Instrument Science Group
Royal Greenwich Observatory

The Design and Use of LED Reference Light Sources for Q.E. Calibration.

RGO TECHNICAL NOTE 107.

Simon Tulloch. 6th Nov. 1996

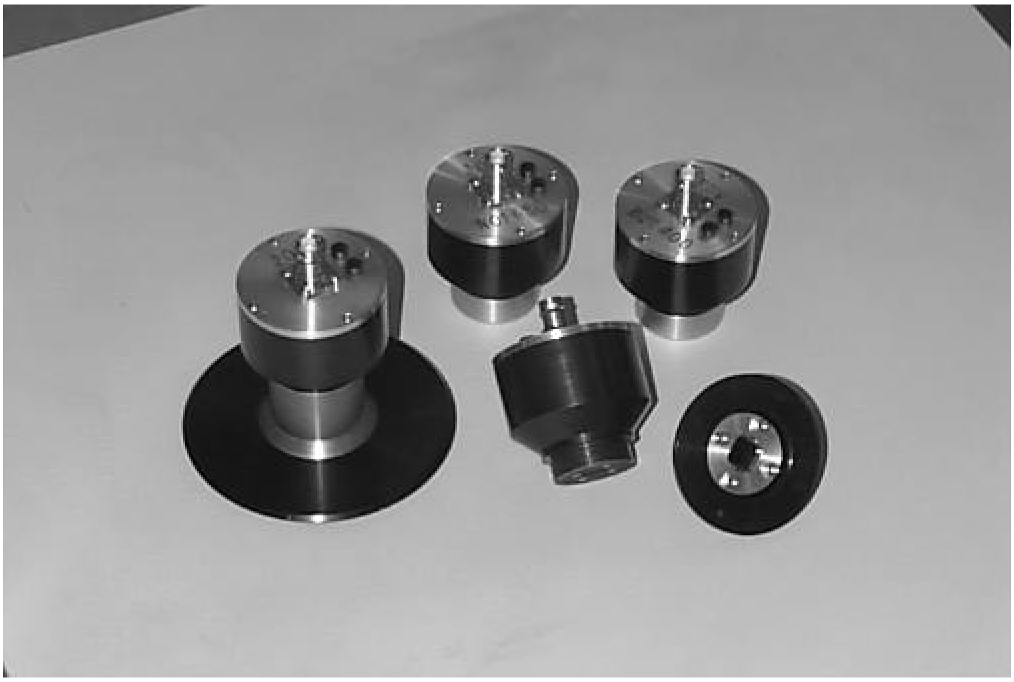
1. Introduction.

The backside charging of CCDs by UV flooding and by a Passivated Platinum coating (such as those provided by M. Lesser at the Steward Observatory) can result in higher Quantum Efficiencies (QE) than with other techniques such as Boron implantation. The crystal structure of the silicon is undamaged and the mobility of photoelectrons in the surface layers undiminished. A disadvantage, however, is that the chip surface is rendered very sensitive to contamination particularly if the camera cryostat is inadvertently allowed to warm up. Considerable out-gassing of cryo-pumped material can occur within a very short time of cryogen exhaustion and inevitably some of this finds its way onto the CCD surface. A simple and quick method of QE determination is required, especially at wavelengths shorter than 400nm where the QE is most strongly affected by contamination. Laboratory based systems for QE measurement are bulky and require the camera to be moved from the telescope environment. If the system contains an incandescent source, then there will be the additional problems of long thermal settling times and red-leak in UV filters .

In response to this need, we have designed a novel LED based light source with none of the above mentioned disadvantages. Four sources, shown in figure 1) have so far been built. They have centre wavelengths of 380,400,650 and 950nm and a bandpass of 10nm. It is expected that spot measurements of QE at these four wavelengths should be sufficient to verify camera performance. These lamps can therefore be seen as a replacement for the portable “Jelley Rig” currently in use at ING La Palma. If used correctly these lamps will allow the user to determine QE to an accuracy limited only by the calibration accuracy of the reference photodiode used.

This technical note explains the detailed design and calibration of these lamps. Full calibration data and advice on how to use them is also included.

Figure 1) Four of the light sources with a calibration photodiode at bottom right.



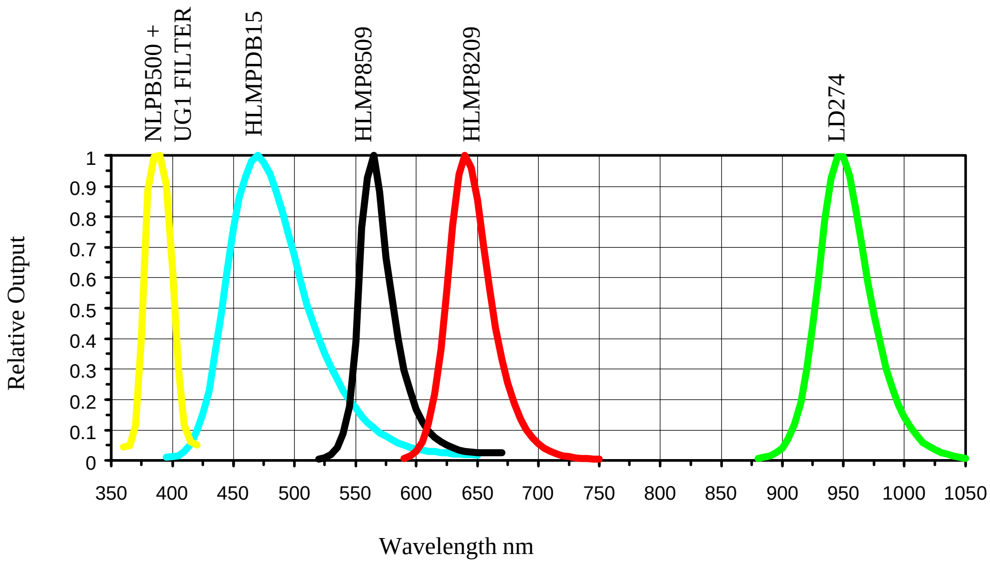
2. LED characteristics.

If supplied with a constant current, the light output of an LED will have a large temperature co-efficient, exceeding 1% / ^{0}C in some cases. Since the telescope dome temperature may vary between 0^{0}C and 25^{0}C, some form of temperature compensation is therefore essential.

The optical bandwidth of an LED is typically 70nm . The peak wavelength will be dependant on LED drive current as well as the temperature. If used for QE measurements it is desirable to narrow the spectral emission using an interference filter of 10nm bandwidth.

LEDs are available in a wide range of colours although there appears to be a gap between about 750 and 850nm in which no devices have been found available. Until very recently it has been impossible to obtain LEDs with output below 400nm. However, Nichia Chemical Industries now manufacture the NLPB range of Gallium Nitride LEDs that emit light down to a wavelength of 370nm. These have no output above 550nm, unlike incandescent sources, and so there are no red-leak filter problems to deal with. The spectra of a number of devices is shown below.

Figure 2) - The Spectra of various LEDs.

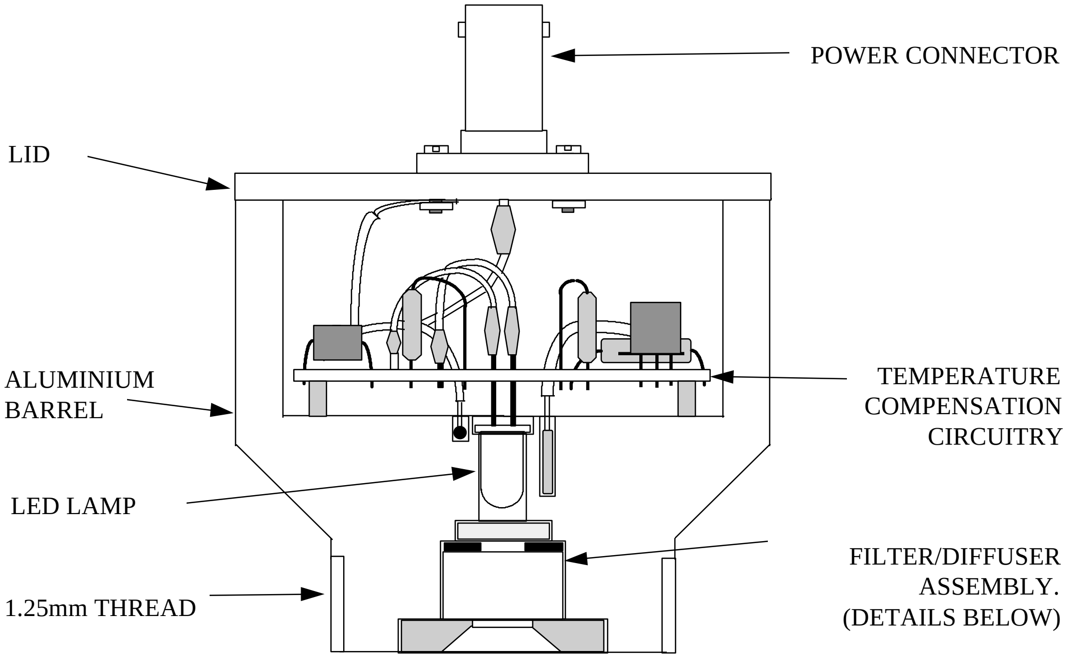


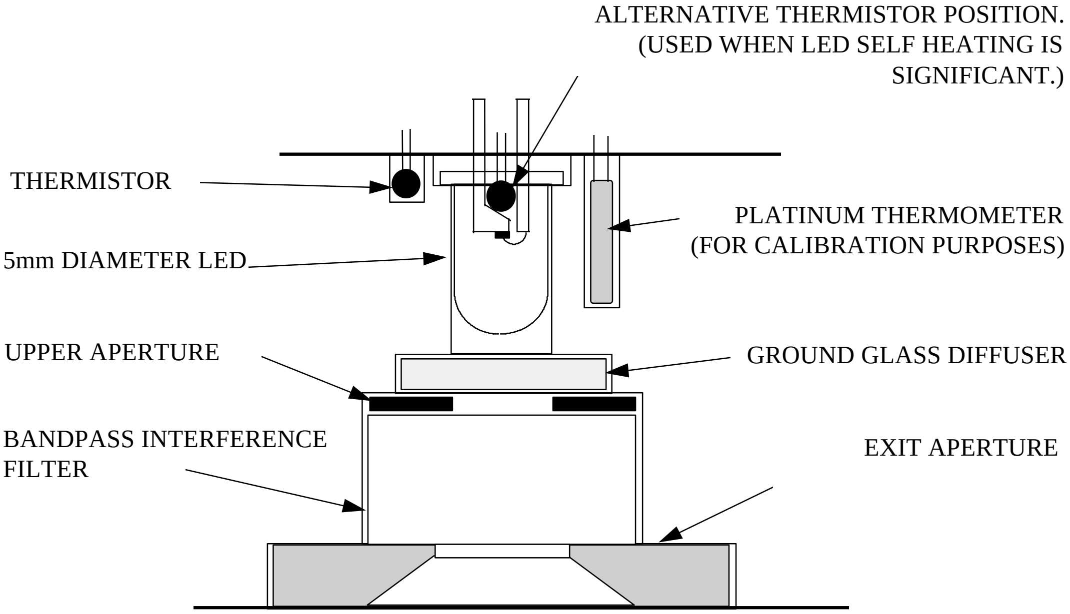
Self heating can be a problem in LEDs if the drive current exceeds a few mA. If soldered to a PCB with the anode and cathode leads cut to a length of 5mm, the junction to air thermal resistance will be about 180^{0}C/Watt. If the LED is used in pulsed operation then self heating will tend to decrease its brightness as the pulse length increases (most LEDs have a negative temperature coefficient).

3. Mechanical Design of Sources.

Each lamp contains a single LED source mounted in an axial bore. Light from the LED passes through a ground glass diffuser followed by a 5mm diameter aperture and a bandpass interference filter. The bore containing these components is first sand-blasted then black anodized to reduce stray light. The lamps contain an internal temperature compensation circuit mounted behind the LED. A thermistor sensor is glued into the lamp body close to the LED. A PT100 platinum sensor is also mounted close by that is used for calibration of the lamp. On top of the lamp are two monopole sockets connected to the PT100 and a BNC connector that supplies power to the internal compensation circuit. The lamp has a 1.25 pitch x 31mm diameter screw mount around its base. The overall dimensions are 55mm x 70mm. Engraving on the lid indicates the serial number and centre wavelength of each lamp.

Figure 3) - Internal Details of the Reference Lamps.





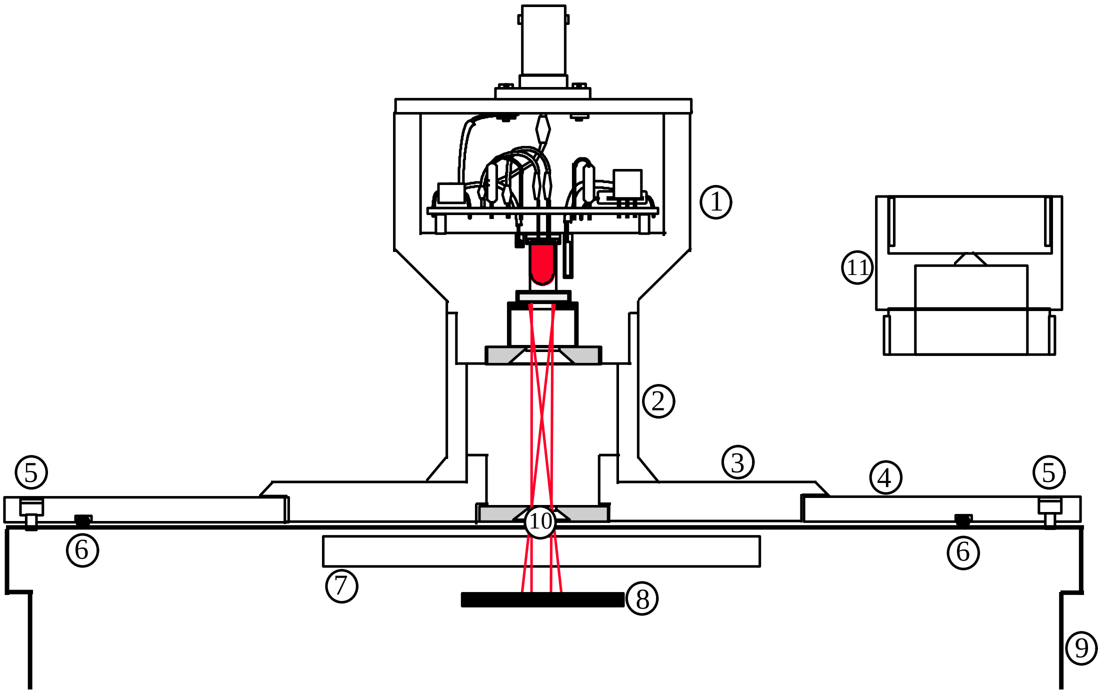
A cryostat interface plate has been built so that a variety of calibration tools, the reference lamps included, can be attached in front of the cryostat window. It is a circular disc with the same diameter as the cryostat faceplate. On its lower face is an 'O' ring situated in a groove to give a light tight seal. It is attached using two or more of the existing faceplate screws.

The centre of this interface plate has a 96mm diameter by 20 t.p.i. threaded hole that leaves the window unobstructed. The lamps are screwed into this opening by a short spacer barrel that has a 5mm aperture at its base. Light from the lamp passes through this aperture and is crudely collimated before reaching the CCD. The beam diameter at the CCD surface is about 8mm and so will underfill almost all the detectors in use at LPO.

When detached from the cryostat, a reference photodiode can be attached to the base of the lamp assembly to measure the light flux emanating from the lower aperture. In this position the photodiode will see exactly the same flux as would the CCD.

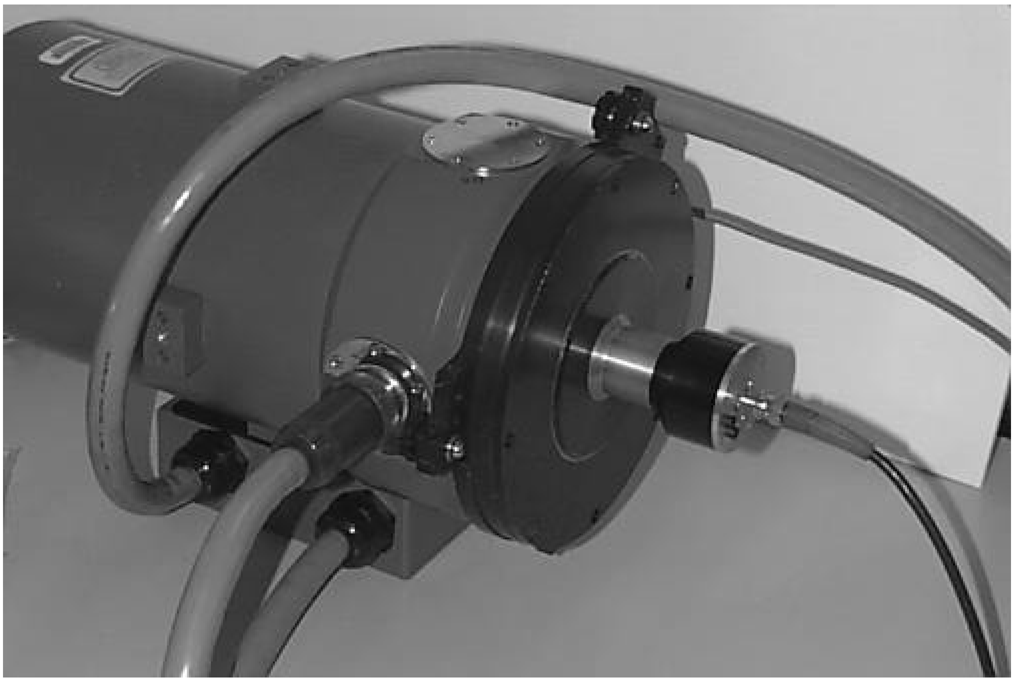
An extender barrel can be inserted between lamp body and spacer barrel (parts 1 and 2 in figure 4) to reduce the intensity of the lamps by a factor of approximately 20. This is needed when the lamps are used for "Imaging Mode" measurements of QE (see section 6).

Figure 4) - The lamp shown attached to a standard RGO detector cryostat showing the light path.



1. Lamp body
2. Brass Spacer Barrel
3. Screw in plate
4. Cryostat Interface Plate
5. Mounting screws
6. Light tight seal
7. Cryostat window
8. CCD
9. Cryostat body
10. Lower Aperture
11. Extender Tube

Figure 5) - A lamp being used for Diode Mode QE checks on a CCD at RGO.



4. Temperature Compensation of LEDs.

It was decided to temperature stabilise the LEDS used in the lamps by varying their drive currents in response to changes in temperature. The temperature was sensed by a small thermistor mounted either close by or actually inside the LED.

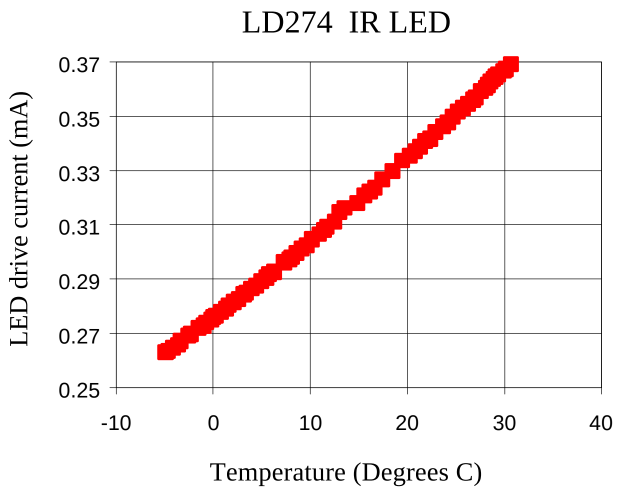
LEDs show a wide spread in response and this requires each lamp to have an individually tuned compensation circuit. Before the compensation circuit is designed the variation in light output with temperature, or rather, *the variation in drive current with temperature required to keep the lamp output constant* must be found by placing the fully assembled lamp in an environmental chamber. A photodiode, with a very low temperature coefficient (measured as less than $0.02\%/^0C$), is attached to the front of the lamp to monitor its output.

The lamp temperature is monitored during calibration using the PT100 platinum resistance sensor. This has a resistance of 100 Ohms at 0^0C and a temperature coefficient of -0.385 Ohms/^0C. After this calibration, this sensor is only used for checking that the lamp is within the calibrated temperature range before use.

For utmost accuracy the resistance of the internal thermistor, ultimately to be used in the compensation circuit, should also be recorded as the temperature is varied. The assembly should be cooled slowly, less than 0.5 degrees/minute, so that thermal gradients in the lamp body are minimised. As the lamp cools the thermistor resistance is noted every degree or so and the LED current adjusted to give a constant photodiode signal. The PT100 temperature, LED current and thermistor resistance data is then entered into a spreadsheet for further analysis. Figure 6 shows actual data from the calibration of a Siemens LD274 Infra-red LED. The graph shows that at higher temperatures an increased drive current was needed to maintain constant light output.

When these measurements are being done it is absolutely essential that the LED emission should be measured using the same interference filter that will be used in the final fully assembled lamp. This is because the spectral distribution of the emitted light is itself temperature dependant.

Figure 6) The variation in drive current required to maintain constant LED output



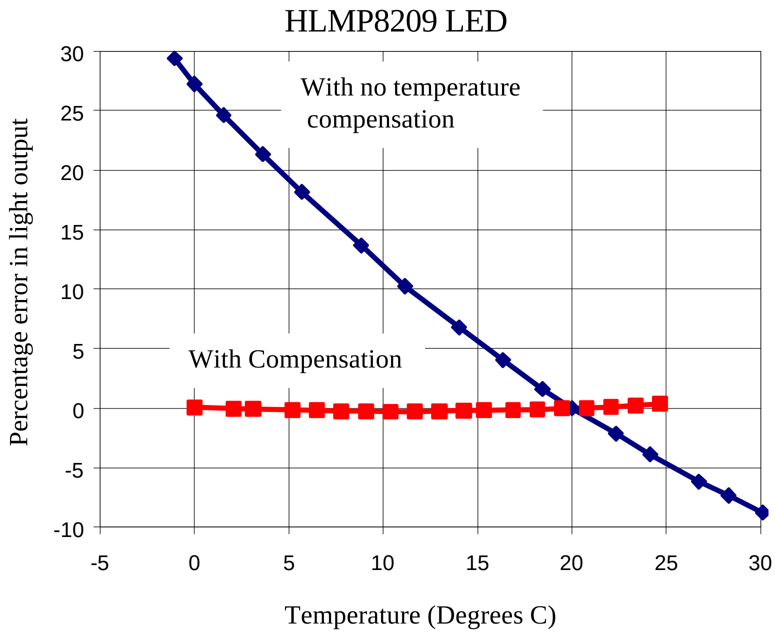
The compensation circuit, which is shown in appendix B, is basically an op-amp based current source. Two circuits were actually needed, one for positive and one for negative temperature co-efficient LEDs. The circuit performance is easily modelled using a spreadsheet. In the case of the circuit designed for negative temperature coefficient LEDs there are three circuit parameters to be varied ; the voltage at the non-inverting input, the resistance in series with the thermistor and the resistance in parallel with the thermistor. These three parameters were varied interactively until the output current versus temperature of the circuit matched the current requirements of the LED. By displaying the error between the two currents as a graph, the circuit values could be arrived at relatively easily.

Generally it was possible to use LED drive currents of less than 1mA to attain the required light output. In the case of the 380 and 400nm lamps, however, the centre wavelength of the bandpass filter was offset considerably from the peak wavelength of the LED emission and much higher currents were required. This introduced the problem of self-heating. For the 380nm lamp, this caused the LED junction temperature to rise by about 10^{0}C. Since this rise will not be detected by a remotely mounted thermistor it was necessary to drill a small hole in the back of the LED and insert the thermistor there.

The power supply to the circuits must be between 15 and 20V, below this range the LEDs will not fully turn on, above it there may be power dissipation problems. An internal diode protects against power polarity accidents.

The compensation circuits worked well. The residual errors in lamp output across the range 0-25 degrees C was reduced to less than +/-1% in all cases. The RO1 lamp performed exceptionally well with an error of +/-0.5 %. Figure 7 shows the temperature variations in the light output of a red LED both with and without the compensation circuit.

Figure 7) - An example of the compensation circuit performance



5. QE Measurement in “Diode Mode”.

The simplest way to measure CCD quantum efficiency is to configure the device as a photodiode. This does not require any bias voltages to be applied. A picoammeter is simply connected between the Substrate (Vss) and the Reset Drains (RD) of the output transistors. The junction potential in the device between the n-type buried channel and the p-type substrate will then sweep apart any photo-generated carriers to produce an external current. The QE determined by this method tends to be several percent lower than that determined by methods that use a CCD in imaging mode. The difference is probably due to the change in electrical field structure in the device.

A special lead was made up to connect a BNC cable to the relevant pins of a 20-41 cryostat electrical connector. The substrate pin was connected to the sheath of the BNC and also connected to the connector shell. This served to ground the cryostat body during measurement and allowed the CCD current to be measured to an accuracy of +/- 1pA. The design of this lead is shown in appendix D. The brightness of the LED reference lamps was chosen so that when mounted on the cryostat faceplate using the barrel extension and 5mm diameter aperture shown in figure 4., they would produce a current of about 5nA in a thinned backside illuminated CCD. Much higher currents than this can cause saturation effects in the CCD, much lower currents would be harder to measure accurately.

This method of QE measurement has been proven with TEK1024, Loral Lick3 2K square and Loral FT512 CCDs. It will not, however, work with EEV42 or EEV39 chips since these have two stage output transistors that have an internal shunt resistor between RD and Vss.

The lamps are initially calibrated by placing a reference photodiode over the lower aperture of the mounting barrel such that all the light that would normally fall on the CCD is intercepted by the diode. The lamps concentrate almost all their energy into an 8mm diameter spot and there is very little scattered light falling outside this area (see the images in figures 8 and 9). A 10mm x 10mm pre-calibrated Hamamatsu diode is used and this will register the same light flux as the CCD. Simply ratioing the CCD and photodiode currents and then multiplying by the photodiode QE at that wavelength gives the CCD QE in one simple stage. No allowance needs to be made for either filter red-leak or background light leakage; the blue LEDs have no red output and the whole apparatus is light tight. Accuracy is limited only by the calibration error on the photodiode. Less accurate but swifter measurement can be done by using the initial calibration data sheet (see Appendix E) showing the nominal output of each lamp without re-checking it each time using the photodiode. The user will then be limited by residual temperature compensation errors (less than +-1%) and long term drift in the lamp, a factor that has not yet been fully investigated.

6. QE Measurement in “Imaging Mode”.

This is a slightly more involved technique of QE determination but has the advantage that the CCD can be left connected to its controller. Disconnection causes a large increase in dark current for several hours after a CCD is switched back on and this may be a problem in certain situations. This method is the only one available for EEV42 and EEV39 devices for the reasons mentioned in the previous section.

The lamps are attached to the cryostat in the same way as for the diode mode measurements but for the inclusion of an extender section between lamp and spacer barrel. A special temperature servo cable must be used to connect the Controller to the camera. This cable, shown in appendix D, connects the heater circuit board within the cryostat to the controller in the normal way but takes the preflash LED control lines away on a separate co-ax cable. The internal cryostat pre-flash LEDs are thus disabled. This co-ax cable is attached to an interface box that opto-couples the preflash signal to a drive circuit that is used to pulse the LED lamps on and off. This circuit is shown in appendix A. (This same box also allows another calibration device: the Flat Field Projector , to be driven by the CCD controller).

To measure the QE in this mode requires two images to be recorded. A windowed image can be used for these exposures as long as the window fully covers the image spot. The first image will be a bias frame. The second is a spot image obtained by doing an “FL” exposure to pulse the lamp on during integration. This exposure should last for at least 250ms. If the lamp is switched on for less time than this then its brightness may change in an unpredictable way. The bias frame is then subtracted from the spot image and the total signal present in the image obtained by summing all the pixel values using the IRAF ‘imstatistics’ function. This number can be converted to the total number of signal electrons recorded by the CCD by multiplying by the system gain (e^-/ADU). The number of photons incident on the CCD during the exposure is easily calculated by using the source calibration data in appendix E, which shows the source outputs in photons/second. Dividing the number of signal electrons by the number of incident photons will give the Quantum Efficiency.

As appendix E indicates the brightness of the lamps can vary quite strongly for very short exposures. This is probably due to self heating and finite switching times in the drive circuit. The lamp fluxes are quoted only for exposures in excess of 250ms.

This method of QE determination requires the system gain to be known accurately. The Photon Transfer method is probably not accurate enough for these purposes and reliable results will only be obtained if the gain of the system has been previously determined using Fe55 X-ray technique.

Figure 8) - An IRAF surface plot of a spot image obtained using one of the calibration lamps. This is a full frame image taken using a CCD measuring 512 x 1024 pixels. Pixel size= 15mm.

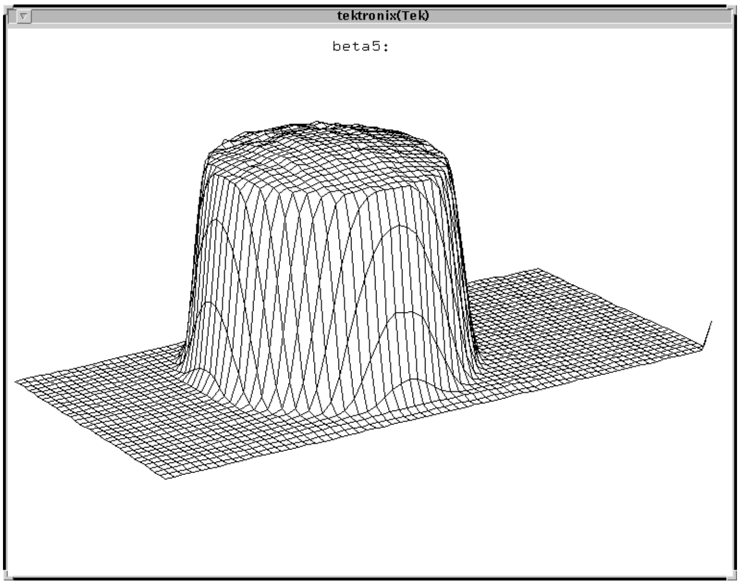
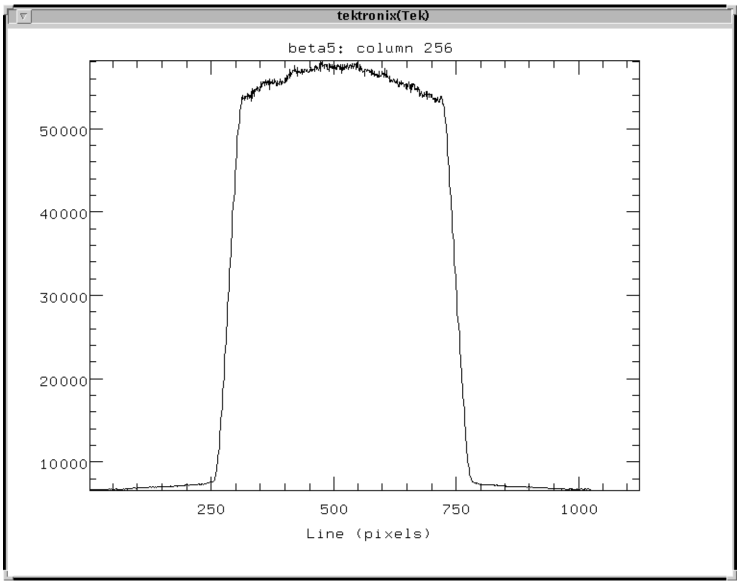


Figure 9) - A cross section of the above image

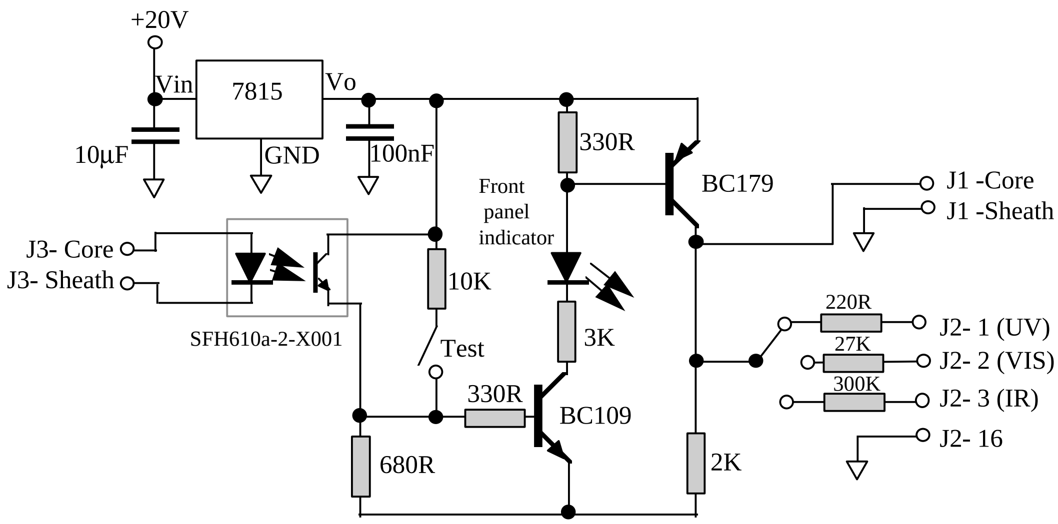


7. Acknowledgements.

I am grateful to Nathalie Falleur who calibrated a number of LED lamps when working as a summer student at RGO. Thanks also to Terry Dobner of the RGO mechanical workshop who manufactured all of the parts.

APPENDICES

A. CCD Controller Interface Box Circuit Diagram.



- J1 is connected to the LED reference lamps.

- J3 receives the ‘preflash’ signal from the CCD Controller using a modified temperature servo cable (see appendix D for wiring details)

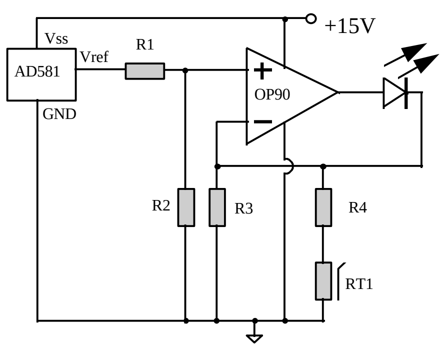
- J2 is used to power another piece of equipment : the flat field projector.

- A front panel indicator LED shows when the circuit is active. A front panel single pole non-latching switch allows the circuit to be activated manually.

B. LED Temperature Compensation Circuits.

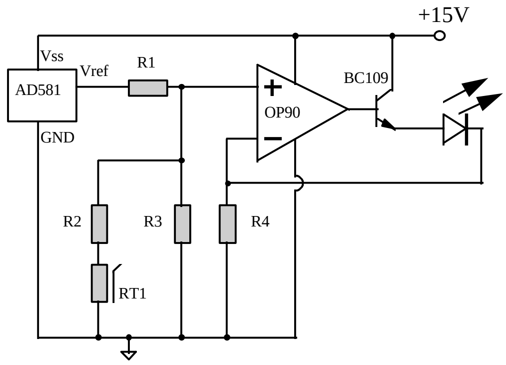
Circuit 1.

For negative temperature coefficient LEDs.



Circuit 2.

For positive temperature coefficient LEDs



Circuit Values

Lamp	LED	LED-MFCTR	Circuit	R1	R2	R3	R4
RO1	HLMP8209	HP	1	30K	15K	6K8	10K
IRO1	LD274	Siemens	1	43K	8K2	5K1	3K9
BO1	NLPB500	Nichia	1	ZERO	ABSENT	1K8	9K1
UVO1	NLPB500	Nichia	2	1K	10K	3K9	390R

- The thermistor used in all the circuits (RT1) had the Farnell reference number 151-591. It was an n.t.c. device with a resistance of 10k at 25^{O}C and a Beta of 3892 Ohms.
- Note that these circuit values apply to the specific LEDs used in each lamp. The same values will not necessarily accurately compensate other LEDs even from the same batch.
- The BC109 transistor used in circuit 2 was needed to provide the required 20mA drive to the LED in lamp UV01. The op-amp can only supply about 7mA.

C. Supplier Details.

Optical Filters

These were supplied by Oriel. the filters were 12.5mm in diameter and had a bandpass of 12.5mm. They were mounted mirror side towards the LED. The part numbers are as follows:

Lamp	Filter
R01	650FS10-12.5
IR01	950FS10-12.5
B01	400FS10-12.5
UV01	380FS10-12.5

Optical Diffuser

These are B270 glass discs with a diameter of 10mm and a thickness of 2mm. They were supplied by UQG of Cambridge. Telephone 01223 420329

LEDs

All the LEDs used in these lamps are now available from RS components. The Part Numbers are shown below.

Lamp	LED type	RS stock No.
RO1	HLMP8209	826-666
IRO1	LD274	195-669
BO1	NLPB500	199-6227
UVO1	NLPB500	199-6227

Calibration photodiode.

This was supplied by Hamamatsu. The part number was S1337-1010BQ. The serial number was Lot 5L- No. 1. The device was calibrated in February 1996.

D. Cable Design

The standard cryostat to CCD controller heater cable has an RS404-468 cable mounting plug at the controller end and an RS404-474 cable mounting socket at the cryostat end. The cable used to connect the controller to the interface box shown in appendix A modified this design by connecting a co-axial cable to the controller end of the cable. The sheath was connected to pin D, the core to pin C.

An Amphenol 2041 plug is used as the standard CCD signal connector on most of the cameras at LPO. When measuring quantum efficiency in diode mode a special co-axial cable is required to connect a picoammeter to the relevant pins of this plug. The sheath of this cable should be connected to pin Y (CCD Substrate), the core to pins X,V,C,r (CCD Reset Drains). The sheath of the co-ax should also be connected to the shell of the 2041 cable mounted socket that mounts it to the cryostat.

E. Source Calibration Data.

- The following data makes no allowance for reflection losses in the cryostat window.

E1. Lamp calibration data when use in DC Mode

The lamps were measured in DC mode using a Hamamatsu calibrated photodiode.

LAMP	WAVELENGTH (nm)	PHOTODIODE CURRENT (nA)	PHOTODIODE QE. (%)
R01	650	6.13	66.7
IRO1	950	15.41	67
BO1	400	6.11	56.4
UV01	380	3.27	51.3

Calibration Date : 31 Oct 96
Calibration Temp : 20^0C

When attached to a detector cryostat the CCD QE can be found easily using the following table.
The CCD current is measured in nA. This value is then multiplied by the relevant factor in column 2 of the table to yield the Quantum Efficiency in percent.

Lamp	Factor
R01	10.88
IR01	4.35
B01	9.23
UV01	15.7

E2. Lamp calibration data when used in pulsed mode.

For exposures greater than 250ms, the lamp outputs are as follows:

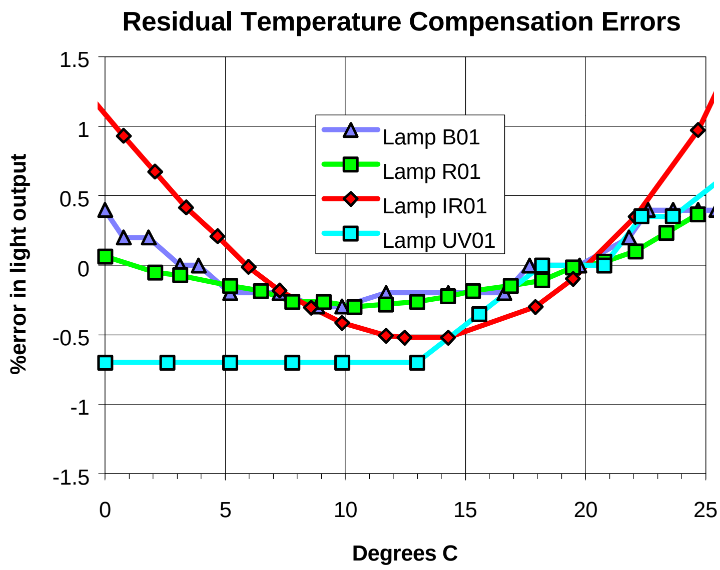
Lamp	Photons/Sec (x 10^9)
R01	7.30
IR01	14.4
B01	12.4
UV01	4.39

Calibration Date : 7 Nov 96
Calibration Temp : 20^0C

Note that these are the fluxes that will be measured passing through the lower aperture (i.e. the aperture immediately next to the cryostat window) ***when the lamp is mounted using the extender tube***.

E3. Accuracy of the Temperature Compensation Circuits.

The fully assembled lamps were placed in an environmental chamber and their outputs measured across the full operational temperature range. The graph below shows the results normalised to the lamp brightness at 20^{0}C.

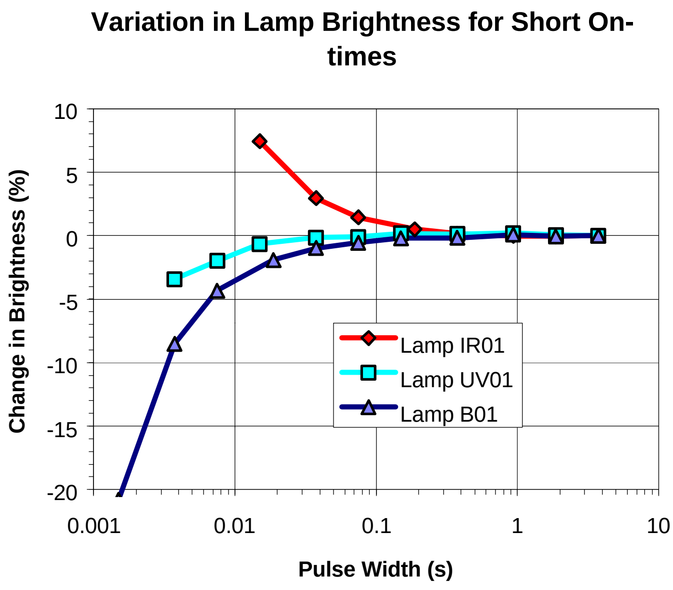


E4. Variation in Lamp Brightness During Short Exposures.

Measuring the lamp brightness for short exposures is a difficult task. An integrating detector such as a CCD can be used but one must be confident that the detector is highly linear. If this is the case then a graph of signal level versus exposure time will show any non-linearities in the lamp at short exposure times. If the detector is not linear then a more complex method is required.

For these measurements the on-time of each lamp was varied between 5s and about 10ms. In order not to saturate the CCD a neutral density filter was placed in front of the lamp. The CCD signal produced by a 5s lamp exposure was recorded and compared with the signal from two 2.5s lamp exposures, four 1.25s exposures and so on. Each image that was read out of the CCD would therefore have a very similar signal level and the measurements would be independent of CCD non-linearities as least to first order.

The graph on the next page show the percentage change in lamp brightness as the pulse width is varied. It shows that for exposures below 250ms, the relationship between total light emitted and the on-time of the lamp is no longer linear.


Variation in Lamp Brightness for Short On-times
Change in Brightness (%)
10
5
0
-5
-10
-15
-20
0.001
0.01
0.1
1
10
Pulse Width (s)
Lamp IR01
Lamp UV01
Lamp B01