PHOTOMETERS

A *photometer* is an instrument for measuring light. The science of light measurement is called *photometry.* Light in the present context is electromagnetic radiation that can be detected by the human eye, extending from a wavelength of about 360 nm at the blue end of the spectrum to about 830 nm at the red end; the actual limits depend to some extent on the individual. The terminology of photometry is covered in Refs. 1 and 2.

THREE BASIC CLASSES OF PHOTOMETERS

The earliest form of photometers used the human eye as a detector. The eye, because of its accommodation to light and other physiological factors, cannot be used to quantify light with accuracy, but it does rather precisely discern differences in brightness. This is the basis of the *visual (subjective) photometer.* This type of photometer, first developed in the nineteenth century, allows an observer to visually compare light from two (test and reference) sources. The sources illuminate adjacent screens as they are viewed simultaneously. The distances between the sources and screens are adjusted until a match in brightness of the screens is observed. The light output of the test source can then be calculated from the known intensity of the reference (known) source and the measured distances between the sources and the screens using the inverse square law (explained below). One embodiment of visual photometer is called a *bench photometer,* shown schematically in Fig. 1.

Beginning in about 1940, another type of photometer using an electronic detector instead of the eye came into use, the *photoelectric (objective or physical) photometer.* In this type of photometer, a photoelectric detector converts light into an electrical current. In its most basic form, this current, which is proportional to the amount of incident light, is measured by observing the deflection of the needle of a galvanometer, as shown schematically in Fig. 2. Photoelectric photometers range from small, battery-powered portable instruments to large, precise laboratory instruments. Such physical photometers are made to mimic the human eye in terms of spectral response. The relative spectral responsivity of the average human eye was defined by the International Commission on Illumination (CIE) in 1924, and is generally called the $V(\lambda)$ function, see Ref. 3.

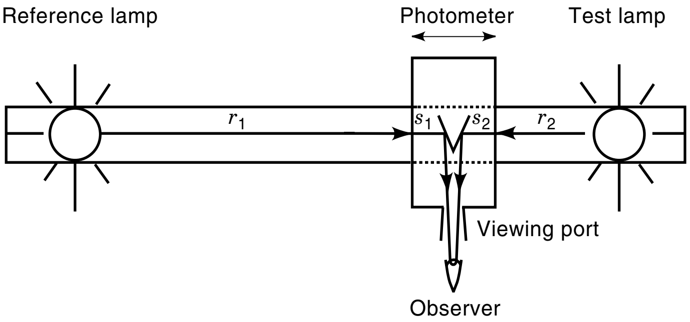

Figure 1. Schematic of a bench photometer. The distances between the photometer head and the lamps, r_1 and r_2, are adjusted until screens S_1 and S_2 appear to the observer to be of equal brightness.

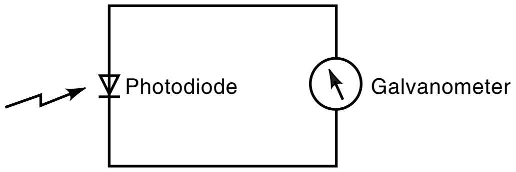

Figure 2. Schematic of the basic photoelectric photometer. An electrical current generated within the photodiode is proportional to the intensity of the light being measured. The deflection of the galvanometer is proportional to the light intensity.

In addition to the two basic types of photometers, a number of specialized photometers have been developed. Rather than measure the quantity of light directly, these instruments either measure parameters that have some relationship to the amount of incident light or have some relationship to the amount of light absorbed or scattered from a light beam. Unlike the former two types of photometers, these specialized photometers may not necessarily measure light according to the spectral response of the human eye. All three types (visual, photoelectric, and specialized) are described in detail in this article.

UNITS OF PHOTOMETRY

The photometric quantities used in this article are *luminous flux* [light output of a source, in lumens (lm)], *luminous intensity* [luminous flux emitted per unit solid angle, in candelas (cd)], *luminance or brightness* [luminous flux emitted per unit area per unit solid angle, in candelas per square meter (cd/m^2)], and *illuminance* [incident luminous flux per unit area in lux (lx)]. The units are Système International (SI) (see RADIOMETRY).

THE DISTINCTION BETWEEN PHOTOMETERS AND RADIOMETERS

The distinction needs to be made between a photometer and a radiometer. While the photometer is designed to have a spectral response range equivalent to that of the human eye, a radiometer generally has a spectrally uniform response and is used to make measurements at wavelengths outside and, in some cases, inside of the visible range as well. The equivalent to photometry in this sense is radiometry. In some countries, the translated word for photometer has the same meaning as radiometer. A few exceptional cases where a specialized photometer senses radiation outside of the visible range will be noted in this article.

VISUAL PHOTOMETERS

As described above, visual photometers depend on the ability of the human eye to match the brightness of two adjacent screens, one illuminated by a reference source, the other by a test source. We will describe the bench photometer mentioned above in more detail. The luminous intensity of the test lamp, assumed to be a point source of light, is calculated from the positions of the test and reference lamps and the known intensity of the reference lamp using the inverse square law,

Figure 3. A commercially available bench photometer. The photometer is moved in relation to the two light sources located near the ends of an optical bench until equal brightness on two fluorescent disks is observed through the eyepiece. (Courtesy of PASCO scientific.)

$$E = I/r^2$$

This law states that the illuminance (E) at the given distance (r) from a light source is directly proportional to the luminous intensity of the source (I) and inversely proportional to r^2.

When the observed illuminance levels on the two screens are the same, the unknown intensity can then be calculated using

$$I = I_0(r/r_0)^2$$

where I and I_0 are the luminous intensities of the test and reference lamps, respectively, and r and r_0 are the corresponding distances from the screen.

In addition to its use to measure unknown sources, the bench photometer can be used together with calibrated light attenuating filters to demonstrate the inverse square law. A commercially available bench photometer is shown in Fig. 3. This photometer is normally attached to an optical bench, which allows it to be moved between sources located near each end of the bench. Fluorescent disks are used as screens in the instrument shown in the figure; the conical tube is the eyepiece.

Another form of visual photometer, which is similar to the bench photometer, is called the *wax* or *grease-spot photometer*. A flat surface is coated with either wax or grease to make it translucent. Light coming from both sources can be observed from one side of the translucent material until both the greased (or waxed) areas have the same observed brightness.

The *Lummer–Brodhun photometer,* or contrast light box, is a more sophisticated and compact from of visual photometer. This instrument consists of a several prisms (as well as mirrors in some designs) arranged to allow a viewer to see adjacent screens through an eyepiece while moving the sight box between the two sources. This is a more compact, flexible configuration than the bench style of instrument, but works on the same principle. The basics of visual photometry, including the *Lummer–Brodhun* photometer, are discussed in Hausmann and Slack (4).

If the colors of the two lamps are not matched, it is difficult for an observer to compare to the brightness of the two screens. To solve this problem, the *flicker photometer* was developed. In this instrument, light from the two sources is alternately imposed on a screen at such a rate that the observer can no longer discern that there are two colors. Measurement is made when the sources are adjusted so that the observer is no longer aware of flicker.

Visual photometers are rather cumbersome to use and depend on the observer's subjective ability to make contrast or flicker distinctions. Photometry became a much more exacting and easily implemented science with the advent of the photoelectric detector. Photoelectric instruments have largely supplanted visual photometers; visual instruments are rarely used today except for educational purposes.

PHOTOELECTRIC PHOTOMETERS

Photoelectric photometers depend on the ability of certain nonmetallic materials or combination of materials to generate an electric current in the presence of light. The first photoelectric detector used to any great extent was the selenium cell. Selenium is a polycrystalline, nonmetallic element and is used in photovoltaic (i.e. generating an electric current without an external electrical power source in the presence of light) detection devices. Selenium cells were widely used for illuminance meters, photographic light meters, and many other applications until the early 1980s. These early day detectors could drive a sensitive galvanometer movement without use of an external power source, making them ideal for portable light meters. The selenium detector has a spectral response (i.e., response as a function of wavelength) that overlaps the visible region and the spectral response of most photographic films.

Today the silicon detector has replaced selenium cells. Silicon is an element used as a detector in single-crystalline form. The material is doped with small amounts of impurities to form a barrier junction where current is generated by entering photons. Silicon has a significant response that overlaps the visible region. This detector can be used in either photovoltaic mode or photoconductive mode, the latter requiring an external current source. When used in either mode, the electric current is proportional to the incident light over several decades. A special optical filter is used to match the spectral response to that of the average human eye, the V-lambda or $V(\lambda)$ function (see Fig. 4). An operational amplifier (also called a current-to-voltage converter or transimpedance amplifier) is generally used to convert the detector's output current to a voltage proportional to the light signal. This output voltage is detected using a calibrated readout device (analog or numerical display) (see Fig. 5).

Photomultiplier tubes may be used as detectors in place of silicon detectors for increased sensitivity, especially toward the short-wavelength end of the visible spectrum.

A representative high-accuracy laboratory photoelectric photometer is shown in Fig. 6. This instrument may be con-

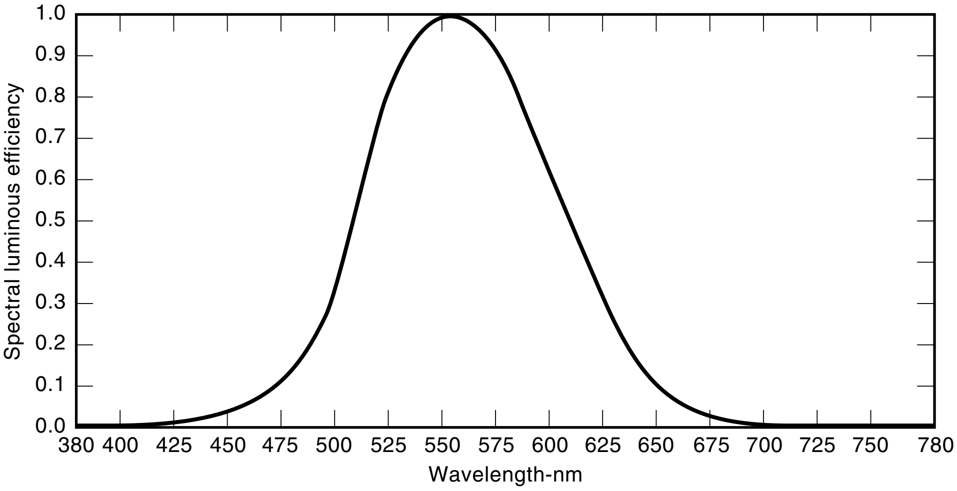

Figure 4. Photopic spectral luminous efficiency function, $V(\lambda)$, for CIE 1924 standard photometric observer.

figured to measure luminous flux, luminous intensity, luminance, or illuminance. The unit on the right is used to measure luminance or luminous intensity; the operator aims the detector head at the area to be measured by looking through a viewfinder. To measure illuminance, a cosine receptor consisting of a transmitting diffuser or an integrating sphere is used as an alternative detector head. Some laboratory photometers can be computer-controlled and can be configured with a number of program-selected detector heads connected to one controller. An instrument designed to measure only illuminance or luminance is called an illuminance meter (or illuminometer) or luminance meter respectively.

An instrument for measuring the total luminous flux is called an *integrating sphere photometer.* It consists of two joined hemispheres coated on the inside with a light-scattering, diffuse white material, typically barium sulfate. The spheres can be opened so that a light source can be placed inside. After the hemispheres are closed to form a sphere, all of the light emitted by the source is captured inside of the sphere and scattered uniformly in all directions by a number of interreflections between the sphere wall surfaces. A detector is attached to the side of the sphere and produces a signal proportional to the total flux emitted by the source. One or more diffuse white baffles are placed inside the sphere, so the detector does not receive light directly from the source; only light that has been reflected from the sphere wall (i.e., the light scattered a number of times off of the sphere's surface and baffles) will reach the detector. An example of an integrating sphere photometer is seen in Fig. 7.

The fundamentals of photoelectric detectors and transimpedance amplifiers are covered in Deboo and Burrous (5).

SPECIALIZED PHOTOMETERS

The word *photometer* has its roots in the Latin word *photometrum,* from *phot-* (light) + *metrum* (meter), and is used in the

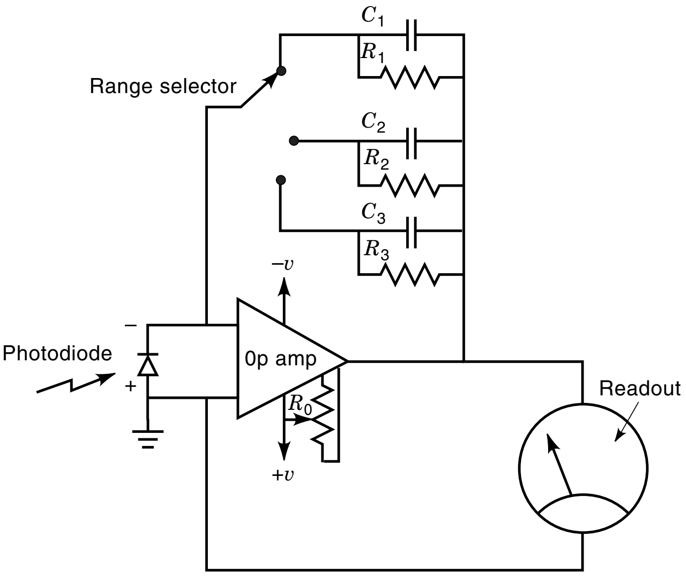

Figure 5. Schematic of silicon detector operated in photovoltaic mode with operational amplifier and readout device. Resistors R_1 to R_3 are used to set the sensitivity range, and resistor R_0 is used to set the zero. Bypass capacitors, C_1 to C_3, are used to suppress alternating-current noise.

Figure 6. A high-accuracy laboratory photometer. The programmable controller is on the left, and a detector head for measuring luminance or luminous intensity is on the right. (Courtesy of Optronic Laboratories.)

Figure 7. Two-meter-diameter integrating sphere photometer. (Courtesy of the UK's National Physical Laboratory. Copyright © Crown 1998. Reproduced by permission of the Controller of HMSO.)

broadest sense to describe a number of instruments used to make light measurements. The visual or photoelectric photometers described previously are instruments for directly measuring one or more of the photometric quantities. The present section will describe examples of different types of photometers that measure quantities directly related to the amount of light or the amount absorbed or scattered by various substances.

The *photographic light meter* or *exposure meter* is an example of a photometer calibrated in other than photometric units. In one form of light meter, the deflection of a needle is proportional to light level. The instrument is constructed so that when a manually aligned pointer coincides with the needle, the photographic exposure (*f*-stop and exposure time) corresponding to the preset film speed can be read directly from a dial. One variant of this concept includes light meters integral to the camera itself, so that the aperture and speed can be adjusted to match needles while looking through the camera's viewfinder. Modern exposure meters, such as the one shown in Fig. 8, use digital displays to indicate exposure. Some light meters are manufactured to read either incident or reflected light; some are calibrated in photometric units as well as units of exposure.

A number of photometers are designed for measuring the optical properties of substances. The word *colorimeter* is used to describe photometers for chemical analysis based on light absorption by either the test substance or a chemical product of the test substance obtained by use of a reagent. These instruments consist of one or more light sources, narrow band-pass interference filters for selecting wavelengths specific to the substance being measured, and a detection system. Some of them employ a transparent sample holder (cell, ampoule, or curette). A measurement is taken with an empty sample holder in place, and a second measurement is taken with a sample in the holder. The ratio of the two measurements is a measure of the opacity of the sample at the selected wavelength and can be converted to the amount of a specific substance in the sample.

An example of this type of photometer is the *water analysis photometer*. A typical instrument of this type has five filters in the visible region, uses a blue-enhanced silicon photodiode detector, and can measure 40 water parameters. An example is shown in Fig. 9.

Another example of this type of photometer is the *flame photometer,* also called an *atomic-absorption photometer*. Rather than using liquids, the flame photometer burns the test substance in propane or natural gas. Here the strength of absorption lines from the burned substance at filtered wavelengths are a measure of the amount of unknown in a given amount of substance. An *optical-emission spectrometer* is similar to a flame photometer except that an electric spark rather than a flame is used to vaporize the sample.

A *light-scattering photometer* makes use of the light-scattering properties of particles suspended in a jet of gas. Light from particles is primarily scattered in the forward direction, so the detector is aimed at angles looking toward the forward direction of the incident light. This technique can be used to obtain particle size distributions in clean-room environments, clouds, smoke stacks, and so on. Lasers are generally used in this application, because they are monochromatic (single

Figure 8. A modern photographic exposure meter with digital readout. The translucent white diffuser is used for incident light measurements. (Courtesy of the Minolta Corporation.)

wavelength) and highly collimated so that the scattering volume can be accurately defined. An instrument for measuring airborne particles is called a *nephelometer.*

Some photometers are very specific to a given profession or industry. For example, a specialized photometer for measuring blood hemoglobin is called a *hemoglobinometer.* A specialized photometer for evaluating the brightness of paper and similar products is called a *brightness meter;* it measures the diffuse reflectance of the paper in the blue range of the spectrum. A similar instrument, the *glossmeter,* is used to measure specularly reflected light from a flat sample, with the incident and reflected light making the same angle with the test surface. A *saccharimeter* is a type of photometer for analyzing the concentration of sugar solutions based on the angle of rotation of plane-polarized light passing through the sample. Photometers utilizing polarization are known as *polarimeters.*

A *spectrophotometer* consists of a light source, a monochromator, a sample space, and a photodetector. In one type, wavelengths are selected by using a scanning monochromator, where a diffraction grating is rotated to select the appropriate wavelengths. Another version uses a grating and diode array detector, which simultaneously detects multiple wavelengths at discrete intervals. These instruments are made to operate in the infrared (*infrared spectrophotometer*), ultraviolet (*ultraviolet spectrophotometer*), and visible regions of the spectrum. Sometimes a spectrophotometer will have two independent channels (reference and test), referred to as a *dual-beam spectrophotometer.* A portable, abridged dual-beam, array detector spectrophotometer is shown in Fig. 10.

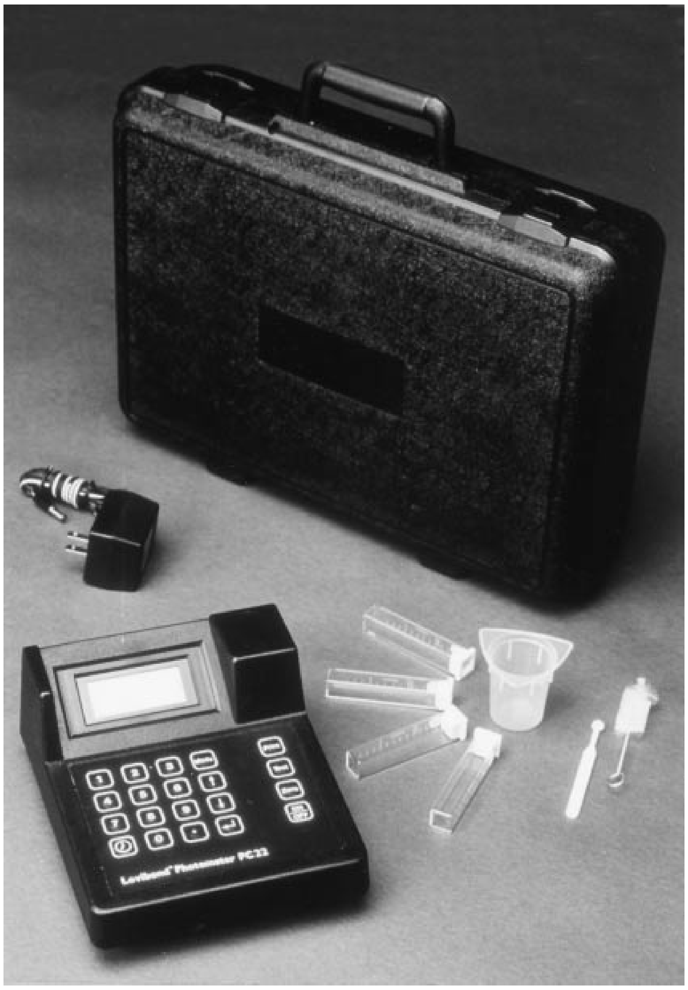

Figure 9. A single-channel, microprocessor-controlled photometer used to measure impurities in water. The transparent cells shown on the right each hold 10 ml of water and reagent. (Courtesy of VWR Scientific Products.)

Figure 10. Portable, dual-beam, array detector spectrophotometer used for making precision color measurements. The sample material is illuminated by a pulsed-Xe lamp built into the instrument. (Courtesy of GretagMacbeth, © 1998. GretagMacbeth™ is a trademark of GretagMacbeth LLC. All rights reserved. Color-Eye® is a registered trademark of GretagMacbeth LLC. All rights reserved.

Additional information on specialized photometers can be found in Horton (6).

SUN PHOTOMETERS

The *sun photometer* is one of the more interesting and complex types of photometers and deserves special mention. This instrument is used to measure certain optical properties of the earth's atmosphere, and information about atmospheric constituents can be derived from these measurements. Since there is increasing interest in the effects of ozone depletion, atmospheric pollution, and water vapor on visibility, health effects, air quality, and global warming, there is increasing interest in this type of photometer. A sun photometer consists of a basic filtered photometer in which the viewing field-of-view has been limited (typically to about 2°) by use of a tube containing one or more apertures. Sun photometers can be used either on the ground (terrestrial) or from an airborne platform. The optical path between the instrument and the sun must be cloud-free.

The instrument is aimed at the sun either manually or with an automatic solar tracker, so that it is measuring incoming solar energy over a narrow wavelength band (typically 10 nm wide) of radiation coming directly from the sun (plus a small scattered component). Since certain atmospheric constituents attenuate and/or scatter solar radiation in a wavelength-dependent way, information about the atmospheric constituents can be measured at the appropriate critical

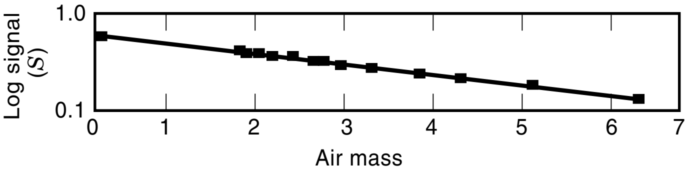

Figure 11. Langley plot of log signal versus air mass. The y-axis interception of the best linear fit to the data gives the calibration constant V_0 for the instrument.

wavelengths. Sun photometers are used to measure atmospheric aerosol optical thickness (turbidity), ozone, and water vapor. Measurements taken at discrete wavelengths can be entered into atmospheric transmission models that calculate an approximation to the entire solar spectrum.

Operation of the sun photometer is based on Beer's law, namely,

$$S(\lambda) = S_0(\lambda)e^{-\delta(\lambda)M}$$

where

$S(\lambda)$ = the terrestrial signal at wavelength λ
$S_0(\lambda)$ = the extraterrestrial (i.e., outside the earth's atmosphere) signal at λ
$\delta(\lambda)$ = the total optical depth at λ
M = the relative air mass

Taking the log of both sides of this equation,

$$\ln S(\lambda) = \ln S_0(\lambda) - \delta(\lambda)M \tag{1}$$

yields a linear equation with dependent variable $S(\lambda)$, independent variable M, slope $\delta(\lambda)$, and y-axis intercept $S_0(\lambda)$. A plot of this equation (Fig. 11) is called a Langley plot, in honor of its inventor.

The relative air mass M is defined as unity at the zenith; neglecting atmospheric refraction, it is the relative atmospheric path length through the atmosphere, namely,

$$M = 1/\cos(\theta)$$

where θ is the angle between the zenith and the solar position.

The total optical path, $\delta(\lambda)$, is composed of three components:

$$\delta(\lambda) = (p/p_0)\delta_R(\lambda) + \delta_0(\lambda) + \delta_a(\lambda) \tag{2}$$

where

p/p_0 = ratio of surface atmospheric pressure to reference atmospheric pressure, $p_0 = 101.3$ kPa
$\delta_R(\lambda)$ = Rayleigh (molecular) scattering optical depth at λ
$\delta_0(\lambda)$ = ozone optical depth at λ
$\delta_a(\lambda)$ = aerosol optical depth at λ, also called turbidity

$\delta_a(\lambda)$ can be determined from any reading $V(\lambda)$ under cloud-free conditions, solving Eq. (1) for $\delta(\lambda)$ and calculating $\delta_a(\lambda)$ from Eq. (2) since $\delta_R(\lambda)$ values are available as a function λ and $\delta_0(\lambda)$ can be estimated based on location on the earth's surface and date.

A sun photometer is calibrated by taking successive readings throughout a clear, stable (pristine) day, determining a best-line fit to the Eq. (1), and then calculating $V_0(\lambda)$, the y-axis intercept. The World Meteorological Organization (WMO) recommended wavelengths are 368, 500, 778, 675, and 862 nm, with either 5 nm or 10 nm band pass (see Ref. 7). Typical field of view for these instruments is 2.3°. A four-channel sun photometer with solar tracker is shown in Fig. 12.

In addition to measuring aerosol optical depth, sun photometers can be used to measure the amount of water vapor in the atmosphere using channels centered in the near infrared at 862 nm and either 942 nm or 1020 nm. The 862 nm channel is an atmospheric transmission window; that is, there is no significant absorption of solar radiation by water vapor or aerosol, while there is a significant water vapor absorption band centered at 942 nm and 1024 nm. The amount of precipitable water vapor as a function of optical transmission can be derived from fundamental equations of optical transmission. A good reference on sun photometry is found in Ref. 8. Note that in this case the wavelengths used for water vapor determination are outside of the visible region.

A simple hand-held sun photometer can be constructed for around $25. Rather than use an expensive filter and detector combination, a red light-emitting diode (LED) is used as detector. In this reverse role, the LED generates a voltage proportional to the incident optical signal at its normal radiating wavelength. This instrument can be used to monitor atmo-

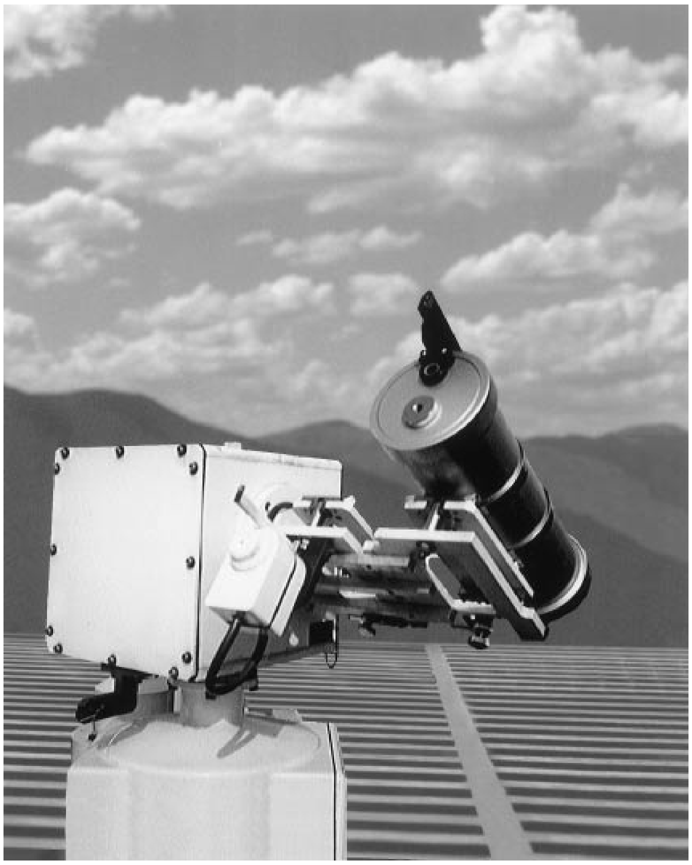

Figure 12. Automatic four channel sun photometer. (Courtesy Eko Trading Co., Ltd.)

spheric pollution and haze [see Carlson (9) and visit the Concord web site (10)].

CALIBRATION OF PHOTOELECTRIC PHOTOMETERS

Calibration of photoelectric photometers is based on a unit of luminous intensity, the candela. The candela was originally defined in 1948 by the Conférence Générale des Poids et Mesures (CGPM) as 1/60 of the luminous intensity per square centimeter of a blackbody at the solidification temperature of platinum (2042 K). This calibration was based on basic physical principles—that is, the Stefan–Boltzmann radiation law for blackbody radiators. A point source of 1 cd luminous intensity radiates one lumen of luminous flux into a solid angle of one steradian. However, this old definition using the platinum blackbody was difficult to achieve. The advent of the highly accurate electrical substitution radiometer made it possible in 1979 to redefine the candela as "the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiance intensity in that direction of (1/683) watt per steradian."

In the United States, the candela is maintained on a set of eight *standard photometers* maintained at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. Each standard photometer consists of an Si detector, a $V(\lambda)$ filter, and an electronic amplifier. The $V(\lambda)$ filter is matched to each detector to give a response representative of the average human eye. Each detector is calibrated for its radiometric response by interpolation of its spectral response (A/W) measured using a high-accuracy cryogenic radiometer (HACR) at selected stabilized laser beam wavelengths over the visible portion of the spectrum. The illuminance responsivity scale (A/lx) is realized by adding a precision aperture (to define the detector's sensitive area) and an accurately characterized $V(\lambda)$ filter. Since the illuminance can now be accurately measured and the geometry can be well established, luminous intensity (cd) of transfer lamps can be accurately measured using the standard photometers.

The NIST luminous flux unit (lm) is defined from the detector-based candela using a calibrated integrating sphere photometer. Calibration is implemented by introducing a precisely measured amount of flux into the sphere from external standard lamps. Lamp standards are then calibrated by placing them inside of the calibrated integrating sphere.

An NIST standard of luminance is realized by use of a calibrated integrating sphere source. Using the standard photometers, precision apertures at the sphere's exit port, and precise aperture-to-photometer distance, the luminance at the aperture plane is established. A reference luminance meter is used as a working standard for routine calibrations.

The NIST provides photometric calibration services for photometer heads, luminance meters, and illuminance meters. Artifacts used to calibrate photometers include lamps calibrated in units of luminous intensity, luminous flux, and illuminance at specified distances. Integrating sphere calibration sources are calibrated by NIST in units of luminance (see Fig. 13). Intercomparisons of photometers and artifacts between national standardizing laboratories are used to ensure the integrity of standards throughout the world. A detailed description of photometric units and photometric calibration techniques used at NIST can be found in Ohno (11).

Figure 13. Integrating sphere uniform source for luminance calibration of photometers and imaging systems. (Courtesy of Labsphere Inc., North Sutton, NH)

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