Compact light-emitting-diode sun photometer for atmospheric optical depth measurements

Y. B. Acharya, A. Jayaraman, S. Ramachandran and B. H. Subbaraya

A new compact light-emitting diode (LED) sun photometer, in which a LED is used as a spectrally selective photodetector as well as a nonlinear feedback element in the operational amplifier, has been developed. The output voltage that is proportional to the logarithm of the incident solar intensity permits the direct measurement of atmospheric optical depths in selected spectral bands. Measurements made over Ahmedabad, India, show good agreement, within a few percent, of optical depths derived with a LED as a photodetector in a linear mode and with a LED as both a photodetector and a feedback element in an operational amplifier in log mode. The optical depths are also found to compare well with those obtained simultaneously with a conventional filter photometer

Key words: Light-emitting diode, sun photometer, optical depth, operational amplifiers, nonlinear element.

1. Introduction

Atmospheric aerosols are a mixture of solid or liquid particles suspended in the medium of air. Their physical properties (size, shape, and texture) and chemical properties vary over a wide range, and consequently their removal processes (and hence their residence times) also vary greatly. Aerosol particles of different sizes and composition play a vital role in many atmospheric processes, such as visibility, radiation balance, atmospheric electricity, air pollution, and cloud formation.[1] Systematic monitoring of aerosol parameters is necessary because of their spatial and temporal variations. Sun photometry[2] is one of the most widely used techniques for measuring aerosol properties; optical depths can be directly obtained with this technique, unlike other remote sensing techniques in which the data have to be analyzed by the use of complex inversion algorithms to evaluate the optical depths. Also, no absolute calibration of the instrument is necessary in the case of sun photometers, and comparison of results with other measurements is relatively easy because the optical depths are directly derived. The Volz sun photometer[3] is one of the most widely used instruments for atmospheric turbidity measurements.[4,5] From turbidity measurements, attempts are made to draw an inference on the aerosol properties.[6]

Numerous multichannel sun photometers (manual or automatic Sun tracking) are in use around the world to measure optical depth on regular basis.[7] Photometers consist basically of an interference filter to select a desired wavelength band and a suitable photodiode. A sun photometer with a light-emitting diode (LED) as a spectrally selective detector has been reported by Mims.[8] The visible region of the solar electromagnetic spectrum is generally used for aerosol optical depth measurements.

The advantage of a LED photometer is that it is much more compact and sturdier than the conventional photometer that is fitted with a photodiode and an interference filter. We developed a photometer system using the LED's as spectrally selective photodetectors as well as nonlinear elements in the feedback loop of operational amplifiers to permit direct measurement of atmospheric optical depths. Commercially available (at a much lower cost than a photodiode) LED's that operate in visible regions are used; these LED's are, in general, adequate for aerosol optical depth studies.

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2. Principle

Solar radiation intensity or current measured by a conventional photometer is given by the Beer–Lambert law:

$$I = I_0 \exp(-\tau m) \tag{1}$$

such that

$$\ln I = -\tau m + \ln I_0, \tag{2}$$

where I_0 is the solar radiation intensity at the top of the atmosphere, τ is the total optical depth, and m is the air mass factor, which is defined as

$$m = \sec\{[(r^2 \cos^2 \chi + 2rH + H^2)^{1/2} - r \cos \chi]/H\}, \tag{3}$$

where r is the radius of the Earth at the observation latitude, H is the scale height, and χ is the solar zenith angle. The total integrated columnar optical depth of the atmosphere is

$$\tau = \tau_{\mathrm{rs}} + \tau_{\mathrm{aerosol}} + \tau_{\mathrm{ma}}, \tag{4}$$

where τ_{rs} is the Rayleigh scattering optical depth (scattering that is due to air molecules), τ_{aerosol} is the aerosol optical depth, and τ_{ma} is the optical depth that is due to molecular absorptions, such as ozone, water vapor, or nitrogen dioxide. The aerosol optical depth τ_{aerosol} can be obtained when τ_{rs} and τ_{ma} are subtracted from τ. τ_{rs} and τ_{ma} are obtained from the model atmospheric values.

In conventional sun photometry, the current produced by the detector, which is due to solar radiation, is converted into voltage by a linear current–voltage converter. The logarithm of the output is plotted against air mass and is referred to as a Langley plot. The slope of the curve gives the total optical depth of the atmosphere.

We have developed a new and compact photometer whose output is proportional to the logarithm of solar radiation intensity, which could be used to obtain the optical depth directly. It requires only a LED and a low leakage current operational amplifier. A LED is used as a spectrally selective detector and is connected as a feedback element of the operational amplifier. As I-V characteristics of the p–n junction diode are exponential, the output of the operational amplifier is directly proportional to the logarithm of incident light intensity.

LED's are devices that are designed to convert electrical energy into electromagnetic radiation efficiently. The spectral emission band depends on the composition of the material used. A LED is a junction diode that can emit light or exhibit electroluminescence. The emitted light in this case comes from hole electron recombination. The recombination radiation is then emitted in all directions, but most of the light is observed at the top surface, as the amount of material between the junction and the surface is the least.

A p–n junction diode being used as a light source and a photodetector are complementary in function. A LED can function as a photodetector with a spectral response that is similar to its spectral emission band.[9] A typical bandwidth of the emission is of the order of 25–50 nm at the half-maximum points. The above property of a LED has been used to replace the conventional photometer assembly, which consists of an interference filter and a photodiode. As the logarithmic I-V characteristic of a LED is quite linear (Fig. 1) over a large dynamic range,[10] the instrument can be used for large solar input variations.

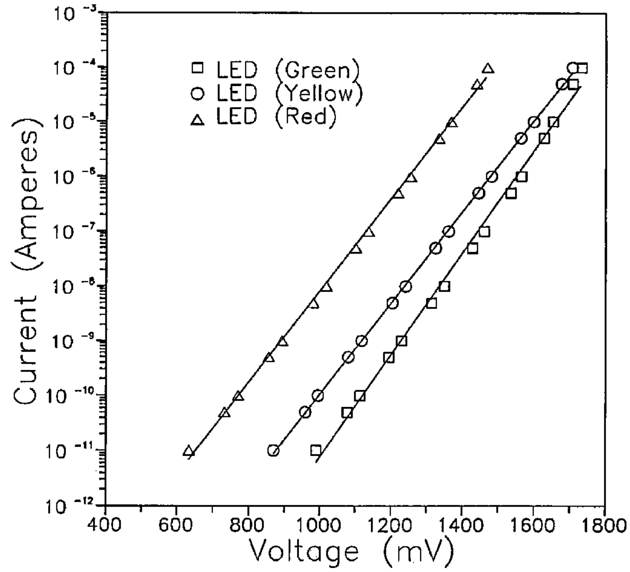


Fig. 1. Current–voltage characteristics of green, yellow, and red LED's.

The current–voltage characteristics of a GaAs p–n junction diode is given by the classical diode equation,

$$I = I_s[\exp(qV/nkT) - 1], \tag{5}$$

where q is the electronic charge, k is Boltzmann's constant, T is the absolute temperature, n is an empirical factor that has a value between 1 and 3, V is the voltage across the diode, and I_s is the reverse saturation current that sets the lower measurement limit.

A logarithmic amplifier is made when a nonlinear device is connected as a feedback element in the operational amplifier circuit (Fig. 2). In this configuration, input current I_{in} and output voltage V_o are

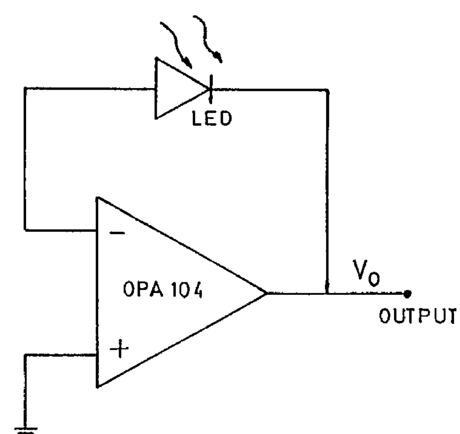


Fig. 2. Schematic of a LED sun photometer operating in the log mode configuration. OPA 104 is an operational amplifier.

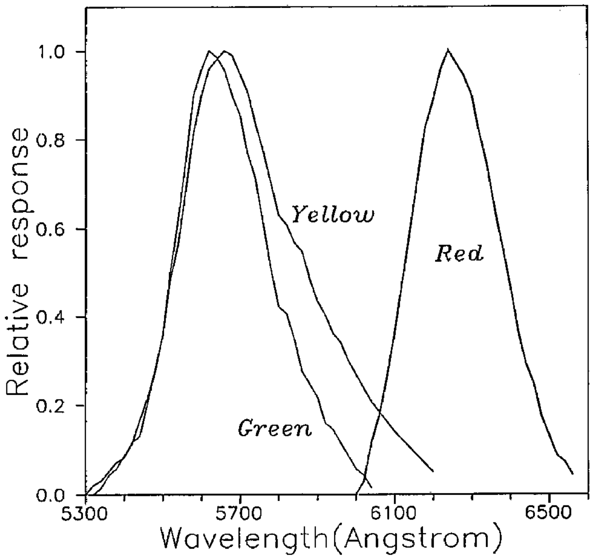


Fig. 3. LED emission spectra.

related by

$$I_{\text{in}} = I_s \exp(qV_o/nkT) - I_s. \tag{6}$$

For $V_o \gg nkT/q$,

$$I_{\text{in}} = I_s \exp(qV_o/nkT), \tag{7}$$

$$qV_o/nkT = \ln I_{\text{in}} - \ln I_s, \tag{8}$$

Using Eq. (2), we can rewrite Eq. (8) as

$$-\tau m + \ln I_0 = V_o/K_1 + \ln I_s, \tag{9}$$

$$V_o = -K_1\tau m + K_2, \tag{10}$$

where $K_1 = nkT/q$ and $K_2 = K_1(\ln I_0 - \ln I_s)$. V_o, which is plotted for various Sun positions as a function of the air mass factor, m, gives a straight line whose slope corresponds to $K_1\tau$ and the Y intercept to the instrument constant K_2.

Figure 1 shows the current–voltage characteristics of the three LED's used in this study. By fitting Eq. (5) through the experimentally observed points, we determine the constant K_1 of the three LED's, which is found to be 0.0467, 0.0521, and 0.0517 V for green, yellow, and red LED's, respectively.

3. System Details

The circuit diagram of the system is shown in Fig. 2. It consists of only a LED connected in the feedback loop of a low leakage current operational amplifier OPA 104 (Burr Brown). Three readily available LED's (green, yellow, and red) are used for the different wavelengths. The LED's are mounted in a cylindrical baffle to give a total field of view of 9°. The baffles are also blackened inside to reduce any internal reflection. A separate guider that consists of a cross-bar assembly attached above the LED assembly is used to orient the detectors manually toward the Sun. Spectral characteristics of the LED's, which were obtained with a 0.67-m McPherson Monochromator, are shown in Fig. 3. Center wavelength and full width at half-maximum (FWHM) are given in Table 1.

Table 1. Spectral Characteristics of the LED's Used

Type	Center Wavelength (nm)	Bandwidth (nm)
Green	562	22
Yellow	566	19
Red	624	19

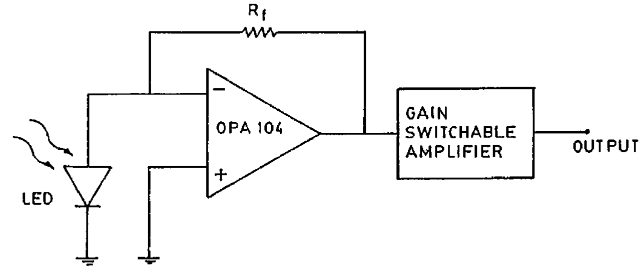


Fig. 4. Schematic of LED sun photometer operating in the linear-mode configuration.

Three sets of circuits, such as those shown in Fig. 2 are used for different LED's and are hereafter referred as log-mode operations. To validate the performance and the results of the new LED photometer, we also made simultaneous measurements with the same set of LED's, but this set was connected as shown in Fig. 4. In this linear-mode configuration, the current produced by the LED is converted to voltage by a linear current–voltage converter with a sensitivity of 1 V/μA. The output is further amplified by a gain switchable amplifier to accommodate the large dynamic range encountered during measurements that correspond to various Sun positions.

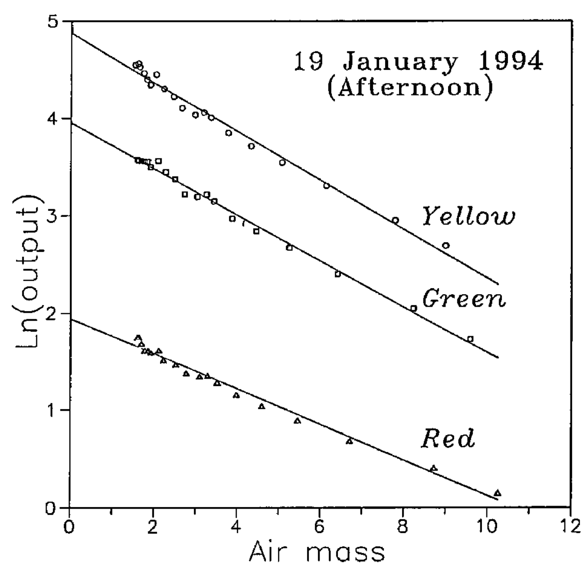


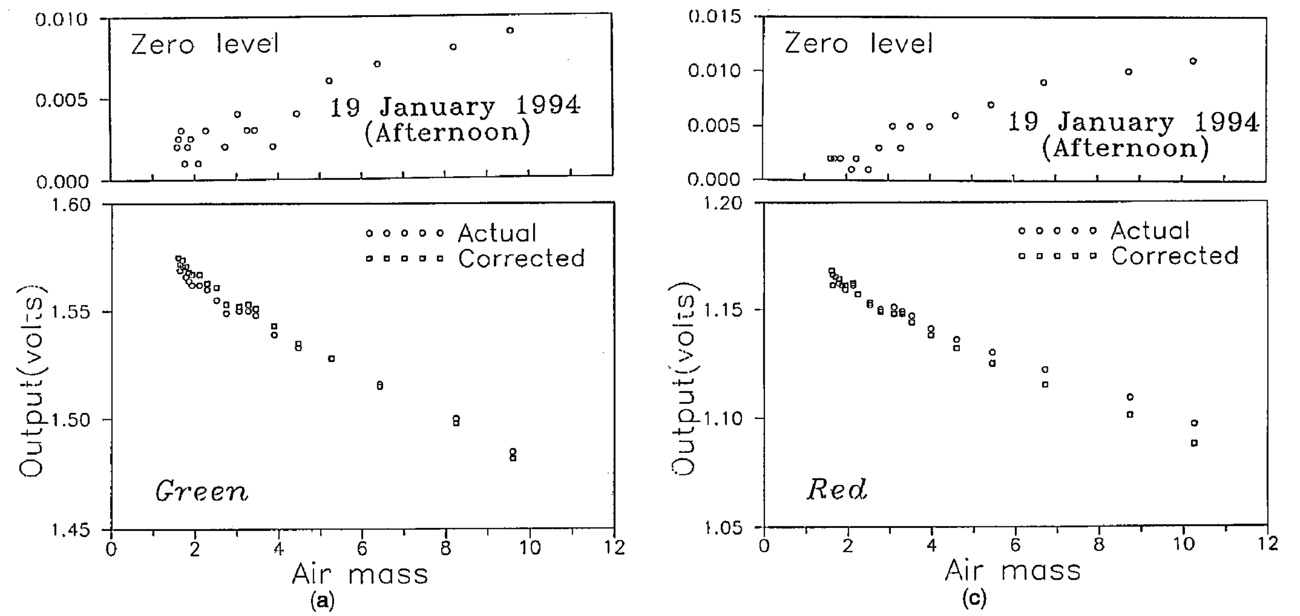
Fig. 5. Results of measurements (Langley plots) made of the LED sun photometer operated in the linear mode on 19 January 1994 (afternoon hours).

4. Experiment

Solar intensity measurements in which both linear and log modes were used were first made on 19 January 1994 at Ahmedabad, India. The same LED's were used for observations in both modes. It should be noted here that the p–n junction characteristics are prone to change with temperature. Also, the ambient temperature changes during the observation period. For example, during forenoon hours, temperature would increase with time. However, in the afternoon hours, temperature would decrease as the observation progressed. To take care of changes in the LED performances with time, zero readings (with the photometer lid closed) for individual LED's were taken and were used to correct the observations. We also made near-simultaneous observations, using the same LED's but operating them in the linear mode, for 19 January 1994 to check the validity of the technique. The natural log of the output obtained in the linear-mode configuration is plotted against air mass for three LED's, as shown in Fig. 5.

Figures 6 show the actual outputs in the case of the log-mode configuration and the zero level changes for the three LED's and the corrected outputs. The corrected signals are used for constructing Langley plots and are shown in Fig. 7. Langley plots for log and linear modes are found to be linear up to an air mass of ~8, which is equivalent to a solar zenith angle of ~83°.

Furthermore, a systematic observation program was undertaken from 30 April to 8 May 1994 over Ahmedabad, and Langley plots were obtained for the



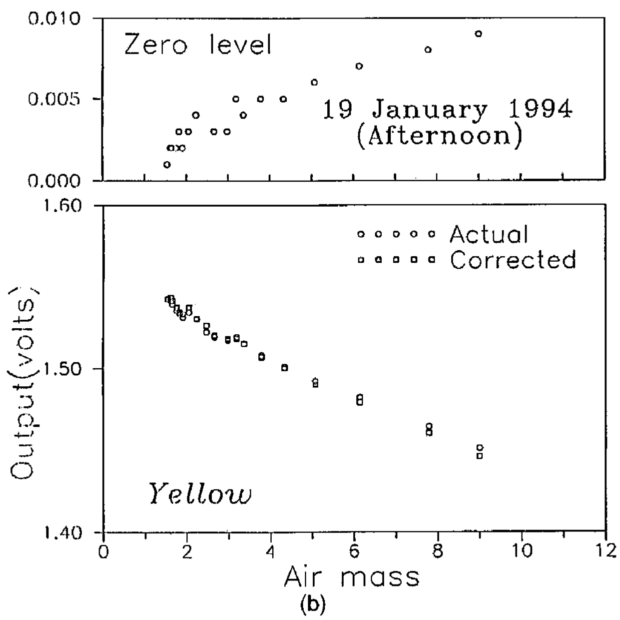


Fig. 6. Plots of LED sun photometer outputs along with the simultaneous dark current observations for (a) green, (b) yellow, (c) red.

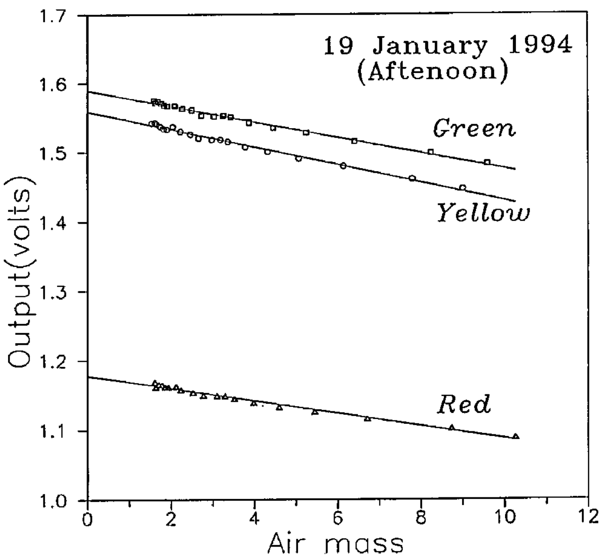


Fig. 7. Results of measurements (Langley plots) made of the LED sun photometer operated in the log mode on 19 January 1994 (afternoon hours).

Table 2. Results of LED Sun Photometer Observations made over Ahmedabad[a]

		Intercept		Optical Depth		
LED	Date	Linear	Log	Linear	Log	Difference (%)
Green	1/19	4.000	1.589	0.237	0.248	−4.437
	4/30	4.040	1.588	0.420	0.405	3.417
	5/1	4.092	1.594	0.397	0.398	−0.323
	5/2	3.963	1.591	0.318	0.321	−0.911
	5/3	4.119	1.596	0.402	0.420	−4.378
	5/4	3.977	1.588	0.319	0.317	0.717
	5/5	4.011	1.590	0.475	0.500	−5.249
	5/6	3.968	1.587	0.412	0.424	−2.889
	5/7	4.047	1.590	0.419	0.431	−2.855
	5/8	3.784	1.578	0.527	0.537	−1.986
Yellow	1/19	4.875	1.559	0.252	0.251	0.422
	4/30	4.944	1.561	0.432	0.420	2.908
	5/1	4.893	1.562	0.366	0.361	1.559
	5/2	4.826	1.562	0.318	0.312	1.833
	5/3	4.922	1.565	0.368	0.389	−5.865
	5/4	4.860	1.560	0.320	0.313	1.955
	5/5	4.862	1.559	0.469	0.485	−3.412
	5/6	4.890	1.551	0.429	0.421	1.858
	5/7	4.956	1.563	0.427	0.422	1.232
	5/8	4.721	1.547	0.545	0.548	−0.599
Red	1/19	1.942	1.117	0.181	0.167	8.138
	4/30	1.976	1.116	0.342	0.314	8.959
	5/1	1.963	1.119	0.307	0.294	4.344
	5/2	1.883	1.120	0.264	0.244	8.033
	5/3	1.989	1.122	0.301	0.295	2.089
	5/4	1.906	1.118	0.248	0.235	5.353
	5/5	1.930	1.118	0.392	0.393	−0.218
	5/6	1.979	1.118	0.366	0.340	7.604
	5/7	2.029	1.119	0.366	0.345	5.978
	5/8	1.823	1.107	0.465	0.443	5.041

[a]The values shown are intercepts and optical depths obtained from linear and log modes of green, yellow, and red LED photometers.

linear- and log-mode configurations for all days, as described above. Table 2 gives the intercept (instrument constant) and the slope (total optical depth) for all three LED photometers. It should be noted here that, although in the case of a linear-mode operation the slope of the Langley plot directly gives the total optical depth, in the case of a log-mode operation, the slopes are divided by the constant K_1, which is obtained individually for the three LED's from the I-V characteristics (Fig. 1).

A conventional filter photometer with a UV 100 (EG&G) photodiode and an interference filter with a 500-nm center wavelength and a 10-nm bandwidth were put into use simultaneously, and the optical depths were obtained during the above period. The results are discussed below.

5. Results and Discussion

Table 2 shows the results of 10 days of observations made over Ahmedabad, during which LED's in both linear and log modes were used. From the Langley plots, the intercepts and the slopes are obtained and are listed for the three LED's. The instrument constants given by the intercept are found to be stable to within 0.4% for all three LED's in the case of the log mode, whereas in the case of the linear mode the instrument constants are found to vary by 2.3% (green), 1.4% (yellow), and 3.0% (red). The optical depths derived by the use of both techniques and their percentage differences are listed in Table 2. The values, in general, agree to within approximately ±5%, although, in the case of a red LED, there are occasions when the difference is larger, by ~9%. These observed variations are due to differences in the performance of the three LED photometers. In the case of the log-mode configuration, the instru-

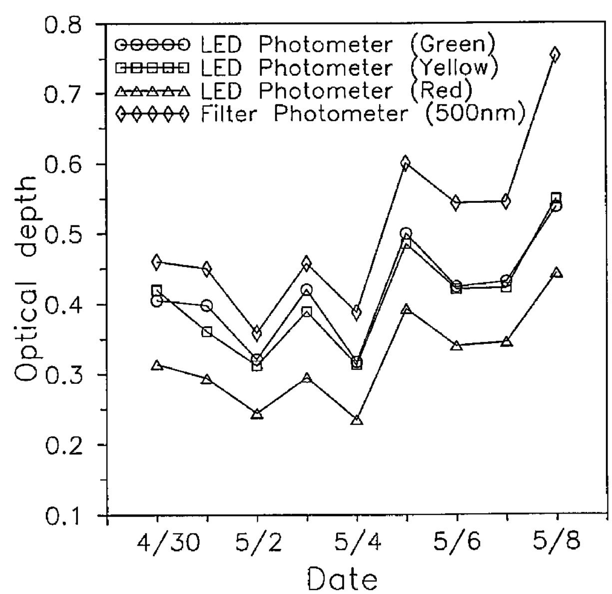


Fig. 8. Total optical depths obtained over Ahmedabad between 30 April and 8 May 1994 with LED photometers operated in the log mode and with a conventional filter photometer at 500 nm.

ment constants for the three LED's are found to be very stable (to within 0.4%) during the observation period, whereas in the case of the linear-mode configuration, the stability was not as good; in fact, it was relatively poor (3.0%), particularly in the case of the red LED, which explains the larger differences observed in the optical depth in the red region.

Figure 8 is a composite plot of the optical depths obtained with the LED photometers during the observation period as well the optical depth obtained at 500 nm with a conventional filter photometer. In general a good agreement is seen in the day-to-day variations in the total optical depths obtained with the LED photometers. The optical depth obtained with the filter photometer also shows a similar trend that is in good agreement with the LED results. Also it can be seen that the obtained optical depth increases with decreasing wavelength as it incorporates Rayleigh scattering as well as aerosol extinction. The observed large day-to-day variations in the total optical depth are caused mainly by wind-derived aerosols in the atmosphere, which is a common feature over Ahmedabad during summer.[11]

6. Conclusions

A compact and sturdy LED-based sun photometer was designed and operated for atmospheric optical depth measurements. This simple configuration is much cheaper and avoids the use of costlier interference filters and photodiodes and avoids degrading the interference filter characteristics with time in the case of long-term monitoring. Use of the LED as a nonlinear feedback element has the advantage of direct measurement of the optical depth once the system constants K_1 and K_2 are obtained. Thus the system is an ideal alternative for monitoring visibility and atmospheric turbidity on any remote location on a continuous basis.

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