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ABSTRACT

This paper describes an IBM-PC compatible computer program, called Mfactor, developed in the Photovoltaic Device Measurement Laboratory (PDML) at Sandia that uses a generalized procedure for making spectral mismatch corrections. The program operation is described, and several examples are given. A new method to calibrate primary reference cells using a National Institute of Standards and Technology (NIST) lamp in conjunction with Mfactor is also presented.

INTRODUCTION

Reference cells are frequently used to determine incident light intensity during solar cell performance measurements. A problem arises when comparisons are made between cells tested under different spectral irradiances (spectra). This occurs because the short-circuit current of a cell depends on the spectral response of the cell and the spectral content of the test illumination. In addition, the spectral response of the reference cell is often different from the cell under test. The problem is further complicated when short-circuit current is desired under a standard spectrum such as the Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface (ASTM E892-87) or the Air Mass 0 Extraterrestrial Solar Irradiance. The Air Mass 0 spectra adopted for use at Sandia was defined by the World Radiation Center (WRC) and is normalized to 1372 W/m^2 as used by NASA Lewis. To provide short-circuit current under the desired spectral conditions, it is necessary to apply spectral mismatch corrections to the measured short-circuit current of the cell under test. The ASTM standard equation [1] for spectral mismatch calculations is:

$$M = \frac{\int SR_t(\lambda)\, E_t(\lambda)\, d\lambda \int SR_r(\lambda)\, E_s(\lambda)\, d\lambda}{\int SR_r(\lambda)\, E_t(\lambda)\, d\lambda \int SR_t(\lambda)\, E_s(\lambda)\, d\lambda} \qquad (1)$$

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Where:
M - Spectral mismatch parameter (divisor)
SR_t - Measured spectral response of test cell
SR_r - Measured spectral response of reference cell
E_t - Measured spectral irradiance of test spectrum
E_s - Defined spectral irradiance of standard spectrum

The M value is used to correct a measured short-circuit under a test spectrum by dividing this value by M to obtain the current under a desired reference spectrum:

$$I_{td} = \frac{I_{tt}}{M} \qquad (2)$$

Where:
I_{td} - Isc of the test cell under the desired spectrum
I_{tt} - Isc of the test cell under the test spectrum

A more generalized formula for the spectral mismatch correction has been derived and the uncertainty associated with the procedure has been evaluated [2]. This formula allows reference cell calibration under one spectrum, testing using a second, and spectral correction to a third (desired) spectrum. It also allows the reference cell short-circuit current under the test spectrum to be different from its calibration current, as is typically the case for outdoor testing. This generalized method has been incorporated into an IBM-PC compatible program called Mfactor. This formulation uses a spectral mismatch multiplier (SMM) to correct the current measured under a test spectrum to the current under the desired spectrum. The terminology used to define the cells and spectra involved were changed from those used by ASTM in order to clarify the procedure for a variety of potential users. Using SMM as a multiplier gives us:

$$I_{td} = SMM \cdot I_{tt} \qquad (3)$$

The more general equation is:

$$SMM = \frac{I_{rc}}{I_{rt}} \cdot \frac{\int SR_t(\lambda)\ E_d(\lambda)\ d\lambda \int SR_r(\lambda)\ E_t(\lambda)\ d}{\int SR_t(\lambda)\ E_t(\lambda)\ d\lambda \int SR_r(\lambda)\ E_c(\lambda)\ d\lambda} \qquad (4)$$

Where:

SMM = Spectral mismatch multiplier
I_{rc} = Isc of reference cell under calibration spectrum
I_{rt} = Isc of reference cell under test spectrum
SR_t = Measured spectral response of test cell
SR_r = Measured spectral response of reference cell
E_t = Measured spectral irradiance of test spectrum
E_c = Measured spectral irradiance of calibration spectrum
E_d = Measured spectral irradiance of desired spectrum

PROGRAM DESCRIPTION

The software for Mfactor was written in the IBM-Pascal programming language and is menu-driven and window-oriented. The program runs in graphics mode and requires a CGA, EGA or VGA display. It will also support several commercially available pointing devices. Data input includes test cell spectral response, reference cell spectral response, test spectrum, and desired spectrum. The spectrum under which the reference cell was calibrated, the reference cell calibration current and insolation to which it was normalized, and the total insolation of the desired spectrum are read by the program from user-defined data files. The program also allows the user to select an insolation level to which the desired spectrum is normalized, for example 1000 or 1372 W/m^2. The terrestrial photovoltaic community has arbitrarily chosen to normalize the short-circuit current from reference and test cells to an insolation level of 1000 W/m^2 even though the total insolation associated with standard ASTM spectra is not 1000 W/m^2. Mfactor performs the spectral mismatch corrections using currents and spectra that have not been normalized. Subsequent to spectral correction, the user then has the option of normalizing the final results to any desired insolation level. The use of unnormalized spectra facilitates the calibration of reference cells using NIST light sources, as will be discussed later. Figure 1 is a photograph of a typical output screen from the program.

DATA INPUT

Test-cell spectral response, reference-cell spectral response, test spectrum, and desired spectrum files are all selected by the user from windows that display a list of each file type. The reference-cell spectral response file contains the name of the file containing its calibration spectrum which is automatically read by the program. The same file also contains the short-circuit current of the reference cell under the calibration spectrum and the total insolation to which it was normalized. If the reference-cell short-circuit current during testing is different from its calibration current, which is typically the case in outdoor testing, it can be input from the keyboard. The short-circuit current of the test cell can also be input from the keyboard. The normalized insolation value for typical desired spectra is automatically set by the program, such as 1000 W/m^2 for ASTM AM1.5 Global and Direct and 1372 W/m^2 for WRC AM0. At the user's option, the normalized insolation value for the desired spectrum can also be input from the keyboard. The program is designed such that it is not necessary to input all data to get some results. For instance, if only the calculated insolation of the test spectrum is desired, then the only input that is required is the test spectrum.

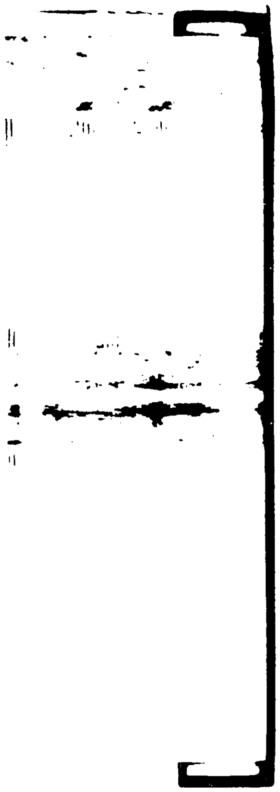

Figure 1: Typical screen showing the Main Menu, the files that have been read, and calculated results for a typical case.

DATA FORMAT

The data files are all in ASCII format and may be edited by virtually any word processor. The first line of the file contains the number of data pairs in the file, followed by three lines that contain various values depending on whether the file contains spectral response or spectrum data. The remaining lines contain the x,y data pairs, with x being the wavelength (in nm) and y being either the spectral response (in A/W) or the spectral irradiance (in W/m^2/nm). A file called Mfactor.dat contains default values for filename extensions, data drive and directory, and graphics output. These values can be changed to suit the user.

DATA OUTPUT

In addition to the spectral mismatch multiplier (SMM), the program provides several other output values. The filenames that were read by the program and the short-circuit currents that were either read by the program or input by the user are all indicated. Other outputs include: calculated short-circuit current density (Jsc) of the test cell under the test and desired spectrums; calculated Jsc of the reference cell under the test and calibration spectrums; calculated insolation of the test, desired and reference spectrums; and total (known) insolation of the test, reference, and calibration spectrums as read from their respective data files. If the test cell short-circuit current is input by the user, the corrected short-circuit current under the desired spectrum is indicated. All values are calculated for both normalized and unnormalized spectra. All data output is presented on the screen and, optionally, there is provision to print a hardcopy of the data.

GRAPHICS CAPABILITIES

The program is capable of displaying graphs of test or reference cell spectral response of the test, calibration or desired spectrum. Graphs can be overlaid for comparison purposes, such as comparing the test cell spectral response with the reference cell spectral response. Graphs of like files, such as two or more test cell spectral responses, can also be overlaid and compared. This is accomplished by reading a file, graphing it, reading another file, graphing and so on. At this time there is no provision for hardcopy of graphics.

MFACTOR EXAMPLE

A comparison of short-circuit current measurements from several cells was made using both a Spectrolab XT-10 solar simulator and an ELH lamp as light sources. Using Mfactor, the short-circuit currents for both light sources were corrected to the ASTM AM1.5 Global spectrum (E892-87). Table 1 gives the measured short-circuit currents before spectral mismatch correction and Table 2 gives the short-circuit currents after spectral mismatch correction using Mfactor. Note that measured currents in Table 1 differ by over 10% prior to spectral mismatch correction. Figure 2 shows the spectral response curves associated with the reference cell used and the test cells in Table 1. Figure 3 shows typical test spectrums, and Figure 4 shows typical desired spectrums.

Table 1

Cell Type		Measured Isc (A) XT-10	ELH	Ratio XT-10/ELH
Si #1	(3 cm^2)	.1978	.2231	.887
Si #2	(4 cm^2)	.1043	.1030	1.013
GaAs	(8 cm^2)	.1605	.1520	1.056

Table 2

Cell Type		AM1.5G Isc (A) XT-10	ELH	Ratio XT-10/ELH
Si #1	(3 cm^2)	.2022	.2062	.981
Si #2	(4 cm^2)	.1043	.1030	1.002
GaAs	(8 cm^2)	.1598	.1583	1.009

Figure 2: Spectral response of test cells and reference cell used in Table 1.

Figure 3: Typical test spectrums; a Spectrolab XT-10 Xenon simulator, an ELH lamp, and an NIST FEL lamp.

Figure 4: Typical desired spectrums; WRC-AM0, ASTM AM1.5 Global (E892-87), and ASTM AM1.5 Direct (E891-87).

REFERENCE CELL CALIBRATION

Calibration of primary reference cells is a difficult, time-consuming process. Outdoor calibration requires variety of instrumentation and careful attention to equipment calibration as well as atmospheric conditions during the procedure. These calibrations can often take weeks or months to accomplish depending on weather conditions. A procedure for calibrating primary reference cells has been implemented in the PDML that is more straightforward than currently defined ASTM methods. The short-circuit current of the PDML primary reference cell (MK-25) was measured under a quartz-tungsten-halogen FEL lamp by the Radiometric Physics Division at the National Institute of Standards and Technology (NIST). The spectral content of the lamp is very well known and provides an absolute calibration spectrum [3]. The uncertainty associated with the NIST spectral irradiance including both random and systematic errors is less than 2% for wavelengths from 300 to 1600 nm. The short-circuit currents for the ASTM AM1.5 Global, the ASTM AM1.5 Direct, and the WRC-AM0 spectrums were calculated using the NIST measurements and the spectral mismatch corrections provided by Mfactor. To check these calibration values, MK-25 was sent to SERI for comparison measurements. Table 3 shows the results of that comparison for the MK-25 reference cell.

Table 3

	MK-25 Isc (A)		Ratio
Spectrum	Sandia	SERI	Sandia/SERI
Global	.1211	.1217	.995
Direct	.1193	.1203	.992
AM0	.1461	.1472	.993

The calculated currents from Mfactor differ by less than 1% from SERI's measured currents. Using MK-25 as the primary reference-cell, a secondary calibration for several other cells was determined using Mfactor. Two of these cells were sent to SERI for outdoor calibration and one was flown by NASA for an AM0 calibration. Tables 4, 5, and 6 show the results of those calibrations. The MK-34 cell is a packaged silicon reference cell essentially identical to MK-25. The Y-15 cell is an older vintage silicon reference cell, and the UNSW-A142R is an unpackaged, high-performance silicon cell fabricated by the University of New South Wales.

Table 4

	MK-34 Isc (A)		Ratio
Spectrum	Sandia	SERI	Sandia/SERI
Global	.1191	.1177	1.012
Direct	.1176	.1163	1.011
AM0	.1434	.1431	1.002

Table 5

Spectrum	Y-15 Isc (A) Sandia	SERI	Ratio Sandia/SERI
Global	.08864	.08699	1.019
Direct	.08869	.08714	1.018
AMO	.1056	.1042	1.013

Table 6

Spectrum	UNSW-A142R Isc (A) Sandia	NASA	Ratio Sandia/NASA
AMO	.1954	.1959	.997

The results of these and other interlab comparisons demonstrate the validity of the spectral mismatch procedure used in Mfactor, as well as the reference cell calibration procedure developed in conjunction with NIST.

Calibration of reference cells using this method is much easier and quicker to implement than the standard ASTM procedures. The uncertainty associated with this procedure is small as is reported elsewhere [2].

CONCLUSIONS

Mfactor is an easy-to-use IBM-PC compatible program that has many applications throughout the photovoltaic community. With this program, the short-circuit currents of cells measured under a wide variety of illumination sources can be compared, and performance under virtually any desired spectrum can be determined. Primary reference-cell calibration has been shown to be greatly simplified using Mfactor and a calibrated light source from NIST. This program is now available to the photovoltaic community by mailing a request to the author.

ACKNOWLEDGEMENTS

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REFERENCES

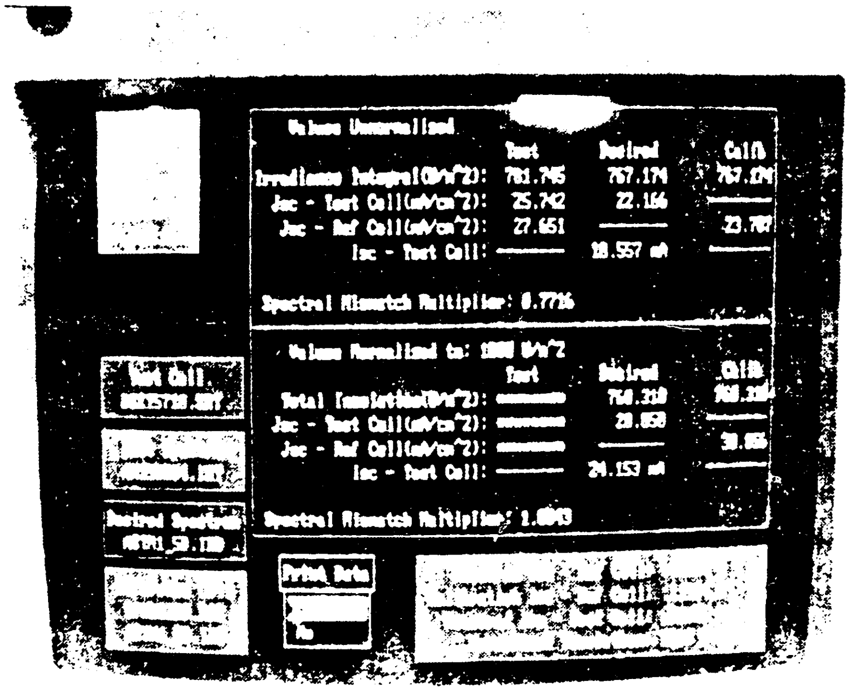
[1] "Standard Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell", ASTM Standard E973 Philadelphia, PA: American Society for Testing and Materials, 1991.

[2] "A Sensitivity Analysis of the Spectral Mismatch Correction Procedure Using Wavelength Dependent Error Sources", D. L. King and B. R. Hansen, this conference.

[3] "Spectral Irradiance Calibrations", J. H. Walker, R. D. Saunders, J. K. Jackson, D. A.

McSparron, NBS Special Publication 250-20, 1987.

Figure 1



```
Values Unnormalized
                              Test      Desired     Calib
Irradiance Integral(W/m^2):   781.745   767.174     767.174
Jsc - Test Cell(mA/cm^2):     25.742    22.166      ———
Jsc - Ref Cell(mA/cm^2):      27.651    ———         23.787
Isc - Test Cell:              ———       18.557 mA   ———

Spectral Mismatch Multiplier: 0.7716

Values Normalized to: 1000 W/m^2
                              Test      Desired     Calib
Total Irradiance(W/m^2):      ———       768.310     768.310
Jsc - Test Cell(mA/cm^2):     ———       28.858      ———
Jsc - Ref Cell(mA/cm^2):      ———       ———         30.855
Isc - Test Cell:              ———       24.153 mA   ———

Spectral Mismatch Multiplier: 1.0043
```

Figure 2

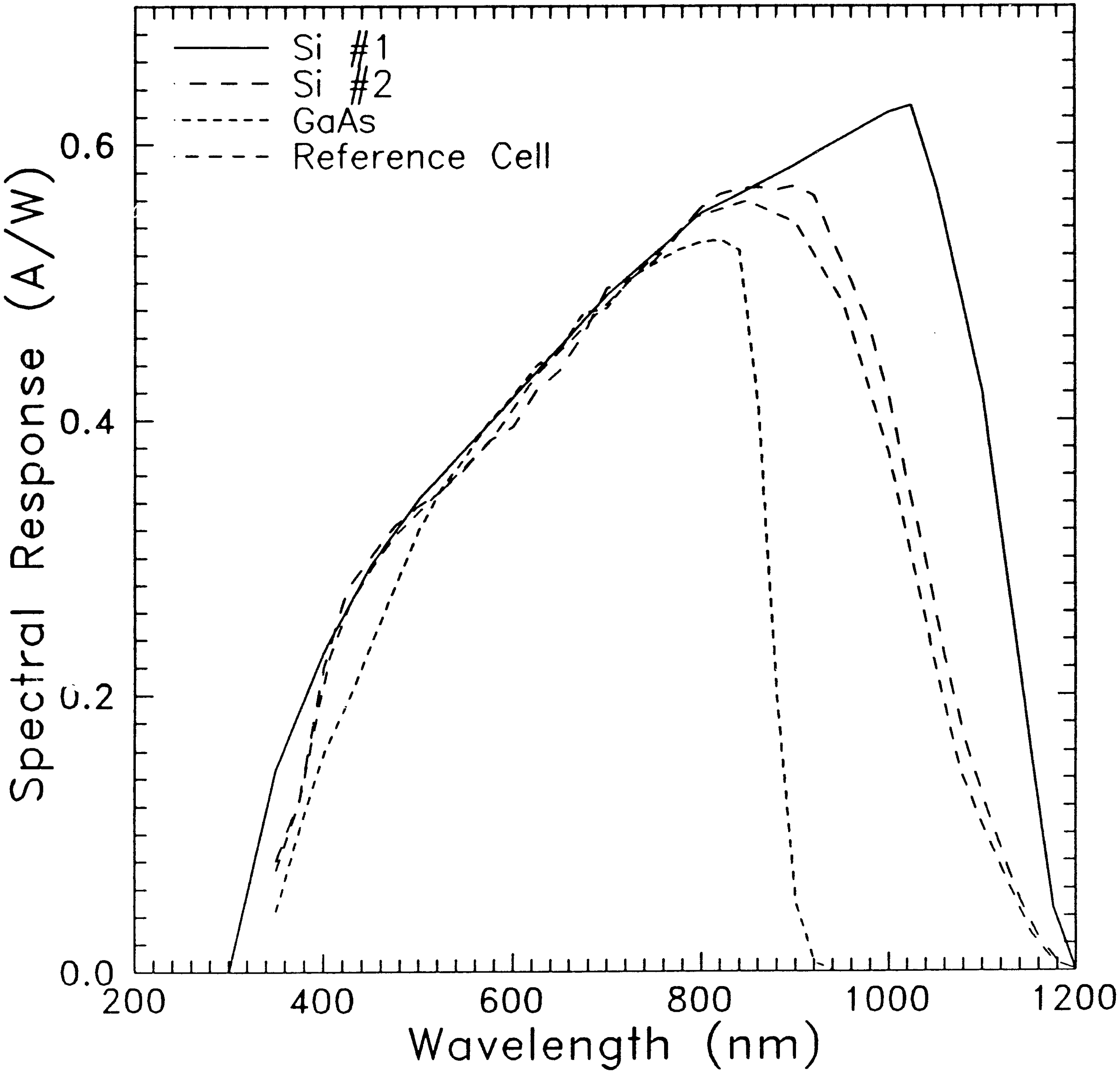

Si #1
Si #2
GaAs
Reference Cell
Spectral Response (A/W)
0.0
0.2
0.4
0.6
200
400
600
800
1000
1200
Wavelength (nm)

Figure 3

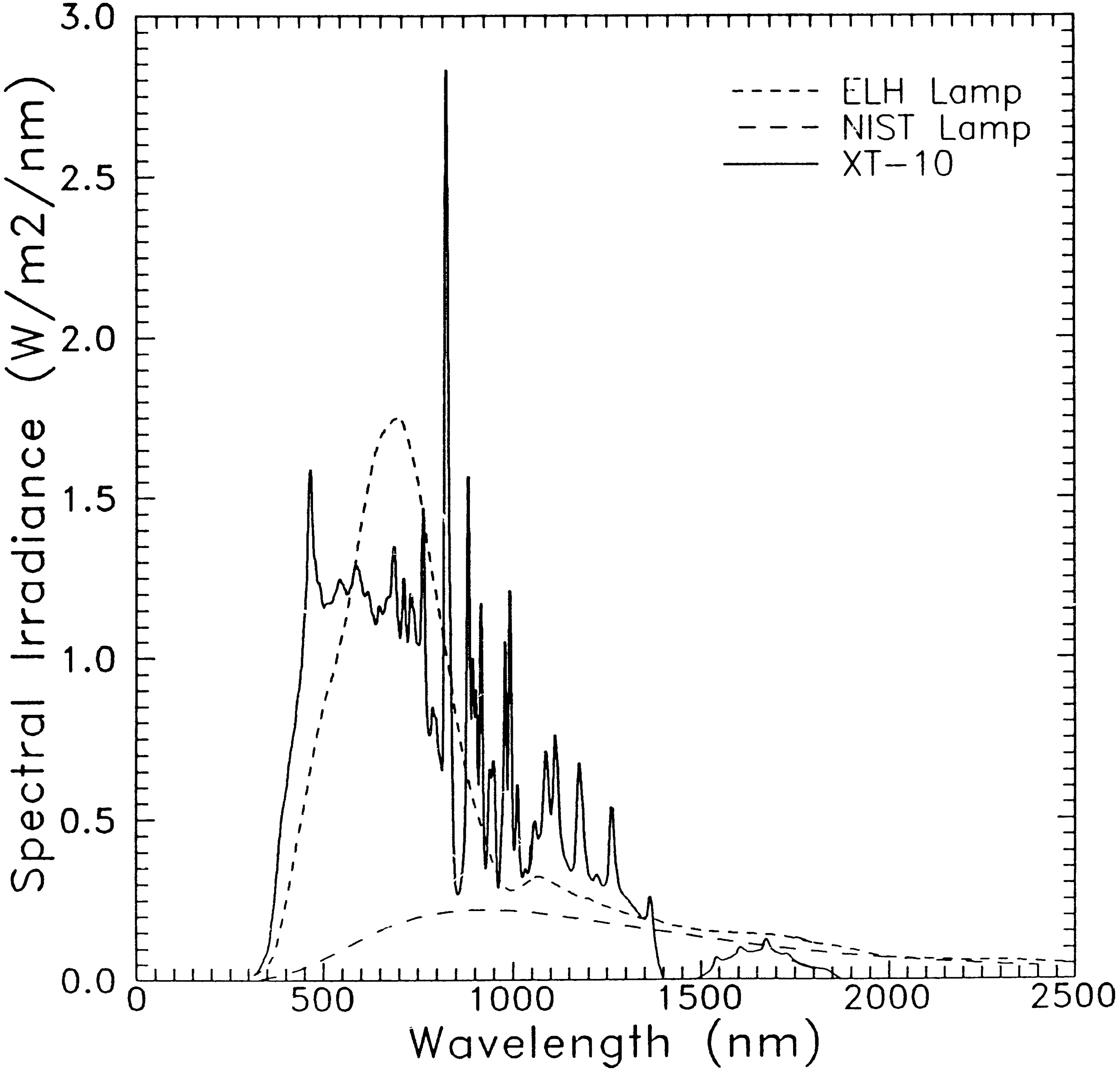
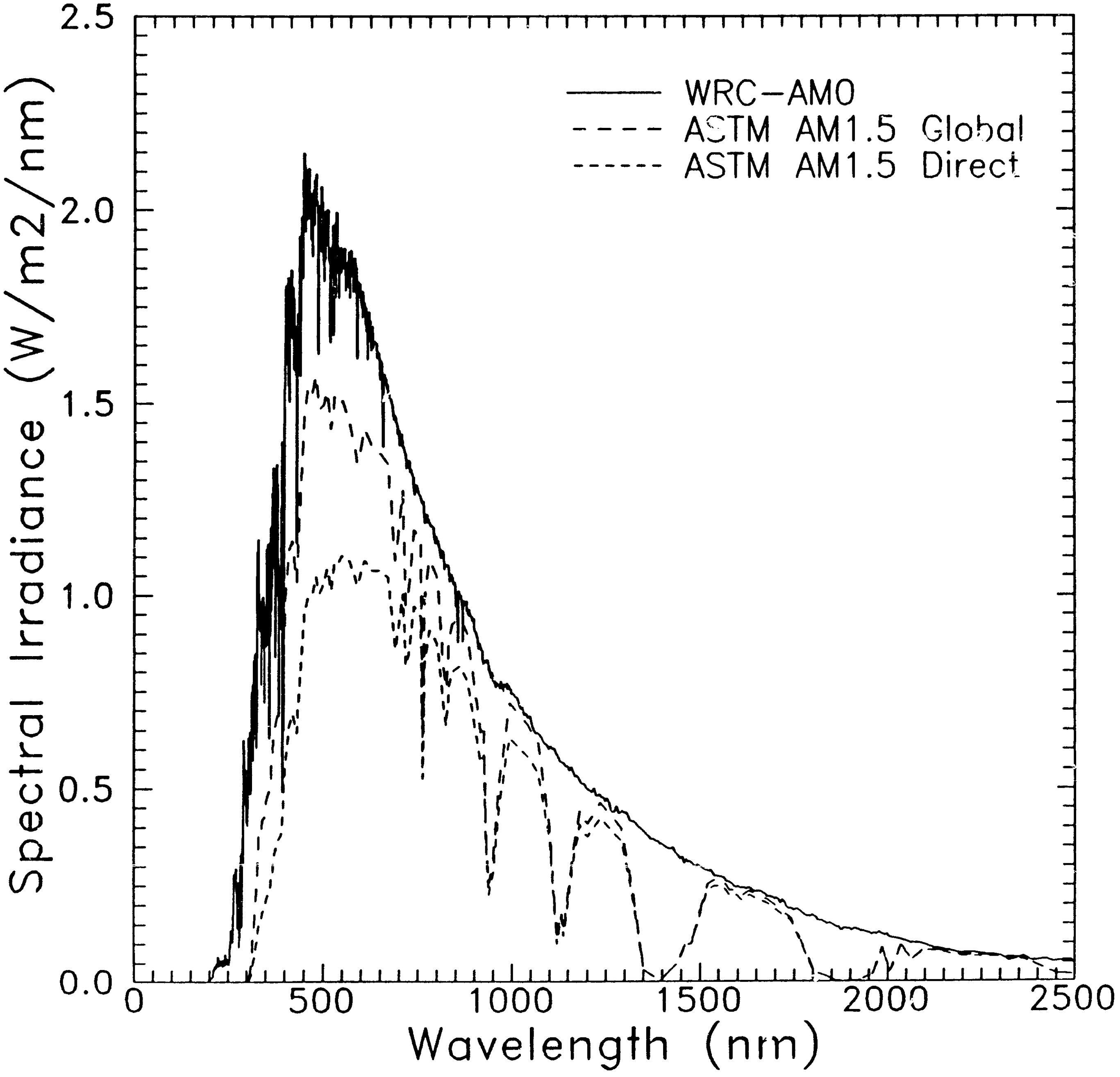

ELH Lamp
NIST Lamp
XT-10
Spectral Irradiance (W/m2/nm)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
1500
2000
2500
Wavelength (nm)

Figure 4


WRC-AM0
ASTM AM1.5 Global
ASTM AM1.5 Direct
Spectral Irradiance (W/m2/nm)
0.0
0.5
1.0
1.5
2.0
2.5
Wavelength (nm)
0
500
1000
1500
2000
2500

END

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