SENSITIVITY CALIBRATION OF NARROW FIELD OF VIEW OPTICAL INSTRUMENTS

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Abstract – The increasing number of low light level optical instruments operated in Svalbard (Longyearbyen, Barentsburg and Ny-Ålesund) for monitoring auroras and airglow phenomena emphasizes the need for establishing accurate calibration routines of international standard. This paper reviews the mathematical frame work and the experimental setup of absolute calibration of narrow field of view instruments. A presentation of the new optical laboratory at UNIS is given. The results of secondary standard lamp certification and brightness control are demonstrated.

1. INTRODUCTION

The throughput or the useable photon flux at the exit of an optical instrument depends first of all on input flux. Secondly, it depends on the instrument's ability to accept light (geometrical extent [1]) and the quality of the optical components used. The efficiency of each component, whether they are lenses, mirrors, gratings or filters, limits the sensitivity and the wavelength region of the instrument. The process of transforming the exit flux to electronic counts by the detector also involves loss of photons.

It is therefore necessary to calibrate the instrument against a source of known intensity in order to obtain the ratio of electronic counts out to the number of photons incident on the instrument. The source of the calibration could be a lamp or any other object with known spectral characteristics. In addition, a diffuse reflective surface is needed to make sure that the instrument's field of view is uniformly illuminated.

This paper describes the theoretical concept and the experimental setup of sensitivity calibration using a Lambertian surface and a standard tungsten lamp. A method to transfer lamp certificates and a procedure to regulate source brightness of the screen without change in spectral shape is demonstrated.

2. THEORETICAL BASIS

2.1 The Lambertian Surface

A surface that has a perfectly diffuse / matte property is Lambertian. The radiant intensity reflected in any direction is proportional to the cosine of the angle of the normal to the surface. This is known as Lamberts Cosine law [2].

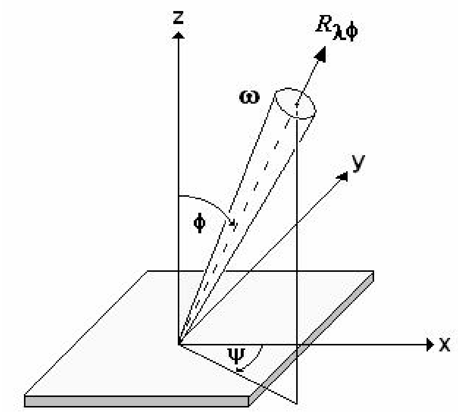

Fig. 1. The radiant intensity of a Lambertian surface.

According to Fig. 1, the radiant intensity is expressed as

$$R_{\lambda\phi} = R_{\lambda 0} \times \cos\phi, \quad \left[\frac{\#\,photons}{s\,sr\,\mathring{A}}\right] \tag{1}$$

where λ subscribes the wavelength and ϕ is the angle with respect to the normal. The total emission rate in the wavelength interval $d\lambda$ is the radiant intensity integrated over the hemisphere

$$N_\lambda = \int_0^{2\pi}\int_0^{\pi/2} R_{\lambda\phi}\, d\lambda \sin\phi\, d\phi\, d\psi. \tag{2}$$

Inserting Eq. (1) into (2) gives

$$N_\lambda = 2\pi\, R_{\lambda 0}\, d\lambda \int_0^{\pi/2} \cos\phi \sin\phi\, d\phi. \tag{3}$$

$$= 2\pi\, R_{\lambda 0}\, d\lambda \int_0^{\pi/2} \frac{1}{2}\sin 2\phi\, d\phi. \tag{4}$$

Consequently,

$$N_\lambda = \pi R_{\lambda 0}\, d\lambda. \quad \left[\frac{\# photons}{s}\right] \tag{5}$$

The total emission rate for a Lambertian surface is independent of the angles ϕ and ψ.

Our surface (SRT-99-180) is made of Spectralon and is produced by the company Labsphere, Inc. The reflectance factors of the screen are nearly constant *(*$\rho_\lambda = 0.98$*)* throughout the visible and near infrared regions of the spectrum. Table 1 shows the certificate of the screen.

Wavelength [Å]	Reflectance factors
3000	0.975
3500	0.981
4000	0.984
4500	0.984
5000 - 8500	0.986
9000	0.984
9500	0.986
10000	0.983
10500	0.986
11000	0.987
11500	0.985
12000	0.983

Table 1. Hemispherical spectral reflectance factors for SRT-99-180 from 3000 to 12000 Å. The factors are obtained at an angle of 8 degrees to the normal of the screen.

2.2 Calibration setup

Fig. 2 shows the setup for the calibration. The tungsten lamp (FEL) is located a distance $z = 6.9\ m$ from the centre of the screen and the angle between the screen and lamp axis is given by α. $B_{o\lambda}$ is the known radiance (certificate) of the lamp in units of *[#photons* $cm^{-2}\ s^{-1}$ $Å^{-1}$*]*, initially obtained at a distance of $z_o = 1\ m$. The source for our calibration is then the screen, not the lamp itself.

The lamp is treated as a point source, radiating photons isotropically. The total number of photons that pass through a sphere with radius z_o must be the same for a sphere with radius z

$$4\pi z_o^{\ 2} B_{o\lambda} = 4\pi z^2 B_{z\lambda} \tag{6}$$

We assume no absorption of photons in the space between the spheres. The radiance that hits the screen is then simply

$$B_{z\lambda} = B_{o\lambda} \times \left(\frac{z_o}{z}\right)^2 \quad \left[\frac{\# photons}{cm^2 s\, Å}\right]. \tag{7}$$

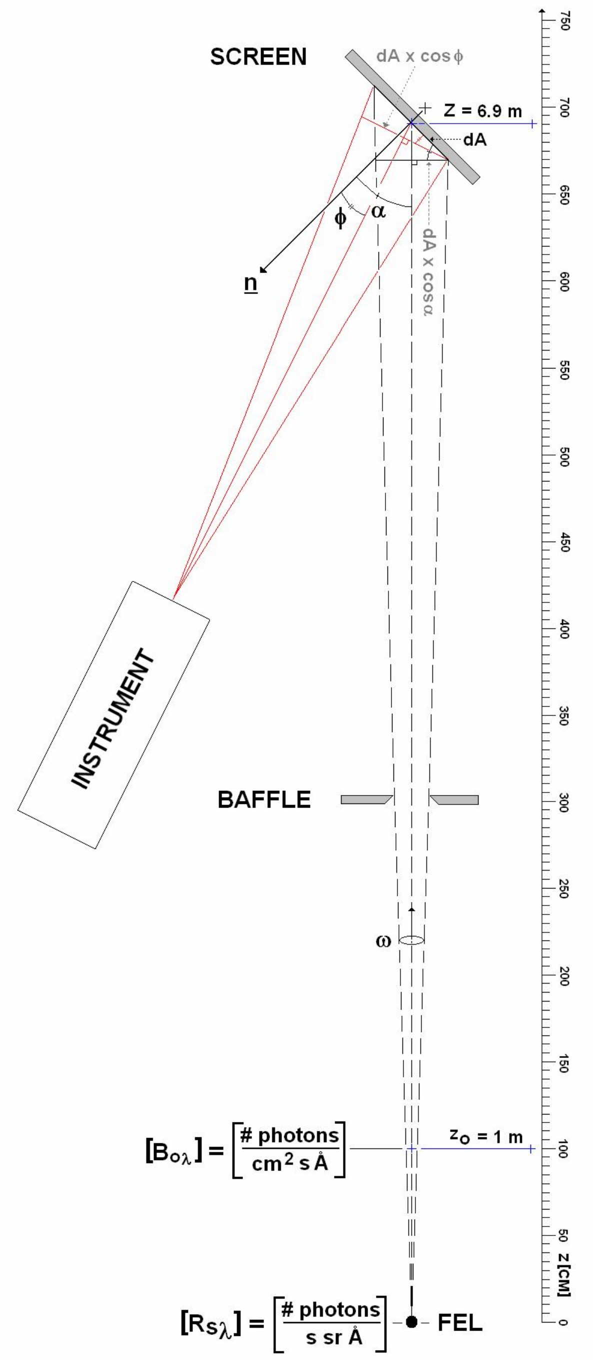

Fig. 2. Setup for absolute calibration of narrow field of view instruments.

Correspondingly, the emission rate that enters the screen in terms of the radiant intensity $R_{s\lambda}$ is

$$R_{s\lambda}\, d\lambda\, \omega = R_{s\lambda}\, d\lambda \left(\frac{dA \times \cos\alpha}{z^2}\right), \tag{8}$$

where ω is the solid angle and dA is the illuminated area of the screen.

The reemitted radiation of the screen is then

$$N_\lambda = R_{s\lambda}\, d\lambda\, \rho_\lambda \left(\frac{dA \times \cos\alpha}{z^2} \right) = \pi\, R_{\lambda 0}\, d\lambda. \quad (9)$$

From Eq. (1) we obtain

$$R_{\lambda\phi} = \rho_\lambda \left(\frac{R_{s\lambda}}{\pi} \right) \times \left(\frac{dA \times \cos\alpha}{z^2} \right) \times \cos\phi. \quad (10)$$

The effective illuminated area of the screen as seen by the instrument is $dA \times \cos\phi$, where ϕ is the angle between the optical axis and the screen normal. The radiance towards the instrument then becomes

$$L_\lambda = \frac{R_{\lambda\phi}}{dA \times \cos\phi} \quad \left[\frac{\#\, photons}{s\, sr\, \AA\, cm^2} \right] \quad (11)$$

$$= \rho_\lambda \left(\frac{R_{s\lambda}}{\pi} \right) \times \left(\frac{1}{z^2} \right) \times \cos\alpha\,. \quad (12)$$

From the inverse square law and Eq. (7) we know that

$$R_{s\lambda} = B_{z\lambda}\, z^2 = B_{o\lambda}\, z_o^{\,2}. \quad (13)$$

The radiant exitance of the screen is by definition given as

$$M_\lambda = \pi\, L_\lambda. \quad \left[\frac{\#\, photons}{cm^2\, s\, \AA} \right] \quad (14)$$

Finally, we obtain

$$M_\lambda = B_{o\lambda}\, \rho_\lambda \left(\frac{z_o}{z} \right)^2 \times \cos\alpha\,. \quad (15)$$

Eq. (15) expresses the brightness of the screen as seen by the instrument in terms of the lamp and screen certificates, the distance between screen and lamp, and the angle of the screen to the lamp, α. Note that as long as the field of view of the instrument is filled, neither the angle ϕ, nor the distance of the instrument to the screen matters. The changing size of the field of view at the screen compensates for the distance and the angle, ϕ.

Table 2 shows the lamp certificate for our standard 1000 W tungsten source. Note that the irradiances are given both in terms of energy and photon flux. The conversion from energy to photon flux requires a division with the photon energy at the specific wavelength.

3. THE OPTICAL LABORATORY AT UNIS

The described procedure requires a dark room to eliminate extraneous scattered light from the screen. Fig. 3 shows the new calibration laboratory at UNIS. The facility contains 3 rooms. The lamp room is separated from the screen room by a baffled door. The control room with the lamp power supply and a calibration spectrograph is located next to the lamp room and the screen room. A fiber bundle acts as entrance optics to the spectrograph, and it runs through a hole in the wall between the control room and the screen room. The distance between the lamp and the screen is controlled by mounting the lamp on a mobile table. Two rails are used to obtain smooth travel and constant horizontal centre distance parallel to the screen. The table is adjustable in height and a fixed laser is used to align the lamp with the vertical centre of the screen.

Wavelength [Å]	**Irradiance [#photons / cm² s Å]**	**Irradiance [mW / m² nm]**
3000	2.50864×10^{10}	1.66323
3100	3.69681×10^{10}	2.37192
3200	5.23677×10^{10}	3.25498
3300	7.24319×10^{10}	4.36567
3400	9.79227×10^{10}	5.72848
3500	1.29415×10^{11}	7.35449
3600	1.67399×10^{11}	9.24877
3700	2.13774×10^{11}	11.49182
3800	2.69263×10^{11}	14.09381
3900	3.33435×10^{11}	17.00517
4000	4.07353×10^{11}	20.25562
4500	9.34056×10^{11}	41.28528
5000	1.73395×10^{12}	68.97640
5550	2.90009×10^{12}	103.93302
6000	3.97636×10^{12}	131.81648
6546	5.33603×10^{12}	162.13524
7000	6.45602×10^{12}	183.44323
8000	8.58708×10^{12}	213.49618
9000	1.01746×10^{13}	224.85917
10500	1.12813×10^{13}	213.70087
11500	1.14098×10^{13}	197.34076
12000	1.13833×10^{13}	188.67887

Table 2. Certificate of 1000W tungsten lamp model 83350 (ORIEL SN7-1275) from 3000 to 12000 Å. These values are obtained at a nominal distance of $z_o = 0.5\ m$. The current through the filament is 8.2 A and the voltage is 109.6.

In this configuration, the maximum distance between screen and lamp is $z = 8.56\ m$. The screen normal is pointing directly towards the lamp with $\alpha = 0$ degrees. The room lights are adjustable +12 VDC lamps. When these lamps are turned off, they do not produce any low level background emissions as gas discharge tubes have a tendency to do.

The lamp power supply (ORIEL 68835 1KW) is coupled to a Light Intensity Controller (LIC). The intensity of the lamp is monitored and the current through the filament is adjusted to keep the intensity constant. The 1000 W lamp runs at *8.2* Ampere. The main idea is to control the brightness of the screen only varying the distance *z*. See Eq. (15).

Fig. 3. The calibration laboratory at UNIS: (1) 18 x 18 inch^2 Lambertian surface, (2) rails, (3) adjustable mobile table, (4) entrance fiber to spectrograph, (5) door with baffle, (6) room lights, (7) tungsten lamp, (8) power cable to lamp filament.

The spectrograph is made by ORIEL. It uses a concave holographic grating (230 grooves / mm). The nominal spectral range is 4000–11000 Å. The detector is a 16-bit dynamic range thermoelectric cooled CCD from the company Hamamatsu (model INSTASPEC IV).

Fig. 4 shows the optical diagram of the instrument. A field of view of 22 ^{o} matches the fused silica fibre bundle used as entrance optics. The F-number is 2.1. The entrance slit is in the focal plane of the concave grating. The focal length varies from 129.4 - 132 mm, depending on wavelength. The diffracted light from the grating is focused and dispersed onto the exit plane. This is illustrated in Fig.4, where the blue, green and red rays represent the start, centre and stop wavelength

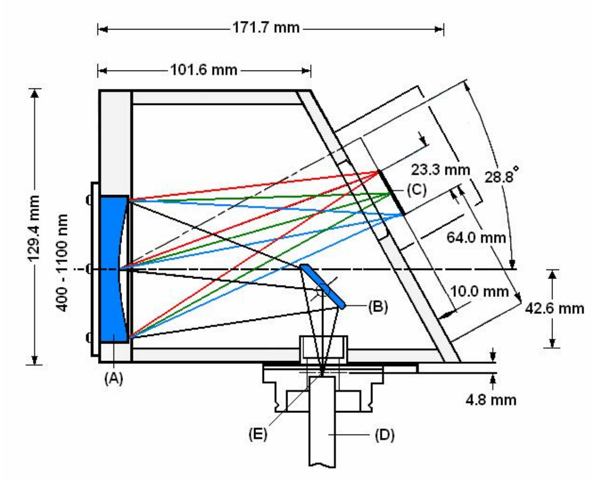

Fig. 4. Fixed Imaging Compact Spectrograph (FICS SN 7743): (A) concave holographic grating, (B) flat mirror, (C) detector (CCD), (D) fiber bundle, (E) entrance slit.

recorded by the CCD, respectively. The bandpass is approximately 80 Å with a 100 μm wide entrance slit. The spectral resolving power of this instrument is moderate, but for our purpose it is enough. The spectrum of a tungsten lamp is smooth and continuous. There are no line structures that need to be resolved.

4. RESULTS

4.1 Wavelength calibration of spectrograph

Wavelength calibration using spectral gas tube lamps with known emission lines must be carried out before any sensitivity calibration can take place. The most common way is to identify the pixel value associated with the a priori known wavelength of the emission line. At least three lines must be identified in order to minimize wavelength errors and check for non – linearity along the wavelength scale. The wavelength pixel relation is given as

$$\lambda \approx a_0 + a_1 \cdot p + a_2 \cdot p^2 , \quad [\text{Å}] \qquad (16)$$

where p is pixel value. The result of the procedure is the constants a_0, a_1 and a_2.

The FICS 77443 spectrograph was calibrated in wavelength using 3 different gas discharge mercury (Hg) lamps (see Fig. 5). Note that no order sorting filter is used to block out wavelength regions originating from higher spectral orders of the grating. The strong Hg emission line at wavelength 2537 Å is repeating itself 3 times at 5074 Å, 7611 Å and 10148 Å. The latter corresponds to spectral orders 2, 3, and 4, respectively. This effect is used in the calibration to obtain emission lines in the deep red part of the spectrum and up. Table 3 shows the result.

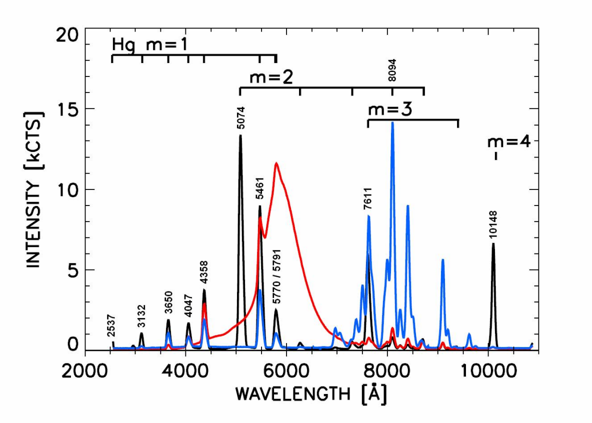

Fig. 5. Wavelength calibration of FICS 44773 spectrograph. The spectrum plotted with the colour black is a low pressure mercury pen lamp (model MS-416 from Acton Research Corporation). The blue spectrum is from a mercury vapour tube supplied by Edmund Optics Ltd (SN K60-908). The red curve represents the spectrum of a battery powered fluorescent tube (OSRAM F6T5). Each mercury emission line is marked according to wavelength and spectral order m.

Coefficients	Constants
a_0	$2.56026 \times 10^{+3}$
a_1	7.99624×10^{0}
a_2	1.95299×10^{-4}

Table 3. Wavelength calibration factors for the FICS 77443 spectrograph according to Eq. (16). The detector (CCD) has 256 x 1024 pixels. The spectral range is from 2560 Å to 10945 Å.

4.2 Transfer of lamp certificate

Our 1000 W tungsten lamp (ORIEL SN7-1275) is a traceable National Institute of Standards (NIST) source. This lamp is first used to calibrate the spectrograph in the wavelength region 4000 – 8000 Å. The calibration factor as a function of wavelength is then simply

$$K_\lambda = \frac{M_\lambda}{C_\lambda^{1000W}}, \quad \left[\frac{\#\,photons}{cm^2\, s\, \mathring{A}\, cts}\right] \qquad (17)$$

where C_λ^{1000W} is the count rate in units of counts per second [cts]. Next, the primary lamp is replaced by our secondary standard, a 200 W tungsten lamp. The lamp screen distance is 8.56m and the exposure time is 160 msec for both cases. This is important since the count rate as a function of exposure time is not necessarily linear. In addition, a cutoff filter is used in front of the fiber bundle to avoid overlapping spectral orders. The optical window is made of BK-7 and blocks out the UV part of the spectrum. Fig. 6 and Table 4 show the results of the certification.

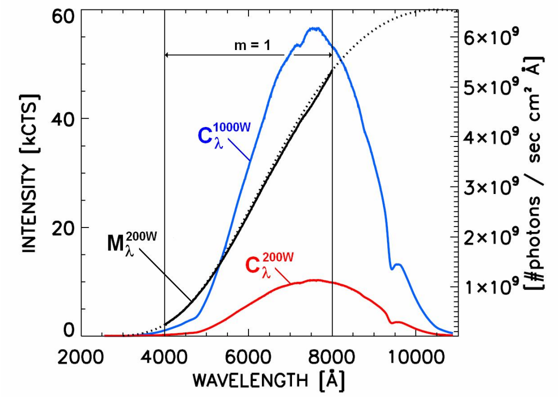

Fig. 6. Spectra of Lambertian screen (SRT-99-180). The blue curve is raw counts in units of [kCTS] from the screen using the 1000W tungsten lamp (ORIEL SN7-1275). Correspondingly, the red curve represents the 200W secondary tungsten lamp. Exposure time is 160 msec. Screen lamp distance is z =8.56 m. The 1000 W lamp runs on 109.6V at 8.20A. The 200 W lamp has a filament current of 6.50 A at a voltage of 31.7 V. The screen angle $\alpha = 0\,^o$. The black curves are the brightness of the screen in absolute units [#photons / cm^2 s Å] using the 200 W lamp. The valid wavelength region of certification is marked for spectral order m=1.

Wavelength [Å]	Irradiance [#photons / cm^2 s Å]	Irradiance [mW / m^2 nm]
4000	2.38984×10^{8}	1.18835×10^{-2}
4278	4.00913×10^{8}	1.86331×10^{-2}
4500	5.65822×10^{8}	2.50093×10^{-2}
4709	7.52522×10^{8}	3.17816×10^{-2}
4861	9.05840×10^{8}	3.70645×10^{-2}
5000	1.05729×10^{9}	4.20591×10^{-2}
5550	1.78254×10^{9}	6.38825×10^{-2}
5577	1.81933×10^{9}	6.48862×10^{-2}
6000	2.45369×10^{9}	8.13398×10^{-2}
6300	2.92463×10^{9}	9.23284×10^{-2}
6364	3.02521×10^{9}	9.45447×10^{-2}
6546	3.29816×10^{9}	9.99407×10^{-2}
6563	3.32326×10^{9}	1.00716×10^{-1}
7000	3.97446×10^{9}	1.12932×10^{-1}
8000	5.33294×10^{9}	1.32590×10^{-1}

Table 4. Secondary certificate of 200 W tungsten lamp (FRED SN01) from 4000 to 8000 Å. These values are obtained at a distance of $z = 8.56\ m$. The current through the filament is 6.5 A and the voltage is 31.7 V.

Note that a certification above 8000 Å requires an order blocking filter with cutoff wavelengths above 4000 Å. A filter wheel will be installed to handle this issue in the near future.

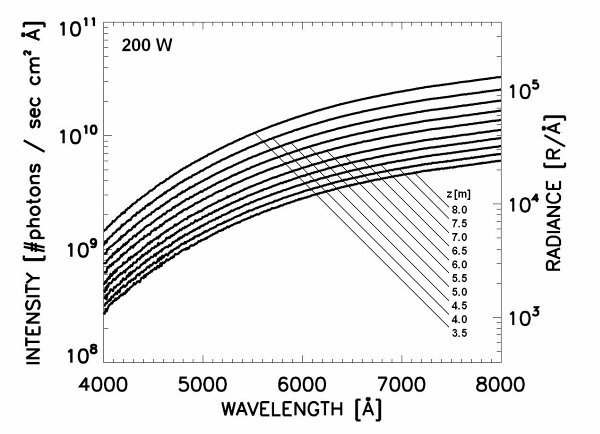

Fig. 7. Calibrated spectra of Lambertian screen (SRT-99-180) as a function of screen to lamp distance *z*. The source is the 200 W tungsten lamp (FRED SN01).

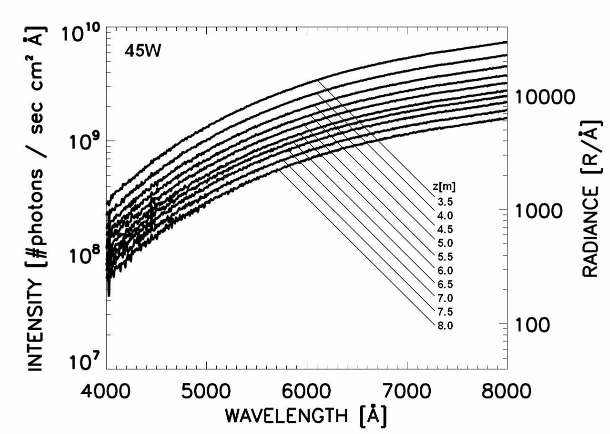

Fig. 8. Calibrated spectra of Lambertian screen (SRT-99-180) as a function of screen to lamp distance *z*. The source is a 45 W tungsten lamp (ORIEL SN7-1633).

As a temporally solution, the dotted black curve in Fig. 6 represents a functional fit to the 200 W secondary certificate based on a method developed by Saunders at NIST [3]

$$M_{\lambda}^{200W} \approx \lambda^{-5} \times \exp\left(a - b\lambda^{-1}\right). \qquad (18)$$

The equation has only two unknowns. In our case the solution becomes: $a = 73.9$ and $b = 52568$. The fit is obtained by using the irradiance values in Table 4 at 4000 Å and 8000 Å.

4.3 Screen brightness control

According to Eq. (15) the brightness of the screen is adjustable as a function distance *z*. Another approach would be to vary the current through the lamp filament. A disadvantage of this technique is that the spectral shape changes with lamp current. It would also require a lamp certification for each current setting.

In order to save burning time or life time of the 1000 W tungsten lamp, the 200 W lamp is used to demonstrate the screen brightness control using only distance as variable. The exposure time of the spectrograph is again kept constant at 160 msec. The mobile table is moved towards the screen is incremental steps of 0.5 m. As seen in Fig. 7 the spectral shape remains the same and the intensity rises with the inverse of the distance squared.

The above procedure was repeated using a 45 W tungsten lamp (ORIEL SN7-1633). Fig. 8 shows the results. Intensities are now down by a factor close to 5. Note that the signal to noise, especially in the blue part of the spectrum, may be improved by simply rising the exposure time of the spectrograph. An exposure time of 4000 instead of 160 msec at a distance of 8 m, generate raw spectra that span the whole dynamic range of the detector (16-bit).

Note that the left ordinates of Fig. 7 and 8. are given in units of Rayleigh per Ångstrøm [R/Å]. The generalized definition is [4, 5]

$$1R \equiv (1/4\pi) \times 10^{6}\,\#\,photons\ cm^{-2}\sec^{-1} sr^{-1}, \quad (19)$$

and it applies directly to the radiance L_{λ}. In Eq. (12), a multiplication factor of ($4\pi / 10^6$) is used to convert the number flux of #photons cm^{-2} sec^{-1} sr^{-1} $Å^{-1}$ to R/Å.

5. EXPERIMENTAL UNCERTAINTY

The 1000 W tungsten lamp supplied by Oriel is provided by a calibration uncertainty of ±3 % in the wavelength range 4000 – 8000 Å. The life time of the lamp certificate is 50 hours. After this, the lamp should be recalibrated. Oriel reports drift rates in the range 1 to 2 % per 100 operating hours over the wavelength range 4000 to 8000 Å, respectively.

Furthermore, our secondary transfer procedure will introduce errors [6,7] due to distance (0.14 %), lamp orientation and alignment (0.3 %), spectrograph stability (0.3 %), measurement repeatability (0.15 %), spectrograph nonlinearity (0.2 %) and laboratory stray light (0.2 %) [8].

Based on the above numbers our total calibration transfer uncertainty is estimated to be below ±4 %.

6. CONCLUDING REMARKS

The new calibration laboratory at UNIS has been constructed to calibrate narrow field of view instruments with variable source brightness control.

Two tungsten lamps with power of 200 W and 45 W are certified in the visible part of the spectrum (4000 – 8000Å) within an uncertainty of ±4 %. By varying the screen to lamp distance from 8 m down to 3.5 m, screen intensities in the range 200 – 132k R/Å were detected.

The outlined calibration procedure will be repeated to include extended wavelength coverage by using proper cut off filters to block out higher overlapping spectral orders of the FICS 7743 spectrograph. In addition, we aim to use a tungsten lamp of lower power (12 – 20 W) to cover intensities below 200 R/Å.

Acknowledgement
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