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Measurement of Aerosols Optical Thickness of the Atmosphere using a Handheld Sun Photometer

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Corresponding Author:	Morewell Gasseller, Ph.D Xavier University of Louisiana New Orleans, Louisiana UNITED STATES
Corresponding Author's Institution:	Xavier University of Louisiana
Corresponding Author E-Mail:	mgassell@xula.edu
Order of Authors:	Morewell Gasseller, Ph.D
	Maryssa Bradley
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TITLE:

Measurement of Aerosols Optical Thickness of the Atmosphere using the GLOBE Handheld Sun Photometer

AUTHORS AND AFFILIATIONS:
Maryssa Bradley[1] and Morewell Gasseller[1]
[1]Department of Physics, Xavier University of Louisiana, USA.

Corresponding Author:
Morewell Gasseller (mgassell@xula.edu)
Tel.: +1-504-520-7644

Email Address of Co-Author:
Maryssa Bradley (mbradle6@xula.edu)

KEYWORDS:
sun photometer, aerosols, aerosol optical thickness (AOT), dark voltage, green channel, red channel.

SUMMARY:
The goal of the methods presented here is to measure aerosol optical thickness of the atmosphere. The sun photometer is pointed at the sun and the largest voltage reading obtained on an in-built digital voltmeter is recorded. Atmospheric measurements such as barometric pressure and relative humidity are also performed.

ABSTRACT:
Here, we describe the measurement of aerosol optical thickness using the GLOBE handheld sun photometer. Aerosol optical thickness (AOT) was measured at Xavier University of Louisiana (XULA, 29.96° N, 90.11° W and 3 m above sea level). The measurements were done at two different wavelengths, 505 nm and 625 nm. AOT measurements were done 6 times a day (7:00 AM, 9 AM, 11 AM, solar noon, 3 PM and 5 PM). The data shown in this paper are the monthly average AOT values taken at solar noon. During each measurement time; at least five values of the sunlight voltage V and the dark voltage V_{dark} are taken for each channel. The mean for these five measurements is taken as the average for that measurement time. Other meteorological data such as temperature, surface pressure, rainfall and relative humidity are also measured at the same time. The whole protocol is completed within a time span of 10–15 minutes. The measured AOT values at 505 nm and 625 nm are then used to extrapolate the AOT values for wavelengths 667 nm, 551 nm, 532 nm and 490 nm. The measured and extrapolated 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 33 m above sea level), which is about 96 km 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. We also compared AOT data from two independently calibrated GLOBE handheld sun photometers at the XULA site. The data show that the two instruments are in excellent agreement.

INTRODUCTION:

Atmospheric aerosols are minute solid and liquid particles (ranging from submicron to millimeter size) suspended in the air. Some aerosols are produced through human activity and others are produced by natural processes[1-4]. Aerosols in the atmosphere reduce the amount of solar energy reaching the earth's surface by scattering or absorbing light and thermal radiation from the sun. The amount of aerosol in the atmosphere varies significantly with location and time. There are seasonal and annual changes as well as episodic changes due to events such as large dust storms, wild fires or volcanic eruptions[5-8].

The impact of aerosols on the climate and on public health are among the dominant topics in current environmental research. Aerosols affect the weather by scattering or absorbing light and thermal radiation from the sun and by acting as condensation nuclei in the formation of clouds. Aerosols also play a role in the dispersal of pathogens in the air and they can cause or enhance respiratory and cardiovascular diseases. Aerosol optical thickness (AOT) is a measure of the amount of sunlight that is absorbed or scattered by these aerosols. There are several ground-based methods for monitoring AOT[9-11]. The biggest of the ground-based AOT monitoring system is the Aerosol Robotic Network (AERONET) project. AERONET is a network of over 400 monitoring stations spread all over the world[12,13]. Despite this large number of monitoring stations, there are still large gaps world-wide that are not monitored for AOT. As an example, the nearest AERONET station from our study site is about 90 km away. This paper describes the use of a portable handheld sun photometer that can be used to bridge the gaps between AERONET monitoring stations. The portable handheld sun photometer is an ideal instrument for use by students around the world in a global aerosol monitoring network[14,15]. The Global Learning and Observations to Benefit the Environment (GLOBE) program provides a platform for such a network, through thousands of schools in all the 50 states of the United States and in nearly 120 other countries[16,17]. The primary idea of the GLOBE program is to use students all over the world to provide scientifically valuable measurements of environmental parameters using inexpensive equipment. With proper guidance, students and other non-specialist can form networks of handheld sun photometers to fill the gaps between the AERONET monitoring stations. The biggest advantage of the handheld sun photometer is that it can be taken to even the remotest parts of the world. AOT measurements with other small and transportable instruments have been successfully used in the past to carry out research studies in remote and hard to access areas[17-18]

The main goal of this study is to use the GLOBE handheld sun photometers to track the annual, daily and hourly variation of AOT 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, 505 nm and 625 nm. The AERONET site at Wave CIS Site 6 measures AOT at 15 different wavelengths. For our comparison we focused on these 4 wavelengths, 667 nm, 551 nm, 532 nm and 490 nm. We chose these because they are the 4 AERONET wavelengths nearest to the GLOBE sun photometer wavelengths. To make the comparison, we extrapolated AOT values at these wavelengths for XULA site.

Measurements of AOT are done every day when the weather conditions permit. Measurements that are done when there are cirrus clouds within the vicinity of the sun are 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.

[Place **Table 1** here]

AOT measurements were done 6 times a day (7:00 AM, 9 AM, 11 AM, solar noon, 3 AM, and 5 AM). 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 sunlight voltage V and the dark voltage V_{dark} are taken for each channel. 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. AOT values are obtained using the equation shown below[16]:

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

V_0 is the calibration constant of the sun photometer, R is the earth-sun distance in astronomical units, V_{dark} is the dark voltage recorded when light is blocked from passing through the hole on the top bracket of the sun photometer, V is the sunlight voltage recorded from the sun photometer when light passes through the hole on the top bracket, a_R represents the attenuation of light due to Rayleigh scattering, P and P_0 are the measured and standard atmospheric pressure, respectively, and m is the relative air mass. The relative air mass is calculated from data provided by the National Oceanic and Atmospheric Administration (NOAA). Other meteorological data such as temperature, rainfall and relative humidity are also measured at the same time. Equation 1 as given above includes the contributions of optical thickness from ozone. The effect of ozone on AOT values is calculated based on tabulated values of the ozone absorption coefficient and assumptions about the ozone amount in the atmosphere[19]. Bucholtz[20, 21] has produced tabulated values of a_R based on standard atmospheres. For the 505 nm channel $a_R \approx 0.13813$ and for the 625 nm channel it is ~0.05793.

The data presented here represents an example of how teams of students can be organized to take long and sustained AOT measurements. In this study, two student teams used two independently calibrated 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. The two Globe sun photometers used in this investigation were purchased from the IESRE (Institute for Earth Science Research and Education; one had serial number RG8-989 and the other had serial number RG8-990). Before the data from the two instruments could be combined, a regression analysis was carried out to ascertain the agreement

PROTOCOL:

1. Photometer operation

NOTE: These protocols are best done by two people working together. One person holds and aligns the sun photometer while the second person record the measurements.

1.1. Measure the longitude and latitude for the site using GPS. At the site, the first step is to activate the GPS by choosing sensor set-up from the sensor menu and select GPS. Once GPS has acquired enough satellites, latitude and longitude values will be displayed. Once values are displayed press collect data and then press save.

1.2. Make sure the sun photometer is working well. A properly calibrated sun photometer should produce a stable voltage of ~ 0.03 V indoors and up to 5 V when light is directed on the detector. The voltmeter on the Globe sun photometer is in-built on the sun photometer

1.3. Record the air temperature. If using an alcohol in glass thermometer, give the thermometer 3–5 minutes to adjust to the outside temperature before recording the stable reading. If using the sun photometer's in-built thermometer, turn the rotary switch to T and record the voltage reading on the voltmeter. The voltage reading multiplied by the 100 will give the air temperature in degrees Celsius at that time.

1.4. Set the rotary switch to the green channel of the sun photometer.

1.5. Have one person align the sun photometer so that light passing through the hole on the top bracket produces a sunlight spot centered over the colored dot on the bottom bracket. For best results, use a table and a chair. The person aligning the sun photometer should sit on the chair and rest his/her arms on the table in order to obtain a steady reading.

1.6. Have the second person record the reading on the voltmeter. Make sure the sun spot is stable on the dot before taking a reading. If voltage reading is fluctuating, just record the maximum value shown.

1.7. Record the time at which the reading was taken. Time must be recorded to the nearest 30 seconds. A digital watch serves this purpose better than an analogue one.

1.8. Obtain the dark voltage. Have the person sitting down keep the sun photometer aligned to the sun with one hand and then cover the hole on the top bracket with a finger from the other hand. The second person will record the voltage reading.

1.9. Set the rotary switch to the red channel and repeat steps 1.4–1.7.

1.10. Repeat steps 1.4–1.8 four more times to obtain five voltages readings for the green channel and five voltage readings for the red channel

1.11. Measure the air temperature again as in step 1.2.

2. Collection of metadata

2.1. Use the Globe cloud chart to observe and record the clouds near the sun. This is done by looking into the sky and checking off observed features from the GLOBE cloud chart (https://www.globe.gov/documents/348614/24331082/GLOBE+Cloud+Chart.). Visible cirrus clouds are easy to observe because of their characteristic thin wispy strands. Invisible cirrus clouds are inferred if the sunlight voltage reading on an apparently clear day is less than 0.5 V.

2.1.1. Use a hygrometer to measure and record the relative humidity: Hold the hygrometer with an extended arm away from the body, leave it in the air for about 3 minutes, and then take the dry bulb reading first followed by the wet bulb reading. Find the difference in the two readings and use the relative humidity chart to establish the relative humidity

2.1.2. Use a barometer to measure and record atmospheric pressure.

2.2. Calculate AOT by plugging the measured values and the constants into Equation 1 given above.

3. Temperature regulation

NOTE: The electronics of the sun photometer are sensitive to temperature. For optimal performance, the following steps are recommended.

3.1. If outside temperature is more than 5 degrees below room temperature, keep the sun photometer wrapped in thermal foam when not in use.

3.2. When taking measurements during the hot summer months, keep the sun photometer in the shade when not in use.

REPRESENTATIVE RESULTS:

The GLOBE sun photometer measures AOT at λ= 505 nm and λ= 625 nm. 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: 667 nm, 551 nm, 532 nm and 490 nm. To make a comparison between the two stations, we extrapolated AOT at 667 nm, 551 nm, 532 nm and 490 nm for the XULA site**.** This is done using the XULA site's Angstrom coefficients. For any given site and instrument, the optical thickness τ, the wavelength λ, and the atmospheric turbidity coefficient β are connected through Angstrom's turbidity formula

$$\tau = \beta\lambda^{-\alpha} \qquad (2)$$

Where α is the Angstrom's exponent. α and β are independent of the wavelength at which the optical thickness is measured. They are parameters that describe the atmosphere being measured. Given AOT at two different wavelengths (λ_1 = 505 nm and λ_2 = 625 nm, for our sun photometer), and the measured AOT (τ_1 and τ_2), the Angstrom exponent α for the XULA site is calculated from the equation,

$$\alpha = ln\left({}^{\tau_1}/_{\tau_2}\right)/ln\left({}^{\lambda_2}/_{\lambda_1}\right) \quad (3)$$

The AOT (τ_3) at a third wavelength, λ_3 can be extrapolated for the same XULA atmospheric conditions using the equation:

$$\tau_3 = \exp\left[\ln(\tau_1) - \ln\left({}^{\lambda_3}/_{\lambda_1}\right)\alpha\right] \quad (4)$$

τ_1 and λ_1 can be replaced with τ_2 and λ_2 in equation 4 to get the same value for τ_3. This calculation is used to compare τ values obtained by two instruments that uses different wavelengths. Ideally the two instruments must be used at the same locality. In our case it must be noted that the two instruments were ~ 96 km apart.

[Place **Figure 1** here]

Figure 1 shows a sample of the typical daily average AOT values calculated using equation 1. This figure shows the AOT data for both the green and the red channels of the GLOBE sun photometer for the month of October.

[Place **Figure 2** here]

Figure 2a 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 were applied to the 505 nm and 625 nm optical thickness values, respectively. The data shows that the AOT measured at wavelength 505 nm (green light) dropped continuously from September to January and then peaked up in February. The AOT measured at wavelength 625 nm (red light) followed a similar trend but reached a minimum in December and started going up for January and February. AOT measured at 505 nm is on average higher than AOT measured at 625 nm. **Figure 2b** shows the average AOT values per season. The seasons were 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 had the highest average AOT and winter had 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 vapor 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.

[Place **Figure 3** here]

To make a comparison between the XULA site and the AERONET site, we extrapolated AOT values at wavelengths 667 nm, 551 nm, 532 nm and 490 nm for the XULA site. This was done using equation 3 above. **Figure 3a** shows the extrapolated AOT at XULA for the wavelengths 667 nm, 551 nm, 532 nm and 490 nm. **Figure 3b** shows the measured 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 observed peaks in February and May, the average AOT for the winter and spring months were the lowest. This suggests that these peaks are due to some random events. These events could be anything from smoke from forest fires and agricultural activities in neighboring states to aerosols coming from across the Gulf of Mexico. It requires measurements for many seasons to be definitive about the cause of the AOT peaks in May and February.

[Place **Figure 4** here]

We checked the reliability of the GLOBE sun photometers by comparing two independently calibrated instruments against each other. **Figure 4** shows AOT data from the GLOBE sun photometer with serial number RG8-989 and another with serial number RG8-990. The figure shows that the agreement between the two sun photometers is stronger for the 505 nm channel than the 625 nm channel. The R-squared value for the 505 nm (green) channel was 95.3% and the slope of the linear regression line between the two sun photometers was 0.89. For the 625 nm (red) channel, R-squared was 91.6% and the slope linear regression line was 0.82. The agreement on the red channel is lower because of the effects of heating on the red LED. The red LED is more sensitive to temperature than the green LED. Agreement for both channels is improved when data collectors control the exposure of the instrument to direct sunlight between measurements.

[Place **Figure 5** here]

Figure 5 shows the hourly variation of AOT averaged over the 12-month period. Each data point was an average of 194 measurements. The daily variation was between 0.265 in the morning and 0.06 in the evening for the 505 nm channel, which corresponds to about 77% variation. The data shows a peak at 9:00 AM of 0.265 and another peak at 3:00 PM of 0.182 for the 505 nm channel. The 625 nm channel showed similar peaks. Even though these times coincided with the traffic peak hours in New Orleans, more investigations are needed to establish if the peaks are solely due to vehicle emissions.

FIGURE AND TABLE LEGENDS:

Figure 1: A sample of the daily average AOT values for the red and green channels measured at XULA, calculated using equation 1. The figure shows data for the month of October only.

Figure 2: **Seasonal variation of AOT.** (**a**) Variation of the monthly average AOT values measured at XULA over the 12-month period. AOT values were measured at wavelengths 625 nm and 505 nm. Ozone correction was applied to this data. The error bars show the standard deviation of the five measurements taken for each measurement time. The arrows show the AOT peaks in February and in May. (**b**) Seasonal variation of AOT at the XULA site. Seasons were categorized thusly: winter (Dec, Jan, and Feb), spring (March, Apr, May), summer (Jun, July, Aug) and fall (Sept, Oct, Nov).

Figure 3: **Comparison between XULA and AERONET.** (**a**) Extrapolated AOT at XULA. These AOT values were extrapolated for 4 wavelengths (667 nm, 551 nm, 532 nm and 490 nm) using equation 3. (**b**) AERONET AOT at the same wavelengths. The AERONET data used here is classified as level 2.0. Cloud screening and ozone correction algorithms and were automatically applied to the data. The error bars in panel b are based on the minimum uncertainty of 0.02 AOT units for the level 2.0 AERONET data[25]. The arrows show the AOT peaks in February and in May for both (a) and (b).

Figure 4: **Linear regressions curves for AOT values from two different handheld sun photometers at the XULA site.** Serial numbers RG-989 and RG-9990. (**a**) 625 nm and (**b**) 505 nm.

Figure 5: **Diurnal variability of hourly mean values of AOT computed over the 12-month period.** The time shown on the graph is local time.

DISCUSSION:

The first step in this protocol is to define the study site. This is done by using a GPS to find the longitude and latitude of the study site. The longitude and latitude values are critical in the calculation of AOT using equation 1. During measurement, it is crucial that the sun photometer is pointed directly and firmly at the sun. The tiny hole at the top bracket of the handheld sun photometer reduces the amount of scattered light reaching the LED detectors in the sun photometer. Equation 1 is an approximation that assumes that no scattered light passes through the hole at the top bracket. If the sun photometer is aligned properly, the error introduced by this assumption is negligible compared to other sources of error in the measurement[22-24]. The LEDs in the sun photometer are sensitive to extreme temperatures. During the hot summer months, the sun photometer must be kept in the shade when not in use. During the cold winter months, the sun photometer must be wrapped in protective thermal cloth between measurements. In extremely cold environments, thermal protection must be used throughout the measurements. When operating normally, the sun photometer should read a few millivolts in the dark and between 1.0 V and 3.0 V when directly pointed at the sun. Measurements with the sun photometer are reliable when the sun is clear of any clouds. Wearing sunglasses with an auburn tint will help to detect faint clouds which are otherwise invisible to the necked eye[25, 26].

The AOT calculated from equation 1 must be corrected for ozone contribution to AOT. This is done by subtracting ~0.01 and ~0.03 from the AOT values calculated for the green and red channels respectively[22]. When these protocols are carefully followed, the accuracy should be ~ 0.02 AOT units. This level of accuracy allows us to ignore any contributions to AOT due to water vapor absorption. The protocols given above are simple and can be followed by students from middle school to college level. The handheld sun photometer uses LEDs which are inexpensive and are easily obtained from electronic shops. The instrument itself is robust and does not need special care.

At present there are over 400 AERONET monitoring stations around the world, but even these are not enough to cover the whole planet. Handheld sun photometers, using the protocols described here can be used to bridge the gaps left out by AERONET. The thousands of schools around the globe can be organized to form a network of ground-based monitoring stations that are much closer to each other than the AERONET stations[27-28]. The handheld sun photometer with the given protocols can also be used to validate current and future space-based aerosol monitoring platforms.

One of the limitations of the protocols given here is that the alignment with the sun is done manually, which is susceptible to human errors. There are also limitations brought about by the design of the LED based handheld sun photometer. The bandwidth (FWHM) for the LED detectors is ~75 nm which could cause errors in the measurement. The other challenge with the given protocols is to organize student teams so that data is collected continuously and on a regular basis. Students can be motivated to collect data by giving them some credit towards their final grade.

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DISCLOSURES:

The authors declare no conflict of interest.

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Figure5

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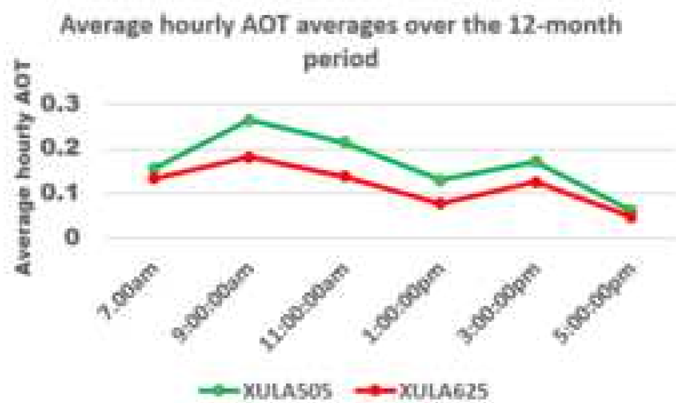

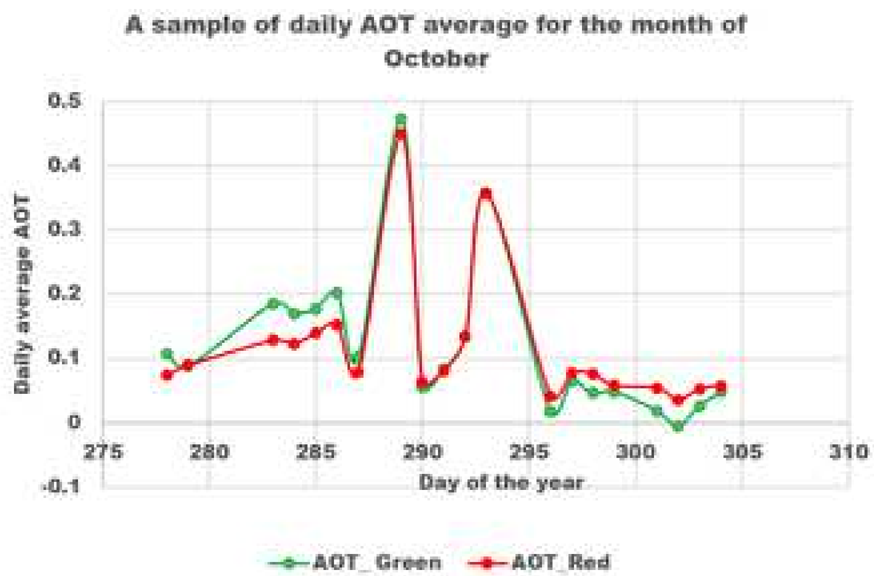
A sample of daily AOT average for the month of October
Daily average AOT
0.5
0.4
0.3
0.2
0.1
0
-0.1
275
280
285
290
295
300
305
310
Day of the year
AOT_ Green
AOT_Red

Figure

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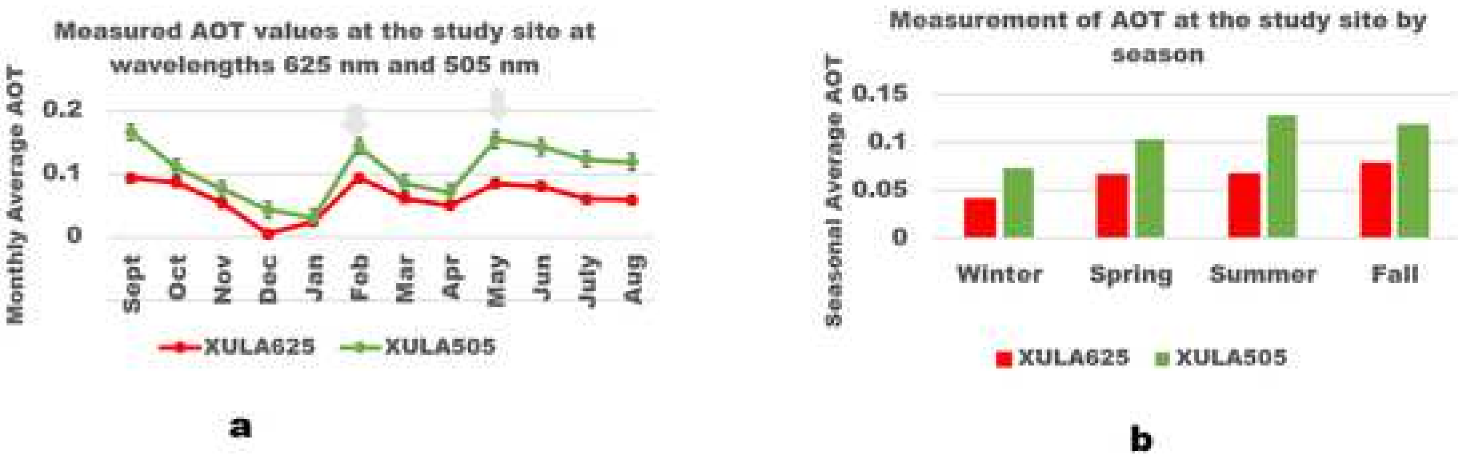
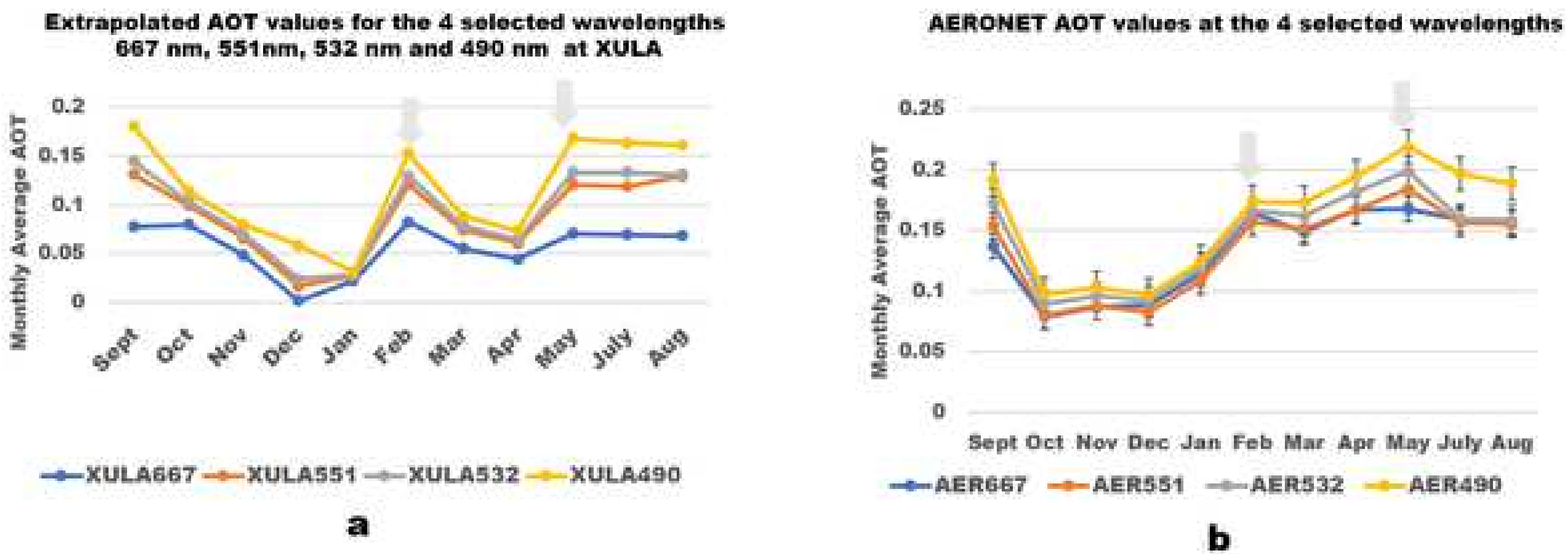
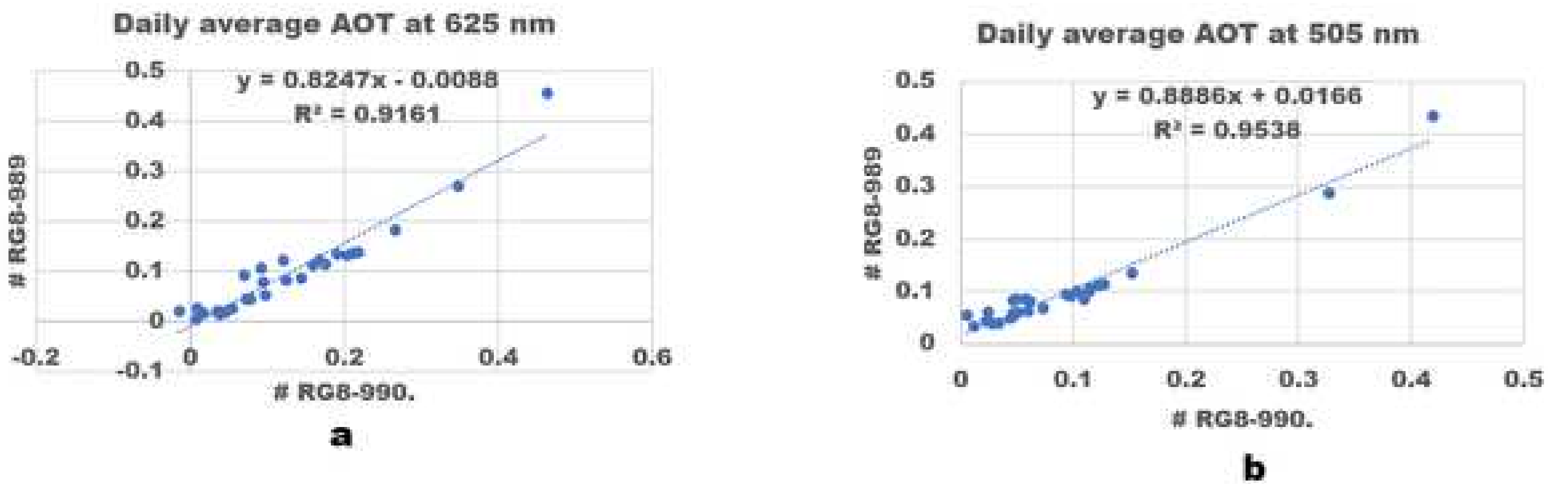



Extrapolated AOT values for the 4 selected wavelengths 667 nm, 551nm, 532 nm and 490 nm at XULA
Monthly Average AOT
0.2
0.15
0.1
0.05
0
Sept Oct Nov Dec Jan Feb Mar Apr May July Aug
XULA667 XULA551 XULA532 XULA490
a
AERONET AOT values at the 4 selected wavelengths
Monthly Average AOT
0.25
0.2
0.15
0.1
0.05
0
Sept Oct Nov Dec Jan Feb Mar Apr May July Aug
AER667 AER551 AER532 AER490
b


Daily average AOT at 625 nm
y = 0.8247x - 0.0088
R² = 0.9161
# RG8-989
# RG8-990.
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0
0.2
0.4
0.6
a
Daily average AOT at 505 nm
y = 0.8886x + 0.0166
R² = 0.9538
# RG8-989
# RG8-990.
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
b

Month	Sept	Oct	Nov	Dec
Number of Days	18	20	16	15

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
15	15	16	15	18	15	15	16

Name of Material/ Equipment	Company
A Calibrated GLOBE handheld sun photometer	IESRE, USA (GLOBE sun photometer) and TERNUM, UK (Calitoo sun photometer
Barometer	Forestry suppliers, USA, Cat# 43316
GLOBE cloud chart	Forestry Suppliers, USA Cat#33485
Hygrometer	Forestry suppliers, USA, Cat# 76254
Labquest2 GPS	Vernier, USA, Cat LABQ2
Taylor Orchid Thermometer	Forestry Suppliers, USA Cat# 89129
Watch	Forestry suppliers, USA, Cat# 39137

Catalog Number
43316
33485
76245
LABQ2
89129
39137

Comments/Description

The GLOBE sun photometer measures AOT at 505nm and 625nm.

The aneroid barometer must have a clear scale with a pressure range between 940 and 1060 millibars.
A free cloud identification chart is obtained from www.globe.gov.
Any digital hygrometer which measures relative humidity in the range of 20-95% with an accuracy of 5% is acceptable.
Vernier LabQuest 2 is a standalone interface used to collect sensor data with its built-in graphing and analysis application. GPS is one of its bu

The watch must be digital and capable of measuring time up to seconds.

ılt-in sensors

ALA

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Author(s): Maryssa Bradley and Morewell Gasseller

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CORRESPONDING AUTHOR: Morewell Gasseller

Name:

Department: Physics & Computer Science

Institution: Xavier University of Lousiana

Article Title: Measurement of Aerosol Optical thickness of atmosphere using handheld sun photometers

Signature: MGasseller Date: 10/15/18

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Rebuttal

Editorial comments:

General:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.

The manuscript was proofread by 3 other people.

2. Please ensure that the manuscript is formatted according to JoVE guidelines–letter (8.5” x 11”) page size, 1-inch margins, 12 pt Calibri font throughout, all text aligned to the left margin, single spacing within paragraphs, and spaces between all paragraphs and protocol steps/substeps.

Manuscript was formatted according to the guidelines given above.

3. Please revise lines 93-97, 160-162, and 216-219 to avoid overlap with previous work.

Lines 93-97 has been rephrased as: V_0 is the calibration constant of the sun photometer, R is the earth-sun distance in astronomical units, V_{dark} is the dark voltage recorded when light is blocked from passing through the hole on the top bracket of the sun photometer, V is the sunlight voltage recorded from the sun photometer when light passes through the hole on the top bracket, a_R represents the attenuation of light due to Rayleigh scattering, P and P_0 are the measured and standard atmospheric pressure respectively and m is the relative air mass.

160-162 has been rephrased as: τ_1 and λ_1 can be replaced with τ_2 and λ_2 in equation 3 to get the same value for τ_3. This calculation is used to compare τ values obtained by two instruments that uses different wavelengths. Ideally the two instruments must be used at the same locality. In our case it must be noted that the two instruments were ~ 96 km apart.

216-219 has been rephrased as: The agreement on the red channel is lower because of the effects of heating on the red LED. The red LED is more sensitive to temperature than the green LED. Agreement for both channels is improved when data collectors control the exposure of the instrument to direct sunlight between measurements.

Summary:

1. Please revise the summary to be 10-50 words long.

Summary is reduced to 47 words.

Protocol:

1. There should be at least 1 page of filmable steps in the protocol section; please expand this (see below).
2. Please add more details to your protocol steps. Please ensure you answer the “how” question, i.e., how is the step performed, including specific software/hardware steps.

Alternatively, add references to published material specifying how to perform the protocol action. If revisions cause a step to have more than 2-3 actions and 4 sentences per step, please split into separate steps or substeps.

More "how to" details were added to the protocol section.

Figures, Tables, and Figure Legends:
1. Please upload each Figure individually to your Editorial Manager account as a .png or a .tiff file (i.e., 6 files in total). Please combine all panels of one figure into a single image file.

All the images have been saved as TIFF with a resolution 1920 x 1080 pixels.

2. Please remove the embedded figures and table from the manuscript. All figures should be uploaded separately to your Editorial Manager account. Each figure must be accompanied by a title and a description after the Representative Results of the manuscript text.

All embedded figures and tables have been removed from the manuscript and will be uploaded separately. The title and description are given after representative results.

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We have no figures from previous publications.

4. Please remove 'Figure 1' etc. from the Figures themselves.

Figure labels have been removed from the TIFF figure files.

5. Please define error bars and arrows in the Figure legends.

Error bars and the arrows have been defined in the figure legends.

6. Figure 1: It's unclear what this demonstrates separately from what would be presented in the video-either remove or clarify.

Figure 1 was removed from the manuscript

7. Figure 3: Please explicitly explain panel c in the legend.

Panel c was removed from figure 3 since the same data is shown in figure 4.

8. Figure 3b: Please include a label for this panel. Also, please capitalize 'summer'.

Figure 3b is now clearly labelled and summer is capitalized.

Discussion:
1. As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3–6 paragraphs with citations:
a) Critical steps within the protocol
b) Any limitations of the technique

Discussion is rewritten.

References:
1. Please do not abbreviate journal titles.

Journal titles are written in full in the reference section.

Table of Materials:
1. Please ensure the Table of Materials has information on all materials and equipment used, especially those mentioned in the Protocol.

All materials and equipment used are included in the Table of materials.

Reviewers' comments:

Reviewer #1:
Manuscript Summary:
The manuscript provides nice and simple instructions how to measure the AOT without high end equipment. The titel appropriately describes the method presented. The abstract has a nice length and provides a nice overview of the paper. The introduction describes the presented method and explains why the presented method can be useful. The steps in the protocol are clearly explained and the results are reasonable. The results show the magnitude of the deviations to expect from a nearby AERONET station.

There are some suggestions how to further improve this paper, below:

Introduction:
Provide motivation why to measure AOT? (Health, meteorology), Why do you focus on these four wavelengths (667 nm, 551 nm, 532 nm, 490 nm)?

The following statements were added into the introduction:

The impact of aerosols on the climate and on public health are among the dominant topics in current environmental research[24]*. Aerosols affect the weather by scattering or absorbing light and thermal* *radiation from the sun and by acting as condensation nuclei in the formation of clouds. Aerosols also play a role in the dispersal of pathogens in the air and they can cause or enhance respiratory and cardiovascular diseases.*

For our comparison we focused on these 4 wavelengths, 667 nm, 551 nm, 532 nm and 490 nm. We chose these because they are the 4 AERONET wavelengths closest to the GLOBE sun photometer wavelengths. To make the comparison, we extrapolated AOT values at these wavelengths for XULA site.

What make the wavelengths 505 nm and 625 nm suitable for this?

Generally, sun photometry is based on single wavelengths. Filter-based photometers have very narrow response bandwidth (~few nanometers). The GLOBE sun photometer is an LED based sun photometer. LED response bandwidths are typically several tens of nanometers. 505nm and 625nm were chosen because the LEDs for these wavelengths have the smallest bandwidths. Other than that there is no particular reason to select these particular colors.

Protocol:
Please clarify whether the voltmeter is a part of the photometer or it is a separate part which has the be manually connected to the photometer (the second sentence in the summary might be read this way)

The following statement was added to the to the protocols section:

The voltmeter on the Globe sun photometer is in-built on the sun photometer.

12 A: please describe the way clouds near the sun are recorded in more detail.

Results:
Please add a y axis label to all the plots

Figure 2: please make the description of this plot more clear. What does "calculated by Globe" mean? This can easily be mixed up with the measured data., because it is measured with the "GLOBE" photometer.
In Figure 3, the "b" is cropped

Protocol step 12A was rephrased to:

Use the Globe cloud chart to observe and record the clouds near the sun. This is done by looking into the sky and checking off observed features from the GLOBE cloud chart. Visible cirrus clouds are easy to observe because of their characteristic thin wispy strands. Invisible cirrus clouds are inferred from unexpected voltage readings on the sun photometer.

Figure 2 has been modified and the description clarified, it now shows the daily variation of AOT for the red channel and the green channel for the month of October. The cropped part of Figure 3 has been corrected

Table of materials:
Please include a GPS
Parts of the description of the "Watch" are missing.

Labquest2 GPS has been included in the Table of materials and the description on the watch has been corrected

Reviewer #2:
Manuscript Summary:
The manuscript describes a method to monitor aerosol extinction (in terms of AOT) in the visible spectral range using a low-cost hand-held instrument (a sun photometer). The protocol is in principle useful, as it is part of large-scale student project.

Major Concerns:
The manuscript is poorly written, with a systematic incorrect terminology. This must be addressed during the revision stage of the manuscript. A sample dataset obtained with this method is compared with more established automated AOT measurements from a global network; by the way, this comparison is not acceptable, in my opinion, because the validation observatory is too far from the sun photometer site - and in fact the validation results are not good. Mathematical formalism and a few aspects in AOT calculations must be clarified (see Minor Concerns).

The mathematical formalism for comparing AOT values obtained from two different instruments is given in detail below. We added a few of these details into the manuscript.

Wavelength, optical thickness, and atmospheric turbidity are related through Angstrom's turbidity formula:

$$\tau = \beta \cdot \lambda^{-\alpha} \qquad (2)$$

where τ is the optical thickness, β is Angstrom's turbidity coefficient, λ is wavelength and α is the Angstrom exponent. α and β are independent of wavelength and they are properties of the atmosphere being measured. For two different wavelengths,

$$\tau_1 = \beta \cdot \lambda_1^{-\alpha}$$
$$\tau_2 = \beta \cdot \lambda_2^{-\alpha}$$

from which we get

$$\tau_1/(\lambda_1^{-\alpha}) = \tau_2/(\lambda_2^{-\alpha})$$

Solving for α:

$$\alpha = \ln(\tau_1/\tau_2)/\ln(\lambda_2/\lambda_1) \qquad (3)$$

From the two τ equations above we can solve for β

$$\beta = \tau_1 \bullet \lambda_1^{\alpha} = \tau_2 \bullet \lambda_2^{\alpha}$$

Given τ at two different wavelengths, the τ at a third wavelength can be deduced for the same atmosphere.

$$\ln(\lambda_3/\lambda_1)\, \alpha = \ln(\tau_1/\tau_3) = \ln(\tau_1) - \ln(\tau_3)$$
$$\ln(\tau_3) = \ln(\tau_1) - \ln(\lambda_3/\lambda_1)\alpha$$

$$\tau_3 = \exp[\ln(\tau_1) - \ln(\lambda_3/\lambda_1)\, \alpha] \qquad (4)$$

This analysis is used for a rigorous comparison of AOT values obtained by two instruments that uses different wavelengths. Ideally the instruments should be at the same locality. In our case the two instruments are ~90km apart. Thus, at this stage our data can only be used for basic analysis and trend comparison as we did.

Minor Concerns:
1) Title: Please provide a more specific title (e.g., "...using a GLOBE handheld sun photometer"), as this protocol is specific to this sun photometer. Same in the Abstract: please mention the photometer type.

The title was changed to "Measurement of Aerosols Optical Thickness of the Atmosphere using the GLOBE Handheld Sun Photometer" and the GLOBE sun photometer is specifically mentioned in the abstract.

2) L41: "Microscopic": Aerosols size span submicron to millimeters

L41 was changed to "Atmospheric aerosols are minute solid and liquid particles (ranging from submicron to millimeters) suspended in the air".

3) L44: "Light...": and thermal radiation

Line 44 was changed to "Aerosols in the atmosphere reduces the amount of solar energy reaching the earth's surface by scattering or absorbing light and thermal radiation from the sun".

4) L45: "Arbitrary": that's not "arbitrary" of course, maybe "episodic"

Line 45 was changed to "There are seasonal and annual changes as well as episodic changes due to events such as large dust storms, wild fires or volcanic eruptions"[5-8].

5) L47: "Sunlight...": it depends on the spectral region. AOT in the UV/VIS mesures "sunlight extinction" while AOT in the TIR measures "thermal radiation extinction"

The GLOBE sun photometer is an LED based sun photometer. The green LED spectral response ranges from 400nm-575nm and the red LED spectral response ranges from 575nm-675nm. Thus they measure sunlight extinction in the Visible range.

6) L52: "Miles...": please use SI units

The unit miles were changed to km throughout the manuscript.

7) L53-54: Being "handheld", so requiring a continuous human non-automatic operation, this is a strong statement that must be mitigated

AOT measurements are done 6 times a day. Unlike an automatic operation like AERONET, students observe the sky and make a decision on whether to accept the measurement or to disregard it.

8) L64: I recommend to mention that other, more precise handheld sunphotometers have been used in the past to carry out research studies, e.g. in areas of difficult access, for exemple: Sellitto, P., G. Salerno, A. La Spina, T. Caltabiano, L. Terray, P.-J. Gauthier, and P. Briole (2017), A novel methodology to determine volcanic aerosols optical properties in the UV and NIR and Ångström parameters using Sun photometry, J. Geophys. Res. Atmos., 122, 9803-9815, doi:10.1002/2017JD026723.

This line was added at L64: AOT measurements with small and transportable handheld sun photometers have been successfully used in the past to carry out research studies in remote and hard to access areas[17]

9) L79-80: How cirrus clouds are detected?

Visible cirrus clouds are easy to observe because of their characteristic thin wispy strands. Invisible cirrus clouds are inferred from unexpected voltage readings on the sun photometer. As part of our Advanced Earth Science Class, students observe clouds on a daily basis using the GLOBE cloud protocol. All our daily cloud observations are compared with NASA's cloud observation satellites. Observations that coincide with satellite observations receive a 'match' email which summarizes both ground and satellite observations. Overtime students became very experienced in cloud observations and in many cases their observations and the NASA satellite observation matched.

10) Eq1: How Rayleigh scattering-related optical depth is calculated?

The contribution to AOT due to Rayleigh scattering is derived from the fundamental physics of the atmosphere. Bucholtz [21] produced tabulated values of a_R based on standard atmospheres at sea level and has given analytical representations for those tabulations in the form

$$a_R = A\lambda^{-(B+C\lambda+D/\lambda)}$$

Where λ is specified in microns and A, B, C and D are coefficients obtained in the standard atmosphere table. For the red channel $a_R \approx 0.05793$ and for the green channel it is ≈ 0.13813.

11) How ozone-related optical depth is calculated?

The contribution to AOT due to ozone is calculated using climatological and latitude-dependent average ozone values. Satellite-based instruments such as Total Ozone Mapping Spectrometer (TOMS) are sources of such data. For the GLOBE handheld sun photometer, a typical ozone contribution to non-Rayleigh optical thickness is ~0.01 for green channel and ~0.03 for the red channel. (Ref 22).

12) L100-101: I don't understand this sentence, please explain

Line 100-101 was removed from the manuscript.

13) Eq2: Where is tau2 and lambda2 in this equation? How do you calculate alpha?

For clarity, that part of the manuscript was expanded as follows:

To make a comparison between the two stations, we extrapolated AOT at 667nm, 551 nm, 532 nm and 490 nm for the XULA site. This is done using the XULA site's atmospheric parameters. For any given site and instrument, the optical thickness τ, the wavelength λ and the atmospheric turbidity coefficient β are connected through the Angstrom's turbidity formula

$$\tau = \beta\lambda^{-\alpha} \qquad (2)$$

Where α is the Angstrom's exponent. α and β are independent of the wavelength at which the optical thickness is measured. They are parameters that describe the atmosphere being measured. Given AOT at two different wavelengths (λ_1=505 nm and λ_2=625 nm, for our sun photometer), and the measured AOT (τ_1 and τ_2), the Angstrom exponent α for the XULA site is calculated from the equation,

$$\alpha = ln\left({}^{\tau_1}/_{\tau_2}\right)/ln\left({}^{\lambda_2}/_{\lambda_1}\right) \qquad (3)$$

The AOT (τ_3) at a third wavelength, λ_3 (λ_3 being any of the 4 wavelengths of the AERONET site) can be extrapolated for the same XULA atmospheric conditions using the equation:

$$\tau_3 = \exp\left[\ln(\tau_1) - \ln\left({}^{\lambda_3}/_{\lambda_1}\right)\alpha\right] \qquad (4)$$

τ_1 and λ_1 can be replaced with τ_2 and λ_2 in equation 3 to get the same value for τ_3. This calculation is used to compare τ values obtained by two instruments that uses different wavelengths.

14) L164-165: I don't understand here: XULA is a site and Globe is an instrument? What are the different series in the comparisons of Fig2?

L164-165 was replaced by:

Figure 1 shows a sample of the typical daily average AOT values calculated using equation 1. This figure shows the AOT data for both the green and the red channels of the GLOBE sun photometer for the month of October.

15) L200-201: One might argue that there is no reason to compare the two datasets due to their distance and typical aerosol horizontal variability...

I agree that we cannot do a rigorous comparison of the two datasets. Because of the distance between the sites, the extrapolated AOT values are at best approximations and cannot be considered for rigorous scientific examination. They were used here for basic analysis and trend comparison. In future we plan to acquire the portable Calitoo sun photometer with blue (465nm), green (540nm) and red (615nm) channels. With these we can validate the GLOBE handheld sun photometer at the XULA site and use both instruments at the AERONET site.

16) L328-330: Is it not trivial and to avoid to be mentioned in the paper?

L328-330 is removed from the manuscript.

17) L330-332: Cirrus just add extinction to the observation, so an additional apparent AOT, please use correct terminology.

L330-332 was changed to: Cirrus clouds adds an additional extinction to the sunlight from the sun.

Reviewer #3:
Manuscript Summary:
This manuscript used two handheld Sun Photometers to measure the aerosol optical depth (AOD) at Xavier University of Louisiana campus site at two wavelengths. The results were compared with the measurement obtained from the AERONET site. The procedures and the mathematical calculation to obtain the AOD were discussed in the manuscript, as well as some critical steps.

Major Concerns:
The method is lack of a few key considerations, which makes the values obtained from the handheld Sun Photometers doubtful. Equations (1) and (2) are two major equations that the authors used to obtain the AOD. However, equation 1 is different from the original citation (citation 18), because the citation 18 mentions it is important to consider the absorbance of water vapor and other gas species that can absorb in the visible range. For instance, there are water absorption peaks around ~505nm and ~600 nm, so has the author considered subtracting these absorptance caused by the water molecules in the atmosphere? How about other gases?

The method also lacks direct comparison with other instrument to validate the results. Although the authors compared the results with the data obtained from the AERONET site, however there was significant difference between these two sources during 278-288th day of the year (Figure

The correct citation for equation 1 should be [16], David R. Brooks, Development of an inexpensive handheld LED-based Sun photometer for the GLOBE program, Journal of Geophysical Research. ***106 (****5), 4733-4740 (2001).*

The GLOBE sun photometer has two channels at 505nm and 625nm. The absorption of most gases in the atmosphere is outside this band and their contribution to AOT is usually ignored. Only water vapor and ozone are the gases likely to affect AOT especially on the red channel. The contributions to AOT due to ozone is calculated using climatological and latitude-dependent average ozone values. Satellite-based instruments such as Total Ozone Mapping Spectrometer (TOMS) are sources of such data. For the GLOBE handheld sun photometer, a typical ozone contribution to optical thickness is ~0.01 for green channel and ~0.03 for the red channel. This is cited from ref 22. These values are subtracted from the value obtained in equation 1.

The absorption by water vapor occurs in three regions of the spectrum. Rotational transitions absorb in the microwave and far infrared, vibrational transitions absorb in the mid infrared and near infrared. Because of the wide spectral response of our LEDs, it is possible that the red LED's responds curve is coincident with water vapor absorption region in the near infrared. Ref 24 showed that the estimated error introduced by absorption due to water vapor in the near infrared region is between 0.0015 and 0.0012 AOT units. Measurements made carefully with our GLOBE sun photometer are only accurate to about 0.02 AOT units. Because of this limitation we can also ignore the effects of water vapor.

In future we plan to acquire the portable Calitoo sun photometer with blue (465nm), green (540nm) and red (615nm) channels. With these we can validate the GLOBE handheld sun photometer at the XULA site and also use both instruments at the AERONET site.

2). The difference was near 100%, instead of 5% claimed by the author in the main text. In addition, the AERONET site was too far (60 miles away) to be used as a good validation for the method. Figure 3 also shows a significant difference of AOD between the AERONET site and the campus site, however the author could not give a valid reason to convince the reader that the method proposed was valid. For instance, a recent paper by Toledo et al. (JGR, 2018) shows the effects of water and other trace gases could heavily impact the AOT results. Unless the author can provide direct evidence to validate the method described in the manuscript, the quality of the data is doubtful.

Because of the distance between the sites, the extrapolated AOT values are at best approximations and cannot be considered for rigorous scientific examination. They were used here for basic analysis and trend comparison.

Because of the limitations imposed by the design of the GLOBE sun photometer, we can only measure AOT to 2 decimal places with a minimum uncertainty of about ± 0.02 AOT units. It is true that this presents a substantial percentage error particularly for clear skies where the AOT can be as low as 0.05 AOT units. However, this level of accuracy is still extremely useful to the atmospheric science community.

Thirdly, the graphs in the manuscript could not meet the standard for atmospheric sciences academic publication. The author should use Matlab or Igor to make serious scientific plots instead of Excel. The x and y axes did not have labels and units either.

We currently do not have Matlab or Igor. However, our plots have been converted to TIFF images and the x and y axis are labelled

The discussion part explaining why AERONET site and the campus site had significant difference was not clear. The author did not provide any concrete reasons for the difference and attribute the AOD peaks in February and May to random factors. Did the authors do research to justify whether there were any significant regional pollution? Did the author correlate the AOD data with any major pollution events or forestry fires?

One very importance parameter for a new method is the standard deviation or the error caused by this method compared with the true value. What is the error bar range of this method? The authors need to perform such calculations to show the error bar of the proposed method.

The data for the XULA site and the AERONET site both shows a peak in February and May. We cannot corelate this data with any major pollution events or forest fires. To understand this trend, we need to take measurements for many seasons to add to this preliminary data and see if a definite trend emerges.

During each measurement time, at least 5 values of the voltage V and the dark voltage V_{dark} are taken and AOT values are calculated using equation 1. Error analysis considerations shows that the retrieval of AOT using the GLOBE sun photometer is most sensitive to errors in calibration constant V_0 and the measured voltages $V-V_d$. The refrence voltage V_0 is a result of calibration measurements performed by *IESRE at Mauna Loa Observatory. The uncertainty in the two sun photometers we have is between 3% and 5%. The uncertainty in the value of $V-V_d$ recorded by students was calculated based on the standard deviation of the of the 5 values of V and V_d recorded during each measurement time. This ranged between 2% and 6%.*

Minor Concerns:
The author used the abbreviation AOT however the full spelling was "aerosol optical depth". The abbreviation of "aerosol optical depth" is "AOD" and the abbreviation of "aerosol optical thickness" is "AOT". Please use the correct abbreviation in the manuscript.

The author stated that their calculation and the value from the GLOBE was only less than 5% difference, but from Figure 2 it shows the difference could be nearly 100% at certain days. The author should make the proper correction in the manuscript.

Aerosol optical depth was replaced with aerosol optical thickness. Figure 2 was replaced and the proper correction was made in the manuscript.

Editorial comments:

1. Step 12.A: Please provide a link to the GLOBE cloud chart and/or include it in your submission (with appropriate permission). Also, is inference of invisible cirrus clouds something you do here? If so, please provide more details.

Link to cloud chart.

https://www.globe.gov/documents/348614/24331082/GLOBE+Cloud+Chart

I asked the GLOBE support team for permission to include the GLOBE cloud chart in a publication and they said that all GLOBE online resources are free to the public. Globe's response to my enquiry is given below:

Jorge Arias via RT

Greetings.
The content on the GLOBE website is open to the public.

Here's a statement from GLOBE saying our materials are available for use by anyone https://www.globe.gov/about/policies/terms-of-use
Here's a link to download the GLOBE Cloud Chart https://www.globe.gov/documents/348614/24331082/GLOBE+Cloud+Chart
We want your feedback, please let us know how we did. https://www.research.net/s/5BGPLQ2

Sincerely,
GLOBE Community Support Team
Phone: 1-800-858-9947
Email: help@globe.gov

On a clear day, the sunlight voltage reading ranges from about 0.5-2.0 V. If we observe sunlight voltages smaller than 0.5V on an apparently clear day, then we infer that there could be some invisible cirrus clouds in the vicinity of the sun and we disregard those readings.

2. Table 1 is missing from your submission; please upload as an .xlsx-formatted file using the 'Table' file upload option in Editorial Manager.

Table 1 has been uploaded to the Editorial manager as an .xlsx file

3. Figures 2, 3, 4: Please include spaces between numbers and units; e.g., '667 nm' instead of '667nm'.

Figures 2, 3, and 4 have been corrected

4. Figure 3b: What are the error bars here?

The error bars in figure 3 are based on the minimum uncertainty of ±0.02 AOT units for the level 2.0 AERONET data[25].

5. Figure 4: In the figure itself, panel a contains data from 505 nm and panel b data from 625 nm, but this is reversed in the legend. Please clarify. Also, please remove the period from the end of the title for panel b.

Panel a of figure 4 contains data from 625 nm and panel b contains data from the 505 nm. (this was corrected on figure 4).

P.S

New edits to the manuscript are highlighted in blue.