# SPECTRAL MEASUREMENTS BY THE FILTER METHOD ON LEW

# CARBON ARC SOLAR SIMULATORS



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## INTRODUCTION

There exists a problem in the measuring of the spectral irradiance of solar simulators. This difficulty has manifested intself in both monochromator and filter measurements. This report is the discussion of the measurements by Eppley Laboratory on the Lewis carbon arc solar simulators, the further analysis of the method of filter radiometry made by Lewis personnel, and the comparison with the monochromator measurements.

Previously when the filter technique was used it was assumed that the a priori knowledge of the source's spectral characteristics must be known. In this report it will be shown that for a carbon arc source a knowledge of the source is not required after the filters have been properly chosen.

## THE EPPLEY REPORT

In June of 1963, Eppley Laboratory, under contract to Lewis, sent representatives to Cleveland to measure the spectral distribution of three operational carbon arc solar simulators using the filter method and their prototype Mark IV filter radiometer. Measurements were made on air on the two smaller systems and in air, vacuum, and vacuum and cold walls on the 30-inch-diameter system. The air measurements were repeated for reproducibility. The results was essentially six sets of narrow band filter data supplemented by four sets of broad band data.

The final report, dated November 5, 1963, averaged all the narrow band data together. Figure 1 is the resultant continuous curve taken from the report of all the narrow band data versus the extraterrestial sun curve.

Because this curve was an average of three different systems under many different conditions, because there was an abundance of narrow band data available, and because we were to receive a similar instrument for filter measurements, we began to analyze the mathematics of filter radiometry.

After an analysis of Eppley's method, which follows immediately, we developed what we feel are more rigorous treatments to the filter data that will be presented later.

# THE EPPLEY METHOD

Using the filter method to obtained spectral measurements, one essentially has a total thermopile detector. When the detector is covered with various filters the energy within a given bandwidth is then isolated. If this method is repeated throughout the spectrum with the available filters, the energy within all the small segments making up the total spectrum can be found.

If the transmission of each filter is known, as in figure 2, where $\tau(\lambda)$ is the transmission of the filter, $\lambda$ is the wavelength, and $\lambda_1$ and $\lambda_2$ are the bandpass limits of the filter, the center wavelength $\lambda_0$ or the center of gravity of the transmission curve can then be found by

$$\lambda_0 = \frac{\int_0^\infty \tau(\lambda)\lambda \, d\lambda}{\int_0^\infty \tau(\lambda) d\lambda}$$

A more suitable form for machine computation can be made by breaking up $\tau(\lambda)$ into small increments $\Delta\lambda$ and by summing:

$$\lambda_0 = \frac{\sum_{N=1}^{L} \lambda_N \tau_N \, \Delta\lambda_N}{\sum_{N=1}^{L} \tau_N \, \Delta\lambda_N}$$

If all the $\Delta\lambda_N$'s are equal and the appropriate $\tau(\lambda)$ is used for each filter, $\lambda_{OF}$ is calculated by

$$\lambda_{OF} = \frac{\sum_{N=1}^{L} \lambda_{NF} \tau_{NF}}{\sum_{N=1}^{L} \tau_{NF}}$$

where $\lambda_{OF}$ is the center wavelength for the $F^{th}$ filter and L is the number of increments within the transmission curve for the filter. This result is similar to the reference wavelength discussed in Eppley's report.

To compute the spectral irradiance of the source at the target plane the report indicates that prior knowledge of the spectral distribution of the bare source is required and that the distribution be a reasonably smooth curve. It was further stated that the carbon arc satisfies these conditions. A quantity is defined that, when applied to the data, will indicate the energy that would fall on the detector within the bandpass limits $\lambda_1$ and $\lambda_2$ if the filter were not in place. This quantity is given by

$$F = \frac{\int_0^\infty J(\lambda)S(\lambda)d\lambda}{\int_0^\infty J(\lambda)\tau(\lambda)S(\lambda)d\lambda}$$

where $J(\lambda)$ is the assumed spectral irradiance curve (usually taken from monochromator data of the bare source), $S(\lambda)$ is the sensitivity of the detector (in this case a constant over the limits involved), $\tau(\lambda)$ is the transmission of the filter in question, and $F$ is the filter factor, which is approximately equal to the reciprocal of the transmission of the equivalent square filter. The denominator of the fraction is the measured voltage output of the detector. When the previous expression for $F$ is rewritten, it is found that

$$F_F = \frac{S\int_{\lambda_1}^{\lambda_2} J(\lambda)d\lambda}{S\int_{\lambda_1}^{\lambda_2} J(\lambda)\tau(\lambda)d\lambda} \tag{1}$$

or

$$F_F = \frac{S\int_{\lambda_1}^{\lambda_2} J(\lambda)d\lambda}{V_F}$$

where $V_F$ is the voltage output of the detector with the $F^{\underline{th}}$ filter is in place, $\lambda_1$ and $\lambda_2$ are the band pass limits of the filter, and $F_F$ is the filter factor for the $F^{\underline{th}}$ filter.

The average energy to the detector within the limits $\lambda_1$ and $\lambda_2$, if the filter were not present, is given by

$$\bar{J} = \frac{\int_{\lambda_1}^{\lambda_2} J(\lambda)d\lambda}{\lambda_2 - \lambda_1} \qquad (2)$$

where $J(\lambda)$ is the spectral irradiance of the source at the target plane, $\lambda_1$ and $\lambda_2$ are the band pass limits, and $\lambda_2 - \lambda_1$ is the bandwidth. If equation (1) is solved for the integral and the result substituted into equation (2), the new expression for $\bar{J}$ is

$$\bar{J} = \frac{FV}{S(\lambda_2 - \lambda_1)}$$

If the bandwidths are normalized to 50 millimicrons, the average irradiance at the target plane within the given bandwidth limits is then

$$\bar{J}_F = \frac{F_F V_F}{S}\left(\frac{50}{\lambda_2 - \lambda_1}\right)$$

This process is repeated for all F filters, and the report lists twelve values of $\bar{J}_F$ corresponding to twelve values of $\lambda_{OF}$ through which a smooth continuous curve is drawn to indicate the approximate spectral distribution of the source.

To calculate this spectrum the contractor chose values of $J(\lambda)$ from the curves published by the National Carbon Company indicating the spectral distribution from a "High Intensity" electrode. Since the three systems at Lewis use "Ultrex" electrodes with a significantly different source distribution, we recalculated the spectrums using the new values of $J(\lambda)$ published for the "Ultrex" electrode. The final results did not change.

## MODIFIED EPPLEY METHOD

The altering of assumed irradiance curves leading to no change in the results led us to the conclusion that once the filters were judiciously chosen based on prior knowledge of a smooth carbon arc spectrum, the calculated results were relatively insensitive to the chosen spectral irradiance curve. Continuing along this line of reasoning it was found that any continuous curve, straight line, or segmented line curve will serve quite well as the chosen $J(\lambda)$. The filter factor $F_F$ and the average irradiance within the given bandwidth of the filter $\bar{J}_F$ were calculated and a linear interpolation between all twelve points resulted in a segmented line curve. With this new $J(\lambda)$ new values of $\bar{J}_F$ and $F_F$

were again calculated and with these twelve new points a new $J(\lambda)$ was calculated. When the iterative method and the available computer were used, it was observed that the results converged rapidly, and the spectrum calculated using this method is very close to that calculated using the method indicated in the Eppley report. This shows it is possible to calculate the spectral irradiance produced by a carbon arc or any smooth source using filter measurements and having no prior knowledge of the spectral radiance of the bare source.

## NONFILTER FACTOR METHOD

Another method of calculating spectral irradiance using the same raw data was developed at Lewis. This method uses no filter factors or bandwidth limits. In its use we assume a spectrum and by an iterative process alter the assumed spectrum to match the measured data. To use this method the measured data must be available and related by the expression

$$V_{FM} = \int_0^\infty S(\lambda)\tau_F(\lambda)J(\lambda)d\lambda$$

where $V_{FM}$ is the measured voltage output from the detector with a filter in place, $S(\lambda)$ is the sensitivity (a measured constant), $\tau_F(\lambda)$ is the measured transmission of the filter, and $J(\lambda)$ is the spectral irradiance at the target plane we are trying to measure. Again one assumes <u>any</u> set of $F$ number points ($F$ corresponds to the number of filters) and a value of irradiance is chosen for each value of $\lambda_{OF}$. Then if a linear interpolation is performed between the points, a segmented line curve of irradiance $J_A(\lambda)$ is developed, which may also be a straight line as shown in figure 3. Using this assumed irradiance curve calculate

$$V_{FA} = \int_0^\infty J_A(\lambda)\tau_F(\lambda)S(\lambda)d\lambda$$

or

$$V_{FA} = S\sum_{N=1}^{L} J_{AN}\tau_{FN}\,\Delta\lambda_{FN}$$

where $V_{FA}$ is the voltage, with the $F^{th}$ filter in place, calculated using the assumed irradiance curve $J_A(\lambda)$, $L$ is the number of increments, and $\Delta\lambda_{FN}$ is the width of each increment. Now calculate the ratio

$$\frac{V_{FA}}{V_{FM}} = R_F$$

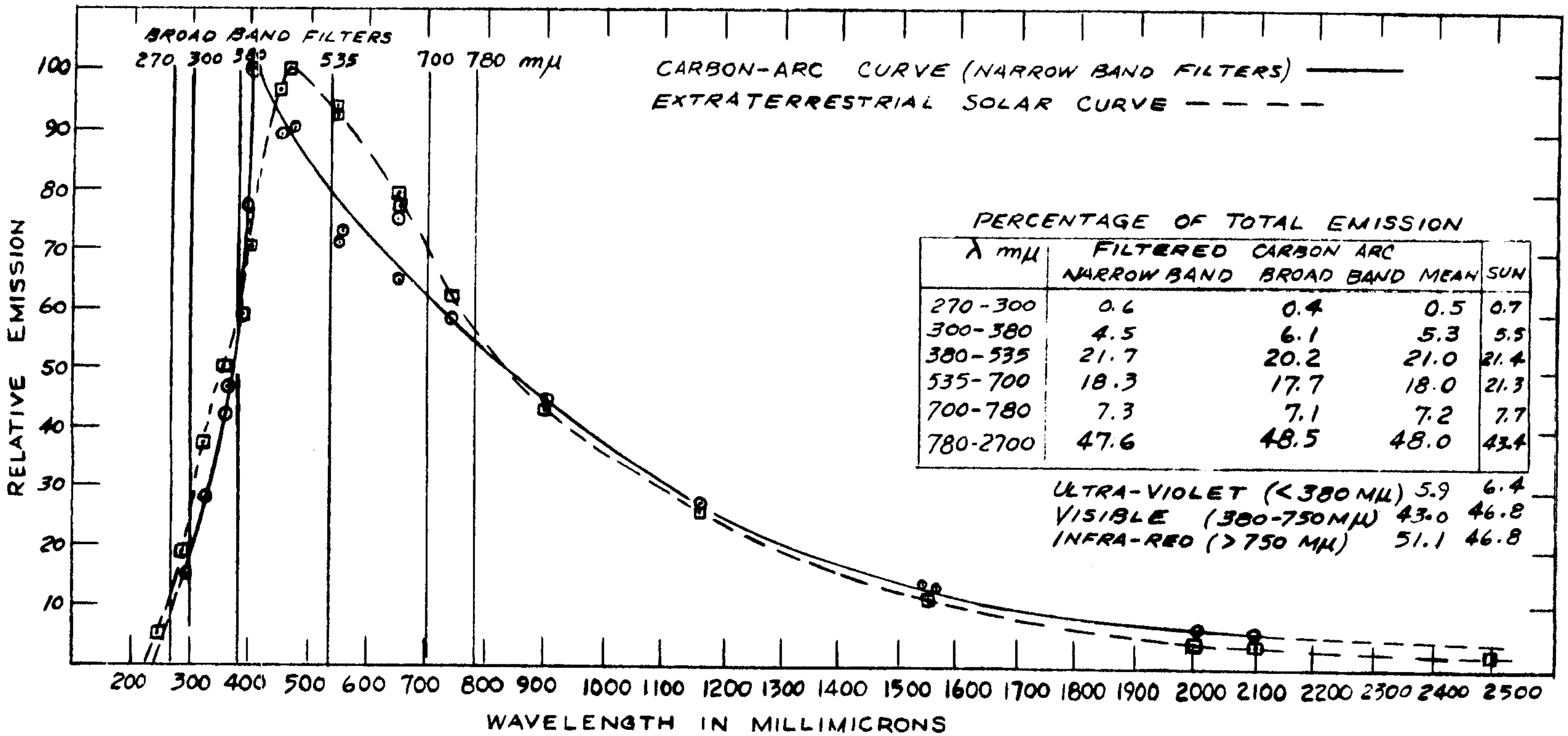
and if $R_F$ is less than one raise $V_{FA}$, if $R_F$ is greater than one lower $V_{FA}$, and, finally, if $R_F$ is equal to one keep $V_{FA}$ unchanged. Due to the overlapping of filters a change in $V_{FA}$ affects $V_{FA+1}$, so again an iterative process is called for. This method converges to the same results regardless of the initial assumed irradiance curve.

## RESULTS AND CONCLUSION

Figure 4 is a chart showing a comparison among the three methods of filter calculations. Figure 5 is a plot of irradiance versus wavelength of a carbon arc simulator using three different methods of calculations. All three of these methods agree very closely with each other indicating after the filters have been chosen for a continuous source there is no need for prior knowledge of the source or to arbitrarily choose correct band pass limits.

## FUTURE WORK

Figure 6 is a plot of the irradiance of a carbon arc solar simulator as a function of wavelength using one of the filter methods and an equally normalized monochromator measurement. Also on Figure 6 is the normalized Johnson extraterrestrial sun curve. The discrepancy between the two methods of measuring spectral irradiance on the same system is under continuing investigation at Lewis. One member of the staff is concentrating on a theoretical approach to predict the uncertainty in filter measurements, others are working in the problem areas associated with the monochromator measurement.




| λ mμ | FILTERED CARBON ARC NARROW BAND | BROAD BAND | MEAN | SUN |
|---|---|---|---|---|
| 270-300 | 0.6 | 0.4 | 0.5 | 0.7 |
| 300-380 | 4.5 | 6.1 | 5.3 | 5.5 |
| 380-535 | 21.7 | 20.2 | 21.0 | 21.4 |
| 535-700 | 18.3 | 17.7 | 18.0 | 21.3 |
| 700-780 | 7.3 | 7.1 | 7.2 | 7.7 |
| 780-2700 | 47.6 | 48.5 | 48.0 | 43.4 |

COMPARISON BETWEEN N.A.S.A. CLEVELAND CARBON-ARC SOURCES AND THE EXTRATERRESTRIAL SUN

FIGURE 1. CURVE OF CARBON ARC AS APPEARED IN THE EPPLEY REPORT.

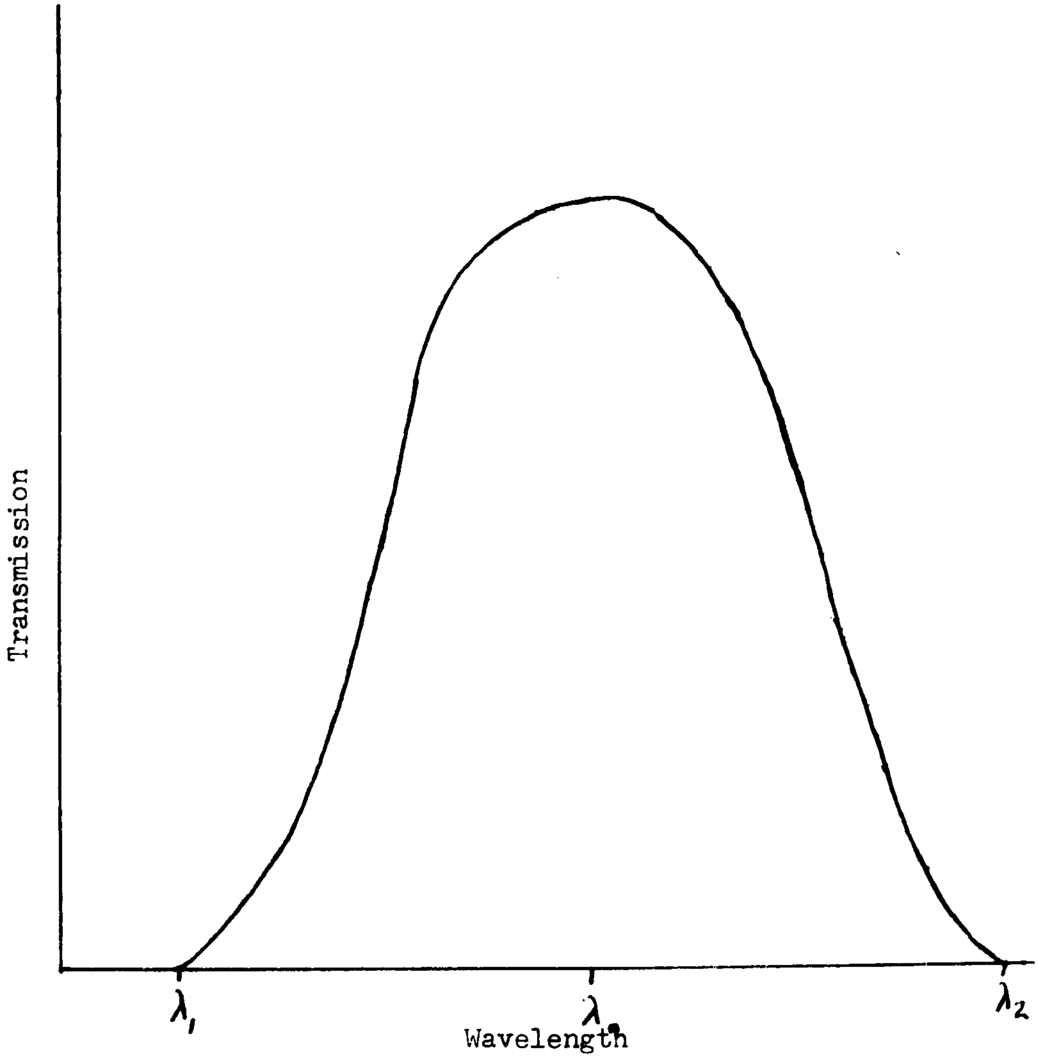
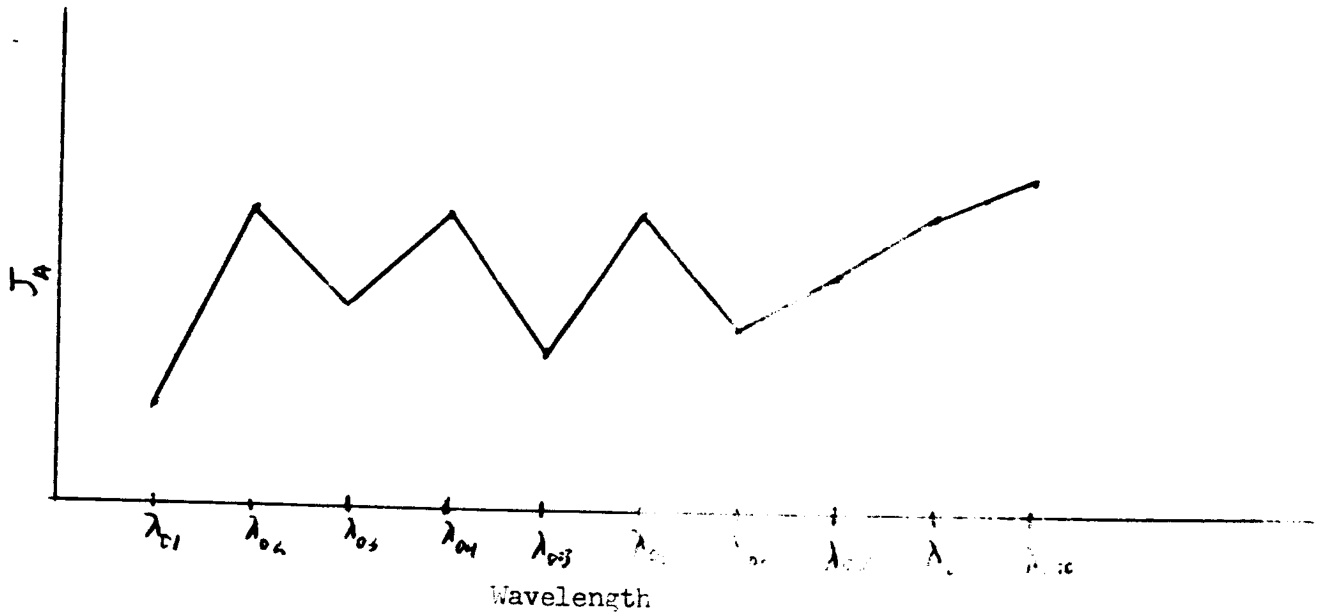



**Figure 2.** TRANSMISSION OF TYPICAL FILTER AS A FUNCTION OF WAVELENGTH



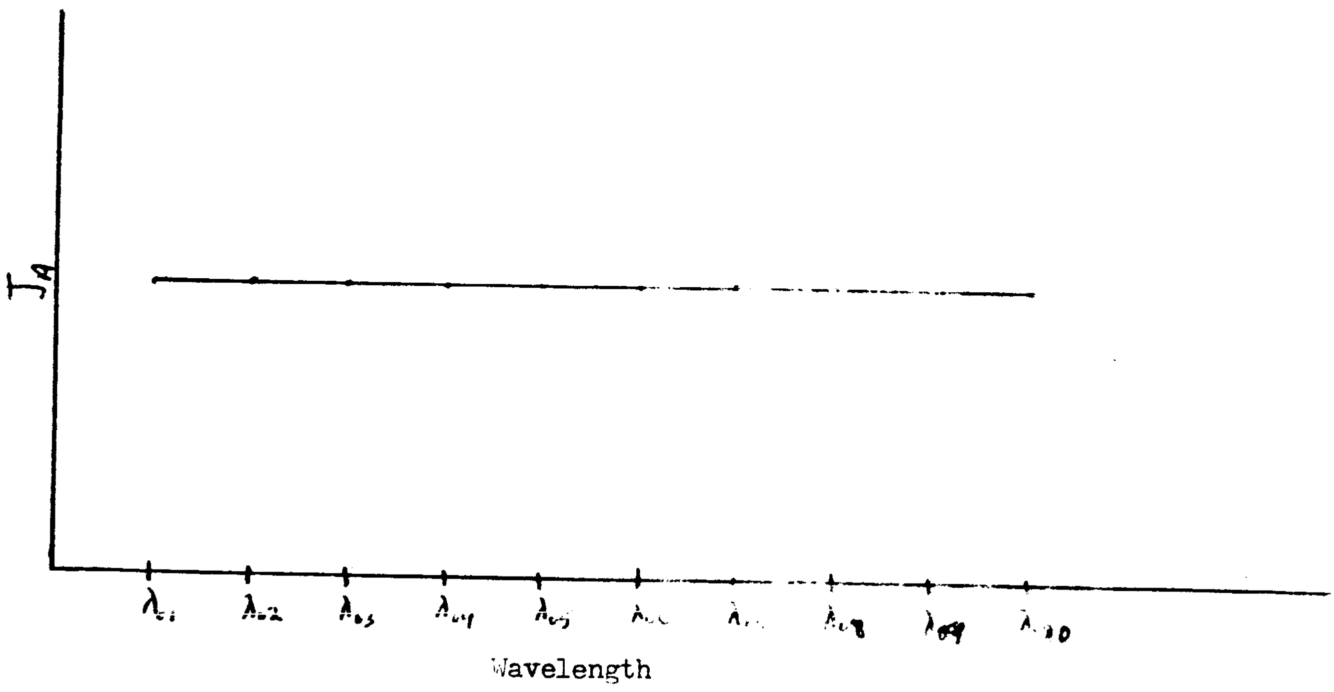




Figure 3. POSSIBLE ASSUMED IRRADIANCE CURVES $J_A$, AS A FUNCTION OF WAVELENGTH

| | Non-filter Factor Method | Modified Eppley Method | Eppley Method |
|---|---|---|---|
| $\lambda_0$ | $= \dfrac{\sum_{N=1}^{L} \tau_N \lambda_N}{\sum_{N=1}^{L} \tau_N}$ | $= \dfrac{\sum_{N=1}^{L} \tau_N \lambda_N}{\sum_{N=1}^{L} \tau_N}$ | Approximated |
| Assumed spectral distribution | Any segmented line | Any segmented line | Monochromator data of bare source |
| Filter factor | None | $= \dfrac{\sum_{N=1}^{L} J_N}{\sum_{N=1}^{L} J_N \tau_N}$ | $= \dfrac{\sum_{N=1}^{L} J_N}{\sum_{N=1}^{L} J_N \tau_N}$ |
| Bandpass limits | Not needed | 0% trans. | 1% trans. |
| Number of calculations | Iterative | Iterative | One |
| Agreement with data | Exact | Approximated | Approximated |

Figure 4. COMPARISON CHART SHOWING DIFFERENCES IN TECHNIQUES OF EVALUATING FILTER DATA

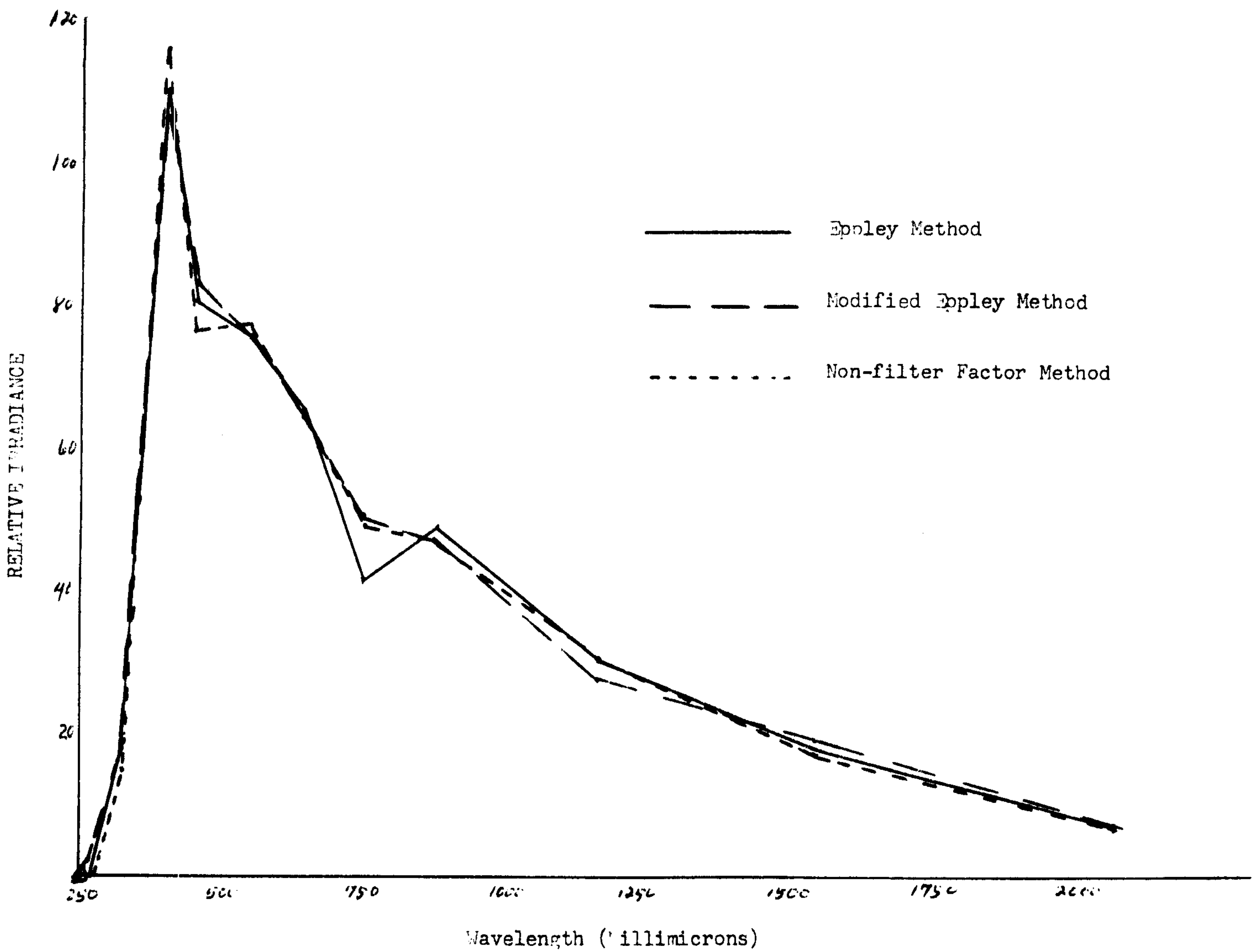



Figure 5. RELATIVE IRRADIANCE OF IRL SOLAR SIMULATOR AS MEASURED BY FILTER METHODS

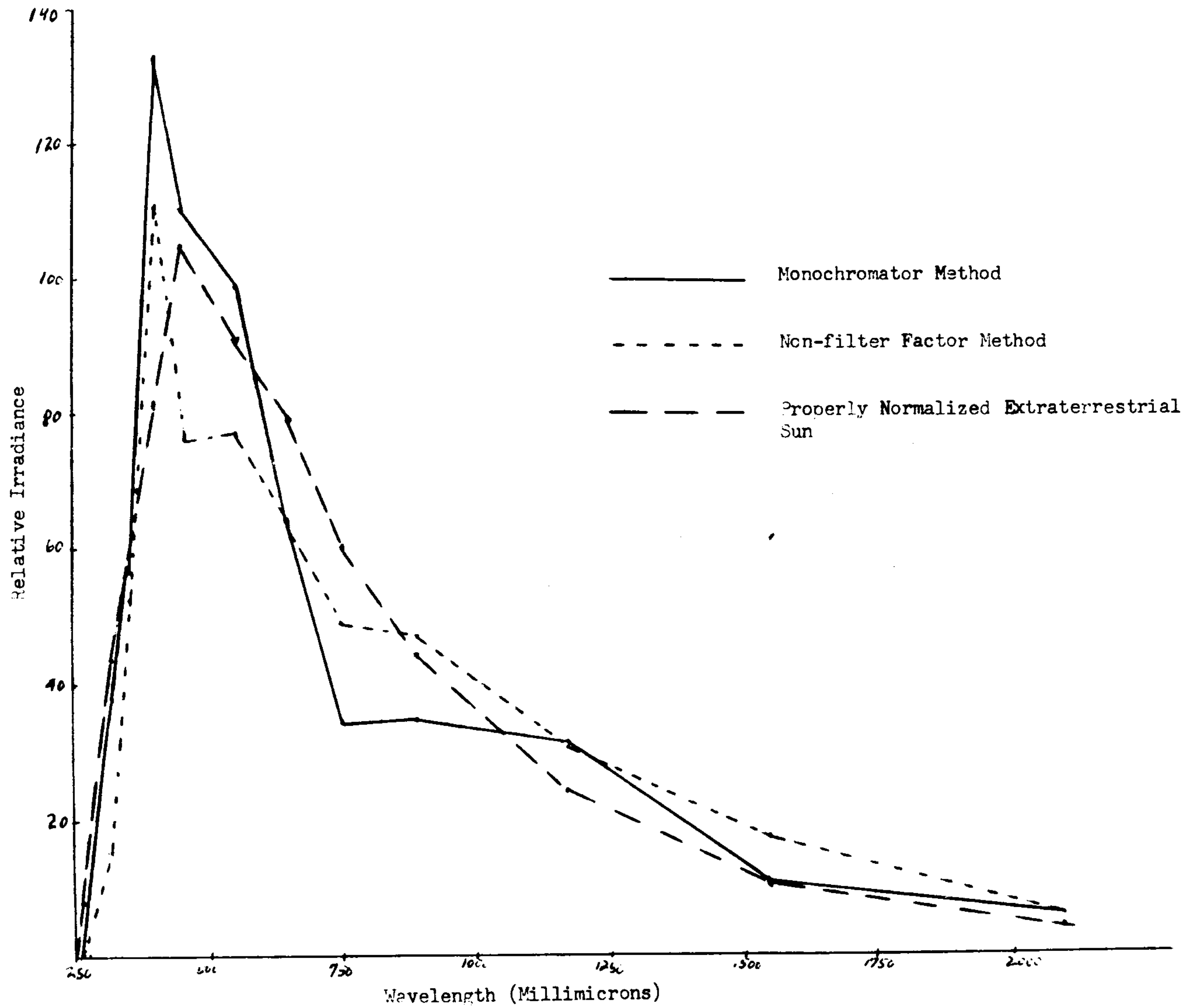



**Figure 6.** RELATIVE IRRADIANCE OF IRL SOLAR SIMULATOR AS MEASURED BY FILTER AND MONOCHROMATOR VS SUN