Nikon D850
camera calibration report

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1. Calibration Summary

To transform raw camera counts to radiance values, use this calibration equation:

$$\boldsymbol{Radiance} = \frac{(\boldsymbol{raw\_counts} \ - \boldsymbol{black\_level})}{\boldsymbol{exp} * \boldsymbol{iso} * \boldsymbol{scf} * \boldsymbol{acf} * \boldsymbol{wlcf} * \boldsymbol{vcf}}$$

with these definitions:

raw_counts – raw camera counts as read from NEF or DNG image file
black_level – the black level of the camera; (=400 within calibration limits, otherwise must be obtained from dark images)
exp – exposure time, in seconds
iso – ISO value
scf – Spectral calibration factor, in counts/s/ISO/(ph/s/sr/m^2/nm) (see Table S4)
acf – Aperture correction factor (see Table S8)
wlcf – White light correction factor (see Table S9)
vcf – Vignetting correction factor (=1 in the image centre, see 10)

Table S4: Spectral calibration factors in counts/s/ISO/(ph/s/sr/m^2/nm) for the Nikon D850, for each colour channel. Calibration is based on responses to monochromatic light (6).

	red	green	blue
scf	9.6461e-14	2.0125e-13	1.8720e-13

Table S8: Aperture correction factors for the Nikon D850, for all available f-numbers (8).

f-number	aperture correction factor *acf*	s. d. (%)
3.5	1	5.0
4	0.8439	10.8
5.6	0.3579	12.1
8	0.1751	12.1
11	0.0786	9.5
14	0.0341	7.2
22	0.0158	4.3

Table S9: White-light correction factors for the Nikon D850, for each colour channel. Calibration is based on responses to broad-spectrum white light (8).

	red	green	blue
wlcf	1.0881	1.1101	1.0962

General shooting tips to minimise errors

ISO: Don’t use L1.0 ISO (ISO-32). It doesn’t do anything.
If you need to use ISOs above ISO-1600, activate Long-exposure NR and take dark images.

Aperture: Use fully open (f/3.5) or fully closed (f/22) aperture.

Exposure: Don’t use 1/8000 s exposure, it isn’t accurate. 1/4000 s and longer are fine.
If you need to use exposures longer than 1 second, activate Long-exposure NR and take dark images.

- Whenever possible, increase exposure rather than ISO
- Stay below ISO-1600 and 1 s exposure
- In dim light, if longer exposures are needed, take dark images at the beginning and end of your session. Ideally, **also** use Long-exposure NR to keep down pixel noise.

Contents

2. General calibration procedures and equipment

All calibration measurements were performed in a dark, temperature-controlled room at 20° C. Photographs were taken with a Nikon D850 (serial number 6078868) with a Sigma 8mm fisheye lens (serial number 16192076) and a Nikon MC-36A remote (serial number 126652) attached. The camera was set to Manual mode, and all other settings were left at our default values except where otherwise specified below. To check for differences between cameras, we performed selected measurements with three identical cameras at the same time (camera 1: as above; camera 2: SN 6079465, lens SN 16192093, remote SN 126938; camera 3: SN 6080451, lens SN 16191611, remote: Dörr SRT N1 with SN 371472).

Stimuli were generated by four Xenon-arc lamps connected to a 30.5 cm diameter integrating sphere (ISV410-UV, Electro Optical Industries, USA), which provided a bright, broadband, white light stimulus of even radiance across its 10 cm aperture. The intensity of this light source is controlled in closed circuit using feedback from a manufacturer-calibrated light sensor inside the integrating sphere. For the spectral calibration, monochromatic light stimuli were created using a TILL Polychrome V monochromator (serial number 0910-2-544; TILL Photonics GmbH, Germany) with a 150 W Xenon high-stability lamp. The light was guided through a fibre-optic cable (fibre ID: 510423) into the integrating sphere. To accurately measure the intensity and spectrum of the calibration light sources, we made use of a PR-680L spectrophotometre (Photoresearch, JADAK, New York, USA). Spectral measurements were taken for every block of camera images; in most cases, this meant that for each new camera or light setting, we took 20 photos and 1 spectrophotometric measurement.

For each set of calibration measurements, we aimed to cover the full range of potentially relevant settings. Wherever possible, the order of conditions was balanced or randomised to prevent time- or temperature-dependent and hysteresis-like effects from going undetected. Photographs were imported into Matlab following the procedures laid out in Sumner (2014). The integrating sphere's aperture was detected in the raw image using a simple thresholding algorithm, and its centre determined as the median x- and y-position of all included pixels. Stimulus brightness was then determined for each of the photographs as the mean over a 1.5° radius around this centre point. Since the camera and light source were stationary for all measurements, the aperture's position was only detected once per data set, in a single image where it was easily visible. In all cases, the results of the automatic detection were manually checked for each image set.

3. Dark signal and dark noise

In any real camera system, the current through a sensor pixel depends on other factors than light, such as temperature, leading to a noisy signal that only imperfectly represents the radiance of the absorbed light. One important aspect of this noise is the raw signal that can be measured in the absence of light. Its mean (the *dark signal*) raises the dark level of the image, and can be seen as a reduction in contrast, or fog-like effect in noisy images. Its standard deviation (which we here call the *dark noise*) randomly increases or decreases the value of each pixel, and leads to a speckled noise pattern on the resulting images. While the dark signal can easily be removed from the image, e.g. by subtracting a *dark image* (an image taken under the same circumstances and with the same camera settings, but in complete darkness), the dark noise is much harder to eliminate from the image and should therefore be kept to a minimum whenever possible. We measured the dependence of this dark signal and noise on exposure time and on ISO-speed.

Measurements

To measure the magnitude of the dark signal in the Nikon D850, we took repeated measurements across exposure and ISO values in a completely dark, windowless room, with a lens cap covering the lens mounted on the Nikon D850, and the lens and camera body wrapped in black cloth. We measured across exposure times at low (ISO-100) and high (ISO-6400) gain, and across ISO settings (ISO speeds) at short (1/1000 s) and long (4 s) exposure time. At each setting, up to 20 images were taken in succession using an MC-36A remote control (Table S1). The remote was set to take an image every second for short stimuli. For stimuli longer than 1 second, this interval was set to create a one-second pause between the end of one exposure and the beginning of the next, taking into account that exposures taken with “Long-Exposure Noise Reduction” take twice as long because the camera takes an additional (dark) image. All measurements were performed once with the internal noise reduction mechanisms (“High ISO NR” and “Long Exposure NR”) of the D850 turned off, then with each one turned on individually (High ISO NR was then set to “High”), and finally with both of them turned on.

Table S1: Dark signal calibration protocol

	apt	ISO	exp (s)	Exp-NR	ISO-NR	rep.	# files
1a	f/3.5	100	1/8000, 1/1000, 1/125, 1/15, 1/2, 4, 30, 120, 30, 4, 1/2, 1/15, 1/125, 1/1000, 1/8000	off	off	20	300
1b			same as 1a	ON	off		300
2a		32 (L1.0), 100, 400, 1600, 6400, 25600, 102400 (H2.0)	4	off	off	10	70
2b		same as a		ON	off		70
2c		same as a		off	ON		70
2d		same as a		ON	ON		70
2e		51200 (H1.0), 12800, 6400, 3200, 800, 200, 64		ON	ON		70
2f		same as e		off	ON		70
2g		same as e		ON	off		70
2h		same as e		off	off		70
3a		32 (L1.0), 100, 400, 1600, 6400, 25600, 102400 (H2.0)	1/1000	off	off	20	140
3b		same as a		ON	off		140
3c		51200 (H1.0), 12800, 6400, 3200, 800, 200, 64		ON	off		140
3d		same as c		off	off		140
4a		6400	1/8000, 1/1000, 1/125, 1/15, 1/2, 4, 30*, 120*	off	off	20/ *5	130
4b			same as a	ON	off		130
4c			same as a	off	ON		130
4d			same as a	ON	ON		130
4e			30*, 4, 2, 1, 1/2, 1/15, 1/125, 1/1000, 1/8000	ON	ON		165
4f			same as e	off	ON		165
4g			same as e	ON	off		165
4h			same as e	off	off		165

Analysis

After importing the raw images into Matlab and subtracting the Nikon-D850 standard dark value of 400, we calculated the mean (*dark signal*, Figure S1) and standard deviation (*dark noise*, Figure S2) of all raw pixel values for each image. For display purposes, we present the average of the three colour channels. Because the green channel's noise is consistently lower than that of the other channels, its value was increased by a factor of $2^{1/4}$ (due to its double representation in the Bayer Array, we'd expect the noise to be $2^{1/4}$ lower).

We found the *dark signal,* which in an ideal, noise-free environment should be 0, to increase only moderately with exposure time at the two ISO values measured (Fig. S1a,c). The fact that it is below 0 for many measurements, and far smaller than might be expected from the comparatively high dark noise values (see below) indicates that it is reduced by internal noise reduction mechanisms (e.g. by subtracting the value of out-of-image dark pixels), even in the RAW image format. Even at ISO-6400 and 30 seconds exposure time, it is still only 2 counts above the expected value of 0 when noise reduction if turned off. We found no noticeable effect of High-ISO noise reduction on dark signal. Long Exposure NR, on the other hand, had a surprising effect: it increased the dark signal drastically to about 8 counts already at 2 seconds integration time (the lowest setting at which Long Exposure NR will activate), and to over 30 counts for a 2 minutes exposure at ISO-6400.

When analysing the dark signal as a function of ISO value (Fig. S11b,d), we found that at the two exposure times we analysed, the dark signal was small at all but the very highest ISO-values, as long as NR was switched off. Especially the comparison to our calibration of the Nikon D810 (Fig. S1b, grey dots) shows that the dark signal at ISOs up to 25600 has been reduced dramatically, and is negligible at these integration times. Again, however, we found that Long Exposure NR drastically increased the dark signal by 10-150 counts at high ISOs.

For the *dark noise* (Fig. S2), we observed a similar picture when noise reduction was turned off. Overall noise was lower than on the D810. The dependence on exposure time (Fig. S2a,c) was small even at ISO-6400 below an exposure time of about 4 seconds. Even at a 2 minute integration time, the dark noise only rose to just over 100 counts at ISO-6400. The dependence on ISO, on the other hand (Fig. S2b,d), was independent of exposure time, and much stronger in the high values. At the highest ISOs, dark noise rose to over 400 counts for a 4-second exposure.

Again, we found no effect of High-ISO noise reduction, indicating perhaps that this feature makes use of image statistics, edge detection, or other algorithms that will only function in a properly exposed image, but not in a dark exposure. The effect of Long-Exposure NR, however, was very evident. When it was activated (i.e. in exposures longer than 1 second), it reduced dark noise by at least 1/3.

Note: Information on whether the two NR algorithms are active is NOT included in EXIF data. If you decide to use either, it is therefore important to note this at the time of data collection!

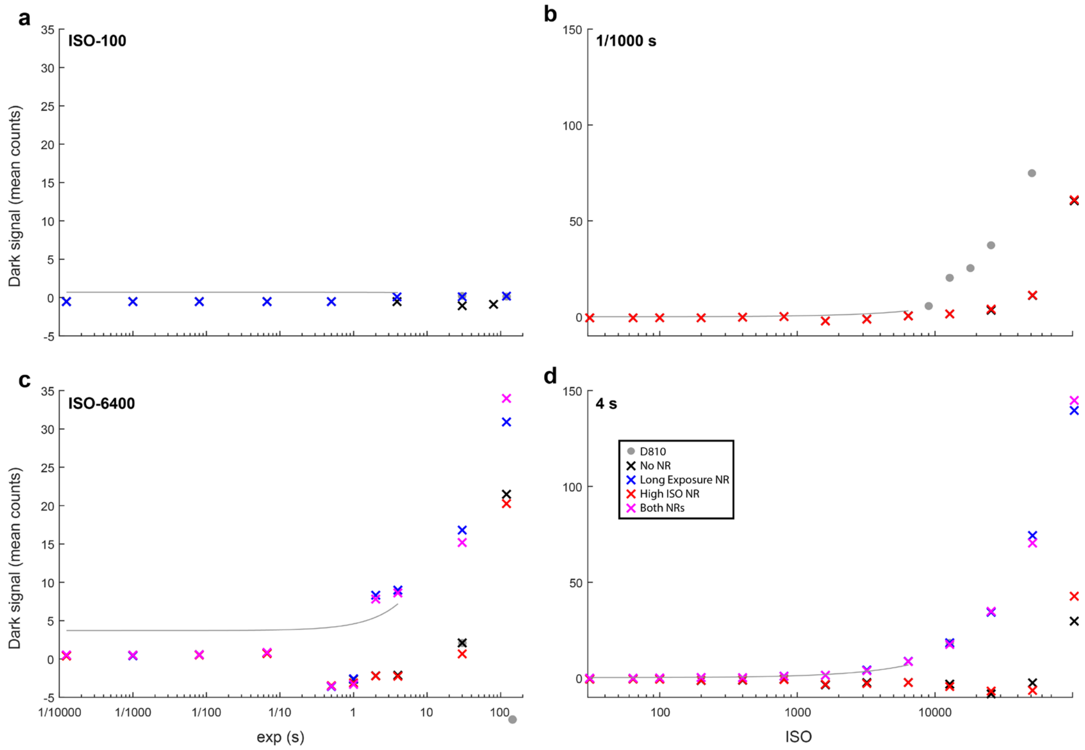

Figure S1: Increase in the Nikon D850's **dark signal** with exposure time at ISO-100 **(a)** and ISO-6400 **(c)**, and with ISO value at 1/1000 s **(b)** and 4 s exposure time **(d)**. Dark signal is calculated as the mean of all raw pixel values within a single dark image, after subtracting the manufacturer black level (400). Crosses are the mean of a single test condition (averaged over all repetitions), colours indicate which Noise Reduction mechanisms were active (black – no NR; blue – Long Exposure NR set to "On"; red – High ISO NR set to "High"; purple – both). Grey dots and lines indicate the results of our previous calibration for the Nikon D810. Note that for exposures up to 4 s and ISO-value up to 6400 (the maximum values we suggest using without taking dark images), the dark signal is never more than 10 counts, no matter the NR setting.

Conclusion:

To keep the *dark signal* below 10 counts, keep ISO below 6400 and exposure time below 30 seconds. Within these limits, ELF makes no attempt to correct for the dark signal, because given the effect of temperature and NR algorithms (neither of which can be automatically detected),

If these limits are exceeded, we generally recommend the use of dark images to avoid a systematic error in measurements (low intensities will be overestimated).

To keep *dark noise* below 10 counts, **keep ISO below 1600 and exposure time below 1s**. Outside of these limits, dark noise can only be kept down by activating long-exposure NR (which increases the dark signal, and therefore increases the necessity of taking dark images).

From this (limited) data, we see no reason to ever activate High-ISO noise reduction, since it had no effect on noise or dark signal.

4. Dark signal and dark noise – cross-camera comparison

To get an idea how much dark signal and/or dark noise vary across individual cameras of the same model, we repeated some of the last section's dark measurements with three Nikon D850 cameras at the same time and under the same conditions.

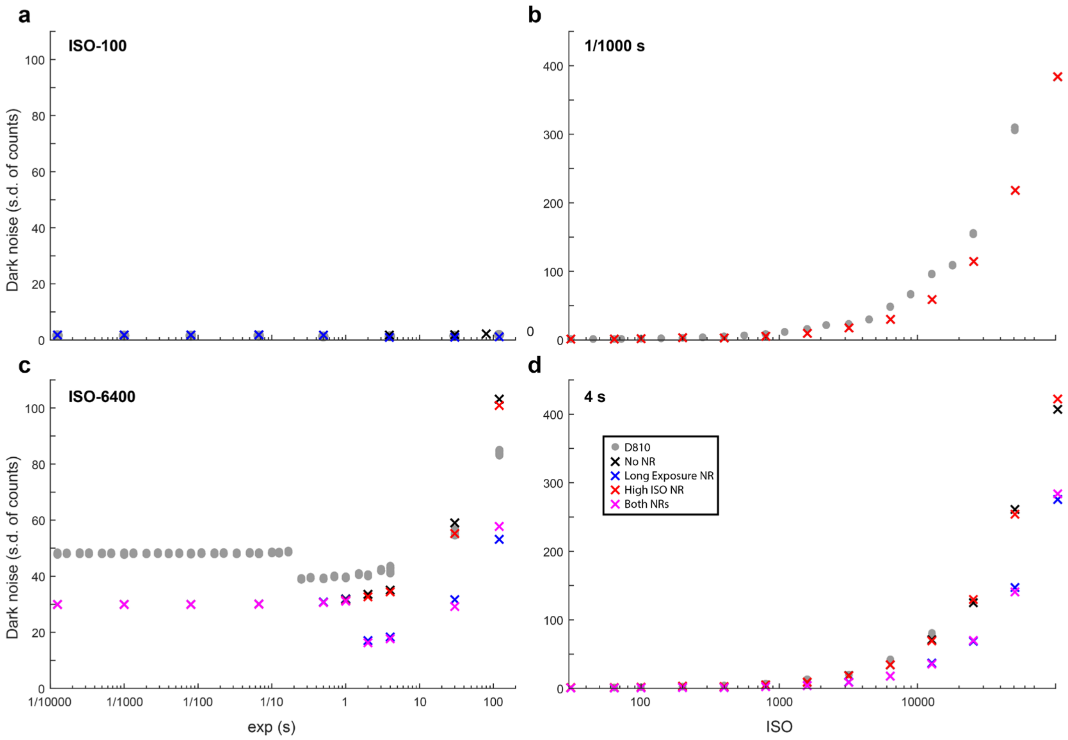

Figure S2: Increase in the Nikon D850's **dark noise** with exposure time at ISO-100 **(a)** and ISO-6400 **(c)**, and with ISO value at 1/1000 s **(b)** and 4 s exposure time **(d)**. Dark noise is calculated as the standard deviation of all raw pixel values within a single dark image. Symbols and colours as in Fig. S1.

Measurements

We chose to focus our measurements on points in the parameter space where noise was already comparatively high and/or where interesting transitions take place (Table S2). Specifically, we tested exposures around 1 second at ISO 6400 (repeating measurement we had taken before), and at ISO 1600 (since this is our maximum recommended ISO to keep noise down). We also re-tested the full range of ISOs at short (1/1000s) and long (1s and 4s) exposure times. All measurements were taken with all NR mechanisms turned off.

Analysis

We analysed all images as in the previous noise measurements. We found that the three cameras differed very little in the dark noise and dark signal:

- the average difference in *dark signal* was less than 1 count at ISOs up to 6400, but up to about 20 counts at the highest ISO at 4 s integration time (Figure S3);
- the average difference in *dark noise* was no more than 2 counts at ISOs up to 6400, and no more than 5% (20 out of 400 counts) even at the highest ISO at 4 s integration time (Figure S4)

For all three cameras, we confirmed our previously stated recommendations to keep dark noise below 10 counts: **ISO<=1600 and exposure <=1 s** (although 2 s seemed fine in this instance, as well).

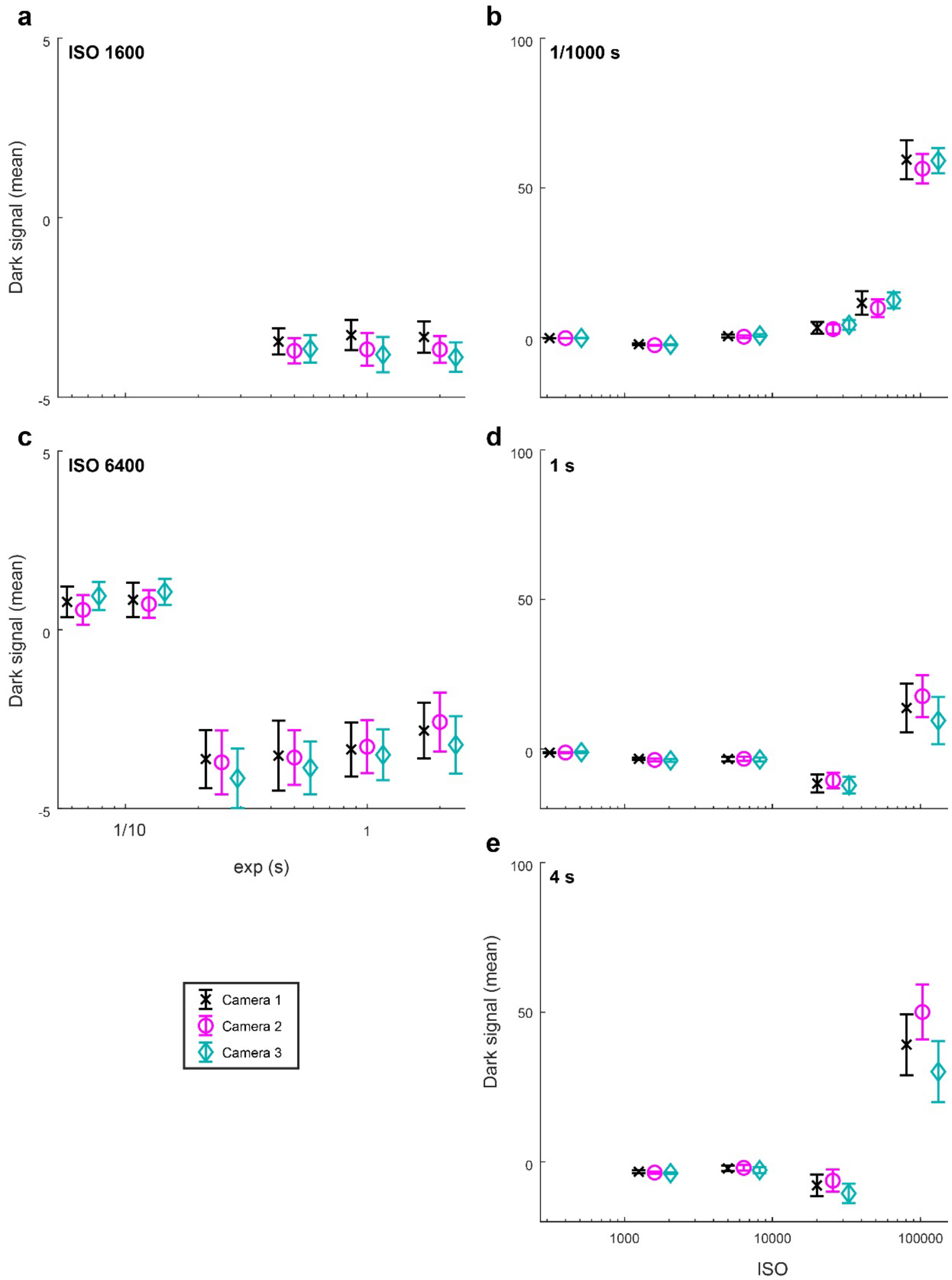

Figure S3: Comparison of the Nikon D850's **dark signal** across three cameras, at ISO-1600 **(a)** and ISO-6400 **(c)**, and at 1/1000 s **(b)**, 1 s **(d)** and 4 s exposure time **(e)**. Dark signal is calculated as the mean of all raw pixel values within a single dark image, after subtracting the manufacturer black level (400). Crosses/circles/diamonds are the mean dark signal for a single test condition (averaged over all repetitions). All measurements were taken with all noise reduction settings turned off. Differences between cameras are consistently small compared to the inter-image variation.

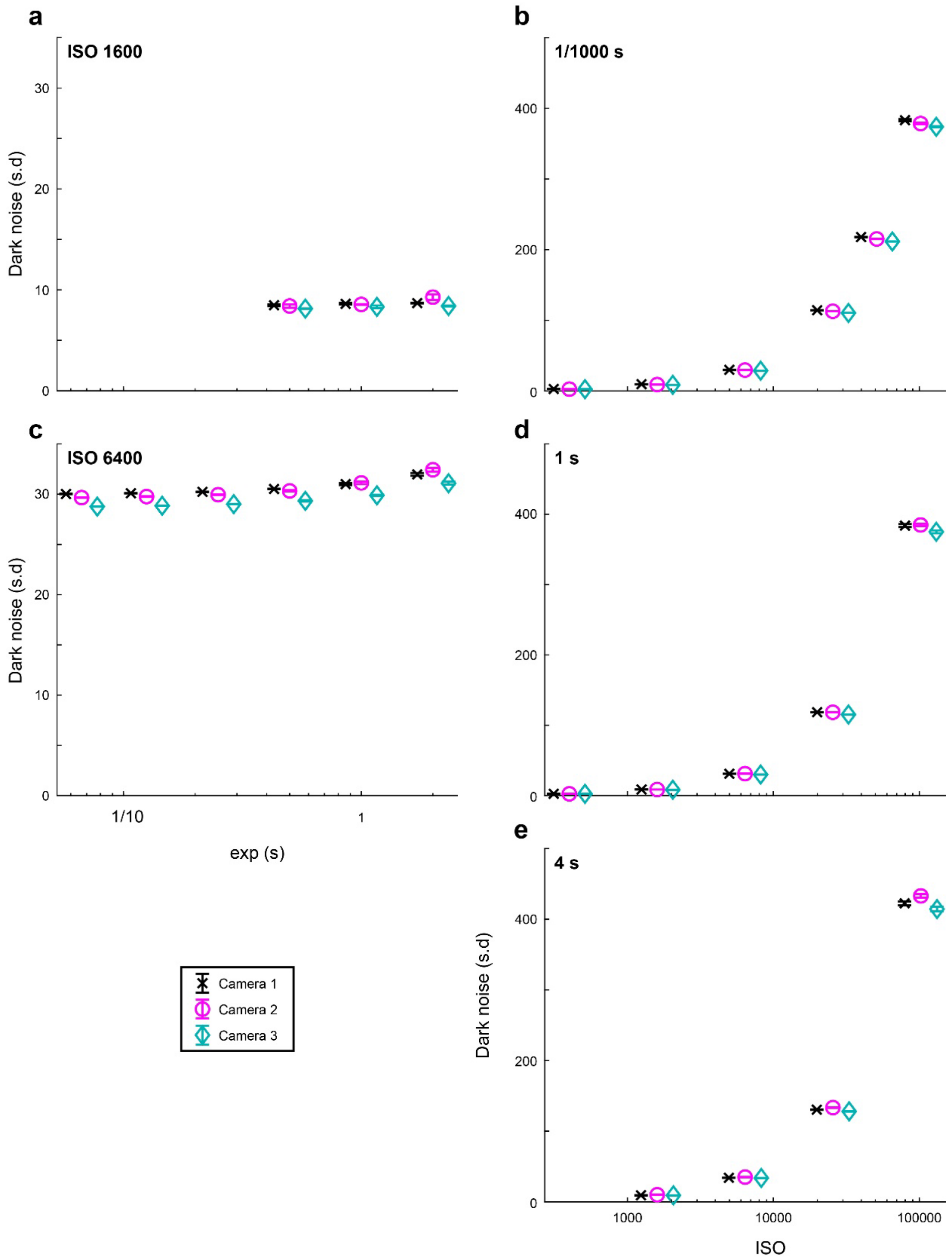

Figure S4: Comparison of the Nikon D850's **dark noise** across three cameras, at ISO-1600 **(a)** and ISO-6400 **(c)**, and at 1/1000 s **(b)**, 1 s **(d)** and 4 s exposure time **(e)**. Dark noise is calculated as the standard deviation of all raw pixel values within a single dark image. Crosses/circles/diamonds are the mean dark noise for a single test condition (averaged over all repetitions). All measurements were taken with all noise reduction settings turned off. As for dark signal, differences between cameras are consistently small compared to the inter-image variation.

Table S2: Camera dark signal comparison calibration protocol

	apt	ISO	exp (s)	Exp-NR / ISO-NR	rep.	# files
1a		1600	1/2, 1, 2, 2, 1, 1/2		20	120
2a		6400	1/15, 1/8, 1/4, 1/2, 1, 2, 2, 1, 1/2, 1/4, 1/8, 1/15		20	240
3a		400, 1600, 6400, 25600, 51200 (H1.0), 102400 (H2.0), 102400 (H2.0), 51200 (H1.0), 25600, 6400, 1600, 400	1/1000		20	240
4a	f/3.5	400, 1600, 6400, 25600, 102400 (H2.0), 102400 (H2.0), 25600, 6400, 1600, 400	1	off	20	200
5		1600, 6400, 25600, 102400 (H2.0), 102400 (H2.0), 25600, 6400, 1600	4		20	160
4b		same as 4a	1		20	200
3b		same as 3a	1/1000		20	240
2b		6400	same as 2a		20	240
1b		1600	same as 1a		20	120

5. Temperature

To get an estimate of how much camera dark signal and noise in the D850 depend on temperature, we took a number of images under hot and cold conditions. We took an image at 4 seconds exposure time and ISO-6400, with Noise Reduction switched off, every 3 minutes for 5 hours while the camera was stored in a dark refrigerator, and then for another 5 hours while the camera was stored in an infrared sauna set to 40°C. A small digital thermometer next to the camera indicated that the temperature in the refrigerator varied between 1°C and 7°C during the experiment, while the sauna temperature varied between 30°C and 35°C. Images were analysed as for our other dark measurements. We repeated the experiment with all Noise Reduction mechanisms switch on.

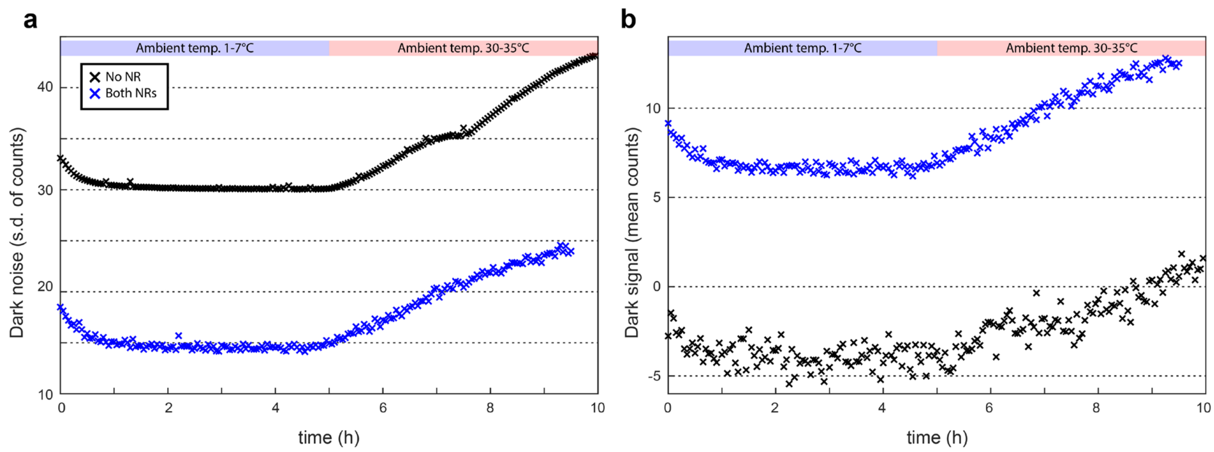

Figure S5: The variation of dark noise (a) and dark signal (b) with temperature (4 s exposure, ISO-6400).

The results show that even at these relatively high-noise conditions, the influence of temperature is small. Over the full range of temperatures we tested (which can be argued to reasonably reflect the normal operating conditions under which ELF images will be taken), dark noise and signal varied by less than about 15 counts (Figure S5). Noise reduction seemed to have no or very little effect on the additional noise imposed by higher temperatures.

6. Spectral calibration

To determine the absolute spectral sensitivity of the Nikon D850's CMOS sensor, we took a series of photographs of monochromatic stimuli between 320 nm and 700 nm wavelength, while at the same time monitoring the absolute spectral photon radiance of the stimulus with a calibrated spectroradiometer.

Measurements

For this measurement, light from the monochromator was guided into the integrating sphere to create a 10 cm, monochromatic stimulus at the sphere's aperture. The monochromator's entrance slit was set to produce a spectral half-width (full width at half maximum) of 5 nm. We measured the spectrum of the calibration stimuli with the GS-1290 spectroradiometer, set to automatic integration time and an acceptance angle of 1°, at the exact same time as the photographs with the D850 were taken. The spectroradiometer and the camera were set up on tripods, side-by-side, at a distance of about one metre from the integrating sphere's aperture.

In a first sweep across the wavelength spectrum, we set the camera to a fully open aperture (f/3.5) and low ISO setting (ISO-100). At each wavelength, we then took seven consecutive images at exposure times of 1/125, 1/60, 1/30, 1/15, 1/8, 1/4 and 1/2 seconds, which ensured that at each wavelength above 400 nm, we had acquired several photographs that were not under- or overexposed. We scanned the wavelengths in an order designed to minimise the effect of changes in lamp or camera over time, by first scanning up and down the spectrum at coarse resolution, and then repeating this at a finer resolution until we had achieved an overall resolution of at least 5 nm (Table S3).

Table S3: Camera settings and wavelength order during spectral calibration (0 indicates monochromator at resting wavelength, which was used to characterise dark noise and stray light)

<table>
<tr><th></th><th>Apt</th><th>ISO</th><th>Exposure</th><th>Wavelength order</th></tr>
<tr><td>Sweep 1</td><td rowspan="2">f/3.5</td><td>100</td><td>1/125, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2</td><td>0 300:50:650 694 675:-50:325 0
0 350:20:690 694 680:-20:360 350 0
0 355:20:675 694 685:-20:365 350 0</td></tr>
<tr><td>Sweep 2</td><td>6400</td><td>1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2, 1</td><td>0 300:10:410 405:-10:305 300 0</td></tr>
</table>

To properly capture the range between 350 nm and 400 nm, we performed a second sweep in this wavelength range with the same settings as before, but at ISO-6400, and with a 9-exposure bracket.

Analysis

Camera raw images were downloaded and converted as usual. To account for the effect of stray light from other light sources in the room (status LEDs, computer screens and light from the monochromator's Xenon lamp escaping through the cooling vents, photos were dark-corrected using images that were taken with the monochromator set to its resting wavelength (where the Xenon lamp provides no light).

To guard against the effects of saturation and excessive noise, we removed from the analysis any images where the raw signal was greater than 15520 counts or lower than 50 counts after dark correction.

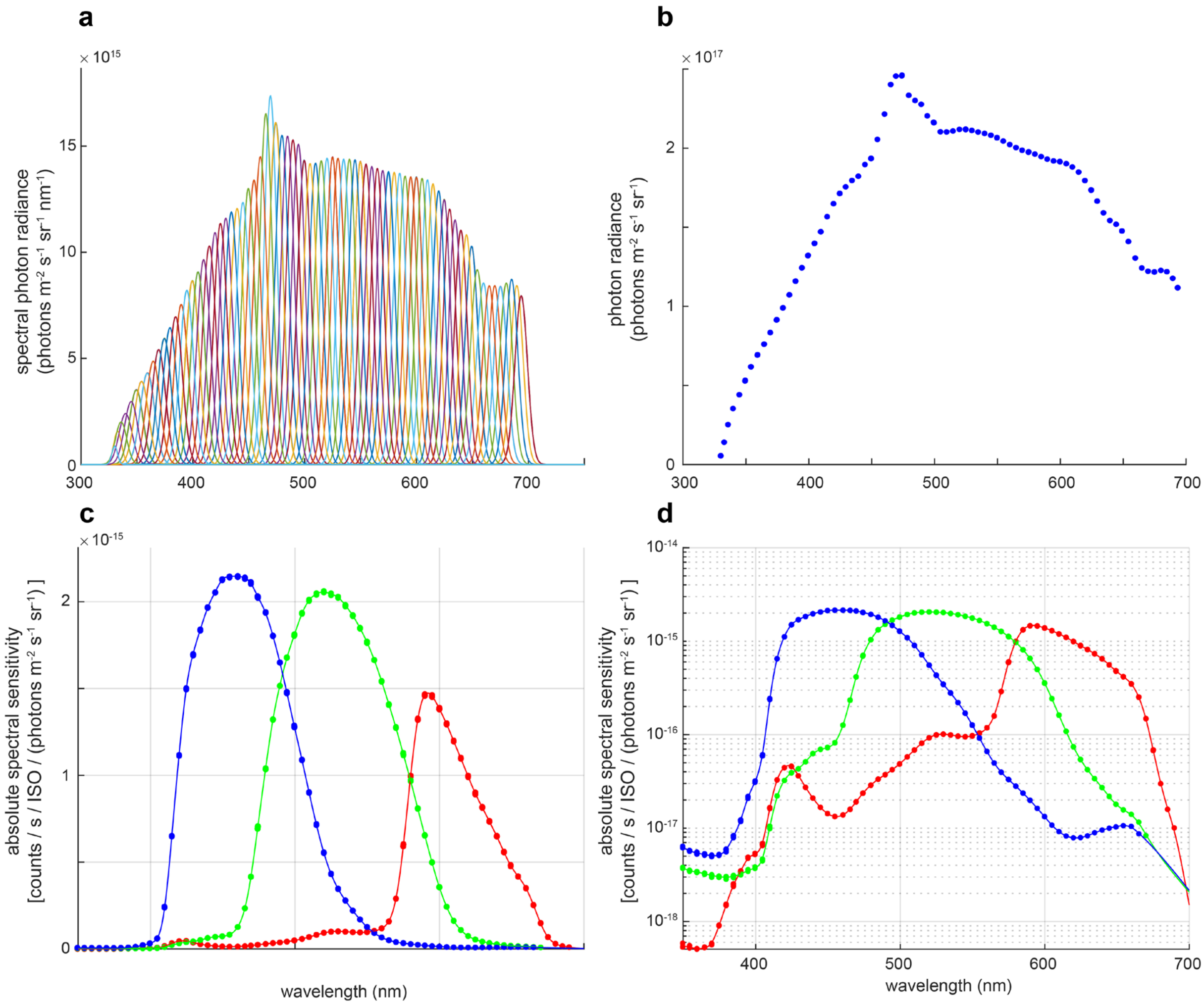

Figure S6: Spectral sensitivity of the Nikon D850 with a Sigma 8 mm fisheye lens. (a) Spectrum overlay of all individual monochromatic stimuli. **(b)** Total photon radiance of monochromatic stimuli at each wavelength. Dividing the camera's response signal by the exposure time, ISO value, and this radiance results in each channel's spectral sensitivity curve **(c)**: linear y-axis, **(d)**: logarithmic y-axis). Dots represent repeated measurements, which were then fitted with a smoothing spline (solid line). Colours in **(c)** and **(d)** indicate red, green and blue colour channels.

The absolute photon radiance of each stimulus was determined by fitting the measured spectrum with a Gaussian function and integrating over wavelengths. We also recorded the central wavelength of this Gaussian fit and used it, rather than the wavelength set on the monochromator, for any further analysis, even though it never differed by more than 1 nm in the relevant wavelength range. By dividing the camera signal (in counts/s/ISO) in each colour channel by the absolute photon radiance (in photons/s/sr/m^2) delivered by the stimulus at that wavelength, we then obtained the camera's absolute spectral sensitivity (Figure S6c, d). We then allowed a single scaling factor for each unique exposure value to shift all measurements taken at that exposure to be in line with the middle exposure (1/15 s).

In comparison to the D810, we found little difference in spectral sensitivity (Figure S7). Only the lower-wavelength flanks of the green and red sensitivity have been reduced somewhat, leading to a set of spectral sensitivities with less overlap, which is arguably better suited for ELF analysis.

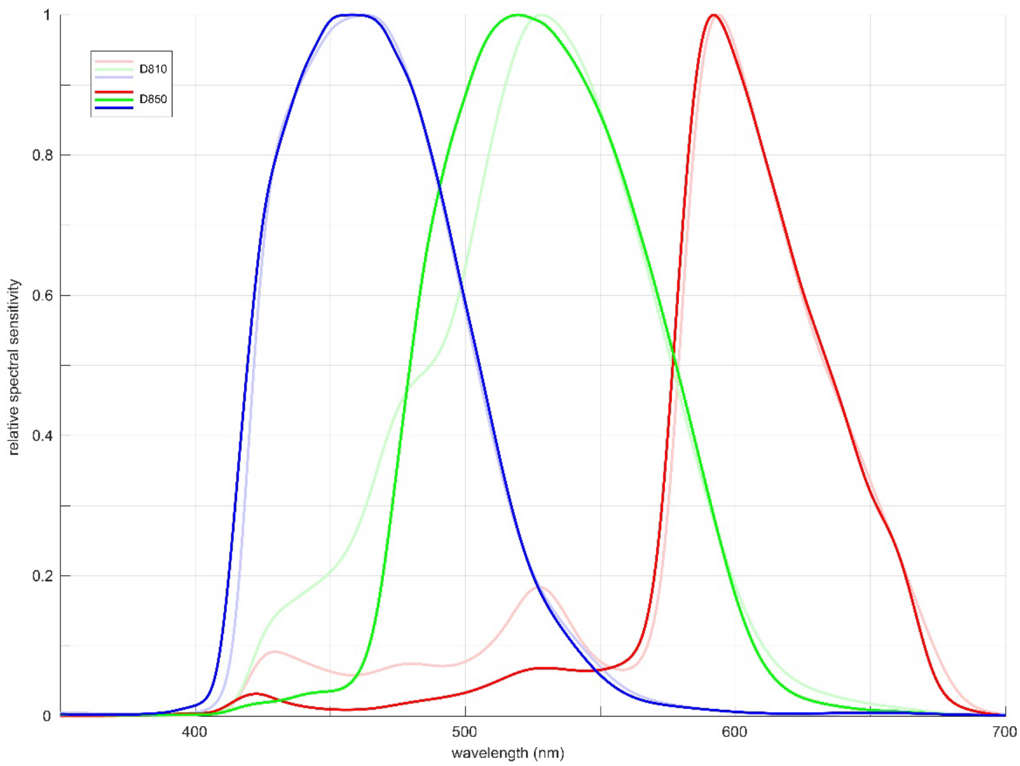

Figure S7: Spectral sensitivity comparison between the Nikon D810 and the Nikon D850. While the blue sensitivity seems to be unchanged, both the green and the red sensitivity seem to have reduced lower-wavelength flanks, leading to overall narrower, more distinct sensitivities.

For the calibration routine in ELF, we considered two strategies for applying this information to the raw camera signal:

A) Simple method: Each channel's raw signal is individually divided by the integrated sensitivity of that channel. The resulting number then indicates the number of photons (per s, per sr, per m^2) absorbed across the whole sensitivity function of that channel.

B) Deconvolution method: By comparing the signal in all three channels, it is easily possible to construct a hypothetical spectrum, with constant radiance across three bins (400-500 nm, 500-600 nm, 600-700 nm) that would result in the observed camera signal.

While the second method results in more easily interpretable numbers, it has a major drawback: Flawed data, due to noise or saturation, "spreads" across channels. For example, if the blue channel is at or near saturation (which, despite all precaution, occasionally happens), this will naturally result in an incorrect value in the blue channel for both methods; for method B, however, it will lead to an incorrect value in *all* channels. We therefore decided to apply method A as a standard in ELF processing (Table S4).

Table S4: Spectral calibration factors in counts/s/ISO/(ph/s/sr/m²/nm) for the Nikon D850, for each colour channel. Calibration is based on responses to monochromatic light.

	red	**green**	**blue**
scf	9.6461e-14	2.0125e-13	1.8720e-13

7. Linearity

Measurements

We tested the range over which the D850's image sensor reacts linearly to the incoming radiance by recording the response to light from the integrating sphere at 13 different brightness levels between 3.4 and 32547 cd/m^2 (Table S5). 40 photographs were recorded at each stimulus brightness, and the mean raw pixel value inside the aperture determined as usual. Dark levels were subtracted by taking a set of dark measurements at the end. The actual radiance delivered by the light source was monitored by the GS-1290 spectrophotometer, with two spectral measurements taken for each 40-repetition block of photographs.

We repeated these measurements at a later date with three cameras pointed at the light source from adjacent tripods, triggered by remote controls at the exact same time.

Table S5: Camera chip linearity test protocol

apt	ISO	exp (s)	luminance (ft-lambert = 3.426 cd/m^2)	rep	# files
f/3.5	100	1/8000	9500, 1, 2, 10, 46, 215, 1000, 4642, 2154, 464, 100, 22, 5, 1, 9500, dark	40	600

Analysis

The resulting relationship between luminance and camera raw count was fitted with a robust linear fit, allowing only for a slope coefficient, but no constant term (Figure S8a). Plotting the fit residuals over the raw camera count shows that above as little as 20 counts, the signal rarely strays more than 5%, and never more than 10%, from linearity (Figure S8b). Taking this into account, and leaving some extra safety margin for an uncertainty in the determination of the dark signal, we set a minimum threshold of 50 counts for all following calibrations. Signals below this level were considered too noisy to contribute to the calibration.

In a series of separate measurements (not shown), we determined the maximum raw count that linearly follows the intensity signal, before camera pixels should be considered to go into saturation. A recommendation for this level can be read from a DNG file's EXIF information, presumably stored there by Adobe during image conversion. For the Nikon D850, this level is at 15520 counts. Since in our measurements, we never found saturation values below 16000 counts, we decided to adopt the more conservative value of 15520 for all our calibrations, and for HDR image generation.

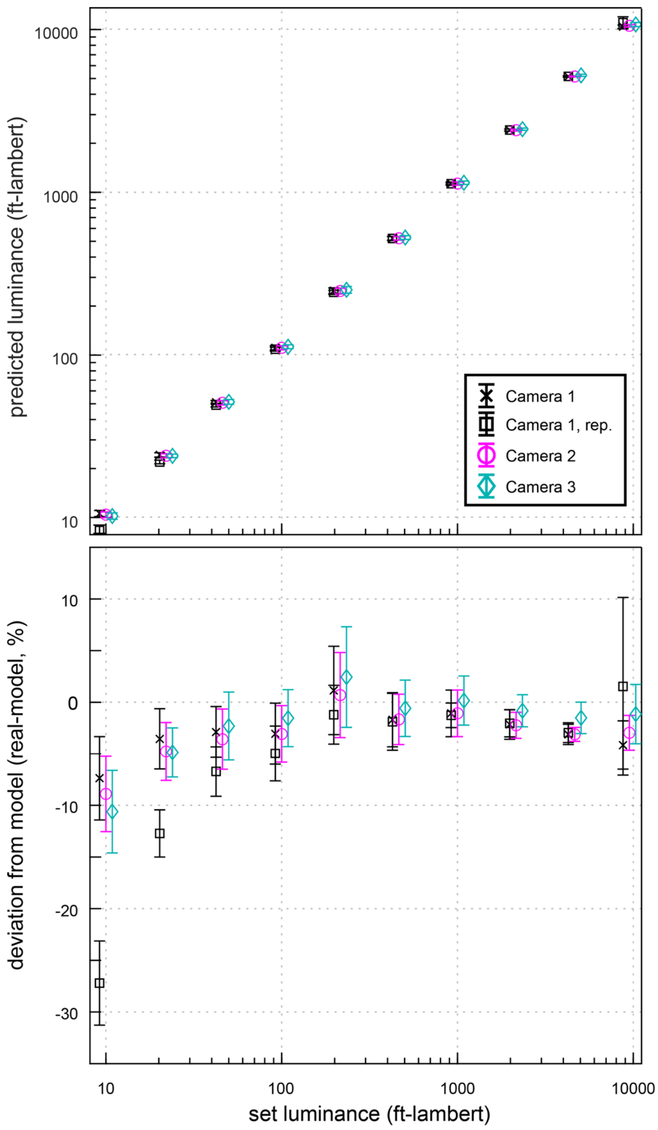

Figure S8: Linearity of the D850's chip. Camera signals were measured in response to 15 different light levels of the integrating sphere lamp **(a)**. Dots and error bars show mean and standard deviation across the 40 images taken at each level (colour-coded for the red, green and blue channels). Data for camera 1 and 3 was shifted by 5% to the left and right, respectively, for clarity. Errors relative to the linear prediction drop below 10% at 20 counts **(b).**

8. Camera parameter calibration

In a perfect camera system, we would expect the number of raw image counts to be linearly proportional to exposure time, ISO setting (representing the gain of the system), and the reciprocal square of the aperture value (representing the area of the entrance pupil). To test whether this was the case for the Nikon D850, we took photographs of the test stimulus across the full range of ISO-settings and aperture-values, and with exposure times up to 1 second.

Measurements

We took photographs with a Nikon D810 set up on a tripod at approximately 2 metres distance from the integrating sphere. The design of the 20 measurement blocks can be found in Table S6. Within each block, we kept two parameters constant, while sweeping across the full range of the third parameter, as far as over- and underexposure limits allowed.

To test for differences between cameras and lenses, we repeated sweeps of aperture values (at a single ISO value and three exposure values) with three different camera-lens combinations . As described in section 2, the images were taken at the exact same time with all cameras, thus minimising the effect of differences in temperature, light level or other factors.

Table S6: Camera parameter calibration protocol

	ISO	apt	exp (s)	rep	# files
1a	100	f/3.5	1/8000, 1/2000, 1/500, 1/125, 1/30, 1/8, 1/2, 1/4, 1/15, 1/60, 1/250, 1/1000, 1/4000, 1/8000	20	280
1b	100	f/8	1/8000, 1/2000, 1/500, 1/125, 1/30, 1/8, 1/2, 1/4, 1/15, 1/60, 1/250, 1/1000, 1/4000, 1/8000	20	280
1c	100	f/22	1/8000, 1/2000, 1/500, 1/125, 1/30, 1/8, 1/2, 1, 1/4, 1/15, 1/60, 1/250, 1/1000, 1/4000, 1/8000	20	300
1d	1600	f/3.5	1/8000, 1/2000, 1/500, 1/125, 1/250, 1/1000, 1/4000, 1/8000	20	160
1e	1600	f/8	1/8000, 1/2000, 1/500, 1/125, 1/30, 1/60, 1/250, 1/1000, 1/4000, 1/8000	20	200
1f	1600	f/22	1/8000, 1/2000, 1/500, 1/125, 1/30, 1/8, 1/2, 1/4, 1/15, 1/60, 1/250, 1/1000, 1/4000, 1/8000	20	280

1g	25600	f/3.5	**1/8000, 1/2000, 1/4000, 1/8000**	20	80
1h	25600	f/8	**1/8000, 1/2000, 1/500, 1/1000, 1/4000, 1/8000**	20	120
1i	25600	f/22	**1/8000, 1/2000, 1/500, 1/125, 1/30, 1/60, 1/250, 1/1000, 1/4000, 1/8000**	20	200
2a	100	**f/3.5, 5.6, 11, 22, 16, 8, 4, 3.5**	1/8000	20	160
2b	100	**f/3.5, 5.6, 11, 22, 16, 8, 4, 3.5**	1/100	20	160
2c	100	**f/3.5, 5.6, 11, 22, 16, 8, 4, 3.5**	1	20	160
3a	**32 (L1.0), 100, 400, 1600, 6400, 25600, 102400 (H2.0), 51200 (H1.0), 12800, 3200, 800, 200, 64, 32 (L1.0)**	f/3.5	1/8000	20	280
3b	**32 (L1.0), 100, 400, 1600, 800, 200, 64, 32 (L1.0)**	f/3.5	1/125	20	160
3c	**32 (L1.0), 100, 400, 1600, 6400, 25600, 102400 (H2.0), 51200 (H1.0), 12800, 3200, 800, 200, 64, 32 (L1.0)**	f/22	1/125	20	280
3d	**32 (L1.0), 100, 400, 1600, 800, 200, 64, 32 (L1.0)**	f/22	1/2	20	160
3e	**3200, 12800, 51200 (H1.0), 102400 (H2.0), 25600, 6400, 3200**	f/22	1/8000	20	140
4a	**as 3a, but with all NR on**			20	280
4b	**as 3c, but with all NR on**			20	280
4c	**as 3e, but with all NR on**			20	140

Table S7: Camera parameter calibration protocol

	ISO	apt	exp (s)	rep	# files
2a	100	**f/3.5, 5.6, 11, 22, 16, 8, 4, 3.5, 5.6, 11, 22, 16, 8, 4, 3.5**	1/125	20	300
2b	100	**f/3.5, 5.6, 11, 22, 16, 8, 4, 3.5, 5.6, 11, 22, 16, 8, 4, 3.5**	1/30	20	300
2c	100	**f/11, 22, 16, 8, 11, 22, 16, 8**	1	20	160
2d	same as 2b			20	300
2e	same as 2a			20	300

Analysis

For each raw image, we obtained a mean signal for a 3° diameter circle as described above. We discarded any measurement that indicated an overexposed (>15520 counts) or underexposed (<50 counts after dark correction) signal. For each of the three camera parameters, we then plotted the raw camera signal as a function of that parameter, taking into account only measurement blocks where that parameter was altered: for exposure time, blocks 1a-1i; for aperture, blocks 2a-2c; and for ISO, blocks 3a-4c. To cancel out the effect of changes in the other parameters between blocks, we allowed a correction factor for each curve, to align its mean with that of all other curves. We also allowed for a single factor to correct for the sensitivity difference between colour channels. The resulting data was fitted with a robust linear regression model, allowing only for a slope to be fitted, but not a constant term (Figure S9).

For **aperture** (Figure S9a, b), we expected a slightly complicated linear relationship. In our calibration of the Nikon D810, we found that counts were well predicted once aperture was raised to the power of 2.292 (rather than 2 as expected). In the measurements presented here, we could not find such an easy solution, and instead decided to allow an individual scaling factor for each individual aperture, taking into account measurements from all three tested camera/lens combinations. The resulting model (Figure S9a, Table S8) has a residual error (RMSE) of 9.4%, mainly due to the differences between cameras/lenses (Figure S9b). Interestingly, the differences are smallest at fully open (f/3.5) and fully closed (f/22) aperture, so we recommend using these values whenever possible.

Table S8: Aperture correction factors for the Nikon D850, for all available f-numbers (8).

f-number	aperture correction factor *acf*	s. d. (%)
3.5	1	5.0
4	0.8439	10.8
5.6	0.3579	12.1
8	0.1751	12.1
11	0.0786	9.5
14	0.0341	7.2
22	0.0158	4.3

For **exposure** (Figure S9c) and **ISO speed** (Figure S9e), we found a near-perfect linear relationship (residual error (RMSE) of 5% and 3.5%, respectively), with nearly all measurements lying within 20% of the value predicted by the model (Figure S9d, f). There were three exceptions:

- At the shortest exposure time (1/8000 s), raw counts were up to 30# higher than expected, indicating that this exposure is actually longer than 1/8000 s. We recommend not using this exposure setting.
- The lowest ISO-value (L1.0) is indistinguishable from the second-lowest (ISO-64). We would have expected this value to approximate ISO-32 (and this is supported by the EXIF information, which lists the "ISOSpeedRating" as 31), but this is clearly not the case. We recommend not using this ISO setting.
- At the highest ISO settings (>=12800), raw counts are substantially higher than expected. This is not surprising given the high noise and dark signal found for these settings. We recommend not using these ISO settings without corresponding dark images.

Finally, we compared how well our full model of exposure, aperture and ISO speed would predict measurements across the whole experiment (Figure S10), without allowing any correction factors between experimental blocks other than those predicted by the camera parameters. Overall, these findings suggest that we can predict the radiance of a 3° light spot to an accuracy of at least 15%.

Based on all measurements in this section (after excluded the above exceptions), we also calculated a white-light correction factor for each channel (Table S9), to account for the fact that the counts reported by the camera were on average above 10% higher than what we would have predicted from our spectral calibration.

Table S9: White-light correction factors for the Nikon D850, for each colour channel. Calibration is based on responses to broad-spectrum white light (8).

	red	green	blue
wlcf	1.0881	1.1101	1.0962

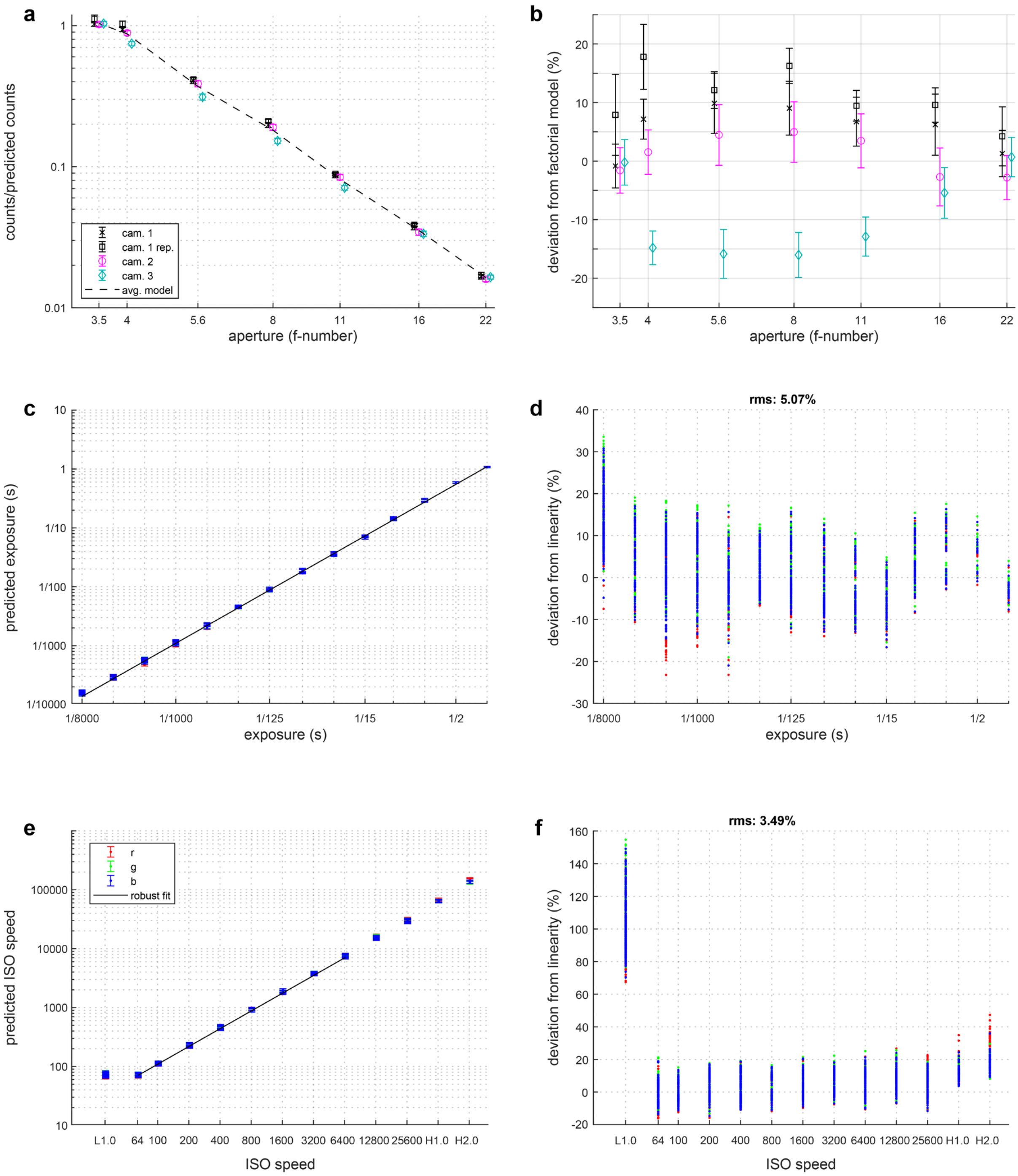

Figure S9: Camera parameter model for aperture values (a, b), exposure times (c, d) and ISO speeds (e, f). Colour in panels **a** and **b** indicates camera replicates, while in panels **c-f** it indicates colour channels. Dots and bars **(a, b, c, e)** indicate the mean and standard deviations of a value across images, whereas individual dots **(d, e)** indicate the mean of that value across an individual image. Solid lines indicate the line of linearity, and their range on the x-axis indicates the values over which the residual error was calculated. For **aperture** values, we could not find a good linear model (the best model had a residual root-mean-square error of 20.7%), so we decided to use individual calibration factors for each aperture value (resulting in a residual root-mean-square error of 9.4%). For **exposure**, we found a highly linear response, with a residual RMS deviation from linearity of 5.1%. The shortest exposure (1/8000s) presents an exception, with pixel values generally higher than expected, and we recommend not using this exposure setting, if it can be avoided. For **ISO speeds**, we again found a highly linear response, with a residual RMS deviation from linearity of only 3.5% for ISO values between 64 and 6400. The L1.0 ISO setting, which we expected to represent ISO-32, seems to be no different from ISO-64, and should therefore not be used.

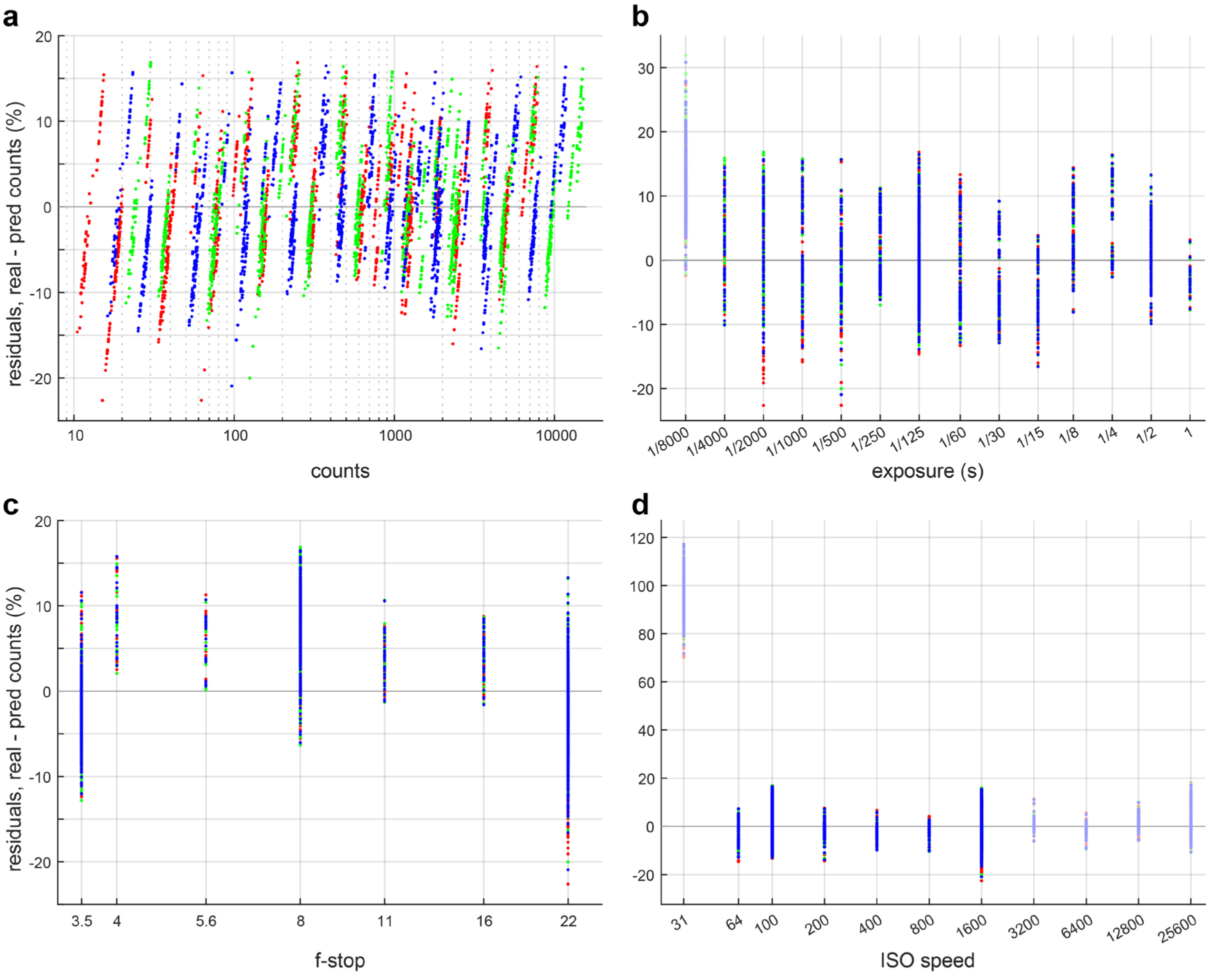

Figure S10: Overall camera calibration residuals. Residuals here are those of all measurements taken in this test versus the final model, allowing for no other correction factors between experiments. Colours indicate the colour channel. Dots in faded colours indicate exception points that are not included in other panels (exposure 1/8000 in **b**; ISO-31 and ISOs above ISO-1600 in **d**). As in Figure S9, the majority of residuals were within a ±15% error band.

9. Vignetting calibration

Note: We assume that vignetting depends entirely on the lens, not on the camera body/chip. This time-consuming calibration was therefore not performed again for the Nikon D850. The following section is a copy of our calibration report for the D810 (with numbering adapted).

Camera serial number: 6037507

Due to mechanical and optical limitations in lens design, and the angular dependence of camera chip pixels, the brightness of a raw camera image generally decreases towards the image periphery. This *vignetting* effect depends strongly on lens aperture.

Measurements

To measure vignetting in the Nikon D810 / Sigma-fisheye combination, we took images at our three standard apertures at a variety of angles. The camera was mounted at approximately 2 meters distance to the integrating sphere, on a panoramic tripod head (Nodal Ninja Ultimate M2, Fanotec, USA), which allowed us to rotate the camera precisely around all three rotational axes. We then took repeated images at a number of angles covering the whole horizontal, and part of the vertical, field of view of the camera (see Table 10 for details).

As we were expecting successively larger spread at higher f-numbers, we took 20, 30, and 40 successive images at each position for f/3.5, f/8, and f/22, respectively. These repetitions were triggered automatically, 1 second apart, by an attached remote to reduce the chance of any accidental camera movement during measurements. Before each set of repetitions, we acquired a dark image, which was used in the analysis to get a better estimate of noise levels. At the same time as the dark image, we also measured the radiance of our test stimulus with the PR-680 spectroradiometer.

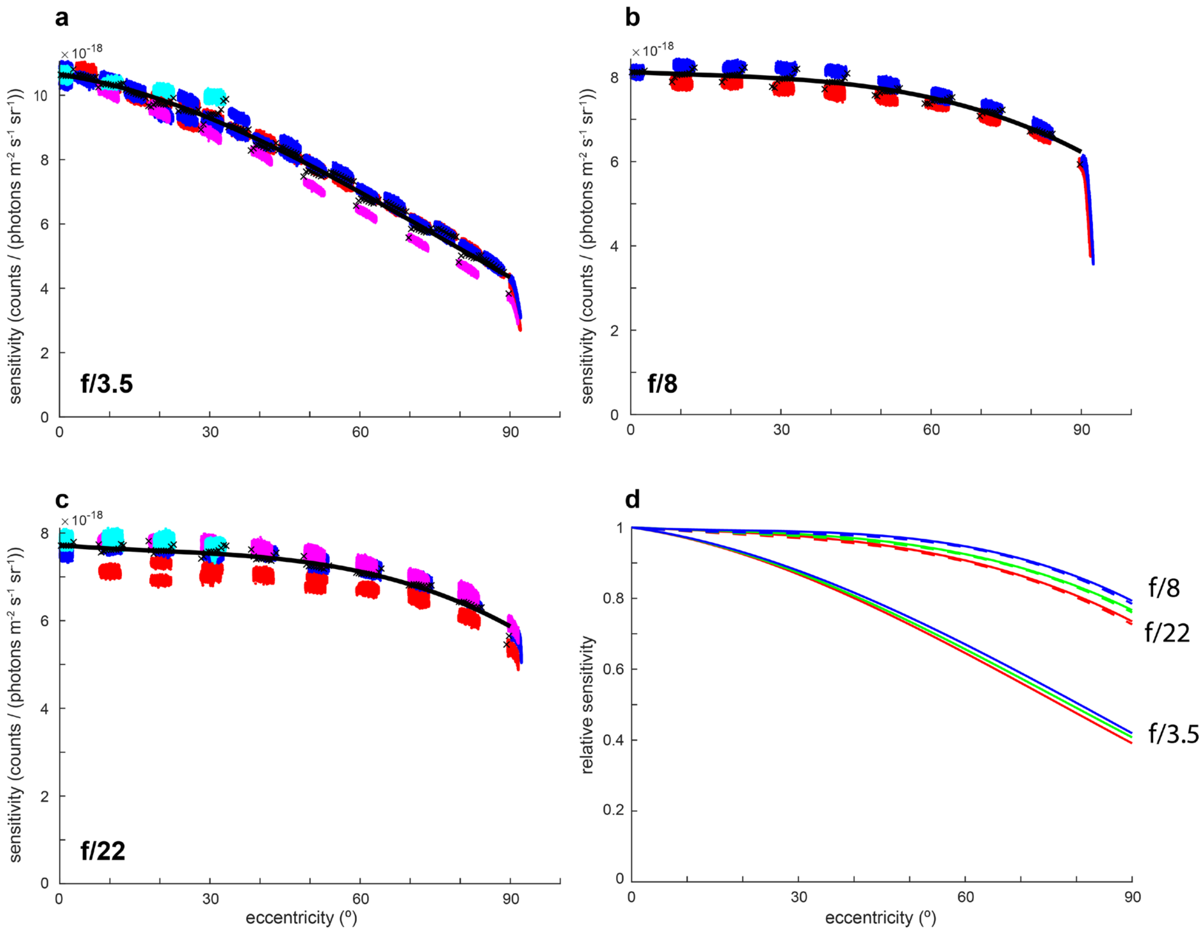

Figure S11: Results of the vignetting calibration for apertures f/3.5 (a), f/8 (b) and f/22 (c). Point clouds indicate the sensitivity estimates for individual pixels within a 2° radius circle around stimulus centre. Colours indicate the part of the camera's visual field: red – left; blue – right; purple – upper; cyan – lower. Black crosses are means for each 0.5° eccentricity bin, which were then fitted using a cubic polynomial (solid line). Panels **a**, **b**, and **c** show data for the green channel, while panel **d** shows fitted vignetting correction functions for all three channels for f/3.5 (lower lines), f/8 (upper solid lines) and f/22 (upper dashed lines).

Analysis

For each aperture, we calculated a sensitivity estimate for each individual pixel inside the detected light stimulus. Using our spatial calibration, we also calculated the eccentricity of each pixel. Plotting sensitivity over eccentricity, we get an estimate of how much sensitivity falls off towards the periphery (Fig. S8a-c). As at least part of this effect is due to optical effects inside the lens, it is dependent on wavelength, and we therefore analysed the three colour channels separately. For each aperture and channel, we then fitted a cubic polynomial to the obtained data (Fig. S8d).

Interestingly, vignetting curves at f/8 and f/22 are essentially identical (Fig. S8d), meaning that this curve can be used to calibrate any aperture values between those two. Vignetting between f/3.5 and f/8, on the other hand, changes drastically, indicating that these aperture values should not be used in ELF processing with this camera without additional calibration measurements.

Table 10: Vignetting calibration design

	ISO	apt	exp (s)	eccentricity	# files
1	100	f/3.5	1/6400	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*20
2	100	f/3.5	1/6400	-30° to +90° elevation in 10° steps, in random order. Then, repeat in reverse.	26*20
3	100	f/8	1/1250	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*30
4	100	f/22	1/125	-90° to +90° azimuth in 5° steps, in random order. Then, repeat in reverse.	74*40
5	100	f/22	1/125	-30° to +90° elevation in 10° steps, in random order. Then, repeat in reverse.	26*40

10. References

Sumner, Rob (2014) “Processing RAW Images on MATLAB”, https://rcsumner.net/raw_guide/RAWguide.pdf