Optical calibration system of NIPR for aurora and airglow observations

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Abstract

Calibration of optical instruments is important for accurate measurement of the absolute emission intensity of aurora and airglow. The National Institute of Polar Research (NIPR), Japan, has been operating a facility for the optical calibration which consists of three independent calibration systems to share it with collaborating researchers. This paper introduces an outline of the facility and specifications of each system, calibration procedures, and examples of calibration results. With this facility, we can obtain the calibration data for the absolute sensitivity of optical instruments with an accuracy of about 2\% within the wavelength range between 420 and 1050 nm. In addition, it is possible to obtain wavelength characteristics of optical filters and detectors used for aurora and airglow observations. Current facility, upgraded in 2012 has been used by many researchers to calibrate their various optical instruments.

1. Background

Aurora and airglow phenomena have been studied for a long time. Since their emission intensity is often very weak, it is important that instruments for their observations should have enough sensitivity even for such a weak emission, and they should be calibrated to assure their sensitivity before the observations. In particular, such a calibration facility for the instruments becomes more important because aurora and airglow observations become more sophisticated (e.g., observations of monochromatic spectrum and/or wide wavelength with various optical detectors, lenses and filters). Calibration of absolute sensitivity using a standard light source and stars has been classically performed (e.g., Brändström et al., 2012). A sensitivity calibration system for digital color cameras for aurora study has been developed and improved by using a monochromator (Sigernes et al., 2008; Sigernes et al., 2009). Sensitivity calibration of all-sky cameras has been recently performed by using a 1-m integrating sphere in The University Centre in Svalbard (UNIS) (Sigernes et al., 2014).

The National Institute of Polar Research (NIPR), Japan, has installed the calibration facility with an integrating sphere and has been sharing it with collaborating scientists since 1997 (e.g., Okano et al., 1998; Shiokawa et al., 2000; Yamamoto et al., 2002). The housing environment of the optical calibration facility
was upgraded when NIPR moved from Itabashi to Tachikawa, Tokyo in 2009. After the relocation, a new integrating sphere system had been installed in March, 2012. This paper introduces the current status, specifications, and usage procedures of the NIPR optical calibration facility. Some of the information on the facility are open for public via the following web page: http://polaris.nipr.ac.jp/~uap/IntegrationSphere/.

2. Equipment in the optical calibration facility of NIPR

The optical calibration facility in NIPR consists of three independent systems. Figure 1 shows their pictures. First, the integrating sphere system shown in Figure 1 (a) is used to measure the absolute emission intensity. Secondly, the monochromator system shown in Figure 1 (b) is used to examine the wavelength characteristics of an entire optical instrument. Thirdly, the spectrophotometer shown in Figure 1 (c) is used to examine the wavelength characteristics of filters used in an optical instrument. By using these three systems in combination, quantitative investigations for aurora and airglow phenomena become possible. Each system is introduced in sections 2-1, 2-2, and 2-3, respectively in this paper. Housing environment of the NIPR calibration facility is maintained at a temperature of 23°C and a humidity of 50%. Before entering the room, it is required for users to pass through an air shower to keep the facility as clean as possible.

2-1 The LMS-760 integrating sphere system

Previous integrating sphere system (using the OL462-80A integrating sphere) had been replaced with the new integrating sphere system (see Figure 1 (a)) in March, 2012. The new 2-m integrating sphere made by the Labsphere Co., Ltd. is environmentally and optically stable, and provides high diffuse reflectance over a wide wavelength range from ultraviolet to near-infrared. A halogen tungsten lamp and a spectrometer are attached to the integrating sphere, and a hole of 48 cm is made so that most of optical instruments can be inserted in the integrating sphere. Table 1 shows specifications of the system.

Optical instruments to be calibrated receive a uniform light generated by the lamp and integrating sphere in this system. The spectrometer can measure spectrum distribution of the lamp light in the integrating sphere. As a result, the system can be used for sensitivity calibration of image sensors (such as charge-coupled devices (CCDs)) of the optical instruments that capture weak lights of aurora and airglow. The diameter of the insertion port (i.e., aperture) of the integrating sphere is designed to be 48 cm so that the optical instruments with a large lens (up to ~30 cm) can be accommodated. Such a diameter of ~2-m is required to produce a uniform light at the wide aperture.

Figure 2 shows a configuration diagram of the integrating sphere system (including light source, light slit controller, spectrometer, and control/recording unit (using a laptop PC)). All-sky imagers, digital cameras, photometers, etc. are inserted through the insertion port of the integrating sphere, and then characteristics of their optical sensitivity are measured. Special functions of this system are listed as follows: (1) A
feedback mechanism of spectral intensity setting, using the photo-sensor (S2281-01) and lamp slit controller, (2) measurement of spectrum distribution of radiance in the integrating sphere with the spectrometer MCPD-9800, and (3) calibration of an all-sky imager with a large fish-eye lens (up to ~30 cm).

Figure 3 shows an example of capturing inside of the integrating sphere with an all-sky imager. The image inside has shadows on the seam of the integrating sphere and also on the left side. The reason for the shadow on the left side is considered to be the positional relationship between the halogen tungsten lamp and the camera insertion port. Figure 4 shows how the intensity of the lump light quantitatively changes in the integrating sphere. Otsuka Electronics Co., Ltd. measured it using a mirror and spectrometer. The mirror was placed at the center of the integrating sphere, and then its angle was changed from left side to right side in order to measure their intensity changes with the spectrometer located at the insertion port of the integrating sphere. The intensity at the angle of 0 degrees (see Figure 3) is normalized as 1. The shadow portion at the left side of the integrating sphere (between -90 and -140 degrees) has the lowest brightness value of about 94-98%. In addition, the luminance value is slightly higher (within 2%) at the right side (more than 90 degrees) due to relative location of the halogen tungsten lamp. As a result of this measurement, we found that lights in the integrating sphere were mostly uniform within the range of ± 8%. We expect that their secular change was very small because results obtained in March, 2012 were almost the same as those in October, 2016. Because of the higher uniformity in the center of the integrating sphere (in a range of ± 90 degrees as shown in Figure 4), one is able to measure brightness of higher uniform lights with one’s all-sky optical instrument if one put it into the center of the integrating sphere and reduce the influence of the shadows. Note that vignetting of each optical instrument with wide FOV/Fish-eye lens usually has a greater effect than the influence of the shadow. For example, there is about 20% of vignetting in the configuration of the Watec imager and Fujinon fisheye lens (see Figure 4 (b) of Ogawa et al., 2020).

Figures 5 and 6 show results of the absolute intensity calibration of the MCPD-9800 spectrometer. Its calibration has been performed almost every year. The solid lines in Figure 5 are the spectral intensities of halogen tungsten lamp in the integrating sphere measured with the MCPD-9800, and the dotted lines are by the spectrometer HS-1000 calibrated by the National Institute of Standards (NIST). The setting of 30 μW/m²/str/nm at the wavelength of 630 nm was used for all the calibration. Here, the conversion of the radiation intensity units from the watt value [μW/m²/str/nm] to the Rayleigh value [R/nm] at the wavelength λ [nm] can be written by using the following equation:

\[
I [R/nm] = \frac{4\pi}{hc} \cdot 10^{-25} \cdot I [\mu W/ m^2/ str/nm] \cdot \lambda [nm]
\]

(1)

\[
= 6.326 \cdot I [\mu W/ m^2/ str/nm] \cdot \lambda [nm]
\]

, where \( h \) is Planck’s constant and \( c \) is the speed of light. Basically, the radiation intensity of a halogen tungsten lamp increases at the longer wavelength side. Figure 6 shows the difference between the spectral
distributions of radiance in the integrating sphere measured with the MCPD-9800 and HS-1000 spectrometers. The output of the MCPD-9800 spectrometer has been calibrated almost every year so that accuracy of the measurement with MCPD-9800 at the wavelengths between 430 and 1000 nm becomes within ~0.2%. At the shorter wavelength side, each difference was ~2% at 400 nm, ~5% at 360 nm, and ~15% at 340 nm, respectively. At the longer wavelength side above 700 nm, there was a difference of the emission intensity every year (see Figure 5), but we can see that the calibration of the MCPD-9800 spectrometer has been performed correctly every year (as shown in Figure 6). Calibration results become worse at the wavelength of 1050-1100 nm (~3%). Based on these results, the system has a capability to calibrate optical instruments with approximately 2% accuracy within the wavelength range from 420 nm to 1050 nm.

To show the accuracy of repeatability of this integrating sphere system, Figure 7 indicates the standard deviations of measured intensity values at each wavelength when the same setting was used several times. In this graph, the target radiance was changed from 0.01 to 30 μW/m²/str/nm at a wavelength of 630 nm. We used samples obtained from January 2019 to January 2020, and the number of their samples at each target radiance was 13 on average. When setting values of radiance at the wavelength of 630 nm were 1-30 μW/m²/str/nm, their variations at the wavelength range between 400 and 1050 nm were within 0.5%. On the other hand, in the cases of 0.1-0.01 μW/m²/str/nm at the wavelength of 630 nm, their variations increase up to ~1% (see Table 2 for their specific values). At the shorter wavelength side (< 480 nm), the accuracy of repeatability tends to decrease as the wavelength becomes shorter. In the case of luminance of 1-30 μW/m²/str/nm at a wavelength of 630 nm, the accuracy of repeatability becomes ~10% at a wavelength of 340 nm. These values are within the range of the annual calibration of luminance accuracy made with the HS-1000 spectrometer. It was also confirmed that the accuracy of repeatability investigated in January, 2013 was almost the same as that in Figure 7. Thus it indicates that there was almost no aging. The brightness of the integrating sphere system at typical aurora wavelengths and its error are summarized in Table 2.

2-2 The DK240 monochromatic light source system

This system is used for measuring wavelength characteristics of optical instruments. It consists of a monochromatic light source combining a hybrid light source and a monochromator, and a spectroradiometer for measuring the spectrum of the light source, and so on. The hybrid light source (ASTN-D1-W150, manufactured by Spectral Products Co., Ltd.) consists of a 30 W deuterium lamp and a 150 W tungsten halogen lamp, and covers a wide wavelength range from the ultraviolet to the infrared. The brightness of the halogen tungsten lamp can be adjusted by changing its driving voltage. A monochromator (DK240, manufactured by Spectral Products Co., Ltd.) can separate light in a wide wavelength range from the ultraviolet to the infrared by switching between three types of diffraction gratings. This DK240 monochromatic light source system obtains monochromatic light by installing this monochromator downstream of the hybrid light source. Switching of diffraction gratings and angle adjustment are
performed using a dedicated controller connected via RS232C. There are slits at the entrance and exit of
the light to the monochromator, and the amount of light and the wavelength width of the light to be extracted
are adjusted by selecting the slit width using the controller. Specifications of the DK240 monochromator
and the three types of diffraction gratings are summarized in Table 3.

When measuring the wavelength characteristics of optical instruments, the spectrum of the light emitted
from the monochromator is simultaneously measured using the spectroradiometer (CS-2000A
manufactured by Konica Minolta Co., Ltd.), to guarantee wavelength accuracy of the monochromatic light
source. The measurable wavelength range of the spectroradiometer is between 380 and 780 nm, and the
wavelength resolution is 0.9 nm/pixel. Therefore, the measurable wavelength range of the DK240
monochromatic light source system is currently limited to the visible light range, because it depends on the
specifications of the spectroradiometer.

Figure 8 shows examples of the device layout when using this monochromatic light source system. The
wavelength characteristics of the optical instruments can be examined as (1) wavelength of the
monochromatic light source was scanned by the monochromator, and then (2) the monochromatic light was
simultaneously measured by the optical instruments and the CS-2000A spectroradiometer (see Figure 8 (a)).
An example of the calibration result for a color digital camera was shown in Figure 4 of Hozumi et al.,
(2016). The area of the light source (emitted from the DK240 monochromator) can be increased by using a
diffuser plate or a small integrating sphere (see Figure 8 (b) and (c)). When using a diffusion plate, the light
emitted from the monochromator is enlarged using an appropriate lens. A single optical fiber is used when
the monochromatic light enters the small integrating sphere. The calibration method using the small
integrating sphere (Figure 8 (c)) is similar to that described in Sigernes et al. (2009). Note that the amount
of light per unit area is reduced when using the small integrating sphere or the diffuser plate.

2-3 The U-3300 Spectrophotometer

The U-3300 Spectrophotometer is a device for examining the transmission characteristics of filters, and its
specifications are shown in Table 4. A deuterium lamp (for ultraviolet lights) and a tungsten halogen lamp
(for visible lights) are used in the spectrophotometer, and it can measure transmission characteristics in the
wavelength range of 190-900 nm with a resolution of up to 0.01 nm. For this spectrophotometer incident
angle of light to the filter can be changed between 0 and ~90 degrees. Examples of transmittance of filters
with the changed incident angles (for 428 nm, 558 nm, and 630 nm wavelengths for aurora observations)
were shown in Figure 3 of Ogawa et al. (2020). The relationship between the change of incident angle and
shift of transmission wavelength can be theoretically described by the following equation.

\[
\lambda_\theta = \lambda_0 \left(1 - \left(\frac{N_e}{N^*}\right)^2 \sin^2 \theta\right)^{1/2}
\]

\[
\sim \lambda_0 \left(1 - \theta^2 / 2 N^*^2\right),
\]

\[\text{for } \theta = 0 \]

where \(\theta\) is the incident angle, \(\lambda_0\) is the wavelength when the incident angle \(\theta\) equals to zero, \(N_e\) is the
refractive index of outside media (equal to 1.0), and $N^*$ is the refractive index of the filter (typically ~2.05 for band-pass filters by Andover Co., Ltd.). Note that a shape of filter transmission function changes in addition to the shift of transmission wavelength, as shown in Figure 4 of Katoh et al. (1999).

3. Calibration method

3-1 Method to convert from counts of optical instruments to emission intensities using calibration results

The count detected by each optical instrument can be generally represented by the following equation:

$$N = \int S(\lambda) I(\lambda) d\lambda t$$  \hspace{1cm} (3)

where $N$ is the device count [cts], $S$ is the device sensitivity [cts/s/R/pixel], $I$ is the source luminosity [R/nm] = $[10^6$ photon / cm$^2$/sec/nm], $t$ is exposure time [sec], and $\lambda$ is wavelength [nm]. Note that the count includes the exposure time, that means that it is not per unit time. Here, noises such as dark currents of each optical instrument are not taken into account, in order to discuss the relationship between the brightness in the integrating sphere and count of each optical instrument more simply. Theoretical sensitivity can be expressed as

$$S(\lambda) = \frac{10^6}{4\pi} A \Omega G \eta(\lambda) T_L(\lambda) T_F(\lambda)$$  \hspace{1cm} (4)

where $A$ is other optical coefficients, $\Omega$ is the solid angle of one pixel of CCD [str], $G$ is gain of each instrument [%], $\eta$ is the quantum efficiency of CCD [%], $T_L$ is transmissivity of lens of each instrument, and $T_F$ is transmissivity of filter(s) of each instrument. From this equation, Eq. 3 becomes

$$N = \frac{10^6}{4\pi} A \Omega \eta G T_L \int I(\lambda) T_F(\lambda) d\lambda t = B \int I(\lambda) T_F(\lambda) d\lambda t$$  \hspace{1cm} (5).

It should be noted that the dependence of $\eta$ and $T_L$ on wavelength can be assumed to be sufficiently smaller compared to the dependence of filter $T_F$. Thus, the $\eta$ and $T_L$ are included in $B$ as variables independent of wavelength.

Typical auroras at wavelengths of 557.7 and 630.0 nm are known as line emissions, whereas filters have a wider wavelength range. Figure 9 shows the difference of light emission observations between aurora and the integrating sphere cases. The aurora counts $N_A$ (see Figure 9 (a), and also Figure 6 of Hosokawa et al., 2019) can be expressed as follows:

$$N_A = B \int I_A(\lambda) d\lambda t_A = B T_F(\lambda_A) I_A(t_A)$$  \hspace{1cm} (6).

On the other hand, the counts $N_S$ for the integrating sphere case in the calibration facility (see Figure 9 (b)) is written as follows.
\[ N_s = B \int I_s(\lambda) T_F(\lambda) \, d\lambda \, t_s \]  

(7)

We can erase \( B \) using Eq. 6 and Eq. 7, and then auroral emission intensity \( I_d \) can be expressed in the following equation.

\[ I_d = \left( \frac{\int I_s(\lambda) T_F(\lambda) \, d\lambda}{T_F(\lambda_A)} \right) t_s N_s t_A^{-1} N_A \]  

(8)

Note that the dependence of \( I_s \) on wavelength is usually smaller compared to the dependence of filter \( T_F \).

When examining the emission brightness of only aurora, counts of background light need to be subtracted from the total count of \( N_A \). After that, it becomes possible to quantitatively derive emission intensity of the aurora emission line \( (I_d) \) from the aurora counts \( (N_d) \) using the relationship between \( N_A \) and \( I_s \) obtained from the calibration with the integrating sphere system and the wavelength characteristics of the filter \( T_F \).

Regarding the exposure time \( (t_s) \) when using an integrating sphere, calibration experiments are usually performed in accordance with the exposure time \( (t_d) \) used for field observations. If we can separately evaluate errors such as dark currents and so on, it is possible to derive emission brightness from observation data using different exposure times as shown in Eq. 8.

### 3-2 Summary of the calibration systems and their procedures

Figure 10 summarizes the features of three calibration systems described so far. The results of the filter characteristics shown in Figure 10 (c) are used for both the integrating sphere system (Figure 10 (a)) and the monochromatic light source system (Figure 10 (b)). Since optical instruments receive continuous light in the integrating sphere as shown in Figure 5, it is particularly important to combine the results of filter characteristics with the calibration using the integrating sphere system, in order to quantitatively understand the relationship between the absolute emission intensity and the device count. Using the monochromatic light source system shown in Figure 10 (b), angle dependence of the spatial resolution of the instruments can be obtained by changing angles of the light-receiving surface if the field of view (FOV) of the instruments is wide enough. Calibration procedures for some different types of optical instruments are briefly summarized as follows.

1. In the case of an all-sky/wide-FOV monochromatic imagers, measurement of filter characteristics by the U-3300 spectrophotometer and calibration of absolute luminescence intensity by the LMS-760 integrating sphere system are performed. The DK240 monochromatic light source system is used to measure the incident angle dependence of the spatial resolution as demonstrated in Figure 6 of Taguchi et al. (2004).

2. In the case of photometers and narrow-FOV monochromatic imagers, it is effective to calibrate the wavelength characteristics of the entire device using the DK240 monochromatic light source system, as well as measuring the filter characteristics and calibrating the absolute emission intensity using the spectrophotometer and the integrating sphere system. As summarized in section 2-2, two measurement...
methods using the diffuser plate and the small integrating sphere can be utilized (each method is described in Figure 8 (b) and (c)).

(3) In the case of color digital cameras, the measurement of wavelength characteristics by the DK240 monochromatic light source is effective. Both the narrow field of view and the all-sky cameras can be measured with the arrangement shown in Figure 8 (a) to understand the wavelength characteristics of the RGB filters in the digital cameras.

4. Usage of the calibration facility in NIPR

NIPR is the only institute in Japan promoting joint use of a large integrating sphere system, and has been developing facilities and infrastructure for calibration of optical instruments. To date, NIPR has made continuous contributions, through the usage and lending of the optical calibration equipment, to researchers in Universities/institutes in Japan (For examples, Nagoya University, Hokkaido University, Tohoku University, Kyoto University, the University of Electro-Communications, and Kochi University of Technology) that promote research and observations of aurora and airglow. Table 5 summarizes representative optical instruments calibrated using the updated LMS-760 integrating sphere system. In particular, the calibration systems are used for calibration of ground-based observation instruments such as all-sky/wide-FOV/narrow-FOV imagers, color digital cameras, and photometers. The annual number of their usage during the past five years (2015-2019) was 17 times and 34 scientists (including 12 students) on average. The average usage time of the integrating sphere lamp was ~106 hours/year. In addition to the ground-based observation instruments, the calibration systems of NIPR have been used for an instrument onboard the JAXA-ISAS Planetary Spectroscopy Satellite “Hisaki” (SPRINT-A) (Yamazaki et al., 2017).

In the future, we hope to promote cross-calibration with Nordic collaborative research institutes such as The University Centre in Svalbard (UNIS) and Swedish Institute of Space Physics (IRF) to maintain correctly calibrated optical datasets and also promote the mutual use of instrument data from other institutes.

5. Summary of this paper and future works

In this paper, we introduced the outline and accuracy of the calibration systems maintained and operated by NIPR, as well as examples of calibration procedures for several instruments to measure aurora and airglow. After the update of the integrating sphere system in March, 2012, calibration data of absolute sensitivity can be obtained with an accuracy of about 2% in the wavelength range from 420 nm to 1050 nm. In addition, it is possible to calibrate the wavelength characteristics of the optical instruments by using the DK240 monochromatic light source system. These systems are widely used by researchers in many Universities/institutes in Japan, and plans to promote international cross-calibration in the future.

Limitation of the calibration at short-wavelength (< 430 nm) using the integrating sphere system is to be improved near the future. As can be seen in Table 2, the brightness remains 50 kR/nm at 427.8 nm even
when the maximum specified value of 30 $\mu$W/m$^2$/str/nm at 630 nm is used. We consider that the problem can be solved by opening the shutter of the lump (light source) more widely. The increasing brightness of the integrating sphere system would be useful not only for calibration of aurora and airglow, but also for calibration of sprite (lightning) observers (e.g., Armstrong et al., 1998). Then we are investigating the introduction of a hemispherical type integrating sphere to solve the problem of the shadow due to the location of the lamp and insertion port. We are also considering expanding the measurable wavelength range of the monochromatic light source system, by introducing ultraviolet and infrared spectrometers into the system.

Data Availability:

Datasets related to this article can be found at http://polaris.nipr.ac.jp/~uap/IntegrationSphere/.

Acknowledgments:

We thank Prof. Makoto Taguchi and Dr. Su Takeshita for their advice on the entire optical calibration system in NIPR. We also appreciate participants of the calibration lab meeting held in NIPR in July, 2009, and all researchers who responded to the questionnaire on an update of the NIPR optical calibration system. We would also like to thank the Otsuka Electronics Co., Ltd. for their cooperating with the introduction of the LMS-760 integrating sphere system and regular calibration of the system.

References:


Figure captions:

Figure 1: Photos of the calibration systems in the calibration facility in NIPR. (a) The LMS-760 integrating sphere system, (b) The DK240 monochromatic light source system, and (c) The U-3300 Spectrophotometer.

Figure 2: Configuration diagram of the LMS-760 integrating sphere system. It consists of an integrating sphere, a lamp, a spectrometer, and a control/recording PC.

Figure 3: Example of an image taken inside the integrating sphere with an all-sky imager.

Figure 4: The emission intensity within the integrating sphere. The result is obtained by placing a mirror at the center of the integrating sphere, changing its angle, and then measuring its emission intensity at the insertion port by a spectrometer. The positive angle indicates the right-side region (as viewed from the opening of the integrating sphere, see Figure 3).

Figure 5: Comparison results of the LMS-760 integrating sphere system using the HS-1000 spectrometer calibrated by the National Institute of Standards (NIST) between 2014 and 2020. Solid lines show the spectral distribution of radiance in the integrating sphere measured by the MCPD-9800 in the system, and dotted lines show the spectral distribution by the HS-1000 spectrometer. Settings of the Lamp for all the calibration were 30 μW/m²/str/nm at a wavelength of 630 nm.

Figure 6: Difference between the spectral distribution using the calibrated HS-1000 spectrometer and the MCPD-9800 in the integrating sphere system.

Figure 7: The standard deviations of measured intensity values at each wavelength. The emission intensities at 630 nm are changed from 0.01 to 30 μW/m²/str/nm.

Figure 8: Schematic drawings of calibration methods using the DK240 monochromatic light source system: (a) Arrangement for direct measurement of a monochromatic light from a monochromator, (b) configuration when using a diffuser plate, and (c) configuration when using a small integrating sphere.

Figure 9: Schematic of light emissions passing through the filter. (a) In the case of bright-line spectrum of aurora, and (b) In the case of lights in the integrating sphere system.

Figure 10: Usage of the three calibration systems combined. In particular, the result of the filter transmission characteristics (c) is used for the calibrations of the absolute emission intensity characteristics (a) and the wavelength sensitivity characteristics (b).
### Table 1: Specification of the LMS-760 integrating sphere system

<table>
<thead>
<tr>
<th>Product name of the integrating sphere</th>
<th>LMS-760 (manufactured by Labsphere Co., Ltd.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Size</strong></td>
<td>2300 mm (W) x 2100 mm (H) x 2400 mm (L)</td>
</tr>
<tr>
<td><strong>Inner diameter of the integrating sphere</strong></td>
<td>1908 mm</td>
</tr>
<tr>
<td><strong>Coating material of the inner surface</strong></td>
<td>Spectraflect (Barium sulfate coating)</td>
</tr>
<tr>
<td><strong>Diameter of the exit port</strong></td>
<td>Introductory part: 600 mm (15 mm depth)</td>
</tr>
<tr>
<td></td>
<td>Insertion opening inside: 480 mm (15 mm depth)</td>
</tr>
<tr>
<td><strong>In-plane uniformity</strong></td>
<td>±5.0% (Solid angle of 2π) (Refer Figure 4)</td>
</tr>
<tr>
<td><strong>Wavelength Range</strong></td>
<td>330-1100 nm</td>
</tr>
<tr>
<td><strong>Spectral Radiance Range</strong></td>
<td>0.01 to 30 μW/m²/str/nm at 630nm wavelength (50 to 100,000 Rayleigh)</td>
</tr>
</tbody>
</table>

#### Details of each part of the system

**Lamp**
- Product name: PAN16-10A (manufactured by Kikusui electro Co., Ltd.)
- Lamp type: Halogen tungsten lamp
- Dimming accuracy: ±0.05% (30 μW/m²/str/nm at 630nm wavelength)

**Spectrometer**
- Product name: MCPD-9800 (manufactured by Otsuka electronics Co., Ltd.)
- Wavelength Range: 330-1100nm
- Wavelength width per element: 3nm (Wavelength resolution: ±0.5nm)
- A/D converter resolution: 16 bit
- Measurable brightness range: 0.0005-1.2 cd/m²

**Monitor light receiving part**
- Product name: S2281-01 (manufactured by Hamamatsu photonics Co., Ltd.)
- Material: Silicon photodiode
- Sensitive wavelength range: 190-1000 nm
Table 2: Brightness and error corresponding to the setting of the integrating sphere system. Typical wavelengths of aurora/airglow emissions are listed.

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>Brightness in Rayleigh/nm at the setting of 0.1 (\mu)W/m(^2)/str/nm @ 630 nm</th>
<th>Its repeatability accuracy [%]</th>
<th>Brightness in Rayleigh/nm at the setting of 10 (\mu)W/m(^2)/str/nm @ 630 nm</th>
<th>Its repeatability accuracy [%]</th>
<th>Calibration error of the integrating sphere system (measured at 30 (\mu)W/m(^2)/str/nm @ 630 nm) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>427.8</td>
<td>47.81</td>
<td>1.3</td>
<td>4781</td>
<td>0.29</td>
<td>0.36</td>
</tr>
<tr>
<td>486.1</td>
<td>112.53</td>
<td>1.0</td>
<td>11253</td>
<td>0.23</td>
<td>0.16</td>
</tr>
<tr>
<td>557.7</td>
<td>246.62</td>
<td>0.81</td>
<td>24662</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>630.0</td>
<td>398.12</td>
<td>0.42</td>
<td>39812</td>
<td>0.10</td>
<td>0.18</td>
</tr>
<tr>
<td>670.5</td>
<td>485.10</td>
<td>0.73</td>
<td>48510</td>
<td>0.08</td>
<td>0.22</td>
</tr>
<tr>
<td>777.4</td>
<td>747.32*</td>
<td>0.71</td>
<td>74732*</td>
<td>0.07</td>
<td>0.20</td>
</tr>
<tr>
<td>844.6</td>
<td>904.23*</td>
<td>0.64</td>
<td>90423*</td>
<td>0.14</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Note *: At wavelengths of above 700 nm, it is desirable to read the measured values of the MCPD-9800 spectrometer and derive the emission intensities in Rayleigh/nm using Eq. 1.
<table>
<thead>
<tr>
<th>Hybrid light source</th>
<th>ASTN-D1-W150 (Spectral Products) &lt;br&gt;Light sources: 30W deep UV Deuterium lamp &lt;br&gt;150W Tungsten-Halogen lamp &lt;br&gt;Wavelength: 180 nm – 2.6 μm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monochromator</td>
<td>DK240 (Spectral Products) &lt;br&gt;Wavelength Drive: Worm and wheel with microprocessor control. Bi-directional. &lt;br&gt;Design: Czerny-Turner, triple-grating turret &lt;br&gt;Wavelength range: 180–3000 nm &lt;br&gt;Maximum Resolution: 0.2 nm with 1200 g/mm grating &lt;br&gt;Wavelength Accuracy: ± 0.3 nm with 1200 g/mm grating &lt;br&gt;Wavelength Precision: 0.01 nm with 1200 g/mm grating</td>
</tr>
<tr>
<td>Slits</td>
<td>straight entrance and straight exit &lt;br&gt;Width: 10 mm to 3000 mm &lt;br&gt;Height: 2 mm to 20 mm</td>
</tr>
<tr>
<td>Gratings</td>
<td>AG1200-00250-686 (Ruling: 1200 g/mm, Peak: 250 nm (Peak T% = 70%), Range: 180–460 nm) &lt;br&gt;AG1200-00600-686 (1200 g/mm, 600 nm (80%), 400–1500 nm) &lt;br&gt;AG0600-01600-686 (600 g/mm, 1600 nm (93%), 950–3000 nm) &lt;br&gt;Focal Length: 240 mm &lt;br&gt;F/#: 3.9</td>
</tr>
</tbody>
</table>

**Details of other parts of the system**

<table>
<thead>
<tr>
<th>Optical diffuser plate</th>
<th>SRT-99-100 (manufactured by Labsphere Co., Ltd.) &lt;br&gt;Reflection rate: 99% (at wavelengths of 250~2500 nm) &lt;br&gt;Size: 10×10 inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mini-integrating sphere</td>
<td>Product name: ISC-080-ST &lt;br&gt;Diameter: ~20 cm (8 inch) &lt;br&gt;Port size: ~5 cm (2 inch)</td>
</tr>
</tbody>
</table>
| Spectroradiometer     | CS-2000A (manufactured by KONICA MINOLTA Co., Ltd.) <br>Wavelength range: 380–780 nm <br>Wavelength resolution: 0.9 nm/pixel <br>Display wavelength bandwidth: 1.0 nm <br>Wavelength precision: ±0.3 nm (median wavelength: 435.8 nm, 546.1 nm, 643.8 nm Hg-Cd lamp) <br>Spectral bandwidth: 5 nm or less (half bandwidth) <br>Measuring angle: 1 degree / 0.2 degree / 0.1 degree (selectable) <br>Accuracy: Luminance (Standard light source A)*1 : ±2% <br>*1: Average of 10 measurements in Normal mode at a temperature
Table 4: Specifications of the U-3300 Spectrophotometer

<table>
<thead>
<tr>
<th>Product name</th>
<th>U-3300 UV-VIS Spectrophotometer (manufactured by Hitachi Co., Ltd.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinds of lamps</td>
<td>Deuterium lamp (for ultraviolet range), and halogen tungsten lamp (for visible light range)</td>
</tr>
<tr>
<td>Wavelength scan range</td>
<td>190 ~ 900 nm</td>
</tr>
</tbody>
</table>
| Wavelength Accuracy | + 0.3 nm Wavelength Accuracy.  
| | + 0.05 nm Wavelength Setting Repeatability. |
| Slit Width | Wavelength Display in Steps of 0.01 nm.  
| | 5, 4, 2, 1, 0.5, 0.1 nm Slit Width Display. |
| Wavelength Drive Speed | Wavelength Drive Speed: 0.3, 3, 15, 30, 60, 120, 300, 600, 1200, 1800 nm/min |
| Sample Compartment | 120 (W) x 300 (D) x 140 (H) mm  
| | Dimensions 100 mm distance between the reference light beam and the sample light beam |
Table 5: Representative instruments calibrated using the NIPR calibration systems

<table>
<thead>
<tr>
<th>Instrument names</th>
<th>Main institute(s) with the instrument (and its reference(s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow-FOV and all-sky high-speed EMCCD imagers</td>
<td>NIPR, etc. (e.g., Kataoka et al., 2015)</td>
</tr>
<tr>
<td>Multi-wavelength Watec imagers</td>
<td>NIPR, etc. (Ogawa et al., 2020)</td>
</tr>
<tr>
<td>Optical Mesosphere Thermosphere Imagers (OMTI)</td>
<td>ISEE, Nagoya University (Shiokawa et al., 1999; Shiokawa et al., 2017)</td>
</tr>
<tr>
<td>Multi-wavelength photometers for auroras</td>
<td>ISEE, Nagoya University (Nozawa et al., 2018)</td>
</tr>
<tr>
<td>All-sky high-speed monochromatic EMCCD imagers</td>
<td>ISEE, Nagoya University, the University of Electro-Communications, NIPR, etc. (Oyama et al., 2018)</td>
</tr>
<tr>
<td>All-sky monochromatic EMCCD imagers</td>
<td>Kyoto University and the University of Electro-Communications (e.g., Taguchi et al., 2012)</td>
</tr>
<tr>
<td>Imagers/cameras onboard sounding rockets</td>
<td>Tohoku University, etc.</td>
</tr>
<tr>
<td>Imagers/cameras onboard the International Space Station (ISS)</td>
<td>Kyoto University, etc. (Hozumi et al., 2016)</td>
</tr>
<tr>
<td>Extreme ultraviolet spectroscope (EXCEED) onboard the HISAKI (SPRINT-A) satellite</td>
<td>JAXA-ISAS, etc. (Yamazaki et al., 2017)</td>
</tr>
</tbody>
</table>
Fig 2

MCPD-9800 Photo-sensor Amp

1908mm

480mm

300mm

600mm

An imager to be calibrated

Lamp slit controller

Lamp Unit

Control PC

USB

USB

MCPD-9800
Uniformity inside the integrating sphere

Radiance (arbitrary unit)

[degree]

-140 -120 -100 -80 -60 -40 -20 0 20 40 60 80 100 120

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05

20161118

201203
Spectral Radiance

Radiance $[\mu W/m^2/str/nm]$

Wavelength $[nm]$
Fig 7

STD/AVE [%]

Wavelength [nm]

0.01 μW/m²/str/nm @ 630nm

0.1
1
10
30
**Measurement of filter transmission characteristics**

- Filter transmission characteristics include half width at half maximum (HWHM), center wavelength, angle dependence, etc.

**The U-3300 Spectrophotometer**

![Image of the U-3300 Spectrophotometer]

Measurement of filter transmission characteristics (HWHM), center wavelength, angle dependence, etc.

**Expression:**

\[ T_F(\lambda, \theta) \]

**The LMS-760 integrating sphere system**

Measuring at absolute light emission intensities to quantitatively understand the relationship between counts of each optical instrument \((N_S)\) and absolute light emission intensities \((I_S)\).

\[ N_S = B I_S \int T_F(\lambda) \, d\lambda \, t_S \]

**The DK240 monochromatic light source system**

Measurement of wavelength sensitivity characteristics of each optical instrument. When the field of view of the instruments is wide enough, angle dependence of the spatial resolution is also obtained by changing the angle of the light receiving surface.

\[ N \propto \int \eta(\lambda) I(\lambda) T_L(\lambda, \theta) T_F(\lambda, \theta) \, d\lambda \, t \]