near-infrared band, specifically 360 to 1000 nm. A typical light spectrum from the integrating sphere across this band is shown in Fig. 3. The horizontal axis gives light wavelength (nm) and the vertical axis gives spectral radiance at that wavelength ($\text{W}/\text{m}^2 \text{sr nm}$). [See McCluney (1994) for definition of spectral radiance.]

Detailed data about this spectral curve, combined with the real-time intensity level from the silicon detector, allow the integrating sphere support software to calculate precise radiance information for any given sub-band in this spectrum down to a resolution of 1 nm. Since auroral imagers often use filters to image specific spectral bands, this capability provides an accurate intensity value for how much light is reaching the imager’s sensor.

Auroral researchers are often interested in dynamic range

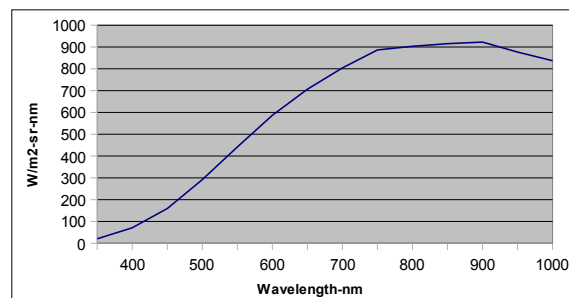


Fig. 3. Integrating sphere spectrum (typical)

requirements specified at individual wavelength bands and in units of rayleighs (R). In these terms, the integrating sphere dynamic range for any 1 nm wavelength band within the 360 to 1000 nm spectrum is approximately 100 R to 50,000 R. This is the same general range of intensity observed in an aurora.

Finally, it should be noted that in order to maintain the NIST traceable certification of the integrating sphere, the manufacturer recommends annual recalibration at their laboratory.

4 Other test instruments

An optical device or camera being tested can be roughly broken down into two components: the *sensor* and the *optical pathway*. In such a device, the system of lenses that focus the image (the optical pathway) rarely presents a “perfect” image to the optical sensor. Optical design tradeoffs are often made which affect the image quality in sometimes subtle ways. For example, a wide-angle lens is designed to have a wider than normal field of view (FOV). The tradeoff made for this type of lens system is that the image will be somewhat distorted, with a pin-cushion or fish-eye look as seen by the sensor.

The integrating sphere, as described above, is used predominantly to calibrate the sensor of the optical device. FOCAL³ has two other instruments that are used more for testing the optical path: a collimator and a monochromator. Commonly tested attributes of the optical path include distortion, chromatic aberration, crisp resolution of lines and points, and filter performance.

4.1 Collimator

In order to test for distortion or sharpness within the optical pathway, test patterns must be captured with the camera. Ideally, the test patterns are placed or projected on a flat surface inside the calibration chamber. However, many of the optical devices to be tested are designed to focus on objects

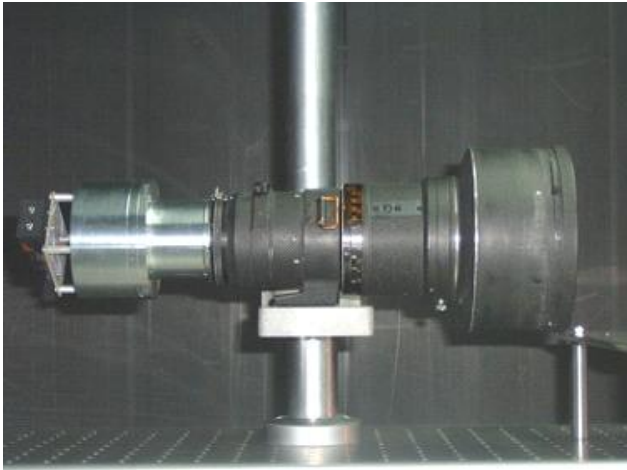


Fig. 4. FOCAL³ collimator

which are further away than the available distance within the cleanroom. A *collimator* is used to overcome this difficulty.

The FOCAL³ collimator is constructed using a Nikon 300 mm f 2.8 telephoto lens, from a standard 35 mm camera, with the focus set to infinity. (See Fig. 4.) The 35 mm camera body is replaced by a projection chamber which holds a standard 35 mm slide in the lens's focal plane. A "white" LED illumination source in the chamber projects the image of the slide through the front of the telephoto lens as parallel rays. When the imager to be tested is placed directly in front of the collimator these parallel rays enter the imager and are focused as it would for an object "at infinity". Thus, the collimator allows a focused test pattern to be projected into an optical device at short distances (a few centimeters) without regard to long focal lengths.

There are a number of test patterns that are used with the collimator to help determine distortion characteristics in the camera being tested. To test for sharpness of focus, high-contrast patterns of straight lines and pin-holes can be used. Analysis algorithms, such as modulation transfer function (MTF) or point spread function (PSF) can then be used to test quantitatively how well the camera resolves those images. To test for distortion and pin-cushion effects, a simple checkerboard test pattern is used. The image captured by the camera is then examined: non-parallel lines in the captured image indicate distortion. All of the collimator test patterns are printed on high-resolution 35 mm slides.

4.2 Monochromator

Auroral imagers often use filters to single out one particular emission wavelength. If the optical passband of the filter is known with sufficient detail, then imagers of this type can be calibrated with a high degree of accuracy, resulting in much higher quality data obtained from the field. To measure the

passband curve, light from monochromator (a variable wavelength monochromatic light source) is passed into the camera and filter. Using the camera as a detector, the intensity is measured at a number of wavelengths across the expected passband of the filter.

The monochromator used at FOCAL³ is a Newport Oriel Cornerstone 260. This monochromator is computer controlled and includes software to automatically scan through a selectable range of wavelengths. Appropriate slits and gratings are available to measurements at two different wavelength resolutions. For measuring narrow passband filters (2 to 5 nm wide), slits and gratings for 0.1 nm resolution are used; for wider filters, the 1.0 nm slits and gratings are used.

To insure proper absolute calibration of the monochromator, the manufacturer recommends periodic recalibration using a spectral line source such as a mercury lamp or laboratory laser.

5 Recent calibration projects

Current applications using this facility include the ePOP satellite (aurora imagers), ROPA rocket (aurora imagers), and the Star Sensor for the IBEX mission (PMT star sensor). A few details on the first of these are provided below.

5.1 ePOP Fast Auroral Imager

The Enhanced Polar Outflow Probe (ePOP) is a Canadian small satellite mission which will investigate the dynamics of the upper atmosphere in the earth's polar region (Yau et al., 2006). One of the eight instruments onboard is the Fast Auroral Imager (FAI) which is being calibrated at FOCAL³. A full complement of tests and calibrations are being performed for this imager including dark current, uniformity, linearity, absolute sensitivity, photon transfer curve and distortion tests. One early result from these calibrations, a uniformity correction, is described below.

As explained above in Sect. 3.1, CCD imagers often have intensity readout variations across the photosites of the CCD array. Figure 5, a sample "uncorrected" image captured from the FOCAL³ integrating sphere, shows two types of inherent intensity variations within FAI. First, small areas of localized non-uniformity are clearly visible as dark spots. Second, an overall gradual change in intensity from the center to the edge is apparent. If left uncorrected, these intensity variations will negatively affect the accuracy of any scientific data obtained in the field.

During FAI calibration, dozens of integrating sphere images (like Fig. 5) were captured at a variety of intensity levels. Since the input light source (the integrating sphere) presented a known uniformity ($\pm 2\%$) across the field of view, these calibration images were used to calculate a "correction factor" for the inherent uniformity flaws in FAI. This uniformity correction factor can subsequently be applied to

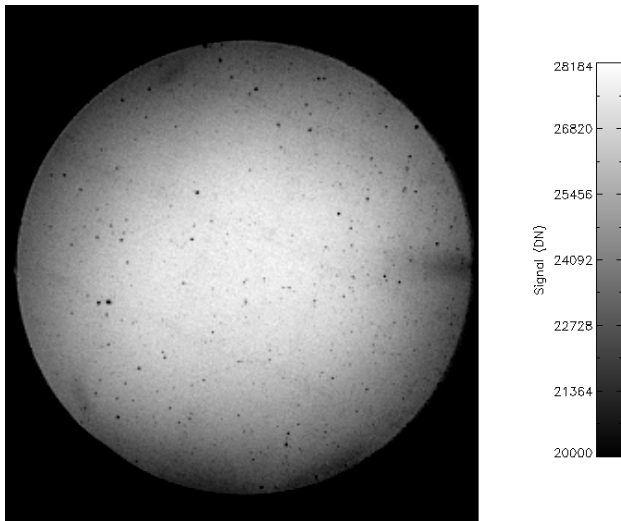


Fig. 5. Sample “uncorrected” (raw) image from FAI.

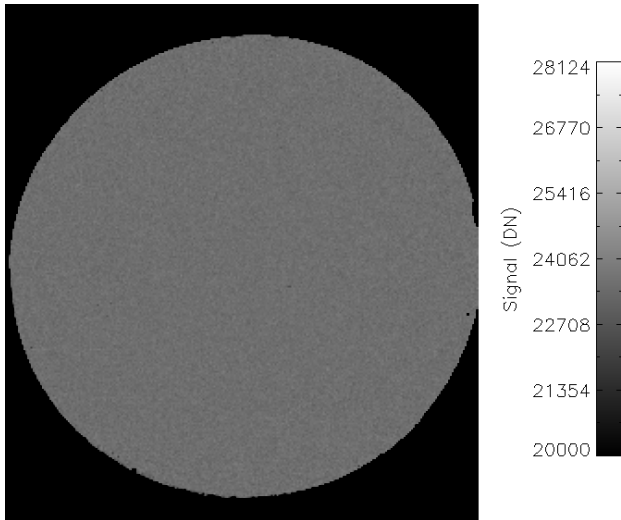


Fig. 6. Same image, with uniformity correction applied.

any FAI image to remove the imperfections. As an example, Fig. 6 shows a “corrected” version of the same image shown in Fig. 5, which shows a noticeable improvement. When this correction is applied to FAI image data collected from the field, the precision and quality of the gathered information is greatly enhanced.

6 Conclusions

FOCAL³, a new facility which specializes in the calibration of low light optical devices, was described. This facility, with its instruments and properly controlled environment, enhances the quality and precision available for calibration of

low light optical devices. As a result, this should enhance the quality and precision of the scientific data collected by those devices in the field.

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