Chapter – 2

Multi-Wavelength solar Radiometer and its data analysis
2.1 Instrumentation

As the aerosol size spectrum runs over five decades of size range and the affects of aerosols are strong functions of their size, no single technique can provide complete information on aerosols. Thus several techniques are used to probe atmospheric aerosols depending on the parameters of interest (Diermendjian, 1980). For aerosol-radiation interaction, the size range scatters and absorbs (depending on their chemical composition) the down coming solar radiation with consequences on the radiation budget of Earth-Atmosphere system. In assessing the radiative forcing of aerosols the parameters of importance are the columnar spectral optical depth ($\tau_{\text{p}}$), the size distribution function [$n(r)$] and the complex refractive index ($m$). Several active and passive remote sensing methods are used for retrieving these properties. Of these, the solar radiometers (or sun photometers, as they are popularly known) provide a simple and efficient passive techniques, particularly suitable for long-term measurements, even from remote and isolated locations. The instrument makes continuous measurements of ground reaching directly transmitted solar flux at one or more narrow wavelength bands from which the columnar optical depth of the atmosphere can be estimated. Aerosol optical depth can be deduced from this and making such estimates at a number of wavelengths, interference can be made on the size distribution of aerosols. The instrument, quite simple to develop and operate, uses sun as the source and can be ruggedised for field use.

Historically the origin of sun photometry goes back to Volz (1959) who developed a single wavelength sun photometer for measurements of atmospheric turbidity. Later the instrument was modified to incorporate three wavelengths with different cut-off in the visible spectrum and the instrument has been extensively used for aerosols studies (e.g., Angstrom, 1961; Mani et al., 1969). However, the broadband filters used in these instruments and the limited
number of wavelengths employed were insufficient for the spectrally resolved measurements of aerosol properties (Krishna Moorthy et al., 1989). In the early seventies multi-wavelength solar radiometers were developed (Shaw et al., 1973) based on the principle of filter wheel radiometry which provided measurements at a number of narrow wavelength bands selected using interference filters. Such radiometers are now widely used globally for systematic studies on aerosols.

The Multi-Wavelength solar Radiometer (MWR) or SPL has designed following the principles of filter wheel radiometers to make continuous spectral extinction measurements of ground reaching, directly transmitted solar flux at ten narrow spectral bands. In the eighties (i.e., during the IMAP) the MWRs were semi-automatic in nature and the data were recorded on thermal printers, which were then entered into a computer for further analysis. These systems are gradually being replaced by fully automatic PC based system which provide easy acquisition and archival of the data as well as speedy analysis. In either case the MWR made spectral extinction measurements in ten wavelength bands, centered at 380, 400, 450, 500, 600, 650, 750, 850, 935 and 1025 nm. These wavelengths are selected using narrow band interference filters with full-width-at-half-maximum bandwidth of 6 to 10 nm. Beyond the pass band the filters are blocked from far UV to far IR with blocking transmittance less than $10^{-4}$ of the peak transmittance. A three-cavity structure is selected to shape the pass band. These filters for selecting the desired wavelength bands are mounted sequentially on a dull black-ended circular disc known as filter wheel (FW) at an angular separation of 36°. During operation, these filters are brought sequentially into the optical channel by rotating the FW in a programmed manner using a stepper motor gear assembly. The radiation is made to pass through a field limiting optics, which limits the field of view of the MWR to 2°(thereby considerably reducing the errors in the estimates of the optical depth caused by the contribution due to diffusely scattered radiation) and using as photo-detector
amplifier UDT 455 UV as a field stop. The output of the detector is directly proportional to the solar flux incident upon it. The FW and the optical channel including the photo detector are housed in a mechanical housing to protect them from the environment and to shield from any undesired radiation. The inner surfaces of this optical unit are dull blackened to prevent any stray reflections from the walls. The optical unit is kept on adjustable equatorial mount and is moved at every 12s about an orthogonal axis with an angular speed equal to that of the Sun (0.05° in 12 s), in order to keep the system always aligned towards the Sun, once set initially. The mount also has provision for adjusting the solar declination.

The output of the photodetector, which is in analog form, is digitized using a 12 bit sampling ADC, and averaged over a period of 1s before recording. To this output other information such as the time of data acquisition, the filter identification and the system noise when no external radiation is incident into the system are appended. The data is then automatically transferred to the non-volatile memory of the personal computer, which also acts as the heart of the control system. The entire operation of the MWR and data acquisition system (C and DA system), interfaced with the Personal Computer and operated using a user friendly menu driven software developed at SPL. The schematic diagram of the automatic control and data acquisition system is shown in Fig.2.1. This C and DA system is developed in house at SPL on a custom built PC compatible add-on card. This card accommodates the programmable timer counter (PTC), the programmable peripheral interface (PPI) as well as the 12-bit sampling analog to digital converter (ADC) on it. The design of the card also provides sufficient breadboard area for any future augmentation. The optics unit is then interfaced with the control unit and the PC as well as the driver circuits for the motors. The optics unit is kept on a pedestal in the open field such that it can have unobstructed solar visibility throughout the year for major part of any day. A
Fig. 2.1: Schematic of the PC based programmable Control and Data Acquisition (C & DA) system developed by SPL for the MWR.
photograph of the complete MWR system designed and developed in SPL and installed at Anantapur is shown in Fig. 2.2.

2.2 Data analysis

The MWR has been operated during apparently clear days when no visible clouds were present in the neighborhood of solar disc. The period of data is from March to May 2002. The data are generally collected from morning 6.30 A.M. till evening 6.15 P.M. on most of the days, the minimum period of collection being 3 hr. Each set of observations comprises time in hr and min of IST and the output voltage $V_{\lambda}$ at each of the 10 wavelength ($\lambda$) bands. The recording period has generally been limited to solar zenith angle ($\chi$) values less than 70°, so that effects of refraction and curvature of the earth can be neglected. Each set of measurements is repeated at an average interval of 15 min, the spacing being closer during morning and evening periods when the variation of sec $\chi$ with time is faster.

Analysis of solar radiometer data to compute the optical depths involves spectral measurement of ground reaching solar flux $F_{\lambda}$ as a function of solar zenith angle and evolving a linear least square fit to the Lambert-Bouguer-Beer law connecting $F_{\lambda}$ to the extra terrestrial flux $F_{0 \lambda}$. This method, called Langley technique, has been widely described in literature (Shaw et al., 1973; Pitts et al., 1977; Tomasi et al., 1983; Krishna Moorthy et al., 1988; 1989; 1993). However, for the sake of continuity and completeness, the main steps followed are presented here.

As the MWR provides output voltage $V_{\lambda}$ that is directly proportional to the incident solar flux $F_{\lambda}$ at a wavelength $\lambda$, for solar zenith angle $\chi \leq 70^\circ$, the Lambert-Bouguer-Beer law can be written as

$$\ln V_{\lambda} = \ln C_{\lambda} + \ln F_{0 \lambda} + 2 \ln (r_0/r) - \tau_{\lambda} \sec \chi$$  \hspace{1cm} (1)
MULTI-WAVELENGTH RADIOMETER

AUTOMATIC WEATHER SENSORS

8-CHANNEL DATA LOGGER WITH DATA ACQUISITION
where $C_\lambda$, System constant at $\lambda$.

$r$ Instantaneous value of sun-earth distance

$r_0$ Mean sun-earth distance

$\tau_\lambda$ Integrated columnar optical depth of the atmosphere.

Here the atmospheric airmass term is approximated to $\sec \chi$. Eq. (1) represents in linear relationship between $\sec \chi$ and $\ln(V_\lambda)$. The slope of the best-fit line will yield $\tau_\lambda$ and the Y-intercept extrapolated for zero airmass condition ($\sec \chi = 0$) will yield the system-measured value of solar flux at the top of the atmosphere. We define

$$\ln V_{0\lambda} = \ln C_\lambda + \ln F_{0\lambda}$$

as the zero airmass intercept corrected for the variations in sun-earth distance. As the day-to-day variations in $F_{0\lambda}$ can be completely neglected, all variations in the system parameters, and variations arising out of inadequacy of the fit to Eq.(1) arising either due to strong short term temporal variations in $\tau_\lambda$ and influences of unidentified clouds or due to system misalignment etc. resulting in variations in $C_\lambda$, will be readily reflecting on $\ln (V_{0\lambda})$. Thus the constancy or extent of variations $\ln(V_{0\lambda})$ can effectively be used as check on the system stability, and hence to assess the quality and reliability of data collected. The term $\sec \chi$, relevant to each observation has been computed from corresponding time information by converting it to local mean time and using the equation of time and solar declination angle ($\delta$) for the day from almanac (2002) using the equation

$$\sec \chi = [\sin \delta \sin \phi + \cos \delta \cos \phi \cos H]^1$$

where $\phi$ is the latitude of Anantapur and $H$ is hour angle.
After computing \( \ln(V_x) \) and corresponding \( \sec \chi \) for all the data, Langley plots are made. Through the experimental points a linear regression fitted line is drawn, and is extrapolated to meet the ordinate corresponding to zero value in the abscissa. This intercept is then corrected for the sun-earth distance of that day to get \( \ln(V_{0x}) \). The slope of the straight line yields \( \tau_\lambda \). Other statistical parameters like variance of \( \tau_\lambda \) and correlation coefficient \( \rho_\lambda \) are also estimated. Any spurious points resulting from nonalignment of optics, sudden and brief cloud cover etc and also points depicting strong short term temporal variations in \( \tau_\lambda \) during observations will produce undesirable weightages to the mean \( \tau_\lambda \) for the day. These points are removed by assigning a 99.5% correlation coefficient to the data using the relevant Student 't' statistics and \( \tau_\lambda \), \( \rho_\lambda \) and \( \ln(V_{0x}) \) are re-estimated. Fig.2,3 shows a typical Langley plot obtained. The experimental points are marked and the regression fitted line is drawn through them. The intercept is also shown. Above each plot the wavelength, slope and correlation coefficient are also shown.

The atmospheric columnar total optical depths (\( \tau_\lambda \)) estimated following Langley technique is the sum of contributions due to molecular (Rayleigh) scattering \( \tau_{RLx} \), aerosol (Mie) scattering and absorption (\( \tau_{px} \)), and absorption due to \( O_3 \) (\( \tau_{03x} \)) and water vapour (\( \tau_{Wx} \)), so that

\[
\tau_\lambda = \tau_{RLx} + \tau_{px} + \tau_{03x} + \tau_{Wx}
\]

From Eqn.(4), aerosol optical depth can be deduced as

\[
\tau_{px} = \tau_\lambda - \tau_{RLx} - \tau_{03x} - \tau_{Wx}
\]

Each term on R.H.S. of Eqn.(5) is a separate function of \( \lambda \). The details of estimation of \( \tau_{RLx} \), \( \tau_{03x} \) and \( \tau_{Wx} \) are given in the literature (Krishna Moorthy et al., 1988). However, the main points are briefly summarized as follows:
Fig. 2.3: A typical Langley plot constructed using the MWR data at Anantapur. The points are the measurements and the lines are regression fitted. The regression and other statistical coefficients are written in the graph for each spectral channel.
Optical depth due to molecular scattering at the MWR wavelength is computed using the analytical expression

$$\tau_{\text{mol}} = \frac{24\pi^2}{N_0} \left( \frac{n_0^2 - 1}{n_0^2 + 2} \right)^2 K_\lambda \int_0^{h_m} n(h) \, dh$$

(6)

where, $N_0$ is the molecular number density at sea level, $n_0$ the refractive index of air at STP, $K_\lambda$ the wavelength development Rayleigh depolarization correction factor (Bates, 1984) and $n(h) \, dh$ the altitude profile of neutral atmosphere from 0 to 80 km. The upper limit $h_m$ for integration in Eqn.(6) is taken as 80 km, and $n_0$ is evaluated using the expression given by Kniezys et al. (1980). The value of $\tau_{\text{mol}}$ obtained using Eqn.(6) will correspond to $\tau_{\text{R}0}$ for stations at sea level. For other stations, $\tau_{\text{R}0} = \tau_{\text{mol}} \left( \frac{P}{P_0} \right)$, where $P_0$ (=1013.15 mbar) is the surface pressure at sea level and $P$ the mean surface pressure at the station. The seasonal variations in $\tau_{\text{R}0}$ is less than 1% and are not considered.

For Ozone, the wavelength dependent absorption cross-section $\sigma_{\text{O}3}(\lambda)$ for the Chappius bands (Kniezys et al., 1980) are used for the MWR wavelengths of 500-650 nm. Then

$$\tau_{\text{O}3,\lambda} = \sigma_{\text{O}3}(\lambda) \int_0^{h_1} N_{\text{O}3}(h) \, dh$$

(7)

where $N_{\text{O}3}(h) \, dh$ is the altitude profile of O3 number density for the altitude region 0 to $h_1$ (=60 km). Maximum seasonal variation in total O3 is reported to be ~10% of the mean (Kundu, 1982). However, the contribution of this to $\tau_{\text{O}3}$ itself is generally much smaller than other optical depths.

The values of $\tau_{\text{W}0}$ has been evaluated using optical depths at 935 nm along with those at 850 and 1025 nm, following the empirical transmission functions and wavelength dependent mass absorption coefficient given by Leckner (1978). Its value depends strongly on the amount of atmospheric water
vapour content and shows large variability. In general, it lies between 0.0001 and 0.008 at 750, 850 and 1025 nm, while at 935 nm its value ranged between 0.2 and 1.4 depending on the content of water vapour.

Generally data collected over a day (for a minimum of 3h duration) is treated as a single set and a single set of $\tau_p$ values are obtained for that period. A typical graph drawn for the $\tau_p$ values at all the wavelengths is shown in Fig.2.4. More frequently at Anantapur station, the Langley plots revealed presence of two slopes one for the forenoon and the other for the afternoon part of the day. The data is considered as two separate sets, one for the FN and the other for the AN part and two separate $\tau$ values are deduced. Typically the number of days of data lies between 20 and 5 per month, depending on the sky conditions. But owing to the FN-AN differences, the number of data sets per month sometimes goes up to as much as 40. The period from June to October of any year is considered as data lean period due to the prevailing monsoon conditions, particularly over the peninsular regions.

2.3 Measurement of Meteorological parameters

The daily meteorological conditions during the study period were recorded using the meteorological station at the observational site. Wind speed ($U$, m s$^{-1}$), wind direction ($\theta^\circ$), relative humidity (RH%) and air temperature (AT, °C) were measured at 15 min. intervals.

To measure the wind speed, a fast response, low threshold opto-electronic cup anemometer was used. When rotated by wind, a chopper on the anemometer shaft interrupts an infrared light beam 22 times per revolution generating pulses from a phototransistor. The signal is amplified and fed through a line driver, which can drive 500 meters of cable. The frequency is proportional to wind speed.
Fig. 2.4: A typical graph has drawn for the $\tau_{ph}$ values at all the ten wavelengths.
For the measurement of wind direction a counter balanced, low threshold wind vane was used. Linear, wire wound endless potentiometer is coupled to the vane by SS shaft. As the vane turns, it rotates a stainless steel shaft, which is coupled to the potentiometer. This potentiometer has excellent linearity, very low torque. The use of single wiper increases the life expectancy of the potentiometer. The north of the wind vane is marked on its body. This line is to align with magnetic North of the earth with the help of prismatic compass, at the time of installation. Sensor gives minimum resistance at North (i.e., 0 degree approximately 20 ohms). The position of the wind vane is proportional to the resistance.

The humidity sensor is a thin film capacitor element. A dielectric polymer absorbs water molecules from the air through a thin metal electrode and this causes a capacitance change proportional to humidity. The response is essentially linear. A sintered filter is provided to protect the sensor element from dirt, atmospheric pollutant and water condensation. A Solid State electronic circuit is built in each probe to produce 0 to 1000mv output signal corresponding to relative humidity value 0 to 100 %. The output is signal ended.

The sensor used for air temperature measurement is a standard Platinum RTD (PT 1000). Here the resistance of the element varies with temperature (increases with temperature), approximately 3.9 ohm / degree Celsius.

Automatic weather station containing the above sensors was installed at observational site to study the variations of aerosol optical depth values with wind speed, wind direction, relative humidity and air temperature.