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SPECTRAL ULTRAVIOLET MEASUREMENTS AND UTILIZATION OF STANDARDS

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Spectral Ultraviolet Measurements and Utilization of Standards

Introduction

Accurate spectroradiometric measurements in the ultraviolet region of the spectrum involves the proper use of exceptionally high quality instrumentation and calibration standards. This paper describes the essential components of an automated spectroradiometric measurement system and discusses the selection and proper use of calibration standards. The effects of wavelength accuracy and precision, sensitivity, linearity, slit function, stray light, scanning speed, input optics, temperature dependence, and system calibration on the overall performance of the measurement system is discussed with particular emphasis given to the problems unique to measuring solar ultraviolet spectral irradiance.

Spectroradiometric Instrumentation

Spectroradiometers determine how radiation is distributed across the optical spectrum. The essential components of an automated spectroradiometer include: a tunable optical dispersive mechanism, a photodetector and signal detection system, an automatic wavelength drive, a motorized second order blocking filter wheel, appropriate input optics, an automatic data reduction system with system calibration and measurement software, and appropriate calibration standards. A block diagram of an automated spectroradiometric measurement system is shown in Figure 1.

The principle component of a spectroradiometer - the optical dispersive element - is the device used to isolate or "break-up" the spectrum of a radiating source into it's spectral components. It may be a diffraction grating, prism, interference filter or interferometer. The most common type of optical dispersive element, by far, is the diffraction grating monochromator. Diffraction gratings are optical elements, either plane or concave, with surfaces having a large number of equidistant grooves that reflect or transmit incident radiation in directions as a function of wavelength. Gratings can be obtained with different groove densities and different peak wavelength efficiencies. The three principle factors that determine spectral resolution or bandwidth of a grating monochromator are: focal length of the collimating and imaging mirrors; grating groove density; and entrance and exit slit widths. Monochromators have either (1) fixed, non-removable slits, (2) multiple sets of interchangeable slits, or (3) adjustable slits. Precision interchangeable fixed slits are recommended as they ensure repeatability. Adjustable slits are subject to non-repeatabilities, thus, requiring recalibration after every slit width change.

Monochromators can be obtained in single or double grating configurations. Two single monochromators mounted back to back on a single, rigid frame comprise a double monochromator. Double monochromator based spectroradiometers (Figure 2) are essential for obtaining accurate measurements in the ultraviolet.

Spectroradiometers employing multi-channel detectors, such as charge-coupled devices (CCD) and photodiode arrays (PDA), can perform measurements in much shorter times. However, while it is possible, in theory, to produce meaningful spectroradiometry from such systems, the practical difficulties are generally ignored by many of their users. Multi-channel spectroradiometric systems use a single monochromator without an exit slit (spectrograph). Spectrographs, by virtue of having no exit slit, generally exhibit much higher stray light levels than single spectrometers which in turn have much higher stray light levels than double monochromators. This severely limits the use of multi-channel devices for measurements in the UV as they are not compatible with double monochromators.

High quality monochromators have precision, automatic wavelength drives and motorized second order blocking filter wheels to eliminate second order (harmonic) spectra and reduce the effect of scattering and stray light.

Most measurements in the ultraviolet require the use of a PMT (photomultiplier) detector as they are generally thousands of times more sensitive than uv-enhanced silicon photodetectors. PMT's can be obtained with different cathode sensitivities. A solar blind response PMT is exceptionally useful for the 200 to 320 nm range while an S-20 response PMT is sensitive over the entire 200 to 800 nm wavelength range.

The means by which a detector signal is acquired, amplified and processed is designated as the "signal detection system". Spectroradiometers can employ DC amplification, AC synchronous lock-in amplification, or photon counting methods of signal detection. When used with silicon or PMT detectors, a well designed DC amplification signal detection system is generally slightly superior to the AC synchronous lock-in amplifier. Photon counting is the most sensitive of the signal detection systems; however, it has a more limited dynamic range. Cooling of the detectors reduces the dark current and ultimately increases the sensitivity. Table 1 gives general detector specifications for silicon, solar blind PMT's, and S-20 response PMT's when operated at different temperatures and with DC amplification and photon counting type signal detection systems.

A well designed spectroradiometer system capable of performing a variety of optical radiation measurements will have a wide selection of input optic modules along with the appropriate standards for calibrating the system as an integral unit. The input optics refers to the front end optics used to collect and transfer the incident optical radiation into the measurement system. The various types of input optics that can be used with a spectroradiometer consist of cosine collectors, telescopes, microscopes, fiberoptic probes, and field-of-view baffle attachments. Under certain measurement conditions, no special input optics are needed.

Present day spectroradiometric systems can be automated in either of two ways: by interfacing the spectroradiometer to a computer or by employing complete on-board microprocessor control of all crucial functions. Both options require appropriate software. Automated measurement systems are available with software that combines data reduction and utility programs with measurement application software for a completely integrated operating package. It enables the user to control: shutter, wavelength scan, filter trip points, start/stop/pause, wavelength scan, PMT voltage, graphic data display, wavelength and system spectral response calibration, and spectral measurement. In addition, a well designed spectroradiometer will have built in protection against misuse by detecting "flux overload" conditions. When the current generated by the PMT reaches a preset level, this important feature automatically turns off the PMT's bias voltage before damage to the PMT occurs. It is also quite useful if the acquired data is stored in an ASCII format that can be accessed by off-the-shelf statistical and graphical software packages to produce data in a user defined format.

Calibration Standards

A well characterized spectroradiometer is calibrated for wavelength accuracy and spectral sensitivity. Wavelength calibration can be performed to 0.1 nm or better using any of a number of different line emission sources - mercury arc lamps, lasers, etc. Some grating monochromators have provision for performing automated wavelength checks by scanning above and below the zero order. This procedure can be performed using either continuous or line emission sources.

High accuracy, NIST traceable, 1000-watt, tungsten-halogen lamp standards of spectral irradiance are available for calibrating spectroradiometers for spectral irradiance response to wavelengths as low as 250 nm. The operation and use of these standards requires (1) careful positioning, alignment and orientation of the standards, (2) proper shielding between the lamp standard and the spectroradiometer in order to eliminate reflections, and (3) setting the lamp current as accurately as possible. An error of 0.1% in the current setting of the lamp standard will generate a 1% error in the spectral irradiance of the standard at a wavelength of 250 nm. Accordingly, a precision, constant current DC power supply that has a current uncertainty of ± 0.01% or less should be used to operate the tungsten lamp standards. The errors associated with positioning, alignment, and orientation as well as shielding of the lamp can be significantly reduced by using plug-in, pre-aligned standards as shown in Figure 3.

Deuterium lamp standards are available for calibrating spectroradiometers for spectral irradiance response to wavelengths as low as 200 nm. Although deuterium lamps are also quite sensitive to positioning and must be properly shielded to reduce unwanted reflections, they are not as sensitive to current settings as the tungsten lamp standards. Plug-in, pre-aligned, deuterium lamp standards of spectral irradiance are also available. In all cases, the spectroradiometer's configuration must be exactly the same when calibrating the system for spectral response as it is when using the system to make spectral measurements.

Measuring Solar Spectral Irradiance

The accurate measurement of solar UV spectral irradiance is considerably more difficult and much more complex than measuring the spectral output of most other types of light sources. The exponential decrease in the spectral irradiance of sunlight with decreasing wavelengths, coupled with the relatively large amount of solar irradiance at longer wavelengths, puts very stringent requirements on the measurement instrumentation. The region of particular interest is the UVB band, ranging from 280 to 320 nm. For extraterrestrial solar radiation, the UVB portion comprises about 1.4% of the total solar flux. After attenuation by the earth's atmosphere, however, the percentage of UVB reaching the surface (including direct and scattered solar flux) is reduced to about 0.4% of the total. Figure 4 shows the typical relative spectral irradiance of sunlight on a linear scale over the wavelength range of 295 to 800 nm. Figure 5 is a semi-log plot of the same irradiance data over the abbreviated wavelength range of 295 to 320 nm. From an analysis of this data, the critical performance parameters that the measuring spectroradiometer must have can be determined.

Wavelength Accuracy and Repeatability - The difference between the actual (true) wavelength and the wavelength setting is the wavelength accuracy. Wavelength precision (repeatability) is the accuracy to which a wavelength setting can be repeatedly set. Wavelength accuracy and precision can be expressed in units of wavelength (i.e. nm, μm. etc.) or as a percentage of wavelength setting. When measuring solar spectral irradiance, small errors in the wavelength accuracy of the monochromator will lead to relatively large errors in the measured spectral irradiance. For example, as shown in Table 2 an error of 1 nm in the wavelength calibration of the monochromator will produce an irradiance error of almost 119% at 300 nm. At longer wavelengths, the effect of a 1 nm wavelength error is less severe (7% at 350 nm and a only 0.1% at

600 nm). The ability to set and reset a particular wavelength is similarly critical at the shorter wavelengths.

Stray Light - Stray light is radiant flux at the exit slit of the monochromator caused by either a) random scatter from mirrors, gratings, etc. or b) directional scattered light such as reflections, re-entry spectra, grating ghosts and grating generated focused stray light. The out-of-band rejection of the monochromator can be more critical than wavelength accuracy and repeatability. The integrated irradiance over the entire band from 295 to 800 nm is 3×10^{-2} W/cm², while the irradiance over a 1 nm bandwidth at 295 nm is 9×10^{-9} W/cm². The ratio of these two values is 3×10^{-7}. If the stray-light rejection of the monochromator at 295 nm is 10^6, the out-of-band flux incident on the detector will be 10 times greater than the actual spectral irradiance at 295 nm, producing an error of 1000%. Accordingly, a stray light rejection of at least 10^8 is required in order to make accurate measurements. In actual fact it is the signal at 295 nm vs. the integrated signal = irradiance x responsivity which should be compared for stray light. This is one reason why stray light is worse in the UV - the system response is lower than in the visible.

Bandwidth - The full width of the bandpass of the monochromator at the half power wavelengths is referred to as HBW (half-bandwidth) or FWHM (full width at half maximum). The bandwidth of the monochromator must be relatively narrow in any region where the flux is changing rapidly with wavelength. However, as the bandwidth is decreased, the flux incident on the detector is also decreased. For broad band sources, reducing the monochromator slits from a 10 nm HBW to a 1 nm HBW actually decreases the flux on the detector by a factor of 100. Depending on the situation, 1 to 2 nm HBWs are generally recommended.

Sensitivity - The sensitivity of a spectroradiometer configured for measuring spectral irradiance is generally expressed as the NEI (noise equivalent irradiance) and is the spectral irradiance level that generates a detector signal equivalent to the detector's electrical noise level. An extremely low NEI is essential for measuring UV solar spectral irradiance. For example, to measure spectral irradiance levels at 295 nm of 9×10^{-9} W/cm²nm with a 100:1 signal-to-noise ratio requires an NEI of 9×10^{-11} W/cm²nm. For measurements below 295 nm, an even lower NEI is required.

Dynamic Range and Linearity - The dynamic range of a detection system covers the minimum level that can be measured to the maximum level before saturation or damage to the detector occurs. A detection system that is linear over the useful dynamic range of the system has a constant response or constant calibration factor over this range. As can be seen from Figures 4 and 5, the dynamic range of the detection system must be linear for at least six orders of magnitude. A set up for determining linearity of spectroradiometers is shown in Figure 6. The radiating port of a continuously variable, integrating sphere calibration standard is placed directly in front of the entrance slit of the double grating monochromator. The radiance of the sphere source can be accurately attenuated over a dynamic range of 10^7 without changing the color temperature. Thus, the linearity of the entire detection system can be verified as a function of wavelength over seven decades.

Scan Speed - Since the spectral output of sunlight changes with time, the scanning time must be minimized. For the UVB range, recording data at a rate of about 1 to 2 data points per second is generally sufficient.

Stability - A spectroradiometric measurement system must maintain its calibration for both wavelength and spectral irradiance response over prolonged periods. To reduce both long and short-term changes in sensitivity and drifts in detector dark current, temperature stabilization of the detector and auto-zeroing of dark current prior to each scan are essential. The use of low thermal expansion components in the monochromator to increase stability is also recommended.

Input Optics - For measurements of global solar spectral irradiance, the input optics or collecting optics must have a good cosine response. In addition, the diffuse solar radiation produced by Raleigh scattering is polarized, with the degree of polarization dependent on the scattering angle. Thus, the collecting optics should also serve as a depolarizer. Although a number of transmitting type cosine collectors are available, they have a limited angular cosine response and are also wavelength dependent. These factors lead to relatively large errors when measuring global radiation. By far the most efficient cosine receptor is a properly designed integrating sphere as shown in Figure 7. Figure 8 plots the cosine response as a function of angle and wavelength and Figure 9 plots the deviation from an ideal cosine response as a function of wavelength.

System calibration - As previously stated, both wavelength and spectral irradiance standards are required to ensure accurate measurements. In most cases, the plug-in standards are the easiest to use and significantly reduce errors associated with positioning and stray reflections.
In general, calibration of the spectroradiometer for spectral irradiance response can be made with a transfer uncertainty of about ± 1%.

Portability - Since most solar spectral irradiance measurements are made in non laboratory environments, an automated spectroradiometric measurement system should be truly portable, rather than merely movable. The system should be compact and sufficiently rugged for shipment and use under harsh conditions. Battery operation is highly desirable, although not truly essential for all measurement situations. The capability of performing field calibration checks quickly and accurately is extremely important. The key optical parameters most susceptible to change during shipment or when subjected to adverse handling are the monochromator wavelength calibration and the gain of the electro-optical system. The ability to verify both in the field is essential. Software that has a "sleep" mode feature to save battery power and on-board programming and data memory capability which will eliminate the need to leave expensive computers in the field is also recommended. Finally, environmental protection is also a key factor. If the system will be left unattended for extended periods in the field, all exposed components of the system (including the computer) should be mounted in an environmental enclosure to protect the measurement system.

Table 1

General Detector Specifications

Detector	Mode	Temperature	Peak λ	NEP @ 300 nm	% of Peak
Silicon	DC	Ambient	960 nm	2-5 x 10^{-14}W	27%
PMT (S-20)	DC	Ambient	400 nm	4 x 10^{-16}W	95%
PMT (S-20)	DC	-20°C	400 nm	5 x 10^{-17}W	95%
PMT (S-20)	PC	Ambient	430 nm	1 x 10^{-17}W	75%
PMT (S-20)	PC	-20°C	430 nm	2 x 10^{-18}W	75%
PMT (SB)	DC	Ambient	200 nm	3 x 10^{-14}W	2%
PMT (SB)	DC	-20°C	200 nm	4 x 10^{-15}W	2%
PMT (SB)	PC	Ambient	200 nm	8 x 10^{-17}W	2%
PMT (SB)	PC	-20°C	200 nm	4 x 10^{-17}W	2%

Integration Time = 5 sec

Table 2

Spectral Irradiance Uncertainty
for
Wavelength Uncertainty of ±1 nm

	Effective Error	
Wavelength	Sunlight	Tungsten Lamp Standard
295 nm	± 253 %	± 3 %
300 nm	± 119 %	± 2.6 %
325 nm	± 17 %	± 2 %
350 nm	± 7 %	± 1.9 %
400 nm	± 5 %	± 1.5 %
600 nm	± 0.1 %	± 0.46 %
800 nm	± 0.4 %	± 0.20 %

Block Diagram of Automated Spectroradiometer

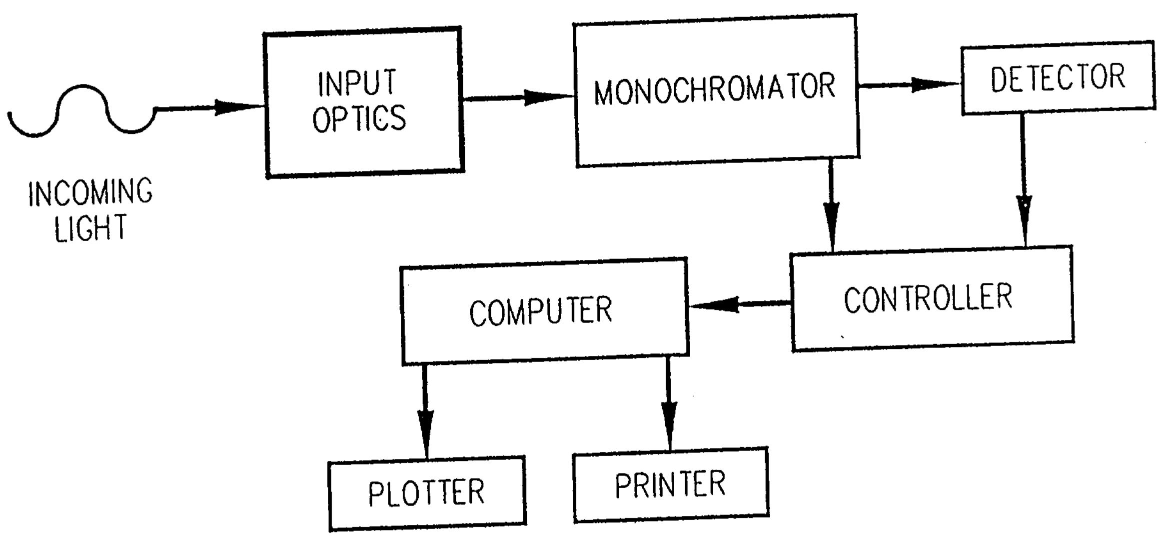

Figure 1

Portable Double Monochromator Based Spectroradiometer

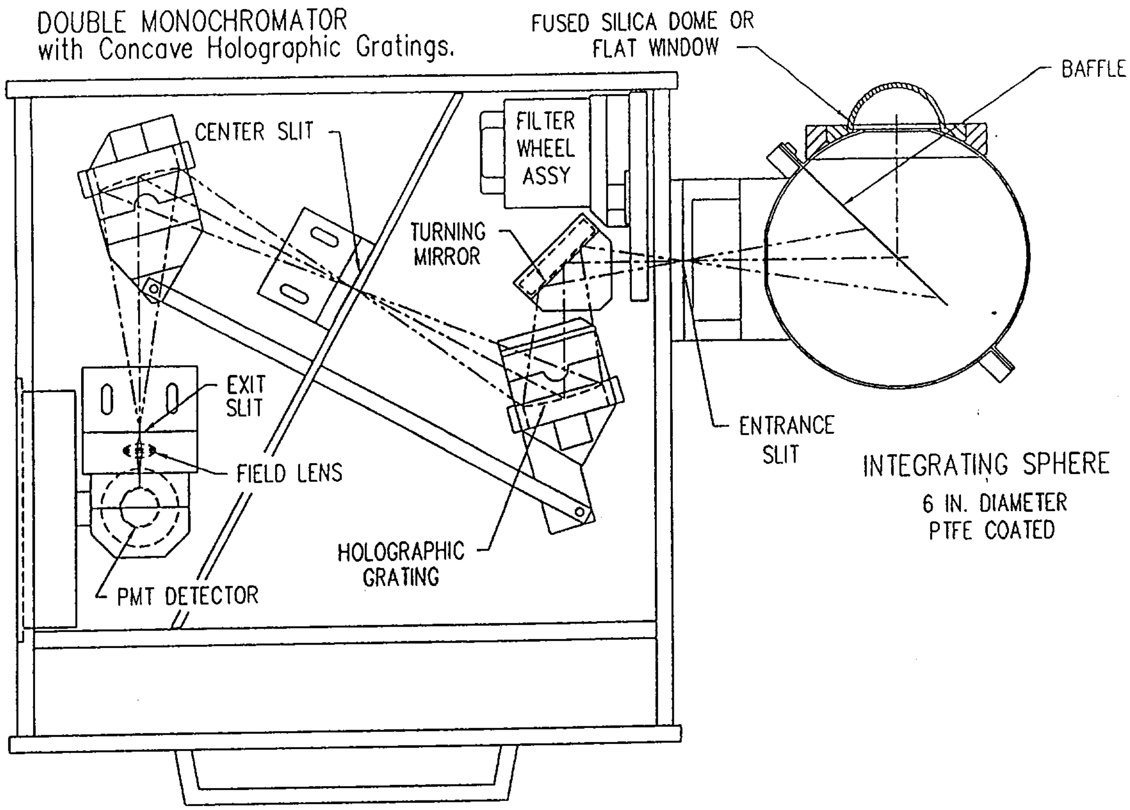

Figure 2

Spectroradiometer Calibration Set-Up Using Plug-In Irradiance Standard

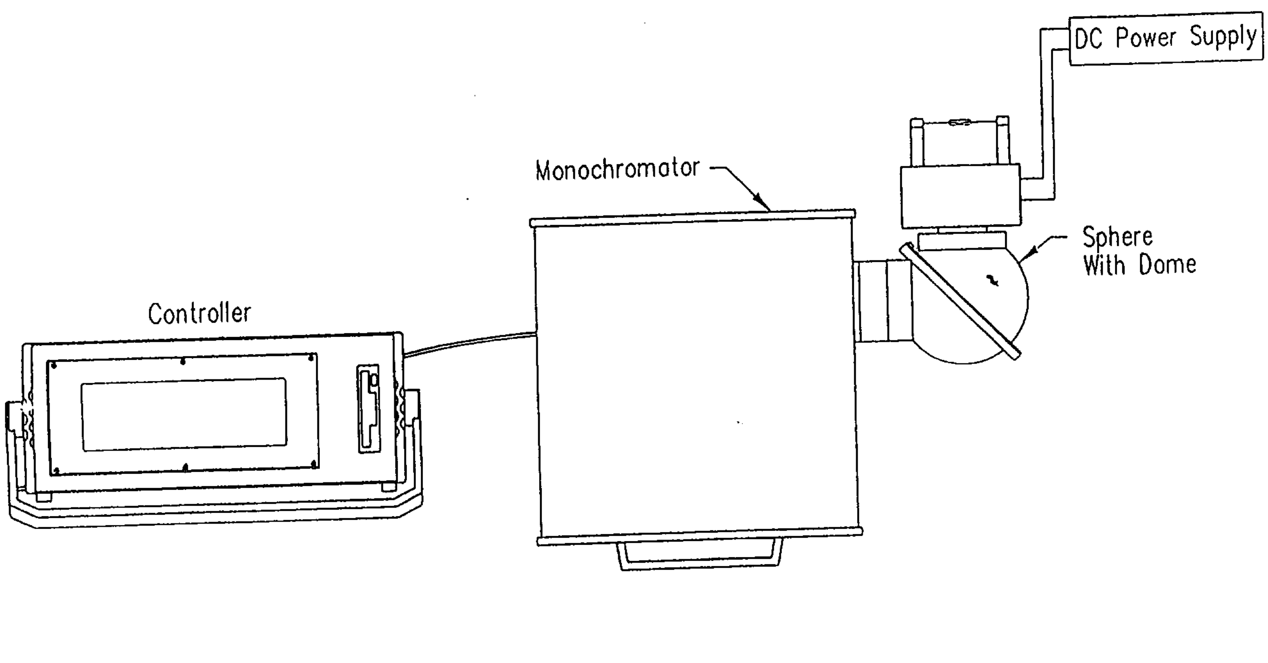

Figure 3

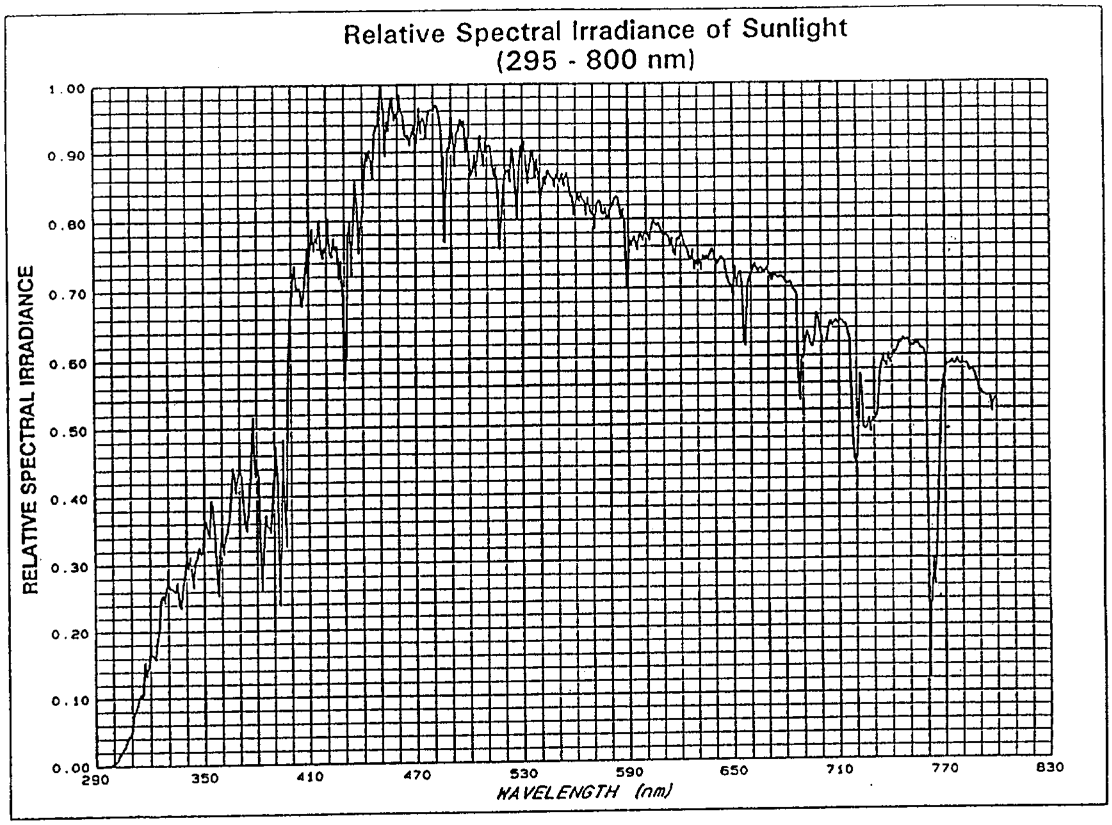

Figure 4

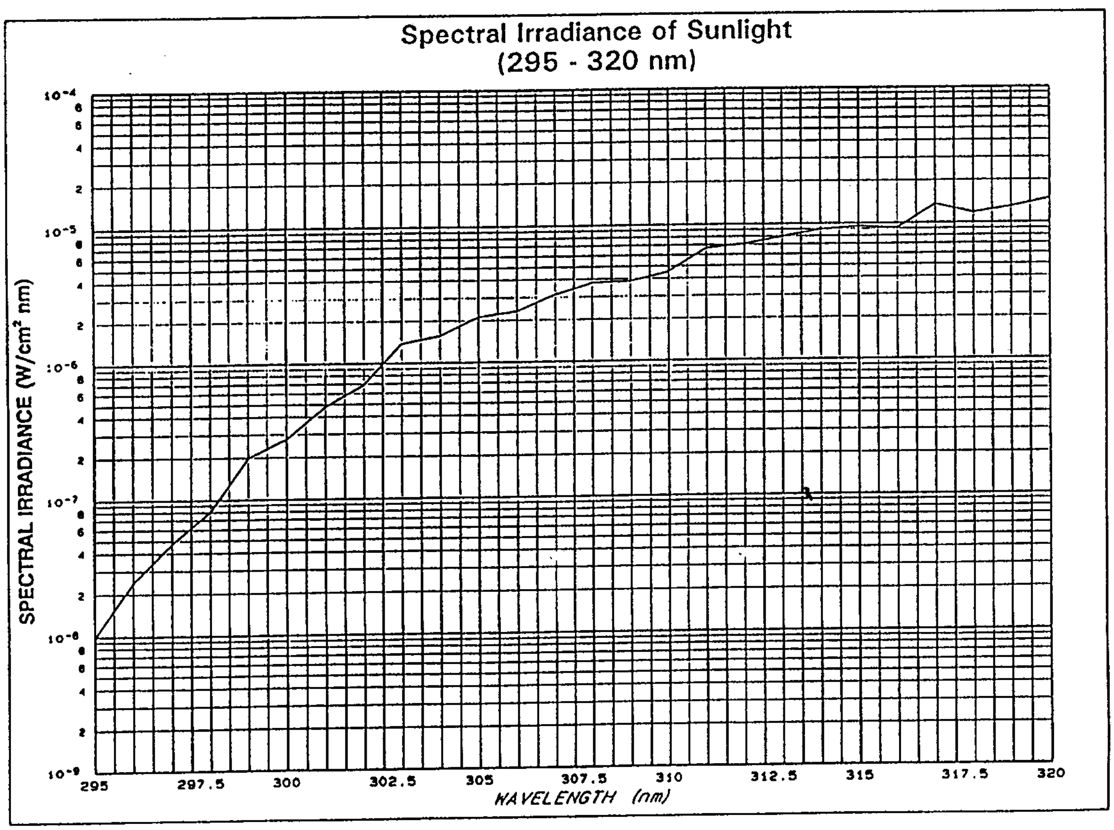

Figure 5

Set-Up for Determining Linearity

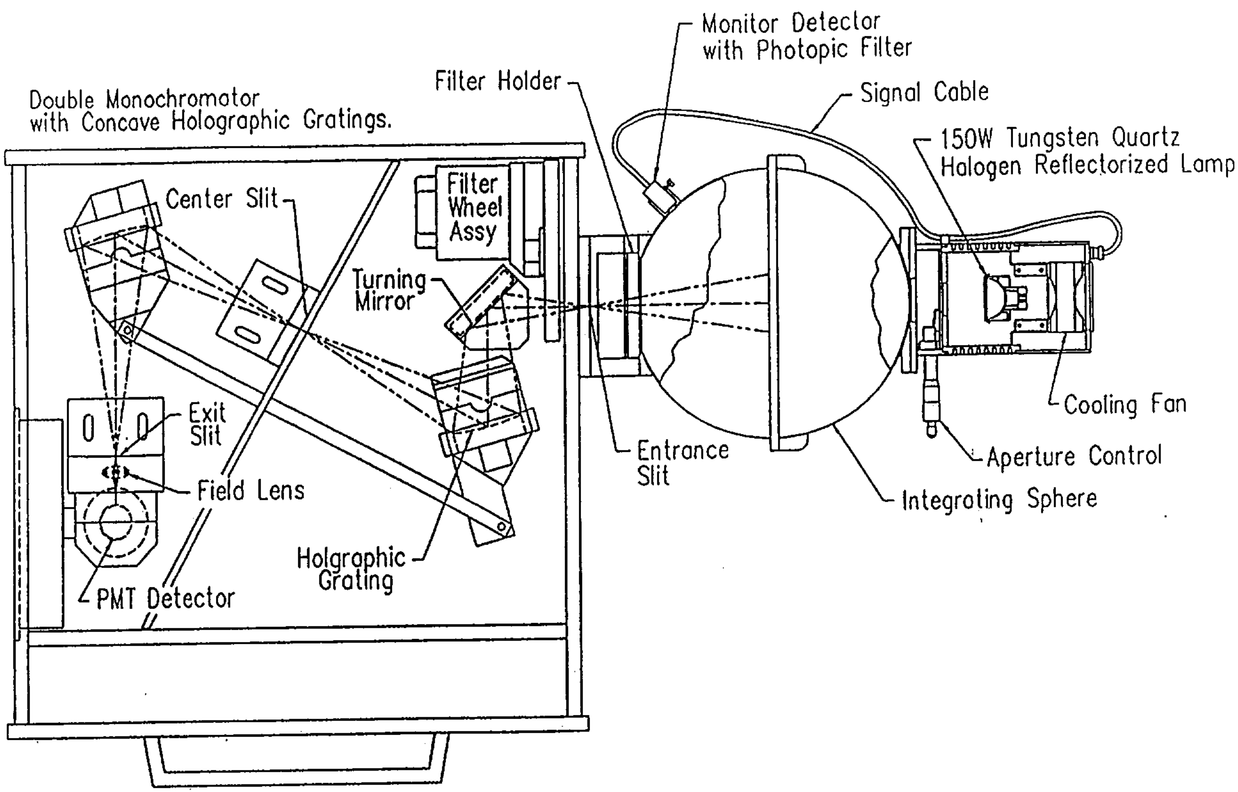

Figure 6

Integrating Sphere - Superior Design

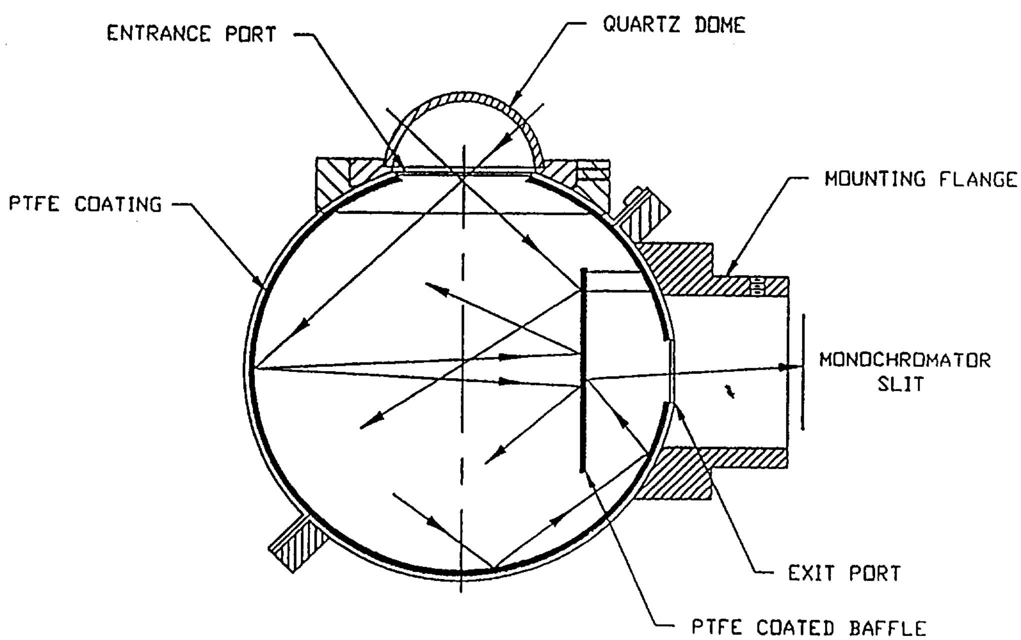

Figure 7

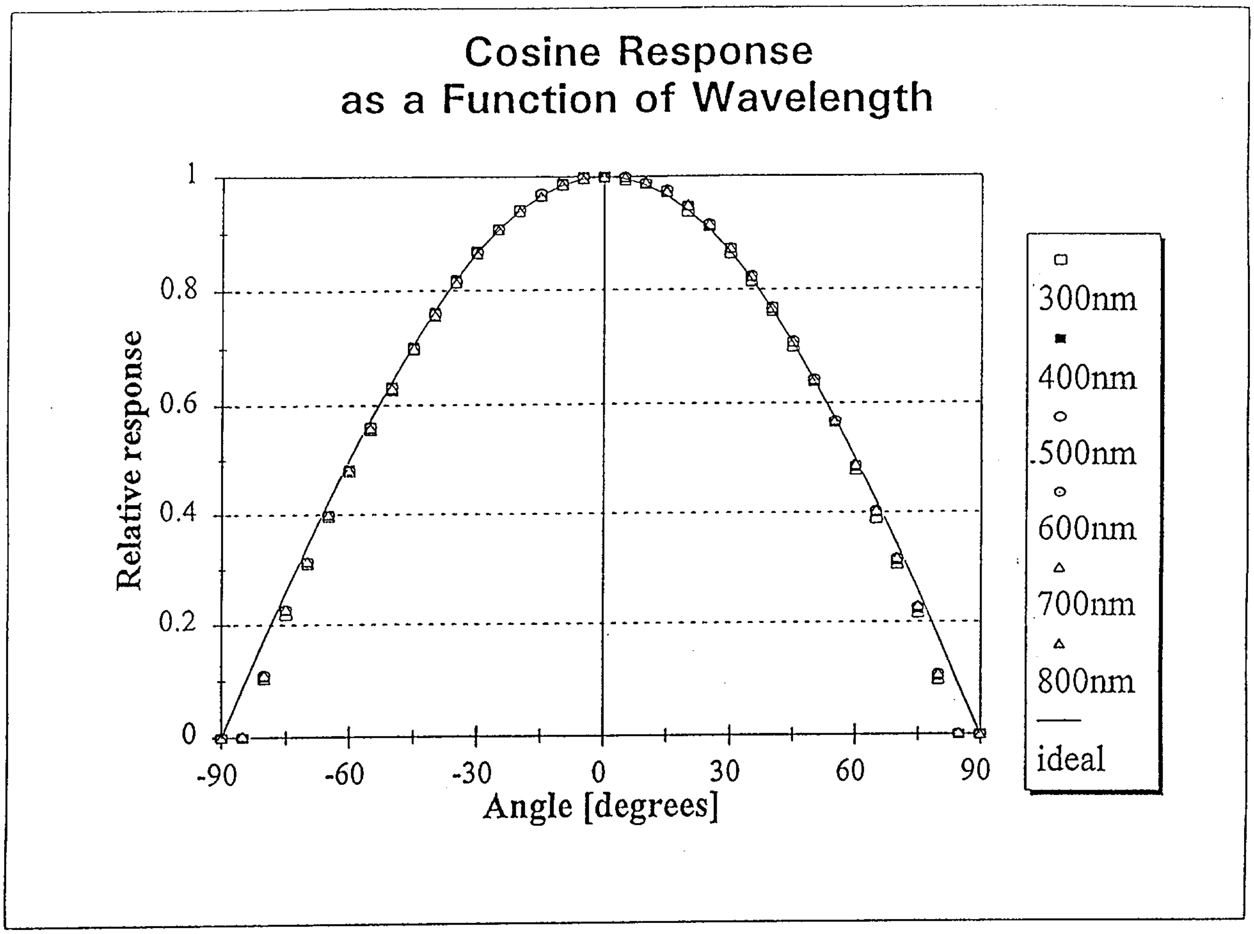

Figure 8

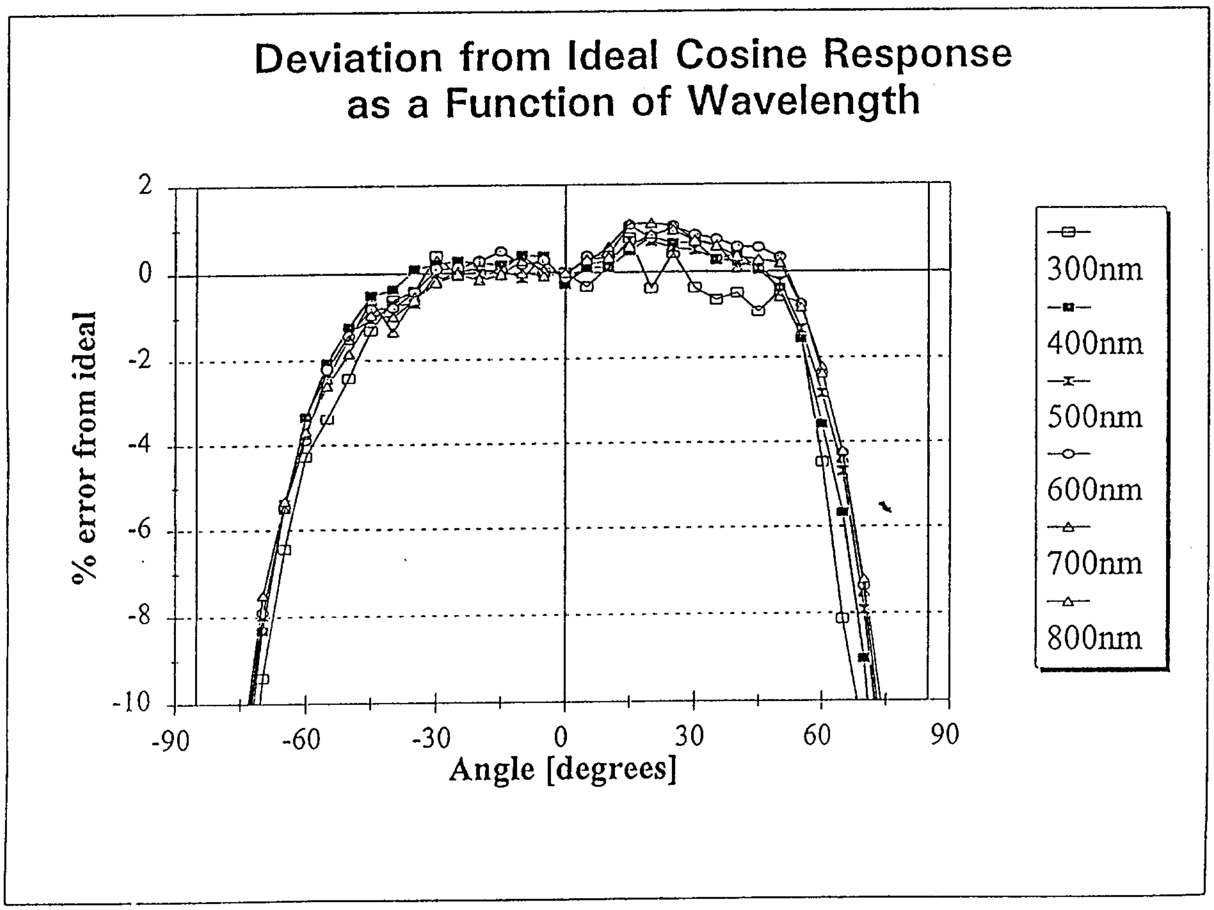

Figure 9