Exploring Atmospheric Aerosols by Twilight Photometry

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(Manuscript received 6 November 2007, in final form 28 January 2008)

ABSTRACT

The instrument twilight photometer was designed, developed, and installed at the Indian Institute of Tropical Meteorology (IITM), Pune, India (18°43′N, 73°51′E), to monitor the vertical distribution of atmospheric aerosols. The instrument, based on passive remote sensing technique, is simple and inexpensive. It is operated only during twilights, and the method of retrieval of aerosol profile is based on a simple twilight technique. It functions at a single wavelength (660 nm), and a photomultiplier tube is used as a detector. The amplifier, an important component of the system, was designed and developed by connecting 10 single integrated-circuit (IC) amplifiers in parallel so that the noise at the output is drastically reduced and the sensitivity of the system has been increased. As a result, the vertical profiles are retrieved to a maximum of 120 km. A brief description of the basic principle of twilight technique, the experimental setup, and the method of retrieval of aerosol profiles using the above photometer are detailed in this paper.

1. Introduction

It is important to understand the role of aerosol physical and optical properties in altering the radiation budget of the earth's atmosphere. Along with other constituents of the atmosphere, such as molecular gases and clouds, aerosols determine what fraction of the solar radiation incident at the top of the atmosphere reaches the earth's surface and what fraction of the thermal radiation emitted from the earth escapes to space. These two processes essentially determine the earth's climate. Retrieval of vertical profiles is important to study the tropospheric and stratospheric aerosol properties separately. Long series of frequent observations averaged on a weekly or monthly basis are required to study the long-term trends. In addition to in situ measurements carried out on balloons or rockets, ground-based remote sensing techniques appear well adapted for long-term monitoring.

The twilight photometry technique, involving ground-based photometry of the twilight sky brightness, is used to derive the vertical distribution of dust particles in the earth's atmosphere. The term "twilight" refers to the optical phenomena that take place in the earth's atmosphere when the sun is near the horizon. The main factor controlling the course of the twilight phenomena is scattering of sunlight in the earth's atmosphere and the accompanying attenuation of the direct solar rays. The most important circumstance, which gives an altitudinal sounding ability to the twilight event, is that only a comparatively thin layer of air above the earth's shadow contributes the maximum to the sky brightness at every given moment. The logarithmic gradient of twilight sky intensity at a fixed angle above the horizon where the earth's shadow traverses different layers of the atmosphere gives information about the vertical distribution of aerosols in the atmosphere (Bigg 1956, 1964; Volz and Goody 1962; Shah 1970; Jadhav and Londhe 1992; Nighut et al. 1999; Mateshvili et al. 2000; Padma Kumari et al. 2003). This method is analogous to the method of rocket sounding. In it the solar radiation scans the earth's atmosphere during twilight, and the scattered radiation received from any part of the sky is primarily due to the light scattered by illuminated molecules and aerosols. Any rapid change in their concentration with height will lead to a corresponding change in illumination at the ground. Thus the scattered intensity is assumed to be proportional to the particle number density.

The twilight photometric measurements have been carried out by a number of workers, and the results of many of the earlier investigations have been reviewed in detail by Rozenberg (1966). The twilight method has been used as a useful tool for the study of stratospheric

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DOI: 10.1175/2008JTECHA1090.1

aerosol (Shaw 1980). Enhanced optical effects due to the eruption of Mount Agung on Bali (8°25′S, 115°30′E) on 17 March 1963 have been reported by many observers using photometric observations (Meinel and Meinel 1963, 1964; Volz 1964). Measurements of twilight-scattered light were made with a photometer during the International Geophysical Year–International Geophysical Campaign period (1957–59), at Mount Abu, India (Shah 1970). The twilight method was used to detect volcanic dust from the eruption of Mount St. Augustine, Alaska, in 1976 (Meinel et al. 1976). The occurrence of a novel feature associated with the stratospheric aerosol layer, due to the eruption of El Chichon volcano, in Mexico, has been reported at Ahmedabad, India (23°N, 72°30′E), using twilight sky brightness measurements (Ashok et al. 1984). Twilight photometric observations carried out at location Pathardi, India (19°9′ N, 75°10′E), during 1993 and 1994 showed the presence of a broad stratospheric aerosol layer peaking at ~20 km, indicating the effect of the Mount Pinatubo, Philippines, eruption (Nighut et al. 1999). Recently the seasonal variability in the stratospheric aerosol layer in the current volcanically quiescent period has also been studied using the twilight method (Padma Kumari et al. 2006).

Twilight photometry has also been utilized to study the influx of extraterrestrial dust in the upper atmosphere and its subsequent descent to lower altitudes as it could probe the atmosphere up to mesospheric altitudes (Link 1975; Mateshvili et al. 1997; Mateshvili et al. 1999, 2000; Padma Kumari et al. 2003, 2005). The present paper contains a brief description of the basic principle of the twilight technique, and the experimental setup and method of retrieval of aerosol profiles by using the twilight photometer, which is designed, developed, and installed at the Indian Institute of Tropical Meteorology (IITM), Pune, India, are detailed.

2. Basic principle of twilight technique

A schematic diagram of the twilight phenomena is shown in Fig. 1. When the sun is within 0°–12° below the horizon, the lower part of the atmosphere comes under the earth's shadow while the upper part is sunlit. The boundary between the illuminated and shadowed parts is monotonously shifting up during the evening twilight and down during the morning twilight. The twilight technique is based on the fact that the luminosity of the twilight sky at a given moment depends on the momentary height of earth's shadow. The twilight sky brightness at any given moment is caused by the sum of all light that is scattered toward an observer from all air molecules and aerosol particles above this boundary. It is assumed that the bulk of the scattered light comes to an observer from the lowest, and therefore densest, layer in the sunlit atmosphere at the time of measurement. The contribution of the rest of the atmosphere above this layer can be neglected because of an exponential decrease of air density with increasing altitude. The height of this lowest layer, called the twilight layer, increases with increasing earth's shadow height. The lower atmospheric layers, now submerged in shadow, no longer contribute to the sky brightness, and the scattered light comes more and more from the higher altitudes, which are still illuminated by direct sunlight.

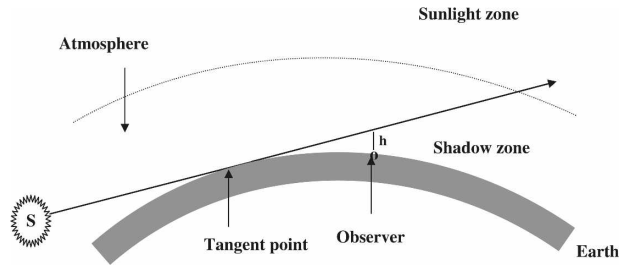

FIG. 1. Schematic diagram of the twilight phenomenon.

3. Instrument design

The twilight photometer was designed and developed indigenously at IITM. A block diagram of this photometer is shown in Fig. 2. The various components of the photometer are described below.

a. Telescopic lens

The photometer consists of a convex lens of diameter 15 cm having a focal length of 22 cm. It is used as a

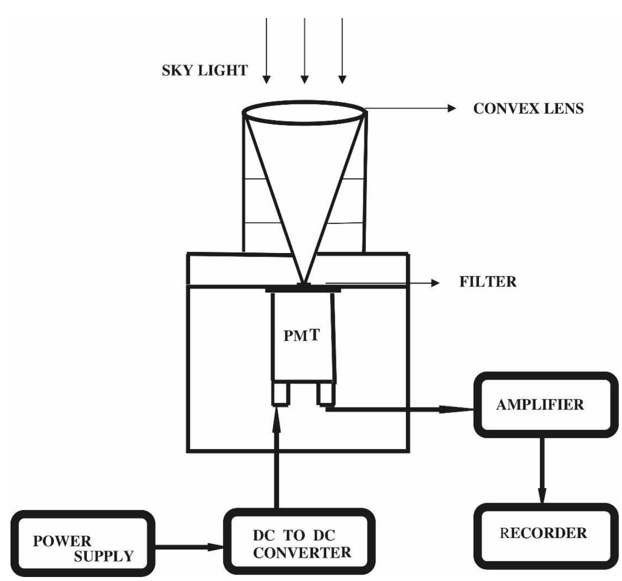

FIG. 2. Block diagram of the twilight photometer.

telescopic lens for gathering the scattered zenith sky light intensity from the ground.

b. Filter

A red glass filter peaking at 660 nm with a half-bandwidth of about 50 nm is used. The longest wavelength has been selected in order to reduce the Rayleigh scattering contribution. The filter used has a wavelength cutoff at about 620 nm, and therefore most of the Chappius band with maximum ozone absorption at 610 nm would remain in the cutoff region of the filter. At this wavelength no other gas with maximum absorption is present. Therefore, the information that is obtained at this wavelength is predominantly of aerosol scattered light.

c. Detector

A photomultiplier tube (PMT) is used as a detector. Photomultipliers are extremely sensitive light detectors, providing a current output proportional to incident light intensity. The PMT consists of a photoemissive cathode called a photocathode, focusing electrodes, series of dynodes for electron multiplication, and an electron collector (anode) in a vacuum tube. When light (photons) falls on the photocathode, it emits electrons by photoelectric effect. These photoelectrons are electrostatically accelerated and focused onto the first dynode of an electron multiplier. On impact, each electron liberates a number of secondary electrons, which are, in turn, electrostatically accelerated and focused onto the next dynode. The process is repeated at each subsequent dynode, and the secondary electrons from the last dynode are collected at the anode. Thus, the photomultiplier produces a current output at the anode, which is the amplified photocathode current. The electron multiplier acts as a very low-noise, high-gain, wideband amplifier for the small photocathode current, providing an output matching the sensitivity of the instrumentation. The ratio of secondary to primary electrons emitted at each dynode depends upon the energy of the incident electrons and is controlled by the interelectrode electrostatic potentials. By using a variable high voltage supply and a resistive voltage divider network to provide the interelectrode voltages, the PMT output signal can be varied over a wide range. The PMT used in the twilight photometer is a Thorn EMI 9798B of 30-mm (1.18 in.) cathode diameter and 112 ± 3 mm length. It is box-and-grid (BG) type with 11 dynodes.

The quantum efficiency (QE) of the PMT at wavelength λ is the average photoelectric yield per incident photon and is normally expressed as a percentage. The QE curve for the PMT is given in Fig. 3. The photometer response function is derived from the transmission function of the filter and the QE curve of the PMT. The overlapping of the two functions is the response function of the photometer, seen in Fig. 3.Notice that, though the detector–filter combination is wide in wavelength, the response of the photometer is good, with maximum efficiency at wavelength 660 nm.

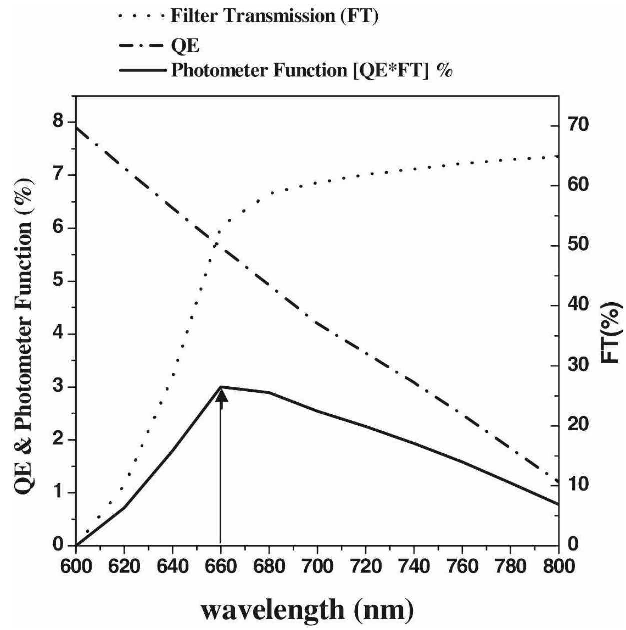

FIG. 3. The response function of the photometer.

d. Dc–dc converter

A dc–dc converter is used to produce low output voltage from high input voltage or high output voltage from low input voltage. The PMT requires a variable high-voltage supply, and, hence, a dc–dc converter with high output voltage is used as a power supply for the PMT.

e. Fast preamplifier

The output signal (current) of the PMT, used for detecting light intensity during the twilight period, is very low. It is of the order of nano- to microamperes. The amplitude or strength of this low signal is amplified by using a fast preamplifier for recording with a digital multimeter or for storing on the data acquisition system. By using a single integrated-circuit (IC) amplifier, the internal noise of the system also gets amplified along with the signal. Hence, to keep the noise at a minimum level and to improve the signal-to-noise ratio, multi-IC amplifiers have been incorporated in the sys-

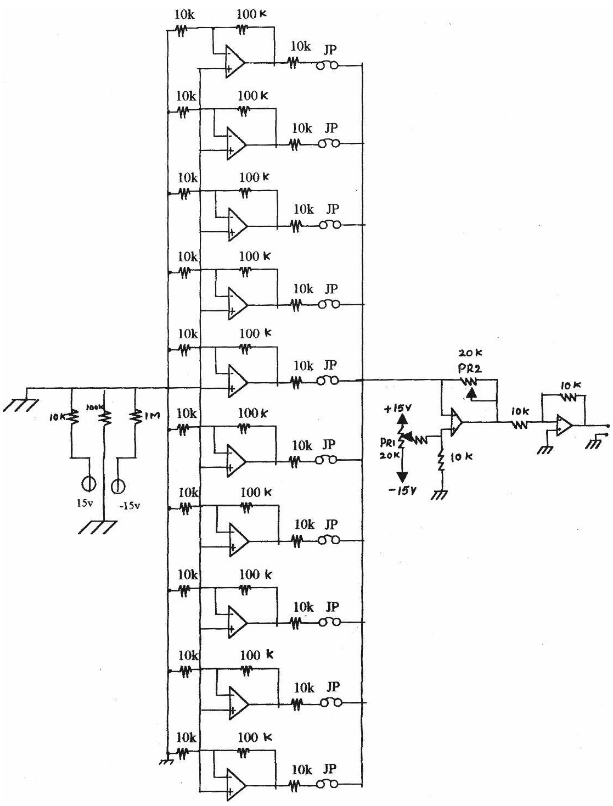

FIG. 4. Circuit diagram of a past preamplifier.

tem. The amplifier is designed and developed by connecting 10 single-IC amplifiers in parallel. Each amplifier was built by using IC-356, an eight-pin IC used for current-to-voltage conversion.

An amplifier circuit diagram is shown in Fig. 4. In the first stage the noninverting amplifiers are connected in parallel. This stage converts the current into voltage. The second stage is voltage amplification, which is achieved by integrating the inverting amplifiers. By doing so, the noise at the output signal of each amplifier is not in phase with the other amplifier signal, and so a random noise is generated. The output of all these amplifiers is added by connecting to the summer circuit by using an OP-07. As a result, noise is drastically reduced at the final output signal. The signal-to-noise ratio is increased by 10 times that obtained with a single IC amplifier. As a result, the vertical profiles are obtained to a maximum height of 120 km. The amplifier output is observed on a cathode ray oscilloscope (CRO). The averaged half-width of the pulse is taken as a time constant of the amplifier. The amplifier output recorded varies from 2 to 12 V depending upon the twilight intensity.

The twilight photometer with various components described above has been utilized to collect the twilight intensity observations. An aperture of 0.4-cm diameter is made at the focus of the telescopic lens, which provides an approximately 1° field of view. The wide field of view is used in order to enhance the observable twilight radiation. The red glass filter of 2-cm diameter is placed over the aperture. The PMT is placed at a distance of 1 cm from the filter. Different baffles are used in the focal plane of the lens to avoid internal reflection in the photometer. The instrument is made very compact so that it can be carried for field experiments also.

4. Experimental technique and data acquisition

The twilight photometer is operated during evening and morning twilights. During evening twilight, it is operated for ~45 min after the local sunset, and during morning twilight it is operated ~45 min before sunrise. Throughout the experiment the PMT supply voltage (600 V) is kept constant. The light exposure area of the telescopic lens is increased or decreased by using proper apertures of different areas over the telescopic lens. The apertures of different areas are made in such a way that the output varies within 2–12-V limits during twilight. During evening twilight, initially the twilight intensity is more, and hence a very small area of the lens is exposed. With time the scattered light intensity decreases, so the exposure area is slowly increased. In the morning twilight, initially the intensity is less and increases with time. Therefore, at the beginning a maximum area of the lens is exposed to light and then is decreased with increasing intensity. Thus, to increase the dynamic range of measurements, only the light exposure area of the lens is changed, and during this process no gain factors are changed and no instrumental function is changed. The system output signal is measured with a digital multimeter, which is connected to a data storage adaptor, for every 30-s interval. The measured voltage varied linearly with the incident illumination. Hence the measured quantity, hereafter called twilight intensity or the scattered light intensity (I), is expressed in relative units. Dark current of the system without light exposure is noted before starting and at the end of the experiment by closing the photometer. It is in a millivolt range, and the averaged value is subtracted from the output signal. Thus, the internal noise in the signal is eliminated. The instrument looks only at the zenith, and hence zenith sky light intensity is measured, as observations at low angles of elevation are increasingly disturbed by the long tropospheric absorption path. The measured scattered light intensity and the corresponding time constitute the raw data. These measured quantities are analyzed for retrieving the aerosol vertical profile.

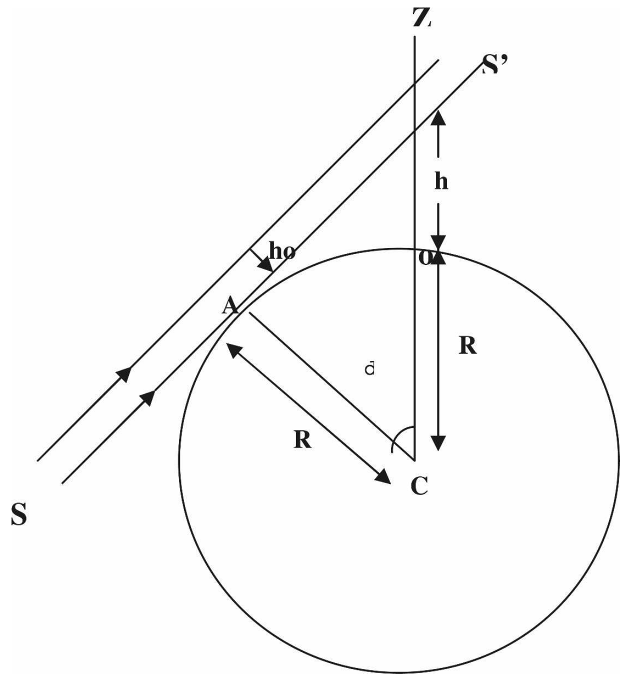

FIG. 5. Schematic diagram of the solar rays grazing the earth's surface, where R is radius of the earth, C is center of the earth, δ is depression angle, h is the earth's geometrical shadow height, h_0 is screening height, SS′ is the solar ray grazing the earth's surface, O is observer, and Z is zenith.

5. Retrieval of aerosol vertical profile

Each twilight sky-brightness record contains information on scattered light intensity at a height corresponding to the lowest layer above the shadow boundary and the corresponding time. The observation time is converted to solar zenith angle Z, which in turn is used in the computation of shadow height of the earth. A time sequence of such records is converted to a record of variations in the light-scattering ability of the atmosphere as a function of altitude. The logarithmic gradient of intensity parameter provides information about dust particles. Thus, the earth's shadow height and the logarithmic gradient of intensity are the important parameters of twilight method. The computation of these parameters is detailed below.

a. Earth's shadow height

The earth's geometrical shadow height is defined as the vertical height from the surface of the earth to a point where the solar ray grazing the surface of the earth meets the line of sight. Figure 5 shows the schematic diagram of the solar grazing rays illuminating the twilight sky, where C represents the center of the earth, SS′ represents the solar ray grazing the earth's surface at A, and h is the height of the earth's geometrical shadow at the point where the line of sight from O toward the zenith Z meets the tangential ray from the sun. If R is the radius of the earth and δ is the depression of the center of the sun below the observer's horizon, then by using simple geometry, the height of the earth's geometrical shadow is given by

$$h = R[\sec\delta - 1]. \quad (1)$$

An important aspect to be taken into account while interpreting photometer data is that the information on the scattering ability of the air originates at every moment of the twilight but from a level slightly higher than the height h of the earth's geometrical shadow. This is related to the strong extinction of the lowest sunrays by a denser layer of the atmosphere. So, some portion of the earth's atmosphere will be almost opaque to the grazing rays, and a correction has to be applied to the geometrical earth's shadow height in order to get the effective height of the earth's shadow. This is known as screening height (h_0), which is dependent upon the wavelength of the scattered light.

In addition, a tangential ray passing completely through the lower atmosphere with the closest approach at height h_0 km from the earth's surface would be deviated by refraction. The refraction causes a decrease in δ ranging from about 0.55° at sunset to 1.1° for values of δ not exceeding a few degrees (Bigg 1964). By applying the above two corrections, Eq. (1) reduces to the form

$$h = (R + h_0)\sec\theta - R, \quad (2)$$

where h is the effective height of the earth's shadow, and $\theta = \delta - \omega$, where ω is the correction factor due to refraction of the solar ray in the earth's atmosphere; it is taken as 0.6° in the present study.

b. Logarithmic gradient of intensity

The most effective way of retrieving the aerosol layer is by the logarithmic gradient of intensity when the measured intensity I is in relative units and is expressed as

$$q = -d\log I/dh = -dI/(Idh), \quad (3)$$

where dh is the change in vertical height in the direction of observation corresponding to change of $d\delta$ in solar depression, and dI is the corresponding change in twilight scattered intensity. In an actual atmosphere, aerosols other than molecules are also present. Most of the light received at the ground will be the primary scattered light by molecules and aerosols. But in the shortwave region of the spectrum, scattering by the gaseous phase plays the principle role, while at long wavelengths, aerosol scattering predominates. In the present study, the longest wavelength of 660 nm is used in order to reduce the scattering contribution by air molecules. Also, variations in the vertical profile of the molecular density are very small, and their effect on the observed intensity is nearly constant. Hence, the variations in q can be assumed to be mainly due to changes in aerosol density, and therefore I is assumed to be proportional to aerosol number density (n); that is,

$$q = -d\,\log I/dh \approx -d\,\log(n)/dh. \qquad (4)$$

6. Results and discussion

Using a twilight photometer, aerosol vertical profiles are derived in terms of logarithmic gradient of intensity. To validate the photometer-derived profiles, simultaneous observations of photometer and lidar were carried out at the National MST Radar Facility (NMRF), Gadanki, India. The comparison is found to be very good, and it is proved that the twilight technique provides qualitative information on the vertical distribution of aerosols. The comparative study showed that the screening height (discussed in section 5a) for the twilight technique is about 6 km, below which no direct information on atmospheric aerosols can be obtained [the validity of the technique has been explored by Padma Kumari et al. (2004)]. The effective height h is computed by using $h_0 = 6$ km in Eq. (2). Hence, the profiles are derived from 6 km and above.

A typical photometry curve of the twilight scattered light intensity I, as a function of the effective height h of the earth's shadow, computed for 18 November 2003, is shown in Fig. 6. It shows the large range of decrease in scattered light intensity (from 1 to 10^{-3}–10^{-4}) within 45 min following the local sunset. The lower atmospheric layers, submerged in shadow, no longer contribute to the sky brightness. The scattered light comes more and more from the higher layers, which are still illuminated by direct sunlight. As the air density decreases with height, the scattering coefficient also decreases, and sunlight is scattered more weakly. As a result, sky brightness diminishes and so the illumination at the earth's surface falls.

The logarithmic gradient of twilight intensity derived for the data shown in Fig. 6 is depicted in Fig. 7. It is noticed from the figure that the value of $d\,\log I/dh$ decreases with increasing shadow height, implying decrease of aerosol concentration with height. In the lower troposphere a sharp decrease is observed up to 10 km. Above 10 km the intensity seems to be changing very little, showing constant concentration at that level. At the tropopause (~16.5 km) a sharp decrease in intensity is noticed. From the tropopause to about 30 km, the subsequent increase in the logarithmic gradient is observed due to the presence of stratospheric dust layer. Thus, q is the most effective parameter for distinguishing the aerosol layers or to reveal the stratified structure of the atmospheric dust.

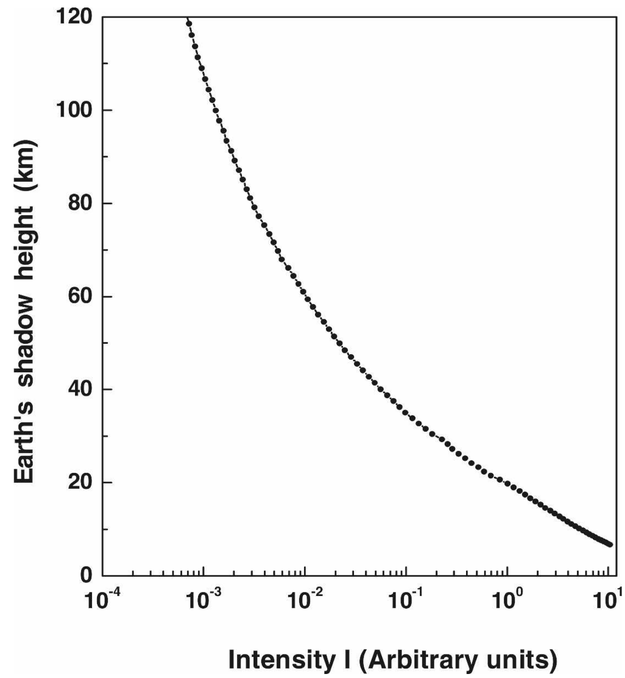

FIG. 6. A typical photometric twilight intensity curve obtained on 18 Nov 2003.

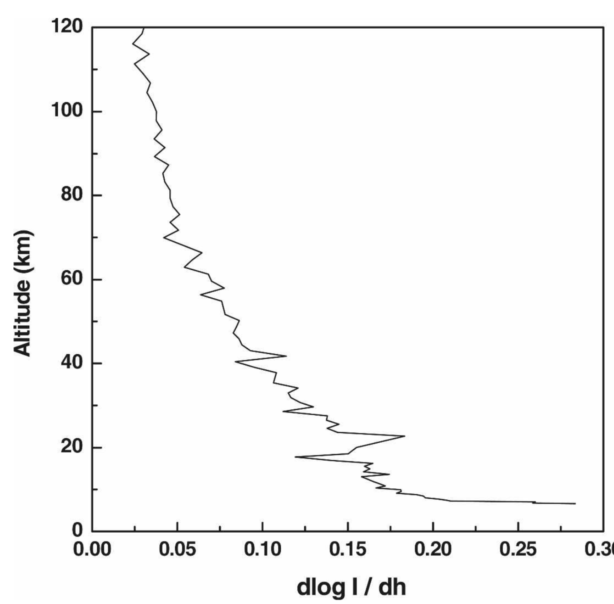

FIG. 7. Logarithmic gradient of the twilight intensity curve for 18 Nov 2003.

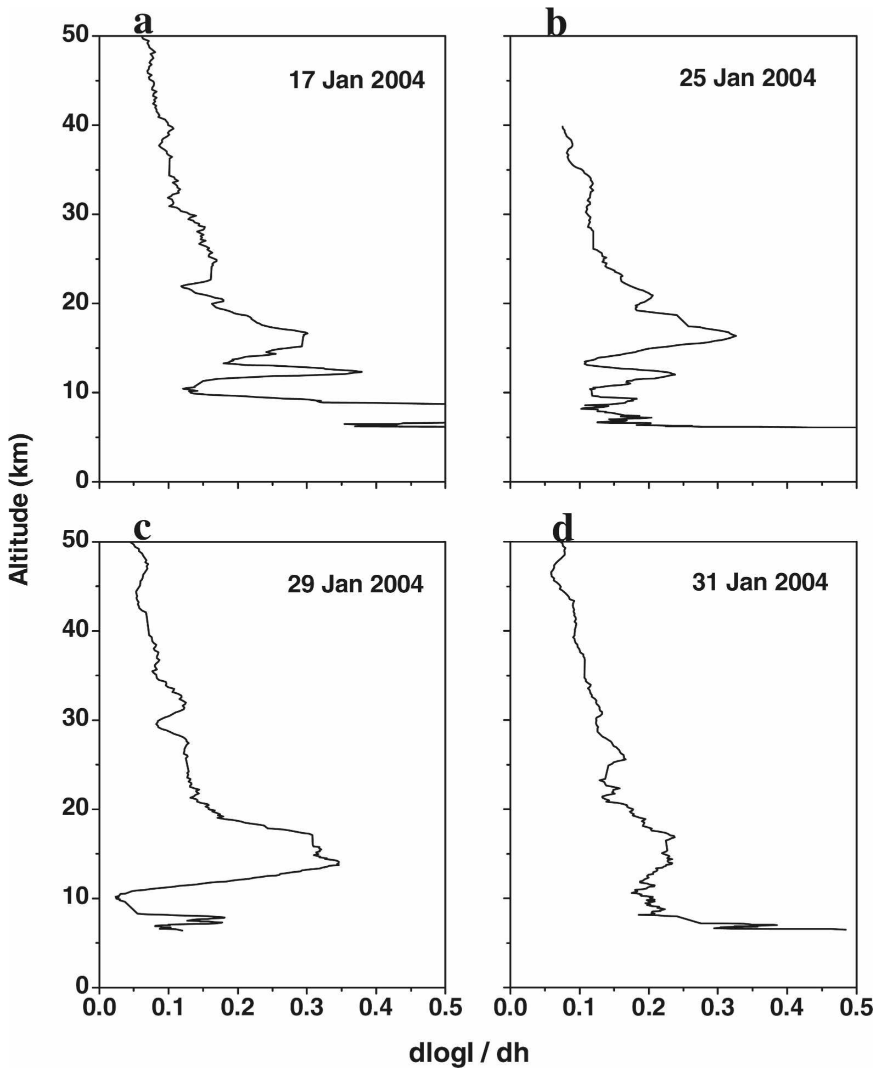

FIG. 8. A few typical profiles obtained with twilight photometer with improved height resolution. (a) 17 Jan 2004. (b) 25 Jan 2004. (c) 29 Jan 2004. (d) 31 Jan 2004.

Actually, the estimated uncertainty in the measurements should increase with altitude (as the signal gets smaller), but to avoid this the signal level is kept constant throughout the experiment by changing only the exposure area of the telescopic lens and maintaining the output in the range 2–12 V. During this process no instrumental function is changed. The error in measurement is found to be ~1%–2%. The threshold level of detection of the photometer is $1 \pm 2 \times 10^{-2}$ particles per cubic centimeter at low altitudes and $0.001 \pm 2 \times 10^{-5}$ particles per cubic centimeter at high altitudes.

The height resolution of twilight method is not constant throughout the period of observation. The altitudinal resolution is obtained on the basis of change in the height of the earth's shadow at a time interval of 30 s. The earth's shadow height increases with increase in solar depression angle. The uncertainty of height determination in the twilight method is found to rise from about 0.45 km at a height of 10 km to ~0.82 km at 20 km, ~1.48 km at 50 km, and ~2.2 km at 100 km. However, the height resolution is improved by increasing the sampling rate of observations. By computing the earth's shadow height at the time interval of 10 s, the height resolution is found to be 0.07, 0.13, 0.23, and 0.34 km at heights of 10, 20, 50, and 100 km, respectively. Because of this improvement in height resolution, the finescale features are also visible in the profiles.

A few typical profiles obtained with improved height resolution in the month of January are depicted in Fig. 8. All these profiles show the presence of high cirrus above 10 km with varying thickness. Figures 8a and 8b show layered structures. However, Fig. 8c shows a very broad layer from 10 to 17 km. The same feature has also been noticed in Fig. 8d, but with less scattered intensity. It looks like there is a drop in q in Fig. 8c at $\sim$30 km and in Fig. 8d at $\sim$45 km, which may be due to sudden enhancements just above these altitudes. These minor enhancements at higher altitudes may be due to stratified layers.

7. Conclusions

The instrument twilight photometer was indigenously designed and developed for monitoring the vertical distribution of atmospheric aerosols. The system, based on passive remote sensing technique, is simple and inexpensive and hence can be operated continuously for monitoring the day-to-day variability of the aerosol profiles. The amplifier, an important component of the system, has been designed and developed in such a way that the noise at output is drastically reduced and the sensitivity of the system has been increased. As a result, the vertical profiles are retrieved to a maximum height of 120 km. But the lower limit is 6 km because of strong extinction of the lowest sun rays by denser layers of the atmosphere. The most effective way of retrieving the aerosol layer is by logarithmic gradient of intensity ($d \log I/dh$), as the measured intensity I is in relative units. By increasing the sampling rate, the height resolution is improved, and so the small-scale features can also be studied. Thus, the twilight technique provides a good opportunity to monitor the dust particles in a wide range of altitudes.

Acknowledgments. The authors thank Dr. P. C. S. Devara, head of the Physical Meteorology and Aerology division, at IITM, and Dr. B. N. Goswami, director of IITM, for their encouragement in carrying out this work, and also the Department of Science and Technology, India, for providing funds for the development of twilight photometer (Grant ESS/63/155/98).

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