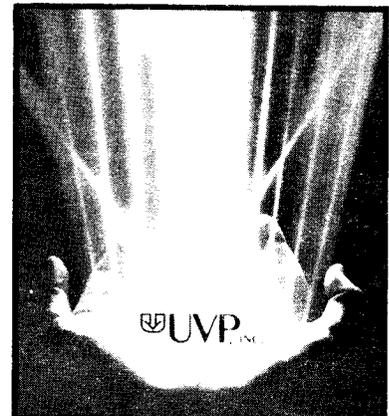


**Guide to Optical
Radiation Measurements**



I. INTRODUCTION

Optical radiation is a difficult multidimensional quantity to measure accurately. State of the art uncertainty ranges from about 1% in the visible and IR to about 3% in the UV at 250nm and about 6% at 200nm (1). This is for the best measurements and is realized only under ideal conditions in a few laboratories. Measurements in the field using different techniques and instruments commonly disagree by 10 to 50% (2). This paper will attempt to explain the major problems associated with optical radiation measurements and guide the reader to more accurate and meaningful measurements. Primary emphasis will be placed on the measurement of irradiance using UVP Inc. UVX Series, J-221, and J-225 Radiometers.

It is assumed that the reader has some familiarity with optical radiation and radiometers.

II. BASIC TERMS (3)

A number of terms commonly used will be defined first:

Incoherent Optical Radiation - Optical radiation whose waves are not in phase in time and space - virtually all optical radiation from non-laser sources.

Irradiance (radiant incidence) - The density of radiant flux incident on a surface. Unit of measure = watts/cm².

Intensity - A shortening of the term radiant intensity. The radiant flux proceeding from the source per unit solid angle in the direction considered. Unit of measure (watts per steradian). This term is often misused for irradiance.

Radiant Flux - The time rate of flow of radiant energy. Unit of measure - watts (joules/second).

Spectral Irradiance - Irradiance per unit wavelength interval.

III. RADIOMETERS

A radiometer is an instrument used to measure the density of radiant flux incident on a surface. This quantity is called "radiant incidence (irradiance)" and is measured in units of power (radiant flux) per unit area, i.e., watts/cm².

Radiometer measurements yield a number, but it should be understood that this number will be completely valid only for a particular type emitter (light source), and for a particular wavelength range, depending on the design and calibration of the radiometer being used. The significance of the radiometer reading depends on important considerations:

- 1) The absolute spectral response of the radiometer; that is, how the radiometer "weights" the different wavelengths of radiation with respect to perfect response and to one another;

- 2) The spectral output of the emitter; that is, the range of different wavelengths of radiation produced by the emitter, and their relative proportions;
- 3) The spatial response of the radiometer; that is, how the radiometer responds to radiation arriving at the sensor surface at angles different from the perpendicular.

IV. INTERACTIONS OF SPECTRAL RESPONSE OF RADIOMETERS AND SPECTRAL IRRADIANCE FROM LAMPS

As discussed above, absolute measurements can only be obtained by using a properly calibrated radiometer. One way to calibrate UV radiometers is to calibrate them against a line source. For example, a radiometer can be calibrated against a 365nm line source so that it gives a direct reading of irradiance from this type of source. A meter calibrated in this way will only give accurate direct measurements of 365nm line sources. Other sources can be measured but the meter reading will have to be adjusted. This is so because the indication of the meter depends not only on the irradiance at the sensor from the source, but also on the interaction of the wavelength distribution of the light source and the meter spectral response.

A "perfect" radiometer would be one responding exactly the same to all wavelengths of radiation in the range of interest and having zero response to all other wavelengths. Real radiometers, however, have a response which peaks at some wavelengths and drops off toward zero away from these points.

The hypothetical radiometer used in the following examples (Figures 1a, 2a, and 3a), has been calibrated to have an absolute response of 1.0 at 360nm. It will respond to 100% of the radiation in the 355 to 365nm range, 60% of the radiation in the 365 to 375nm range, and so on.

Figures 1b, 2b, and 3b are spectral irradiance curves for three different hypothetical UV sources. Figure 1b is a 360 nm line source, Figure 2b is a broad-band source, and Figure 3b is a 380 nm line source.

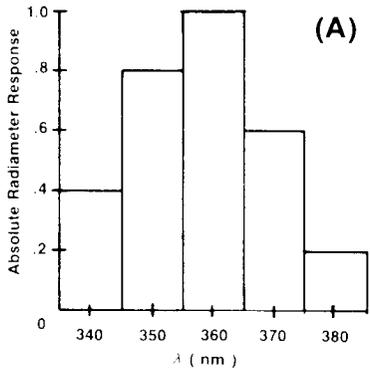
These sources were chosen so that each has a total UV output of 2500 microwatts/cm². This total output is equal to the area under the curve multiplied by the spectral irradiance. Figures 1c, 2c and 3c show how the hypothetical radiometer sensor responds to each of the light sources, based on the radiometer response.

To calculate the meter readings we multiply the lamp output in any wavelength region by the corresponding radiometer response and add the resulting products. This is equivalent to obtaining the following integral:

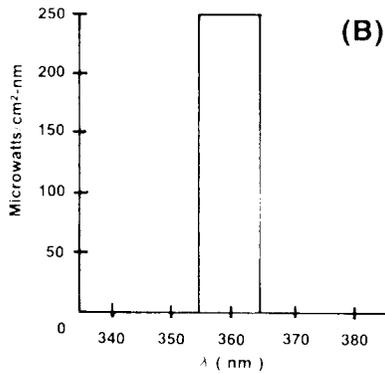
$$\text{Reading} = \int_{\lambda_0}^{\lambda_i} i(\lambda)r(\lambda)d\lambda$$

Where $i(\lambda)$ is the lamp output at the wavelength λ , and $r(\lambda)$ is the response of the radiometer at the same wavelength.

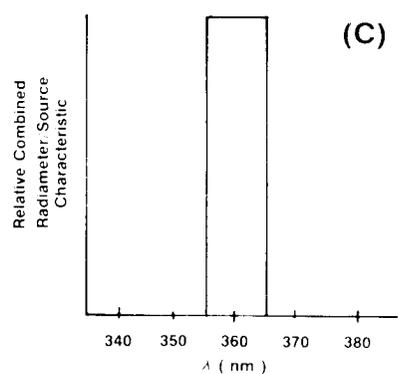
Figure 1.



Response of hypothetical radiometer (line source calibrated at 360nm)



Spectral irradiance from hypothetical 360nm line source.

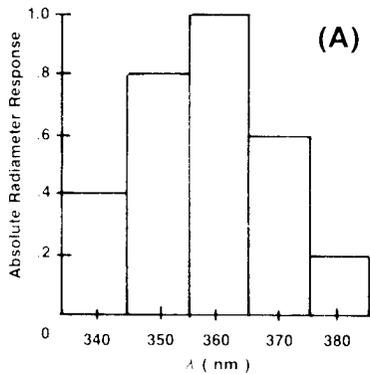


How the hypothetical source and radiometer characteristics combine to produce a reading from the radiometer.

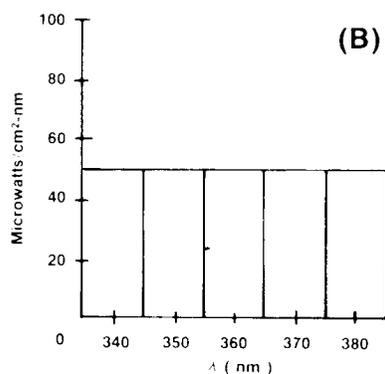
Total source output =
 $(10\text{nm})(250\mu\text{W}/\text{cm}^2\text{-nm}) = 2500 \mu\text{W}/\text{cm}^2$

Radiometer reading = source output at 360nm, times the radiometer response at 360nm -
 $(10\text{nm})(250\mu\text{W}/\text{cm}^2\text{-nm})(1) = 2500\mu\text{W}/\text{cm}^2$

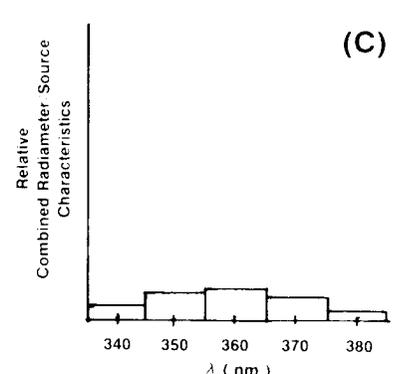
Figure 2.



Response of hypothetical radiometer (line source calibrated at 360nm)



Spectral irradiance from hypothetical broad band source.

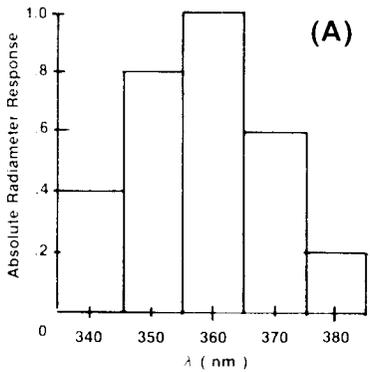


How the hypothetical source and radiometer characteristics combine to produce a reading from the radiometer.

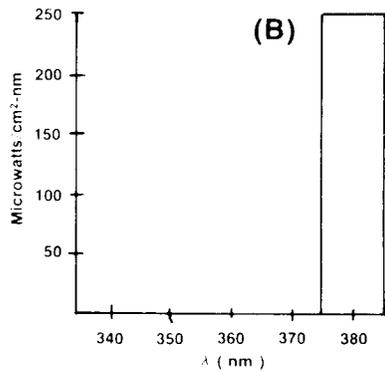
Total source output =
 $(50\text{nm})(50\mu\text{W}/\text{cm}^2\text{-nm}) = 2500 \mu\text{W}/\text{cm}^2$

Radiometer reading = source output for each 10nm bandwidth times the source intensity for that bandwidth times the radiometer response for that same bandwidth. In this case the source intensity is the same for all 5 bands, thus: $10 \times 50(0.4 + 0.8 + 1.0 + 0.6 + 0.2) = 1500 \mu\text{W}/\text{cm}^2$.

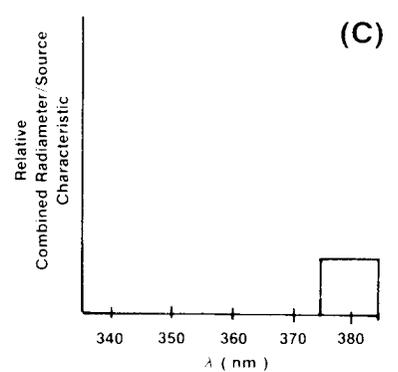
Figure 3.



Response of hypothetical radiometer (line source calibrated at 360nm)



Spectral irradiance from hypothetical 380nm line source.



How the hypothetical source and radiometer characteristics combine to produce a reading from the radiometer.

Total source output =
 $(10\text{nm})(250\mu\text{W}/\text{cm}^2\text{-nm}) = 2500 \mu\text{W}/\text{cm}^2$

Radiometer reading = source output at 380nm, times the radiometer response at 380nm =
 $(10\text{nm})(250\mu\text{W}/\text{cm}^2)(0.2) = 500\mu\text{W}/\text{cm}^2$

The calculations for the three different sources are shown on Figures 1c, 2c, and 3c. Even though all three sources have the same output of 2500 microwatts/cm², the meter readings range from 500 microwatts/cm² for a narrow peak source at 380nm (Figure 3) to 1500 microwatts/cm² for a uniformly broad distribution (Figure 2) to the correct reading of 2500 microwatts/cm² for a narrow peak at 360nm (Figure 1).

If a meter is calibrated to give correct readings with any particular lamp it will not give correct values for lamps with different spectral distributions. However, relative comparisons of lamps with identical spectral distributions of UV light can be made with any stable radiometer, regardless of the calibration method used, as long as the radiometer has sensitivity in the desired wavelength region.

If the spectral response and calibration method of the radiometer and the wavelength distribution of a light source are known, it is possible to calculate correction factors which will allow accurate absolute UV output measurements. The correction factor is defined as follows:

$$\frac{\int_{\lambda_0}^{\lambda_i} i(\lambda) d(\lambda)}{\int_{\lambda_0}^{\lambda_i} i(\lambda) r(\lambda) d(\lambda)}$$

The UVX-36 is calibrated to accurately read the irradiance from 365nm line source (B-100 type) lamps. When it is used to measure the irradiance from a phosphor coated long wave lamp it will read approximately 65% of the true value so that the meter reading should be multiplied by 1/.65 = 1.54 to get the true irradiance.

The J-221 is calibrated to accurately read the irradiance from long wave phosphor coated lamps. If it is used to measure irradiance from a 365nm line source (B-100 type lamp) it will read approximately 35% higher than what the actual irradiance is. To get the true value the reading should be multiplied by 1/1.35 = .74.

V. THE SIGNIFICANCE OF SPATIAL RESPONSE

The number which the radiometer actually reads out will be a function of the spectral response of the radiometer, coupled with the spectral output of the emitter, and taking into account the radiometer spatial response. The term

spatial response is used to describe how completely a radiometer sensor measures energy incident upon it from all directions. The irradiance from a small light source at a point on a sensor surface depends on the angle between the light source and the plane of the surface. If the light source is kept at a constant distance from the surface, the irradiance is greatest when the source is perpendicularly above the point irradiated, and decreases as the angle with the perpendicular is increased. This is so because a unit area of incident light covers a larger area on a plane when it strikes at an oblique angle than when it is perpendicular. Figure 4 shows this in cross section.

In Figure 4 a light beam of dimension d irradiates an area 'A' at normal incidence. If the angle of incidence is θ , the area 'B' irradiated by the same size beam will have a larger area equal to $d \cos \theta$ (cosine theta).

Due to this larger area being covered by the same amount of light, the irradiance of the area will be lowered by the factor $\cos \theta$; i.e., $I = I_0 \cos \theta$, where I is the irradiance at a point on the surface with the light incident at any angle with respect to the perpendicular to that surface and I_0 is the energy of the incident light beam.

A perfect sensor irradiated by a small light source that moves in a semicircle around the sensor (Figure 5) would yield readings which are proportional to the cosine of the angle of incidence θ . This is why the term "cosine response" is frequently used to describe the spatial response of sensors. Figure 6 is the plot of the cosine of the angle vs. the angle, i.e., the curve for a sensor with perfect cosine response.

The spatial response of a radiometer becomes important when measuring the ultraviolet irradiance at a surface near to an extended emitter, such as a long lamp or a bank of small emitters. This means that all sensors will give accurate measurements for point sources or for sources that are small in comparison with distance, as long as the sensor is oriented correctly. All the sensors will give low measurements when used to measure extended light sources at relatively small distances, and the error will be greater for the sensors deviating the most from a perfect cosine response.

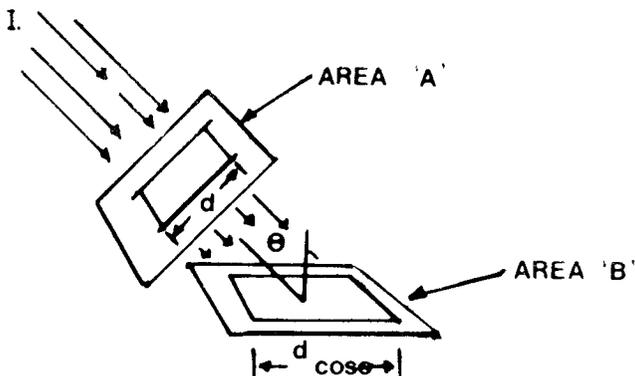


Figure 4.

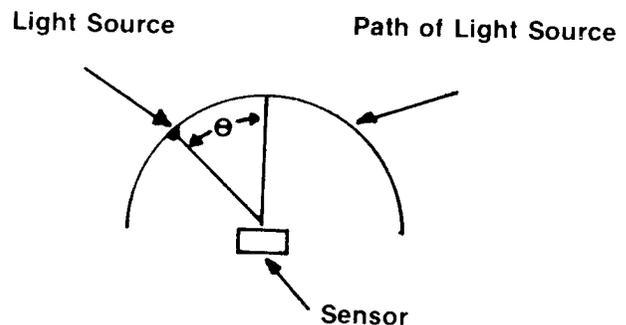


Figure 5.

An example of this seen in actual practice is the use of the UVX-25 to measure 254nm radiation from a 30 watt germicidal lamp. The UVX-25 sensor is designed and calibrated to measure 254nm radiation from low pressure mercury arc lamps. Since the 30 watt germicidal lamp is precisely this type of emitter, there should be no complexities involving the spectral characteristics of either the lamp or radiometer. However, the 30 watt lamp is 36 inches long, which means that measurements close to the lamp will make the spatial response of the sensor important. Two cases will be considered: a measurement 3 inches from the center of the tube, and another 20 inches from the center of the tube.

Integrating the spatial response function coupled with the appropriate inverse square dropoff of irradiance with distance shows that at three inches from the lamp, the UVX-25 will read about 10% low due to the difference between the spatial response of the UVX-25 and ideal cosine response. At the distance of 20 inches, however, the error due to spatial response will be less than 1%. It should be noted here that the spatial response of the UVX Radiometer is a much better approximation to ideal cosine response than that of some other radiometers on the market, and that greater spatial response errors will be encountered when making measurements close to extended sources with those radiometers.

SENSOR RESPONSE VERSUS INCIDENCE ANGLE

SENSOR MODEL NO.	
SERIAL NO	
REPORT DATE	
OPERATOR	

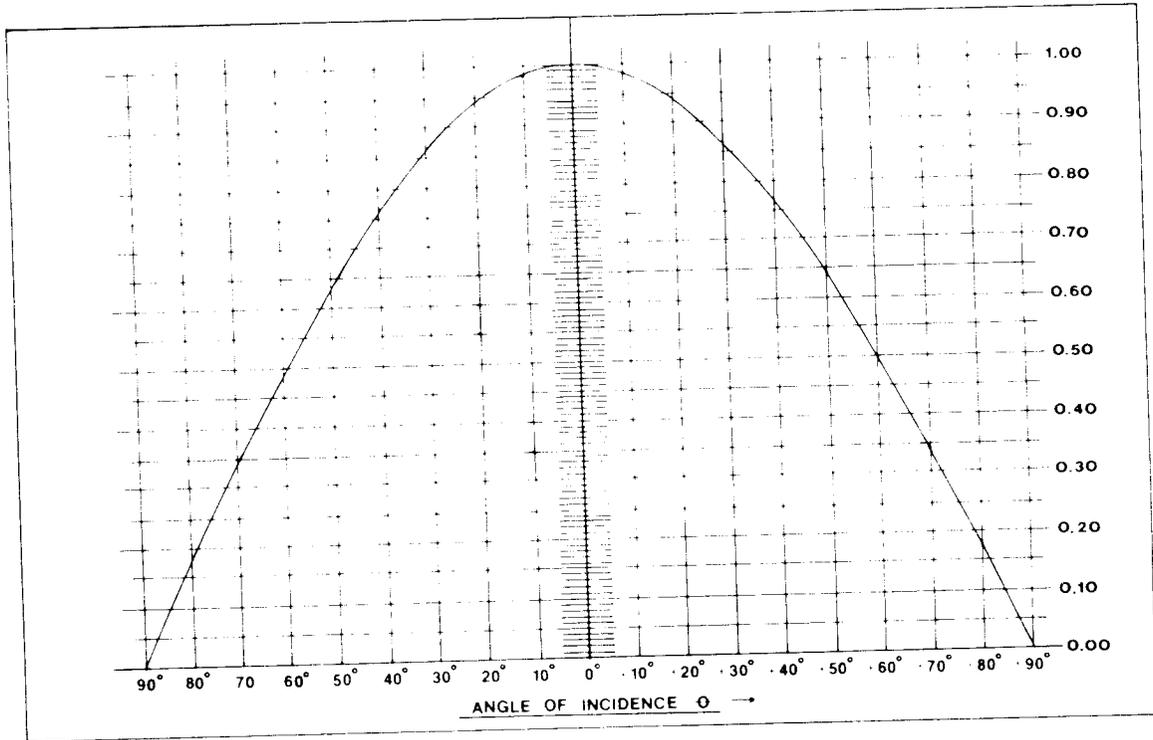


Figure 6.

VI. CONCLUSION

To accurately measure ultraviolet radiation with any radiometer it is necessary to pay attention to the spectral and spatial characteristics of the radiometer's response and to the spectral output of the ultraviolet emitter. Special caution should be exercised when measuring an ultraviolet source for which the radiometer is not specifically designed and calibrated.

VII. REFERENCES

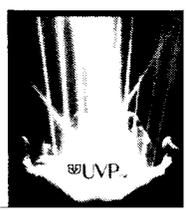
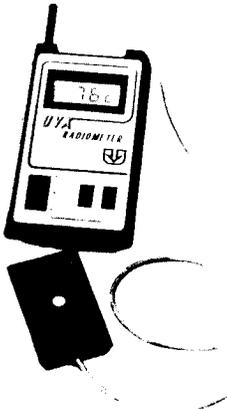
Information for this guide was obtained from papers written by E. Miller formerly of UVP, Inc. and C. Lewis of UVP, Inc. and from the sources below:

- (1) Self Study Guide On Optical Radiation Measurements
- Nicodemus & Kostkowski, NBS
- (2) Uncertainties In The Measurement of Incoherent Optical Radiation
- Kostkowski, NBS
UVX Radiometer Manual
- L. Brady, UVP, Inc.
- (3) IES Lighting Handbook
- 1981 Edition - Kaufman & Haynes.

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