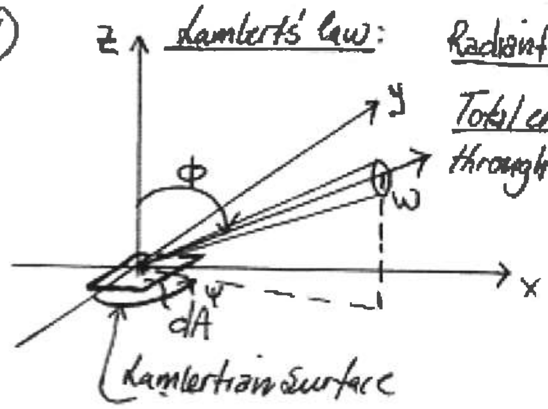
Absolute Calibration of Narrow field of view spectrometers by using a standard Lamp (FEL) and a diffuse re-emitting screen!

①



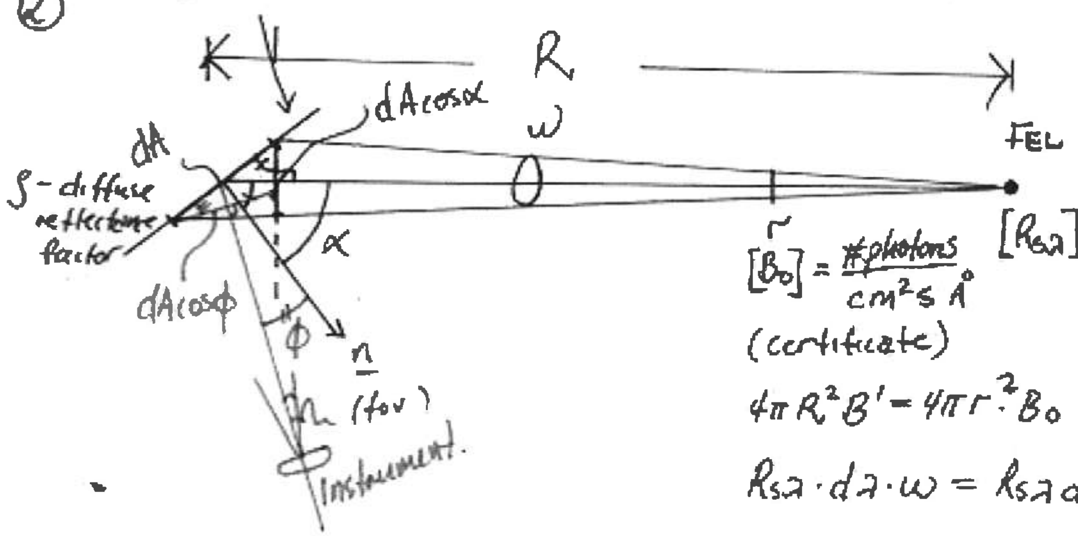
Lambert's law: Radiant intensity: $R_{\lambda\phi} = R_{\lambda 0}\cos\phi$; $\left[\frac{\#photons}{s\ sr\ Å}\right]$

Total emission rate: through hemi-sphere $dN = \int_0^{2\pi}\int_0^{\pi/2} R_{\lambda\phi}\, d\lambda \sin\phi\, d\phi\, d\psi$; $\left[\frac{\#photons}{s}\right]$

$$dN = 2\pi R_{\lambda 0}\, d\lambda \int_0^{\pi/2} \cos\phi \sin\phi\, d\phi$$

$$= 2\pi R_{\lambda 0}\, d\lambda \int_0^{\pi/2} \tfrac{1}{2}\sin 2\phi\, d\phi = \pi R_{\lambda 0}\, d\lambda$$

②



$[B_0] = \frac{\#photons}{cm^2 s\ Å}$ (certificate)

$[R_{s\lambda}] = \frac{\#photons}{s\ sr\ Å}$

$4\pi R^2 B' = 4\pi r^2 B_0 \Rightarrow B' = \left(\frac{r}{R}\right)^2 \cdot B_0$

$R_{s\lambda}\cdot d\lambda \cdot \omega = R_{s\lambda} d\lambda \frac{dA\cos\alpha}{R^2}$; $\left[\frac{\#photons}{s}\right]$

Re-emitted radiation: $dN = R_{s\lambda}\, d\lambda\, \rho \frac{dA\cos\alpha}{R^2} = \pi R_{\lambda 0}\, d\lambda$

$R_{\lambda 0} = \frac{R_{s\lambda}}{\pi} \rho \frac{dA\cos\alpha}{R^2}$; $\left[\frac{\#photons}{s\ sr\ Å}\right]$

Radiance of the screen towards instrument: $L_\lambda = \frac{R_{\lambda\phi}}{dA\cos\phi}$

$\Rightarrow L_\lambda = \frac{R_{s\lambda}}{\pi}\rho \frac{dA\cos\alpha}{R^2}\cdot\cos\phi \Big/ dA\cos\phi$

$L_\lambda = \frac{R_{s\lambda}}{\pi}\rho\cos\alpha\cdot\left(\frac{1}{R^2}\right)$; $\left[\frac{\#photons}{cm^2\ s Å\ sr}\right]$

Inverse Square law: $R_{s\lambda} \doteq B'\cdot R^2 = B_0\left(\frac{r}{R}\right)^2 R^2 = B_0 r^2$

$\Rightarrow L_\lambda = \frac{B_0}{\pi}\rho\cos\alpha\left(\frac{r}{R}\right)^2$, but since $L_\lambda \doteq \frac{M_\lambda}{\pi}$, where M_λ is the exitance of the screen:

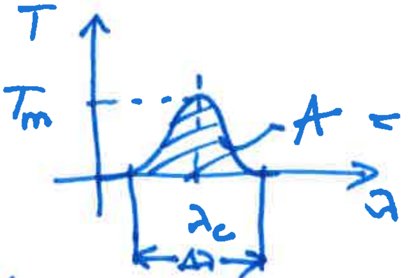
$$\Rightarrow \boxed{M_\lambda = B_0\,\rho\cos\alpha\left(\frac{r}{R}\right)^2 \ ; \left[\frac{\#photons}{cm^2\ s Å}\right]}$$

* If the fov of the instrument is filled, neither φ, nor the distance from the screen appears. (The changing size of the fov at the screen compensates for the distance and the angle, φ)

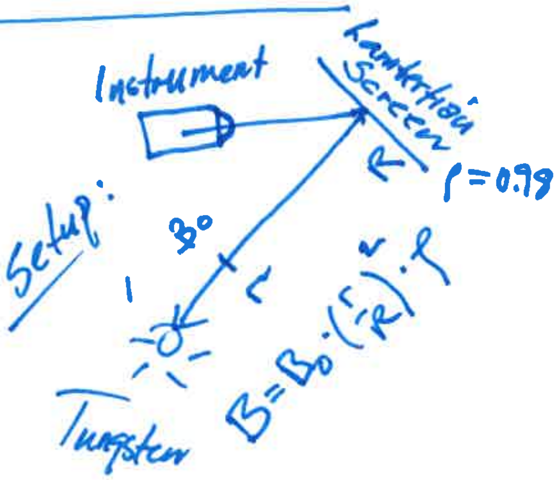
F. Sigernes, Longyearbyen, 12.10.99.

Kangerlussuaq, 10.08.2011

Narrow field of view calibration with filters



$$A = \int T\, d\lambda$$



$$B = B_0 \cdot \left(\frac{r}{R}\right)^2 \cdot \rho$$

Assume that B and all other transmission and efficiencies varies slowly over $\Delta\lambda$.

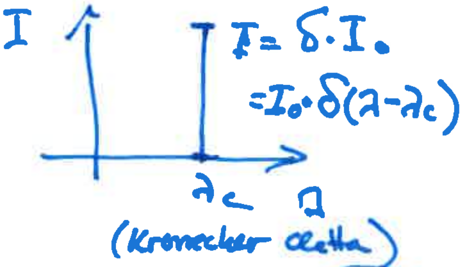
Calibration:

$$\Rightarrow C = \int B \cdot S \cdot d\lambda \quad [\text{cts}] \qquad S = \varepsilon T \quad \left[\frac{\text{cts}}{R/\text{Å}}\right]$$

spectral responsivity.

$$C = B \cdot \int S\, d\lambda = B \cdot \int \varepsilon T\, d\lambda = B \cdot \varepsilon \int T d\lambda = B \cdot \varepsilon \cdot A$$

$$\boxed{\varepsilon = \frac{C}{B \cdot A}}$$; if T narrow and triangular then $A = T_m \cdot BP$



Aurora:

$$I_c = \int I \cdot S\, d\lambda = \varepsilon \int I \cdot T \cdot d\lambda$$

$$= \varepsilon \int \delta \cdot I_0 \cdot T\, d\lambda = \varepsilon I_0 \int \delta T\, d\lambda$$

$$= \varepsilon I_0 \cdot T_m$$

$$\int \delta(\lambda - \lambda_c) \cdot I_0 T\, d\lambda = I_0 T_m$$

$$I_0 = \frac{I_c}{\varepsilon \cdot T_m} = \left(\frac{I_c}{C}\right) \cdot \left(\frac{A}{T_m}\right) \cdot B$$

$$\boxed{I_0 = \left(\frac{I_c}{C}\right)\left(\frac{A}{T_m}\right) \cdot B} \quad [R]$$

if $A = T_m \cdot BP \Longrightarrow I_0 = \left(\frac{I_c}{C}\right) \cdot B \cdot BP$

q.e.d.

F. Sigernes

The absolute sensitivity of digital colour cameras

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Trond Svenøe [2], Karsten Heia [3], Sergey Chernouss [4],
Charles Sterling Deehr [5] and Mike Kosch [6]

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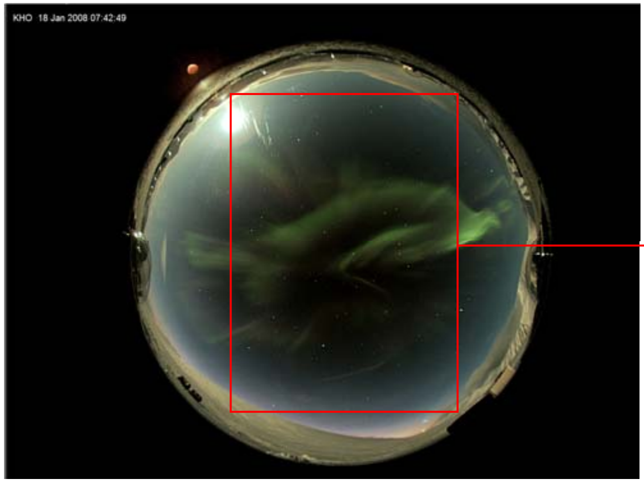
[4] Polar Geophysical Institute, Murmansk Region, Apatity, Russia
[5] Geophysical Institute, University of Alaska, Fairbanks, USA
[6] Communication Systems, Lancaster University, Lancaster LA1 4WA , UK

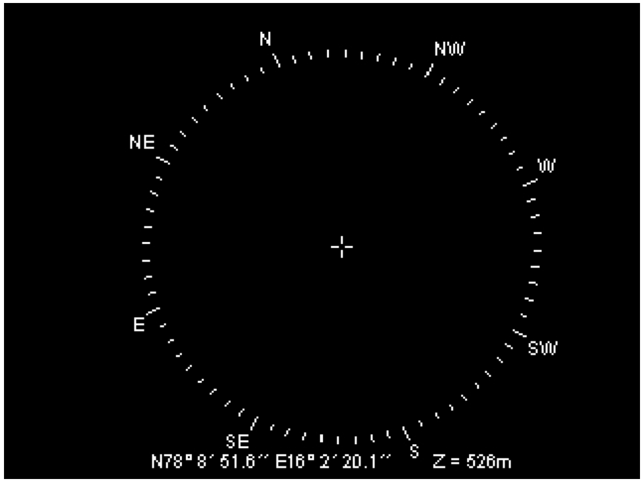
CONTENT

SXVF-H9C & D80 @ KHO



Starlight Xpress Fujinon F/1.4 (McWriter@UCL)<60s

Nikon D80 ISO 1600
F/2.8 20s



Watec 120N+ Fujinon F/1.4 2s

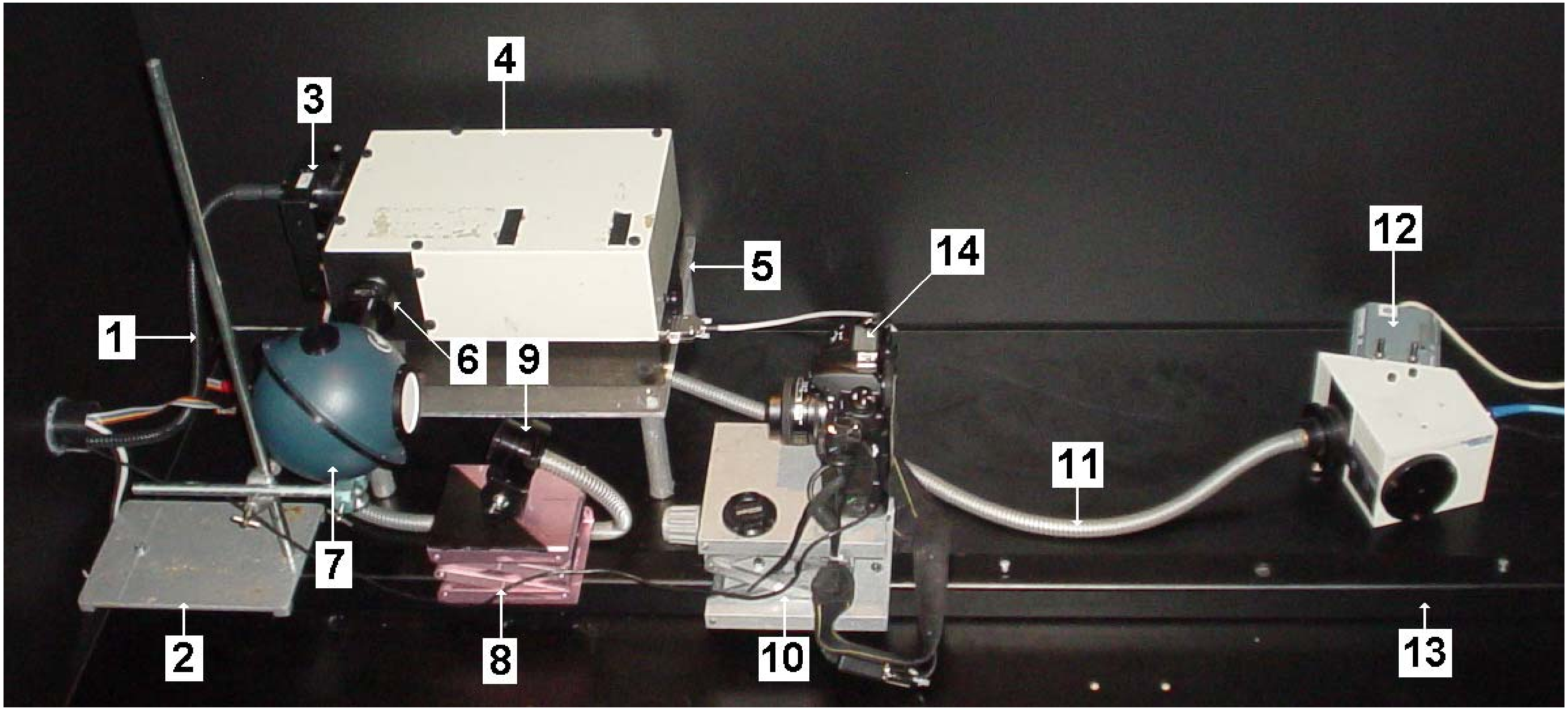
MOTIVATION

1. The cameras are low cost mass products
2. High spatial resolution (stars, satellites...)
3. Sensitivity (<25 000 ISO)
4. Simple optical design
5. The main auroral emissions (4278, 5577 &6300) are well colour channel separated
6. Colour classification of sky conditions (clouds, snow, light pollution & aurora)
7. Can operate in all types of light conditions including periods of full moon.
8. It is relatively easy to flat field calibrate and find mapping functions of lenses by the use of stars.
9. Useful in public presentations
10. The cameras are not intensity calibrated!

EXPERIMENTAL SETUP

Canon 40D

Nikon D300



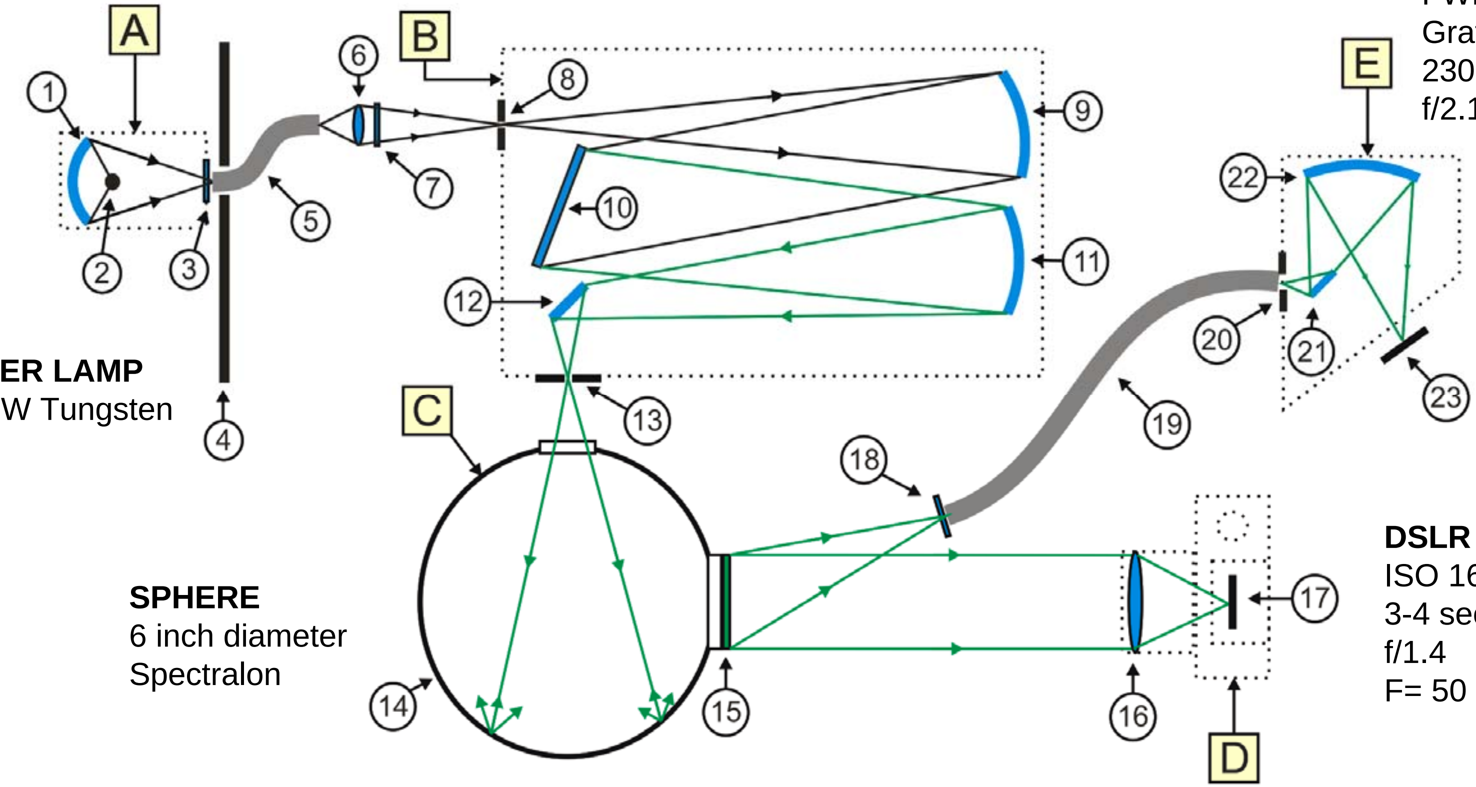
Experimental setup: (1) fiber bundle from lamp located in neighboring room, (2) mount / stand for integrating sphere, (3) order sorting filter wheel in front of entrance slit, (4) Jobin Yvon HR320 monochromator, (5) table, (6) exit slit plane, (7) Edmund Scientific integrating sphere, (8) laboratory lift table, (9) fiber bundle holder, (10) camera table, (11) fiber bundle used as input to spectrograph, (12) Oriel FICS 7743 spectrograph, (13) optical mount rail, and (14) DSLR camera with normal 50 mm f/1.4 objective.

THE CALIBRATION LAB AT UNIS

OPTICAL DIAGRAM

HR320
w x h= 0.5 x 8 mm
FWHM ~ 12 Å
Grating: 68 x 68 mm^2
1200 grooves / mm
F = 320 mm

FICS
16 x 250 um fibers
FWHM ~ 96 Å
Grating: Concave
230 grooves / mm
f/2.1



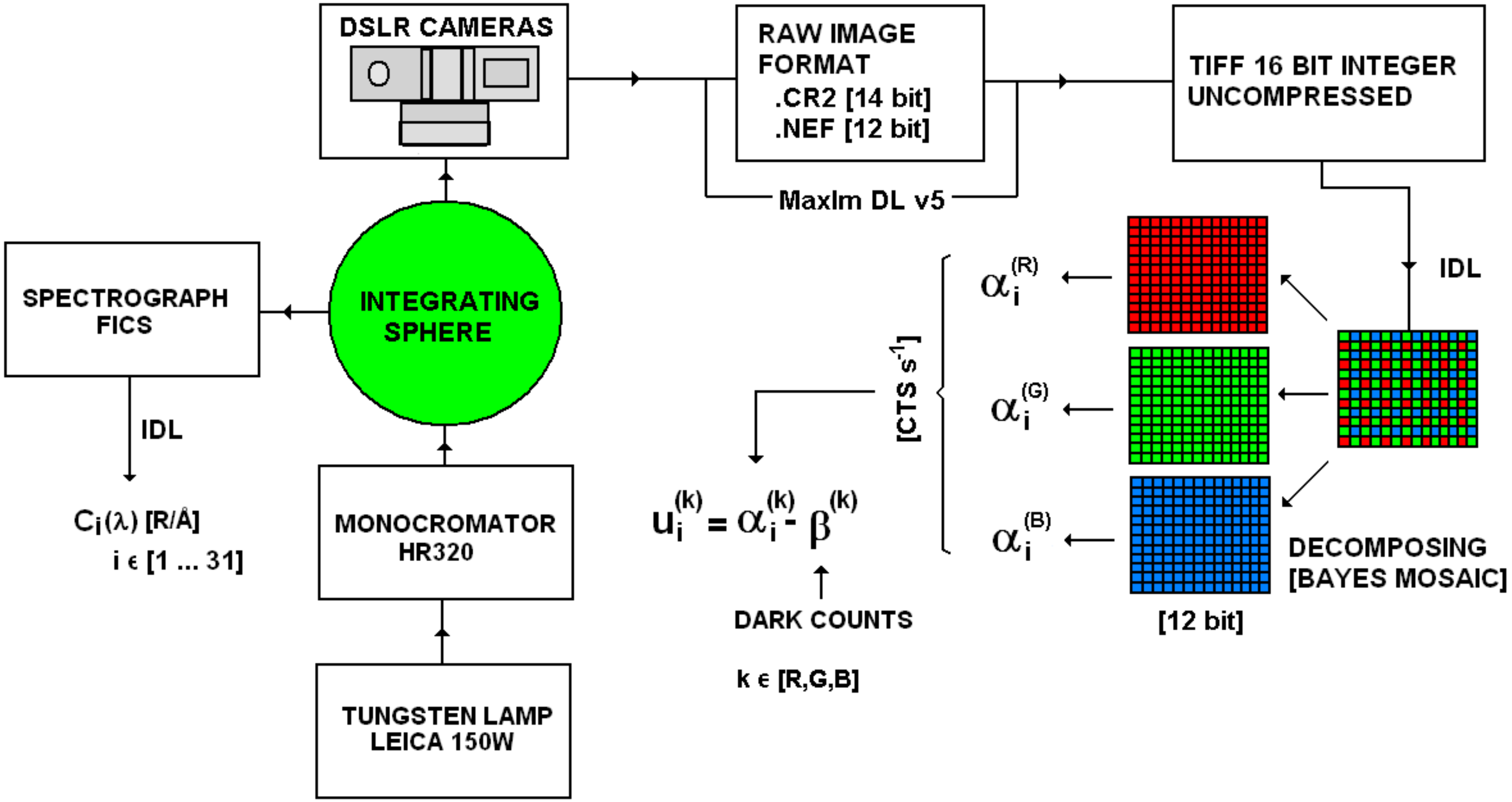
FIBER LAMP
150W Tungsten

SPHERE
6 inch diameter
Spectralon

DSLR Cameras
ISO 1600
3-4 sec exposures
f/1.4
F= 50 mm

Optical elements: [A] Leica 150W fiber illuminator: (1) mirror, (2) Tungsten filament, (3) heat filter, (4) blocking wall, and (5) fiber bundle. [B] Jobin Yvon HR320 Monochromator: (6) f-matching lens, (7) order sorting filter, (8) entrance slit, (9) collimator mirror, (10) plane reflective grating, (11) focusing mirror, (12) flat surface folding mirror, and (13) exit slit. [C] Edmund Scientific General purpose 6 inch diameter integrating sphere: (14) sphere, and (15) transmitting diffuser (Teflon). [D] DSLR camera: (16) 50 mm normal f/1.4 objective, and (17) CMOS / CCD detector. [E] Oriel FICS 7743 spectrograph: (18) order sorting filter, (19) fiber bundle, (20) entrance slit, (21) folding mirror, (22) concave grating, and (23) CCD detector.

DATA HANDLING



DSLR CAMERAS

RAW IMAGE FORMAT
.CR2 [14 bit]
.NEF [12 bit]

MaxIm DL v5

TIFF 16 BIT INTEGER UNCOMPRESSED

IDL

SPECTROGRAPH FICS

INTEGRATING SPHERE

IDL

$C_i(\lambda)$ **[R/Å]**
i ϵ [1 ... 31]

MONOCROMATOR HR320

TUNGSTEN LAMP LEICA 150W

$\alpha_i^{(R)}$

$\alpha_i^{(G)}$

$\alpha_i^{(B)}$

[CTS s^{-1}]

$$u_i^{(k)} = \alpha_i^{(k)} - \beta^{(k)}$$

DARK COUNTS

k ϵ [R,G,B]

[12 bit]

DECOMPOSING [BAYES MOSAIC]

THE SPECTRAL RESPONSIVITY

The camera detects in color channel (k)

$$u_i^{(k)} = \int C_i(\lambda) \cdot S^{(k)}(\lambda)\, d\lambda \qquad [\text{CTS s}^{-1}] \quad (1)$$

Equation (1) in vector form

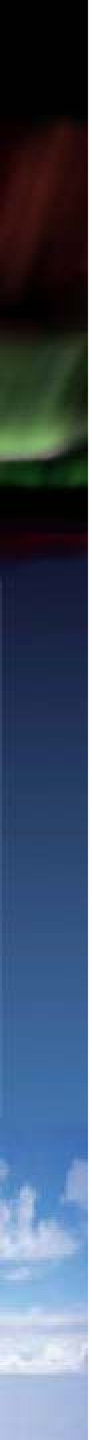
$$u_i^{(k)} = \hat{C}_i^T \cdot \hat{S}^{(k)} \cdot \Delta\lambda \qquad (2)$$

A set of observations may now be formed

$$\hat{u}_i^{(k)} = C \cdot \hat{S}^{(k)} \cdot \Delta\lambda \qquad (3)$$

$$C = \left[\hat{C}_1 \, \hat{C}_2 \cdots \hat{C}_{31} \right]^T \qquad [\text{R/Å}]$$

$\hat{S}^{(k)}$ can now be solved by SVD (Singular Value Decomposition in IDL)



THE QUANTUM EFFICIENCY

The camera Quantum Efficiency (QE) is defined as

$$QE_i^{(k)} \approx \left[\frac{4\pi \cdot u_i^{(k)} \cdot \Delta t \cdot g}{10^6 C_i \cdot \Delta\lambda \cdot \Delta A} \right] \times 100 \qquad [\%] \qquad (4)$$

Δt - Exposure time in seconds

g - Conversion factor between number of photo electrons and raw counts per pixel. Known as the Gain of the detector.

ΔA - Pixel area in units of cm^2

At ISO 1600 the gain is 0.775 and 0.675 electrons per 12-bit data count for the Canon 40D and the Nikon D300, respectively.

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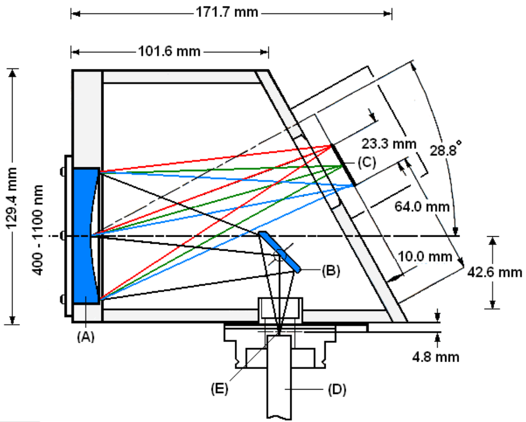
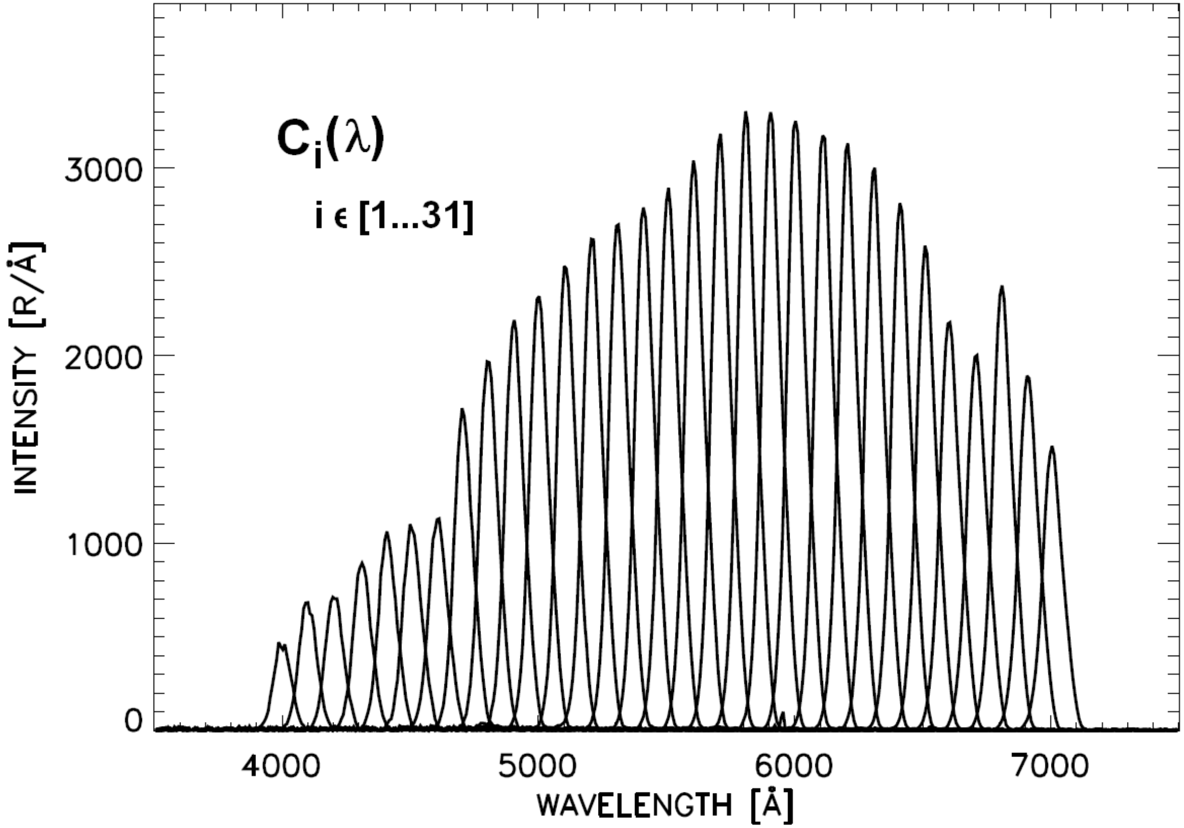
CALIBRATED SPECTRAL LIBRARY

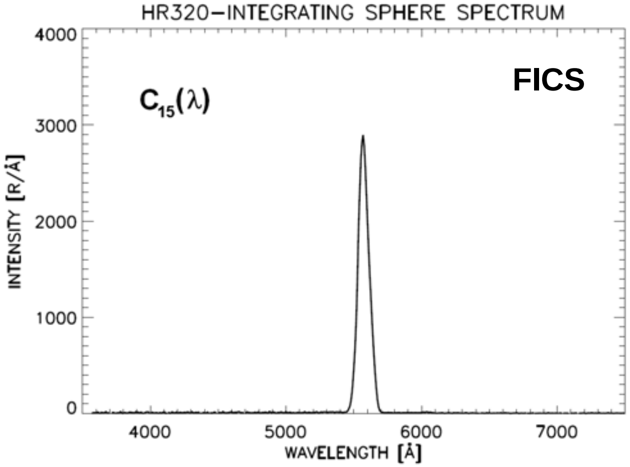


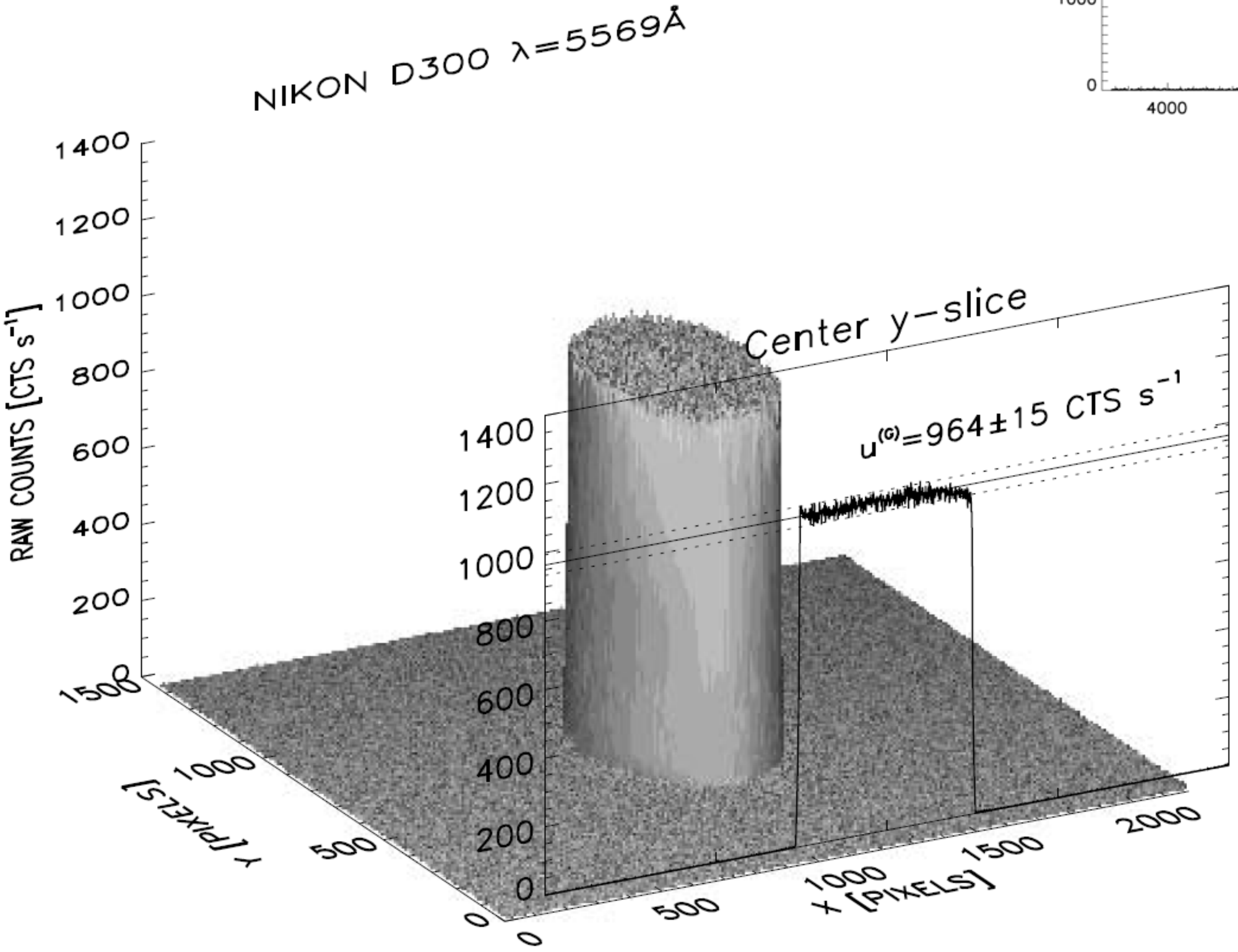
FICS
FWHM ~ 10 nm
VIS / NIR
NA = 0.22



Sphere source functions. $C_i(\lambda)$ is the set of observations that consists of 31 spectra from the monochromator (HR320) illuminating the 6 inch diameter integrating sphere from Edmund Optics.

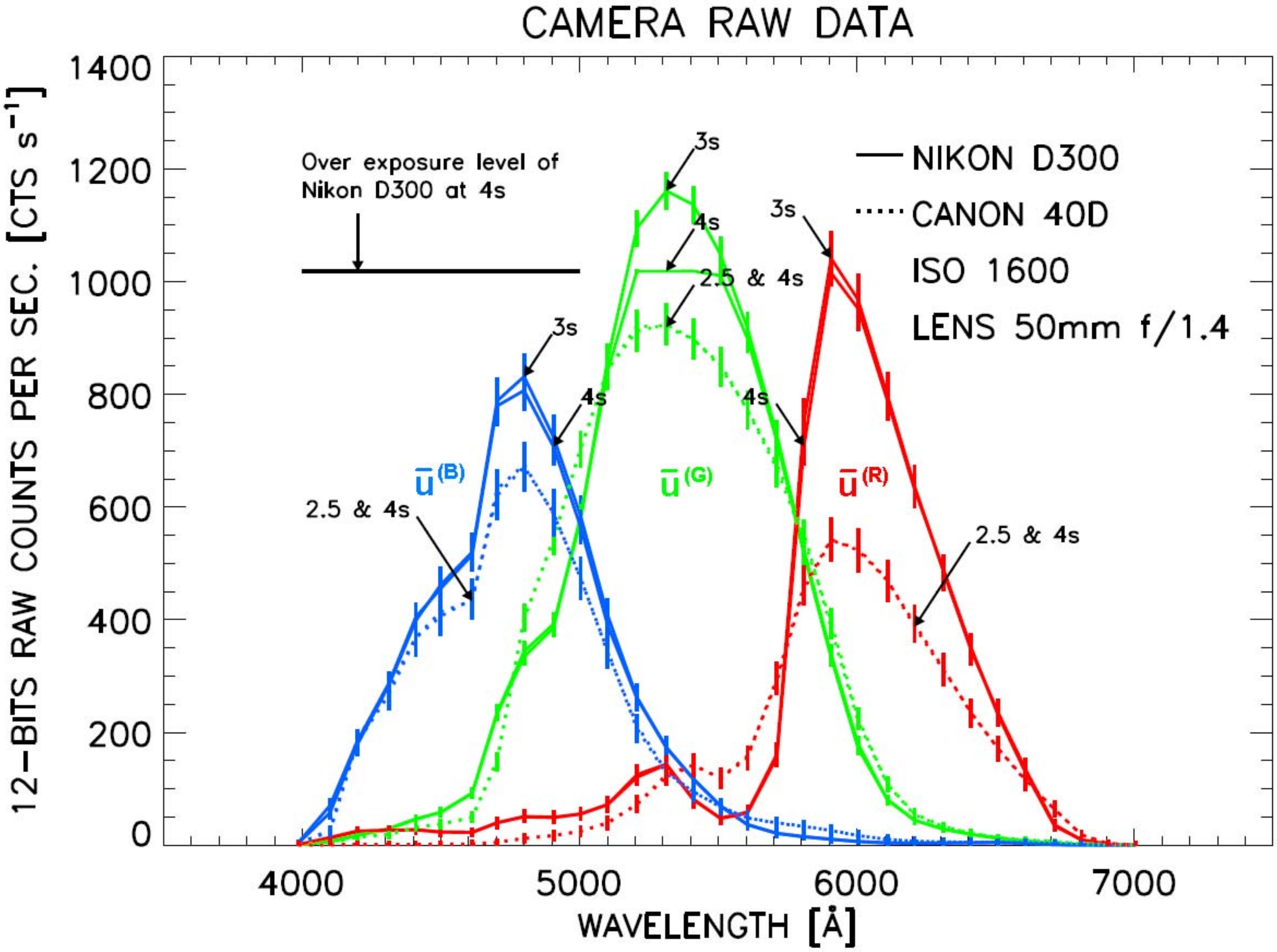
RAW DATA NIKON D300

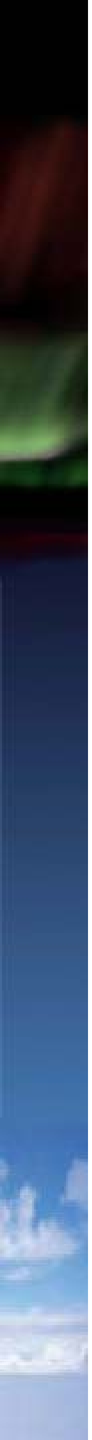




Settings:
ISO 1600
3 sec exposure
F= 50 mm @ f/1.4
Counts per second
[12 bit]

$$u_i^{(k)}$$


CAMERA RAW DATA
12–BITS RAW COUNTS PER SEC. [CTS s⁻¹]
1400
1200
1000
800
600
400
200
0
4000
5000
6000
7000
WAVELENGTH [Å]
Over exposure level of
Nikon D300 at 4s
NIKON D300
CANON 40D
ISO 1600
LENS 50mm f/1.4
3s
4s
2.5 & 4s
3s
4s
2.5 & 4s
3s
4s
2.5 & 4s
ū(B)
ū(G)
ū(R)



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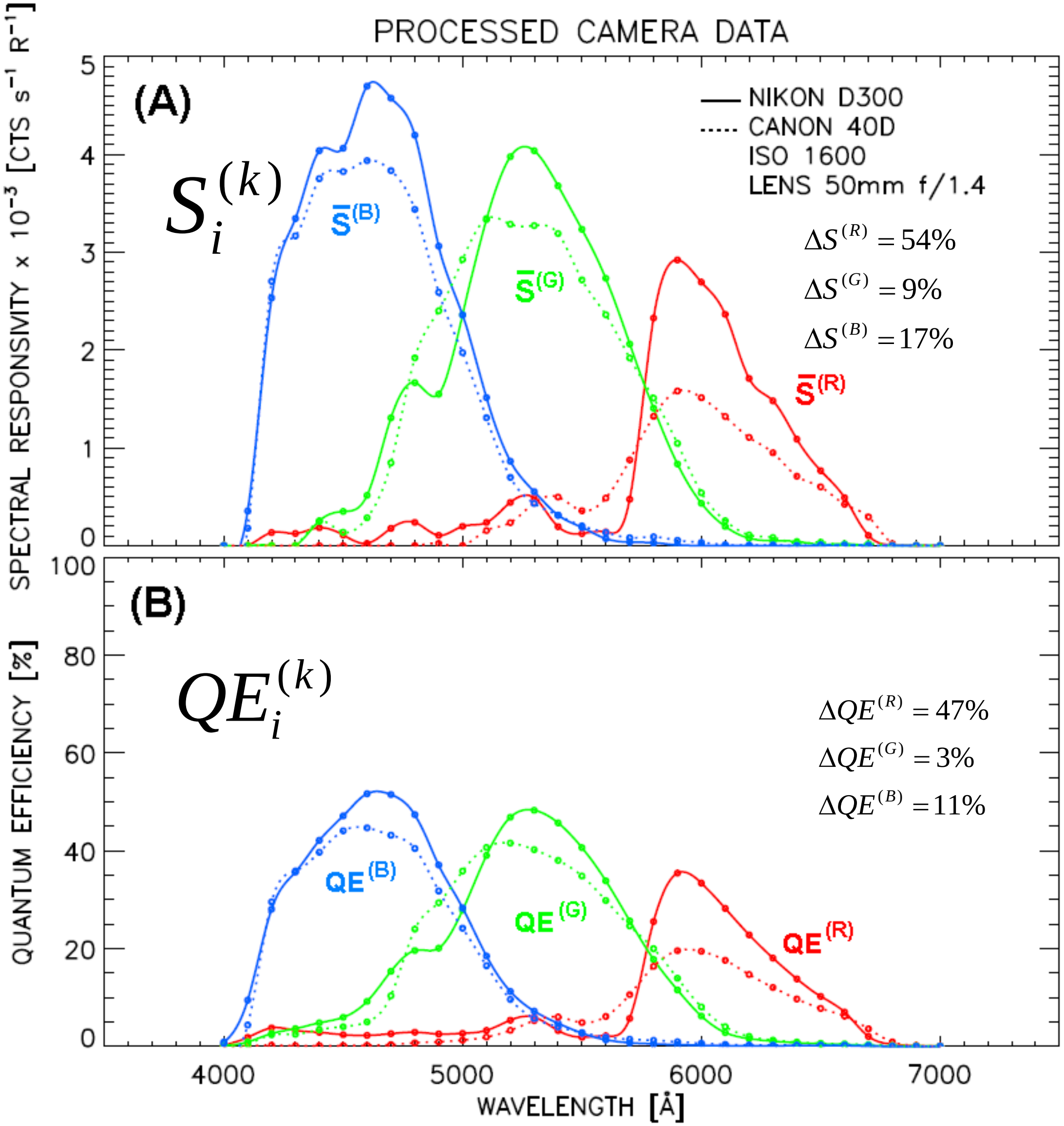


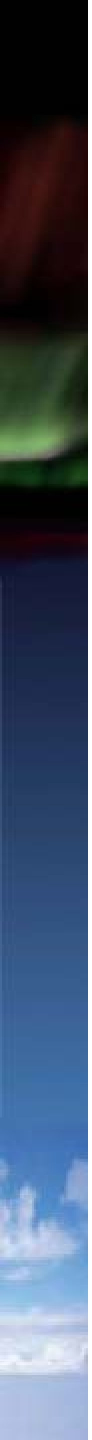
Processed camera data:

Panel (A): Solid lines are the spectral responsivity of the Nikon D300 camera for each color channel (Red, Green and Blue). The dotted lines are for the Canon 40D camera.

$$\Delta S^{(k)} = \left[\frac{\sum_{i=1}^{31} S_{i\,D300}^{(k)} \cdot \Delta\lambda}{\sum_{i=1}^{31} S_{i\,40D}^{(k)} \cdot \Delta\lambda} \right] \times 100$$

Panel (B) shows the corresponding calculated quantum efficiency (QE). Both cameras were operated with identical settings using normal objective lenses (50mm f/1.4) at ISO 1600.

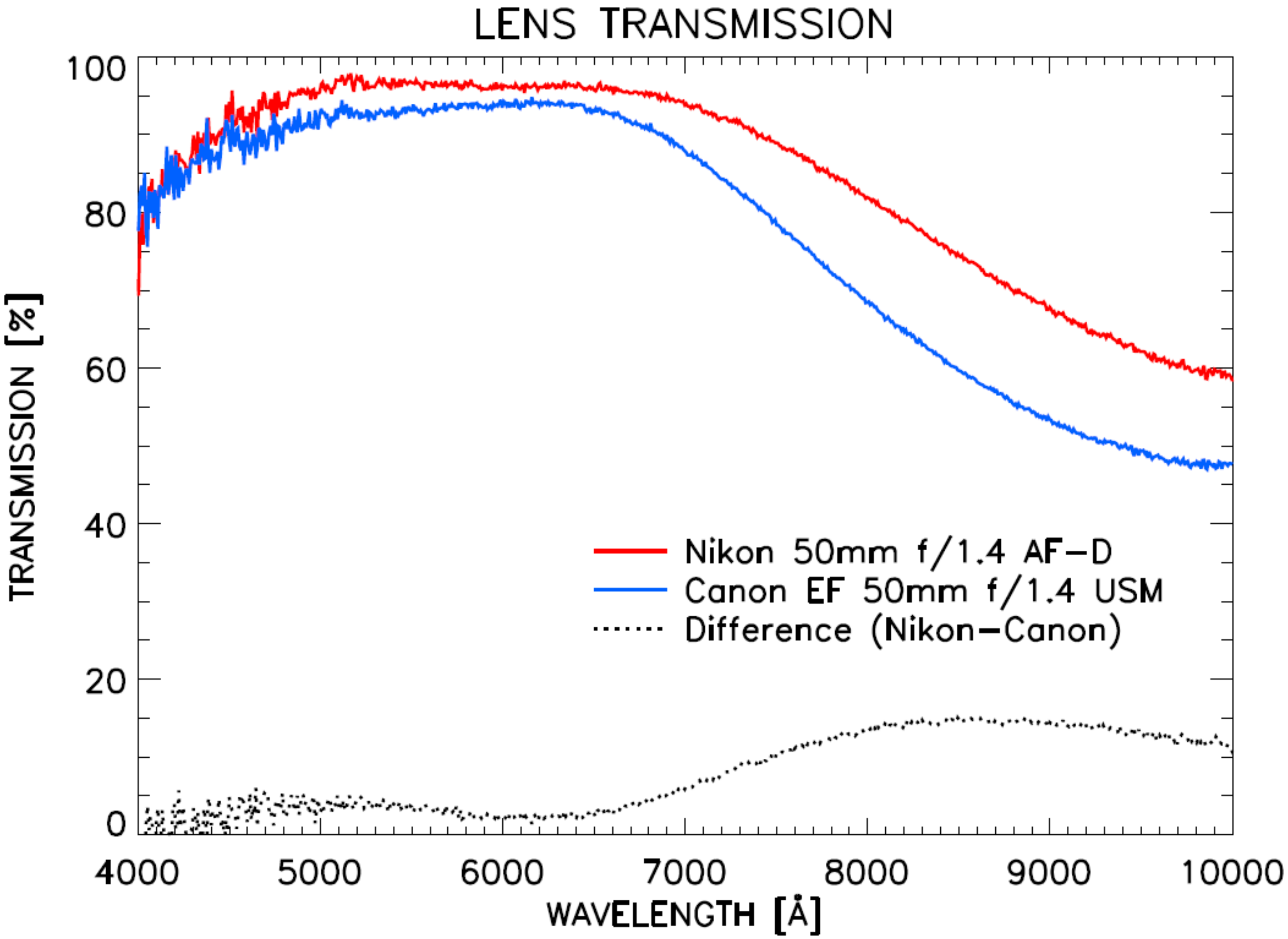
$$\Delta QE^{(k)} = \left[\frac{\sum_{i=1}^{31} QE_{i\,D300}^{(k)} \cdot \Delta\lambda}{\sum_{i=1}^{31} QE_{i\,40D}^{(k)} \cdot \Delta\lambda} \right] \times 100$$



LENS EFFECTS?

Canon EF 50mm f/1.4 USM

Nikon 50mm f/1.4 AF-D



$$\Delta S^{(R)} = 50\%$$

$$\Delta S^{(G)} = 5\%$$

$$\Delta S^{(B)} = 15\%$$

$$\Delta QE^{(R)} = 45\%$$

$$\Delta QE^{(G)} = 0\,\%$$

$$\Delta QE^{(B)} = 7\%$$

CONCLUSION

The principal results obtained by this study can be summarized as follows:

1. A fiber optical lamp is connected to the input of a monochromator which is tunable in wavelength in the visible part of the electromagnetic spectrum (4000 – 7000 Å). The output of the monochromator illuminates an integrating sphere with a bandpass of ~12Å.
2. The brightness of the sphere is monitored by an intensity calibrated spectrograph. A library of source functions consisting of 31 monochromatic lines is obtained in the visible part of the electromagnetic spectrum. The intensities range from ~500 to 3300 R/Å.
3. The intensity of the sphere is sufficiently uniform to obtain the average pixel response for each colour channel of a digital colour camera. As a result, it is possible to retrieve the spectral responsivity and the quantum efficiency of each pixel as a function of wavelength.
4. Two semi-professional DSLR cameras, the Nikon D300 and Canon 40D, have been calibrated. The sensitivities based on calculations of spectral responsivity and quantum efficiency, are found to be higher in the blue compared to the green and red channels. The Nikon D300 has a peak quantum efficiency of 50% at 4600 Å, 48% at 5300Å and 35% at 5900 Å. The corresponding spectral responsivity is found to be 4.3×10^{-3}, 3.9×10^{-3} and 2.8×10^{-3} in units of counts s^{-1} R^{-1}. The D300 is slightly more sensitive than the 40D in the blue and green channels. The main difference is found in the red channel. The 40D is up to 50% less red sensitive than the D300.
5. The ability of a DSLR camera to measure intensity of light in terms of absolute physical units opens up new possibilities. A standard measure such as the quantum efficiency or spectral responsivity could be part of a certificate provided by the manufacturer in the future.