CHAPTER -3
DATA COLLECTION, ANALYSIS AND CALIBRATION

This chapter covers the solar UV-B data collection procedure, the calibration of the system components and the method of data analysis. Derivation of the UV-B flux from the raw data and computation of total ozone from the flux are detailed. The necessity for periodic calibration, the sources of errors in measurement are discussed.

3.1. PROCEDURE OF OPERATION OF THE INSTRUMENT:

In order to make use of the system for monitoring the direct solar UV flux, the following initialization procedure is essential.

(1) Keep the sun tracker such that its axis of tracking is parallel to the geographic north south direction.

(2) Select the asynchronous mode of operation for the sun tracker. Keep the forward/reverse switch in appropriate position and by giving manual command through the push button switch, rotate the sun tracker so that the assembly of the detector optics is approximately pointed towards the sun. Depending on the season of the year, the optics assembly within the sun tracker frame as a whole is tilted to the north or south to make it look at the sun. In this position, the shadow formed by the cell mounted on the hood will have a
minimum area.

(3) Now select the manual mode of operation for the filter wheel. The reference blank of the filter wheel is positioned above the phototube. After clearing the gain switching logic, position the filter say 320 nm, next to the reference blank on the filter wheel above the phototube, by giving a manual command through the push button switch. The solar flux in this wavelength channel being high, this sequence is preferred.

(4) The strip chart recorder and the digital panel meter readings are noted in voltage units. Again, the sun tracker controls are adjusted so that the assembly of the detector optics is made to look at the sun and the readings noted. The optics assembly is adjusted to maximize the readings in this position.

(5) Select the synchronous mode of operation for the sun tracker. Position the remaining filter positions sequentially above the phototube and check the readings. Finally position the reference blank above the phototube. Now select the automatic mode of the filter wheel and clear the gain switching logic.

The setup is now ready for monitoring the radiation. In the event of a power failure, while resetting, steps 2 to 5 are repeated.
3.2. DATA COLLECTION AND REDUCTION:

The solar ultraviolet radiation data are obtained on an analogue strip chart recorder. The output of each channel is in voltage units. There are four levels of voltage each of about a minute duration, corresponding to the three filter position and a blank position (This has later been modified to five positions from 320 to 290 nm. The duration for a filter to stay over the phototube can be altered and typically, this is of the order of a minute or less.). The output corresponding to the blank position in each rotation of the filter wheel enables a correction for the combined drift of the amplifier and the recorder. Typically this drift is within 1% over a day. Data reduction involves the conversion of these voltages to the UV flux incident on the detector. This direct flux is projected on to a horizontal surface taking the cosine component of the direct flux. The normalization to the average spectral width of the interference filter used makes the measurement non-spectral and the introduction of the unit per nm interval, as $\mu W/cm^2/nm$.

Data reduction involves the following steps:
(1) Conversion of output voltage to the electrometer input current, (2) Computation of the energy incident on the phototube from this current and (3) Conversion of the flux per unit area per nm interval from the computed energy.
3.2.1. Conversion of the output voltage to the electrometer input current:

The electrometer input current is given by the ratio of the output voltage to the conversion factor $G$ which is essentially the amplification factor of the amplifier system. The system is calibrated using a pico ampere current source (Keithley Instruments) and the conversion factor is determined for each filter. Fig. 3.1 shows the typical calibration curves. The value of $G$ varies with the filter as the amplifier is gain switched for each filter.

3.2.2. Conversion of current to energy per unit area:

Conversion of the incident UV flux on the photocathode needs the knowledge of the quantum efficiency, $R(\lambda)$, of the photo cathode. This $R(\lambda)$ is the spectral response characteristic of the photo cathode material (Cs-Te) of the photo tube, R-765 used here. It is defined as the photoelectric current that will be generated for unit flux that is incident on the photo cathode at a given wavelength and is expressed in milliampere per Watt (mA/W). By knowing this $R(\lambda)$, the photoelectric current output of the phototube can be converted to the equivalent energy in Watt. The energy density which is limited by the area of the apertures in square cm. is thus expressed in W/cm$^2$.

3.2.3. Conversion of Energy to Flux per unit area per nm interval:

The energy falling on the photo tube is a function of the transmission characteristics $T_1$ of the
Fig. 3.1. Calibration curves of the amplifiers used at different filter positions. The best fit line for the data points is also shown.
interference filter and $T_2$ of the UG-5 colour glass filter. Using the above three steps, the normal component of the incident flux density $\phi(t)$ can be evaluated as

$$\phi(t) = \frac{V(t)}{G \pi a^2 \int_{c-b}^{c+b} T_1(\lambda) T_2(\lambda) R(\lambda) \, d\lambda} \text{W/cm}^2/\text{nm} \quad (1)$$

where $t$ is time in IST hrs,
$V$ is the measured voltage in a given channel at a time $t$,
$c$ is the central wavelength of the interference filter,
$b$ is the half bandwidth of the interference filter,
$\delta\lambda$ is the step of numerical integration (numerical integration is performed here).
$G$ is the conversion factor determined from the electrometer calibration,
a is the radius of the aperture and $\pi a^2$ is the area of the aperture used.
$R(\lambda)$ is the spectral quantum efficiency of the phototube.

Typical transmissions ($T_i$) of the filters at 290, 300, 310 and 320 nm used are given in the Fig 3.2. To determine the value of $b$, the area under the transmission curve is taken. This area is assumed to be equal to the product of the transmission $T_{1/2}$ at half the peak and and the equivalent band width $2b$.

Having evaluated the normal component of the flux density, its projection on a flat horizontal plane, $\phi_h(t)$ is evaluated as

$$\phi_h(t) = \phi(t) \cos \chi \quad (2)$$
Fig. 3.2. Transmission characteristics of the interference filters.
where $\chi$ is the solar zenith angle. In order to determine the solar zenith angle at a given place at a given time the following equation is used.

$$\chi = \arccos \left\{ \cos \Lambda \cos \delta \cos H + \sin \Lambda \sin \delta \right\}$$

where $\Lambda$ is the latitude of the site of observation and $\delta$ is the declination of the sun on that day. The maximum value of solar declination is 23.5° to the north during the summer solstice and 23.5° to the south, during the winter solstice which is taken as negative. $H$ is the hour angle of 15° per hour and it incorporates the correction for local time and apparent local time. The corrections ($\Delta T$) used per year as listed in the Indian Astronomical Ephemeris for 1982 to 1992 are converted to the corrections in decimal hour and are within one minute. The apparent local time (ALT) is computed as:

$$\text{ALT} = \left[ \text{IST} - (82.5 - \text{station longitude}) \times 24 / 360 \right] - \Delta T \text{ hrs}$$

Then the hour angle is given by:

$$H = (\text{ALT} \times 15 - 180)$$

Thus to evaluate the incident UV flux from the measured voltage, the conversion factor $G$, the transmission characteristics of the filters $T_1$ and $T_2$, the quantum efficiency of the phototube $R(\lambda)$ and the aperture area are to be known.

3.3. COMPUTATION OF TOTAL OZONE:

The total ozone content in the atmosphere can
be derived from the measured values of the UV flux, \( \Phi_h \). The energy received at the surface on a flat horizontal plane, \( \Phi_h \), can be written as:

\[
\Phi_h(\lambda, \chi, \Omega) = \Phi_o \cos \chi \exp\left\{ -(\tau_{RS} + \tau_{AA} + \tau_{AS} + \sigma \Omega) \sec \chi \right\}
\]

where \( \lambda \) is the wavelength in nm,
\( \chi \) is the solar zenith angle,
\( \sigma \) is the absorption cross section of ozone in \((\text{atm-cm})^{-1}\),
\( \Omega \) is the total ozone columnar content to be derived usually expressed in Dobson units or milli atm-cm,
\( \tau_{RS} \) correspond to the optical thickness due to Rayleigh molecular scattering,
\( \tau_{AA} \) and \( \tau_{AS} \) are the optical depths corresponding to the absorption and scattering components of the aerosol for a fixed aerosol distribution and loading.

The parameter \( \Phi_h \) is also dependent on the sun earth distance \( r \) on the day of observation and the mean sun earth distance \( r_o \). Incorporating this, the above equation becomes,

\[
\Phi_h(\lambda, \chi, \Omega) = \Phi_o (r_o/r)^2 \cos \chi \exp\left\{ -(\tau_{RS} + \tau_{AA} + \tau_{AS} + \sigma \Omega) \sec \chi \right\}
\]

In this equation 7, we need the values of \( \tau_{RS}, \tau_{AA}, \tau_{AS}, \sigma \) and \( \Phi_o \) to calculate \( \Omega \).

\( \tau_{RS} \) correspond to the optical thickness due to Rayleigh molecular scattering (Penndorf, 1957). This can be computed using the equation:

\[
\tau_{RS} = 4.0 \times 10^{-28} / \lambda^3 \rho_{16} + 0.074\lambda + 0.05/\lambda \text{ cm}^2
\]

after Nicolet et al. 1982. The molecular scattering optical
depth is a function of the equivalent scale height which is about 8 km at this latitude. $\tau_{RS}$ values have also been given by Deshpande and Mitra (1985) which have been used in one of our computations.

$\sigma$ has been taken from Molina and Molina (1986) and converted to the absorption coefficient in (atm-cm)$^{-1}$. These values are also given in Inn and Tanaka (1953), Bass and Paur (1981), Daumont et al. (1983) and Schalter, J (1991).

Since the measurement is predominantly in the absorption spectral regime of ozone, the variations in these aerosol factors will introduce only systematic errors in the measurement and will not grossly distort the estimation of ozone. Here, a constant aerosol optical depth ($\tau_{AA} + \tau_{AS}$) has been used from Dave and Halpern, (1976). $\phi_0$ is the unattenuated solar energy at the top of the atmosphere in the same wavelength range as $\phi_h$, given by Thakkekara (1973) and DeLuissi (1975). The ozone thus derived has been compared with the Dobson spectrometer measurements at similar latitude stations.

The ozone content has also been derived using the aerosol factor extrapolated from the measurements using multiwavelength radiometers (Krishnamurthy et al., 1986, Krishnamurthy et al., 1989). The results are discussed in the next chapter.
3.4. NECESSITY FOR CALIBRATION:

For any system to make reliable and absolute measurements, periodic calibration is essential. Usually calibration is done with respect to a primary standard. Here an optical system which measures solar UV radiation is on a sun tracker. The properties of the optical components such as the interference filters and the UG-5 glass change with time and they can be readily assessed by measuring their transmission characteristics using a UV-VIS spectrometer (Carl Zeiss Jena). It is important to know the transmission range drift, if any, the development of a side band for the filters, especially in the spectral band of the phototube. Similarly, the electrometer amplifier and other electronic components can be checked periodically for their behaviour. The factor which decides the absoluteness of the measurement is the quantum efficiency of the sensor material, (Cs-Te), the photo cathode of the phototube R-765 used in the monitor.

3.5. CALIBRATION OF THE PHOTO CATHODE:

Recent growth in the optical radiation measurements has required development of secondary standards. The accurate measurement of optical radiation involves not only the use of a stable, well-characterized photometer, radiometer or spectroradiometer, but also the use of a standard. The standard can be in the form of a radiating
source whose radiant output and geometrical properties are accurately known. For this system, a 200 W quartz - iodine spectral irradiance lamp was found to have acceptable characteristics for use as a standard. Its spectral output is given in Fig 3.3. It is a rugged lamp in a small quartz envelope. The intensity usually varies little over a considerable solid angle centred normal to the axis of the lamp. The small size of the lamp together with the small area of the filament yields an approximate point source irradiance field at fairly close distances. The lamp spectral characteristics are specified for the typical distance of 50 cm from it. Because of its quartz window, and also its high operating temperature, the quartz halogen lamp emits a significant amount of radiation in the UV unlike the conventional tungsten incandescent lamps. The high temperature is made possible through the unique action of the halogen cycle, which results in the redeposition of the evaporated tungsten on the filament, thereby keeping the envelope clean, thus prolonging the useful life of the lamp. A 200 W quartz iodine lamp available at the Radio Science Division, National Physical Laboratory, New Delhi, was used for the calibration of the photometer.

Keeping the optical system at the fixed distance of 50 cm from the lamp, the photoelectric current output was noted. The experiment was repeated for various filter positions, 280, 290, 300, 310 and 320 nm. Assuming the invariance of the lamp output in the narrow effective
Fig. 3.3. Spectral output of the 200 W quartz iodine NBS secondary standard lamp in the 250 to 350 nm range. Calibration of the UV-B photometer has been done using this lamp available at the National Physical Laboratory, New Delhi.
bandwidth of the filters, the quantum efficiency of the phototube was calculated at a given wavelength using the formula:

\[ R(\lambda) = \frac{V(\lambda)}{G \pi \alpha^2 \int T_1(\lambda) T_2(\lambda) \phi(\lambda) \, \delta \lambda} \]  

where \( V(\lambda) \) is the voltage at a given wavelength \( \lambda \), \( G \) is the gain of the amplifier for that wavelength channel, \( \alpha \) is the aperture radius in cm, \( T_1(\lambda) \) and \( T_2(\lambda) \) are the transmission of the interference and the colour glass filters. \( \phi(\lambda) \) and \( \delta \lambda \) are the flux of the standard lamp at \( \lambda \) and the numerical step of the integration performed between the limits (as in the case of the derivation of the flux at ground described earlier).

The calibration was performed for all the phototubes in use. The phototube with the optical system was kept at various distances, from 40 to 70 cm, from the standard calibration lamp to check the linearity of the response. The linearity of response was decided by the inverse square law strictly valid for a point source. The linear regression between the square of the distance and the output for each filter position, say 320, 310 and 300 nm filters, was done. The linearity of response of the phototube used (R-765) is shown in Fig 3.4.

If a monochromator were available, \( R(\lambda) \) at all wavelengths within the effective band width of each filter could be ascertained. Such calibration systems with the standard spectral irradiance lamps are available in the country now. In the use of these phototubes at the nominal voltage of 15V or below, their life was found to be good over
Fig. 3.4. Linearity of response of the phototube R-765.
more than three years. The exposure of the photo cathode from radiation was limited only for the extent of the measurement and the blank position of the filter was used to protect the tube from light after every cycle of measurement. The phototube in comparison with the photo multiplier tube has the advantage of the ease of operation, but with the limitation of a much lower $R(\lambda)$. The $R(\lambda)$ curves of different phototubes after successive calibrations are shown in Fig 3.5.

Also, the phototube spectral response range in relative units can be ascertained using a UV-Visible spectrometer. The response of the phototube at specific wave numbers corresponding to the range from 200 to 350 nm using the deuterium lamp in the UV-VIS spectrometer as the source was measured. The response in the visible range was observed to be zero using the tungsten incandescent lamp as the source. The phototube was used with the full cathode open to the beam from the lamp. Since the lamps used in the UV-Visible spectrometers are not secondary standards, the output is only relative. Such an exercise would help to see whether there is any abnormal degradation in the phototube.

Relative error in any measurement depends on the magnitude of the quantity measured. Here the flux at three different wavelengths differ by a large magnitude and therefore, the error will depend on the quantity of flux measured. Since the average minimum spectral intensity measured in the 290nm channel is generally about $10^{-9} \text{W/cm}^2\text{nm}$ and the maximum in the 320 nm channel is about 25 $\mu\text{W/cm}^2\text{nm}$,
Fig. 3.5. Quantum efficiency, $R(\lambda)$, of the phototube, R-765 (PT-1) after successive calibrations. Response of another phototube (PT-2) is also shown.
the relative error in each channel of measurement will depend on the measured value at each wavelength. For eg., the error can be as high as 100% at about 297 nm (the average minimum detectable solar radiation at the ground) about 15% near 310 nm, and about 10% near 320 nm, with the sun as the source. This error in comparison, with a standard calibration lamp as the source drops from 10% at 297 nm to less than 1% at 320 nm. The calibration lamp output is known at all the lower wavelengths and that the output is accurately measured, the error estimation is more precise.

3.6. TRANSMISSION CHARACTERISTICS OF THE INTERFERENCE FILTERS:

Interference filters are optical components that are generally used to select a wavelength of a radiation for measurement or use. It is the filter that controls the spectral composition of transmitted energy partially by the effect of the interference. These filters are made up of thin layers of metals and dielectrics, resulting in high transmission in narrow spectral bands. The radiation selected has a central wavelength decided by the peak transmission of the filter and the spectral components decided by the full width at half maximum transmission (FWHM). The peak transmission shift is a function of the angle of incidence of the radiation on the filter and is generally given by the formula:

\[ \lambda_c = \lambda_{\text{max}} \sqrt{1 - \sin^2 \theta} \cdot (n_o/n_e)^2 \]
where $\lambda_c$ is the desired central wavelength and $\lambda_{\text{max}}$ is the peak wavelength for the filter for an external angle of incidence (tilt angle) $\theta = 0^\circ$. It can be observed that for any small angle of tilt, the shift is always to the lower wavelength side. The $n_o$ and $n_e$ are the refractive indices of air ($=1$) and that of the spacer material of the filter respectively. The effective spacer index of refraction is dependent on the wavelength, the spacer material and the order of interference.

The wavelength of the radiation falling on the phototube is selected by the filters used (They also limit the photoelectric current generation depending on the effective bandwidth of the filter used). This effective bandwidth of the filter is decided by the peak transmission percentage, expressed in decimal numbers, and the area of the filter curve which characterizes the amount of light effectively transmitted by it at different wavelengths with the distribution decided by the envelope of the curve. Since the spectral response $R(\lambda)$ of the phototube is not linear within the wavelength regime of each filter, a rectangular window approximation is done to the transmission curve. The typical example of a filter transmission (300 nm) with the a window is shown in Fig 3.6. The width of the window at the half the peak transmission necessarily gives the effective bandwidth and is the ratio of the area of the curve $A$ to the half peak transmission. The elimination of the tail band of the transmission curve is by a ratio (minimum to maximum
Fig. 3.6. Evaluation of the effective bandwidth of an interference filter. Aging of the filter after use is also shown as an example.
transmission) of 1 : 100. The filters were found to age with time and use. Typical change in their characteristics are also shown in the same figure. The error introduced in the flux measurement at each wavelength for a change of unit percentage of the effective bandwidth is tabulated in Table 3.1. Since the photosensor spectral response of most of the low intensity light measuring devices is not flat (independent of the wavelength, $\lambda$), one has to resort to spectral calibration of the system response or go for the approximation technique. The former gives an accurate spectral picture of the sensor behaviour at all wavelengths for a standard input. The latter has certain assumptions such as the integrated flux falling on the sensor in a window of wavelengths (limited by the optical components as interference filters) is having a single response independent of the $\lambda$. However, with different filters of narrow bandwidths close together, the response of the sensor can be assessed approximately.

This approximation technique has been applied in the phototube response part of the Robertson Berger UV radiometer. (Sundararaman et al., 1975) As a rule, the correction done to the flux measurement for the change in filter transmission is taken linear between checks. The actual centre wavelength of the transmission from filter to filter vary by a fraction of a nm. The approximation method averages the flux transmitted by the filter in the entire band. The centre wavelength of the filter serves to indicate that the radiation is measured at those average wavelengths
within the effective bandwidth. This makes the measurement non-spectral as in the case of other filter methods.

3.7. TRANSMISSION OF COLOUR GLASS FILTERS:

Various filters have been used for limiting the radiation frequencies to UV alone blocking the visible and the near IR radiations from being incident on the photo sensors used. The Canterbury equipment used the Corning CS-75 glass with the NiSO₄·6H₂O for this purpose. An NiSO₄·6H₂O crystal was grown in the laboratory by slow evaporation method of a supersaturated solution of the salt. Its typical transmission characteristics shown is in Fig 3.7. As is evident the spectral purity (in terms of smoothness of the transmitted signal) and magnitude of the signal are low. The maintenance of this crystal free from moisture and from dust, even after embedding the crystal in a metal chamber with quartz windows was a problem. As an experiment, an unsaturated solution of the nickel sulphate in water was used in a quartz windowed metal cell as a colour glass filter. Its transmission in the UV range (of interest did not depend on the solution of the salt) was higher than that of the crystal. However, due to the mechanical disadvantage of the cell regarding air tightness etc lead to the formation of air bubble inside the cell, which on day long use, interfered with the measurement. Hence a more stable and reliable method of filtering the
Fig. 3.7. Transmission characteristics of the UG-5 glass and NiSO₄·6H₂O crystal and its aqueous solution.
visible and IR component of the solar radiation had to be resorted to.

Therefore, the UG-5 glass (Uviol Glass of Schott Glass) was used. The transmission as specified by the manufacturer and while it was used (just before and after) are also shown in Fig 3.7. As can be seen, the transmission of the UG-5 glass was observed to be about 60% in the measurement region and its further degradation with use was only marginal.

3.8. RELATIVE ERRORS IN MEASUREMENT:

The equation for the reduction of flux involves the measured voltage, the instrument constants such as the aperture area, the transmission of the filters, the measured quantum efficiency of the phototube etc.

\[
\phi (t) = \frac{V(t)}{G \pi a^2 \int_{c-b}^{c+b} T_1(\lambda) T_2(\lambda) R(\lambda) \Delta(\lambda)} \text{W/cm}^2/\text{nm} \quad (1)
\]

Here, we have evaluated the error in the measurement for an uncertainty of 0.18° (one step) in tracking. Then for an 1% increase in the effective bandwidth of the filter, the error is separately evaluated. Using these two errors an aggregate relative error in the measurement is evaluated at all the wavelengths. This exercise was done for an equinox day and at zero degree zenith. The results of this error evaluation are shown in Table 3.1.
Table 3.1. Relative error in measurement of flux:

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Sun tracker (1 step)</th>
<th>Bandwidth 1%</th>
<th>Total error Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>290</td>
<td>3.4</td>
<td>1.4</td>
<td>5.2</td>
</tr>
<tr>
<td>300</td>
<td>2.1</td>
<td>0.98</td>
<td>3.1</td>
</tr>
<tr>
<td>310</td>
<td>1.1</td>
<td>0.91</td>
<td>2.02</td>
</tr>
<tr>
<td>320</td>
<td>0.6</td>
<td>0.62</td>
<td>1.26</td>
</tr>
</tbody>
</table>

The systematic error introduced by the azimuthal variation during the period of observation of 8 hrs maximum per day has not been taken into account in the above calculations. This azimuthal variation in terms of angle aggregates to a maximum of about 0.08°. This error is inherent in the system as the sun tracker is of a single axis type, but is negligible.