

An Integrating Sphere: When is the data sincere?

Speaker / Author: P. Pomeroy

Co-author: S.V. Marais

Cosine Developments

PO Box 10177, Durban, 4056, South Africa

e-mail: pete@cosine.co.za

Phone: 031 5792172 Fax: 031 5792176

Abstract

An integrating sphere can provide an accurate means of comparing total luminous flux. However, errors can occur due to sensor linearity, lamp geometry, etc. This paper describes sphere theory, practical measurements and pitfalls experienced whilst measuring both lamps and luminaires in an integrating sphere.

1. Introduction

Due to economies of scale, the acquisition of an integrating sphere is no longer confined to larger corporations. This tool is now available, at a reasonable cost, to small companies and research facilities. Indeed, this bodes well for all because the inexorable drive towards energy efficiency must surely drive our industry focus more on luminaire efficacy than extrapolations from quoted lamp luminous flux. Problems may arise when a smaller venture does not have the budget to hire or train apt personnel. Our experiences with our shiny new 2m integrating sphere and ancillary equipment, after hours of exhaustive testing, may be enlightening. This paper will show that training and that a thorough knowledge of the equipment is vital.

The measurement of total luminous flux using an integrating sphere is not a straightforward exercise. In the words of W. Heisenberg: *“An expert is someone who knows some of the worst mistakes that can be made in his subject and how to avoid them.”*

2. Sphere basics



Figure 1: The Integrating Sphere

The total luminous flux from a source (lamp or luminaire) can be measured by an Ulbricht or integrating sphere. The theory of an integrating sphere assumes an empty sphere whose inner surface is perfectly diffusing (Lambertian) and of uniform non-selective reflectance. Every point on the inner surface then reflects to every other point and the illuminance at any point is, therefore, made up of two components; the flux coming directly from the source and that reflected from other parts of the sphere wall. With these assumptions it follows that illuminance and hence luminance of any part of the wall due to reflected light only is proportional to the total flux from the source, regardless of its distribution[1]. The luminance of a small area of the wall *i.e.*, the photometer aperture, carefully screened from direct light from the source, but receiving light from all other portions of the sphere is therefore a relative measurement of flux from the source. The screen should be as small as possible and be positioned one-third of the distance from the lamp to the window.

This arrangement works well with small spherical sources and, if various correction factors are applied, can be used for absolute measurements[3].

3. Sphere components and possible errors

The elegant theory described above is not easily applied in practise due to many compromises: sphere theory applies to point light sources only. For extended light sources, the sphere dimensions should be at least six times the overall length of the lamp[3]. Even with direct substitution the sphere should be at least 1.5 times the length of the lamp[3,6]. Lamp electrical connections, its supports, the necessary shield (baffle) and the aperture are all departures from the basic assumptions of integrating sphere theory[1,3,4,5,6]. Reduction of errors due to the effect of the screen demands a high reflectance paint whereas reduction in absorption errors requires a low value. A compromise is achieved by using paint of about 85% reflectivity[3].

Most literature indicates that the substitution method (like-for-like) is preferable and that an absolute measurement of flux requires many correction factors[3,4,5,6]. Indeed, the IES Handbook suggests a four stage method for measurement of luminaire efficiency[6]. However, in most commercial applications a quick test measuring the relative output of two dissimilar luminaires will be investigated before more thorough testing is warranted. It is imperative that the test officer has a “feel” of the test setup – there is no substitute for many hours of experience. In fact, the integrator geometry can take on other forms such as a rectangular box or room when the standard and test lamps are geometrically similar and have similar polar distributions[3].

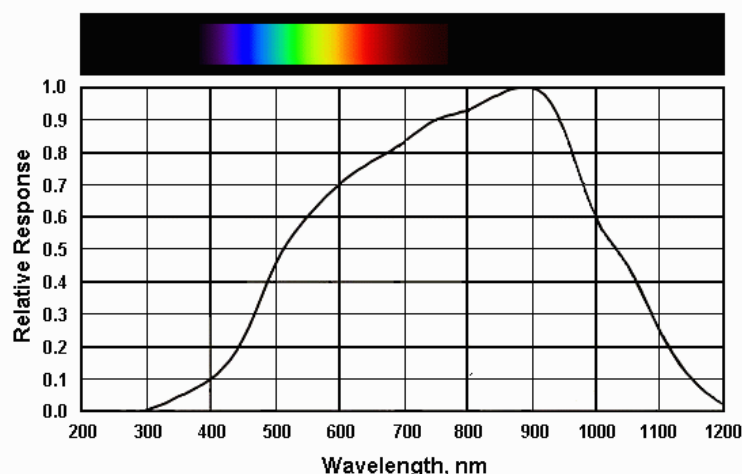
3.1 Photometer processor

Our integrating sphere was purchased with both a photometer head and processor. The photometer head is a $V(\lambda)$ – corrected silicon photodiode with a cosine corrected angular response whilst the processor both amplifies and translates the photometer current into a digital value. In spite of the claims made by the manufacturer we endeavoured to check linearity and dynamic range from first principles. The silicon photodiode can have a linear response over seven orders of magnitude[2]. This only applies if the sensor is loaded with a short circuit and its Norton equivalent constant current generator dominates. Complications arise at low incident flux levels (low sensor current) when the load impedance may rise to improve gain as in a typical ammeter.

Tests on the photometer processor revealed two sources of uncertainty; calibration and errors at low flux. Its calibration procedure yielded unacceptable rounding-off errors which alluded to a low-bit internal arithmetic processor. A variable constant current source was then attached to the photometer head input to characterise its dynamic range. The current versus readout were noted between the ranges of 1 to 180 μA . The tests revealed a significant rise in errors at low currents – easily bettered by a good quality digital ammeter. Despite having numerous features and frills, the photometer processor proved inadequate for the task. All subsequent measurements were conducted using a well characterised digital micro-ammeter.

3.2 The photometer head

A silicon photodiode is predominantly sensitive in the infra-red region, see Figure 2.



Typical Silicon Photodiode Spectral Response

Figure 2

It is quite clear that significant optical filtering is required for photopic correction, with its attentive losses. These losses may be telling at low flux levels when the photodiode response becomes non-linear. The system throughput or scale factor was determined in order to provide a basis for any

subsequent measurements thereby establishing dynamic range and linearity. The scale factor enables quick comparison between dissimilar luminaires or light sources. It is theoretically possible to measure a dynamic range of 10^{-1} to 10^5 lm in a 2 m integrating sphere[2]. By measuring many different lamps of known flux output the relative spectral responsivity of the sphere coating and the detector responsivity were investigated. Lamp orientation of extended sources was varied and effects noted. Both ambient temperature and mains voltage were kept reasonably constant throughout the measurements. The dark current (null condition) was also measured to confirm shielding from ingress of ambient light.

The lower end of the sphere throughput was investigated by using a single white LED. Its nominal power is rated at 70 mW (3.5 V @ 20 mA) with a luminous intensity 15000 mcd and a viewing angle $\Theta = 15^\circ$. Its luminous flux was calculated from the luminous intensity[7]:

$$\text{Solid angle (steradians)} = 2\pi(1 - \cos[\theta/2]) = 0.054 \text{ sr}$$

The luminous flux is therefore:

$$\text{Luminous flux(lm)} = \text{luminous intensity (cd)} \times \text{solid angle (sr)} = 0.806 \text{ lm}$$

Interestingly, this yields a very low efficacy of 11.5 lmW^{-1} . Thereafter more LED's were paralleled to increase the luminous flux and thereby yield a trend. Figure 3 shows a distinct drop in system efficiency below 600 lm. This reduction can only be attributed to optical losses due to $V(\lambda)$ processing. The lower limit of the dynamic range had now been established.

3.3 The sphere throughput

Table 1 and Figure 3 show the measured response to various lamps of random colour temperature and spectral uniformity. What was still unknown at this stage was the large variation in normalised current above 600 lm (from 62.4 to $121.7 \text{ lm}\mu\text{A}^{-1}$) for the various lamps tried, but of initial interest was the fact that there was no trend up or down for increasing lumens. Probable reasons for the variation are dissimilar lamp geometry, selectivity of the sphere coating (spectral mismatch), a singular lamp sample or varying spectral content. Ideally, a large batch of aged lamps should be tested for each type but time and finance did not permit such luxuries. It was noted that lamp orientation could produce variations of approximately 6% thereby revealing the spatial non-uniformity of the sphere.

Table 1: Sphere throughput of assorted lamps

Lamp Type	Quoted flux (lm)	Measured current (μA)	Lumens per μA
One LED	0.81	0.1	8.1
16 LED's	12.8	1.2	10.7
1W LED	35	1.3	26.9
PL-9W	600	6.8	88.2
CFL-13W	900	11.3	79.6
100W incandescent	1330	14.2	93.7
T8-18W	1300	17	76.5
PL-26W	1800	21.7	82.9
2 x PL-26W	3600	38.4	93.7
80W Osram HQL Hg	3800	42	90.5
T8-58W	5200	49.1	105.9
70W Osram Vilox	5600	54.5	102.7
ES 120W	6800	109	62.4
Philips HPL-N 250W	12700	113	112.4
CFL-120W	9000	135	66.7

Philips HPL-N 400W	22000	226	97.3
Osram 250W Vialox	27000	234	115.4

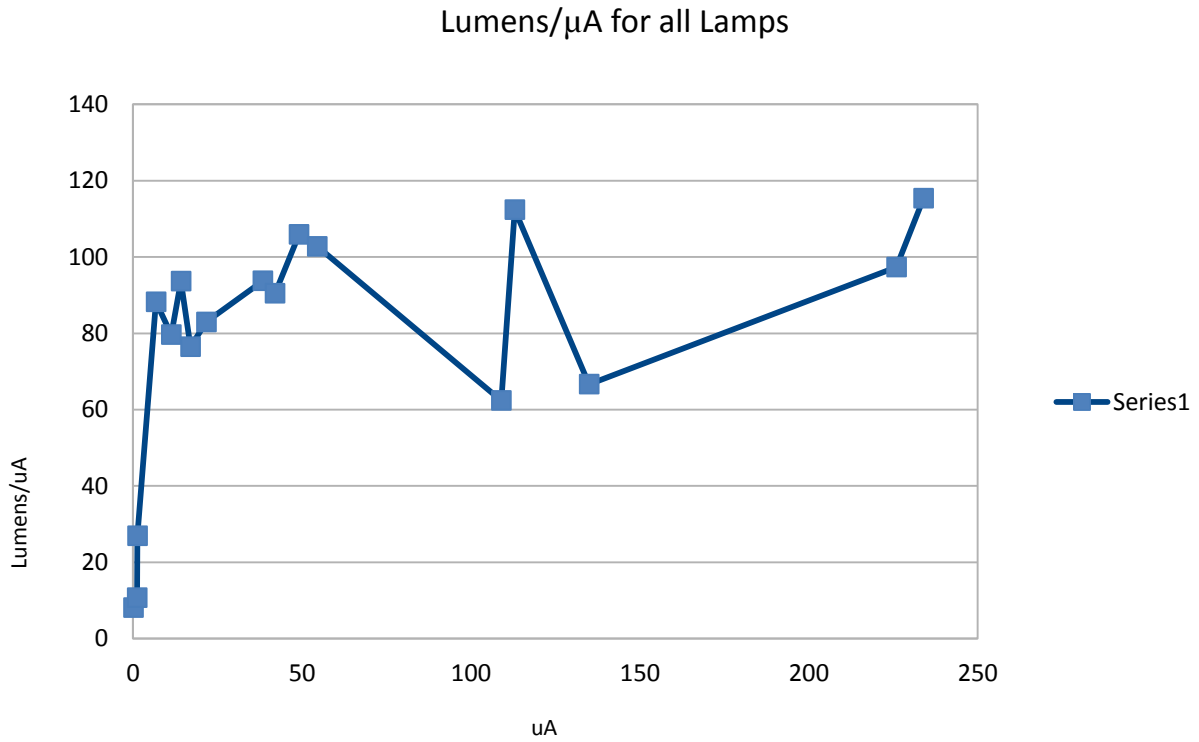


Figure 3: Sphere scale factor variation (assorted lamps)

The spectral mismatch was analysed in greater detail. A small published $V(\lambda)$ deviation may produce far greater deviations between lamps of dissimilar spectral content than expected.

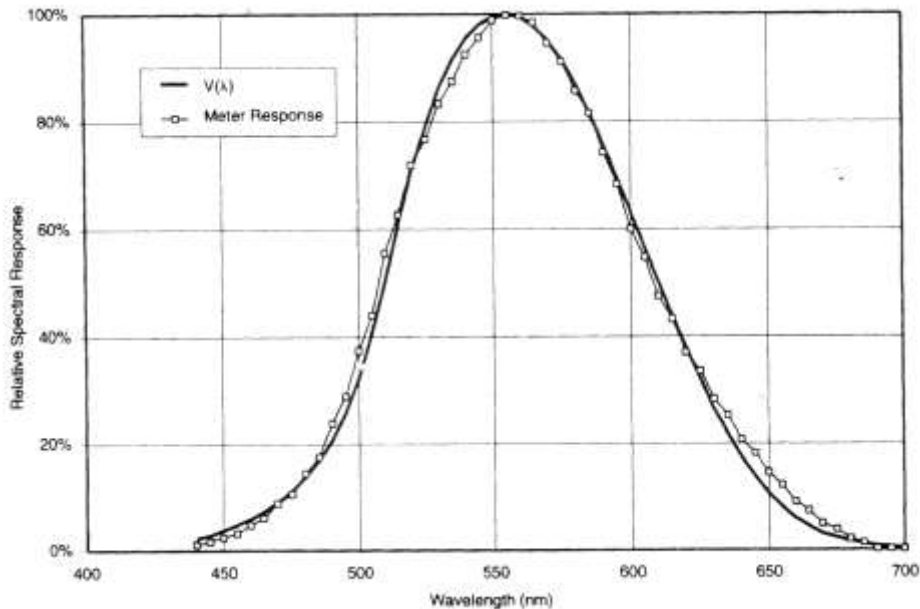


Figure 4: Photometer head published response (courtesy DeCusatis)

Consider a reputable manufacturer’s published photometer response in Figure 4. The meter response closely follows $V(\lambda)$ with maximum deviations of only a few percent. In this case errors incurred when comparing black body spectra will be small. However, for an area where the weighting

function is small, the error can become proportionately very large. If used to measure a laser at 632 nm, after calibration with a black body, the total error is approximately 10%[2]. This indicates a basis of large potential error when comparing sources with dissimilar, or worse, discrete emission spectra.

The scale factor of the sphere became more predictable once lamps of poor colour rendering were removed from the calculations. Table 2 shows the revised measurements without HID lamps. HID lamps are normally not used as transfer standards because of their poor repeatability[2].

Table 2: Sphere throughput of revised selection of lamps

Lamp Type	Quoted flux (lm)	Measured current (μA)	Lumens per μA
One LED	0.81	0.1	8.1
16 LED's	12.8	1.2	10.7
1W LED	35	1.3	26.9
PL-9W	600	6.8	88.2
CFL-13W	900	11.3	79.6
100W incandescent	1330	14.2	93.7
T8-18W	1300	17	76.5
PL-26W	1800	21.7	82.9
2 x PL-26W	3600	38.4	93.7
T8-58W	5200	49.1	105.9
ES 120W	6800	109	62.4
CFL-120W	9000	135	66.7

Figure 5 shows the improved sphere scale factor without HID lamps. Although improved, there still seems to be no trend up or down and no sign of saturation with any of the larger power sources. The scale factor averages to about $90 \text{ lm}\mu\text{A}^{-1}$. This figure will certainly be revised after more exhaustive testing in the future. Corrections due to lamp absorption, lamp geometry and sphere spatial non-uniformity will be further investigated.

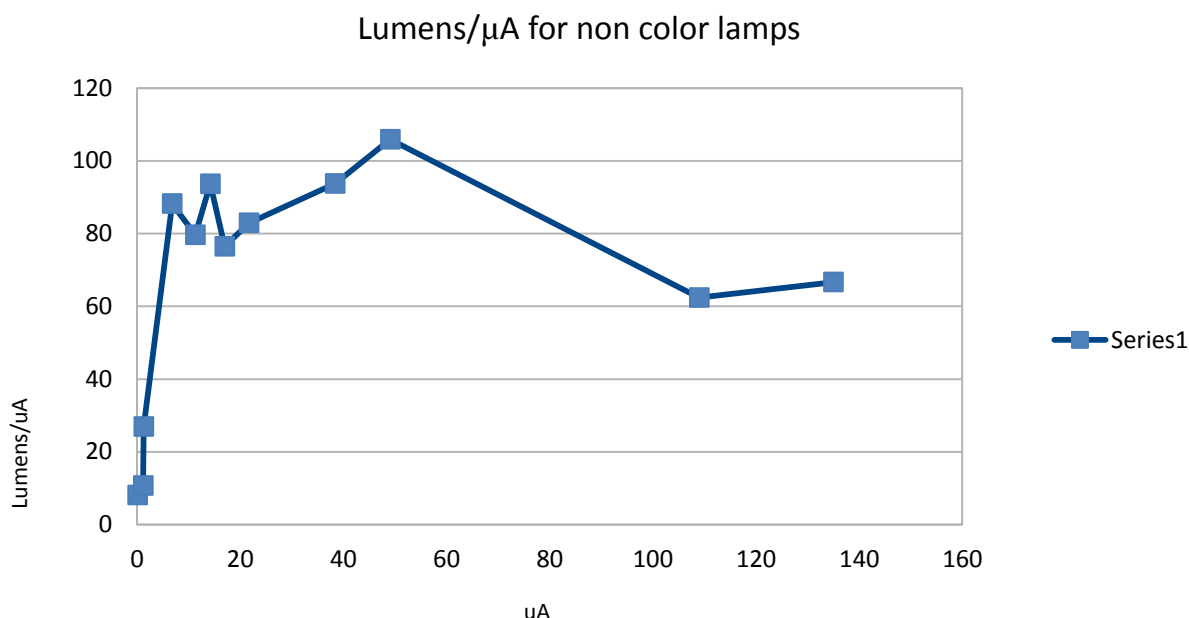


Figure 5: Scale factor with revised selection of lamps

3.4 Spatial uniformity

A single 10 W LED spot lamp was rotated around the centre axis of the sphere and the photometer current noted. The results are shown in Table 3.

Table 3: Spatial non-uniformity

Elevation	Azimuth			
	0°	90°	180°	270°
0°	5.8	5.4	5.3	5.3
+45°	5.7	5.4	5.4	5.3
-45°	5.2	5.3	5.6	5.4
+90°	5.5	n/a	n/a	n/a
-90°	5.5	n/a	n/a	n/a

The photometer current ranged from 5.2 to 5.8 μA . This translates to a flux range of 468 to 522 lm or a maximum variation of 5.5%. A measure of spatial non-uniformity are essential when comparing sources of disparate dispersion angles.

3.5 Sources of error

The numerous sphere compromises and sources of error necessitate attention to detail during measurements. To illustrate this point; fluorescent lamp end blackening violates direct substitution due to increased lamp absorption [6]. The test officer must be aware that changes in atmospheric conditions, variations in electrical power and lamp chemistry can contribute to errors. Sources of error include [2,10,11]:

- New lamps should be seasoned for 5% of their rated life.
- A statistical analysis of a large number of samples is imperative for accuracy.
- The ambient temperature in the laboratory should be controlled to $25\pm 1^\circ\text{C}$.
- Temperature within the sphere must be monitored due to its effect on both the photometer head and the source.
- The mains power must be monitored and controlled.
- The baffle shape should be optimised for every source's geometry.
- Humidity must be controlled as moisture affects the reflectance of the barium sulphate sphere paint.
- Exposure to radiation changes both absorption and transmission causing filter fade.
- Sphere dirt changes spatial uniformity.
- Detector hysteresis; overloading may cause temporary or permanent changes.
- The effects of gravity on incandescent and fluorescent lamp orientation.
- Sphere off-axis response; exact placement within the sphere should be repeatable.
- Stabilisation of light source may take up to 30 minutes.

4. Relative flux measurements

4.1 Luminaire efficacy and self-absorption

A common bulkhead type luminaire fitted with 2 x 9 W CFL lamps with switch start ballast was used to analyse luminaire efficacy and self-absorption. Input power, voltage, current, power factor and power were also monitored. The manufacturer's quoted flux output for these lamps is 600 lm. Initially, a single 9 W lamp was suspended in the sphere alone, *i.e.*, no luminaire, in order to calibrate further measurements. Measurements (current in μA) were taken after the lamp output had stabilised. The

white backing plate was then introduced into the sphere to observe the effects of radiation imprisonment followed by the other lamp and then black bulkhead body.

The absorption experiments consisted of assessing the effects of the black bulkhead body inside the sphere in various off-axis positions. The bulkhead housing was introduced into the sphere with the 2 x 9 W lamps affixed to the backing plate. The photocell current dropped from 8.4 μA to 7.3 μA thereby indicating that the bulkhead housing absorbed 14% of the sphere flux - a correction that had to be factored in with the lens measurements.

4.2 Luminaire efficacy

The measured real power consumption of each 9 W lamp was only 8 W. This correlated well with the measured flux per lamp of only 528 lm, or 88% of rated output. Two lamps should therefore produce 1056 lm.

A 100 W incandescent lamp *i.e.*, the auxiliary lamp, was then used to calibrate the effects of backing plate absorption and sphere spatial non-uniformity. The measured photocell current was 14.2 μA for the lamp alone and 13.1 μA after the backing plate was positioned next to the incandescent lamp. This results in a reduction of 8% due to the combined effects of plate absorption and sphere spatial non-uniformity. It was understood that the incandescent lamp spectral response follows a continuum whilst the PL 9 W lamp response is ragged however; experience has shown that this mismatch could only result in some 8% error.

The introduction of the backing plate into the sphere with a single 9 W lamp revealed an astonishing reduction in flux output. Its flux output was reduced from 75% to 80% due to the proximity of the backing plate. This reduction was very sensitive to the relative position of the lamp and the backing plate; the lamp is only supported at its base. It clearly reveals the CFL sensitivity to self absorption and radiation imprisonment.

With both lamps on the backing plate the photocell current ranged from 8.3 to 8.45 μA depending upon orientation with respect to photocell aperture, which implies a total flux of 747 to 760 lm. The results tally well with the expected output due to reduced operating power and proximity to backing plate. The total flux output is a mere 63% of the manufacturer's quoted output flux, *viz.* 1200 lm for both lamps. This bulkhead, without any lens, has a poor luminaire efficacy of 63% and only provides a maximum of 47 lmW^{-1} . These results compare well with published data.

4.3 Lens transmittance

The same bulkhead used in the previous test (2 x 9W CFL lamps) was used to analyse spatial uniformity and lens transmittance. The results are listed in Table 4.

Table 4: Lens transmittance versus orientation

Lens type	0°	90°	180°	270°	Average current	Lumens = 90 x current
none	7.6	7.4	7.5	7.3	7.4	670.5
prismatic	5.4	5.4	5.6	5.5	5.4	492.7
deep prismatic	5.9	6	5.9	5.8	5.9	531
bird's eye	6.2	5.9	5.9	5.9	5.9	537.7
red prismatic	1.5	1.5	1.5	1.5	1.5	137.9
flat opal	4.4	4.4	4.2	4.2	4.3	387
deep opal	4.1	4.1	4.1	4	4.0	366.7

opal dome	5.4	5.3	5.3	5.2	5.3	477
-----------	-----	-----	-----	-----	-----	-----

The bulkhead was suspended in the centre of the sphere and its self-absorption noted (14%). Measurements (current in μA) were taken after the lamp output had stabilised at various orientations with respect to the photocell aperture. After normalising the output (accounting for luminaire self-absorption) the luminaire efficacies are:

Table 5: Normalised luminaire efficacies

Lens type	Normalised lumens	Luminaire efficacy	Luminaire lmW^{-1}
Bare lamps	1056	100%	66
No lens (body only)	765	73%	48
prismatic	562	53%	35
Deep prismatic	605	57%	38
Bird's eye	613	58%	38
Red prismatic	157	15%	10
Flat opal	441	42%	28
Deep opal	418	40%	26
Opal dome	544	52%	34

Note the poor lumen efficacies of this typical bulkhead. The red prismatic lens was included to show that the efficacies monochromatic light sources using fluorescent lamps are extremely low. These measured efficacies compare well with other published data[8,9].

5. Conclusion

Photometry does not carry the *plug 'n play* moniker – careful consideration must be afforded to measurement and result interpretation. At present our results are presently about 10% accurate but experience will certainly improve this figure. Direct substitution is not really useful for commercial luminaire testing and so it is essential to apply accurate correction factors when comparing dissimilar luminaires or light sources.

6. References

1. S.V. Marais, *et al*, "The design of a compact photometer for tubular fluorescent lamps." SANCI Proceedings 1993.
2. C. DeCusatis, "Handbook of applied photometry." 1998, AIP Press.
3. S.T. Henderson and A.M. Marsden, "Lamps and Lighting" Edward Arnold.
4. D.C. Pritchard, "Lighting" Longman 1970
5. R. Grum and R.J. Becherer, "Optical radiation measurements", Academic Press 1979.
6. Illuminating Engineering Society of North America, "IES Lighting Handbook" 1984.
7. International Association of Lighting Designers
http://www.iald.org/userfiles/file/PDFs/DOESSLMaterials/Appendix3_2Measurement.pdf

8. U.S. Department of Energy:

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/luminaire_efficacy.pdf

9. U.S. Department of Energy:

http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/comparing_white_leds.pdf

10. UL University:

http://www.apec-conf.org/2011/images/PDF/2011/Special_Presentations/sp1.2.3.pdf

11. Lighting Research Centre

<http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/directional3.pdf>

CV of Pete Pomeroy

Qualifications:

- National Diploma in Electronics.
- British Institute of Electronic and Radio Engineers Degree.

Work Experience:

ESKOM (5 years) – training on communications.

SA Railways Laboratory (2 years) – conducting acoustics and general research.

Durban Technical College (4 years) – teaching electronics.

Guys Hospital London (2 year) – clinical physics and bio-engineering research.

UEC/ADS Durban (25 years) – design and development of radar and signal processing for military use.

Freelance for various companies (3 years) – Bluetooth and underwater electronics research.

Cosine Developments (5 years) – development and design of lighting products.