Development of a Low Cost Miniature Device for High Spatial, Distributed Monitoring of Aerosol Optical Depth for Regional Level Microclimatic Studies

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Abstract. Air pollution becomes severe when air contains small particles, toxic gases, dust and smoke emitted from numerous sources such as vehicles, industries, fires or fumes in harmful amount. Aerosols of highly reflective in nature increases albedo of the earth and thereby cools the surface and thus effectively offsets greenhouse gases warming by about 25-50%; whereas, absorbing type of aerosols absorbs solar radiation hence increases the surface temperature. Absorbing type aerosols are largely present in the urban environment due to presence of relatively larger number of vehicular fleet and subsequent more fossil fuel combustion than in rural area. Excessive inhalation of particulate matter is detrimental to human health as it can lead to asthma, lung cancer and cardiovascular diseases. Thus, it becomes essential to monitor aerosols accurately using affordable device having widespread presence and potential to address the related problematic issues. One of the important parameters in aerosol measurement is aerosol optical depth (AOD). Several instruments and techniques are used to measure AOD such as with satellite and ground based sun-photometry, ground and airborne radiometers and LIDARs which are generally costly and non-portable. Hence, an effort has been made to develop an affordable sun photometer using photo-detectors and light filters which will track the sun automatically and retrieve AOD of that location. Device measurement thus built has been correlated with standard instrument measurement like Microtops Sunphotometer

1. Introduction

Aerosols are small solid particles or liquid droplets suspended in air, which are produced naturally or anthropogenically. Natural aerosols are emitted into the atmosphere by natural processes such as sea spray, volcano eruptions, and windblown dust from arid or semi-arid regions; whereas, anthropogenic aerosols are generated from fossil fuels combustion consequently emitted from industrial chimneys and vehicle exhaust.

Aerosols further can be classified into two broad categories based on their nature of formation, viz., Primary aerosols and Secondary aerosols. Primary aerosols are directly emitted as particles or liquid into the atmosphere by processes occurring on land or water, which could be natural or manmade origin. Sources of primary aerosols are sea spray [1], windblown dust [2], volcano eruptions [3], plant pollen particles [4], biomass burning [5], and incomplete combustion of fossil fuels [6] etc. Whereas, secondary aerosols are produced indirectly via atmospheric physical or chemical conversion of gas to
Aerosols have very limited lifetime of about few days to a week. Despite their relative short lifetimes, they regularly travel over long distances through entrainment into air mass. The transport pathways vary seasonally and inter-annually depending upon the air-mass altitude [8].

Unlike greenhouse gases, which possess long lifetime and a near homogeneous spatial distribution, atmospheric aerosols are highly heterogeneous and have limited lifetime [9]. Aerosols exert a variety of impacts on environment depending on their different properties [10]. Aerosols of highly reflective in nature increases the albedo of the atmosphere and thereby cools the surface and thus effectively offsets greenhouse gas warming by about 25-50%[11]; whereas, absorbing types of aerosols absorb solar radiation, hence increases the surface temperature[12]. Absorbing type of aerosols are largely present in urban environment due to presence of relatively larger number of vehicle fleet and subsequent more fossil fuel combustion than in rural areas. This aggravates the already present heat island effect induced atmospheric heating due to almost ubiquitous presence of concrete structures. Excessive inhalation of particulate matter is detrimental to human health as it can lead to asthma, lung cancer and cardiovascular diseases [13, 14, 15]. A few studies have indicated that AOD can be a good marker for city inhabiting human population [16, 17] and a good co-relation for columnar aerosols and ground based PM$_{2.5}$ [18]. Thus, it becomes essential to monitor aerosols accurately using affordable device having widespread presence and potential to address the related problematic issues.

Several instruments and techniques are used to measure AOD such as with satellite and ground based sun-photometry, ground and airborne radiometers and LIDARs [19, 20, 21] which are generally expensive and non-portable. The ground-based sun photometry is preferred more over other approaches because of its customizable spatial and temporal resolution. Yet these are not in widespread use for AOD monitoring because they require complex instrumentation and high maintenance cost is always an issue for areas where technical and financial support are acutely limited [22]. The ground based retrievals of AOD are being carried out by a few devices namely; Microtops Sunphotometer and CIMEL Sunphotometer installed at various locations under National Aeronautic and Space Administration’s (NASA) Aerosol Robotic NETwork (AERONET) program [23]. These instruments are highly accurate and reliable, but they are costly and relatively less affordable preventing studies which could be carried out at regional level. Thus, there is need for low cost device for higher spatial measurement.

In an effort to bring down the cost and increasing the portability, a smartphone camera based AOD retrieval was developed [24] which measured AOD at UV-A range (340-380nm). The efforts made above had certain limitations like [24] worked on making a smartphone based sensors, which requires tweaking to the smartphone’s camera by adding filters to it to prevent image produced by camera from being over exposed due to sunlight. Study [24] had common shortcomings, viz., it lacked sun tracking which could minimize human error. User has to manually track the sun by adjusting it by pointing the device towards the sun. There are chances that user’s hand might get shaken and that could affect the results.

It is clear from the above several studies that it is possible to build affordable sunphotometers using photo-detector and light filters. This work aims upon developing an affordable and portable photometer that will track the sun automatically and retrieve AOD of that location. AOD will be retrieved at 3 different wavelengths of visible spectrum. The developed photometer will be calibrated against standard sunphotometer, namely hand held Microtops Sunphotometer [25]. Several of such photometers can be assembled and installed across any regional areas for regional micro-climatic studies.

2. Methodology

The current research is focused on developing affordable and portable photometer that can automatically track the sun and retrieve AOD. The AOD will be retrieved at 3 different wavelengths of visible spectrum. Several of these can be manufactured keeping in mind to build a network to
monitor AOD at several locations for regional climatic studies. The device consists of following components:

i. Arduino Mega board.

ii. A photo-detector module (TCS 3200) that is used to detect solar intensity at 3 different wavelengths.

iii. Servo motors mounted to make it dual axis.

iv. Light dependent resistors (LDR).

v. GPS module.

Arduino board is programmed to detect the maximum light intensity using two LDR mounted on the dual axis servo motors. A sun positioning algorithm allowed communication between photo-detectors and motors to locate the sun more accurately. Once the position of the sun is locked, microprocessor instructs photo-detectors to record the solar intensity at three different wavelength of visible spectrum. GPS attached to the board automatically records co-ordinates and date and time of the location (local time zone correction is applied, as it provides time in UTC). These data are also given as input to the sun positioning algorithm to obtain altitude angle and azimuth angle which can be used to drive dual axis motor accordingly.

A programmable colour sensor was utilized which comprised of 8x8 array of photo-detectors, 16 photodiodes were green filter, 16 were red, 16 were blue and 16 were clear (no filters). For obtaining respective intensities, the microcontroller board is programmed accordingly to acquire intensities of different wavelengths. Sun tracking was made possible by using two LDRs mounted on dual axis servo motors. The assembly was programmed in a manner that the LDR receiving maximum solar intensity will allow the motor to move in that particular direction. Additional sun positioning algorithm was also made as input to minimize the errors in tracking. Sun positioning algorithm is an algorithm which uses equations and co-ordinates of the place to get the position of the sun at a particular time. To calculate the position of sun relative to the horizon it is necessary to know where the observer is and when spatial and temporal information are required. The position is always defined by latitude and longitude in decimal degrees. The time is determined by the day and time of interest; where day is defined by the day number, month and year. Between hours of sunrise and sunset the sun makes its apparent motion across the sky constantly changing its position. The position of an astronomical object is defined within a spherical coordinate system by the radial distance between the object and observer, angle measured from a fixed zenith direction and elevation angle and the azimuth angle [26]. The azimuth angle is defined by the orthogonal projection of the object on a reference plane that passes through the observer and is orthogonal to the Zenith and that is measured from a fixed reference direction on that plane. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere. The azimuth angle varies throughout the day. At equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thus making azimuth angle 90° at sunrise and 270° at sunset. The azimuth angle can be calculated using following empirical equation:

\[
\text{Azimuth angle} = \cos^{-1} \left( \frac{\sin(\delta) \cos(\theta) - \cos(\delta) \sin(\theta) \cos(HRA)}{\cos(\alpha)} \right)
\]

Where,
\(\delta\) = declination angle
\(\theta\) = sun zenith angle
HRA = hour angle
\(\alpha\) = altitude angle

The declination angle varies seasonally due to the tilt of the earth on its axis of rotation and the rotation of the earth around sun. If earth were no tilted on its axis of rotation, declination angle would always be 0°. However, earth is tilted by 23.45° and the declination angle varies plus or minus this amount. Only at the spring and fall equinoxes, the declination angle would be 0°.

The declination angle can be calculated using equation provided in equation (2).
\[ \delta = 23.45 \times \sin \left[ \frac{360}{365} \times (d + 284) \right] \]  

(2)

Where,
\( d = \) number of day since start of the year

The altitude angle is the angular height of the sun in the sky measured from horizontal. The altitude angle varies throughout the day and it also depends on the latitude of a particular location and the day of the year. Altitude angle can be expressed by the following equation (3).

\[ \alpha = 90 - \theta \]  

(3)

Where, \( \theta = \) Sun Zenith angle.

The zenith angle is the angle between the sun and the vertical. It is similar to the elevation angle but is measured from the vertical rather than from the horizontal. The sun zenith angle can be estimated using following equation (4).

\[ \theta = \cos^{-1}[(\cos(\psi)\cos(\delta)\cos(HRA)) + (\sin(\psi)\sin(\delta))] \]  

(4)

Where,
\( \psi = \) latitude of the location in degree.
\( HRA = \) hour angle in degree

The hour angle converts local solar time (LST) into the number of degree which the sun moves across the sky. By definition, the hour angle is 0° at solar noon. Since earth rotates 15° per hour, each hour away from solar noon corresponds to an angular motion of the sun in the sky of 15°. Hour angle can be estimated from the following equation (5)

\[ HRA = 15^\circ \times (LST - 12) \]  

(5)

Twelve noon local solar time (LST) is defined as when the sun is highest in sky. Local time (LT) usually varies from LST because of the eccentricity of the earth’s orbit, and because of human adjustments such as time zones and daylight saving time. Local solar time can be estimated using following equation (6)

\[ LST = \text{local time} + \left( \frac{4 \times (\text{longitude} - 82.5) + EoT}{60} \right) \]  

(6)

Where,
82.5 is the local solar time meridian viz., the longitude of Allahabad which is referred as reference meridian for Indian Standard time.

The factor of 4 minutes comes from the fact that earth rotates 1° every 4 minutes.

EoT is the equation of time in minutes, an empirical equation that corrects eccentricity of the earth’s orbit and axial tilt and can be given by equation (7)

\[ EoT = (9.67 \times \sin(2 \times B)) - (7.53 \times \cos(B)) - (1.5 \times \sin(B)) \]  

(7)

\[ B = \frac{360}{365} (d - 81) \]  

(8)

Where,
\( B = \) in degree
\( d = \) number of days since start of the year.

The altitude and azimuth angle thus retrieved were made input to the horizontal axis and vertical axis motor respectively that could track the sun in both co-ordinates. As noted earlier, LDRs were also coupled with the assembly to track the sun to minimize the errors in tracking.

The retrieved solar position angles from the calculations were validated against NASA’s Ocean and Atmospheric Administration (NOAA) solar position calculation sheet which takes input as user’s latitude, longitude and date. The analysis is incorporated in Results and Discussion section.

The assembly of the developed device is as shown in Figure 1 below.
3. Results and discussion

An analysis of all the components coupled with the microprocessor board was done individually viz., colour sensor, servo motors, Co-ordinates and date and time extraction from GPS module and sun position calculation to check the functioning of the components and most importantly accuracy of the algorithm.

3.1 Validation of solar angles

A linear regression analysis was performed for the calculated Azimuth angle and Altitude angle against the one provided by NASA’s Ocean and Atmospheric Administration [27]. The data is provided in the form of a spread sheet which takes Co-ordinates of location and date as input to retrieve the sun position angles of desired location. A 6-hour retrieval of solar angles was performed from 10:00 to 17:00 on 4th May 2017; data on half hourly basis were extracted from it. Figure 2 and Figure 3 shows the linear regression analysis of azimuth angle and altitude angle respectively. It is clear from these figures that the data retrieved from the device compares well with that of NOAA.

![Figure 1. Developed low cost miniaturized sun photometer assembly](image)

**Figure 1.** Developed low cost miniaturized sun photometer assembly

![Figure 2. Co-relation of Azimuth angles](image)

**Figure 2.** Co-relation of Azimuth angles
3.2. Correlation of colour sensor signal with Microtops data

Analysis of colour intensity sensed by the sensor was carried out for four days from May 24-Jun 01, 2017 from 10:00 to 15:00 H. Validation was done for limited days because of the availability of the standards instruments for limited time duration. Initially, it was estimated to carry out data collection till 17:00, but due to hindrance cause by shadow of building in the evening on the device at the sampling location it was possible till 15:00 only. Simultaneously, AOD retrieval from Microtops Sunphotometer was also carried out for wavelength of 440 nm (blue), 500 nm (green) and 675 nm (red). The objective was to correlate colour sensed by the sensor against AOD measured by standard Microtops instrument at their respective wavelengths. Few data points were discarded due to presence of cloud cover. Figure 4 - 6 shows the regression analysis of colour sensed by the sensor against AOD retrieved from Microtop Sunphotometer at respective wavelength. A better correlation indicates that the designed device can be used for AOD measurement at three wavelengths.
4. Summary and Conclusion

One of the important parameters in aerosol measurement is aerosol optical depth (AOD). Several instruments and techniques are used to measure AOD such as with satellite and ground based sunphotometry, ground and airborne radiometers and LIDARs which are generally costly and non-portable. Hence, an effort has been made to develop an affordable sun photometer using photo-electronic detectors and light filters which will track the sun automatically and retrieve AOD of that location. Device thus built has been correlated with standard instrument like Microtops Sunphotometer. Past research showed that developing a LED based sunphotometer is very much cost effective and also gives reasonable accuracy comparing with the standard photometer available, an attempt was made to develop a similar photometer but with a different approach using LED as light detecting source, a programmable colour sensor which was utilized for acquiring coloured signals at different wavelengths.

After successfully tracking the sun, a relationship of colour sensed by the sensor against AOD obtained from Microtops was carried out at respective wavelength. The regression analysis showed that the developed sensor can provide reasonable measurement of AOD. Regression was affected because currently instrument is not equipped to minimize the influence of cloud, water vapor and ozone. The study will further try to assimilate more data to the regression with additional sensors for
water vapor and ozone to derive accurate relationship between AOD and signal sensor values for further standalone use of the device for the measurement.

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