Application Note (A1)

The Measurement of Solar Ultraviolet Spectral Irradiance Problems and Solutions

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1. INTRODUCTION

In recent years, researchers involved in many unrelated scientific disciplines have acquired an interest in accurately determining the ultraviolet spectral irradiance of sunlight. It has become more evident that solar radiation (along with the changing level of its UV component due to changes in the concentration of ozone in the stratosphere) is causing a multitude of far reaching effects.

This paper is oriented toward those researchers that have recently become involved with the measurement of optical radiation and have little training in this area of measurement science. In addition it serves as a review of some basic fundamentals and should be helpful to those researchers that are presently involved with solar spectral irradiance measurements.

The complexity and difficulty of accurately measuring UV solar spectral irradiance is described and the critical optical parameters for the measuring system is discussed. Other desired features in a measurement system such as automation and portability are discussed to a lesser extent.

The paper concludes with a description of the portable measurement system developed by Optronic Laboratories designed specifically for accurately measuring the spectral irradiance of various sources such as sunlight and solar simulators in both laboratory and field environments.

2. CRITICAL OPTICAL PARAMETERS

The accurate measurement of solar UV spectral irradiance is considerably more difficult and much more complex then measuring the spectral output of most other types of "light" sources. The extremely rapid decrease in the spectral irradiance of sunlight with decreasing wavelength coupled with the relatively large amount of solar irradiance at the longer wavelengths puts very stringent requirements on the measuring instrumentation - both optical and electronic. The region of the ultraviolet solar spectrum of particular interest is the UVB region (280 to 320 nm). For extraterrestrial solar radiation, the UVB portion comprises about 1.4% of the total solar flux. However, after attenuation by the earth's atmosphere, the percentage of UVB reaching the earth's surface (including direct and scattered solar flux) is reduced to 0.4% of the total.

Figure 1 shows a spectral scan of sunlight over the spectral range of 295 to 800 nm. The values are normalized to 1.0 at the wavelength of peak output. Figure 2 shows the same spectral scan; however, the values are presented on a semi-log scale.

Figure 3 shows an abbreviated portion of the same scan over the UVB region on a normalized scale. Figure 4 shows the abbreviated scan over the UVB region plotted on a semi-log scale.

Table 1 gives the actual spectral irradiance values in watts/cm5 per nm wavelength interval over the 295 to 355 nm region.

A quick analysis of the spectral plots and the tabular values yields the following:

1. Wavelength Accuracy - A small error in the wavelength accuracy of the monochromator will lead to relatively large errors in the measured spectral irradiance. For example, a 1-nm error in the wavelength calibration of the monochromator will result in an irradiance error of almost 100% at 297 nm. The problem becomes less severe at the longer wavelengths where a 1-nm error around 325 nm results in an error of 10-20% and only a couple of percent around 600 nm.

2. Wavelength Repeatability - The ability to set and reset a particular wavelength is also quite critical at the shorter wavelengths. The same errors resulting from an error in the wavelength calibration of the monochromator also apply to the wavelength repeat-ability.

3. Stray Light - The stray light or out of band rejection of the monochromator is of the utmost importance. It is even more critical than the wavelength accuracy and wavelength repeatability characteristics of the monochromator. The importance for an extremely low stray light level can be readily appreciated when one considers that the integrated irradiance of the spectral values in Table 1 over the wavelength range of 295 to 800 nm is 2.914 X 10^{-2} watts/cm5 and that the irradiance (over a 1 nm band) at 295 nm is 9.822 X 10^{-9} watts/cm^2. The ratio of the irradiance at 295 nm to the total irradiance is 3 X 10^{-7}. If the stray light rejection 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. This will result in an error of 1000%.

4. Bandwidth - The HBW (half bandwidth) of the monochromator must be relatively narrow in order to make accurate measurements in the UVB range (or 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. Reducing the monochromator slits from a 10 nm HBW to a 1 nm HBW actually reduces the flux on the detector by a factor of 100. A factor of ten reduction is due to the slit area (which is ten times smaller) and a factor of ten is due to the small bandwidth. Two wide a bandwidth however, can also increases the stray light. Depending on the situation, 1 to 5 nm HBW's are recommended.

5. Sensitivity - An extremely low NEI (noise equivalent irradiance) is, of course, desirable. Table 1 shows that spectral irradiance at 295 nm is 9.822 X 10^{-9} watts/cm^2 nm. In order to measure this level with a 100:1 signal noise ratio, an NEI of 9.922 X 10^{-11} watts/cm5 nm is required. For measurements of sunlight below 295 nm, an even lower NEI is required. However, measurements can be made with signal to noise ratios of 10:1 and in some cases, signal to noise ratios of 1:1 may be acceptable. This can occur when measuring sunlight below 295 nm with relatively narrow slits.

6. Dynamic Range - Since the spectrum of sunlight can easily vary by six decades over the UV-visible region, the dynamic range of the detection system must also be six decades (as a minimum). In addition, the system must be linear in response over this range.

7. Scan Speed - Since the spectral output of sunlight can change significantly with time, the scanning time must be kept to a minimum. Unfortunately, all rapid scan or diode array type measurement systems have extremely serious deficiencies and are not at all suitable for measurements of UV-visible solar spectral irradiance. For the UVB range, it appears that recording data at a rate of about one data point per second is required for obtaining accurate spectral irradiances.

8. Stability - The ability of a spectroradiometric measurement system to maintain its calibration (for both wavelength and spectral irradiance response) over prolonged periods is also of great importance. In order to reduce both long term and short term changes in sensitivity and drifts in detector dark current, temperature stabilization of the detector and auto zeroing of dark current is essential.

9. System Calibration - As mention above, accurate calibration of the system for both wavelength and spectral irradiance response is essential. Wavelength calibration can be performed using any one of a number of different line emission sources, i.e. Hg arc lamps, laser diodes, etc. High accuracy standards of spectral irradiance are available for calibrating the system for spectral irradiance response. However, one must exert extreme care in the alignment and operation of these lamp standards in order to realize the accuracies associated with them. In general, it is possible to calibrate a spectroradiometer relative to the standard lamp and at the standard lamps irradiance level to about ± 1%.

10. Input Optics - Various kinds of optical radiation measurements require specific input optic modules for collecting the radiant flux in a specified geometrical response. For measurement of global solar spectral irradiance, it is important that the input optics or collecting optics have a good cosine response. In addition, the diffuse solar radiation produced by Rayleigh scattering is polarized. The degree of polarization is 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, by far the most efficient cosine collector is the integrating sphere. A properly designed integrating sphere with a highly reflecting, diffusely reflecting coating will serve as a near perfect cosine collector and will also depolarize the incident radiant flux. However, the overall efficiency or throughput of an integrating sphere cosine collector is relatively low. When looking at a point source, the attenuation in detector signal with and without the integrating sphere attached to the monochromator can be as much as 1000.

3. AUTOMATION

In the past, spectroradiometric measurement was a tedious, time consuming task. Many hours were required to calibrate the system for spectral response, collect the data, and calculate and plot the final results. Present day spectroradiometric systems can be automated by either: 1) interfacing the spectroradiometer to a computer, or 2) by employing complete on-board microprocessor control of all crucial functions. Both options require appropriate software for calibrating the system, collecting the data and computing the results.

Basic requirements for automated spectroradiometric systems include:

1) Accurate wavelength data available in a digital form.
2) A precise wavelength motor drive to position gratings within 0.1 nm.
3) A digital motor control interface with remote START, STOP, FORWARD and REVERSE capability.
4) An electronic limit circuit to prevent damage to drive gears by accidentally hitting mechanical limits.
5) A motorized filter wheel mechanism to automatically insert the proper second order blocking filters and shutter in the optical path.
6) An autoranging amplifier system for the detector signal.
7) Digital detector signal and amplifier range signal.

4. PORTABILITY

Since most spectral irradiance measurements that are made on sunlight are made in the field (or in non-laboratory environments), an automated spectroradiometric measurement system should have the following features:

1. Portability - The measurement system should be compact and sufficiently rugged for shipment and use under extremely demanding conditions.

2. Battery Operation - Although not essential for all measurement situations, battery operation of the complete system (spectroradiometer and computer) is highly desirable.

3. Calibration Checks - The ability to perform system calibration checks in the field is extremely critical. The key optical parameters which are 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 of the parameters in the field is essential.

4. Environmental Protection - If the system is to be left unattended for extended periods in the field, all exposed components of system (including computer) should be mounted in an environmental enclosure.

5. OL 752 HIGH ACCURACY UV-VISIBLE SPECTRORADIOMETER.

The optics head consists of a small, high efficiency monochromator and integrating sphere. The ultra-low stray light level required for accurate UV solar spectral measurements is achieved by using a double monochromator with dual holographic gratings. The microprocessor controlled electronics control/display unit is housed in a compact, rugged aluminum enclosure designed for easy portability.

The standard system includes "User Intimate Software"® on ROM, which allows total control of the optics head and basic arithmetic data manipulations. The touch panel display allows the user to interactively control/setup the:

- Shutter
- Wavelength scan
- Filter trip points
- Start/stop/pause wavelength scan
- PMT voltage (200 - 1100V)
- Graphical display of data
- Flux overload set point
- File transfer utilities for the RS 232 or IEEE 488 interface
- Measurement of irradiance
- Scan limits

Additionally, the manual mode allows individual data points at selected wavelengths to be acquired.

Features of the OL 752 system include:

- High wavelength accuracy (+/- 0.2 - 0.3 nm)
- Low stray light (10^{-8} @ 285 nm typical)
- High sensitivity
- Thermoelectrically cooled S-20 PMT detector for improved noise performance
- Computer controlled dark current "auto zero" function
- Integrating sphere input optics module
- Automated second order filter wheel and shutter
- High performance, minimum temperature sensitivity sine bar mechanism for accurate wavelength control
- Plug-in tungsten and deuterium calibration sources to facilitate accurate calibration for spectral irradiance response
- RS 232 interface
- 720 KB (up to 100 scans) data storage on 31/2" MS DOS® compatible disks
- Optional dual wavelength calibration and gain check source module
- Optional battery module for stand-alone field operation
- Optional carrying cases for the optics and electronics modules Optional IEEE 488 communications interface

The OL 752 high accuracy portable spectroradiometer is extremely useful for studies involving:

- Solar radiation
- FDA compliance testing
- Lighting in greenhouses, field plots and growth chambers
- UV - Visible radiation levels in psoriasis chambers, suntanning booths
- Commercial lighting applications
- Solar simulations
- Photoresist

For more detailed information concerning the OL 752, please refer to Optronic Laboratories Bulletin No. 100.

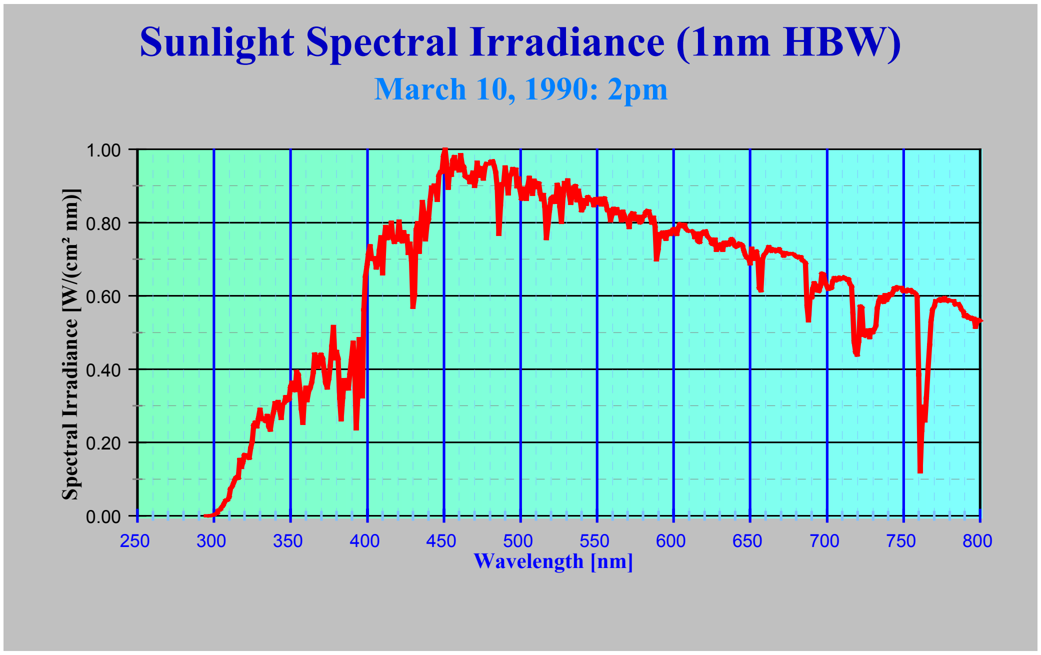

Figure 1

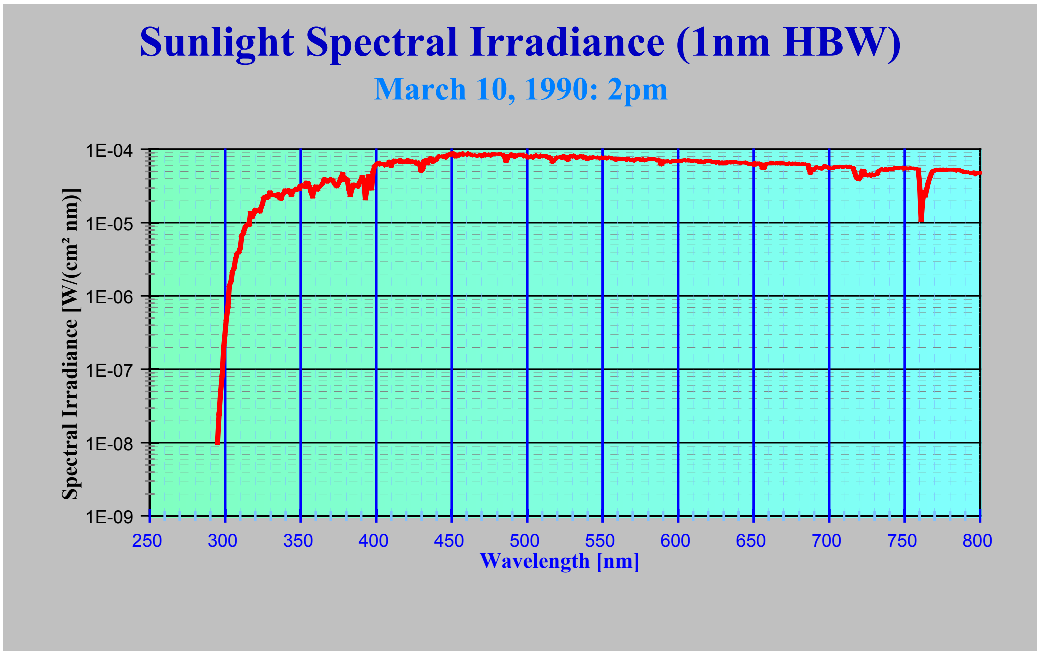

Figure 2

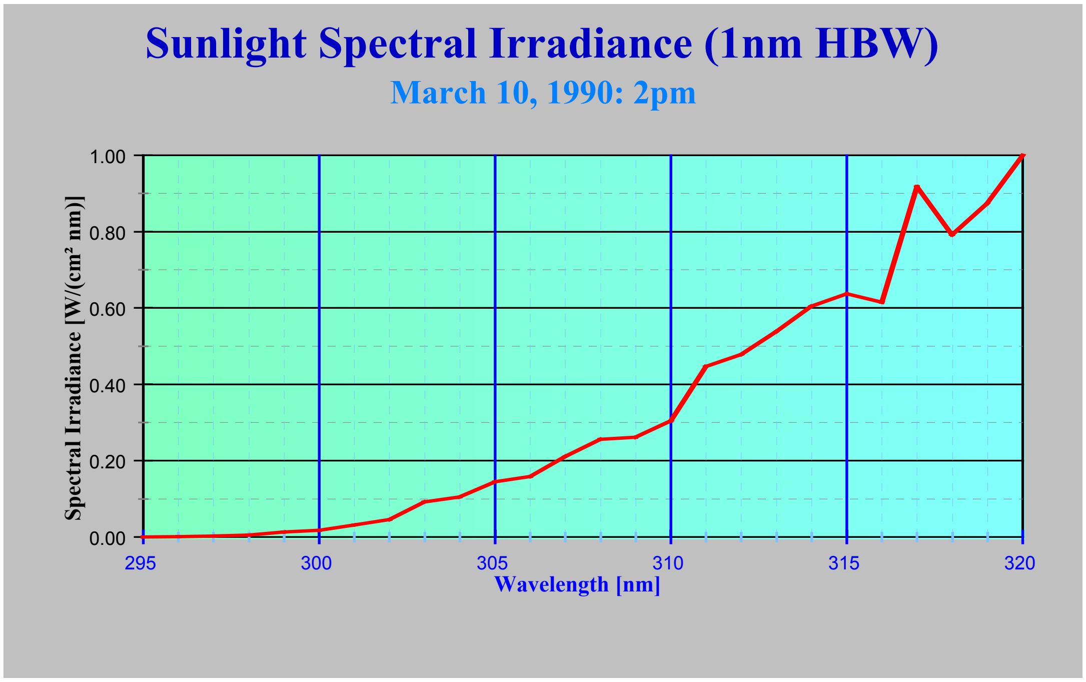

Figure 3

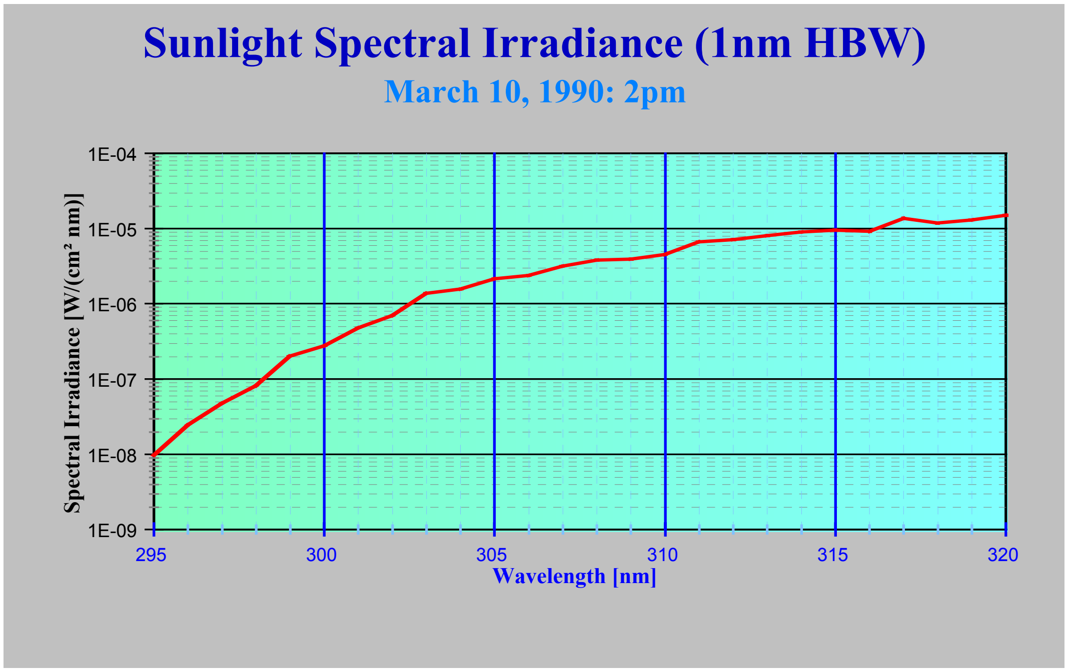

Figure 4

Spectral Irradiance of Sunlight
March 10, 1990 2:00 pm, Orlando, Florida

Wavelength (nm)	Spectral Irradiance (W/cm^{2}nm)	Wavelength (nm)	Spectral Irradiance (W/cm^{2}nm)
295.0nm	9.822E-09	325.0nm	1.812E-05
	2.480E-08		2.219E-05
	4.758E-08		2.285E-05
	8.149E-08		2.173E-05
	2.022E-07		2.380E-05
300.0nm	2.766E-07	330.0nm	2.600E-05
	4.812E-07		2.353E-05
	6.960E-07		2.379E-05
	1.385E-06		2.344E-05
	1.576E-06		2.309E-05
305.0nm	1.167E-06	335.0nm	2.450E-05
	2.385E-06		2.171E-05
	3.163E-06		2.096E-05
	3.830E-06		2.357E-05
	3.919E-06		2.525E-05
310.0nm	4.554E-06	340.0nm	2.758E-05
	6.689E-06		2.621E-05
	7.164E-06		2.792E-05
	8.060E-06		2.575E-05
	9.052E-06		2.376E-05
315.0nm	9.541E-06	345.0nm	2.719E-05
	9.208E-06		2.761E-05
	1.374E-05		2.907E-05
	1.184E-05		2.812E-05
	1.308E-05		2.847E-05
320.0nm	1.496E-05	350.0nm	3.151E-05
	1.476E-05		3.261E-05
	1.467E-05		3.110E-05
	1.408E-05		3.056E-05
	1.661E-05		3.525E-05

* 1 nm HBW