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ORIGINAL PAPER

Performance Analysis of Light-weight Scattering Coefficient Counter with AURORA 3000 Nephelometer over Delhi

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Abstract: From past many decades, the integrating nephelometers are generally used to measure the aerosol scattering coefficient for ground level at different wavelengths. In recent years, the research focus has been shifted toward the airborne observations using either tethered balloons or drones. For this particular purpose, one needs light-weight instruments which are capable of measuring the aerosol scattering coefficient suitable for airborne activities. Thus, we report the design and development of a light-weight scattering coefficient counter (weight $\sim$ 500 g, 7″ × 3″) with high sensitivity. This instrument has been specifically designed and developed for the measurement of aerosol scattering coefficient at 633 nm wavelength. The aerosol scattering coefficient calculation becomes extremely important for modeling aerosol optical/radiative properties. Delhi is one of the regions with high aerosol loadings, so one needs such Light-weight instruments for the aerosol scattering coefficient measurements. At present, this instrument has only been evaluated at ground level. But, before using the developed instrument for airborne observations, there is a strong need for comparison of the instrument against routinely used nephelometers for performance evaluation. Comparisons were performed between the light-weight scattering coefficient counter and high-end **AURORA 3000** Nephelometer for two different seasons. For both the seasons, i.e., the monsoon season (July 25–August 24, 2017) and the winter season (February 1–28, 2018), we found a strong correlation (i.e., R^2 = 0.99). However, the highest value of scattering coefficient was found to be 98 $\pm$ 32 Mm^{-1} with a mean value of 55 Mm^{-1} for the monsoon season, while the same for the winter season was observed to be 270 $\pm$ 108 Mm^{-1} with a mean value of 165 Mm^{-1}. This light-weight instrument could be a potential instrument for aerosol scattering observations, especially for airborne platforms with payload mass limitations.

Keywords: Scattering coefficient; Light-weight; Aerosol; Laser

1. Introduction

Aerosol optical properties such as scattering and extinction play a significant role in the Earth's radiation budget, thereby influencing the atmospheric environment and climate. In particular, the scattering of light by atmospheric aerosols in the visible and near-visible spectral regions influences the Earth's climate because of change in the short-wave radiative forcing [1] and also affects the remote sensing optically by ground-based, airborne and satellite systems [2]. Lidars and other high-end instruments are generally used for measurement of the aerosol optical properties [3, 4]. Integrating nephelometers are typically used for the measurement of particle scattering. They work by measuring the scattering component of extinction, also known as the total scattering coefficient. There are two different methods where scattered light is integrated over all angles geometrically in the instrument: (a) either a light source and the detector are changed in their directions and a parallel light beam is used, and then the scattered light is detected by a cosine detector; (b) or cosine-law diffused

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light source is used to illuminate the instrument that is being viewed with the help of a detector [5, 6]. The second arrangement is most commonly used in the research domain. The first arrangement described here is known as a reciprocal nephelometer which is of not much importance. The definition of an ideal integrating nephelometer is the one which directly measures the total scattering coefficient of suspended particles. It is noteworthy to mention here that the measurement of total scattering coefficient depends on particle's properties such as size and chemical composition. In reality, the integrating nephelometers have some imperfections when compared with the ideal one. These are described mostly as the imperfect angular and wavelength response apart from imperfect particle sampling [7].

From many past decades, scientists have used the integrating nephelometers for the ground-based observations [6–8]. But for the airborne applications, one needs light-weight instrumentation which should be suitable for the measurement of the aerosol scattering coefficient. The light-weight and low-cost features of these instruments make them an attractive option for their use in experiments requiring a large number of installations. These low-cost instruments could be useful for aforesaid studies; however, their accuracy and precision need to be quantified.

Here, we report the design and development of a Light-Weight Scattering Coefficient Counter (LWSCC; weight $\sim$ 500 g, 7″ × 3″). LWSCC has been specifically designed and developed for the measurement of aerosol scattering coefficient at 633 nm wavelength. Aerosol scattering measurements were performed at the National Physical Laboratory (Central Delhi; 28.38°N, 77.10°E) using LWSCC and India Meteorological Department (Central Delhi; 28.61°N, 77.20°E) using AURORA 3000 for the monsoon season (i.e., July 25–August 24, 2017) and for the winter season (i.e., February 1–28, 2018). Principal objectives of the design were light-weight and low-cost, thereby making the LWSCC suitable for balloon-borne or UAV applications.

2. Methodology

2.1. Instrumentation

2.1.1. Major Components of LWSCC System

LWSCC with high sensitivity has been designed at CSIR-NPL and evaluated in the field observation. The design incorporates a moderately priced semiconductor laser diode operating at 633 nm wavelength. The scattered light from the sampled particles is collected with an off-axis lens. This lens has a hole which is drilled specifically to pass the laser beam to a dump.

The main components of LWSCC system include:

1. Semiconductor laser diode (HL63163DG) at 633 nm wavelength.
2. Silicon photodetector (BPX 65).
3. Photodiode amplifier (OPA 381).
4. Filter paper section for offline analysis (GRIMM 1.108).
5. 3 lpm pump for aerosol suction (GRIMM 1.108).
6. Atmega 328PPU microcontroller.
7. A micro SD card for data collection.
8. A Li–Poly battery (12 V DC supply).

This instrument has been specifically designed and developed for the measurement of aerosol scattering coefficient (Fig. 1). Particle sensing is based on the detection of the forward scattering of laser light. The separation between the laser beam and the scattered light is achieved based on a simple optical system [9]. A laboratory prototype system with a 633 nm laser (HL63163DG laser diode; Thorlabs) and fast-response silicon photodetector (BPX 65; Farnell Instrumentations) was used for the instrument development.

LWSCC contains a semiconductor laser diode working at 633 nm wavelength with a photodetector. The laser beam which is emitted from the laser diode illuminates the particles in the airflow. The scattered light intensity is then converted to a 0–3.5 V analog signal by the use of transimpedance amplifier which is inbuilt in the Analog-to-Digital Converter (ADC). The formation of the generated analog signal takes 0.28 ms, thus making the voltage recording on the phototransistor exactly at 0.28 ms. In this design [9], lens 1 (inside the optical chamber) is used for the collimation of the laser diode output into a parallel beam. The beam diameter is of about 2.5 mm. A cylindrical lens is then placed after the lens 1 which focuses the circular laser beam into a rectangular cross section. This cross section is of about 0.1 mm thickness and 2.5 mm width at the air nozzle. The inner diameter of the nozzle is about 0.5 mm. LWSCC is physically robust, in part due to the design simplicity. The power estimation required for the major components is as follows: optical cavity ($\sim$ 2 W), pump ($\sim$ 1 W), data system ($<$ 5 W), flow control ($\sim$ 2 W). Here, it is important to note that one standard-size lithium battery to be used in the operation of LWSCC can provide 10 W of power for about 8 h, sufficient for all power needs including heating. The microcontroller used here is an Arduino Atmega 328PPU (Fig. 1).

The weight of the LWSCC is approx. 500 g, thus putting it in light-weight instrument category. The major weight contribution is due to the cavity segment material which

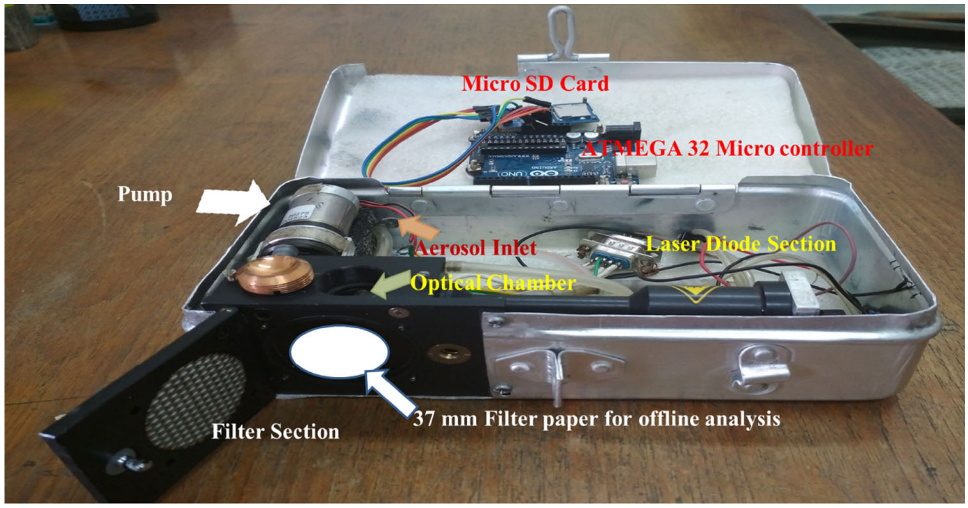

Fig. 1 Light Weight Scattering Coefficient Counter (LWSCC) with all necessary components including laser diode section, optical chamber, aerosol inlet, digital acquisition system, etc

can be replaced easily by the delric carbon material. The overall weight comes from a small pump, flow controller and the electronics. Thus, in the future, it is possible to limit the total weight up to 200 g or less, which could be more suitable for drone-based observations.

2.1.2. Governing Principle for the Measurement of Scattering Coefficient for LWSCC

From Fig. 2, it is noteworthy to mention that the light intensity coming from the laser diode interacts with the incoming particulates coming from the aerosol inlet. The light intensity is then scattered into all possible directions inside the optical cavity. Fraction of the light intensity is captured by the silicon photodetector. The photodetector will then convert the generated signal into current. The value of the current is too small to get detected by the microcontroller unit, so a photodiode amplifier (OPA 381; Texas Instruments) is used to amplify the signal. Transimpedance amplifier (AD 8015; Analog Devices) converts the analog current signals to analog voltage signals. The detected analog signals is converted into the digital signals via an inbuilt ADC. The digital signals after the computations using the following equations will be stored in the micro SD card (Fig. 1).

Based on the equation used for the design of the nephelometers, we propose the fundamental equation for the LWSCC instrument. The equation used is shown below [6, 7]:

$$B = (I_0/y) \times (b_{\mathrm{scat}}/2\pi), \qquad (1)$$

where y is vertical distance from light source to detector; B, flux of light detected by the detector; I_0 , initial intensity of light; and b_{scat}, aerosol scattering coefficient.

2.1.3. Instrument used for Comparison Purpose

The AURORA 3000 integrating nephelometer is an instrument that measures real-time scattering of light at three wavelengths. The ambient air is illuminated with an array of LED light source at three wavelengths (i.e., 450, 525 and 635 nm, respectively). The scattering of light occurs in total directions, i.e., 9−170°, and back direction, i.e., 90−170°. The aforesaid nephelometer (i.e., AURORA 3000), at 635 nm wavelength, installed at India Meteorological Department (28.61°N, 77.20°E) is used for the performance evaluation of LWSCC. The design of the instrument is such that it consists of total nine LEDs, i.e., three LEDs for each wavelength. The purpose of these LEDs is to simultaneously illuminate the sample. Apart from that, these LEDs also illuminate the photomultiplier tube which measures the scattered light from the sample. Automatic adjustments of the measured values are then done using the inbuilt temperature and pressure sensors in the real time. The sampled air is drawn into the measuring volume, i.e., 10.5 cm^3, through the sample inlet. This can be achieved at the top of the instrument with a flow rate of 5 lpm. In order to limit the scattering angles into a narrow cone of light that spans from an angle of 9–170 degrees, mounting of the baffles is done inside the optical chamber. From this narrow scattering cone of light, the light scattered from aerosols cascades on to the photomultiplier tube (PMT). The PMT then generates an electrical signal which is proportional to the scattered light intensity. The detailed instrument description is given by [8].

2.1.4. Calibration Procedure for AURORA 3000 Nephelometer and LWSCC

The nephelometer is calibrated by relating a known amount of scattering (e.g., the Rayleigh scatter of filtered air or CO_2

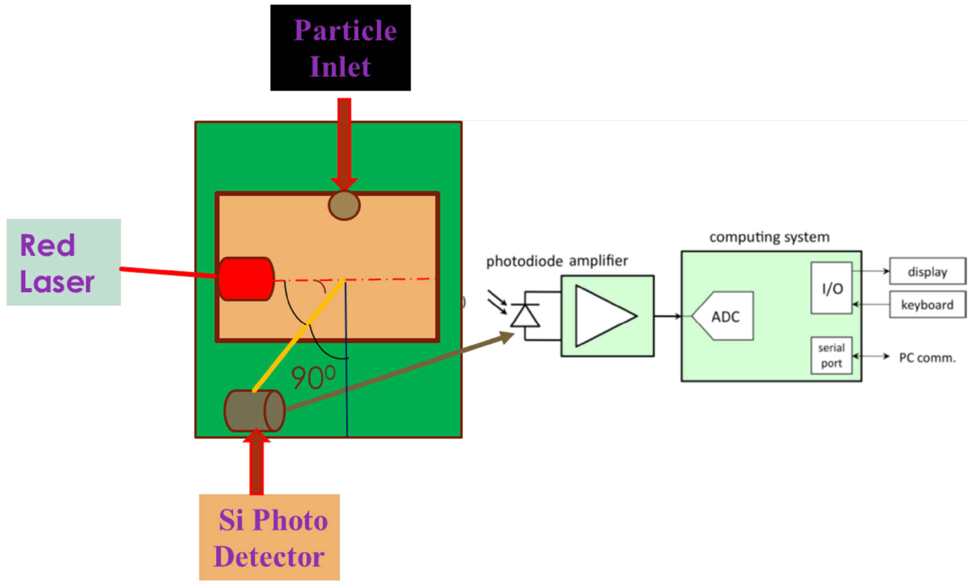

Fig. 2 Schematic structure of LWSCC describing the working principle

at one of the nephelometer wavelengths) to a measured count rate of scattered photons. There can be a drift in the calibrations over time. This can be due to the changing conditions of the calibrator section of the chopper blade or shifting sensitivity of the PMTs. Thus, a recalibration of the nephelometer may become necessary at some point of time.

The first check of the performance evaluation is by putting the series of instrument background checks on filtered air to determine the nephelometer baseline scattering values (i.e., the air Rayleigh and wall scattering contributions that are subtracted from the total measured scattering to give the aerosol scattering coefficients). The indication suggesting no air leaks present in the nephelometer can be easily understood by looking at the consistency in the baseline values.

The second performance check is a check of the calibration of the nephelometer, also referred to as a 'span gas check'. In this check, the scattering coefficients of a low-span gas (typically filtered air) and a high-span gas (for example, CO_2) are measured under instrument conditions of temperature and pressure. The results are used to derive the measured scattering coefficient of CO_2 under standard temperature and pressure conditions (STP, 273.15 K and 1013.25 mb). The measured value of scattering because of pure CO_2 is then compared with the already reported value [7].

The uncertainty of calibration for the Aurora 3000 is given in the user manual to be 2.5% [16].

For the LWSCC instrument, an ideal way would be to use the span gases for its calibration. But we had only compared the instrument with the already calibrated **AURORA 3000** Nephelometer. Corrections for humidity and temperature effects were taken care of in the calibration equation used during programming. There are certain shortcomings which will be dealt in the near future.

2.2. Sampling Sites

The aerosol scattering measurements were performed at the National Physical Laboratory (Central Delhi; 28.38°N, 77.10°E) using LWSCC and India Meteorological Department (Central Delhi; 28.61°N, 77.20°E) using AURORA 3000 discussed in Sect. 2.1.3 in Delhi, the capital of India. The comparison experiments were carried out for the monsoon season (i.e., July 25–August 24, 2017) and for the winter season (i.e., February 1–28, 2018). Both the sites are considered equivalent based on surroundings (green campus alongside with busy road) and meteorological aspects [17]. Delhi lies on the edge of the Gangetic plains and Rajasthan on the western side [10]. Here, the monsoon season starts around late June and lasts until mid of September. The annual average temperatures were found to be around 30 °C. The average temperature has been observed to be around 23 °C on rainy days to 33 °C during dry periods. The winter season starts around early December and then peaks in January, with the average temperatures around 11–12 °C. Winters are typically mild, which is majorly due to the Delhi's geographical location, i.e., closeness to the Himalayas. This results in generation of much colder waves leading to lower apparent temperature [11].

3. Results and Discussions

3.1. Field Performance Testing of LWSCC

The nephelometer instrument (AURORA 3000) was run for the entire day (i.e., 24 h) daily at IMD, while the LWSCC was operated for 8 h daily from 9 am to 5 pm at

CSIR-NPL. In Figure 3 and 4, x-axis represents the measured scattering coefficient from the AURORA 3000, whereas y-axis represents the measured scattering coefficient from LWSCC. Proper care was taken while handling the instruments.

There is a slight overestimation in the scattering coefficient values up to approx. 20 Mm^{-1} obtained from the LWSCC for monsoon season. One of the reasons behind this could be optics dependence because the quality of semiconductor diode laser somewhat lags when compared to the AURORA 3000 inbuilt laser. The AURORA 3000 optical cavity and other instrumentation are well robust and advanced, while despite careful selection of the components, there are still further improvements needed in the LWSCC regarding instrumentation section.

Figures 3 and 4 shows the aerosol light scattering coefficient comparison (LWSCC Vs AURORA 3000) for different seasons.

Figure 3 shows comparison of the aerosol light scattering coefficient measured using LWSCC with that of **AURORA 3000** Nephelometer. Comparison was performed for the monsoon season (i.e., July 25–August 24, 2017). For the monsoon season, we have observed a strong correlation (i.e., R^2 = 0.99). The highest value of aerosol light scattering coefficient was found to be 98 Mm^{-1} for the monsoon season at 633 nm wavelength when compared with that of routinely used nephelometer AURORA 3000. The mean value was observed to be 55 Mm^{-1} with an uncertainty of 32 Mm^{-1}.

Figure 4 shows comparison of the aerosol light scattering coefficient measured using LWSCC with that of **AURORA 3000** Nephelometer for the winter season (i.e., February 1–28, 2018). For the winter season, we have observed a strong correlation (i.e., R^2 = 0.99). The highest

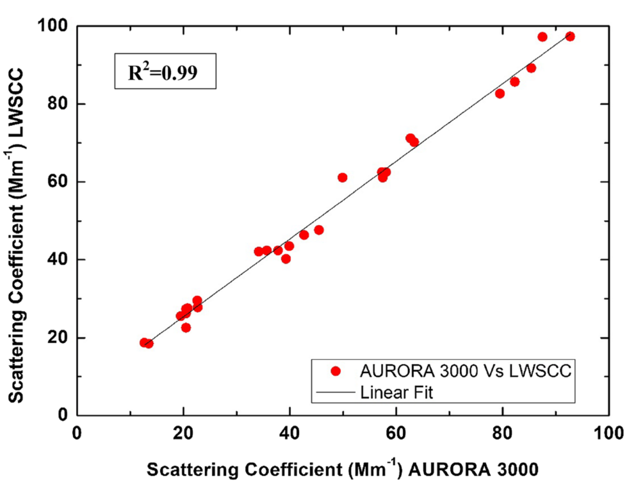

Fig. 3 Comparison of aerosol light scattering coefficients measured using LWSCC with those measured using **AURORA 3000** Nephelometer for the monsoon season (July 25–August 24, 2017)

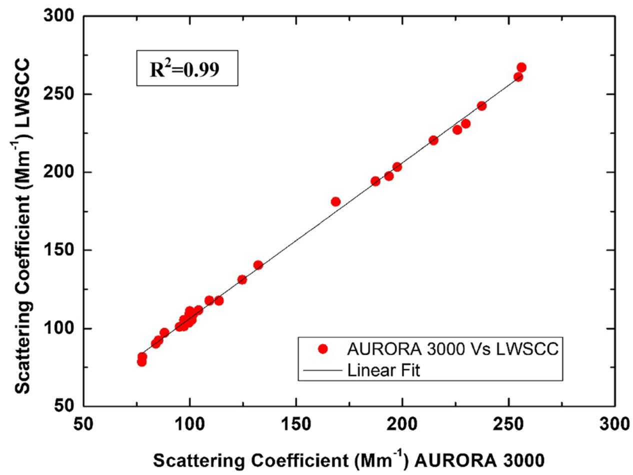

Fig. 4 Comparison of aerosol light scattering coefficients measured using LWSCC with those measured using **AURORA 3000** Nephelometer for the winter season (February 1–28, 2018)

value of aerosol scattering coefficient was found to be 270 Mm^{-1} for the winter season at 633 nm wavelength when compared with that of routinely used nephelometer AURORA 3000. The mean value was observed to be 165 Mm^{-1} with an uncertainty of 108 Mm^{-1}.

Rain in monsoon season washes out the atmospheric pollutants. During our sampling period, there were few rainy events. Winter season in Delhi is dominated by high aerosol loading generally micron-size particles, thus enhancing the particle number concentration. Aerosol scattering coefficient was higher for winter season when compared to that of the monsoon season because of the high particle number concentration during winter season.

The scattering coefficient values measured using LWSCC system have been found to be in good agreement with those measured using **AURORA 3000** Nephelometer for two different seasons of Delhi. The major motive of this work was to check performance of the instrument on ground level, before using it for airborne observations. It is important to note that the LWSCC provides aerosol light scattering coefficient measurement which is useful for modeling aerosol optical/radiative properties and widely used in climate research.

3.2. Uncertainty Budget Estimation of LWSCC

The uncertainty budget is a method used for properly specifying the expanded uncertainty measurement. For the proper evaluation of the standard uncertainty from the parameters of two most important distribution functions, it is appropriate to assume a rectangular distribution with a standard deviation of $a/\sqrt{3}$, if the limits $x \pm a$ are given without a confidence limit. A triangular distribution with a standard deviation of a/$\sqrt{6}$ is assumed if values are given with confidence level [12].

Here, by multiplying the combined standard uncertainty with a coverage factor k, an expanded uncertainty (U) is obtained. The level of confidence decides the choice of coverage factor. For an approximate level of confidence of 95%, the value of k is 2 [13, 14].

Based on the equations, in accordance with GUM (1995) later revised in 2008 as JCGM 100:2008, combined uncertainty for the mathematical model [15] which is a product or quotient form is given by,

$$\left[\frac{u_{c(y)}}{y}\right]^2 = \sum_{i=1}^{N}\left[\frac{p_{iu(x_i)}}{x_i}\right]^2 \tag{2}$$

where u_c (y) is total uncertainty due to y; P_i, probable samples; $u(x_i)$, uncertainty due to x_i; x_i total number of samples from 1 to i; and y total number of outputs.

There are three main factors which can influence the uncertainty calculation for aerosol scattering coefficient using LWSCC.

Referring to Eq. (1), uncertainty due to these three factors is shown below:

1. Uncertainty due to laser intensity, I_0 [it depends upon the laser power per unit area, ultimately errors in current and voltage values associated with the laser].
2. Uncertainty due to detector, B [it depends upon the detector power per unit area, ultimately errors in current and voltage values associated with the detector].
3. Uncertainty due to volume, V of the air sampled through the instrument.

$$\text{Volume of the air sampled } (L) = \text{Time(min)} \times \text{Flow rate (L/min)} \tag{3}$$

Thus, the combined uncertainty can be calculated by the formula mentioned below:

$$\left[\frac{u_{c(b_{\text{scat}})}}{b_{\text{scat}}}\right]^2 = \left[\frac{u_{c(I_0)}}{I_0}\right]^2 + \left[\frac{u_{c(B)}}{B}\right]^2 + \left[\frac{u_{c(V)}}{V}\right]^2 \tag{4}$$

where u_c (b_{scat}) is uncertainty associated with aerosol scattering coefficient; u_c (I_0), uncertainty associated with laser intensity; u_c (B), uncertainty associated with detector intensity; $u_c(V)$, uncertainty associated with volume of the sampled air; and, b_{scat}, I_0, B, V the aerosol light scattering coefficient, laser intensity, detector intensity and volume of the air sampled.

$$\left[\frac{u_{c(b_{\text{scat}})}}{b_{\text{scat}}}\right] = \sqrt{\left[\frac{u_{c(I_0)}}{I_0}\right]^2 + \left[\frac{u_{c(B)}}{B}\right]^2 + \left[\frac{u_{c(V)}}{V}\right]^2} \tag{5}$$

The value of combined standard uncertainty was found to be 32 Mm^{-1} for monsoon season and 108 Mm^{-1} for winter season by putting all the individual uncertainties in Eq. (5).

Putting all values obtained by calculating each separate uncertainty value, we get the combined uncertainty for the instrument so designed:

$u_{c(b_{scat})}$ = combined uncertainty associated with measurement of the aerosol light scattering coefficient calculated after putting the values of various parameters which affects the value of aerosol light scattering coefficient.

$$U = u_{\text{ex(total)}} = u_{c(b_{\text{scat}})} \times 2, \quad \text{at 95\% confidence level, } k = 2 \tag{6}$$

Following the aforementioned approach for the uncertainty budget calculation, the expanded uncertainty was found to be U = 64 Mm^{-1} for monsoon season and 216 Mm^{-1} for winter season.

4. Conclusions

The LWSCC provides aerosol light scattering coefficient measurement which is quite important for modelling aerosol optical/radiative properties and widely used in climate research. The developed instrument is comprised of a 633 nm red laser and fast-response BPX 65 silicon photodetector. LWSCC was tested over urban environment, Delhi, to get the information on one of the important optical properties, i.e., aerosol scattering coefficient. The comparisons were performed between LWSCC and routinely used nephelometer. The results showed a strong correlation coefficient (i.e., R^2 = 0.99) for both the seasons for LWSCC when tested against the **AURORA 3000** Nephelometer. Despite taken care of the humidity effects using silica gel beads, we believe that we have overestimated the value of the scattering coefficient for both of the seasons. This could be taken care by using better drying solutions in the future. The LWSCC could be a potential instrument for aerosol light scattering observations, especially for airborne platforms with payload mass limitations.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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