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An overview of handheld sun photometer measurements of atmospheric aerosols in New Orleans, Louisiana: A case study of the Xavier university study site

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Abstract. Aerosol optical depth (AOT) was measured at Xavier University of Louisiana (XULA, 29.96° N, 90.11° W and 3m above sea level) using a GLOBE handheld sun photometer. The measurements were done at two different wavelengths, 505nm and 625nm. The measured values were used to extrapolate the AOT values for wavelengths 667nm, 551nm, 532nm and 490nm at the XULA site. The measured and calculated AOT values were then compared with values from the nearest AERONET station at Wave CIS site 6 (AERONET, 28.87° N, 90.48° W and 33m above sea level), which is 60 miles south of XULA. In this study we tracked the annual and daily variations of AOT for a 12-month period from September 2017 to August 2018. These data show good qualitative agreement between the two stations in the 12-month period. Both sets of data show distinct peaks in February and May. Both sets of data show low AOT values in the winter months and high AOT values in the summer months. The hourly AOT variations averaged over the 12-month period was also investigated for the XULA site. The data show two peaks, one at 9:00 am and another at 3:00pm. We also compared AOT data from two independently calibrated GLOBE sun photometers at the XULA site. The data show that the two instruments are in excellent agreement. The R-squared value for the 505nm channel is 0.92 and the R-squared value for the 625nm channel is 0.95.

1. Introduction

The atmosphere is made up of molecules of gas and small solid and liquid particles suspended in the air, called aerosols [1, 2]. Some aerosols are naturally produced from volcanoes, sea spray, sand, or wind-driven erosion of surface soil [3]. Some aerosols are a result of human activity, such as dust from agricultural activities, smoke from burning biomass and fossil fuels and photo chemically induced smog due mostly to vehicle emissions. Aerosols are too small to be individually seen by the naked eye, but you can often see their collective effect when the sky is smoky or looks dirty. Bright orange skies at sunrise and sunset may also be pointers that aerosols are present [4].

Aerosols impact our weather and climate because they affect the amount of sunlight reaching earth's surface. Biomass burning causes large local increases in aerosol concentrations that can affect regional weather. Taken together with other meteorological measurements, aerosol measurements help scientists to better understand and predict climate and to understand atmospheric chemistry [5, 6].

Aerosol concentrations vary considerably with location and time. There are seasonal and yearly changes as well as random changes due to events such as large dust storms and volcanic eruptions [7, 8]. Aerosol optical thickness (AOT, also called aerosol optical depth) is a measure of the degree to which aerosols affect the passage of sunlight through the atmosphere [9, 10, and 11]. The LED-based handheld Sun photometers are ideal instruments for use in a global aerosol monitoring network. The Global Learning and Observations to Benefit the Environment (GLOBE) program offers the potential for such a network, through thousands of schools in the United States and nearly 100 other countries. In 1998, GLOBE initiated a project to develop LED-based Sun photometers to monitor aerosol optical thickness and to train teachers and students in their use [12]. The primary idea of the GLOBE program is that students, inspired by appropriately trained teachers and using detailed written procedures with relatively inexpensive equipment, can provide scientifically valuable measurements of environmental parameters. Key to the success of the GLOBE project was the development of a reliable and inexpensive Sun photometer whose performance can be characterized in a way that is acceptable to the atmospheric science community. Potential applications for a globally distributed network of GLOBE Sun photometers include providing large amounts of information about background levels and seasonal variability of aerosols over large geographical areas, tracking the movement of dust clouds and volcanic aerosols, and providing ground validation data for satellite-based and automated aerosol retrievals. Hourly and daily variation of AOT at a locality is important for various applications, including satellite aerosol data validation, radiative forcing computations, public health and studies of aerosol interaction with clouds [13, 14].

The main goal of this study is to use GLOBE handheld sun photometers to track the annual, daily and hourly variation of the aerosol optical thickness of the atmosphere at our XULA study site and compare with measurements from a nearby AERONET station. This paper presents data for a 12-months period from September 2017 to August 2018. This is the first ever AOT recorded for the XULA site. The GLOBE sun photometer measures AOT at two wavelengths, 505nm and 625nm. The AERONET site at Wave CIS Site 6 measures AOT at 15 different wavelengths. For our comparison we focused on these 4 wavelengths, 667nm, 551nm, 532nm and 490nm. To make the comparison, we calculated AOT values at these wavelengths for XULA site. By building a data record that extends across several seasons, we will learn more about the variation of aerosols in our XULA site and the reliability of the GLOBE handheld sun photometers. Comparisons of automated and manual measurements provide a fascinating and extremely important check on the performance of both systems.

2. Site, Instrument and Method

2.1. Site and Meteorology

The study site is at Xavier University of Louisiana (29.96° N, 90.11° W) which is in downtown New Orleans, Louisiana, USA. The City of New Orleans is located on the Mississippi river in southeastern Louisiana. The large Lake Pontchartrain also lays within the city limits. New Orleans has a humid subtropical climate with very hot and humid summers and mild, short-lived winters. Summers in New Orleans are relatively long with high temperatures hovering around 90°F from June to September. In winter, from December to February, temperatures average between 44°F and a comfortable 62°F. New Orleans experiences high annual rainfall, most of it falling in late summer to early winter, often as a spin-off from tropical storms. Snow and ice are rarities in New Orleans, but there have been three incidences of light snowfall in the past ten years. The AERONET site is about 60 miles south of New Orleans at Wave CIS Site 6 (28.87° N, 90.48° W and 33m above sea level)

Figure1. A map of the state of Louisiana in USA showing the Study site at Xavier University of Louisiana (XULA) in New Orleans and the AERONET site at Wave CIS Site 6. The AERONET site is about 60 miles south of the XULA site.

2.2. Instrument and Method

A sun photometer is an electronic device that measures direct sunlight over a narrow range of wavelengths [15]. The GLOBE sun photometer has two channels, one of which is sensitive to green light at wavelength 505nm and the other to red light at wavelength 625nm. Green light is near the peak sensitivity of the human eye; hence, a visibly hazy sky is likely to have a large aerosol optical thickness at this wavelength. Red light is more sensitive to larger aerosols [16, 17]. The GLOBE sun photometer is an LED-based sun photometer. LEDs with smaller full-width half-maximum (FWHM) bandwidths are preferred over wider bandwidths. The FWHM bandwidth used in GLOBE sun photometers is about 75nm. The two Globe sun photometers used in this investigation were purchased from IESRE (Institute for Earth Science Research and Education. One had serial # RG8-989 and the other had serial #RG8-990.

Figure 2. The GLOBE hand held sun photometer. The GLOBE sun photometer has two channels, green light at wavelength 505nm and red light at wavelength 625nm.

Figure 2 above shows the GLOBE sun photometer. It is housed in a plastic case about 15×8×5 cm. On the top and bottom of the case, there are two alignment brackets. In use, the instrument is pointed at the sun so that light passes through the hole in the top bracket and makes a bright spot that shines on a piece of paper covering the bottom bracket. The two LED detectors in the GLOBE sun photometer respond to red or green light. When sunlight strikes one of the LEDs, it produces a very small current which is then amplified and turned into an output voltage. The output voltage is what is measured. The output voltage is affected by the concentration of particles (aerosols) in the atmosphere. The higher the concentration of aerosols, the smaller the amount of sunlight reaching the detector, and the smaller the sun photometer's output voltage. The sun photometers were calibrated using the Langley plot method [18, 19]. The Langley calibration was done by the Institute for Earth Science Research and Education (IESRE). In general, the calibration constant V_0 values of the GLOBE sun photometers vary by about 0.8% over a 10-year period [18,19]. Even though we did not recalibrate our instrument, we believe that the drift in V_0 during this one-year period is negligible.

Measurements of AOT were done every day when the weather conditions permit.

Sun photometer measurements can be interpreted properly only when the sun is not obscured by clouds. The presence of cirrus clouds in front of the sun affect sun photometer readings. It is easy to determine whether low- and mid-altitude clouds are near the sun, but cirrus clouds pose a more difficult problem. Measurements that were done when there were cirrus clouds within the vicinity of the sun were excluded in the analysis. Table #1 shows the number of days in each month that we had completely clear skies. Altogether, about 47% of the data taken was excluded.

Table#1. Shows the number of days in each month that AOT measurements were taken. On average there were about 16.1 completely clear days in each month during the 12-month period

Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Number of days	18	20	16	15	15	15	16	15	18	15	15	16

Most of our daily cloud observations are compared with NASA's cloud observation satellite. Ground observations that coincide with satellite observations receive a 'match' email which summarizes both ground and satellite observations. Overtime we became very good at accurately observing clouds. AOT measurements were done 6 times a day (7:00am, 9am, 11am, solar noon, 3pm and 5pm). The data shown on the plots are the monthly average AOT values taken at solar noon. During each measurement time; at least five values of the voltage V and the dark voltage V_{dark} are taken for each channel. These measurements are done within a time span of 10-15 minutes. The mean for these five measurements is taken as the average for that measurement time. The error in these measurements is calculated as the standard deviations of these five measurements. The accuracy of measurements made carefully with a GLOBE sun photometer are comparable to measurements made with other sun photometers [17]. Measurements taken with the GLOBE sun photometer are in units of volts. These values are then converted to AOT using the equation shown below [20]:

$$AOT = \left[\frac{ln\left({V_0}/{R}\,2\right) - ln(V - V_{dark}) - a_{R}({P}/{P_0})m}{m}\right] \quad (1)$$

V_0 is the calibration constant of sun photometer, R is the earth-sun distance expressed in astronomical units, V and V_{dark} are the measured sunlight and dark voltages from the sun photometer, a_R is the contribution to optical thickness of Rayleigh scattering of light, in the atmosphere, P is the station pressure at the time of measurement, P_0 is the standard sea level atmospheric pressure, m is the relative air mass ($m = 1/\sin\Phi$, where Φ is the solar elevation angle). The solar elevation angle is calculated using the solar elevation calculator provided by the National Oceanic and Atmospheric Administration (NOAA). In the 12-month period from September 2017 to August 2018, the solar elevation at solar noon changes by $\approx 15^0$. Other meteorological data such as temperature, surface pressure, rainfall and relative humidity were also measured at the same time. The values of V, V_{dark} and other site meteorological data were entered into the GLOBE data base to obtain the GLOBE calculated AOT values as a validation of our calculations. Equation 1 as given above includes the contributions of optical thickness from ozone. Ozone has a variable but small effect which can be calculated based on tabulated values of the ozone absorption coefficient and assumptions about the ozone amount in the atmosphere [21]. Based on this calculation ozone reduces the AOT for the 505nm channel by ≈ 0.01 and that of the 625nm channel by $\approx$ 0.03. The XULA AOT data shown here has been corrected for ozone. The contribution due to Rayleigh scattering is derived from the fundamental physics of the atmosphere. Bucholtz [22, 23] has produced tabulated values of a_R based on standard atmospheres (U.S Standard atmospheres, 1962 and 1966). For the 505nm channel $a_R \approx 0.13813$ and for the 625nm channel it is ≈ 0.05793.

3. Results and Analysis

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The GLOBE sun photometer measures AOT at λ= 505nm and λ= 625nm. The AERONET site at Wave CIS Site 6 measures AOT at 15 different wavelengths. For our comparison we focused on these 4 wavelengths of the AERONET site: 667nm, 551nm, 532nm and 490nm. To make a comparison between the two stations, we calculated AOT at 667nm, 551nm, 532nm and 490nm for the XULA site**.** This is done by calculating the XULA Angstrom coefficients and adjusting the XULA AOTs to the AERONET sun photometer wavelengths. Given AOT at two different wavelengths (λ_1=505nm and λ_2=625nm), the AOT at a third wavelength, λ_3 can be inferred for the same atmospheric conditions using the equation:

$$\tau_3 = \exp\left[\ln(\tau_1) - \ln\left(\lambda_3 / \lambda_1\right)\right] \qquad (2)$$

Where τ is the AOT, λ is wavelength in microns, and α is the Angstrom exponent. This calculation is useful when τ values determined with one instrument must be compared to values from another instrument that uses different wavelengths.

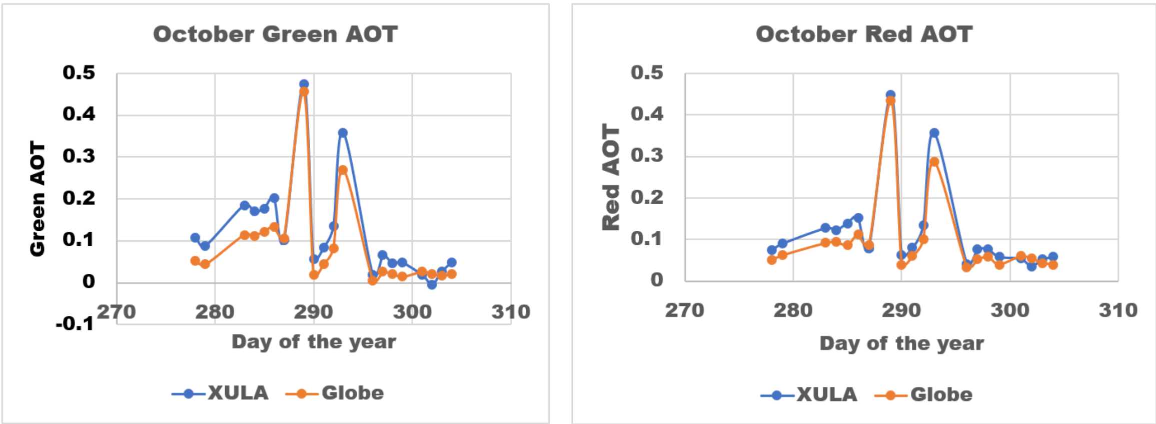

Figure 3. A sample of AOT values measured at XULA, calculated using equation 1 are compared with AOT values retrieved from GLOBE after entering the measured parameters at XULA. The figure shows data for October only. Data for the other months show the same similar agreement between our calculations and the GLOBE calculations.

Figure 3 shows a typical sample of how our calculated values of AOT (XULA) compare with the AOT calculated by Globe. We see that our values and the Globe values agree in most cases, when they differ, the difference is less than 5%. This gave us confidence that our calculations are correct.

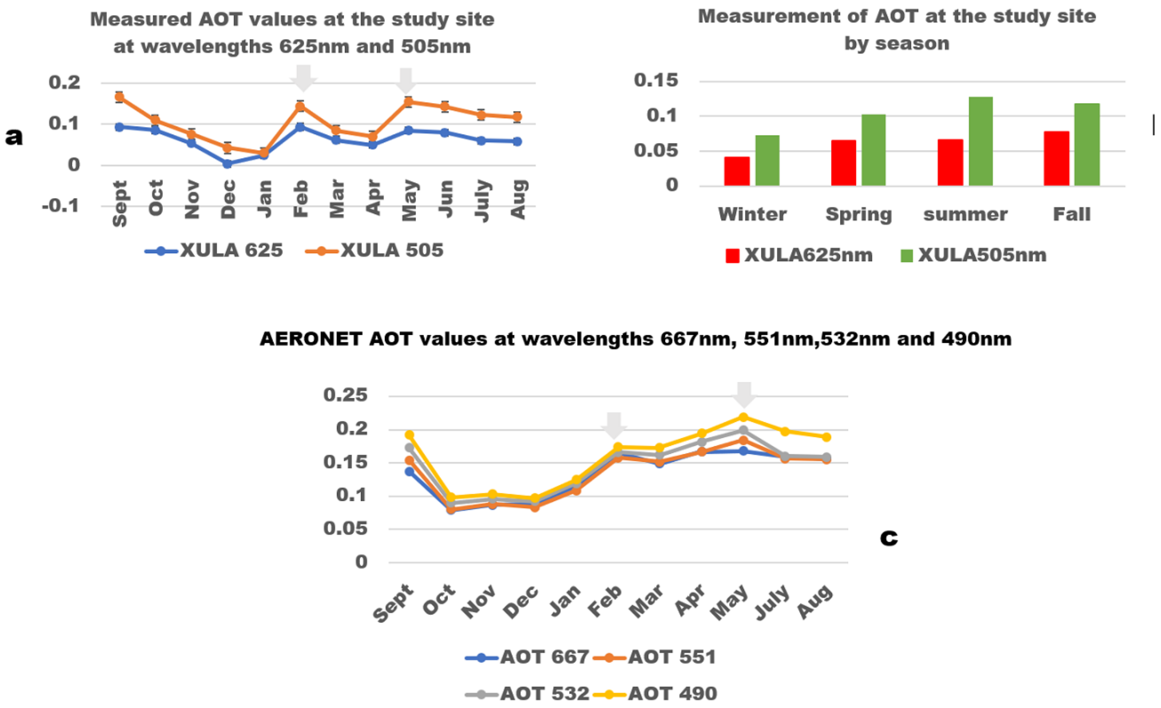

Figure 4. (a) Shows the variation of the monthly average AOT values measured at XULA over the 12-month period. AOT values were measured with two channels at wavelengths 625nm and 505nm and ozone correction was applied to this data. (b) Shows the seasonal variation of AOT at the XULA site. Seasons were categorized thus: winter (Dec, Jan, and Feb), spring (March, Apr, May), summer (Jun, July, Aug) and fall (Sept, Oct, Nov). (b) Shows monthly weighted average AOT values at the AERONET site. The AERONET data used here is classified as level 2.0. Cloud screening and ozone correction algorithms and were automatically applied to the data.

Figure 4a shows variation of the average monthly AOT measured at XULA over the 12 months period. Average ozone optical thickness corrections of -0.01 and -0.03 are applied to the 505-nm and 625-nm optical thickness values. The data shows that the AOT measured at wavelength 505nm (green light) drops continuously from September to January and then picks up in February. The AOT measured at wavelength 625nm (red light) follows a similar trend but reaches a minimum in December and starts going up for January and February. AOT measured at 505nm is higher than AOT measured at 625nm. The maximum value for green AOT is 0.176 (September) and the minimum value is 0.040 (January). For the red AOT the maximum value is 0.123 (September) and the minimum is 0.034 (December). Figure 4b shows the average AOT values per season. The seasons are categorized as follows: winter (December, January and February), spring (March, April and May), summer (June, July and August) and fall (September, October and November). Summer has the highest average AOT and winter has the lowest average AOT. High values of AOT during the summer months may be due to the warming of the earth's surface due to the high air temperatures. The warm earth increases the rate of evaporation. The drops and ice crystals that form when this water vapour freezes or condenses increases aerosols in the atmosphere. Low values of AOT in the winter months may be due to cloud scavenging and rain wash out processes as the winter months are also associated with high rainfall

Figure 4 c shows weighted monthly average AOT values obtained from the AERONET site over the same 12-month period. The AERONET data used here is classified as level 2.0. Cloud screening algorithms were automatically applied to this data. The AERONET data use climatological average modelled ozone corrections. The AERONET AOT values were measured at 667nm, 551nm, 532nm and 490nm. Comparing the XULA AOT and the AERONET AOT, we see a somewhat similar trend. Specifically, both sets of data show peaks in February and May.

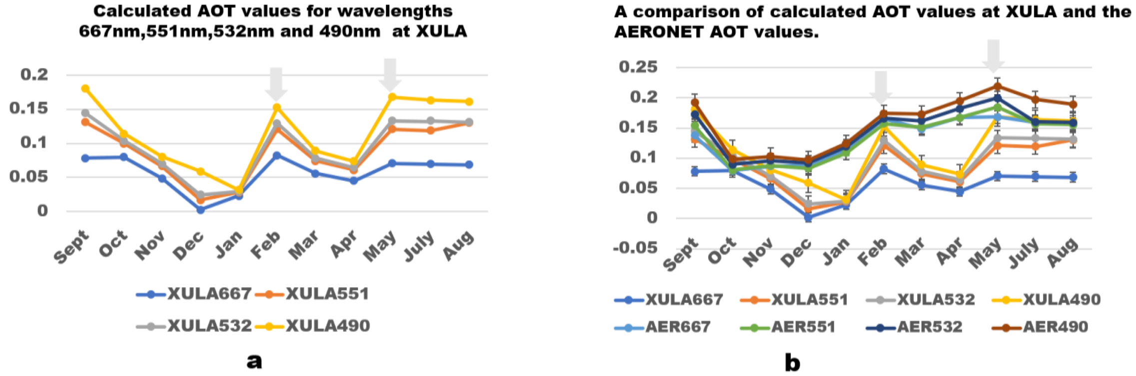

Figure 5. (a) Shows the calculated AOT at XULA. These values were calculated with the AERONET wavelengths using equation 2. (b) Shows the calculated XULA AOT compared with the AERONET AOT at the same wavelengths.

To make a more robust comparison between the XULA site and the AERONET site, we calculated AOT values at wavelengths 667nm, 551nm, 532nm and 490nm. This is done by calculating the XULA Angstrom coefficients and adjusting the XULA AOTs to the AERONET sun photometer wavelengths. Figure 5a shows the calculated AOT at XULA with the AERONET wavelengths. Figure 5b shows the calculated XULA AOT compared with the AERONET AOT at the same wavelengths. These data show good qualitative agreement but, considering the distance between the two sites, there is no justification for more quantitative comparisons. Even though we observe peaks in February and May, the average AOT for the winter and spring months are the lowest. This suggests that these peaks are due to some sporadic events. These events could be anything from smoke from forest fires and agricultural activities in neighboring states to aerosols coming from across the Gulf. There's no reason to doubt the reality of the peaks, but in retrospect it is difficult to assign a specific reason for it. However, it is reassuring that our data and AERONET data both have peaks at the same time.

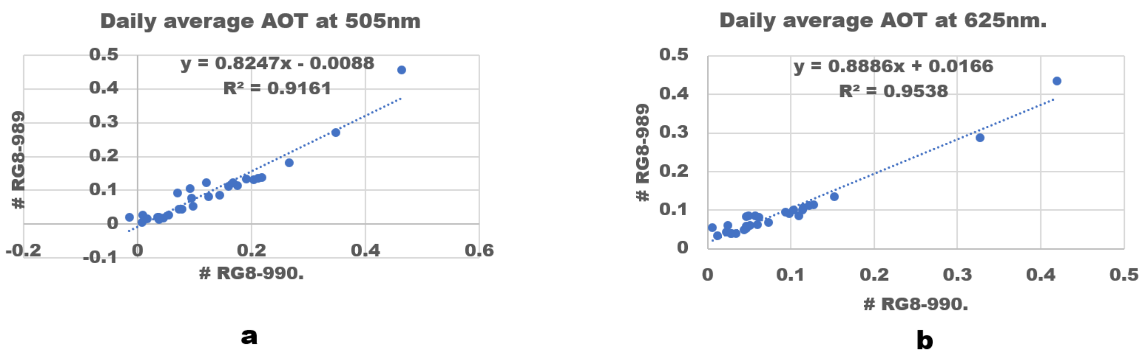

Figure 6. Two Linear regressions curve for AOT values from handheld sun photometer serial# RG-989 versus handheld sun photometer serial# RG-9990 at the XULA site. (a) 625 nm and (b) 505nm.The dotted line represents the linear equation.

Another way of checking the performance of GLOBE sun photometers is to compare independently calibrated instruments against each other. Figure 6 shows AOT data from the GLOBE sun photometer with serial #RG8-989 and another with serial #RG8-990. The figure shows that the agreement between the two sun photometers is stronger for the 505nm channel than the 625nm channel. The R-squared value for the 505nm channel is 95.3% and the slope of the linear regression line between the two sun photometers is 0.89. For the 625nm channel, R-squared is 91.6% and the slope linear regression line is 0.82. The red channel data show the effects of sunlight heating the red LED detector, which is more temperature-sensitive than the green channel. The agreement for both channels could be improved by making sure that data collectors are aware of the importance of controlling heating of the LED detectors.

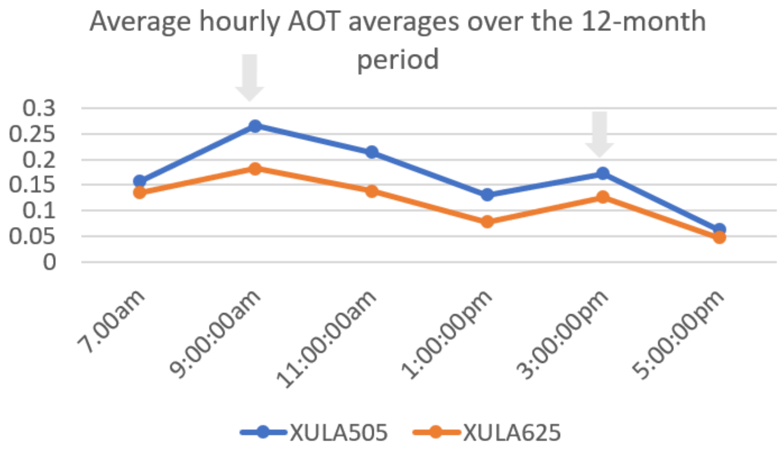

Figure 7. Diurnal variability of hourly mean values of AOT computed over the 12-month period. The time shown on the graph is local time

Figure 7 shows the hourly variation of AOT averaged over the 12-month period. Each data point is an average of 194 measurements. The daily variation is between 0.265 in the morning and 0.06 in the evening for the 505nm channel which corresponds to about 77% variation. The data shows a peak at 9:00am of 0.265 and another peak at 3:00pm of 0.182 for the 505nm channel. The 625nm channel show similar peaks. Even though these times coincide with the traffic peak hours in New Orleans, more investigations are needed to establish if the peaks are solely due to vehicle emissions.

4. Conclusions

The results presented here demonstrate that inexpensive LED based handheld sun photometers can be reliably used to measure AOT. There was good qualitative agreement between measurements done by LED based handheld sun photometers at the XULA site and the AERONET sun photometer 60 miles away. Seasonal variation of AOT at the XULA study site show on average high aerosol loading in the summer months and low aerosol loading in the winter months. The hourly variation of AOT averaged over the entire 12-month period show peaks in the morning at 9:00am and in the afternoon at 3:00pm. The authors know the data set given here is not enough to provide a sound analysis, thus the conclusions of the present study cannot be far-reaching. A much more detailed and long-term investigation of aerosol at the site is underway. This is the first ever AOT recorded for the XULA site.

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