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USAARL Guide for Making Laboratory Light Measurements

By

Clarence E. Rash
Ellen H. Snook
Patricia M. Senn
Everette McGowin III

Sensory Research Division
Visual Sciences Research Branch

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ROGER W. WILEY, O.D., Ph.D.
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This report provides the basic information required to perform routine light measurements encountered in the laboratory environment. Tutorial discussions are provided in identifying the type of measurement required, selecting the appropriate instrument(s), performing the measurement, minimizing errors, and reporting the data. Appendices provide lists of the light measurement instrumentation and light sources available within USAARL, with a summary description of each. In addition, safety steps for the prevention of personal injury and equipment damage are presented.

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Introduction

The objective of this manual is to provide the basic information required to perform light measurements encountered in the laboratory environment. Typically, laboratory measurements are performed on ambient room lighting from incandescent or fluorescent bulbs, computer or television monitors, or lighted displays. The primary step in making light measurements is identifying the type of measurement required. The section on "Identifying the measurement task" will list and discuss the typical light parameters measured in the lab. After defining the measurement of interest, the appropriate instrument(s) must be selected in order to collect reliable data. The section on "Selecting the light measurement instrumentation" will describe the most common laboratory light measurement instrumentation and their capabilities and limitations. Basic procedures for making the measurements will be presented in the section "Making the measurement." The section on "Sources of error in light measurement" will discuss some common measurement errors and provide recommendations for avoiding them. Finally, the section on "Reporting the data" will give guidance on selecting the correct units of measure and provide techniques for presenting the data. Appendices A and B provide a list of the light measurement instrumentation and light sources available within USAARL, with a summary description of each. Most importantly, before beginning any measurement, safety must be considered in order to prevent personal injury or equipment damage.

This manual is intended as an introduction to general light measurement techniques. Questions or problems relating to specific or unusual experimental setups should be directed to investigators within the Visual Sciences Branch of the Sensory Research Division.

An excellent user oriented reference on lighting and light measurement is the IES Lighting Handbook, published by the Illuminating Engineering Society of North America.

Safety precautions

Although the human eye can only "see" energy in the visible part of the spectrum, which is typically defined to be between 380 and 730 nanometers (nm), it is capable of absorbing light energy over the entire electromagnetic spectrum (Figure 1) from ultraviolet (UV) to infrared (IR). Individual parts of the eye, e.g., cornea, lens, ocular media, and retina have different absorption characteristics which are depicted in Figure 2. Energy in the visible and near-IR wavelengths (between 380 nm and 1.4 microns) passes through the cornea, lens, and ocular media of the eye to the back surface called the retina. On the retina, this light energy is converted into an electrical signal and

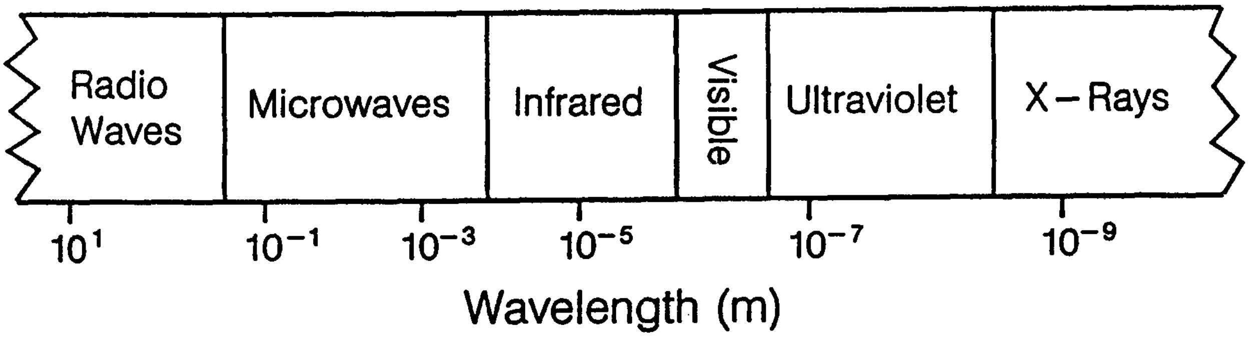

Figure 1. The electromagnetic spectrum.

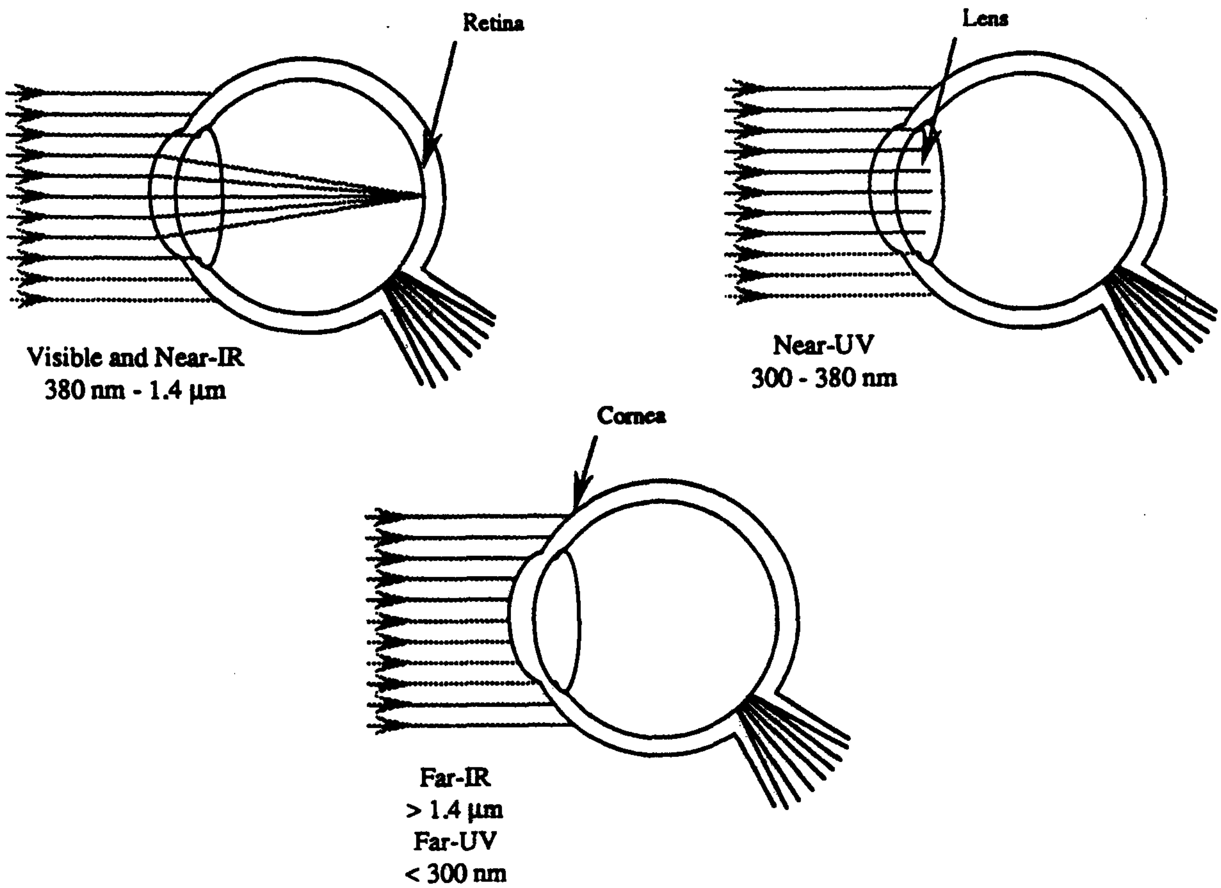

Figure 2. Energy absorption characteristics of the eye.

transmitted to the brain. Due to focusing of light by the eye's lens, very high intensity visible light, e.g., sun, arc lamp, etc., may damage the retina, and light in the near-infrared wavelengths (750 nm to 1.4 microns) can cause severe retinal burns. This can result from gazing directly at high intensity sources without proper eye protection to reduce the energy which falls upon the retina. Light energy in the near-ultraviolet (UV) wavelengths (300 to 380 nm) does not reach the retina because it is absorbed by the lens of the eye. Unprotected exposure to energy in these wavelengths can result in cataracts or other opacities in the lens. Energy in the far-UV wavelengths (less than 300 nm) and far-infrared (IR) wavelengths (greater than 1.4 microns) can cause damage by thermal processes that overheat the tissue when absorbed by the cornea. Therefore, when working with high intensity light sources such as lasers, arc lamps, high wattage incandescent lamps, and any device which may reflect such energy (mirror, lenses, etc.), extreme caution should be exercised and proper eye protection should always be used.

In the same way that the human eye contains a sensitive energy detector (retina), so do light measurement instruments. Therefore, it is necessary to protect instrument detectors from damage as one would protect the eyes. Never exceed the recommended maximum power input to the instrument, and use proper filters to protect the detectors when sources are high in intensity. All measurements should begin with internal or external filters in the highest density configuration, then gradually decrease the filter density until optimum sensitivity is attained.

If accidently exposed to excess energy levels, some detectors may be permanently damaged. However, others only may be temporarily affected. If this occurs, it may "recover" over a period of several minutes to several days.

The operating manuals for light sources and light measuring instrumentation should be consulted for specific safety concerns.

Identifying the measurement task

The first step in any light measurement is to identify the measurement task. A measurement of total energy over the entire electromagnetic spectrum (UV to IR) can be made of light emitted or reflected from a light source or of light falling upon the surface of an object. In the same respect, a measurement of total energy over that part of the spectrum detectable by the human eye (visible energy) can be made. Each of these measurements of total energy are a summed value over the respective ranges of the spectrum. Additionally, a measurement of energy present at individual wavelengths within the spectrum can be made for light emitted from a source or falling upon the surface of an object. For materials such as filters, which allow light energy to pass through, measurements of total energy and energy present at individual wavelengths can also be measured. Color is an additional characteristic of a light source or filter that can be quantified by a measurement. The orientation (polarization) of light waves emitted by a source can also be measured.

The tasks cited above can be categorized as radiometric, photometric, spectroradiometric, transmittance, color, or polarization measurements. Radiometry involves the measure of total energy typically covering the wavelengths from ultraviolet through infrared. Photometry involves the measure of total energy visible to the human eye. Spectroradiometry is the measurement of light energy at individual wavelengths within the electromagnetic spectrum. It can be measured over the entire spectrum or within a specific band of wavelengths. Transmittance of a material is a measure of the light energy passing through and is expressed as a ratio of transmitted energy to incident energy. The color of a light source or filter is defined by a point in a standard color coordinate system or by a correlated color temperature. Polarization is a measure of the orientation of light waves.

Each of these measurement tasks can be performed in the laboratory. The following sections define specific terminology associated with each task and is intended for assisting the user in determining the appropriate measurement task(s).

Radiance and luminance

If the total energy output of a light source is of interest, then radiance or luminance measurements would be made (Figure 3). Radiance and luminance are two closely related measures; radiance is a measure of the total energy output of a source emitted over the entire spectrum, while luminance is a measure of only the total energy output detectable by the human eye. Consider a common light bulb which emits energy from the ultraviolet through the visible and infrared wavelengths. The radiance measure of the light bulb would include energy in the visible and non-visible (UV and IR) wavelengths of the emitted energy. However, the luminance of the light bulb would include only energy in the visible wavelengths. One common error made in discussing visible energy is the use of the term "brightness" to describe luminance. Luminance is a quantifiable measure; brightness describes how visible energy is perceived. The perception of brightness can vary from one observer to another.

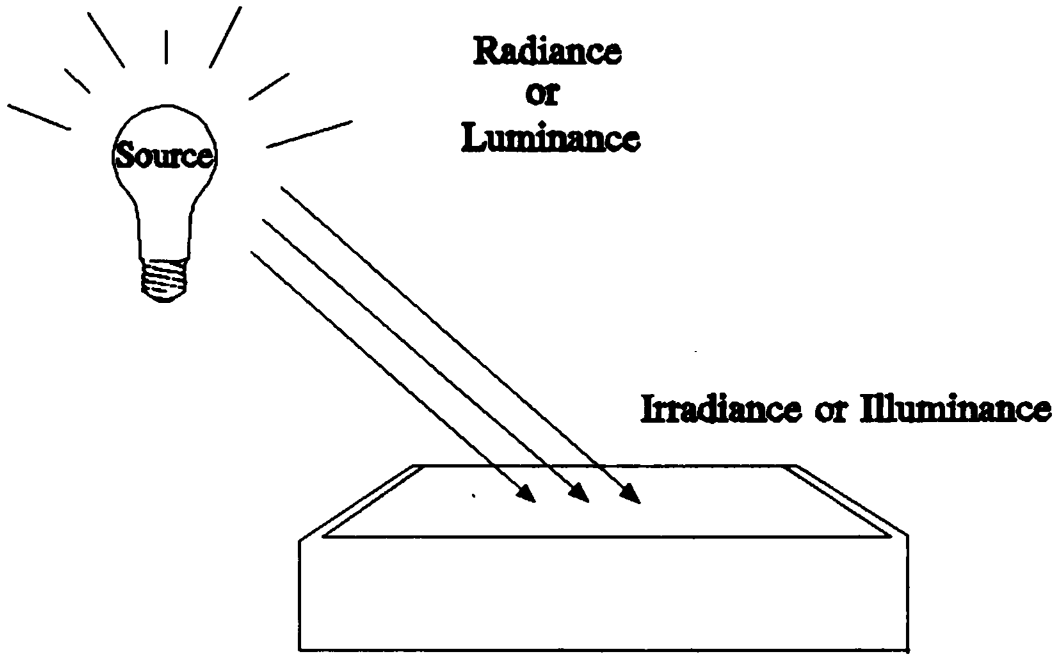

Figure 3. Relationship between radiance, luminance, irradiance, and illuminance.

Irradiance and illuminance

When the amount of light energy falling upon an object is of interest, then irradiance or illuminance (Figure 3) measurements should be made. Irradiance and illuminance are related in much the same way as radiance and luminance. Irradiance is a measure of the total energy falling upon an object's surface; illuminance is a measure of only the visible energy falling upon the same surface. Using the common light bulb as mentioned above, consider the light as it falls on a surface such as a desk top. The irradiance measure of the light energy falling upon the surface would include the visible and non-visible (UV and IR) energy. The illuminance measure would include only the visible energy falling upon the surface.

Spectral radiance

The radiance or luminance of a light source is a single value which is the sum of all energy measured over the respective spectra. If the individual energy values at particular wavelengths are of interest, then a spectral radiance measurement would be made. Spectroradiometry is the measurement of the energy of a source as distributed over the wavelengths in the electromagnetic spectrum. Figure 4 depicts the energy output of a common light bulb (tungsten filament source) over the spectral range from 390 to 950 nm. Using this plot of the spectral radiance measure, an energy value at a particular wavelength can be determined.

Contrast

When two or more adjacent areas have different luminance values, the human visual system will distinguish between them on the basis of their relative luminance. This relative luminance is defined as the contrast between the areas. By convention, the two areas are labeled as target and background, where the target is the smaller area. These labels are very convenient when the desired contrast measurement involves alphanumeric characters or symbols on a chart or display.

Several methods of calculating the contrast value are in common use. The simplest method is the contrast ratio, which by definition is the ratio of the target luminance (L_t) to the background luminance (L_b):

$$C_r = L_t/L_b \ .$$

The contrast ratio can take on values from 1 (when the target and background luminances are equal) to infinity as the target luminance increases with respect to the background.

A second method of expressing contrast is:

$$C = (L_t - L_b)/L_b \ ,$$

where the target luminance (L_t) is assumed to be greater than the background luminance (L_b). This method of calculating contrast produces a value of 0 when the target and background luminances are equal. As the target luminance increases with respect to the background, the contrast values increase towards ∞. For targets having luminances less than the background, this formula for calculating contrast is changed to:

$$C = (L_b - L_t)/L_t,$$

and can take on values of 0 to 1. These two formulae are often used when defining the contrast of a real scene where the relationship between the background and target is known. In situations where the background and target cannot be distinguished, a third contrast expression, referred to as modulation contrast, should be used. Modulation contrast is most often used for periodic patterns such as gratings.

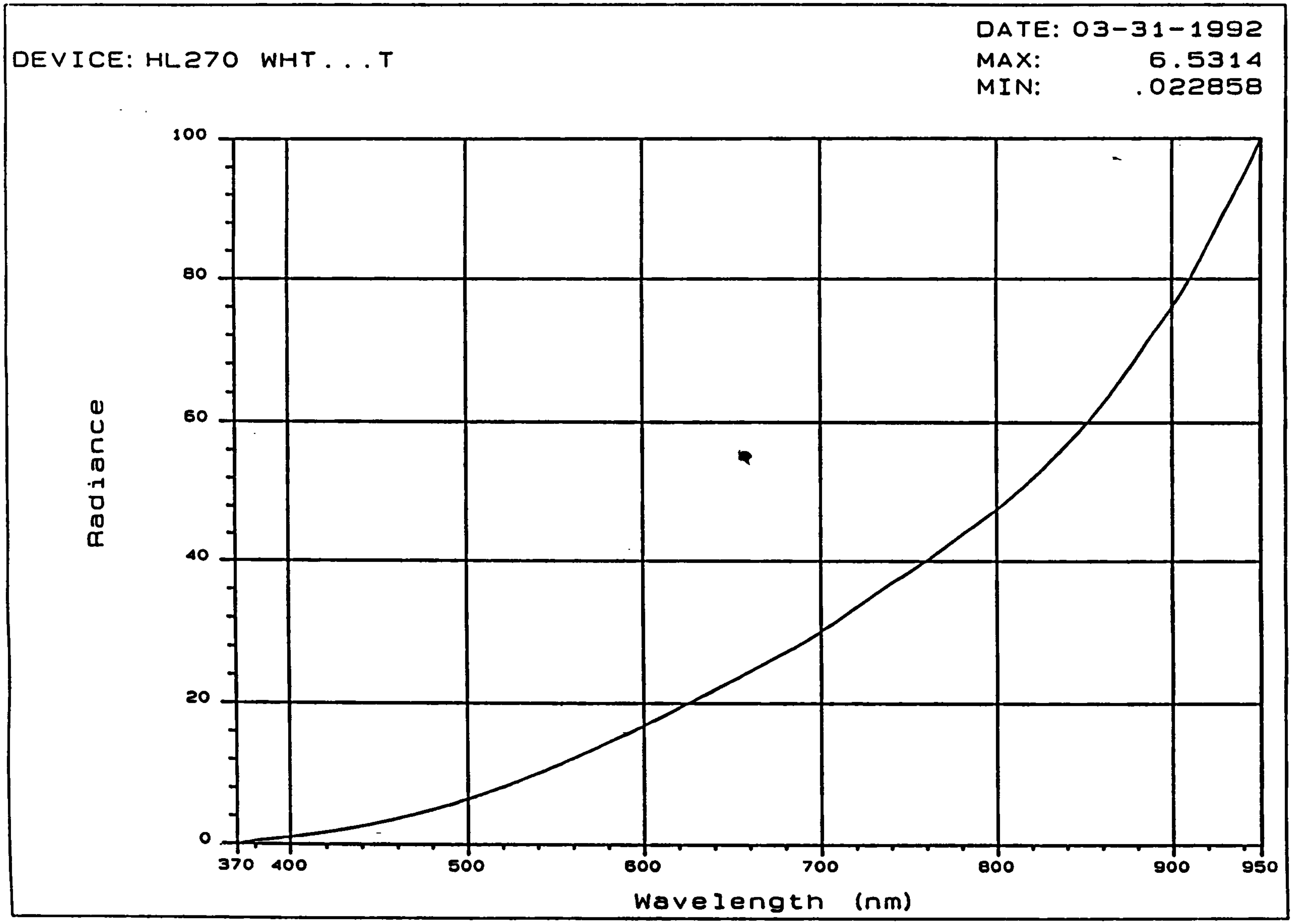

Figure 4. Spectral distribution of a tungsten filament source over the range from 370 to 950 nanometers.

Contrast modulation is defined as:

$$C_m = (L_{max} - L_{min})/(L_{max} + L_{min}),$$

which can take on values of 0 to 1.

Transmittance

It is often desirable to measure the amount of light energy transmitted through an optical material, e.g., glass, plastic, etc. The ratio of the radiant power transmitted through a material to the incident radiant power from the source is a value called the transmittance. A measure of only the visible energy transmitted is referred to as luminous transmittance. Luminous transmittance can be classified further as photopic or scotopic transmittance. These values refer to the luminous transmittance as measured for the "day" and "night" responses of the eye, respectively. Transmittance of a filter may also be expressed as a function of wavelength, which would be referred to as spectral transmittance.

Color

Color is a characteristic of light determined by its spectral composition and the properties of the human eye. Because color is perceived differently by each individual, a system for color standards was developed. There are many standards by which to evaluate color (also referred to as chromaticity). Color perception models are based on the theory that the retina of the eye consists of three different color receptors (tristimulus responses). Each receptor responds to specific wavelengths corresponding to blue, green, and red light (Figure 5). Various chromaticity coordinate systems plot the color of a light source as a two-dimensional point on a chromaticity diagram. The two most widely used coordinate systems are the 1931 Commission Internationale l'Eclairage (Commission on Illumination, CIE) and the 1976 Uniform Color Scale (UCS) systems (Figures 6 and 7, respectively). The 1931 CIE coordinate system uses x,y and the 1976 UCS coordinate system uses u',v' as the coordinate variables. Equations exist for converting between these and other chromaticity coordinate systems.

Correlated color temperature

The spectral distribution of tungsten light sources varies as a function of filament current. Therefore, for reproducibility in experiments using tungsten light sources, it is standard procedure to specify the source's spectral energy distribution. One method of standardization is to specify the source's correlated color temperature.

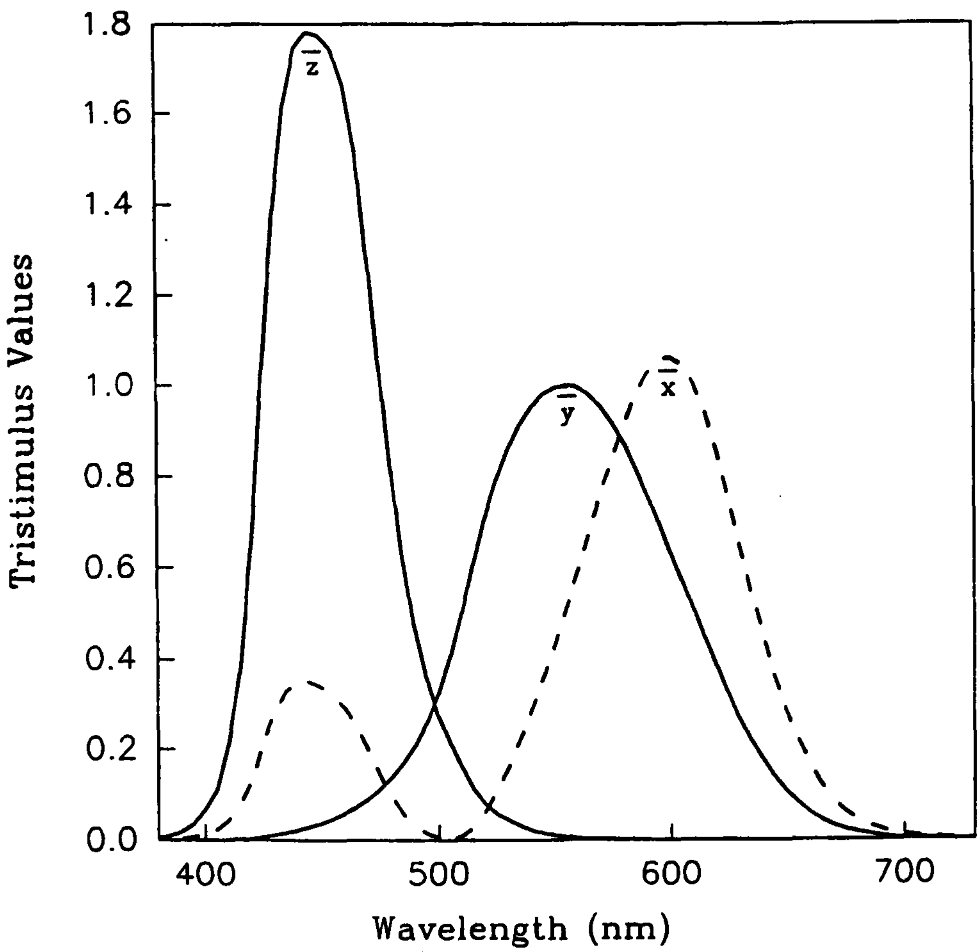

Figure 5. The 1931 CIE tristimulus response curves.

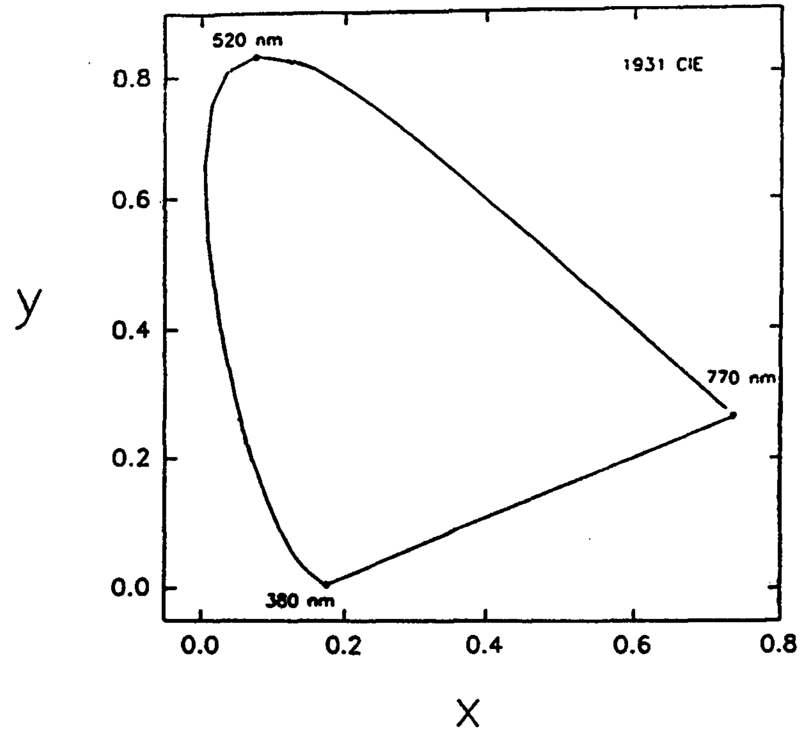

Figure 6. The 1931 CIE chromaticity diagram.

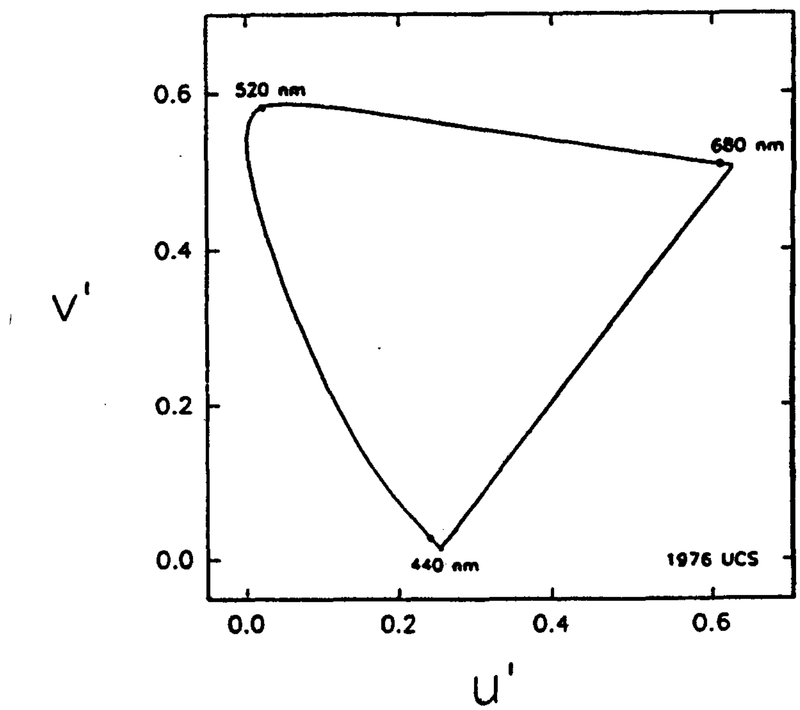

Figure 7. The 1976 UCS chromaticity diagram.

The correlated color temperature of a source is determined by comparing its spectral radiance curve to a set of theoretical curves known as the blackbody spectral emittance curves. All objects, when heated, emit a continuous spectrum of radiation. The emitted spectrum is dependent on temperature of the source as well as the composition of the object. A blackbody radiator is a theoretically ideal emitter of uniform temperature whose radiant emittance in all parts of the spectrum is the maximum obtainable from any radiator at the same temperature. The physicist Max Planck proposed an empirical formula which described all features of the blackbody radiator as a function of wavelength and temperature. When plotted for different temperatures, the blackbody curves appear as shown in Figure 8.

If the spectral distribution of a heated material can approximate a blackbody spectral emittance curve, a correlated color temperature for the source can be determined. This temperature will be that of the blackbody curve which most closely corresponds to the source curve. For example, the spectral distribution curve of a tungsten source is similar to a blackbody spectral emittance curve so that a correlated color temperature can be determined by matching curves. On the other hand, light emitting diode (LED) sources have narrow band spectral emittance curves which cannot approximate any blackbody curve and therefore have no correlated color temperature. Sources such as these are considered non-Planckian.

Polarization

One property of light sources which is often overlooked is polarization. Light is an electromagnetic wave with associated electric and magnetic fields which oscillate as the wave propagates through space. If the electric field always oscillates in some fixed direction, the wave is said to be linearly polarized in that direction. The associated magnetic field is always perpendicular to both the electric field and the direction of wave propagation. Therefore, the magnetic field also oscillates in a single direction. By convention, the polarization of a wave refers to the orientation of the electric field vector. Unpolarized light consists of electromagnetic waves that have transverse vibrations of equal magnitude in an infinite number of directions. Figure 9 depicts an unpolarized light beam as it strikes a vertical polarizer; only light parallel to the polarization axis is transmitted. When the resulting vertically polarized beam then encounters a horizontal polarizer, no light energy is transmitted.

Most common light sources such as the sun, incandescent lamps, and fluorescent lamps produce unpolarized light. However, this light can be polarized by absorption, scattering, or reflection and refraction of the transmitted waves.

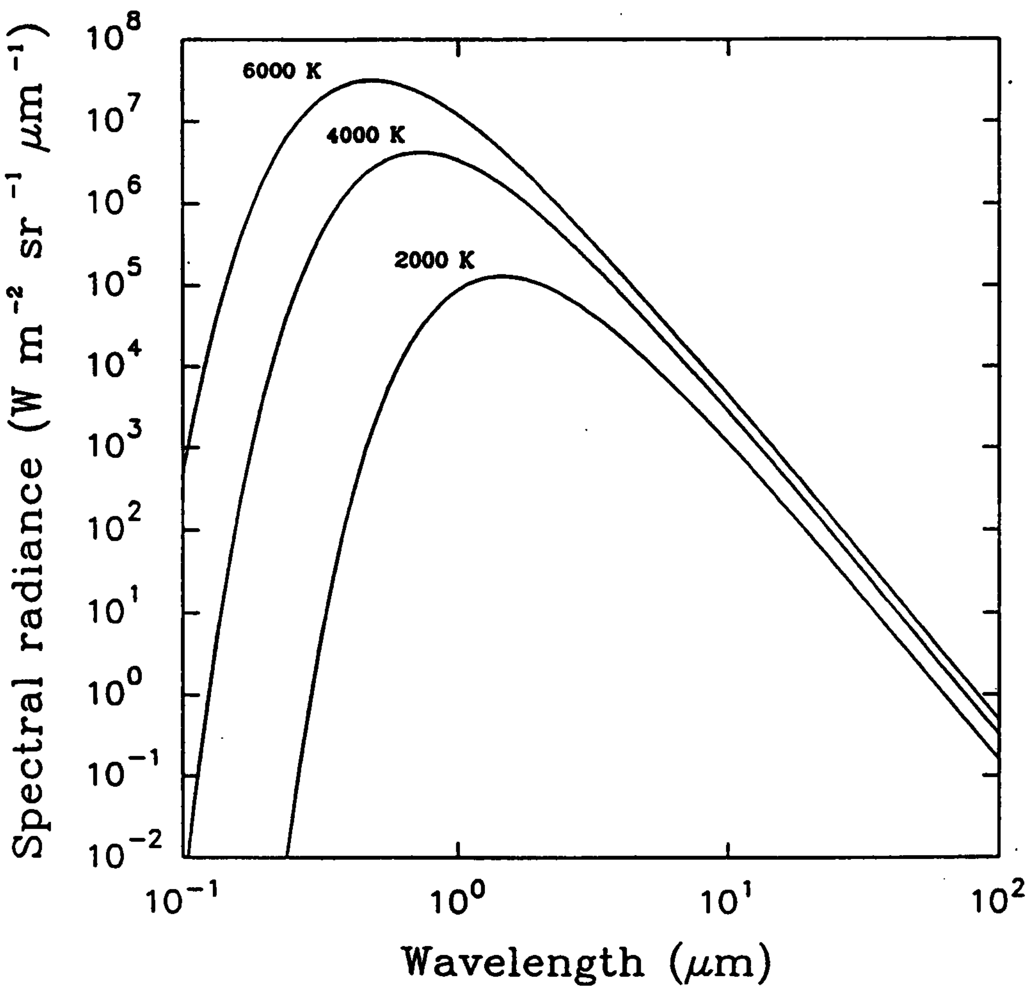

Figure 8. Plankian blackbody radiation curves.

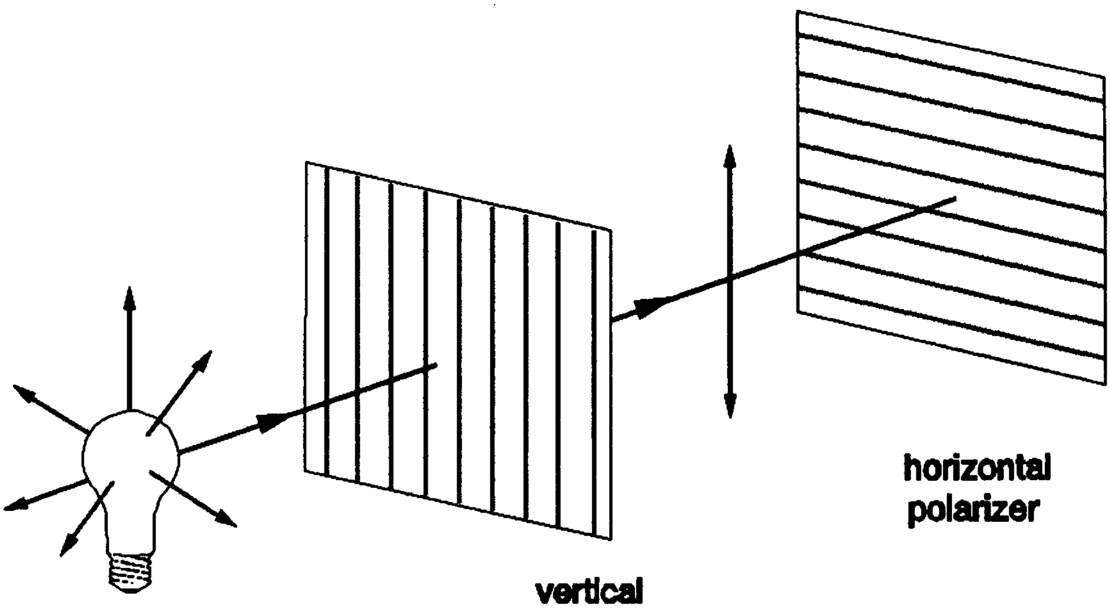

Figure 9. Illustration of polarization.

Absorption is achieved through the use of polarizing filters which absorb light waves propagating in all but the direction of polarization, e.g., horizontal or vertical. A high percentage of polarization can be obtained by this method, but at a loss of luminous transmittance.

Scattering of sunlight within the atmosphere results in polarization. On a clear day, light in the sky is partially polarized by dust particles in the air. This effect can be demonstrated through the use of a polarizing analyzer (a pair of polarizing filters). As the sunlit sky is viewed through the rotating end of the analyzer, the transmitted light intensity will vary markedly.

Light may be polarized when reflected from or refracted through ordinary materials such as glass or water. Generally, light is only partially polarized upon reflection and refraction, but may be completely polarized if the conditions are just right. The degree of polarization depends upon the angle of incidence of the light and the indices of refraction of the media on either side of the reflecting or refracting surface.

Temporal characteristics

Light sources can be described by the temporal characteristics of their luminous output. Most sources have a uniform output (luminance) over a time period. Other sources have outputs which vary with time, but appear to the eye as constant, e.g., cathode ray tube displays (CRTs). And some sources, such as flashing lights, display visually apparent changes in luminance as a function of time. Less common sources exist which produce only a single pulse of light energy.

Any source which changes its output periodically over time can be associated with a frequency. This frequency defines how many times within a certain time period the light undergoes its variation in luminance. In turn, this frequency is associated with a time period between each maximum (or minimum) output value. This period, expressed in seconds or milliseconds, is referred to as the time constant of the source.

All sources have a time constant. Uniform sources, which have a frequency of zero, have an infinite time constant value. Sources with short time constants (as compared to the human eye) are seen as steady sources, while those with relatively long time constants are seen as flashing sources. For the short time constant sources (e.g., CRTs and office fluorescent lamps), the eye responds only to their average "brightness." On the other hand, the output of long time constant sources such as strobe lights appears as distinct flashes. The time constant of a light source is an important factor when luminance measurements are being made.

Selecting the light measurement instrumentation

Having determined the type of measurement desired, the next step is the selection of the appropriate measurement instrumentation. The simplest approach is to select the instrument which allows the most direct determination for the desired type of measurement. Luminance measurements are most easily performed with a photometer. However, the luminance of a light source can be calculated from spectroradiometric data. This spectral distribution requires the use of a spectroradiometer. Color can be measured directly with a specialized color meter (chroma meter), or indirectly using a photometer (with color filters) or a spectroradiometer. Illumination measurements are generally performed using illumination meters. However, photometers can be used to measure the effective luminance of the illuminated surface, from which the illumination can be calculated.

Tables 1 and 2 provide a list of light measurement instrumentation, light sources, and accessories currently available within USAARL. Table 1 also indicates which types of measurements each instrument can be used to perform.

Table 1.

Light measurement instrumentation

	EG&G Gamma digital spectral scanning system	Photo Research PR 710 Spectrascan fast spectral scanner	Photo Research 1980A photometer	Photo Research 1980A-PL photometer	Photo Research LiteMate III photometer
radiance	x	x	x	x	
anvis radiance	x				
spectral radiance	x	x			
luminance	x	x	x	x **	x
irradiance			x	x	
illuminance			x	x	x
correlated color temperature	x	x			
chromaticity	x	x	x *	x *	
polarization			x	x	

	Photo Research Spectra spot meter	Photo Research PR 1530 AR NVISPOT meter	Minolta chroma meter	Minolta illuminance meter	Minolta luminance meter
radiance	x *	x			
anvis radiance		x			
spectral radiance					
luminance	x	x			x
irradiance	x *	x *			
illuminance	x *	x *		x	
correlated color temperature					
chromaticity	x *	x *	x ***		
polarization	x *				

* measurable only with accessories   ** pulsed light integration   *** measurable under Illuminant A and C

Table 2.

Light sources and accessories

Light sources:						
	incandescent	EG&G Gamma RS-10 tungsten	EG&G Gamma RS-12 tungsten	Oriel 6325 20 watt tungsten	Oriel 6436 1000 watt, quartz tungsten-halogen	Photo Research PR 2301 tungsten
	ultraviolet	BHK, Inc. Analamp ultraviolet				
	arc	Oriel 6340 point source tungsten arc				
	laser	Melles Griot 5 milliwatt HeNe laser	Melles Griot 2 milliwatt HeNe laser	Oriel 6611 3 milliwatt HeNe laser		
	line emission	Oriel C-13-02 spectral lamps Ar, He, Hg, Kr, Ne, Xe				
	infrared	Oriel 6363 1 - 25 micron infrared				
Filters:						
	neutral density	0.1 - 0.9 (in 0.1 ND steps)	1.0 - 4.0 (in 1.0 ND steps)			
	cut-off	540 nm				
	cut-on	520 nm				
Integrating spheres:		1	2	*for fiber optic input		
	sphere diameter	20.0 cm (7.87 in)	8.0 cm (3.15 in)*			
	entrance port diameter	2.7 cm (1.06 in)	0.6 cm (0.24 in)*			
	exit port diameter	2.7 cm (1.06 in)	1.2 cm (0.47 in)*			

Light measurement instrumentation fundamentals

An understanding of the basic instruments for performing light measurements is essential in preventing mistakes in such tasks. Figure 10 shows a block diagram of a generic light measurement instrument. The basic functional blocks are collection optics, detector (including aperture and filters), amplifier, display, and power supply.

In order to gain a reliable measurement of a source, the light energy of interest must be directed to the detector. The collection optics of an instrument perform the function of focusing the light energy from a source unto the detector.

The detector takes the light energy provided by the collection optics and converts it into an electrical signal. Often the detector is integrated with an aperture and filter (Figure 11). An aperture is an opening which controls the amount of light energy which reaches the detector. Apertures are usually circular, but can be horizontal or vertical slits. The most common filter is the photopic filter. This filter is specially designed such that its spectral transmittance when coupled with the detector's spectral response simulates the response of the human eye. In such cases the detector/filter combination acts as a photometer, measuring luminance instead of radiance. Scotopic filters, which simulate the night response of the eye, are also frequently used. Most photometers have multiple apertures and filters located on wheels which allow convenient user selection. Combinations of apertures and filters allow control over the level of energy entering the detector. This allows measurement of high energy sources which could not otherwise be measured directly.

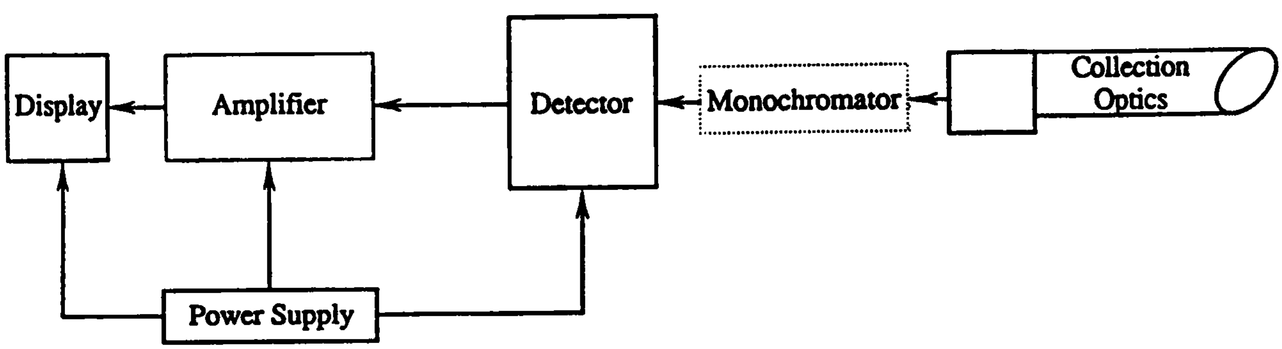

Figure 10. Block diagram of light measurement instrument.

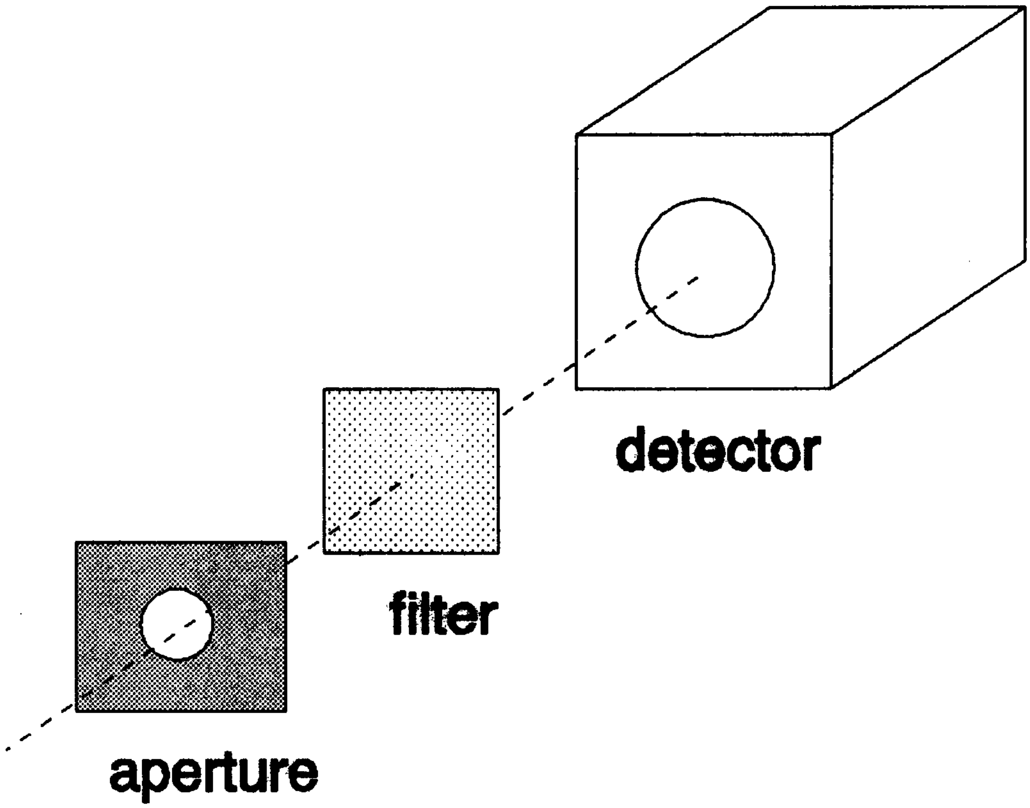

Figure 11. A detector with an aperture and filter.

In spectroradiometry, the amount of light energy as a function of wavelength is measured. To accomplish this, the collected light energy is separated into individual wavelengths (or bands of wavelengths) before being delivered to the detector (Figure 10). This is performed by an instrument known as a monochromater. The resulting output of a monochromater/detector combination is a spectral distribution as depicted in Figure 4.

The amplifier in the system increases the small signal output of the detector to a level which will drive the display electronics.

The display of the instruments can be as simple as a meter needle with appropriate scale markings; or state-of-the-art such as a liquid crystal display (LCD), a light emitting diode (LED) display, or a cathode-ray-tube monitor. Spectroradiometric systems typically are connected to additional output devices, e.g., printers and plotters. With electronic displays, e.g., LCD and LED, the units of measure may be selected. For example, an illumination meter may display its reading in lux or in footcandles. This choice is usually accomplished by means of a switch located somewhere on the meter. The user must be careful in recording the readings in the correct units.

The power supply's function is to provide the necessary electrical power to the other sections of the instrument. The user's concern for this section of the instrument is minimal. An exception may be the use of hand-held instruments. The power supply for most hand-held instruments is one or more batteries. Such instruments may, or may not, indicate a "low battery" condition. The user should always view as suspect unusually low or high readings or readings which do not change with conditions.

Special instrument considerations

Special consideration must be given to the time constant of a light source when selecting the measurement instrument. If the time variation in the source is of interest, the time constant of the detector must be several times smaller than the source's time constant. If the "average" output of the source is of interest, then the time constant of the detector should be several times larger than that of the source. Measurement of the output of sources with a short time period, but which appear constant to the human eye, can be measured with most common instruments. These instruments have a time constant on the same order of magnitude as that of the eye (approximately 20 milliseconds) and measure the "average" luminance of the source. However, for longer time constant sources (those appearing flashing to the human eye), instrumentation with time constants much smaller than that of the source is required. Some instruments have a "pulsed light" or similar measurement mode which allows accurate measurement of pulsed light sources. The Photo Research 1980A-PL photometer is one such instrument which can accurately integrate total light energy in a single pulse or series of pulses for sources with a minimum pulse-duration time of 1.6 to 16 microseconds.

Common and standard light sources

Many laboratory measurements require the use of light sources. These sources may be common in nature, such as the incandescent light bulb, or very specialized, i.e., having required spectral and/or energy content. A class of sources, known as "standard" sources, are available which provide known values of luminance or spectral content. Table 2 lists light sources and accessories available within USAARL.

Common sources of energy emission are divided into two broad categories: continuous emission and line emission. A continuous emission source has some energy present at all wavelengths. A tungsten source is an excellent example of a continuous source (Figure 4). On the other hand, some sources of light only emit energy at discrete or well-defined wavelengths, known as line or discrete emission. A sodium vapor lamp is an example of a line emission source. There are 12 discrete lines between 16 and 819 nm with the two most intense lines at 589.0 and 589.6 nm (Figure 12). Some light sources such as a conventional office fluorescent lamp have a low level continuous spectrum but with a considerable amount of energy at certain discrete wavelengths (Figure 13).

Another type of source is a light emitting diode (LED). The energy emitted from an LED is produced by electrons moving across a junction of semiconductor materials when a voltage is applied to the junction. LEDs produce light in a fairly narrow range of wavelengths (Figure 14). Visible LEDs are often identified by their color, e.g., red, green, yellow, etc.

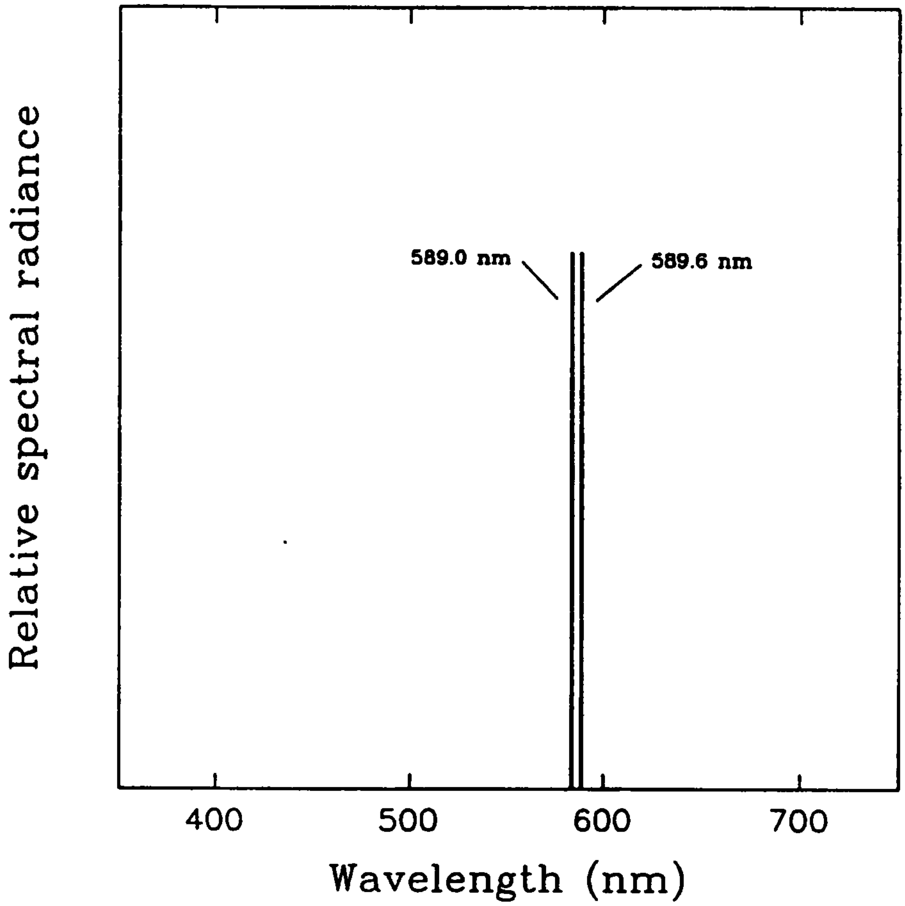

Figure 12. Line emission spectra for sodium vapor gas.

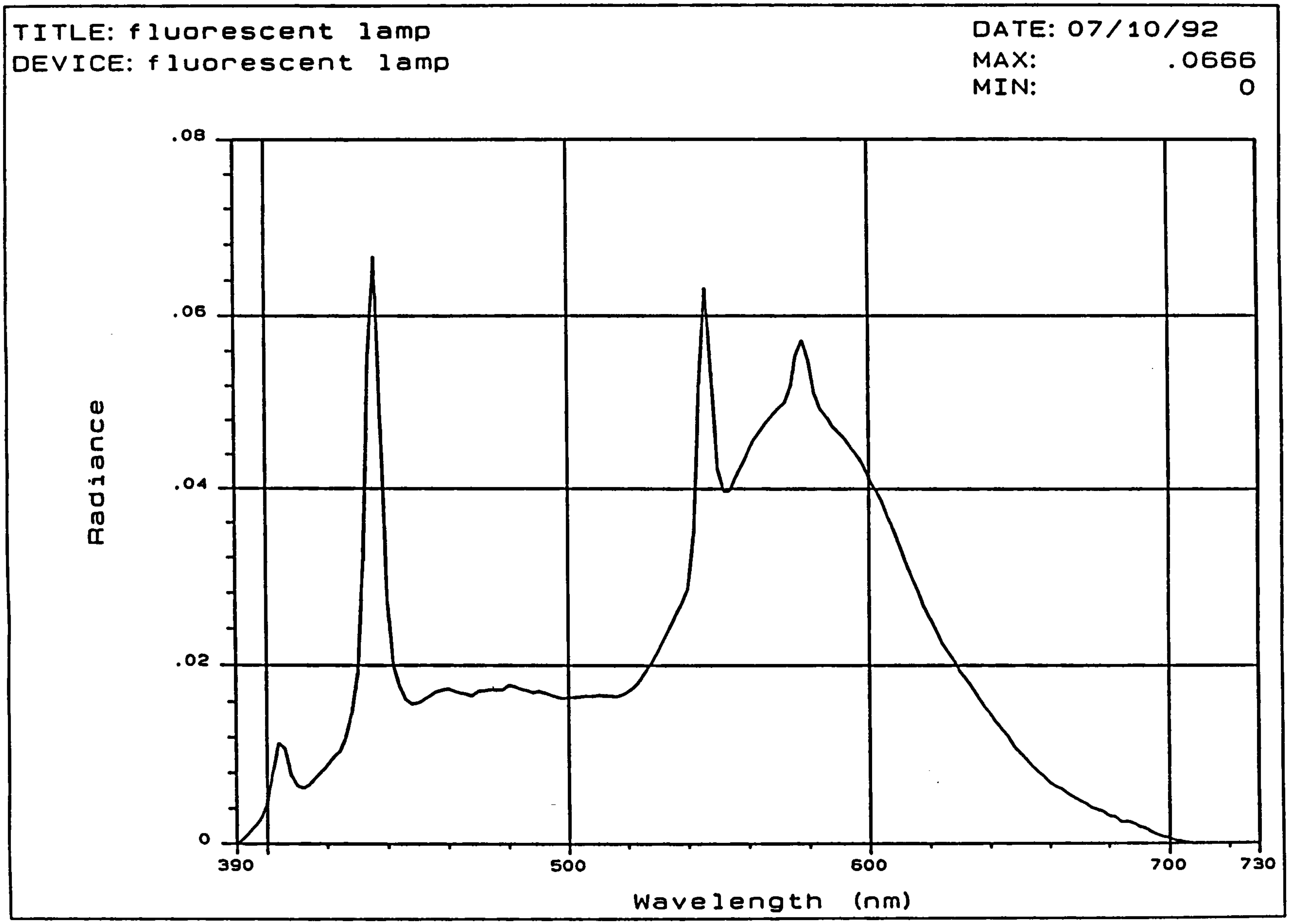

Figure 13. Spectral distribution for fluorescent lamp.

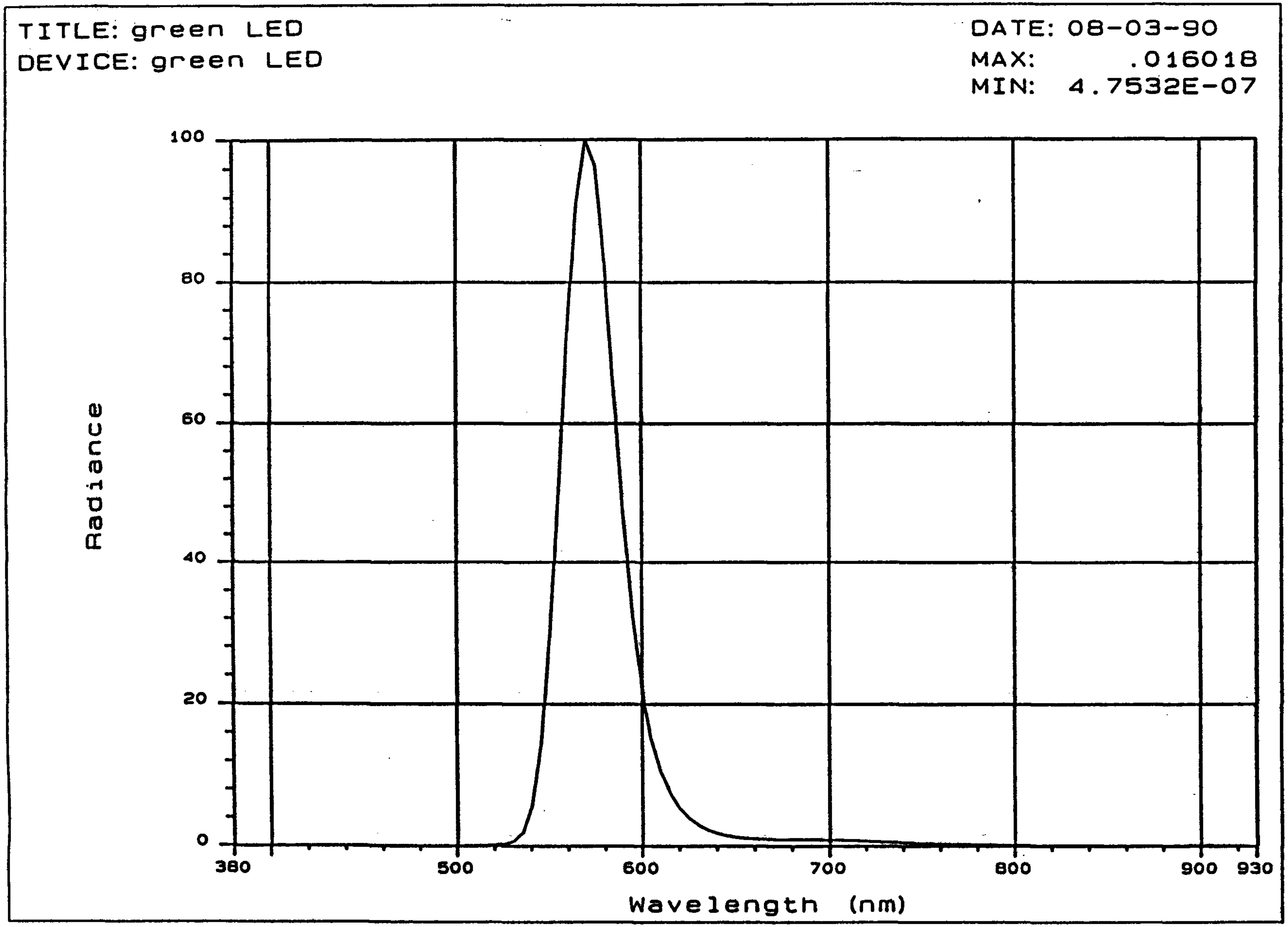

Figure 14. Typical light emitting diode (LED) spectra (green).

Arc lamps are also a common source used in light measurement tasks. An arc lamp is an electric discharge lamp that produces illumination when voltage is applied across electrodes separated by a very short distance. The electrodes are surrounded by a gas mixture which produces a luminous plasma when an electric charge is applied to the electrodes. Arc lamps produce the highest luminance available. Great care should be exercised in protecting the observer and the instrumentation when arc lamps are used. Carbon arcs and high pressure mercury and xenon arcs approach the luminance of the sun and in some cases exceed it.

Lasers (an acronym for "light amplification by stimulated emission of radiation") are another high intensity light source that are commonly used in light measurement. The energy output of lasers is confined within a very narrow band of wavelengths and are often considered to be monochromatic (single wavelength) sources. The most common laboratory laser, frequently used for optical alignment, is a Helium-Neon laser which emits at 632.8 nm (Figure 15). Light from lasers consists of nearly parallel rays and exhibits very little angular divergence. For this reason, they are very intense sources with a large amount of electromagnetic energy concentrated within a small area, even out to moderate distances. As with other high intensity light sources, great care should be exercised in protecting the observer and instrumentation from damage.

A multitude of different sources, mostly incandescent, can be used in the laboratory, all with varying spectral characteristics which can produce different results in distinct circumstances. Due to these differences, a "standard source" was defined by the CIE and is used to facilitate the specification of the spectral composition of illumination. This standard, CIE Illuminant A, is the source that produces a spectral distribution emitted from a incandescent tungsten filament lamp at a color temperature of 2856° kelvin (K). Additional filters are used with Illuminant A in order to obtain other standards of illumination, the most common of which are Illuminants B and C. Illuminant B is used to simulate direct sunlight and has a color temperature of 4870° K. Illuminant C is used to simulate an overcast sky and has a color temperature of 6770° K.

Light sources can also be classified by their geometry: point or extended. Point sources are those having physical dimensions several orders of magnitude smaller than the distance at which measurements are being performed. In such situations, these physical dimensions can be ignored. In comparison, extended sources are those having physical dimensions which are of the same order of magnitude as the measurement distance. The geometry of a source may preclude direct measurement of a particular parameter. In such cases, special formulae may be required to calculate the required data.

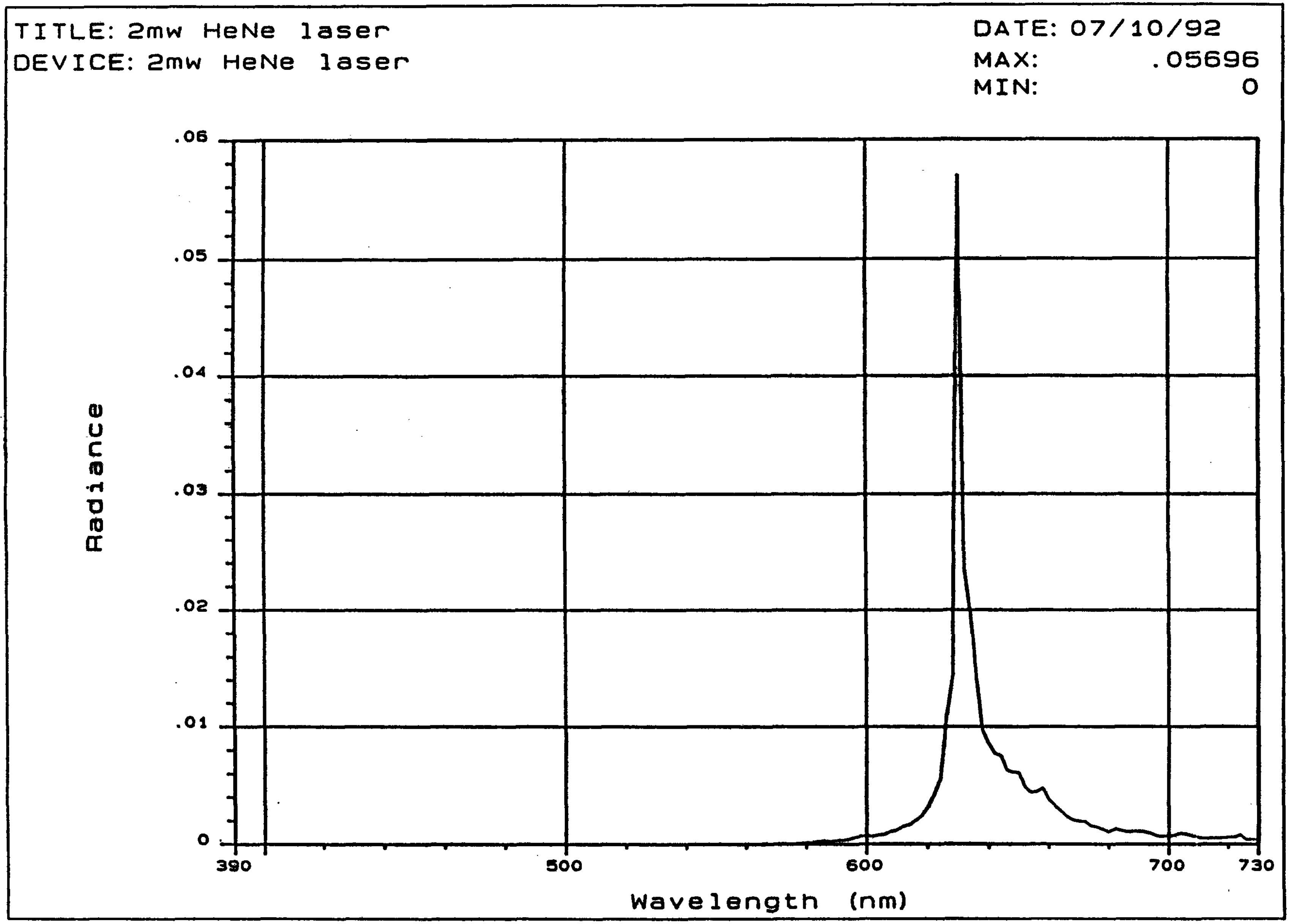

Figure 15. Spectral output of Helium-Neon laser.

Optical accessories

Several accessories may be utilized in performing light measurements. Two such frequently encountered accessories are filters and integrating spheres (Table 2).

Filters

Many experimental setups require modification of the light originating from a source. This modification may be to the radiance (and associated luminance) of the light source or to the spectral distribution. Materials used to achieve these modifications are referred to as filters. Filters are placed between an energy source of known value and the instrument detector. The ratio of the radiant power transmitted through the filter to the unfiltered radiant power from the source is called the transmittance. Filters may be classified as neutral density or spectrally selective.

Neutral density filters are used to attenuate the radiance (and associated luminance) of a source. They are designed to be spectrally neutral, i.e., attenuating all wavelengths uniformly within a spectral range. The experimenter must be careful about assuming the spectral range over which a neutral density filter is actually useful. For example, the spectral transmittance curves in Figure 16 depict 1.0 and 2.0 ND glass filters which attenuate uniformly only between 480 and 700 nm. Filters composed of different media can have slightly different transmittance characteristics. Neutral density filters are generally characterized by their logarithmic attenuation factor. A neutral density filter labeled as ND-1 attenuates the source luminance by a factor of 0.1 (10^{-1}), and a filter of ND-2.0 attenuates the source luminance by a factor of 0.01 (10^{-2}).

The spectrally selective filters can be categorized as cut-off filters or bandpass filters. Cut-off filters can be further divided into low-pass or high-pass, depending upon whether they allow transmission of energy at wavelengths below or above the cut-off wavelength, respectively. Figure 17 shows a high-pass filter having a cut-on wavelength of approximately 475 nm. Note that the transition from blocking to transmission does not occur instantaneously. The cut-off wavelength is most often defined as the 50 percent point.

Bandpass filters allow transmission of energy to pass through a certain band of wavelengths. Above and below this band, energy is attenuated to a much lower level, in effect obstructing the "passing" of this energy. Figure 18 displays the spectral characteristics of a bandpass filter which permits energy at a 475 to 675 nm band to pass (or be transmitted).

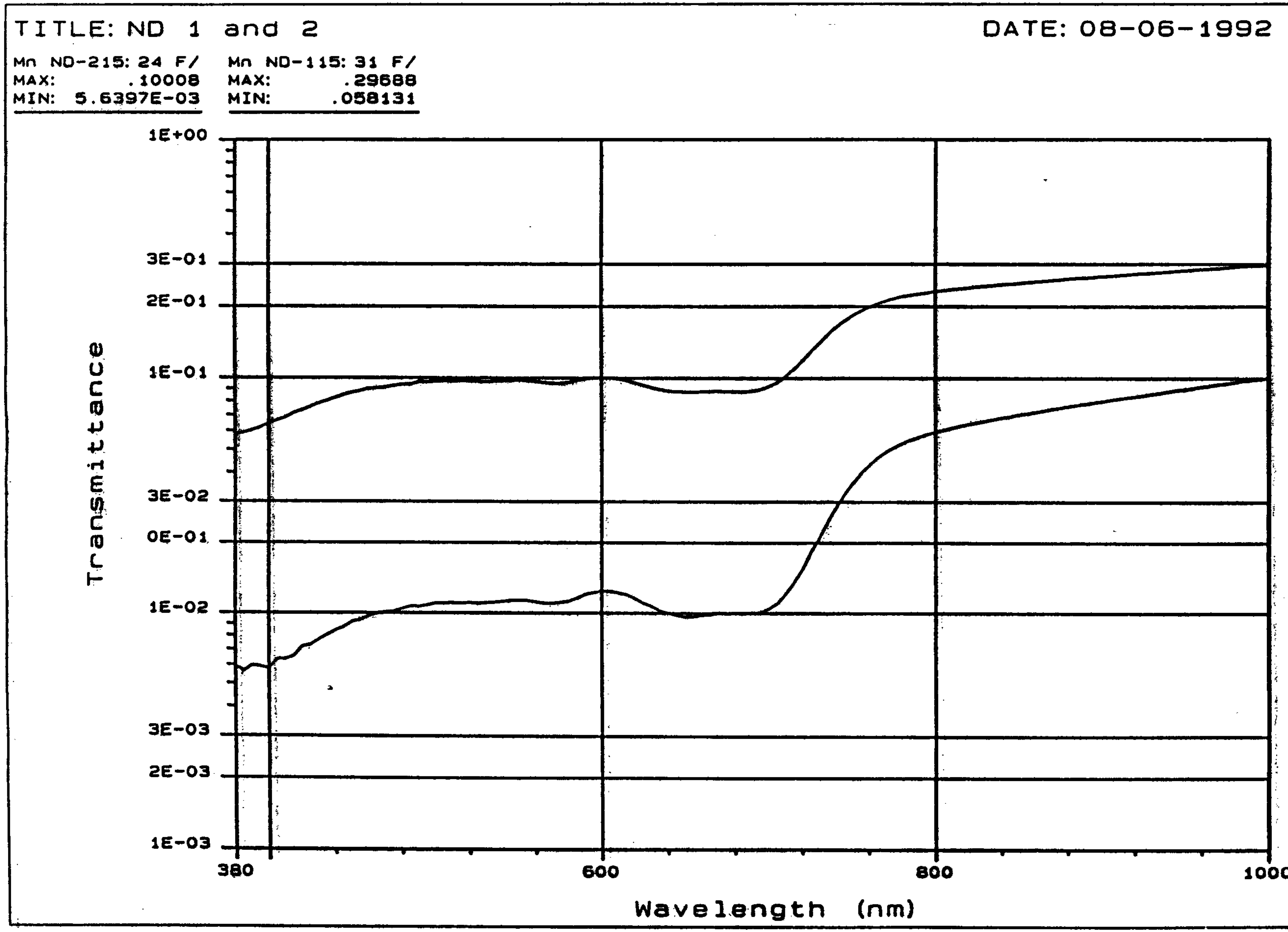

Figure 16. Transmittance curves for 1.0 and 2.0 neutral density (ND) filters.

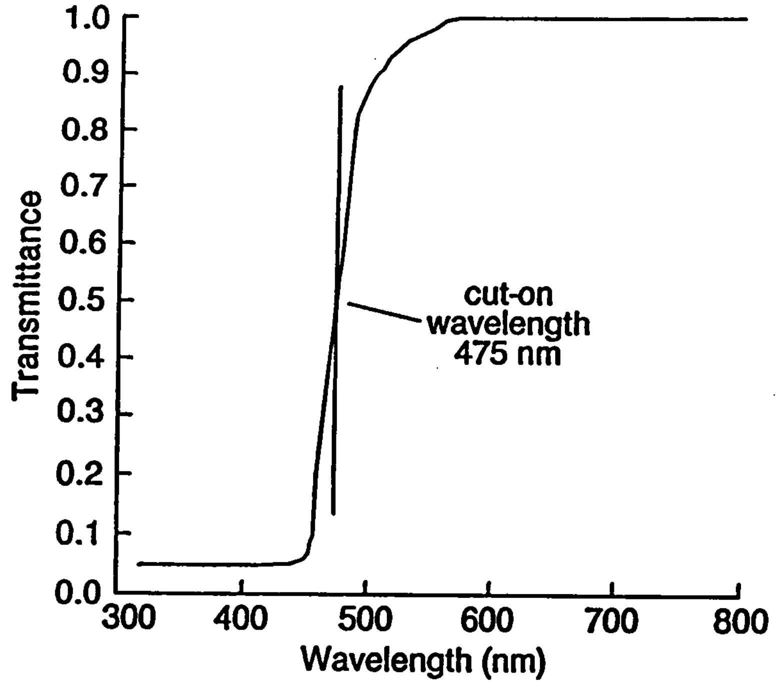

Figure 17. Transmittance curve for highpass filter having a cut-on wavelength of approximately 475 nm.

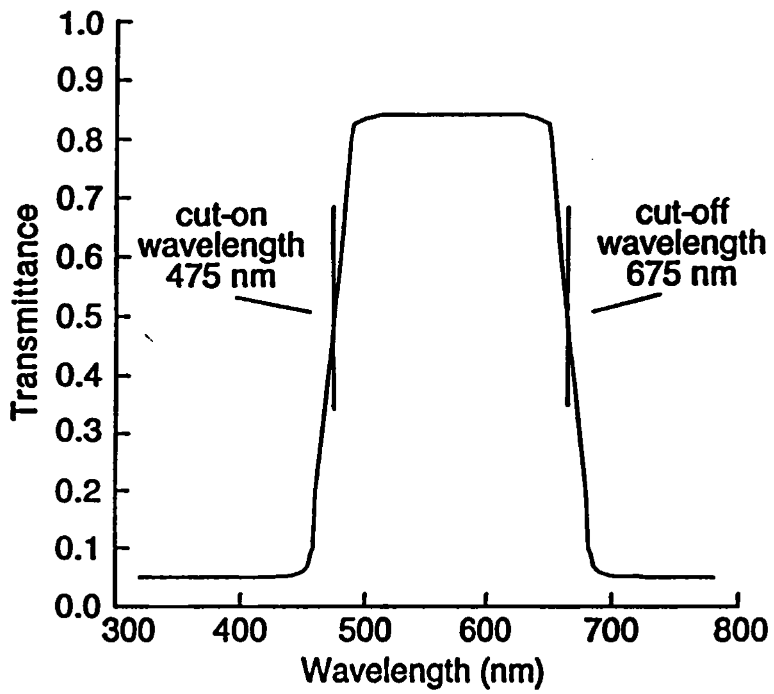

Figure 18. Transmittance curve for a 200 nm bandpass filter which transmits energy from 475 to 675 nm.

Integrating spheres

Integrating spheres are nearly perfect diffusers used for measuring sources or object reflectance and transmittance. They are hollow spheres coated internally with a white diffusing material and have openings for the source input (input port), filter materials, and the detector (output port).

The input light is distributed inside the sphere (Figure 19), uniformly illuminating the output port. Every point on the inner surface reflects to every other point in the sphere, and the illuminance at any point is made up of two components: light energy coming directly from the source, and that reflected from other parts of the sphere wall. Therefore, the illuminance (and associated luminance) of any part of the wall, due to reflected light only, is proportional to the total energy from the source regardless of its intensity distribution. The diffusing effect of the sphere guarantees that the output is insensitive to spatial, angular, and polarization characteristics of the input source, while maintaining its chromatic characteristics.

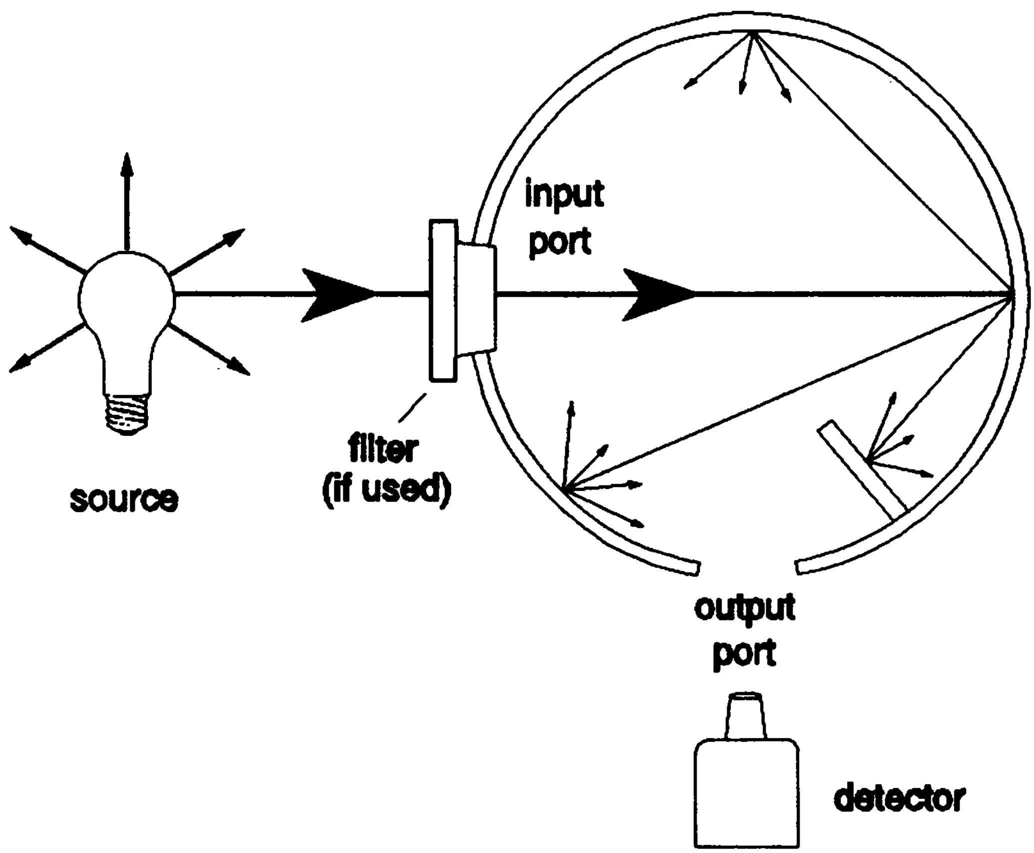

Figure 19. Integrating sphere depicting source, filter, ports, and detector.

Making the measurement

Following a well defined procedure in making light measurements usually will produce more accurate results. These procedural steps consist of: instrument zeroing and calibration, optical alignment, focusing, selecting appropriate aperture and filter, and selecting optimum instrument signal range.

Zeroing and calibration

To obtain an absolute measurement of any physical quantity, the measurement instrument must be zeroed and calibrated. Zeroing the instrument ensures that the output of the detector is zero when there is no input. This is accomplished by blocking all input energy to the detector and adjusting the display reading to a zero value. Most instruments have a shutter which can be closed to perform this operation.

Calibration is achieved by inputting a known amount of energy and adjusting the detector's output until the display reading agrees with the known value. Special energy sources, referred to as "standard lamps," are available for this task. They are manufactured to provide exact values of luminance, radiance, etc. If possible, the instrument should be calibrated against a source which has an output value of the same order of magnitude as the source to be measured. In all cases, operating manuals should be consulted for special calibration procedures.

Zeroing the instrument and calibrating against a known value (other than zero) establishes two points on the output curve of the detector. If the detector is linear (which we will assume), then any additional readings are assumed to be proportional to the input energy.

Optical alignment

Another important aspect to consider in the setup for light measurement is the alignment of a source and intervening optics with respect to the detector. A line called the optical axis is defined as one that is perpendicular to the face of the detector, through the center (see Figure 20). Any optics and light source should be placed in alignment with the optical axis since this is the most direct path for light energy to reach the detector (see "Sources of error in light measurements").

Focusing

In situations where lenses are used (e.g., collection optics), an image of the source is formed. The focusing of this image onto the detector provides the maximum reading. Focusing is achieved using a focus adjustment located on or adjacent to the collecting optics.

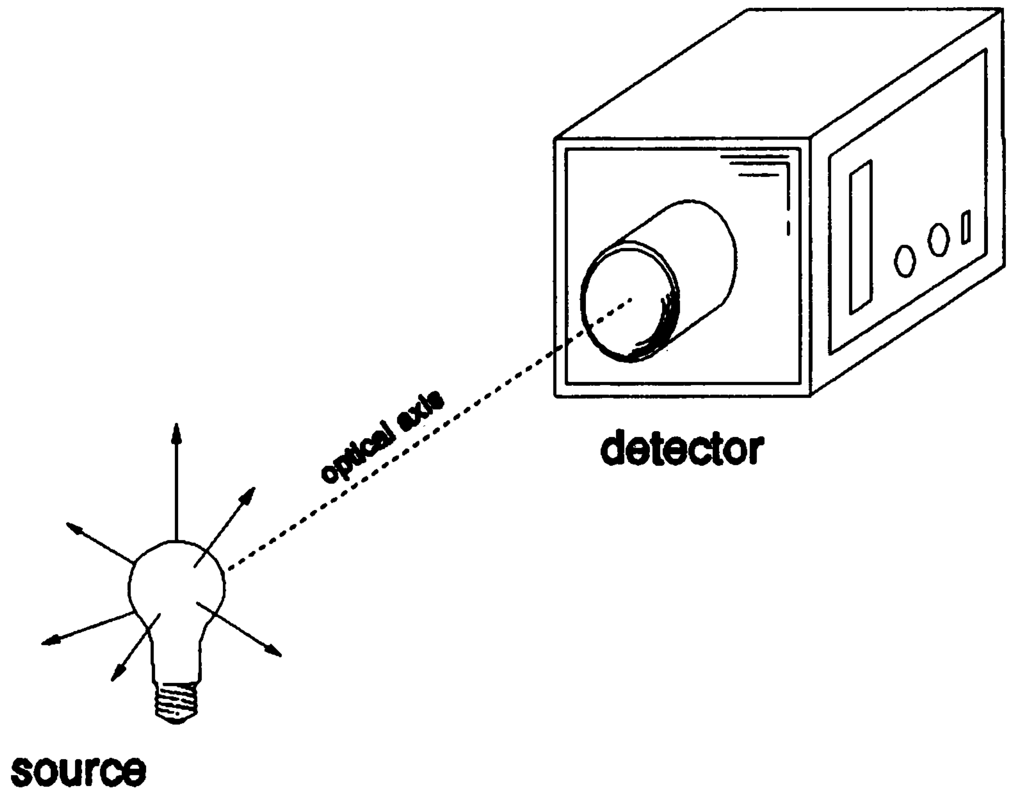

Figure 20. Optical axis of an experimental setup.

Aperture and filter selection

Most instruments allow for user control of the amount of energy entering the detector. This control is achieved through integrated apertures and filters. Apertures regulate the amount of light entering a detector. Filters offer a more selective method of regulating light energy entering the detector by absorbing energy at certain wavelengths and transmitting energy at others. Often, a selection of internal apertures and filters are provided on a given instrument.

The amount of energy allowed to pass through an aperture is directly proportional to the size of the aperture, i.e., a larger aperture will allow a greater amount of energy to pass through. When an aperture is integrated into the collection optics, it also defines the area of the (extended) source from which energy is measured. This area is expressed as the angle it subtends at the detector. Therefore, instrument apertures are often marked in angular measure, e.g., 1-degree, 20-minutes, etc. When characterizing a source, care must be taken to ensure that the selected aperture (subtended angle) is filled by the source (see "Sources of error in light measurement").

The selection of aperture size must take into account the maximum capacity of the detector. The selection of an aperture that is too large for a given high energy source will cause saturation of the detector. This will be indicated by an overranging of the display. A general rule of thumb for selecting the internal aperture size is to start with the smallest aperture available and gradually increase size to the largest aperture possible without overranging.

With instruments that include integrated filters, the filters are used to modify the response of the detector. The two most common filters are the photopic and scotopic filters. These are designed to modify the detector's response to simulate the human eye's day and night response, respectively. These filters are usually mounted in a filter wheel which allows selection among them and other specialized filters. A wheel with an "open" position allows radiance measurements.

Signal range selection

The range of an instrument is defined by the lowest and highest values which can be measured (and displayed). The lowest displayed value is usually zero. On many instruments, only one range is provided, and the highest value defines the overrange condition. However, some instruments allow a selection of choices for the maximum value. These range choices usually increase by decade units, e.g., 0 - 0.999, 0 - 9.99, 0 - 99.9 fL. Instruments with multiple ranges usually provide autorange capability where range selection is left to the instrument. The advantage of one range over another lies in the degree of precision. If, as in the example above, a measured value is approximately 0.5 fL, the most precise reading is obtained using the 0 - 0.999 range. Caution must be used to ensure that display readings are not incorrectly associated with instrument sensitivity (the smallest level of input energy measurable). A "0" display reading cannot be accepted literally . For a display range selection of 0 - 99.9 fL, a "0" display reading can represent a signal value from the lowest detectable level up to approximately 0.05 fL. In other words, "0" is not actually "0".

Sources of error in light measurement

Light measurement tasks are subject to errors which can distort data and cause inaccurate conclusions. Most of these errors can be classified into the following areas: calibration, source-detector geometry, stray light, polarization, spectral considerations, and instrument accuracy (Application Note, "Reduction of errors," Oriel Corp., Stratford, CT).

Calibration

Calibration is critical when making absolute measurements. The calibration of the instrument relates the output of the instrument to a known value. Using an uncalibrated or improperly calibrated instrument will not affect relative measurements, such as luminous transmittance, but will result in incorrect absolute values.

Source-detector geometry

One goal of good measurement technique is to ensure that the light energy to be measured is independent of any changes in orientation. All experimental setups have an optical axis (Figure 20). Proper alignment of source, detector, and intervening elements along this axis will provide accurate measurements. Alignment can be verified by making small movements of each component and noting the effect on the measured value. Optimum alignment is achieved when the measured energy attains a peak value.

Another aspect of source-detector geometry which can produce serious errors is inadequate filling of the detector aperture with the source light. Many measurements are based on calculations involving the total energy collected and the area of the detector. If the aperture is not completely filled, then the resulting measurement will be inaccurately low.

Stray light

As a basic rule of thumb, prior to performing measurements, a "light audit" of the laboratory should be performed to assess the presence of stray light. Stray light is unwanted light energy from the test source or the surrounding area which enters the detector. This extra energy produces an artificially high measurement value. Stray light may originate directly from the source (e.g., reflections from sample holders, walls, tables, light colored clothing, etc.) or from ambient sources (e.g., overhead lights, light leaks around doors or windows, indicator lights on instrumentation, etc.). Some suggested procedures for minimizing stray light include: check for reflections of test source, select optimal external aperture size, baffle along optical axis, perform measurements in darkest environment possible, keep all personnel away from measurement area, and cover all indicator lights on instrumentation.

Polarization

Polarization errors can result when: a) comparative measurements are made between sources which differ in polarization characteristics, e.g., a polarized vs. an unpolarized source or a vertically polarized vs. a horizontally polarized source; b) the polarization characteristics of the source and detector do not match; and c) changes occur in the source's polarization characteristics along the optical path, especially when mirrors and beamsplitters are present.

Time constant considerations

When measuring light sources which are uniform over time, the time constant of the measurement instrument is not important. However, measurement error for time varying sources can occur when the time constants of the source and detector are not properly matched. When the measurement task is to define the actual luminance profile, the time constant of the detector must be several times smaller than that of the source. Failure to select an instrument which meets this requirement will result in an integrated output, rather than a true output profile. Conversely, when the average output of a time varying source is desired, too small a detector time constant will not produce a constant measurement value.

Spectral considerations

Measurements of narrow spectral characteristics may give inaccurate readings due to unwanted energy outside of the spectral band of interest. Stray light "leaking" through the monochromater (narrow band filter) can produce an incorrect high reading. This error is more significant when the source is relatively weak.

Instrument accuracy

While not an error in the sense of the items above, the accuracy of a reading can be affected by the accuracy of the light measuring instrument. Due to the required matching of a detector with a photopic or scotopic filter to perform luminance or illuminance measurements, the accuracy of the reading is a function of how well the detector/filter combination's response matches that of the human eye. Additional factors affecting instrument accuracy include temperature and humidity. As a rule of thumb, photometric measurements can expect to have an error of 2-5 percent.

Reporting the data

The most common formats for reporting light measurement data are graphical curves for spectral data (radiance or transmittance) and tables for radiometric and photometric values. Spectral data are usually presented graphically such as the spectral radiance curve in Figure 4. Radiance values are plotted along the y-axis as a function of spectral wavelength (x-axis).

There is a large selection of units from which one may choose for reporting radiometric and photometric measurements. Table 3 provides a list of the most commonly used units for radiance, irradiance, luminance, and illuminance. The choice of units for a given physical quantity is usually a matter of the preferred measurement system. While the currently agreed upon units of measure are those of the International System of Weights and Measures (SI), units of the English system of measure are often encountered. Table 4 provides conversion factors for common luminance and illuminance units. From the table, it can be seen that 1 nt is equivalent to 0.2919 fL and 0.0929 cd-ft^{-2}. To convert a value expressed in "nt" into "fL", multiply the value in "nt" by 0.2919. For example: A value of 1.2 nt is equivalent to (1.2 x 0.2919) or 0.35 fL.

Color (chromaticity) is expressed in either 1931 CIE (x, y) or 1976 UCS (u′, v′) coordinates. These are usually presented in graphical form (Figures 6 and 7, respectively).

When reporting contrast measurements, it is important to document the method, i.e., definitions and formulas, used in the calculation of the contrast values.

Table 3.
Common photometric units.

Measured quantity	Unit	Abbreviation
Radiance	watt per steradian per square meter	$W\ sr^{-1} m^{-2}$
Irradiance	watt per square meter	$W\ m^{-2}$
Luminance	nit footlambert candela per square foot	nt fL $cd\ ft^{-2}$
Illuminance	lux footcandle	lx fc

* the unit "nit" can also be expressed as "$cd\ m^{-2}$"

Table 4.
Conversion factors for photometric units.

			Luminance			Illuminance	
			nt	fL	$cd\ ft^{-2}$	lx	fc
Luminance	nt	=	1	0.2919	0.0929	--	--
	fL	=	3.426	1	0.3183	--	--
	$cd\ ft^{-2}$	=	10.764	3.1416	1	--	--
Illuminance	lx	=	--	--	--	1	0.0929
	fc	=	--	--	--	10.764	1

Glossary

absorption - partial loss of incident energy in an optical medium due to conversion of energy into other forms.

ANVIS radiance - the measure of total energy output of a source as detected through third generation image intensification night vision imaging systems.

aperture - the opening through which light energy passes through to the detector. The amount of light received by the detector may be regulated through the changing of aperture size. Internal apertures are integrated into an instrument, and external apertures are placed between a source and the detector of an instrument.

arc lamp - an electric discharge lamp that produces light when voltage is applied across electrodes separated by a very short distance. The electrodes are surrounded by a gas mixture which produces a luminous plasma when an electric charge is applied to the electrodes. Arc lamps produce very high luminance values.

bandpass filter - a filter that allows energy within a certain band of wavelengths to only pass. Above and below this band, energy is attenuated to a very low level, in effect obstructing the "passing" of this energy.

beamsplitter - An optical element which divides a light beam into two parts.

blackbody radiator - a temperature radiator of uniform temperature whose radiant emittance in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature. Such a radiator is called a blackbody because it will absorb all the radiant energy that falls upon it.

chromaticity - the classification of color.

collection optics - any lens, mirror, or combination that is used to gather or focus light energy.

colorimetry - methods employed to measure color and to interpret the results of the measurements.

correlated color temperature (CCT) - the temperature of the blackbody curve which is best approximated by a source's spectral energy distribution. For tungsten filament sources, this varies as a function of filament current.

cut-off filter - filter that allows transmission of energy at wavelengths below a specified wavelength. This particular wavelength is referred to as the cut-off wavelength.

cut-on filter - filter that allows transmission of energy at wavelengths above a specified wavelength. This particular wavelength is referred to as the cut-on wavelength.

detector - a device that converts light energy into another form of energy, usually an electrical current.

electromagnetic spectrum - the total range of wavelengths extending from the shortest (zero) to the longest (infinity) wavelength that can be generated physically.

emitted spectra (line, continuous) - the spectrum formed by energy emitted from a source. Emitted spectra are divided into two broad categories: continuous emission and line emission. A continuous emission source has some energy present at all wavelengths. Line or discrete emission sources have energy emitted only at discrete or well defined wavelengths.

filter - a material placed between a light energy source and a detector that attenuates the total amount of energy being transmitted; this attenuation can be uniform across all wavelengths as in neutral density filters or can be spectrally selective.

footlambert - a unit of luminance in the English system of measure equal to $1/\pi$ candela per square foot.

illuminance - the measure of visible energy falling upon a surface.

Illuminant A, B, and C - illuminant A is the standard for a source that produces a spectral distribution which approximates an incandescent tungsten filament lamp at a color temperature of 2854° kelvin (K). Illuminant B is used to simulate direct sunlight and has a color temperature of 4870° K. Illuminant C is used to simulate an overcast sky and has a color temperature of 6770° K.

image intensification - an electro-optical device which converts collected photons into electrons which are then "intensified" by photomultiplication. After intensification, the electrons are converted back into photons (light image) at a phosphor screen.

incandescent lamp - a lamp that emits light when an electrical current passes through a resistant metallic wire positioned in a vacuum tube.

index of refraction - the ratio of the velocity of light in air to the velocity of light in a refractive material for a given wavelength; a measure of the bending properties of an optical material.

infrared spectrum - energy that lies between the wavelengths of 750 nm to 1.4 microns; heat producing energy which is invisible but can be damaging to the retina of the human eye.

irradiance - the measure of total energy falling upon an object's surface; this measurement includes visible and nonvisible (UV and IR) energy.

laser - acronym for "Light Amplification by Stimulated Emission of Radiation." A narrow band of wavelengths, often considered to be a monochromatic (single wavelength) source, which consists of nearly parallel rays and exhibits very little angular divergence. When coupled with the focusing capability of the human eye, lasers become an extreme optical hazard.

light emitting diode (LED) - emits light energy which is produced by electrons moving across a junction of semiconductor materials when a voltage is applied to the junction.

linearly polarized - when the electric field (light energy) oscillates in some fixed direction, the wave is said to be linearly polarized in that direction.

luminance - a measure of energy output (weighted by the human eye's response) leaving or arriving at a surface in a given direction.

luminous transmittance - the ratio of the luminance of a known source as measured through a filter material, to the luminance of the source itself.

monochromater - an instrument which isolates narrow bands of the spectrum allowing the measurement of energy within the band (in practice, the band is very narrow and often referenced by its center wavelength).

neutral density filter - a filter which attenuates the radiance (and associated luminance) of a source. They are designed to be spectrally neutral, i.e., attenuating all spectral wavelengths uniformly.

objective lenses - the optical elements that collect light energy from a source and form the first image to be measured.

photometer - an instrument for measuring photometric parameters such as luminance and illuminance (indirectly). The response of a photometer's detector is tailored to approximate that of the human eye.

photometry - the measurement of light energy as perceived by the human eye (visible light).

photomultiplier tube (PMT) - a tube consisting of a photocathode that emits electrons in proportion to the incident photons.

photopic - values that refer to the light output of a source as modified by the eye's cone photoreceptors' response.

polarization - If the electric field of an energy wave always oscillates in some fixed direction, the wave is said to be linearly polarized in that direction; the polarization of that wave refers to the orientation of the electric field vector.

radiance - the measure of total energy output of a source; this measurement includes both visible and nonvisible (UV and IR) energy.

radiometry - involves the measurement of total electromagnetic energy, typically covering the wavelengths from ultraviolet through infrared.

scotopic - values that refer to the light output of a source as modified by the eye's rod photoreceptors' response.

spectral radiance curve - a graphical representation of the energy emitted per unit wavelength of a particular source over a specified spectral range.

spectral reflectance - the ratio of the reflected energy to the incident energy as a function of wavelength.

spectral transmittance - transmittance of an optical material as a function of wavelength.

spectroradiometry - the measurement of the amount of energy at a particular wavelength or within a band of wavelengths.

ultraviolet spectrum - energy that lies between the wavelengths 100 to 380 nm. This energy is invisible and damaging to the human eye.

visible spectrum - the region of the electromagnetic spectrum which the human eye is sensitive to. It is typically defined to be between 380 to 730 nm.

wavelength - the measure of the physical distance covered by one cycle of a sinusoidal wave of light energy; a variable used to relate to the spectral content of a light source.

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Appendix A.

USAARL light measurement instrumentation

EG&G Gamma Scientific
ANVIS spectroradiometer system
Model C-11ASR

This spectroradiometer system is designed to measure ANVIS radiance, which is a measure of the compatibility of lighting (i.e., instrumentation panels and auxiliary instrument lighting) with image intensification night vision imaging system equipment. The system is comprised of a GS-4100 intelligent radiometer, a DC-49C thermoelectric water-cooled photomultiplier tube, a NM-3DH holographic monochromater, a GS-2110A scanning telemicroscope, and an IBM-PC interface console. This system is used primarily for spectroradiometry. The response range of this system is 380 to 950 nm.

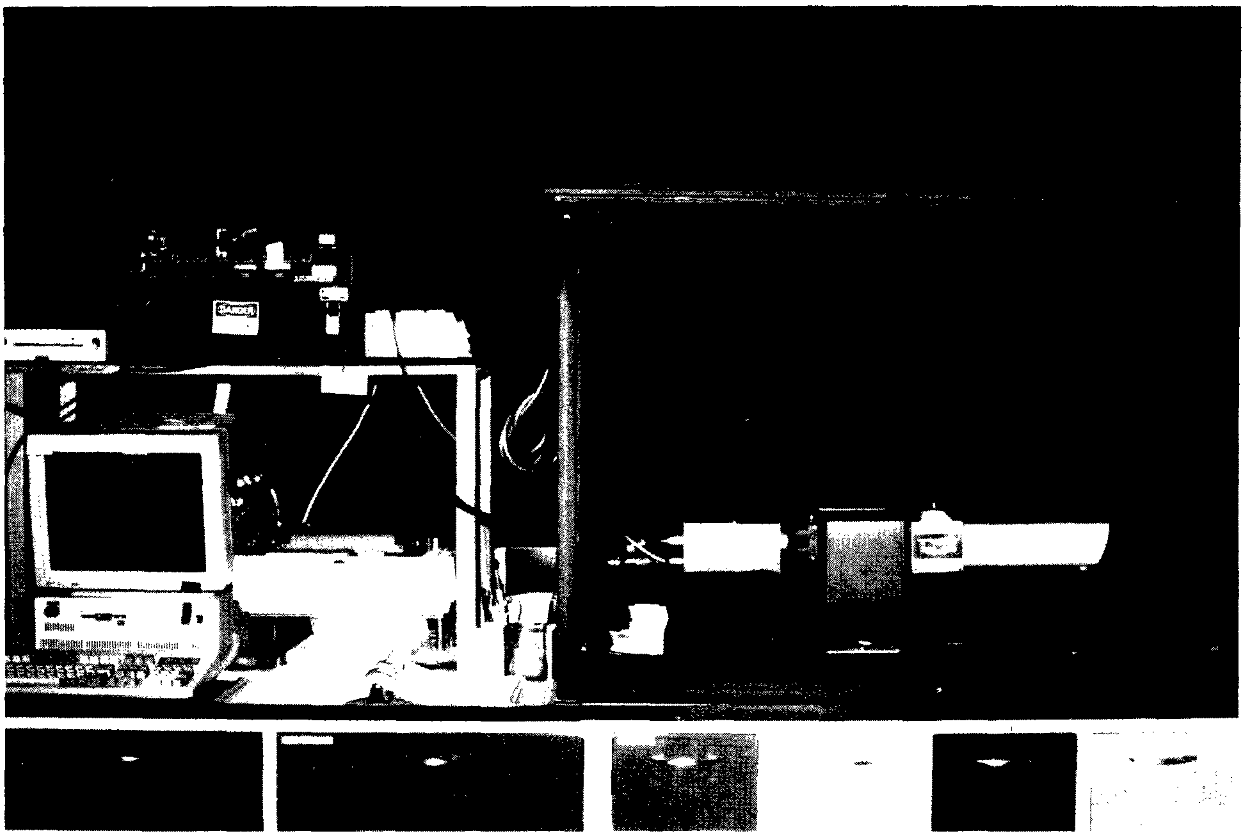

Figure A-1. EG&G Gamma Scientific ANVIS spectroradiometer system.

Minolta
Chroma meter

The Minolta chroma meter is a battery operated, hand-held tristimulus color analyzer utilizing three silicon photo cells which are filtered to match CIE standard observer response. The cells are capable of making readings of light source or reflected color. Chromaticity coordinates (1931 CIE), illuminance (lux), and color temperature (kelvin) are calculated by the meter. Measurements are indicated digitally on a liquid-crystal display. Color temperature range is 1600 to 40,000 K. The illumination range is 10 to 200,000 lux.

Figure A-2. Minolta chroma meter.

Minolta
Model Nt-1°
Luminance meter

The Minolta luminance meter is a battery operated, hand-held luminance meter which focuses using a single-lens-reflex viewfinder. The measuring range is 0.1 to 99,900 cd/m^2 (0.01 to 99900 fL). The acceptance angle is 1 degree. The instrument can focus between 1 meter and infinity.

Figure A-4. Minolta model Nt-1° luminance meter.

Photodyne Inc.
Model 22XL
Optical multimeter

The Photodyne Model 22XL Optical multimeter is the equivalent of a digital multimeter developed specifically for fiber optics applications. The optical multimeter provides for absolute measurements of all aspects of fiber optics systems including light sources and emitters, photoreceivers, fiber cable transmission, and connector and splice loss. Features of the optical multimeter include selectable 0.1 decibel (dB) or 0.01 dB resolution, mode selection for absolute or ratio measurements, current regulated IR source for calibration, and optical plug-in sensor heads for specific range spectral and power applications.

Figure A-5. Photodyne Inc. model 22XL optical multimeter.

Photodyne Inc.
Model 88XLA
Radiometer/photometer

The Photodyne Model 88XLA Radiometer/photometer features direct linear readout for radiant power in units of nanowatts, microwatts, and milliwatts, from 1 picowatt minimum resolution to 2 watts maximum reading. Direct linear photopic measurements are available in footcandles, lux, and candelas. Plug-in sensor heads are available for specific ranges of spectral and power applications.

Figure A-6. Photodyne Inc. model 88XLA radiometer/photometer.

Photo Research
PR-710 spot SpectraScan™
Fast Spectral Scanning System

The SpectraScan PR-710 Fast Spectral Scanning System is a designed for rapid measurement of radiance, luminance, spectral transmittance, spectral reflectance, CIE color coordinates, and correlated color temperature. Typical time required for measurements is less than 15 seconds. It uses a high-resolution, low-flare lens which can be focused from 2 inches to infinity; thus enabling the instrument to be used for either macro-photometry or telephotometry with no accessory lenses or changes in calibration.

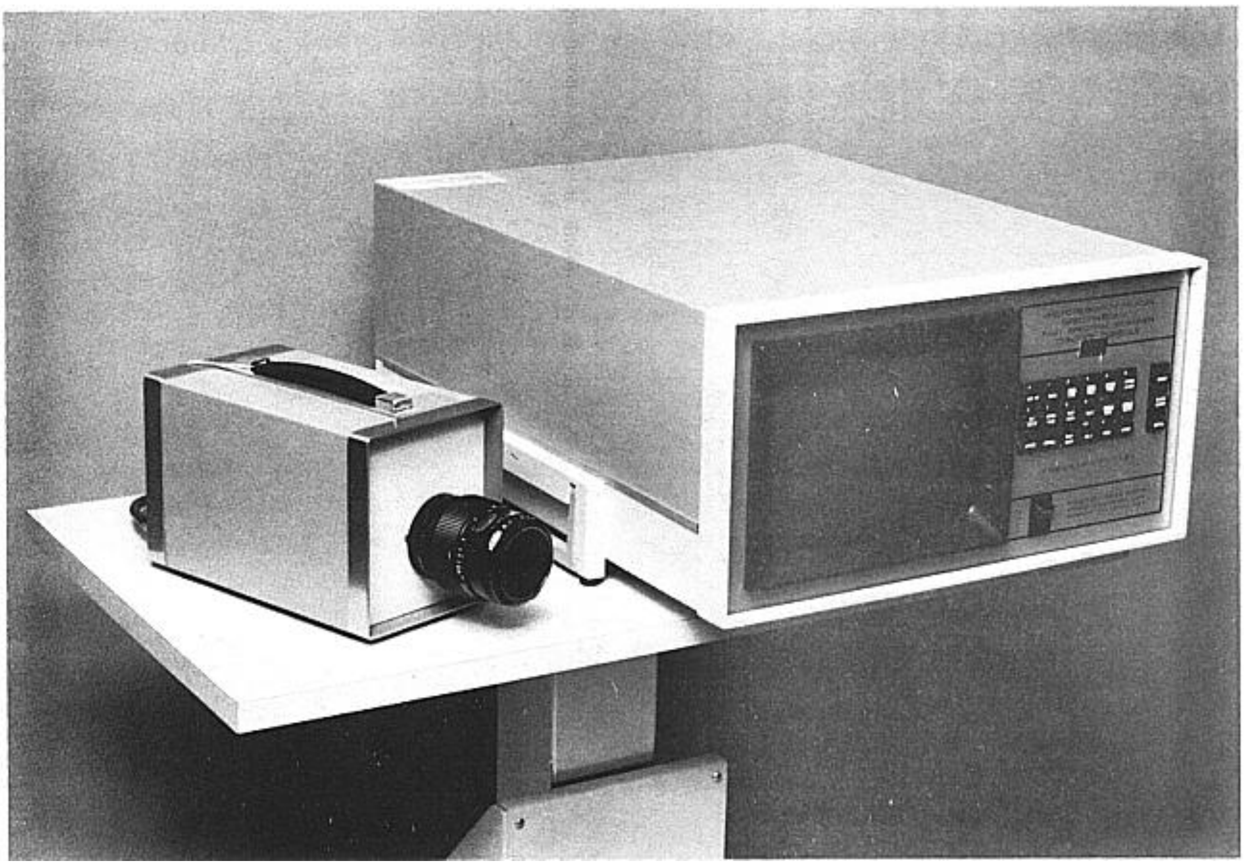

Figure A-7. Photo Research PR-710 Spot SpectraScan™ fast spectral scanning system.

Photo Research
1980A and 1980A-PL
Photometer

The Spectra™ Pritchard™ Photometer consists of two separate units: the photometer unit or "optical head," and the control console. The two units are connected by an 8-foot cable. The optical system has a filter wheel containing neutral density filters (ND = 1, 2, and 3), a photopic correction filter, colorimetry filters, and a polarizing filter. An aperture wheel allows angular measuring fields from 2 minutes (2′) to 3 degrees (3°). The standard objective lens is a high-resolution, low-flare, seven inch, f/3.5 lens which may be focused from 4 feet to infinity. A series of interchangeable and supplementary lenses enable the focusing distance to be reduced to as little as 0.625 inches. The PL modification of the 1980A can measure the integrated (average) value of pulsed sources from 10E-5 to 10E+7 foot-lambert-seconds (full-scale) for pulses as short as 1.6 microseconds.

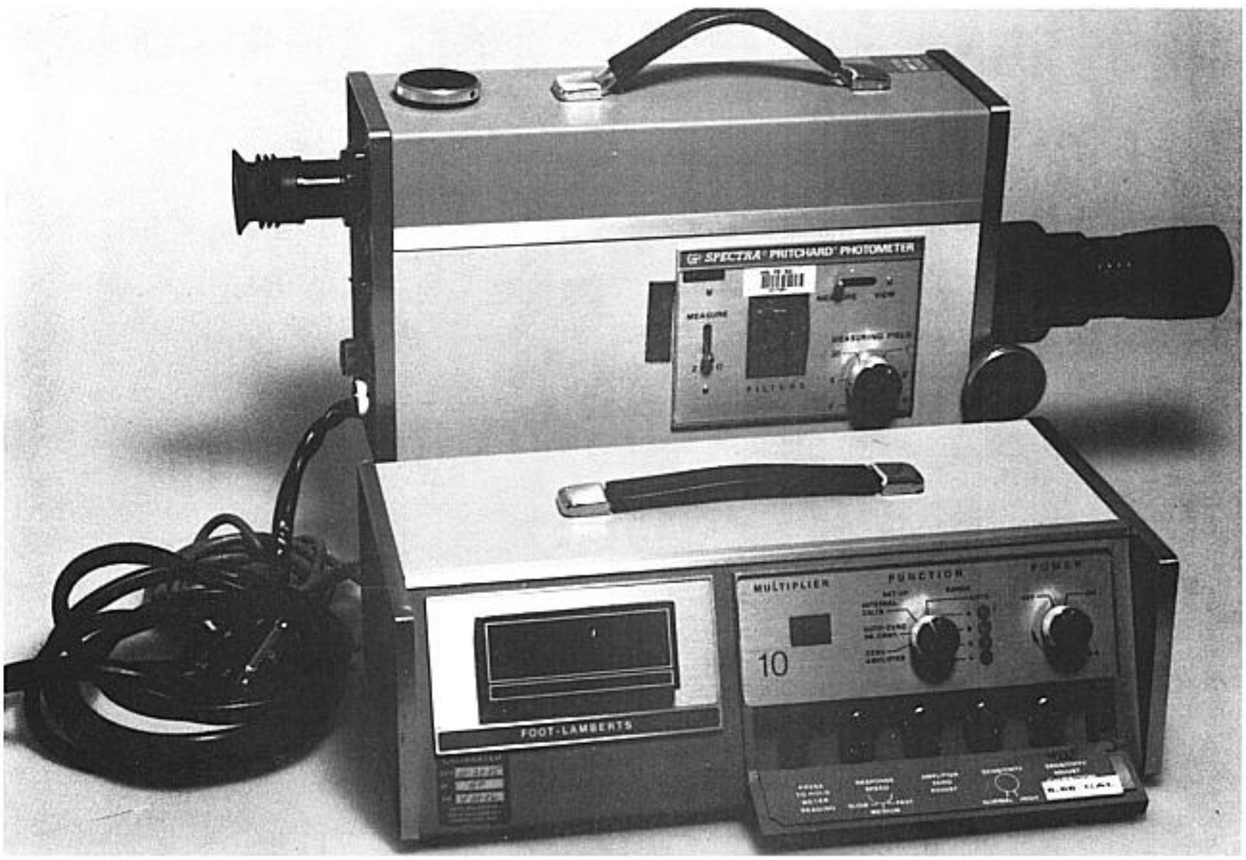

Figure A-8. Photo Research 1980A photometer.

**Photo Research
LiteMate III
Photometer**

The LiteMate Photometer, Model 501, is a compact, hand-held digital photometer. It is capable of making cosine-corrected illuminance measurements over the range from 0.01 footcandles to 19,990 footcandles, with ±5% accuracy and ±1% repeatability. It has a 1 degree acceptance angle.

Figure A-9. Photo Research LiteMate III Photometer.

Photo Research
Spectra® Spotmeter™
Model UBD

The Photo Research Spectra® Spotmeter™ is a photomultiplier tube photometer. Alone it can measure luminance and with accessories or calibrations is capable of measuring illuminance, luminous intensity, color temperature, light polarization, relative color coordinates, radiance, and irradiance.

The optical system consists of a photomultiplier tube, a 100X attenuator, filter turret, a 1 degree aperture mirror, an objective lens, and a focusing eye piece. This high resolution, low-flare lens can be focused from 2 inches to infinity, enabling the instrument to be used for microphotometry or telephotometry. A six-position filter turret is located between the aperture mirror and the photo tube. This filter turret contains a photopic, scotopic, red and blue filters for varying light measurement conditions. The filter also contains an "open" position for radiometric measurements and calibrate position for internal calibration verification. The attenuator reduces the instrument's sensitivity by a factor of 100X (ND = 2).

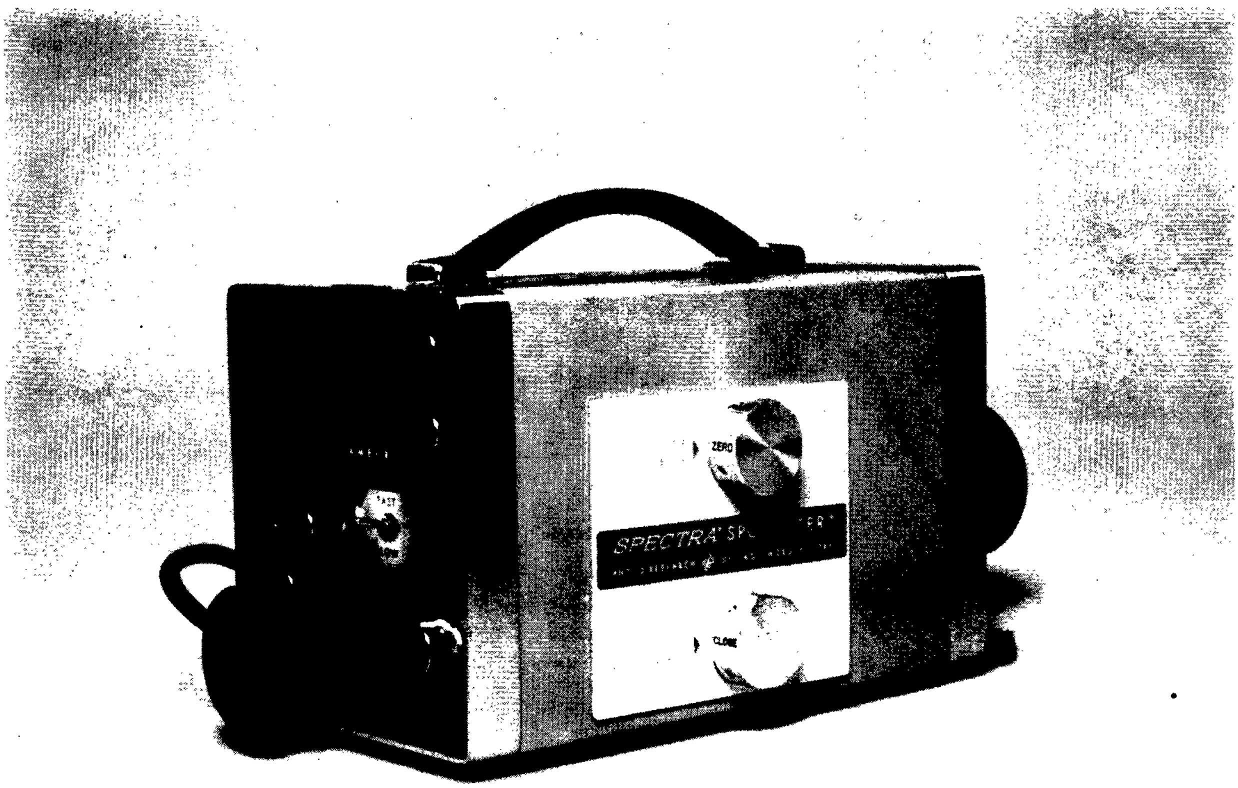

Figure A-10. Photo Research Spectra® Spotmeter™ model UBD.

Photo Research
PR-1530AR
NVISPOT meter

The PR-1530AR NVISPOT is designed to perform ANVIS radiance measurements, but has the capability to perform conventional luminance and colorimetric light measurements.

The PR-1530AR uses an extended-red gallium arsenide photomultiplier tube and is packaged as a portable unit. The measuring field aperture is 3 degrees.

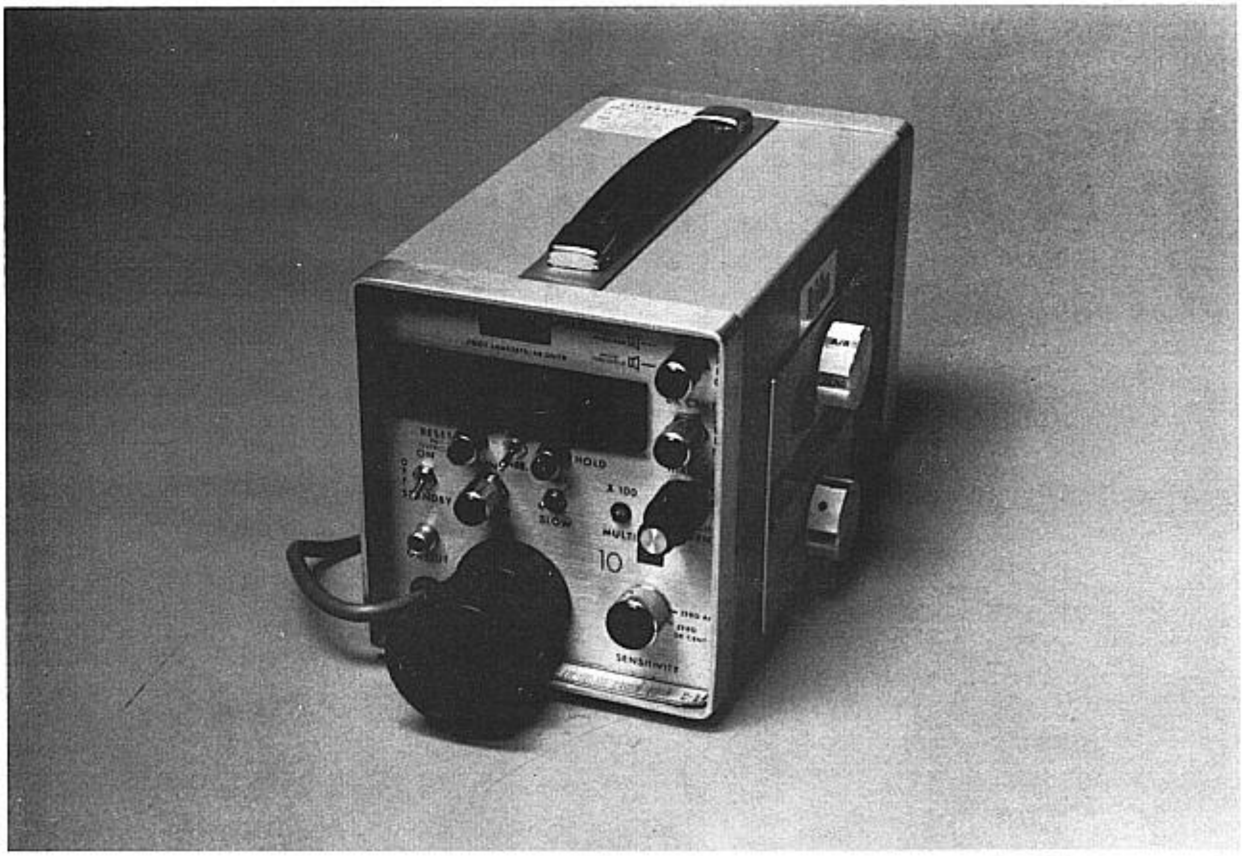

Figure A-11. Photo Research PR-1530AR NVISPOT meter.

Appendix B.

USAARL light sources

BHK, Inc.
Analamp
Ultraviolet lamp

Wavelength reference source for 313.2, 404.7, 435.8, 546.1, 730.8, and 809.4 nm.

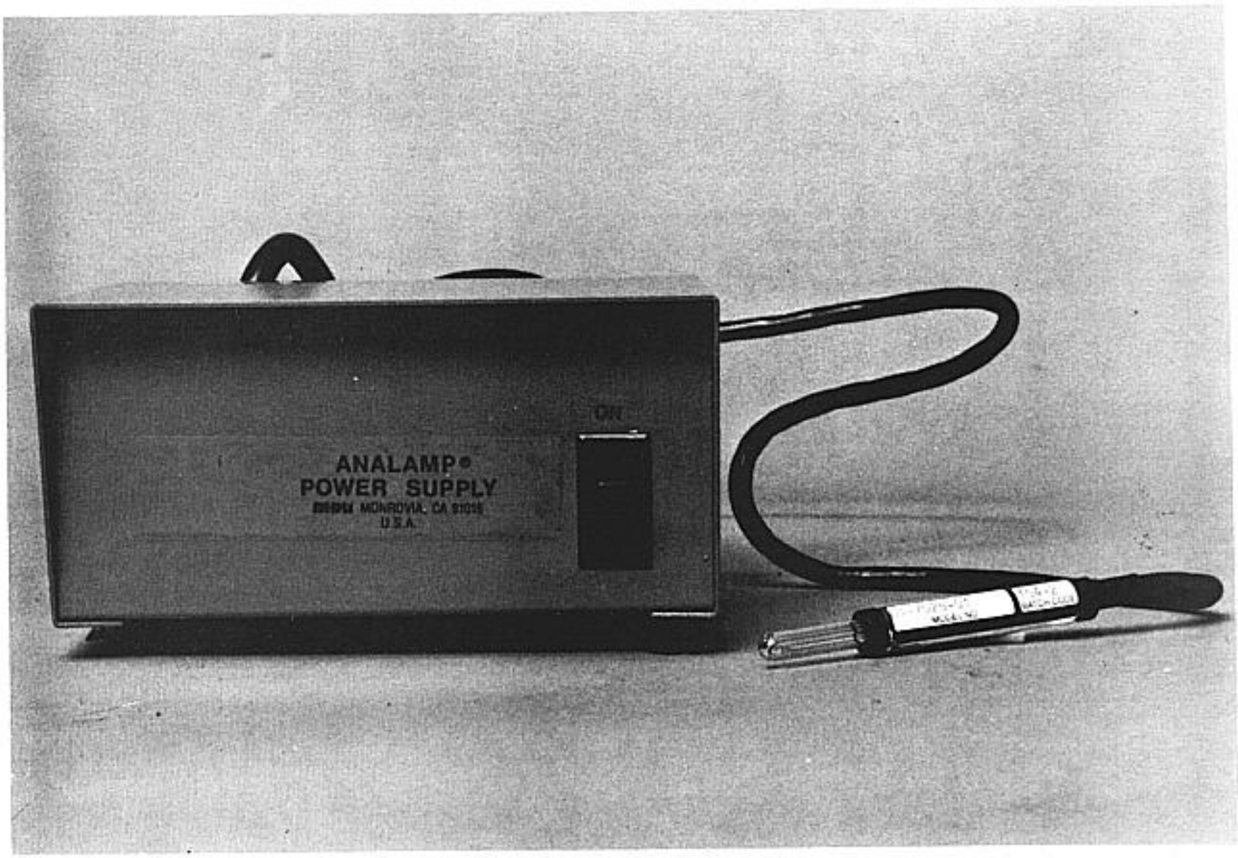

Figure B-1. BHK Inc. Analamp ultraviolet lamp.

EG&G Gamma
RS-10
Tungsten lamp

Luminance reference source for EG&G Gamma spectroradiometric system has a luminance of 179.0 footlamberts and correlated color temperature of 2603°K.

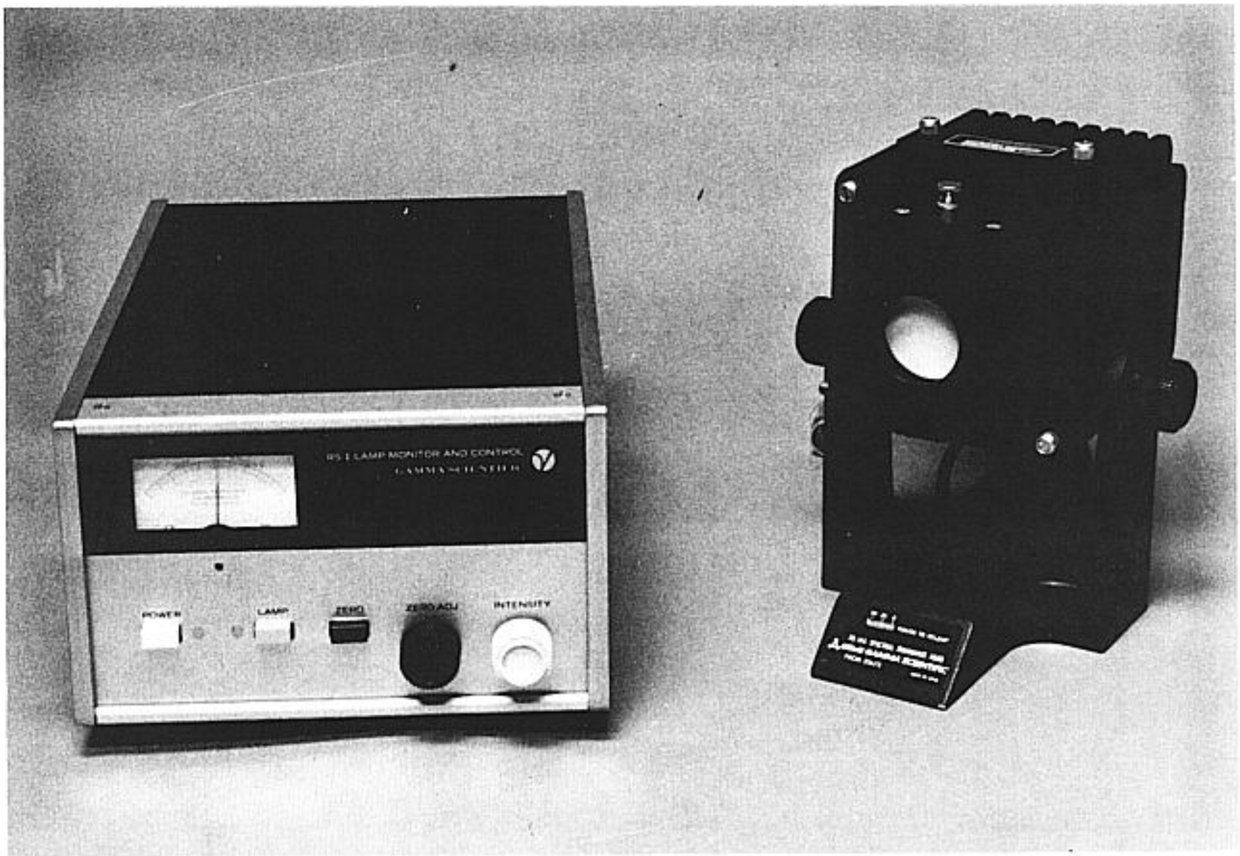

Figure B-2. EG&G Gamma RS-10 tungsten lamp.

EG&G Gamma
RS-12
Tungsten lamp

Luminance reference source for EG&G Gamma spectroradiometric system has a luminance of 358.2 footlamberts and correlated color temperature of 2852°K.

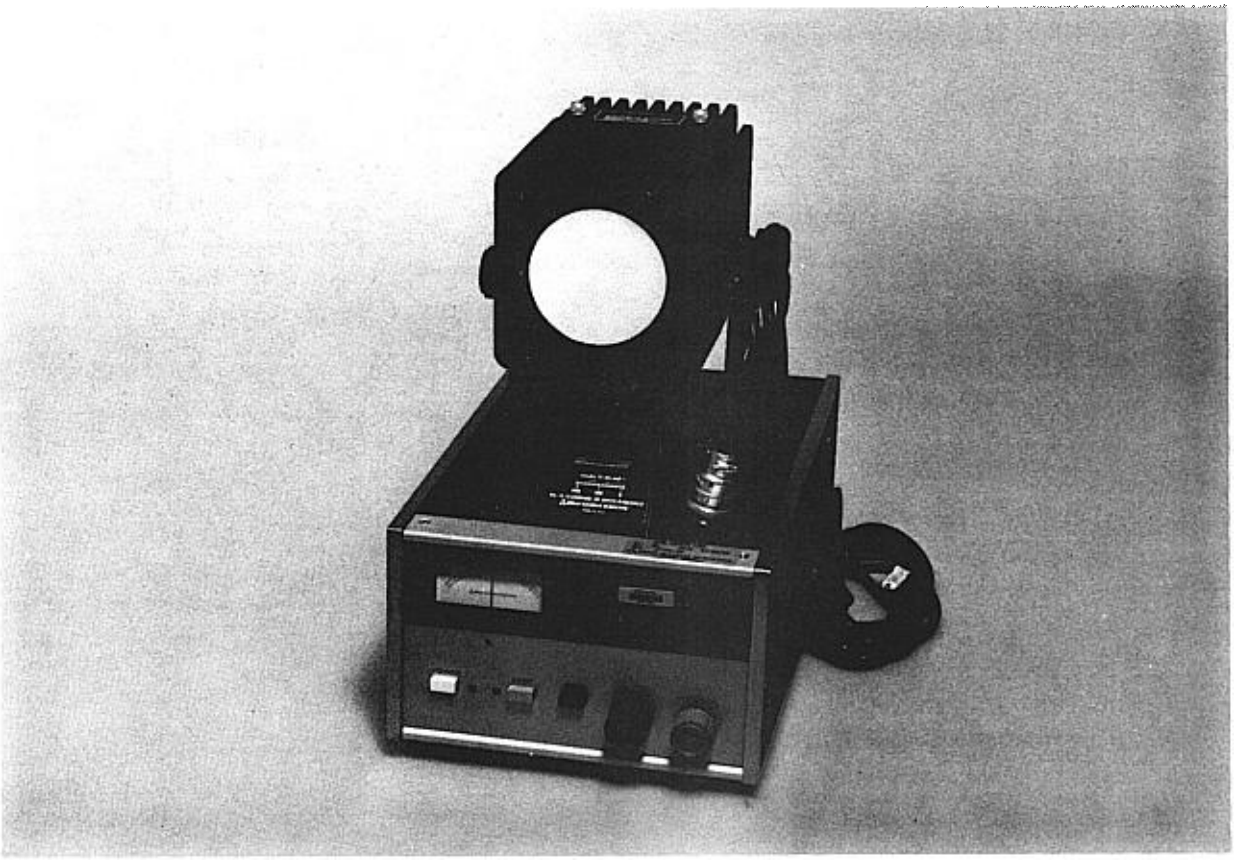

Figure B-3. EG&G Gamma RS-12 tungsten lamp.

**Melles Griot
2 and 5 milliwatt
HeNe lasers**

The helium-neon laser delivers relatively intense coherent electromagnetic radiation at 632.8 nm. The 2 milliwatt laser head has a beam diameter of 0.65 mm and typical beam divergence of 1.3 milliradians with random polarization. The 5 milliwatt laser head has a beam diameter of 0.8 mm and typical beam divergence of 1.0 milliradians with random polarization.

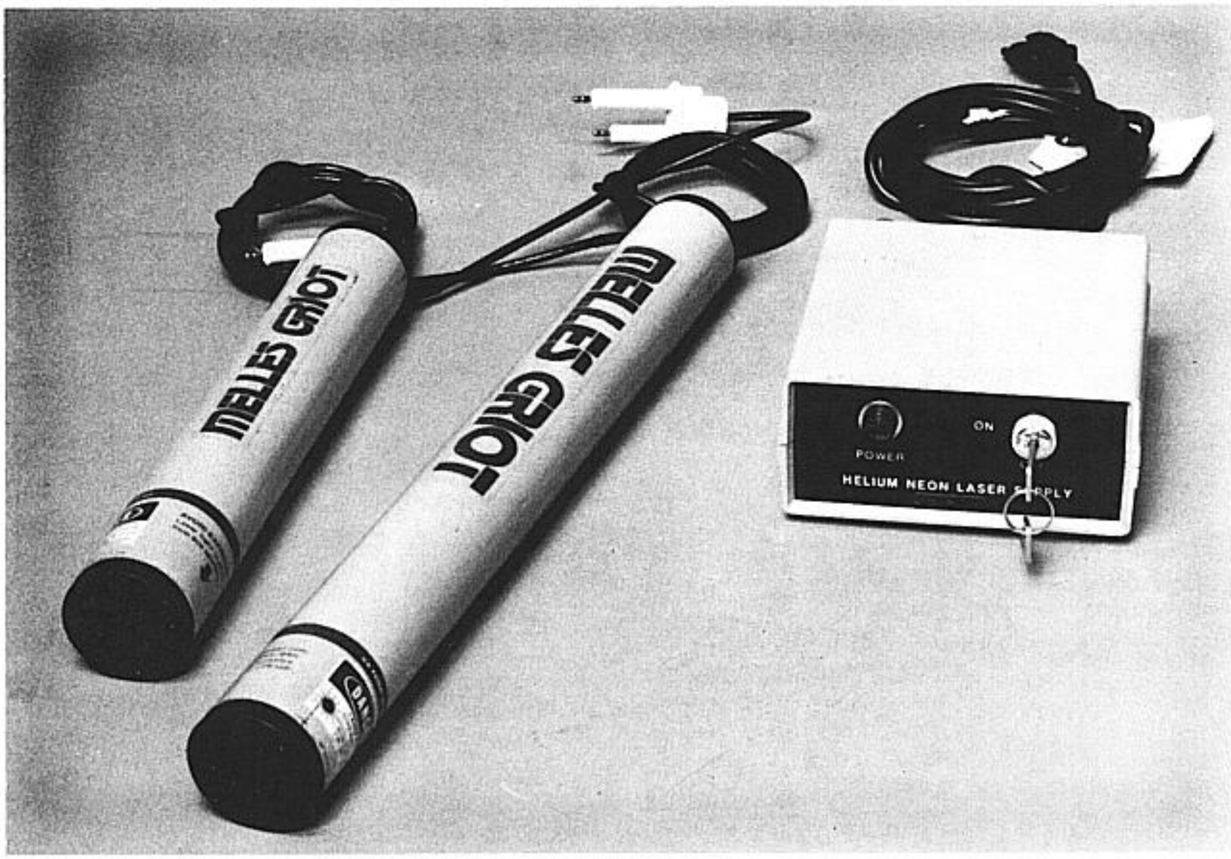

Figure B-4. Melles Griot 2 and 5 milliwatt HeNe lasers.

Oriel 6325
20 watt
Quartz tungsten-halogen lamp

This source has a 2.3 x 0.8 mm dense filament in a small housing that can be mounted and positioned either horizontally or vertically on an accessory rod mount. Spring clips on the housing can hold 2 x 2 inch or 50 x 50 mm filters. The lamp is powered by a constant voltage transformer.

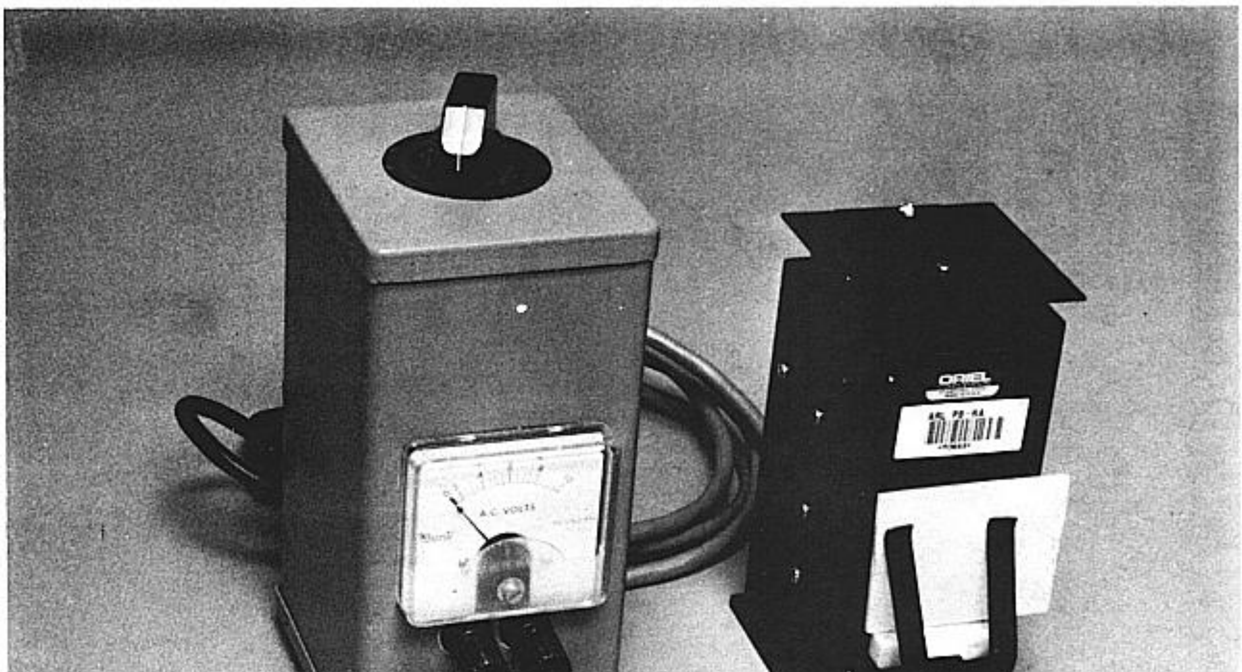

Figure B-5. Oriel 6325 20 watt quartz tungsten-halogen lamp.

Oriel 6436
1000 watt
Quartz tungsten-halogen lamp

This source has a 5 x 18 mm coiled filament lamp. The housing is blower cooled and allows for vertical and horizontal adjustment of the lamp during operation. Condensing lenses and a rear reflector increase the beam power by imaging the filament back onto or adjacent to itself.

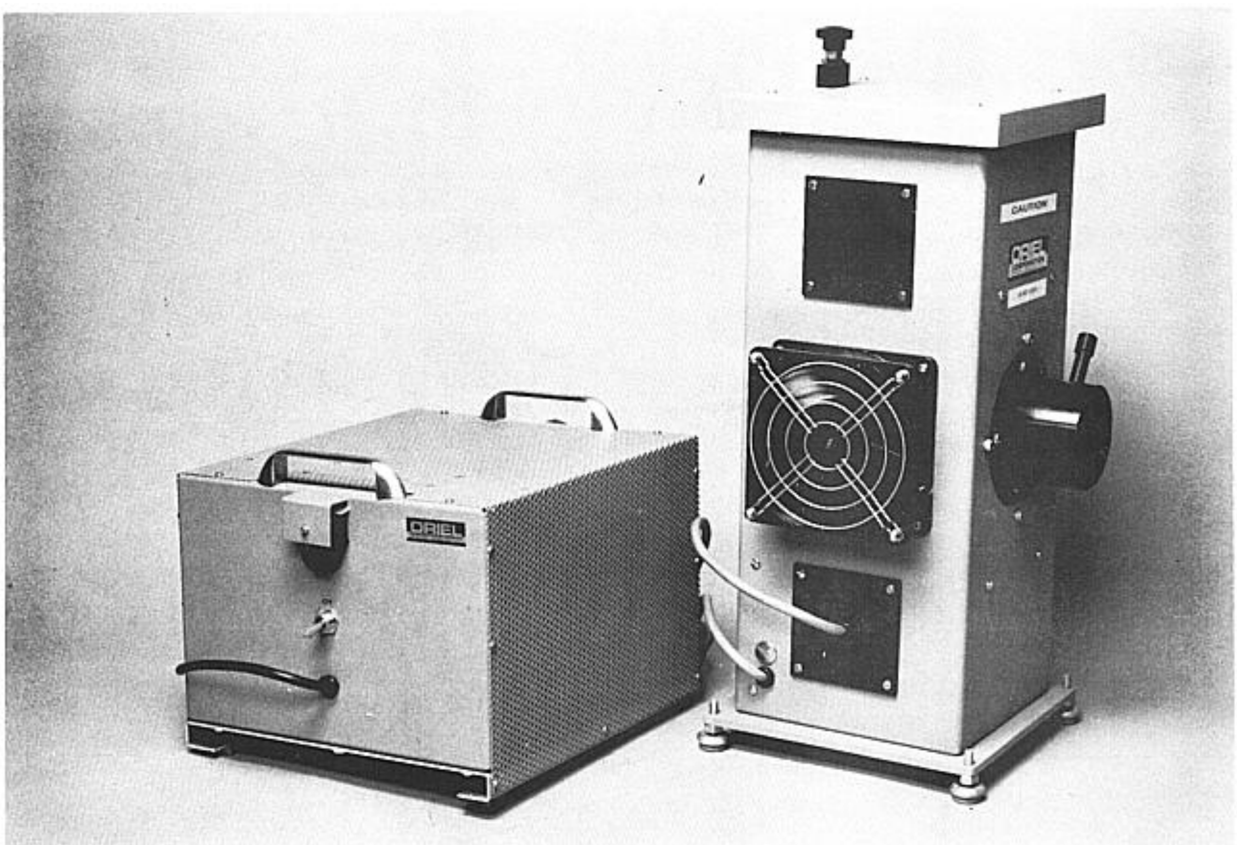

Figure B-6. Oriel 6436 1000 watt quartz tungsten-halogen lamp.

Oriel
C-13-96
Spectral lamps

The Oriel spectral calibration set contains six different line emission gas lamps -- Argon, Helium, Krypton, Neon, Xenon, and Mercury (Argon). Operated with low voltage power supplies, these sources provide strong emission lines at specific wavelengths between 380 to 840 nm. These lamps are typically used for wavelength calibration of monochromaters or detectors.

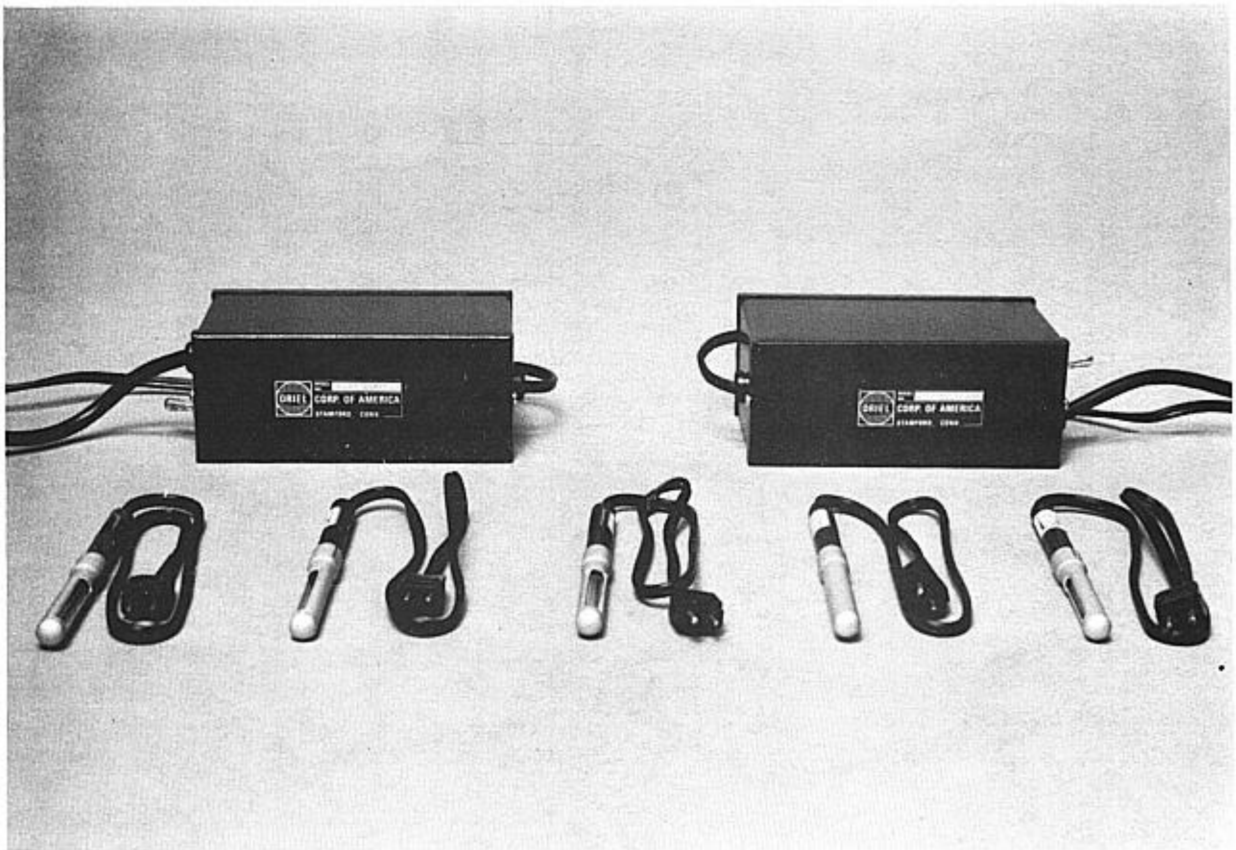

Figure B-7. Oriel C-13-96 spectral lamps.

Oriel 6340
Point source
Arc

This point source is a 0.18 mm diameter tungsten "point" heated by electron bombardment from an inert gas arc. The resulting incandescent point is round and highly uniform with an average brightness of 25 cd/mm^2 and an approximate temperature of 3000°K.

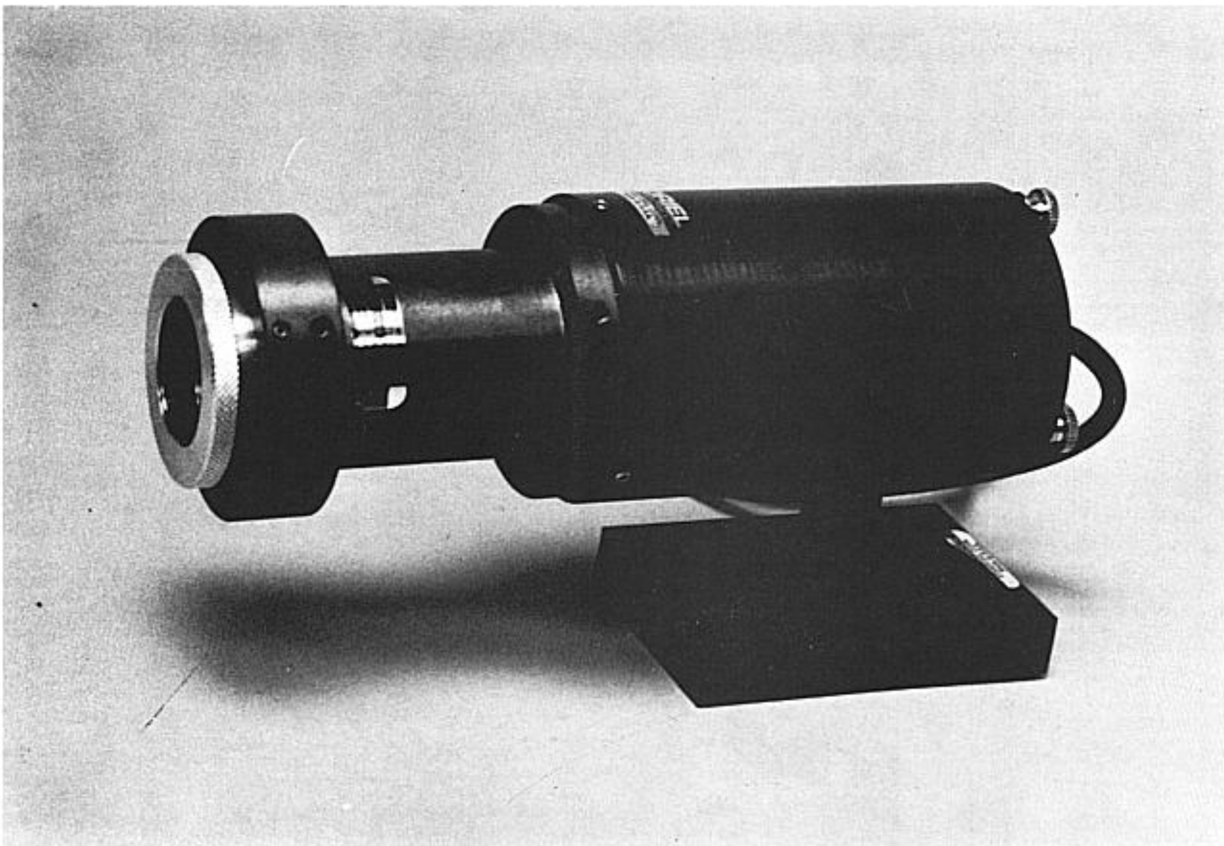

Figure B-8. Oriel 6340 point source, arc.

Oriel 6363
Infrared source

This infrared element continuously radiates in the 1.0 to 25 micron range. The 6.2 mm diameter rod is 100 mm long with a center of silicon carbide (carborundum) providing a 6.2 mm diameter by 20 mm active area. It is heated by electric current with the capability of operating up to 1000°K.

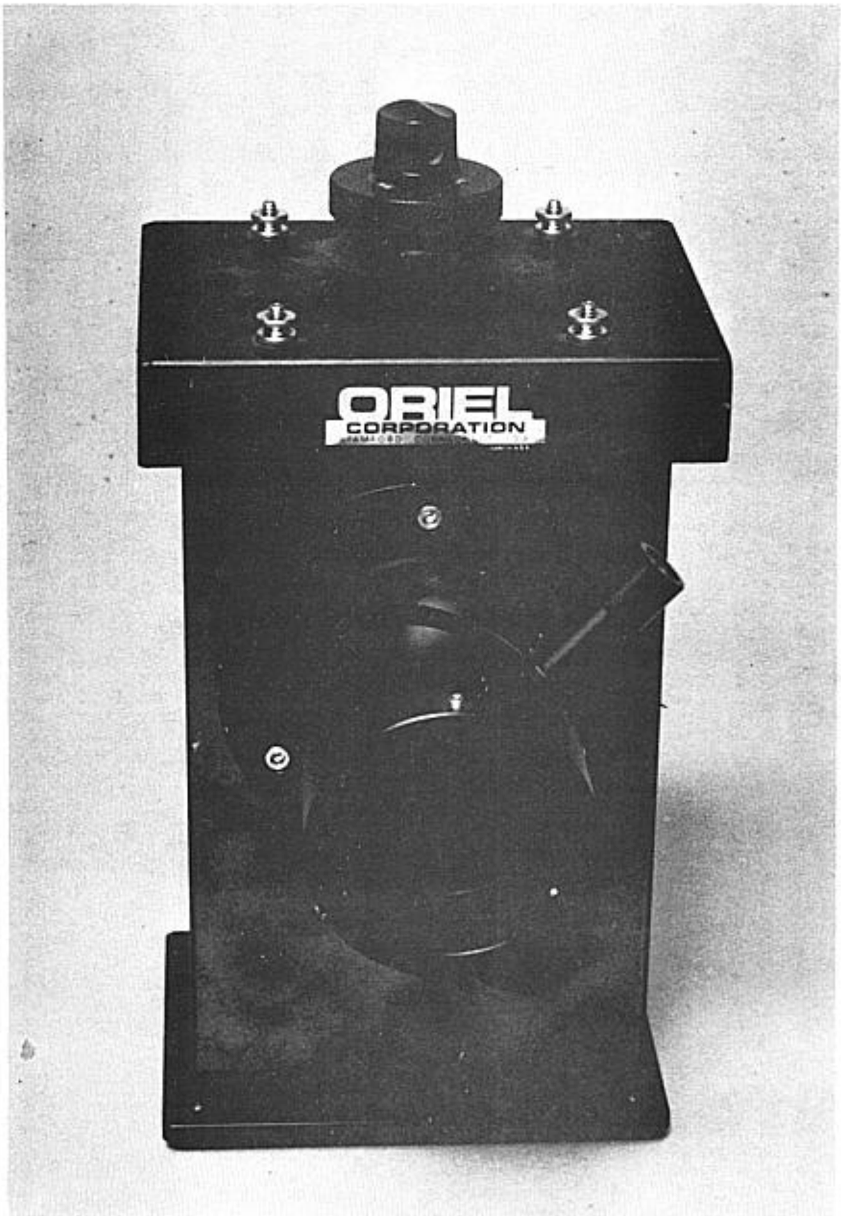

Figure B-9. Oriel 6363 infrared source.

Oriel 6611
HeNe
Research laser

This 3 milliwatt helium neon laser delivers a highly stable 0.8 mm diameter beam at 632.8 nm that is polarized with single spatial mode and is concentric with the tube housing.

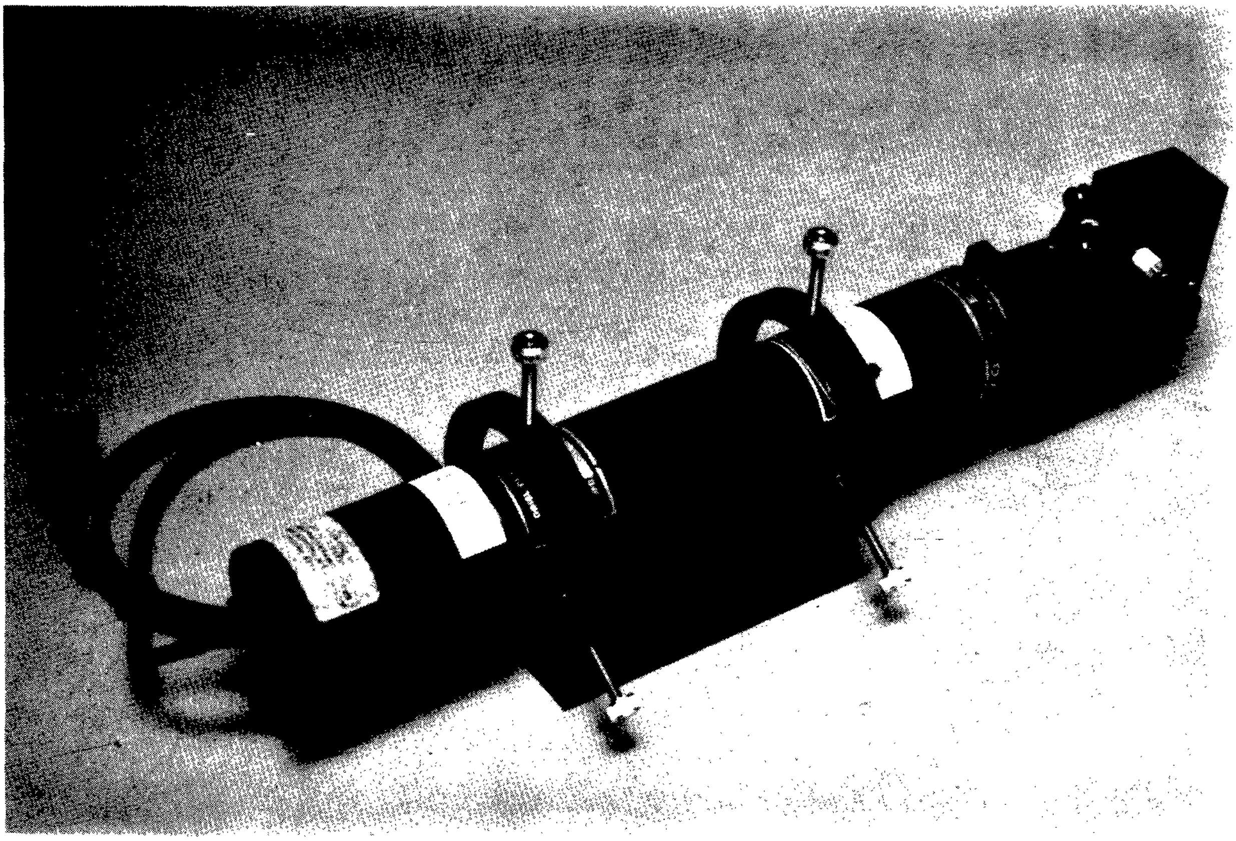

Figure B-10. Oriel 6611 HeNe research laser.

Photo Research
PR 2301
Tungsten lamp

Luminance reference source for PR-1980A system has a luminance of 9.0 footlamberts.

Figure B-11. Photo Research PR 2301 tungsten lamp.