Laboratory simulation of atmospheric transmission

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Abstract
This note discusses the design, development and applications of laboratory simulation of atmospheric transmission. The objective of the experiment is to demonstrate the transmission/absorption through a gaseous medium. The state-of-the-art experimental setup has hardware and software system. The hardware system consists of an optical cell, a smoke generator and an electronic control system. Optical cell is the heart of this experiment and works on the principle of Beer-Lambert law. This law is the basic principle of radiative transfer, and is exclusively used to study various characteristics of atmospheric particles (aerosols). The graphical user interface application software package "Atmospheric Transmission" has been developed in-house using Microsoft Visual Studio 2015 and .NET 4.6 framework. The system has been designed to operate in idle, smoke generation or purge mode. During these modes of operation the graphical user interface displays the detector signal and the computed optical depth along with the real time image within the optical cell. As an application case study we have used two different types of materials: incense stick and coir rope in order to generate the smoke. The incense stick smoke shows more and fast absorption in the optical cell as compared to the smoke from coir rope. The detector signal falls to 68% within 72 seconds and 58% within 244 seconds for the smoke from incense stick and coir rope respectively. This corresponds to observed changes of 96 and 89% in the optical depth. The typical behavior of the smoke from the incense stick and coir rope is because of the contribution of the distinct composition. The incense stick burning gives intense and dense smoke with more black carbon which strongly attenuates the source intensity when compared to the smoke from coir rope burning. The system has been designed to operate easily and safely in order to generate smoke of the required material. The details about the hardware system, data acquisition system and its implementation and applications are presented in this note.

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1. Introduction

The energy that drives the Earth's atmosphere and climate comes from the Sun. The Earth's atmosphere is made up almost entirely of nitrogen (78.08%) and oxygen (20.95%), and other gases (Argon (0.93%), carbon dioxide (0.035%), nitrous oxides (0.00003%), methane (0.00017%), ozone (0.000004%)) existing in very small concentrations [1]. In addition to various gases, aerosols (suspended solid and/or liquid particles in the atmosphere with radius ranging from 0.001 to 100 μm) are also present in the atmosphere. Aerosols of different sizes, magnitude and composition are produced by natural or anthropogenic sources and can be transported to different regions depending on the meteorological conditions. Aerosols have the potential to significantly influence our planet through their role in heterogeneous chemistry, as well as their effect on the Earth's climate as they scatter and absorb visible incoming solar radiation and outgoing terrestrial radiation and serve as condensation nuclei for cloud droplet formation [2]. When the solar radiation reaches the Earth it gets either scattered or absorbed by the molecules/gases/pollutants that exist in the atmosphere by different effects in the atmosphere like scattering by air molecules, scattering by larger particles (aerosols) and absorption by gases in the atmosphere.

When the electromagnetic radiation travels through the medium, it may be scattered or absorbed by the constituent particles of the medium. Scattering is a physical process by which a particle in the path of an electromagnetic wave continuously abstracts energy from the incident wave and re-radiates that energy in all directions. Molecular absorption converts the radiation energy into excitation energy of the molecules. The overall effect is the removal of energy from the incident radiation to yield the transmitted energy (Figure 1). In order to understand the phenomena of transmission/absorption through a gaseous medium, we have developed and demonstrated the transmission experiment. It also helps in understanding the

Sun and Earth-atmosphere interaction with and without atmospheric constituents.

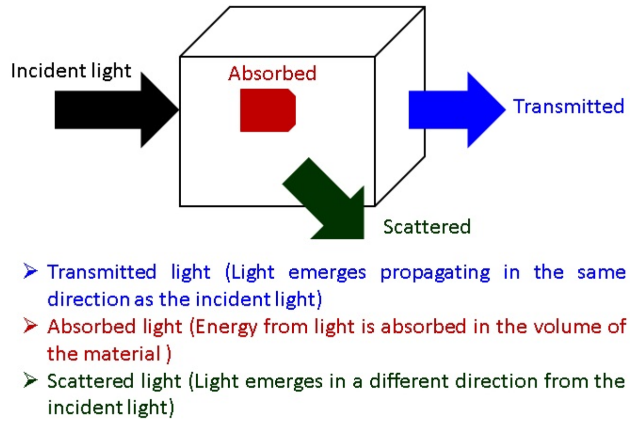

Figure 1. Scattering, absorption and transmission of light

2. Beer-Lambert law

As radiation penetrates through the medium it is progressively absorbed and scattered (Figure 1). The probability of absorption by a species depends on the wavelength of the incoming radiation and the nature of the species. Beer-Lambert law states that "When a beam of light is allowed to pass through a transparent medium, the rate of decrease of intensity with the thickness of medium is directly proportional to the intensity of light".

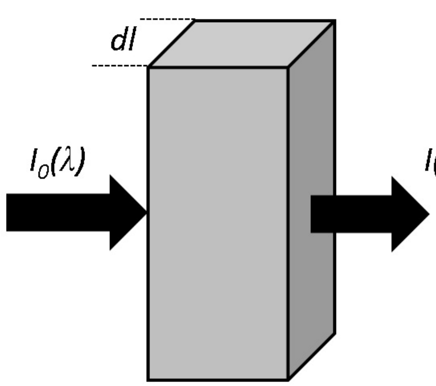

Figure 2. Incident light, $I_0(\lambda)$ passing through an infinitesimally thin layer, dl with 'n' concentration of particles (cm^{-3})

Beer-Lambert law relates the absorption of a ray of incident intensity, $I_0(\lambda)$ and wavelength (λ) passing through an infinitesimally thin layer, dl, the variation of intensity (Figure 2) is given as

$$dI(\lambda) = -K_a I(\lambda) dl \tag{1}$$

where K_a, is the absorption coefficient (cm^{-1}). K_a is proportional to the absorbing particles concentration, n (cm^{-3}) and is related to the effective cross section, σ_a (cm^2) as

$$K_a(\lambda) = \sigma_a(\lambda) n \tag{2}$$

Integrating Equation 1 and using Equation 2, the incident intensity I(λ) at the Earth's surface is given as

$$I(\lambda) = I_0(\lambda) exp\left[\int \sigma_a(\lambda) ndl\right] \tag{3}$$

The optical depth/thickness over the length 'l' is defined as

$$\tau(\lambda) = \int \sigma_a(\lambda) ndl \tag{4}$$

and the corresponding transmission is given as

$$T(\lambda) = exp\left[-\tau_a(\lambda)\right] \tag{5}$$

The exponent represents the attenuation (scattering+ absorption) of light/radiation, and is a unitless quantity. Optical depth gives a measure of attenuation of incident radiation passing through medium. The optical depth of the atmosphere for a slant path is represented using relative airmass m as

$$\tau(\lambda) = \frac{-1}{m}\left[ln\frac{I(\lambda)}{I_0(\lambda)}\right] \tag{6}$$

and for a plane-parallel atmosphere m is approximated as

$$m = sec(\theta) \tag{7}$$

where θ is the zenith angle corresponding to the given path. The role the atmosphere and its constituents play in this interaction is illustrated through Beer-Lambert law. This is the basic principle of radiative transfer, and is exclusively used to study various characteristics of atmospheric aerosols such as their amount, size, scattering and absorption at the surface, in the atmospheric column and as a function of height. The assumptions of the Beer-Lambert law are : (1) homogeneous absorbing medium, (2) incident radiation should be monochromatic, (3) incident radiation must be of parallel rays, (4) absorbers should act independently of each other, and (5) incident flux should not influence the atoms/molecules/particles.

3. Hardware design and implementation

The hardware system consists of optical cell, smoke generator and electronic control system. Figure 3 illustrates the schematic of the laboratory simulation of atmospheric transmission. Optical cell, the heart of the system is a cylindrical tube of length 150 cm and diameter 5 cm, with a 9 W LED lamp at one side and a photodiode OPT301 at other side of the tube (Figure 4). The photodiode OPT301 is an opto-electronic integrated circuit containing a photodiode and transimpedance amplifier on a single dielectrically isolated chip.

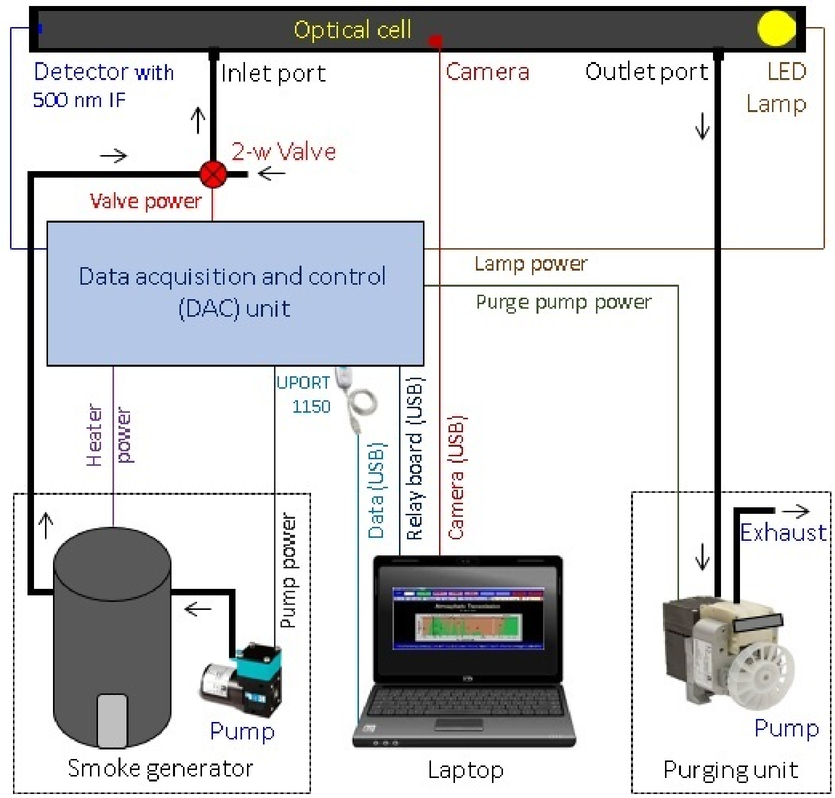

Figure 3. Schematic of the laboratory simulation of atmospheric transmission

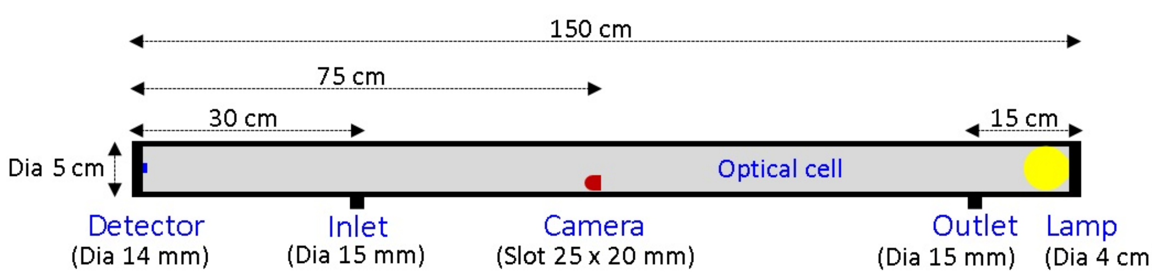

Figure 4. Mechanical schematic of the optical cell

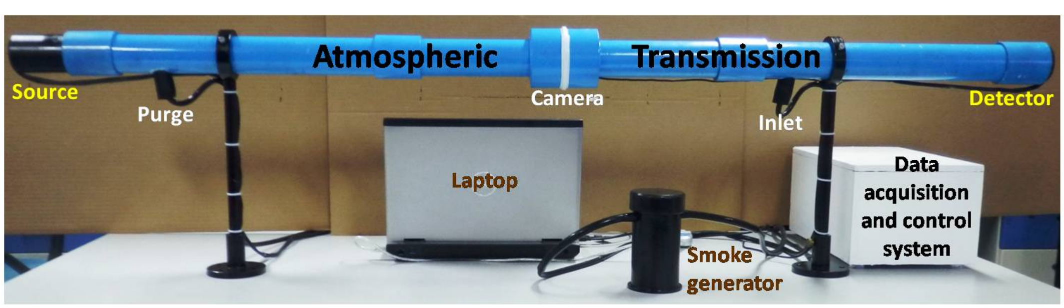

Figure 5. Picture of the laboratory simulation of atmospheric transmission

The transimpedance amplifier consists of a precision FET-input op-amp and an on-chip metal film resistor. The integrated combination of photodiode and transimpedance amplifier on a single chip eliminates the problems related to leakage current errors, noise pick-up and gain peaking due to stray capacitance. OPT301 is coupled and housed along with 500 nm optical interference filter with a bandwidth of 100 nm. It has inlet and outlet ports for smoke input and purging the tube respectively. A high resolution (15 megapixel) Logitech HD Pro Webcam C920 CMOS sensor board has been mounted at the center of the tube and aligned to view the detector plate (Figure 5). The internal surface of the cylindrical tube has been painted with black color in order to reduce dark current from the optical cell.

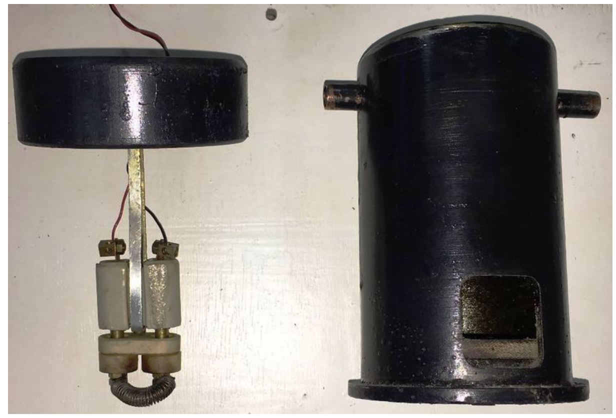

Figure 7. View of the smoke generator used with laboratory simulation of atmospheric transmission

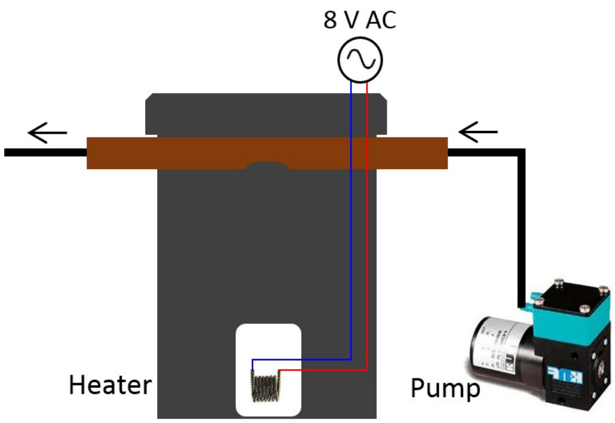

Figure 6. Schematic of the smoke generator used with laboratory simulation of atmospheric transmission

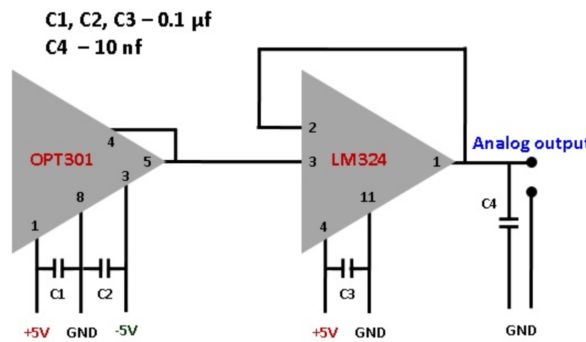

Figure 8. Photodiode signal processing circuit

Smoke generator is a device that emits a continuous smoke of the material under controlled burning. It works on the Bernoulli's principle which states that an increase in the speed of a fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy [5, 6]. It is an aluminum cylinder of height 18 cm and diameter 9 cm with a window of 4 x 2 cm (Figure 6). A nichrome heater coil has been mounted above the base hylam sheet (thickness 10 mm) inside the aluminum cylinder. A copper tube of length 15 cm and diameter 8 mm with a 10 mm hole in the center is placed at the top of the cylinder (Figure 7). Diaphragm pump operating at 1 LPM is used to create the low pressure zone at the center of the copper tube, which enables the smoke generated due to the burning of the material to be sucked and fed into the inlet port. In the present design the heater coil is operated at 8 V AC.

The electronic control system consists of data acquisition and control unit. The photodiode OPT301 has been designed with internal feedback resistor of 1 MΩ and operates at ± 5 V power supply [3]. The detector output signal is buffered using an operational amplifier LM324 operating in non-inverting mode (Figure 8) [4]. The buffered photodiode analog output voltage is fed to a single channel data acquisition module ADAM 4012. It uses a microprocessor-controlled integrating A/D converter to convert sensor voltage and the digital data is sent through a standard RS-485 interface. ADAM 4012 is a single solution for signal conditioning, analog to digital conversion (sampling rates: 10 samples/second and resolution: 16-bit), ranging, and RS-485 digital communication functions [5]. RS-485 signal is converted to USB interface using MOXA UPORT-1150 1-Port RS485 USB-to-serial converter (Figure 9) [6]. We have used multiple signal communication protocols (RS-485 and USB) and commercial-off-the-shelf (COTS) hardware. RS-485 to USB converters are also available from M/s Sunrom Electronics, Ahmedabad (#1430) [7] and M/s Robokits India, Gandhinagar (#RKI-2301) [8]. Sunrom Electronics USB powered relay control board (#1189) is used to interface LED lamp, detector power supply, data acquisition module power supply, smoke generator pump, heater and purge pump [9]. It has four sealed isolated mechanical relays which can be controlled by simple software interface through USB (Figure 10). The data acquisition and control unit comprises of data acquisition module and the programmable relay control board.

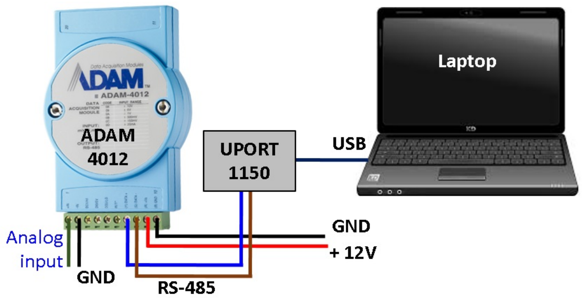

Figure 9. ADAM 4012 and ADAM 4520 based data acquisition system

4. Software design and implementation

The in-house developed data acquisition and control software package "Atmospheric Transmission, Ver: AT.2017.1.C" has been written in Microsoft Visual Studio 2015 an object-oriented programming language. It is a high level programming language, implemented on the .NET 4.6 Framework which enables the rapid application development of graphical user interface (GUI) application software [10]. The setup and deployment packages was developed using Inno Setup Compiler 5.5.8 application package. The GUI application software works in Microsoft Windows 7/8/8.1/10 operating system with .NET framework. Figure 11 shows the flowchart of the laboratory simulation of atmospheric transmission version AT:2017.1.C GUI application software. GUI consists of seven operational menu item; (i) RUN (ii) REFRESH (iii) ABOUT (iv) EXIT (v) Save (vi) SMOKE and (vii) PURGE as shown in Figure 12. The GUI application software is interfaced to relay control board, data acquisition module and web camera through USB port. The GUI software on start-up, fetches and lists the available RS-232 port. Using the combo box the appropriate serial port can be configured. "RUN" command button is used to initialize and execute the GUI application software. The software acquires and displays the real time plot of the detector output, and it also computes and displays the instantaneous optical depth (Figures 12). The "REFRESH" command reloads and re-initializes the software variables. "EXIT" command closes the various port and data files in use and quits the application software. "Save" command logs the time stamped detector output voltage and the computed real time optical depth data. "SMOKE" command button is used to initialize the smoke generator in order to produce the smoke of the required material. It switches the heater

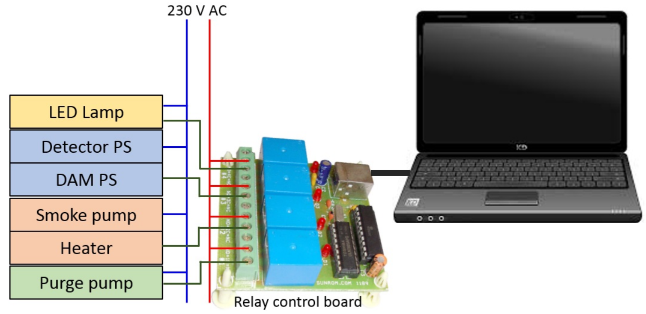

Figure 10. Schematic of the relay control board #1189 interface

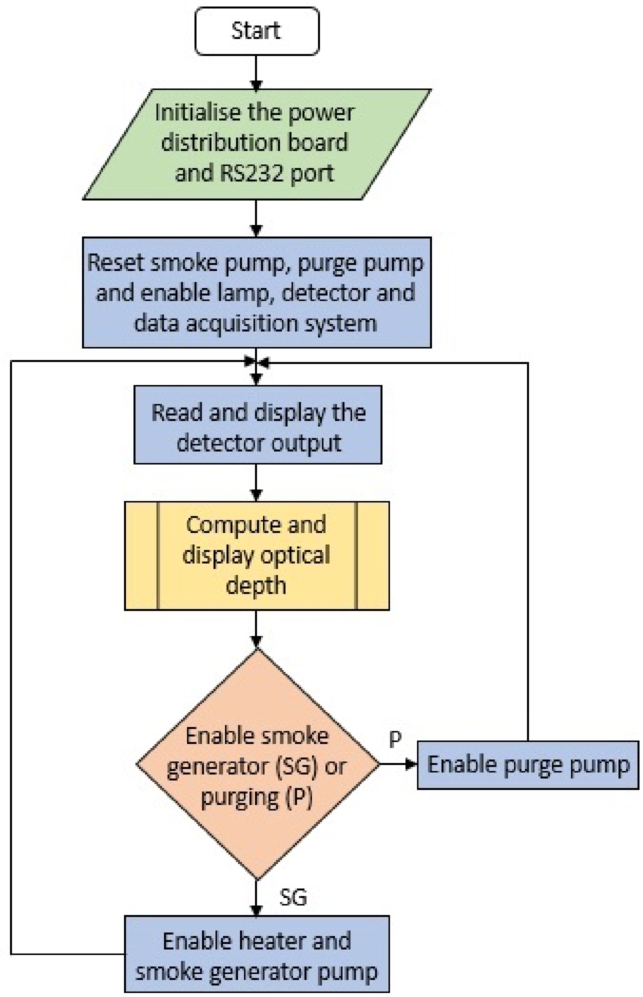

Figure 11. Flowchart for the laboratory simulation of atmospheric transmission

ON and after a preset time the smoke generator pump is switched ON. "PURGE" command triggers the purge pump and puts the optical cell in purging mode. In both the smoke generation and purging modes of operation the software in real time acquires and displays the detector output and optical depth. Logitech webcamera software (Version 2.51) is used to acquire the real time images inside the optical cell from Logitech C920 camera. The camera has been focused on to the detector plate inside the optical cell. The GUI application software ”Atmospheric Transmission” is operated along with ”Logitech webcamera software” in order to acquire the optical cell detector data and the cell real time images.

The asynchronous serial data acquisition is established through ”SerialPort” class in VB.NET using ”System.IO.Ports” namespace. The ASCII file operation has been implemented using System.IO namespace with ”FileStream” class [11]. The instantaneous dynamic plot has been implemented using ZedGraphControl class which provides a user control interface to the ”ZedGraph” class library. ZedGraph is a class library and web-accessible control for creating 2D line, bar, and pie graphs of arbitrary datasets and it provides a high degree of flexibility. The graphpane (plot) can be zoomed or panned by the user, either via a mouse drag operation or by the context menu commands. The timer control has been used to trigger the real-time serial data acquisition subroutine and it plays an important role in the GUI based application programming. The data acquisition system and laptop have been configured for asynchronous serial communication with the following serial port settings; 9600 baud rate, no parity, 8 data bits, 1 stop bit and none flow control. The relay control board is controlled on laptop using dynamic link library ”io1189.dll” through three functions; Read - functions reads the status of all relays, Write - functions writes the status of relays and Store - this function store the current state of relays as power up state.

5. System functions and processes

Optical cell is the heart of the laboratory simulation of atmospheric transmission. The data acquisition module and high resolution camera are interfaced with the laptop through the USB port. The Logitech webcamera software is initiated to detect the Logitech C920 webcamera, then the GUI application software ”Atmospheric Transmission” is executed. The system has been programmed and configured to switch ON the LED lamp, detector power supply and data acquisition module power supply on start-up and disable the smoke and purge pump. The camera displays the clear image of the detector plate. When the GUI application software is enabled to RUN mode, it starts acquiring the data and displays the real time plot. It also instantaneously computes and displays the optical depth. In order to introduce the smoke into the optical cell, the SMOKE is enabled. This process energizes the heater and the smoke generator pump. In the present study we have used incense stick and coir rope as the source of smoke. The incense stick is placed inside the smoke generator. The system generates the smoke and introduces it into the optical cell. The smoke generator pump is operated at a flow rate of 1.0 liter per minute (LPM). The camera captures the smoke movement inside the optical cell (Figures 13) and the GUI software package acquires and displays the light intensity received at the detector. After sometime the smoke generator is disabled and the purging mode is initiated. Purging mode removes the smoke inside the optical cell and the purge pump is operated at 1.5 LPM. After purging the optical cell is restored to its original status depending on the type of materials used for generating smoke (Figures 13).

As an application case study two different types of materials (incense stick and coir rope) have been used to generate the smoke. Generally, the incense stick is made up of a mixture of powdered wood, charcoal, barks, seeds, leaves, roots, rhizomes, flowers etc. with some essential oil, mineral oil, resins, gums and aromatic chemicals. The coir rope or coconut fiber, is a natural fiber extracted from the husk of coconut. With incense stick smoke the detector signal falls to 68% within 72 seconds which gives rise to 96% change in the optical depth. The coir rope smoke shows 58% decrease in detector signal within 244 seconds which give rise to 89% change in optical depth (Figure 14). The real time variations of detector light intensity and optical depth exhibits an opposite behavior (Figure 14). The observed changes with incense stick and coir rope is because of the contribution of the distinct composition and hence the smoke density. Higher values of source intensity indicate clear conditions, and a decrease in the source intensity occurs due to the presence of variant pollutants blocking the source intensity. Due to more contribution of black carbon from the incense stick burning the detector signal falls rapidly with poor visibility in the optical cell. The incense stick burning gives intense and dense smoke with more black carbon which strongly attenuates the source intensity when compared to the smoke from coir rope burning.

6. Summary

The technical note discusses the design, development and functions of laboratory simulation of atmospheric transmission. The hardware system consists of optical cell, smoke generator and electronic control system. Optical cell is the heart of this experiment and works on the principle of Beer-Lambert law. This law is the basic principle of radiative transfer, and is exclusively used to study various characteristics of atmospheric particles (aerosols) such as their amount, size, scattering and absorption at the surface, in the atmospheric column and as a function of height. The graphical user interface application software package ”Atmospheric Transmission” has been developed in-house using Microsoft Visual Basic 2010.NET rapid application development object oriented programming language. The ”Atmospheric Transmission” software package is made compatible to Microsoft Windows 7/8/8.1/10 operating system with .NET framework. The system can be easily and safely operated in order to generate smoke of the required material. The hardware and operating software design enables either the smoke generation mode or the purging mode.

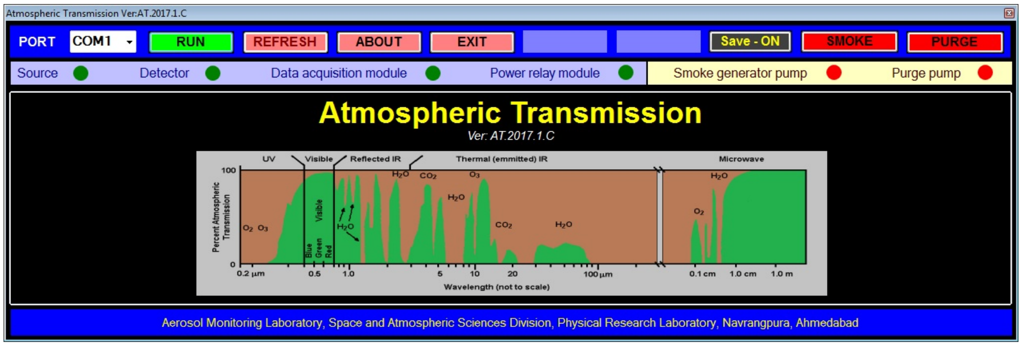

Figure 12. Atmospheric transmission (Ver:AT.2017.1.C) graphical user interface software package

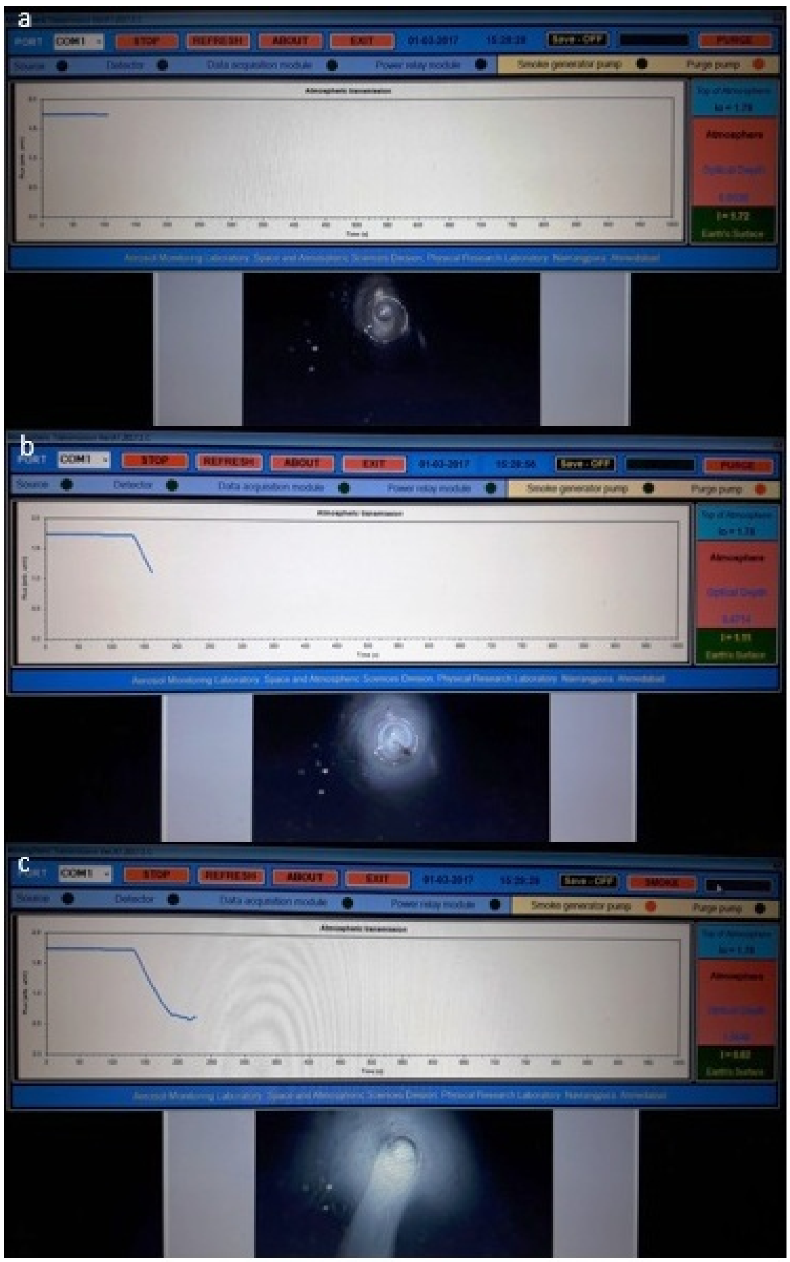

Figure 13. Real time variations of detector light intensity (I) and optical cell images

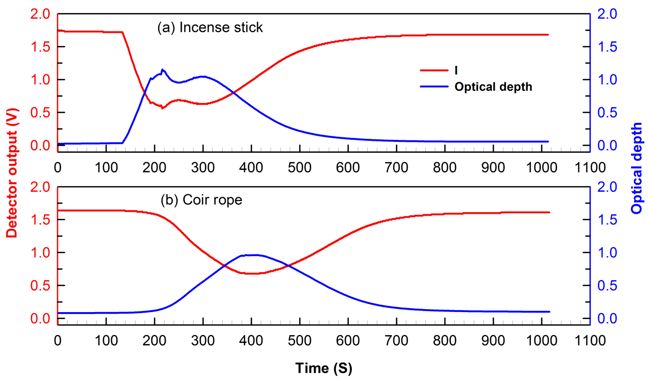

Figure 14. Real time variations of detector light intensity (I) and optical depth with incense stick and coir rope burning

During both the modes of operation the graphical user interface displays the detector signal and the computed optical depth along with the real time image within the optical cell. The acquired and computed data are saved for further analysis and study. As an application case study we have used two different types of materials: incense stick and coir rope in order to generate the smoke. The incense stick smoke shows more and fast absorption in the optical cell as compared to the smoke from cor rope. The detector signal falls to 68% within 72 seconds and 58% within 244 seconds for the smoke from incense stick and coir rope respectively. This corresponds to observed changes of 96 and 89% in the optical depth respectively. The typical behavior of the smoke from the incense stick and coir rope is because of the role of their distinct composition. The objective of the experiment was to demonstrate the transmission/absorption through a gaseous medium. It also helps in understanding the Sun and Earth-atmosphere interaction with and without atmospheric constituents. Atmospheric transmission experiment was successfully demonstrated at PRL National Science Day (NSD) and Open House Exhibition conducted during 25 - 28 February 2017. The mechanical drawing, electronics schematics, GUI application software in the distribution package used in the present work can be made available to any user on request. The various state-of-the-art aerosol monitoring instruments like nephelometer (used for the measurement of aerosol scattering coefficient), aerosol particle spectrometer (used to measure the aerosol size distribution), sunphotometer (used to measure the aerosol columnar loading), etc are the real time applications of the Beer-Lambert law in the study of various properties of atmospheric aerosols. We are in the process of developing a laboratory chamber experiment in order to study and characterize the various aerosol optical, physical and radiative properties from different emission sources (fossil fuel and biomass).

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