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Data analysis and visualization software package for SKYRAD.PACK V4.2

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Abstract
POM-01 is a multiwavelength sky radiometer which measures the direct and diffuse solar irradiances. The POM-01 data is post-processed using inversion software SKYRAD.PACK V4.2 to compute various columnar aerosol properties (aerosol optical depth, single scattering albedo, aerosol phase function and complex and real refractive index for each wavelength and volume size distribution of aerosols). This note discusses the design and application of data analysis and visualization software package for SKYRAD.PACK V4.2. The graphical user interface (GUI) application post-process the SKYRAD output data to provide the various aerosol parameters like the single scattering co-albedo (CSSA), absorbing (AAOD) and scattering (SAOD) components of aerosol optical depth, aerosol asymmetry parameter (ASY), Ångström exponents (AE), absorbing (AAE) and scattering (SAE) component of $\AA$ngstr$\ddot{o}$m exponents, first order derivative of $\AA$ngstr$\ddot{o}$m exponent ($\alpha_0, \alpha_1, \alpha_2$) and $\AA$ngstr$\ddot{o}$m coefficient (β). The software computes and generates the hourly averaged, daily averaged, monthly averaged and hourly time domain monthly averaged data. The details about the GUI software package and output illustrations are presented in this note.

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Contents

1. Introduction

Atmospheric aerosols have received much attention from the scientific community in recent years. Aerosol can change the Earth's atmospheric radiation balance and affect the climate directly by absorbing and scattering solar and terrestrial radiation [1]. It can also influence cloud properties and formation by acting as cloud condensation nuclei (indirect effect) [2], altering the climate and the hydrological cycle. Moreover, aerosols have adverse effects on human health [3]. In order to estimate the radiative effect of atmospheric aerosols within the climate system, it is of the utmost importance to accurately determine their optical and radiative properties in the atmospheric column [4]. When estimating aerosol parameters, the sun–sky radiometric technique is the most accurate and widely used [5]. The technique is used to estimate columnar optical and physical properties of atmospheric aerosols. It consists of measuring both direct solar irradiance and diffuse sky radiance using ground-based sun-sky radiometers. Measurements are taken at different wavelengths in the ultra violet-visible-near infrared bands, within atmospheric windows in order to minimize the absorption of atmospheric gases (such as ozone, water vapor, NO_2). The direct solar irradiance is measured by pointing the sensor normal to the sun direct direction, where as the sky radiance measurements are taken in two different geometries: solar almucantar plane and solar principal plane. In solar almucantar plane geometry, the sensor points at the sky along a conical surface with the same zenith angle as the Sun and varying the azimuth angle, where as in solar principal plane geometry, the sensor points at the sky along a plane with the same azimuth angle as the Sun and varying the zenith angle. Both direct and diffuse radiance measurements are analyzed by inversion algorithms [6, 7] that solve the radiative transfer equation by taking into account the multiple scattering. Columnar optical and physical parameters are retrieved by this technique are: aerosol optical depth, single scattering albedo , scattering phase function, complex refractive index and aerosol volume size distribution. The possible causes of error in the final product are due to (1) errors in the input geophysical parameters, such as ground surface albedo and initial condition values of complex refractive index, (2) instrument errors (minimum observable scattering angle, stray light, calibration constants and solid view angles of the radiometer), and (3) errors caused by inversion algorithms. In this work we will discuss about the multiwavelength sun-sky radiometer POM-01 from Prede Co. Ltd., Japan and the POM-01 data is post-processed using SKYRAD software to retrieve various aerosol parameters (aerosol optical depth (AOD), single scattering albedo (SSA), aerosol phase function and complex and real refractive index for each wavelength and columnar volume size distribution of aerosols). In a step further the in-house developed graphical user interface (GUI) software package further process the SKYRAD output data file to provide various aerosol parameters like the single scattering co-albedo (CSSA), absorbing (AAOD) and scattering (SAOD) components of aerosol optical depth, aerosol asymmetry parameter (ASY), *Ångström* exponents (AE), absorbing (AAE) and scattering (SAE) component of *Ångström* exponents, first order derivative of *Ångström* exponent ($\alpha_0, \alpha_1, \alpha_2$) and *Ångström* coefficient (β), and generate the hourly averaged, daily averaged, monthly averaged and hourly time domain monthly averaged data. The GUI application software also plots the selected aerosol parameters and save it as JPG format for user ready references.

Figure 1. POM-01 Sky radiometer from Prede Co. Ltd., Japan

2. Sky radiometer: POM-01

Sky radiometer is a sun-sky scanning photometer which measure the direct and diffuse solar irradiances as a function of wavelengths. POM-01 is a multiwavelength sky radiometer (Figure 1) from Prede Co. Ltd., Japan. It consists of two state-of-the-art hardware systems; a multiwavelength photometer and a dual axis high speed sun tracker system. The multiwavelegth photometer uses a single photo-diode detector with an amplifier and a rotating filter wheel to measure solar irradiances in seven narrow wavelength bands (315, 400, 500, 675, 870, 940 and 1020 nm) [9]. The detector is kept in a sealed metal cylinder (optical head) behind a quartz window. The metal cylinder of specific length is used for limiting the incident light reaching the detector sensor in order to achieve the half-angle field of view of 0.5°. Due to detector dependence on temperature in the near infrared band, the POM-01 sky radiometer is equipped with a temperature controlled optical head. The dedicated dual axis sun tracker computes the real-time sun position and an integrated sun sensor in closed loop feedback mechanism for active tracking. A rain sensor is integrated along with the radiometer in order to to park the instrument when it rains. POM-01 is connected to a computer running the operating software in order to compute the real-time sun position, make measurements, acquire and store the data. The specifications of POM-01 sky radiometer is listed in Table 1.

Table 1. Specifications of POM-01 sky radiometer

1	Measurement method	Filter wheel
2	Wavelengths	315, 400, 500, 675, 870, 940 and 1020 nm (940 nm is channel for water vapor)
3	FWHM Band width	2 nm (UV), 10 nm (VIS), 40nm (NIR)
4	Wavelength accuracy	2 nm
5	Detector	Si photodiode
6	Half view angle	0.5
7	Min scattering angle	3.0
8	Sun sensor	Si photodiode
9	Tracking control	Dual axis: Azimuth and Zenith
10	Tracking Stepping angle	0.0036/pulse
11	Tracking area	Azimuth: 300 South 0 Zenith: -60 170Horizon 0
12	Temperature control	35
13	Weight	16kg (Tracker + Photometer)
14	Power consumption	200 W
15	Wet sensor	Rain sensor

The POM-01 sky radiometer observes simultaneously direct and solar irradiances at various scattering angles from the Sun which enables estimation of optical parameters of aerosols such as aerosol optical depth (AOD), single scattering albedo (SSA), aerosol phase function and complex and real refractive index for each wavelength and columnar volume size distribution of aerosols. The measured sky radiometer data have been analysed using SKYRAD.PACK software (discussed in next section) [7] for deriving various aerosol optical properties. The sky radiometer requires two different calibrations; (a) Solar calibration constant (I_0): it is the signal corresponding to the solar irradiance incident at the top of the atmosphere, it is retrieved by an in situ procedure called Improved Langley [10, 11]. The Improved Langley is a modified version of the standard Langley plot technique.

In the Improved Langley, I_0 is retrieved by fitting the natural logarithm of the direct solar irradiance versus the product of the relative optical air mass and the total extinction optical thickness (retrieved by the inversion) instead of the air mass alone, as done with the standard Langley plot. Typically, for an urban location, I_0 deduced from the Langley method can have an error of approximately 10%. Hence, an improved method of calibration based on both direct and diffuse radiation data is used [7]. This in situ calibration procedure allows the operators to track and evaluate the calibration status on a continuous basis. (b) Solid view angle: it corresponds to the field of view of the instrument and it can be approached by the geometric solid viewing angle of the optical head. However, several factors contribute to this value: color aberration of the lens, diffraction at the edges, misalignment of the optical axis, and surface non uniformity of filters and sensor. As a consequence, an in situ method is made available for determining the actual solid view angle from optical data. This in situ method consists on performing a scanning of the irradiance field around the Sun, centered at the origin of a local system of rectangular coordinates [12]. The sky radiometers are operated at least once a month in the disc scan mode on a clear sky day to estimate the solid view angles at different wavelengths as part of a recommended calibration procedure. Disk scan is performed by scanning the area of $2^o x 2^o$ around the solar disk from up to down and from left to right, with an angular resolution of 0.1^o. The POM-01 radiometer measure an almucantar scenario every 10 or 20 minutes and a sun direct measurement every minute.

3. SKYRAD.PACK Software

The POM-01 data is post-processed using inversion software SKYRAD.PACK to provide aerosol parameters like aerosol optical depth, single scattering albedo, aerosol phase function and complex and real refractive index for each wavelength and columnar volume size distribution of aerosols. The SKYRAD software has been developed by Prof. Teruyuki Nakajima (CCSR, The University of Tokyo, Japan), and is opened to the public through OpenCLASTR ($http://skyrad.sci.u-toyama.ac.jp$). The SKYRAD algorithm for the retrieval of columnar aerosol properties consists of two different components: an accurate forward radiative transfer model, and an optimized mathematical procedure for the inverse transformation of radiance data with a priori constrains [13, 14]. The algorithm is composed of the radiative transfer model described by Nakajima and Tanaka (1988) [14] and an inversion method similar to the model described by Dubovik and King (2000) [13]. In the radiative transfer model, the direct sun and the sky diffuse radiance components are estimated. The SKYRAD.PACK software version 4.2 is used to process the radiance measurements during almucantar scans to retrieve the aerosol optical depth (AOD), single scattering albedo (SSA), the complex refraction index, and the aerosol phase function. The monochromatic direct sun irradiance I can be described from the extinction of the top of atmosphere solar irradiance, as the Beer's Lambert law expresses

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

where I_0 is the monochromatic irradiance at the top of the atmosphere measured in $Wm^2\ nm^1$, τ is total optical depth (including scattering and absorption by aerosol particles and gas molecules), and m is the optical air mass. m is ratio of path length light beam has actually traveled in the atmosphere to that it would have traveled in vertical direction, and depends upon solar zenith angle (calculated for each latitude, longitude and particular date and time, m=sec(θ), θ being the solar zenith angle). The aerosol optical depth can be retrieved from this equation after subtraction of the Rayleigh scattering and gas absorption (ozone) optical depths from τ. The spectral diffuse sky radiance $E(\phi)$ at a number of azimuth angles is related to the scattering angles ϕ as,

$$E(\phi) = mI \triangle \Omega[\omega\tau P(\phi) + q(\phi)] \tag{2}$$

where $\triangle \Omega$ is the solid view angle of the radiometer, ω is the single scattering albedo, $P(\phi)$ is the phase function at scattering angle ϕ, and $q(\phi)$ is the multi scattering contribution term. From the direct sun irradiance and the sky diffuse radiance, the relative intensity $R(\phi)$ is defined as the ratio between the diffuse to direct components.

$$R(\phi) = \frac{I(\phi)}{mI \triangle \Omega} = \omega\tau P(\phi) + q(\phi) \equiv \beta(\phi) + q(\phi) \tag{3}$$

where $\beta(\phi)$ represents the single scattering term, in opposition to the multi scattering term $q(\phi)$. The ratio $R(\phi)$ is a magnitude less affected by the interference filter degradation, and can be more accurately determined. On the other hand, the inversion algorithm is further used for the retrieval of the spectral optical characteristics of columnar aerosol (aerosol optical depth, single scattering albedo, phase function, aerosol size distribution and complex refractive index [13]). The equations between both sets of aerosol parameters can be found in the following integrals as

$$\tau_{a,ext}(\lambda) = \frac{2\pi}{\lambda} \int_{r_{min}}^{r_{max}} K_{ext}(x,\xi) v(r) dln(r) \tag{4}$$

$$\beta_{\phi} = \frac{2\pi}{\lambda} \int_{r_{min}}^{r_{max}} K(\phi,x,\xi) v(r) dln(r) \tag{5}$$

where x is the size parameter defined as $x = 2\pi r/\lambda$, ξ is the aerosol complex refractive index, $v(r)$ is the columnar aerosol volume distribution and r_{min} and r_{max} are the minimum and maximum aerosol radii, respectively. $K_{ext}(x,\xi)$ and $K(\phi,x,\xi)$ are the kernel functions defined as

$$K_{ext}(x,\xi) = \frac{3}{4}\frac{Q_{ext}(x)}{x} \quad (6)$$

$$K(\phi,x,\xi) = \frac{3}{2}\frac{i_1+i_2}{x^3} \quad (7)$$

where Q_{ext} is the extinction efficiency factor, and i_1 and i_2 are the intensity functions. In case of light scattering by spherical particles, these functions can be computed by the Mie theory, where as for non spherical particles T-matrix method [15] are used [16, 17]. In order to retrieve the aerosol properties, Equation (3) is iteratively inverted. The idea of the method is to iteratively eliminate the multiple scattering term $q(\phi)$ from the ratio $R(\phi)$ to recover the single scattering term $\beta(\phi)$. In each of the iterations, the algorithm obtains the aerosol volume distribution $v(r)$ by inversion of the aerosol optical depth $\tau_a(\lambda)$ and the single scattering coefficient $_a(\phi)$. In each iteration step, the retrieved volume distribution is used as input for the radiative transfer code in order to simulate $R(\phi)$, which is compared with the experimental $R(\phi)$ to evaluate the root mean square difference $\varepsilon(R)$. The process is repeated until $\varepsilon(R)$ is less than a given threshold. In this iteration scheme, the complex refractive index ξ is also evaluated together with $v(r)$. Once $v(r)$) and ξ are optimized by minimization of a quadratic form [13], the aerosol single scattering albedo can be estimated as

$$\omega(\lambda) = \frac{\tau_{a,sca}(\lambda)}{\tau_{a,ext}(\lambda)} \quad (8)$$

where $\tau_{a,sca}$ is obtained by an equivalent integral to Equation (4), substituting $K_{ext}(x,\xi)$ for $K_{sca}(x,\xi)$, the scattering kernel function [18]. For the sky diffuse component, the radiometer is moved along the solar almucantar plane, keeping the zenith angle constant and equal to the solar zenith angle and varying the azimuthal angle. With the instrument calibration factor (S_0), the solar irradiance at ground can be obtained from the instrument signal at ground and the solar irradiance at the top of the atmosphere (I_0). The SKYRAD software package consists of two different modules called *dtform* and *sproc*. The *dtform* module formats the POM-01 data which can be fed in the processing module *sproc*. The SKYRAD package is an offline data inversion package and is generally configured for auto run at 20:00 hrs (LT).

4. Methodology

The SKYRAD software package post-process the POM-01 sky radiometer data to provide spectral aerosol optical depth (AOD), spectral single scattering albedo (SSA), spectral aerosol phase function, spectral complex and real part of refractive index, and columnar volume size distribution of aerosols. The SKYRAD generated aerosol parameters are further used to determine various other aerosol parameters like the single scattering co-albedo (CSSA), absorbing (AAOD) and scattering (SAOD) components of aerosol optical depth, aerosol asymmetry parameter (ASY), *Å*ngstr*ö*m exponents (AE), absorbing (AAE) and scattering (SAE) component of *Å*ngstr*ö*m exponents, first order derivative of *Å*ngstr*ö*m exponent $(\alpha_0,\alpha_1,\alpha_2)$ and *Å*ngstr*ö*m coefficient (β). Aerosol single scattering Albedo (SSA) is the measure of the amount of aerosol light extinction due to scattering and is expressed as the ratio to scattering to extinction, where as the amount of aerosol light extinction due to absorption is defined as single scattering co-albedo (CSSA) and given as

$$CSSA(\lambda) = 1 - SSA(\lambda). \quad (9)$$

Aerosol optical depth (AOD) is a measure of the extinction of the solar irradiance by aerosols. The absorbing (AAOD) and scattering (SAOD) components of the AOD are estimated as

$$AAOD(\lambda) = AOD(\lambda)[CSSA(\lambda)] \quad (10)$$

$$SAOD(\lambda) = AOD(\lambda) - AAOD(\lambda). \quad (11)$$

The asymmetry parameter (ASY) the scattering geometry of the particle is defined as the intensity-weighted average cosine of the scattering angle and is a measure of the angular distribution of scattered light. The value of ASY ranges between -1 for entirely backscattered light to +1 for entirely forward scattered light. ASY can be computed from the aerosol phase function for the scattering angles 0 to 180^0 as

$$ASY(\lambda) = \frac{\int_0^\pi Cos(\theta)P_a(\lambda,\theta)d(Cos\theta)}{\int_0^\pi P_a(\lambda,\theta)d(Cos\theta)}. \quad (12)$$

The spectral variation of aerosol optical depth (τ_a) can be represented by *Å*ngstr*ö*m power law [19] given by,

$$\tau_a = \beta\lambda^{-\alpha} \quad (13)$$

where λ is the wavelength in μm, α and β are *Å*ngstr*ö*m parameters. α is the *Å*ngstr*ö*m exponent which depends on aerosol size distribution and β (AOD at 1 μm), the turbidity coefficient is directly proportional to the amount of aerosol particles along the Sun path. Higher α signifies an increase in the concentration of smaller size particles and a decrease in the concentration of larger particles whereas a lower α indicates an abundance of super micron aerosols. *Å*ngstr*ö*m any pair of wavelengths as,

$$\alpha = -\frac{ln[\tau(\lambda_1)/\tau(\lambda_2)}{ln[\lambda_1/\lambda_2]} \quad (14)$$

and the Ångström exponent (β) can be estimated as

$$\beta = \tau(1.020)\left[\frac{1}{1.020}\right]^{-\frac{ln[\tau(0.87)/\tau(1.020)]}{ln[0.87/1.020]}}. \quad (15)$$

Typically, the size distribution of aerosol in the ambient atmosphere is bimodal and is made up of a fine mode produced by combustion processes and/or gas to particle conversion and, a mechanically produced coarse mode. Therefore, departure from linear behavior of ln(τ_a) versus ln(λ) is observed [20], and a linear fit is found to yield significant difference when compared to the measured AODs. A curvature is observed in the AOD spectra which contains useful information about the aerosol size distribution. A second order polynomial fit is used to correlate with the measured AOD which can be written as,

$$ln(\tau_a) = \alpha_2[ln(\lambda)]^2 + \alpha_1[ln(\lambda)] + \alpha_0 \quad (16)$$

where α_0, α_1, and α_2 are constants. Coefficient α_2 represents the curvature observed in the spectral distribution of AODs. The coefficients α_1 and α_2 can be used to get significant information about aerosol type and size distribution. α_2-α_1 values can reveal the dominant type of aerosols (whether fine or coarse) in the aerosol size distributions. Absorption Ångström Exponent (AAE) and scattering Ångström Exponent (SAE) can be estimated from the absorbing component of aerosol optical depth (AAOD) and scattering component of aerosol optical depth (SAOD) respectively as

$$AAOD = k\lambda^{-AAE} \quad (17)$$

$$SAOD = k\lambda^{-SAE}. \quad (18)$$

Absorption (AAE) and scattering (SAE) Ångström exponent can be computed following the Volz method using any pair of wavelengths as,

$$AAE = -\frac{ln[AAOD(\lambda_1)/AAOD(\lambda_2)}{ln[\lambda_1/\lambda_2]} \quad (19)$$

$$SAE = -\frac{ln[SAOD(\lambda_1)/SAOD(\lambda_2)}{ln[\lambda_1/\lambda_2]}. \quad (20)$$

5. Software design and implementation

The in-house developed state-of-the-art data acquisition and control software package "Data analysis and visualization software package for SKYRAD.PACK V4.2" 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 [21]. The setup and deployment packages was developed using Inno Setup Compiler 5.5.8 application package. The GUI application software works in Microsoft Windows 7/8/10 operating system with .NET framework. The ASCII file operation has been implemented using System.IO namespace with "FileStream" class [21]. 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. Figure 2 shows the flowchart of the data analysis and visualization software package for SKYRAD.PACK GUI application software. GUI consists of six operational menu item; (i) Data folder (ii) Compute (iii) Plot (iv) About (v) Exit (vi) Refresh as shown in Figure 3. 'Data folder' menu is used to generate the consolidated SKYRAD output file for multiple data files analysis. 'Compute' menu can be used to compute the single (daily) or multiple (monthly) SKYRAD output data files. 'Plot' menu is used to visualize the GUI software post-processed various aerosol parameters. 'About' menu gives details about the GUI software package. 'Exit' command closes the data files in use and quits the application software. 'Refresh' command reloads and re-initializes the software variables.

6. System functions and processes

The GUI package has been designed to start with the compilation of consolidated SKYRAD output files (*.out) as $Data-file-list.dat$. Then the software when opted for multiple file data extraction it fetches the $Data-file-list.dat$ file. It fetches and reads each SKYRAD output file (Figure 4) and extracts the non-negative AOD values (as a part of data quality control) to *.S42 data files. Then *.S42 data files are used to compute the various additional aerosol parameters (single scattering co-albedo (CSSA), absorbing (AAOD) and scattering (SAOD) components of aerosol optical depth, aerosol asymmetry parameter (ASY), Ångström exponents (AE), absorbing (AAE) and scattering (SAE) component of Ångström exponents, first order derivative of Ångström exponent ($\alpha_0, \alpha_1, \alpha_2$) and Ångström coefficient (β)) and write as *.XS42 data files. The *.XS42 data file has been used for the further data analysis work. It computes the hourly averaged (*.XHAV) data files and then arrange the data in 0-23 hrs time domain (*.AHAV). The daily data files *.XS42 are further used to compute the daily averaged data files *.XDAV.

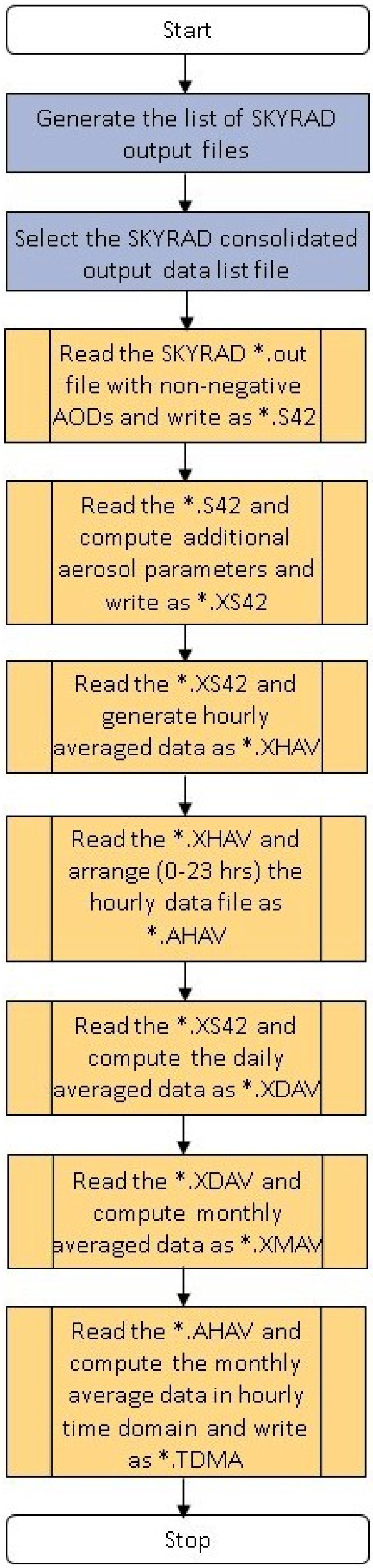

Figure 2. Flowchart of the SKYRAD data analysis and visualization software package

Table 2. Various files used in the data analysis and visualization software package

Sr.	Files extension	Description
1	.OUT	SKYRAD output file
2	.S42	Data extracted from .OUT file and arranged in column
3	.XS42	Additional aerosol parameters computed using .S42 file
4	.XHAV	Hourly averaged data file
5	.AHAV	Arranged hourly data in 1 to 24 hrs
6	.XDAV	Daily averaged data file
7	.XMAV	Monthly averaged data file
8	.TDMA	Monthly data averaged in time domain

The monthly average SKYRAD data (*.XMAV) are determined using the daily averaged files (*.XDAV). In addition, it finally computes the monthly hourly (0-23 hrs) time domain data (*.TDMA) using hourly arranged SKYRAD data (*.AHAV). The GUI software package can also be used to analyse the single day SKYRAD output data in order to generate the corresponding *.S42, *.XS42, *.XHAV, *.AHAV and *.XDAV data files. The application package auto saves the plots in JPG format for the user ready references. The various files used in the data analysis and visualization software package are listed in Table 2.

As an illustration, we have analyzed the SKYRAD data observed using POM-01 sky radiometer over Ahmedabad for April, 01 2014 and the output plots are shown in Figures 5 to 19. Figures 5 and 6 show the instantaneous and spectral variation of aerosol optical depth (AOD) over Ahmedabad. Spectral variation of single scattering albedo and single scattering co-albedo are shown in Figures 7 and 8. The spectral variation of imaginary and real part of the refractive indices are illustrated in Figures 9 and 10. Figures 11 and 12 show the aerosol phase function for the scattering angles 0 to 180^0 and spectral variation of asymmetry parameter. Aerosol volume size distribution in the radius range 0.01 to 16 μm is illustrated in Figure 13. Figures 14 and 15 illustrate the spectral variations of the scattering and absorbing component of the aerosol optical depth. $\mathring{A}ngstr\ddot{o}m$ exponents over Ahmedabad for different wavelength pairs are shown in Figure 16. $\mathring{A}ngstr\ddot{o}m$ coefficients (α, β, α_1, α_2 and α_2-α_1) are illustrated in Figure 17. Figures 18 and 19 show the absorbing and scattering component of $\mathring{A}ngstr\ddot{o}m$ exponents over Ahmedabad for different wavelength pairs.

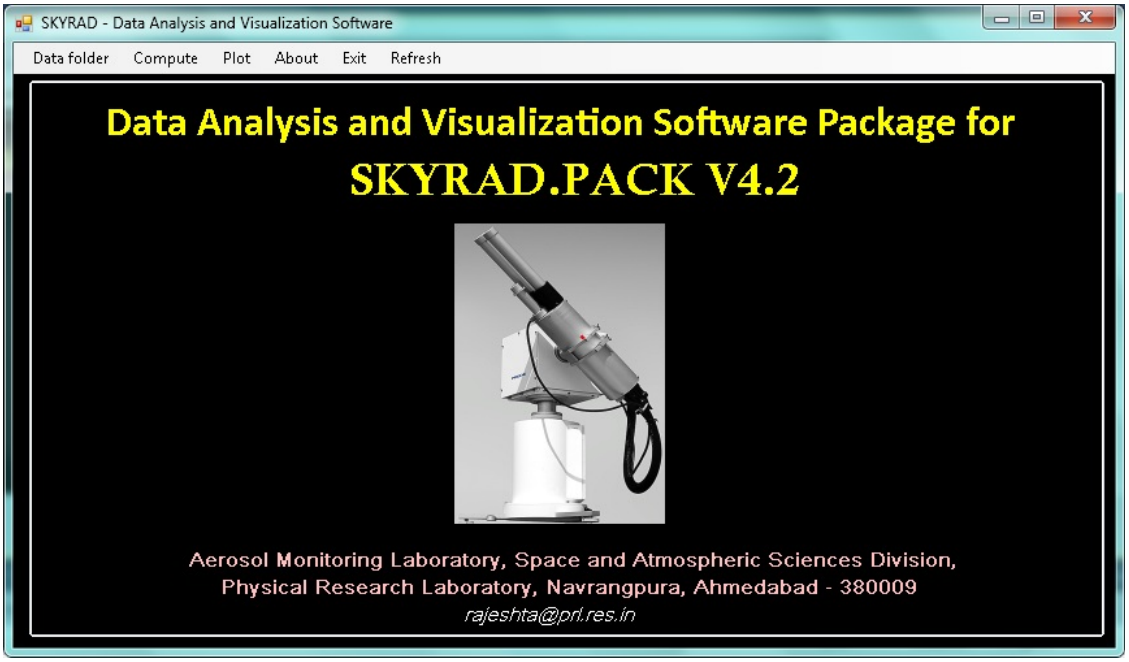

Figure 3. GUI application software for the Data analysis and visualization software package for SKYRAD.PACK V4.2

```
1 2014  1  1 10.33   72.55  23.03  32.29 110.0 110.9 1 1  0.0552 ( 4)
Refractive Indices
 WL     0.4000    0.5000    0.6750    0.8700    1.0200
 Cr     1.4667    1.4429    1.4333    1.4182    1.4003
 Ci   -0.00470  -0.00455  -0.00312  -0.00064  -0.00001
   Radius     Volume
  1.209E-06   4.064E-07
  1.768E-06   1.293E-06
  2.586E-06   1.668E-06
  3.782E-06   8.740E-07
  5.530E-06   1.913E-07
  8.087E-06   1.277E-07
  1.183E-05   1.247E-06
  1.729E-05   6.090E-06
  2.529E-05   1.339E-05
  3.698E-05   1.404E-05
  5.408E-05   8.567E-06
  7.908E-05   7.948E-06
  1.156E-04   1.137E-05
  1.691E-04   9.537E-06
  2.473E-04   3.851E-06
  3.617E-04   9.629E-07
  5.289E-04   1.311E-06
  7.734E-04   2.540E-06
  1.131E-03   2.343E-06
  1.654E-03   1.191E-06
Cross sections
 WL     0.4000    0.5000    0.6750    0.8700    1.0200
 OPT    1.5818    1.3847    1.0593    0.7905    0.6592
 TA     1.5539    1.3979    1.0889    0.8021    0.6397
 WA     0.9520    0.9584    0.9719    0.9938    0.9999
fg    TH     FI     SCA     AUR       AURC
-9   57.7    0.0    0.0   3.690E-06  -1.000E+00
```

Figure 4. Content of the SKYRAD output data file

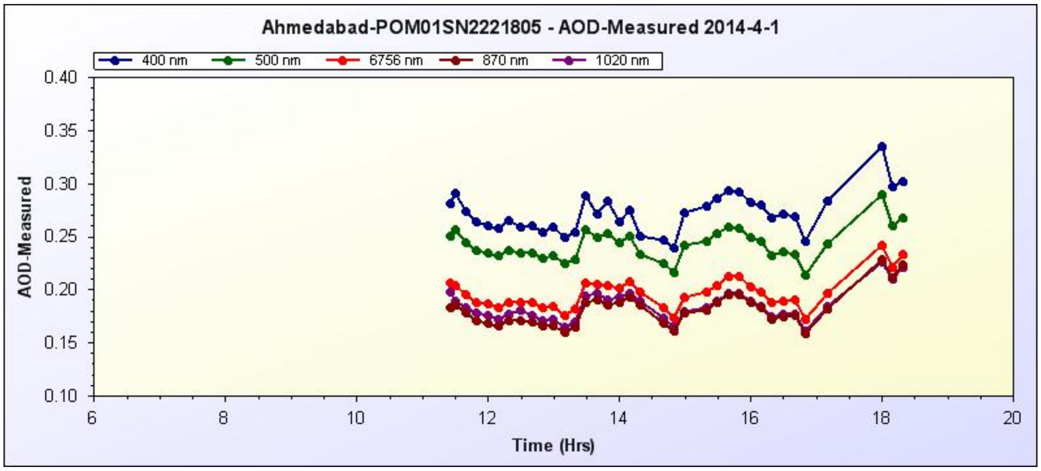

Figure 5. Aerosol optical depth (AOD) variation over Ahmedabad

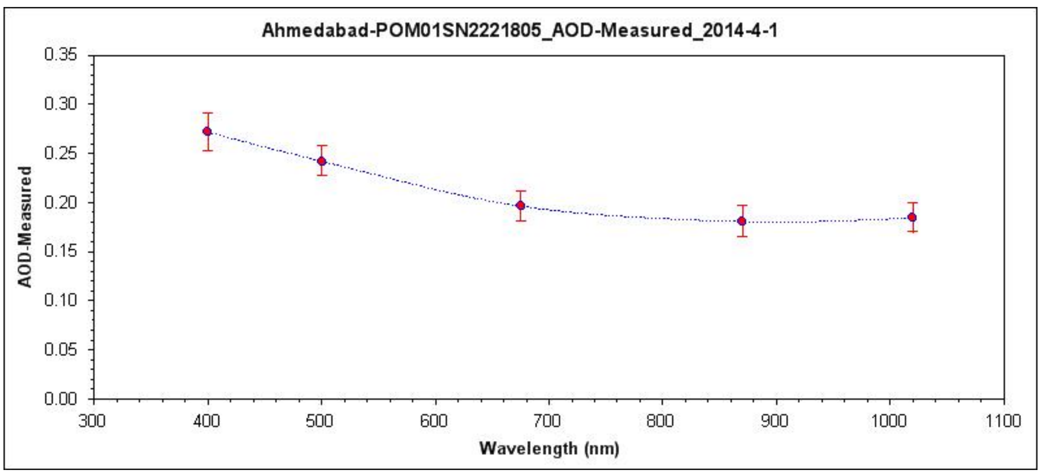

Figure 6. Spectral variation of aerosol optical depth (AOD) over Ahmedabad

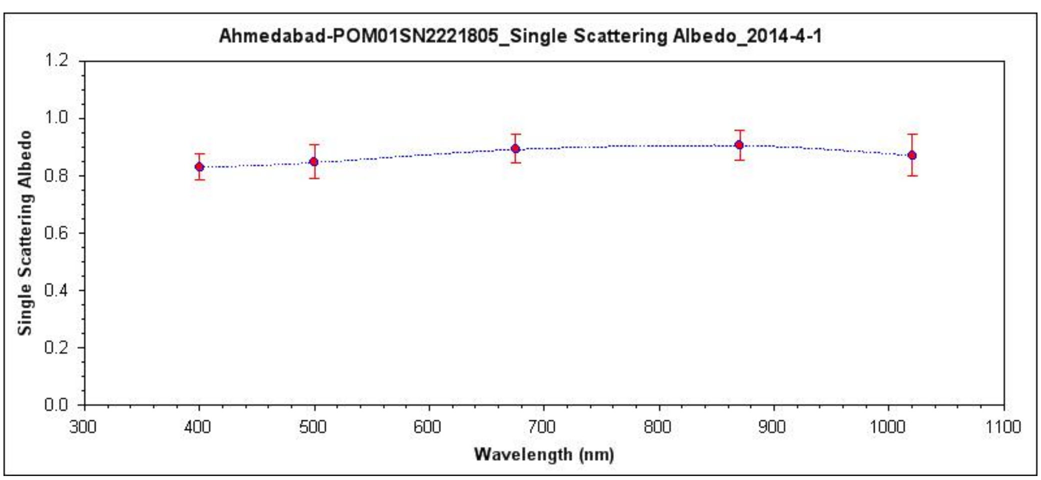

Figure 7. Spectral variation of single scattering albedo (SSA) over Ahmedabad

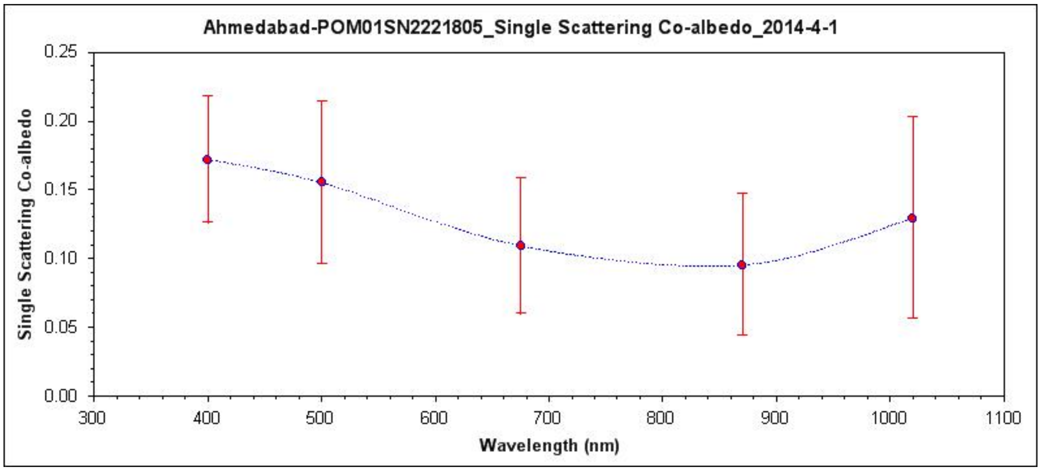

Figure 8. Spectral variation of single scattering co-albedo over Ahmedabad

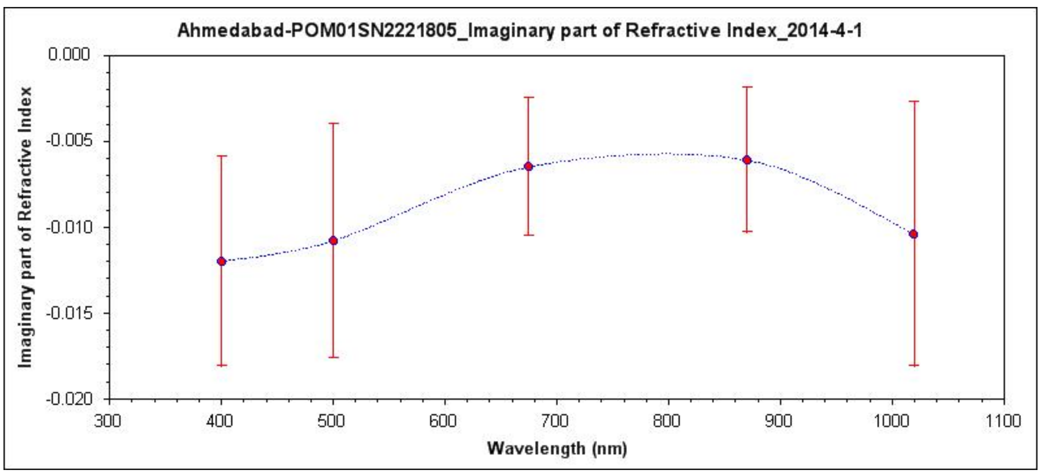

Figure 9. Spectral variation of imaginary part of the refractive index over Ahmedabad

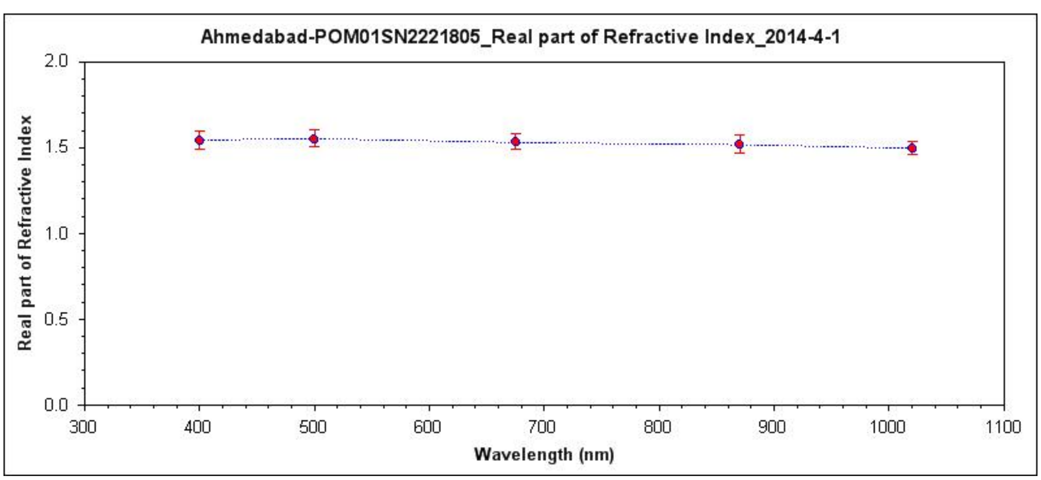

Figure 10. Spectral variation of real part of the refractive index over Ahmedabad

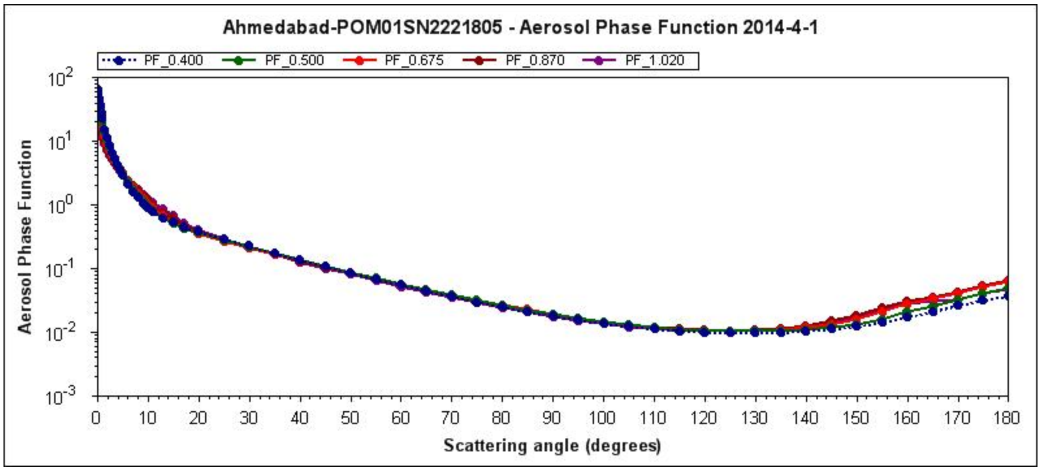

Figure 11. Aerosol phase function for 0 to 180^0 scattering angles over Ahmedabad

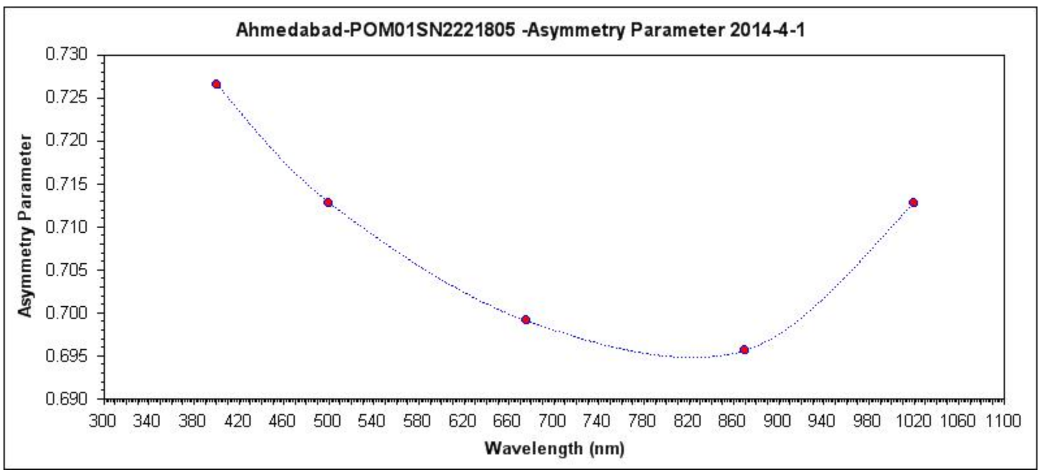

Figure 12. Spectral variation of asymmetry parameter over Ahmedabad

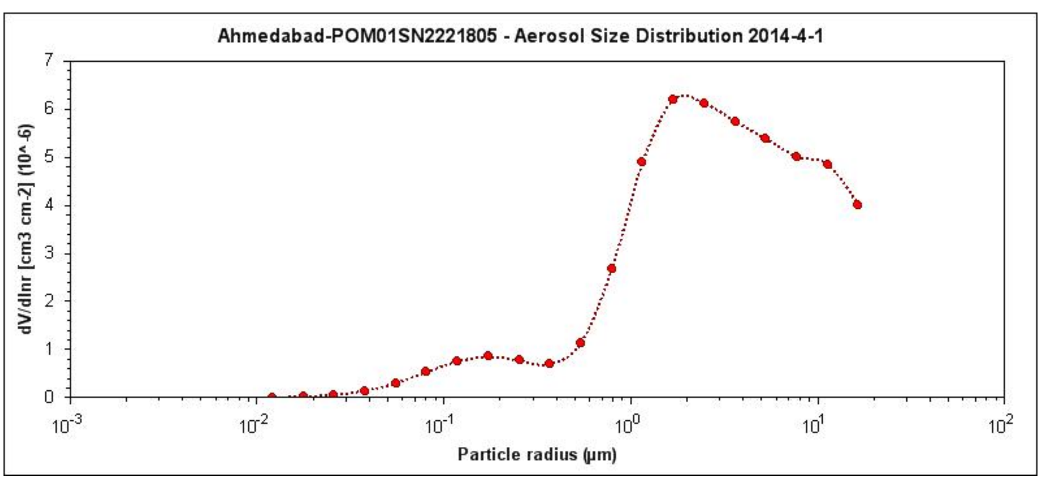

Figure 13. Aerosol volume size distribution over Ahmedabad

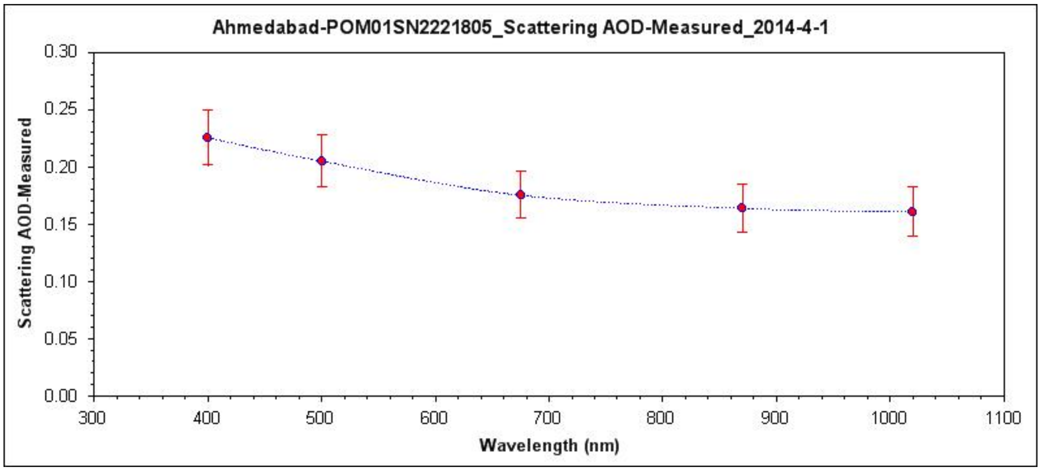

Figure 14. Spectral variation of scattering component of AOD over Ahmedabad

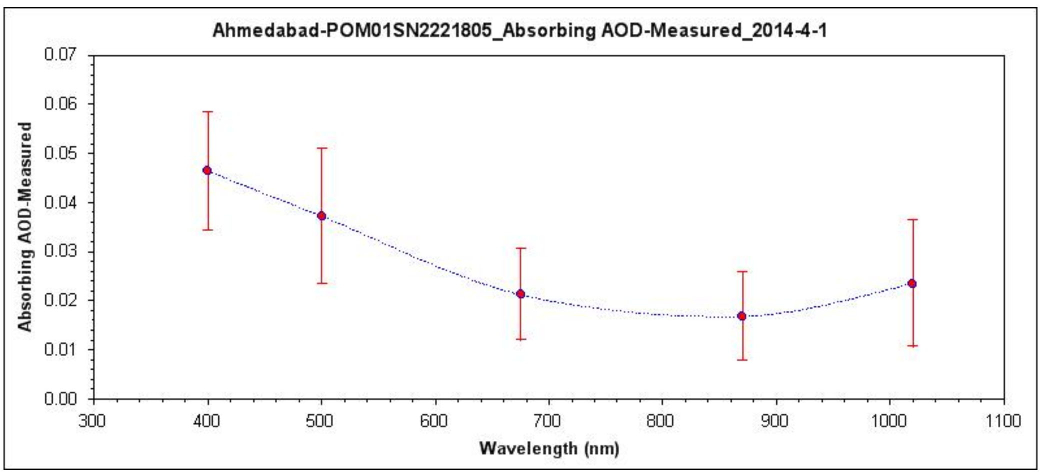

Figure 15. Spectral variation of absorbing component of AOD over Ahmedabad

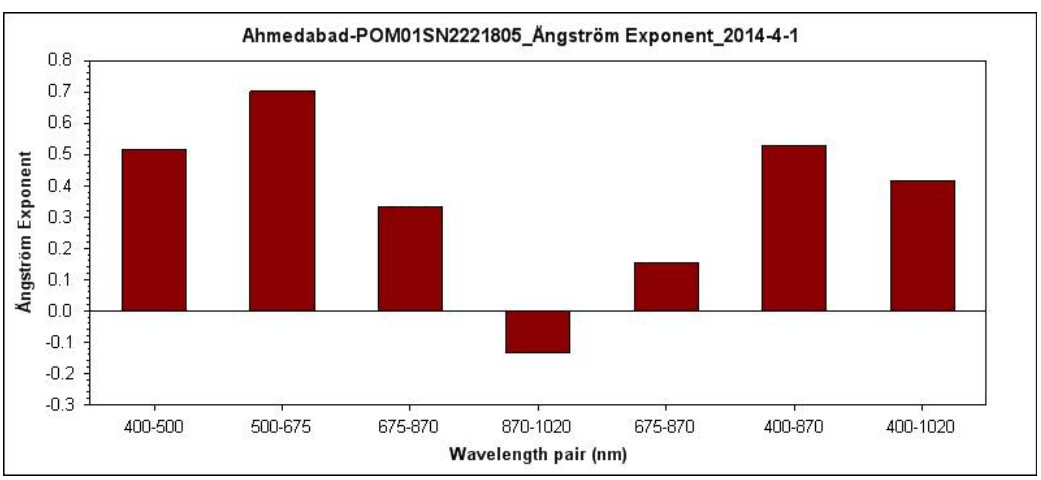

Figure 16. *Å*ngstr*ö*m exponents over Ahmedabad for different wavelength pairs

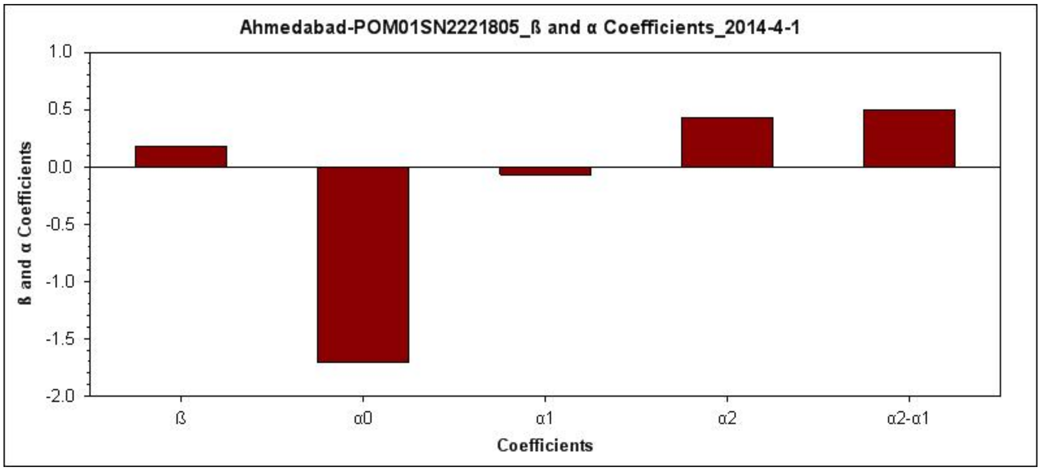

Figure 17. α, β, α_1, α_2 and α_2-α_1 over Ahmedabad

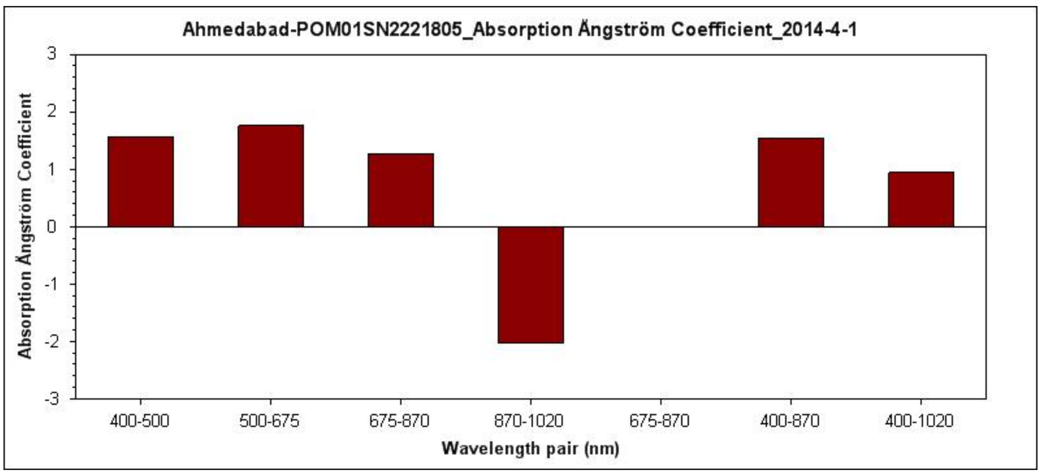

Figure 18. Absorbing component of *Ångström* exponents over Ahmedabad for different wavelength pairs

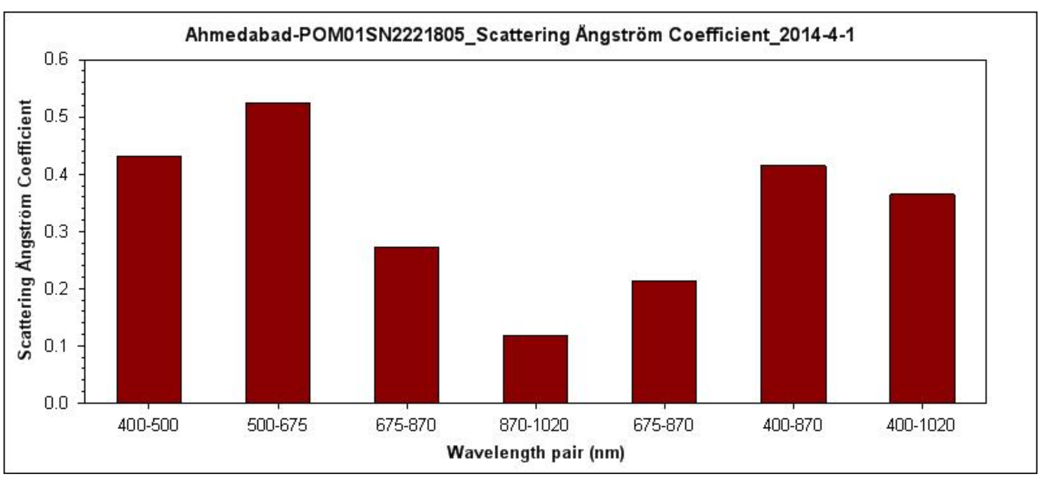

Figure 19. Scattering component of *Ångström* exponents over Ahmedabad for different wavelength pairs

7. Summary

The direct and diffuse solar irradiances are measured using the POM-01 sky radiometer, and the columnar aerosol optical properties (such as, aerosol optical depth, single scattering albedo, real and imaginary part of refractive index phase function, and size distribution) are retrieved by using inversion software called SKYRAD.PACK v4.2. The data analysis and visualization software package for SKYRAD.PACK v4.2 has been in-house designed, developed and successfully implemented for POM-01 sky radiometer at Aerosol Radiation Measurement Laboratory (ARML), Space and Atmospheric Sciences Division, Physical Research Laboratory, Ahmedabad. The graphical user interface application software package has been developed using Microsoft Visual Basic 2010.NET rapid application development object oriented programming language. The software package is made compatible to Microsoft Windows 7/8/10 operating system with .NET framework and is made available in the installer setup and deployment format. The GUI application package post-process the SKYRAD output data file to provide spectral aerosol optical depth (AOD), spectral single scattering albedo (SSA), spectral aerosol phase function, spectral complex and real part of refractive index, and columnar volume size distribution of aerosols. In addition, it also derives the various aerosol parameters like the single scattering co-albedo (CSSA), absorbing (AAOD) and scattering (SAOD) components of aerosol optical depth, aerosol asymmetry parameter (ASY), *Ångströ*m exponents (AE), absorbing (AAE) and scattering (SAE) component of *Ångströ*m exponents, first order derivative of *Ångströ*m exponent ($\alpha_0, \alpha_1, \alpha_2$) and *Ångströ*m coefficient (β). The application package auto saves the plots in JPG format for the user ready references. The GUI software package can be made available to user on request.

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