Aerosols Protocol

Purpose

To measure the aerosol optical thickness of the atmosphere (how much of the sun's light is scattered or absorbed by particles suspended in the air)

Overview

Students point a GLOBE sun photometer at the sun and record the largest voltage reading they obtain on a digital voltmeter connected to the photometer. Students observe sky conditions near the sun, perform the *Cloud*, *Optional Barometric Pressure* (optional) and *Relative Humidity Protocols*, and measure current air temperature.

Student Outcomes

Students understand the concept that the atmosphere prevents all of the sun's light from reaching Earth's surface and they learn what causes hazy skies.

Science Concepts

Earth and Space Science

- The atmosphere is composed of different gases and aerosols.
- The sun is the major source of energy for changes in the atmosphere.
- The diurnal and seasonal motion of the sun across the sky can be observed and described.

Geography

- Human activities can modify the physical environment.

Atmosphere Enrichment

- Aerosols decrease the amount of solar energy reaching Earth's surface.
- Aerosols in the atmosphere increase haze, decrease visibility, and affect air quality.

Scientific Inquiry Abilities

- Use a sun photometer and voltmeter to measure the amount of direct sunlight.
- Identify answerable questions.
- Design and conduct scientific investigations.
- Use appropriate mathematics to analyze data.
- Develop descriptions and explanations using evidence.
- Recognize and analyze alternative explanations.
- Communicate procedures and explanations.

Time

15-30 minutes to collect data

Level

Middle and Secondary

Frequency

Every day, weather permitting

Materials and Tools

- Calibrated and aligned GLOBE sun photometer
- Digital voltmeter
- Watch, preferably digital (or GPS receiver)
- Thermometer
- Hygrometer or Sling psychrometer
- GLOBE Cloud Chart
- Barometer (optional)
- *Aerosols Data Sheet*

Preparation

Practice using a digital voltmeter.

Prerequisites

Cloud, Relative Humidity, and *Optional Barometric Pressure* (optional) *Protocols*

Ability to measure current air temperature

Aerosols Protocol – Introduction

Background

The atmosphere is composed of molecules of gas and small solid and liquid particles suspended in the air, called aerosols. Some aerosols are naturally produced from volcanoes, sea spray, sand, or wind-driven erosion of surface soil. Some aerosols are a result of human activity, such as dust from agricultural activities, smoke from burning biomass and fossil fuels and photochemically induced smog due primarily to vehicle emissions. Drops and ice crystals that form when water vapor freezes or condenses are also aerosols.

Most aerosols are in the troposphere, but large volcanic eruptions can inject aerosols and trace gases much higher into the stratosphere. Aerosols in the stratosphere may remain for years while in the troposphere, precipitation and interactions with Earth's surface remove aerosols in ten days or less.

Aerosols are too small to be individually visible, but you can often see their combined effect when the sky is hazy or looks dirty. Brilliant orange skies at sunrise and sunset may also be indicators that aerosols are present.

Aerosols influence our weather and climate because they affect the amount of sunlight reaching Earth's surface. Volcanic aerosols in the stratosphere have changed surface air temperatures around the world for years at a time. Biomass burning causes large local increases in aerosol concentrations that can affect regional weather. Taken together with other atmospheric measurements, aerosol measurements help scientists to better understand and predict climate and to understand atmospheric chemistry.

Aerosol concentrations vary significantly with location and time. There are seasonal and diurnal variations as well as unpredictable changes due to events such as large dust storms and volcanic eruptions. Aerosols are highly mobile; they can cross oceans and mountain ranges. It is generally agreed that, because of higher concentrations of aerosols, skies in many parts of the world are hazier than they were one or two centuries ago, even in rural areas.

Aerosol optical thickness (AOT, also called aerosol optical depth) is a measure of the extent to which aerosols affect the passage of sunlight through the atmosphere. The larger the optical thickness at a particular wavelength, the less light of that wavelength reaches Earth's surface. Measurements of aerosol optical thickness at more than one wavelength can provide important information about the concentration, size distribution, and variability of aerosols in the atmosphere. This information is needed for climate studies, for comparison with satellite data and to understand the global distribution and variability of aerosols.

Investigating Aerosols

Scientists have many questions regarding aerosols. How do aerosol concentrations change with the seasons? How are aerosol concentrations related to the weather and climate? How does smoke from large forest fires affect sunlight reaching Earth's surface? How long do volcanic emissions stay in the atmosphere and where do they go? How is air pollution related to aerosols? How do large industrial facilities and agricultural activities affect aerosols? How do aerosols affect a satellite's view of Earth's surface? Global measurements are needed to monitor the present distribution of aerosols and to track events that alter aerosol concentrations. Their study can lead to a better understanding of Earth's climate and how it is changing.

By reporting measurements regularly, you can provide scientists with the data they need and you can start to answer some questions about aerosols for your own data collection site. You may even observe plumes of aerosols originating thousands of kilometers away as they pass through your area. By building a data record that extends across several seasons and includes data from many locations, GLOBE can help scientists learn more about the global distribution of aerosols.

Teacher Support

Understanding Measurements of Aerosols

Aerosol measurements are best understood in the context of the other GLOBE atmospheric measurements. There may be observable relationships between aerosols and temperature, cloud cover, relative humidity, and precipitation. Certainly, aerosols vary seasonally. Thus, it is helpful to approach this topic as part of a "big picture" of the atmosphere and its properties.

An introduction to the concepts of solar elevation angle and relative air mass is essential to understanding these measurements. The Learning Activities *Making a Sundial* and *Calculating Relative Air Mass* describe activities to measure these values. Advanced-level students with appropriate mathematics backgrounds can calculate their own value for aerosol optical thickness using the *Looking at the Data* section. They can then compare their calculations to the value calculated by the GLOBE Data Server.

The GLOBE Sun Photometer

The GLOBE sun photometer has two channels, each of which is sensitive to a particular wavelength of light — green light at about 505 nanometers (nm) and red light at about 625 nm. 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. Data from a single channel enables the calculation of AOT in a particular wavelength range but it does not provide information about the size distribution of aerosols. Combining data from more than one channel provides information on size distribution. Knowing the size distribution helps identify the source of the aerosols.

Measurements taken with the GLOBE sun photometer are in units of volts. These values must be converted to aerosol optical thickness. Since the calculations require mathematics (logarithmic and exponential functions) that are appropriate only for high school students taking a pre-calculus mathematics course, the GLOBE Data Server will perform the calculations based on the voltage readings submitted by students and return a value of optical thickness for students to use. There is a *Looking at the Data* section for advanced students that includes the equation for converting sun photometer measurements into aerosol optical thickness. A typical aerosol optical thickness value for visible light in clear air is roughly 0.1. A very clear sky may have an AOT at green-light wavelengths of 0.05 or less. Very hazy skies can have AOTs of 0.5 or greater.

It may be easier to understand the concept of optical thickness when it is expressed in terms of the percentage of light that is transmitted through the atmosphere, according to this formula:

$$\text{percent transmission} = 100 \times e^{-a}$$

where a is optical thickness at a particular wavelength. This calculation gives the percentage of light at a particular wavelength that would be transmitted through the atmosphere if the sun were directly overhead. For an optical thickness of 0.10, the percent transmission is about 90.5%.

For students who are not yet comfortable with exponential functions, Table AT-AE-1 gives percent transmission as a function of optical thickness.

Table AT-AE-1

Optical Thickness	Percent Transmission
0.10	90.5%
0.20	81.9%
0.30	74.1%
0.40	67.0%
0.50	60.7%
0.60	54.9%
0.75	47.2%
1.00	36.8%
1.25	28.7%
1.50	22.3%
2.00	13.5%
2.50	8.2%
3.00	5.0%
3.50	3.0%
4.00	1.8%
5.00	0.7%

Where and When to Take Sun Photometer Measurements

The logical place to take sun photometer measurements is the same place where you do your cloud observations and other atmosphere protocols. If you take measurements at some other place, you need to define it as an additional Atmosphere Study Site.

Ideally, aerosol measurements should be made in the morning when the solar elevation angle is at least 30 degrees. This is because, generally, the air in the morning is less turbulent than air near noon when the sun is high in the sky, or in the afternoon, especially in the heat of summer. The less turbulent the air, the easier it is to obtain reliable measurements. During the winter in temperate and higher latitudes, the relative air mass at your location may always be greater than 2. You can still take measurements, but you should take them as close to solar noon as possible. Although you should try to take measurements during optimum conditions, it is OK to take and report measurements whenever it is convenient and you have an unobstructed view of the sun.

If you wish to collect sun photometer data that support ground validation efforts for Earth-observing spacecraft, you may need to take measurements at specific times, corresponding to spacecraft overflights of your observing site. For more information about this activity, please contact the GLOBE Science Team.

Instrument Care and Maintenance

Your GLOBE sun photometer is a simple and rugged device with no easily breakable parts. However, you must take care of it in order to take accurate measurements. Here are some things you should do (and not do) to make sure your sun photometer performs reliably over long periods of time.

1. Do *not* drop your photometer.
2. *Protect* your sun photometer from dirt and dust by storing it in a sealed plastic bag (such as a plastic sandwich bag) when you are not using it.
3. *Do not* expose your sun photometer to extremely hot or cold temperatures by leaving it in the sun or on a radiator or by leaving it outside.
4. *Keep* your sun photometer turned off when it is not in use.
5. *Check* the battery voltage every few months. See *Checking and Changing Your GLOBE Sun Photometer Battery*. Your sun photometer uses very little power when you take measurements, so the battery should last for many months of normal use. If you accidentally leave the photometer turned on for hours or days when you are not using it, check the battery before taking additional measurements and replace it if necessary.
6. *Do not* modify the electronics inside your sun photometer in any way. The calibration of your instrument depends critically on retaining the original components on the circuit board.
7. *Do not* enlarge the hole(s) in the case through which sunlight enters your sun photometer. The calibration of your sun photometer and the interpretation of its measurements are based on the size of this hole. If you change it, your measurements will no longer be valid.

With a little care, your sun photometer will work reliably for many years. Although the GLOBE Science Team might ask you to return your sun photometer for recalibration, under normal conditions no periodic recalibration is necessary. If your instrument appears not to be working correctly, consult with GLOBE before doing anything else.

Checking and Changing Your GLOBE Sun Photometer Battery

At least every three months, check the voltage of the battery in your sun photometer and replace the battery if necessary. If your sun photometer has a built-in digital voltmeter and a “low battery” indicator appears, or if the voltages from your instrument appear erratic, replace the battery at once. (See the *Checking and Changing Your GLOBE Sun Photometer Battery Lab Guide* for Instructions.) Replacing the battery will not change the calibration of your instrument and measurements made with the old battery will be OK as long as you replace the old battery before its voltage falls below 7.5 V.

Checking and Changing Your GLOBE Sun Photometer Battery

Lab Guide

Task

Check the battery in the sun photometer and replace it if necessary.

What You Need

☐ Small Phillips-head screwdriver

☐ Voltmeter

☐ Any standard, new 9 V battery if the old battery needs replacing (rechargeable batteries are not recommended for this instrument)

In the Lab

1. Open the case by removing the four screws in the cover.

   Do not remove the printed circuit board or disturb the electronics in any way.

   Do not touch the front surface of the LED detectors (the round green and red devices on the front of the printed circuit board).

2. With the instrument turned on, use a voltmeter to measure the voltage across the two connectors on the battery holder.

   Note that new 9-volt batteries typically produce voltages greater than 9 V, and can even produce voltages in excess of 10 V.

3. If the voltage is less than 7.5 V, replace the battery. Any standard 9 V battery is OK. Alkaline batteries are more expensive than other types and are not required. Note that the connectors on the + and -terminals are different, so the battery will fit in its holder only one way. Rechargeable batteries are not recommended for this instrument.

4. When you are done, check the operation of your sun photometer by letting sunlight shine on the LED detectors. You do not have to replace the cover while you are performing this test. Whenever an LED is not shadowed, you should see a voltage substantially larger than the "dark" voltage.

5. When you are sure the photometer is working, replace the cover. If your sun photometer has a foam strip on the lid, make sure the cover is oriented so this strip pushes against the top of the printed circuit board. Tighten the screws until they are snug, but do not force them.

If you want to convince yourself that replacing the battery has not changed the calibration of your instrument, wait for a clear day. Make a few measurements right before and right after you change the battery. These measurements should be consistent as long as the old battery voltage was not significantly less than 7.5 V.

Student Preparation

1. Prior to implementing this protocol, it will be helpful to spend a few minutes in your classroom or lab practicing how to use a digital voltmeter. When the voltmeter is connected to a circuit that is not producing a voltage signal, the digital display may indicate the presence of a small voltage (perhaps a few millivolts). This is normal operation, but it may be confusing to students who are expecting to see a voltage of 0.0 V. (**Note:** If your sun photometer has a built-in voltmeter, you do not need a separate digital voltmeter to take measurements. However, if you have a separate digital voltmeter, this is still a useful activity.)
2. In order to calculate aerosol optical thickness from your measurements, GLOBE must know the true barometric pressure (the station pressure) at your site when you took your measurements. The preferred source for local barometric pressure is an online or broadcast weather source for your area (such as the National Weather Service in the U.S.). See the *Optional Barometric Pressure Protocol*. Locating such a source should be part of student preparation for this protocol. If an online source is not available, there are other options discussed in *Getting Ready to Take Measurements,* below. Almost always, barometric pressure is reported adjusted to what it would be at sea level. This enables meteorologists to draw weather maps over terrain with varying elevation. GLOBE uses the elevation data from your site definition to adjust the sea level pressure you report to the station pressure needed to calculate AOT.
3. Current air temperature and relative humidity are also helpful supporting information for this protocol. Have students practice these measurements as well. See the *Digital Multi-Day Max/Min Current Temperature Protocol Field Guide,* steps 1-5 of the *Maximum, Minimum and Current Temperature Protocol Field Guide,* steps 1-4 of the *Digital Single-Day Maximum and Minimum Temperature Protocol Field Guide* or the *Current Air Temperature Protocol Field Guide* and the *Relative Humidity Protocol.*
4. The presence of thin, high (cirrus) clouds in front of the sun will affect sun photometer readings. This is why it is important that students gain some experience in identifying clouds, especially cirrus clouds, as described in the *Cloud Protocols*.
5. It is especially important to take sun photometer measurements in the prescribed way and under acceptable sky conditions. A *Classroom Preparation Guide* is provided to help you prepare. It describes in detail the steps required to take and record a measurement, along with the reasons for each step. It parallels the *Field Guide* that simply lists the steps in order without explanation. As part of their preparation for this protocol, students should study the *Classroom Preparation Guide* to make sure they understand the critical parts of each step.

Questions for Further Investigation

To what extent is AOT related to other atmospheric variables — temperature, cloud type and cover, precipitation, relative humidity, barometric pressure, and ozone concentration?

How does AOT relate to the appearance of a distant landmark or to the color of the sky?

Does AOT vary with site elevation? If so, how?

How does AOT vary as surroundings change from urban to rural?

How does AOT vary with the seasons?

Aerosols Protocol

Classroom Preparation Guide

Task

Record the maximum voltage reading that can be obtained by pointing your photometer at the sun.

Record the precise time of your measurement.

Observe and record cloud conditions, current air temperature, and relative humidity.

What You Need

☐ Calibrated and aligned GLOBE sun photometer
☐ Digital voltmeter (if your sun photometer does not have a built-in voltmeter)
☐ Watch, preferably digital or GPS receiver
☐ *Aerosols Data Sheet*
☐ GLOBE Cloud Chart
☐ Barometer (optional)
☐ Thermometer
☐ Hygrometer or sling psychrometer
☐ *Field Guides* for cloud, relative humidity and one air temperature protocol
☐ Pencil or pen

Getting Ready To Take Measurements

In order for the Science Team to interpret measurements made with your sun photometer, you must provide the longitude, latitude, and elevation of your observing site, as required for other GLOBE measurements. You do this once, when you define an Atmosphere Study Site. Other values and observations must be provided along with each measurement, as shown on the data entry form. The purpose of this section is to give you the information you need to complete the data entry.

Time

It is important to report accurately the time at which you take a measurement because the Science Team needs to calculate solar position at your site and that calculation depends on time. The GLOBE standard for reporting time is UT, which can be calculated from local clock time based on your time zone and the time of year. For this protocol, it is absolutely essential to convert local time to UT correctly; be especially careful when your local time is summer ("daylight savings") time. For example, you must add 5 hours to convert Eastern Standard Time to UT, but only 4 hours to convert Eastern Daylight Time to UT.

Time should be reported at least to the nearest 30 seconds. A digital watch or clock is easier to use than an analog one, but in either case you must set your timepiece against a reliable standard. The time accuracy requirements for this protocol are stricter than for the other GLOBE protocols. However, it is not difficult to set your clock or watch to meet this standard. You can get time online at www.time.gov. In many places, you can get an automated local time report by phone from a local radio or TV station. Your GPS receiver will report UT. In some places, you can buy a clock that sets itself automatically by detecting radio signals from a government-sponsored official time source. (In the U.S., for example, this so-called "atomic clock" signal is broadcast over station WWBV.)

It might be tempting to use the time stored in your computer as a standard. However, this is not a good idea, as (perhaps surprisingly) computer clocks are often not very accurate, and they must be set periodically according to a reliable standard. Note that some computer operating systems will automatically switch your computer clock back and forth between standard and summer (“daylight savings”) time. You should be aware of when this change occurs if you need to manually convert time from your local clock time to UT.

The preferred time of day for reporting sun photometer measurements at most latitudes, during most of the year, is mid-morning. However, it is acceptable to take these measurements any time during the day between mid-morning and mid-afternoon. No matter what time you take measurements, be sure to report UT as accurately as possible, as noted above. The Science Team understands that it may be most convenient to take these measurements at the same time you collect your other atmospheric data. Measurements should be made at a relative air mass of no more than 2 whenever possible. (Refer to the Learning Activity that discusses relative air mass. A relative air mass of 2 corresponds to a solar elevation angle of 30 degrees.) During the winter in temperate and higher latitudes, the relative air mass at your location may always be greater than 2. You can still take measurements, but you should take them as close to solar noon as possible.

If you are taking sun photometer measurements in support of ground validation activities for Earth-observing spacecraft, then the measurement times will be based on the times of spacecraft overflights of your observing site.

Sky Conditions

When you record sun photometer measurements, you should also record other information about the sky, including cloud cover and cloud type, sky color, and your own assessment of how clear or hazy the sky is.

Sky color and clarity are subjective measurements but, with practice, you can learn to be consistent in your own observations. For example, you can easily learn to recognize the bright blue clear sky associated with low aerosol optical thickness. As the aerosol concentration increases, the sky color changes to a lighter blue color. It may appear milky rather than clear. In some places, especially in and near urban areas, the sky can have a brownish or yellowish tint due to air pollution (primarily particulates and NO_2).

When there are obvious reasons for high values of aerosol optical thickness, the Science Team needs to know about them. This is why you are also asked to comment about why you think the sky is hazy. It could be due to urban air pollution, a volcanic eruption, or dust from agricultural activity, for example.

Sun photometer measurements can be interpreted properly only when the sun is not obscured by clouds. This does not mean that the sky must by completely clear, but only that there must be no clouds in the vicinity of the sun. This is not necessarily a simple decision. It is easy to determine whether low- and mid-altitude clouds are near the sun, but cirrus clouds pose a more difficult problem. These clouds are often thin and may not appear to block a significant amount of sunlight. However, even very thin cirrus clouds can affect sun photometer measurements. For this reason, if you observe cirrus clouds earlier or later in the day relative to when you report measurements, you should note this fact on your data entry form.

Another difficult situation occurs in typical summer weather, especially near large urban areas. In this environment, very hazy skies and hot humid weather often make it difficult to distinguish cloud boundaries. Such conditions can produce relatively large values of aerosol optical thickness (any value greater than about 0.3-0.5) that may not represent the actual state of the atmosphere. It is important to describe such conditions whenever you report measurements.

To get a better idea of where cloud boundaries are, you can observe the sky through orange or red sunglasses, or through a sheet of translucent orange or red plastic. These colors filter out blue skylight and make clouds more distinct.

Never look directly at the sun, even through colored sunglasses or plastic sheets! This can damage your eyes.

Fog is another potential problem. It can make things look hazy. But fog (a stratus cloud at ground level) is not the same as atmospheric haze from aerosols. Conditions where the sun is shining through even light fog are unsuitable for taking sun photometer measurements. In many locations fog dissipates before mid-morning, so it will not affect your measurements.

Whenever you try to determine sky conditions before taking sun photometer measurements, you must block the sun itself with a book, a sheet of paper, a building or tree, or some other object. A sensible rule is that if you can see any shadows at all on the ground, you should not try to look at the sun. If in doubt, or if you believe you cannot determine sky conditions near the sun, do not take a measurement!

Temperature

The electronics in your GLOBE sun photometer, and especially its LED detectors, are temperature-sensitive. This means that the output will change under the same sunlight conditions as the sun photometer warms and cools. Therefore, it is important to maintain your sun photometer at approximately room temperature. To alert the Science Team to potential problems with temperature, we ask that you report air temperature along with your sun photometer measurements.

If you are taking sun photometer measurements at the same time you record temperature data from your weather station, you can use that current temperature. Otherwise, you must measure the air temperature separately. The preferred way to obtain air temperature values is to take them following the GLOBE *Temperature Protocols* using a thermometer that meets GLOBE standards mounted in an appropriate weather shelter. Alternatively, a value can be obtained from an online source or from a thermometer that does not necessarily meet GLOBE standards. Non-GLOBE temperature values should be reported as metadata on the *Data Sheet,* and not in the air temperature field.

In terms of instrument performance, the relevant temperature is not necessarily the outside temperature, but air temperature inside your sun photometer's case. Newer GLOBE sun photometers include a built-in sensor that monitors air temperature inside the instrument, near the LED detectors. These instruments have a rotary switch on the top of the case rather than a green/red channel toggle switch. If your sun photometer includes this feature, there is a place to report case temperature on the *Data Sheet*. The temperature, in degrees Celsius, is 100 times the voltage displayed on the voltmeter when the "T" channel is selected. For example, a voltage reading of 0.225 V corresponds to a temperature of 22.5° C. Ideally, this temperature should be in the low 20's.

There are some steps you should take to minimize temperature sensitivity problems. Keep your sun photometer inside, at room temperature, and bring it outside only when you are ready to take a measurement. In the winter, transport it to your observing site under your coat, for example, to keep it warm. In very hot or very cold weather, you can wrap the instrument in an insulating material such as an insulated sandwich bag, a towel, or pieces of plastic foam. In the summer, keep your instrument shielded from direct sunlight whenever you are not actually taking a measurement. You should practice taking and recording measurements so that an entire set of voltage measurements should take no more than two or three minutes.

Relative Humidity

Relative humidity is a useful addition to the *Aerosols Protocol* metadata because high (or low) values of relative humidity are often associated with high (or low) aerosol optical thickness values. There is a *Relative Humidity Protocol* available for this measurement, which requires a digital hygrometer or sling psychrometer, but it is also OK to use an online or broadcast value from within an hour of your sun photometer measurements. Online values should only be reported as comments while values you obtain following the *Relative Humidity Protocol* are valid GLOBE data and may be reported as such.

Barometric Pressure

Unlike the previous values described in this section, the station pressure at your observing site is *required* in order to calculate aerosol optical thickness. Unless your site is very close to sea level, the barometric pressure reported on weather broadcasts, in your local newspaper, and on the Web is not station pressure. Why? Because in such reports, the true barometric pressure has been adjusted to what it would be at sea level. This enables meteorologists to construct pressure maps that show the movement of air masses over large areas, independent of the varying elevation of the ground. Barometric pressure decreases roughly 1 mbar for every 10 meters of increased elevation. (See Figure AT-I-1 and the *Optional Barometric Pressure Protocol*.)

As noted above, the preferred source of barometric pressure is an online or broadcast value for your area. A second option is to leave the barometric pressure field blank. In this case, GLOBE will fill in the barometric pressure using a computer-generated model value. If you have calibrated your classroom barometer on a regular basis so that it gives sea level pressure and have confidence in that calibration, you may report a reading from your barometer. However, typical classroom aneroid barometers must be calibrated regularly as described in the *Optional Barometric Pressure Protocol*. At higher elevations, it may not be possible to calibrate your classroom barometer to give an equivalent sea level value.

In the Field

It is much easier for two people to take and record measurements than for one person working alone. If you can work as a team, divide up the tasks and go through several practice runs before you start recording real measurements.

1. Connect a digital voltmeter to the output jacks of your sun photometer.

   If your sun photometer has a built-in digital voltmeter, you can skip this step. If you need a separate voltmeter, do not use an analog voltmeter, which cannot be read accurately enough to be suitable for this task. Be sure to put the red lead in the red jack and the black lead in the black jack.

2. Turn the digital voltmeter and sun photometer on.

   If your sun photometer has a built-in digital voltmeter, the same switch turns on both the meter and the sun photometer and you do not need to worry about selecting an appropriate voltage range.

   If you are using an external voltmeter, select an appropriate DC volts range. Be careful not to use an AC volts setting. The appropriate range setting depends on your voltmeter. If it has a 2 V (volts) or 2000 mV (millivolts) setting, try that first. If your photometer produces more than 2 V, use the next higher range, often 20 V. Some voltmeters have auto-ranging capability, which means that there is only one DC volts setting and the voltmeter automatically selects an appropriate voltage range. If you are using an auto-ranging voltmeter, make sure you understand how to read voltages in this range.

   Note that if a digital voltmeter is connected to your sun photometer when the photometer is turned off, you will get unpredictable readings on the voltmeter, rather than the value of 0 V you might expect. This is normal behavior for digital voltmeters. Erratic voltage readings will also occur if the battery in your sun photometer is too low to power the electronics. When you turn your sun photometer on, and it is working properly, the voltmeter should produce a stable reading of no more than a few millivolts indoors or if the sun is not shining on a detector, or a value in the range of roughly 0.5-2 V when sunlight is shining on the detector.

3. If your sun photometer has a rotary switch on the top of the case, select the "T" setting and record the voltage.

   Multiply the voltage reading times 100 and record this value.

4. Select the green channel on your sun photometer (because the GLOBE data entry page asks for the green channel first).
5. Hold the instrument in front of you about chest-high or, if possible, sit down and brace the instrument against your knees, a chair back, railing, or some other fixed object. Find the spot made by the sun as it shines through the front alignment bracket.

   Here is an important safety rule:
   Under no circumstances should you hold the sun photometer at eye level and try to "sight" along the alignment brackets!

   Adjust the pointing of your instrument until the spot of sunlight shining through the front alignment bracket shines on the rear alignment bracket.

6. Adjust the pointing until the sunlight spot is centered over the appropriate colored dot on the rear alignment bracket. Record this value on your *Data Sheet.*

   Your sun photometer case will have either one or two round holes on the front of the case. If it has one hole, the rear alignment bracket will have two colored alignment dots - one green and one red. The sunlight spot must be centered around the green dot when you are taking green-channel measurements and around the red dot if you are taking red-channel measurements. If your sun photometer has two holes, the rear alignment bracket will have one blue alignment dot. The sunlight spot must be centered around this dot regardless of whether you are taking green- or red-channel measurements.

   When you adjust the pointing of your photometer so that the sunlight spot is centered around the alignment dot, the sunlight shining through the aperture hole(s) on the front of the case is centered over the LED detector(s) inside the case. It takes a little practice to learn how to center the sunlight spot over the alignment dot. Be sure the pointing is stable before you record voltages. It may help to steady your instrument against a chair, post, or other stationary object. The entire measurement process should not take more than 15 or 20 seconds for each reading of each channel. Be sure to record all the digits displayed on your voltmeter.

   Unless the sky is very hazy, or unless you are taking measurements late in the afternoon or early in the morning, the voltage should increase to more than 0.5 V. If you are using an auto-ranging voltmeter, the range will change automatically when you point your photometer directly at the sun (from a range appropriate for displaying the dark voltage to a range appropriate for displaying the sunlight voltage).

   Small movements of the sun photometer will cause the voltage to vary by a few millivolts. Even when your sun photometer is completely still and properly aligned with the sun, the voltage will still vary a little. This is due to fluctuations in the atmosphere itself. The hazier the atmosphere, the larger these fluctuations. Do not try to average the voltmeter readings. It is important to record only the maximum voltage you obtain during a few seconds of measurement time, starting only after the pointing of your instrument has been stabilized. There is a slight time delay between the time when the voltage output from your instrument changes and when that change is reflected in the digital reading. With a little practice, you can learn to compensate for this time delay.

7. Record the time at which you observed the maximum voltage as accurately and precisely as possible. An accuracy of 15-30 seconds is required.
8. While still pointing your sun photometer at the sun, cover the aperture with your finger to block all light from entering the case. Take a voltage reading and record this dark voltage reading on your *Data Sheet*.

   Note that the dark voltage **must** be reported as volts rather than millivolts, regardless of the range setting of your digital voltmeter. It is critical to report both the dark voltage and sunlight voltage in units of volts. It is important to record the dark voltage accurately, reporting all the digits displayed on your voltmeter. The dark voltage should be less than .020 V (20 mV). Depending on the characteristics of your instrument and the range setting of your voltmeter, the dark voltage may display as 0 V If so, report 0.000 V for the dark voltage.
9. Select the other channel (the red one, assuming you have started with the green channel) and repeat steps 6-8.

   After you gain experience with your sun photometer, it will be unnecessary to repeat step 8 after every sunlight voltage measurement. Indeed, the dark voltages should not change during a set of measurements. If this value changes by more than a millivolt or so, it means that your instrument is getting too hot or cold during the measurement and you need to develop a measurement strategy that prevents this from happening.
10. Repeat steps 4-9 at least twice and no more than four times.

    This will give you between three and five pairs of green/red measurements in all. It is a good idea to be consistent about the order in which you record measurements; you should record green, red, green, red, green, red, green, red, green, red.

    The time between measurements is not critical as long as you record the time accurately. However, as noted above, you should try to minimize the total time required to collect a set of measurements. Remember that your measurements will not be accurate if your sun photometer is significantly colder or warmer than room temperature.
11. If your sun photometer has a rotary switch on the top of the case, select the “T” setting and record the voltage.

    Multiply the voltage reading times 100 and record this value.
12. Turn off both the sun photometer and the voltmeter (if your instrument does not have a built-in digital voltmeter).

    You can disconnect a separate voltmeter or leave it plugged into the output jacks, depending on whether your class uses the voltmeter for other purposes.
13. Note any clouds in the vicinity of the sun in the *Comments* section of the *Aerosols Data Sheet*. Be sure to note the type of clouds by using the GLOBE Cloud Chart.
14. Do the *Cloud Protocols* and record your observations on the *Aerosols Data Sheet*.
15. Do the *Relative Humidity Protocol* and record your observations on the *Aerosols Data Sheet.*
16. Read and record the current temperature to the nearest 0.5° C following one of the air temperature protocols.

    There are four *Field Guides* from which to choose listed in the *Student Preparation Guide*. Be careful not to touch or breathe on the thermometer.
17. Complete the rest of the *Aerosols Data Sheet*. This may be done back in the classroom.

Aerosols Protocol

Field Guide

Task

Record the maximum voltage reading that can be obtained by pointing your photometer at the sun.

Record the precise time of your measurement.

Observe and record cloud conditions, current air temperature, and relative humidity

What You Need

- ☐ Calibrated and aligned GLOBE sun photometer
- ☐ Digital voltmeter
- ☐ Watch, preferably digital or GPS receiver
- ☐ *Aerosols Data Sheet*
- ☐ GLOBE Cloud Chart
- ☐ Barometer (optional)
- ☐ Thermometer
- ☐ Hygrometer or sling psychrometer
- ☐ *Field Guides* for cloud, relative humidity and one air temperature protocol
- ☐ Pencil or pen

In the Field

1. Connect a digital voltmeter to the output jacks of your sun photometer. (Skip this step if your sun photometer has a built-in digital voltmeter.)
2. Turn the digital voltmeter and sun photometer on.
3. If your sun photometer has a rotary switch on the top of the case, select the "T" setting and record 100 times this voltage.
4. Select the green channel.
5. Face the sun and point the sun photometer at the sun. (Do not look directly at the sun!)
6. Adjust the pointing until you see the maximum voltage in your digital voltmeter. Record this value on your *Data Sheet*.
7. Record the time at which you observed the maximum voltage as accurately as possible, to the nearest 15 seconds.
8. While still pointing your sun photometer at the sun, cover the aperture with your finger to block all light from entering the case. Take a voltage reading and record this dark voltage reading on your *Data Sheet*.
9. Select the red channel (assuming you have started with the green channel) and repeat steps 6-8.
10. Repeat steps 3-9 at least twice and not more than four times.
11. If your sun photometer has a rotary switch on the top of the case, select the "T" setting and record 100 times this voltage.
12. Turn off both the sun photometer and the voltmeter.
13. Note any clouds in the vicinity of the sun in the comments (metadata) section. Be sure to note the types of clouds by using the GLOBE Cloud Chart.
14. Do the *Cloud Protocols* and record your observations on the *Aerosols Data Sheet*.
15. Do the *Relative Humidity Protocol* and record your observations on the *Aerosols Data Sheet.*
16. Read and record the current temperature to the nearest 0.5° C following one of the air temperature protocols.
17. Complete the rest of the *Aerosols Data Sheet*.

Frequently Asked Questions

1. What is a sun photometer and what does it measure?

A sun photometer is a type of light meter that measures the amount of sunlight. Most sun photometers measure the amount of sunlight for a narrow range of colors or wavelengths. All sun photometers should measure only the sunlight arriving directly from the sun and not the sunlight scattered from air molecules and aerosols. Therefore a sun photometer is pointed directly at the sun and the light is collected through a small aperture (hole or opening) that greatly restricts the amount of scattered sunlight that reaches the instrument's detector(s).

2. The GLOBE sun photometer uses a light-emitting diode (LED) as a sunlight detector. What is an LED?

A light-emitting diode is a semiconductor device that emits light when an electrical current flows through it. The actual device is a tiny chip only a fraction of a millimeter in diameter. In the GLOBE sun photometer, this chip is housed in an epoxy housing about 5 mm in diameter. You can find these devices in a wide range of electronic instruments and consumer products. The physical process that causes LEDs to emit light also works the other way around: if light shines on an LED, it produces a very small current. The electronics in your sun photometer amplifies this current and converts it to a voltage.

Generally, the wavelength of light detected by an LED is shorter than the wavelength of light emitted by the same LED. For example, certain red LEDs are relatively good detectors of orange light. The LED in the GLOBE sun photometer emits green light with a peak value at about 565 nm. It detects light with a peak at about 525 nm, which is a little farther toward the blue part of the light spectrum.

3. What is the field of view of a sun photometer, and why is it important?

The equation that describes theoretically how to interpret sun photometer measurements requires that the instrument should see only direct light from the sun – that is, light that follows a straight line path from the sun to the light detector. This requirement can be met only approximately in practice because all sun photometers will see some scattered light from the sky around the sun.

The cone of light a sun photometer's detector sees is called its field of view, and it is desirable to have this cone as narrow as possible. The GLOBE sun photometer's field of view is about 2.5 degrees, which GLOBE scientists have concluded is a reasonable compromise between the theoretical ideal and practical considerations in building a handheld instrument. The basic trade-off is that the smaller the field of view, the harder the instrument is to point accurately at the sun. Very expensive sun photometers, with motors and electronics to align the detector with the sun, typically have fields of view of 1 degree or less. Studies have shown that the error introduced by somewhat larger fields of view is negligible for the conditions under which a GLOBE sun photometer should be used.

4. How important is it to keep the sun photometer from getting hot or cold while I'm taking measurements?

The LED detector in your sun photometer is temperature-sensitive, so its output is slightly influenced by its temperature. Therefore, it is very important to protect your instrument from getting too hot in the summer or too cold in the winter. In the summer, it is essential to keep the instrument case out of direct sunlight when you are not actually taking a measurement. In the winter, it is essential to keep the instrument warm – you can tuck it under your coat between measurements.

Never leave your sun photometer outside for extended periods of time. The sun photometer case itself provides some protection from temperature changes that can affect the electronics inside. (This is why newer GLOBE sun photometers have a built-in temperature sensor to monitor the air temperature inside the case, near the detectors.) If you follow these precautions and take your measurements as quickly as possible, then your measurements will be acceptable.

In extreme conditions (winter or summer), you should consider making an insulating housing for your sun photometer. You can use styrofoam or other foam plastic. Cut holes for the on/off switch and the sunlight aperture(s), and a channel for sunlight to get from the front alignment bracket to the target on the back bracket. The hole for a sunlight aperture should be no smaller in diameter than the thickness of the insulating material itself, and in no case should it be smaller than about 1 cm.

5. I dropped my sun photometer. What should I do now?

Fortunately, the components inside your sun photometer are virtually indestructible, so they should have survived being dropped. Check the case for cracks. Even if the case is cracked, you should still be OK. Just tape over the cracks — use something opaque, such as duct tape. Open the case and make sure that everything looks OK. In particular, make sure that the battery is still firmly attached to the terminals on the battery holder.

If the alignment brackets have moved or are loose as a result of the fall, then your sun photometer should be returned to the GLOBE Science Team for realignment and recalibration.

6. How do I know if my sun photometer is working properly?

When you turn your sun photometer on without pointing it at the sun, you should measure a voltage in the range of no more than 20 mV. On some instruments, dark voltages are less than 1 mV. When you point your instrument directly at the sun, the voltage should increase to a value in the range of about 0.5-2.0 V. Only in very hazy conditions, late in the afternoon, or early in the morning, should you see a sunlight voltage less than 0.5 V. If you do not see the expected voltages, then your sun photometer is not working.

The most likely reason for a sun photometer not to work is that the battery is too weak to power the electronics. If you suspect this is the case, then test the battery voltage and replace it according to the instructions given in *Checking Your GLOBE Sun Photometer Battery.* Remember that a dead or very low battery will not produce a sunlight voltage of 0 V, but will instead cause your voltmeter to display erratic values. If you still believe you have a problem, contact GLOBE for help.

7. What does it mean to calibrate a sun photometer?

A sun photometer is considered to be calibrated if its extraterrestrial constant is known. This is the voltage you would measure with your sun photometer if there were no atmosphere between you and the sun. As an exercise, you could think about pointing your sun photometer at the sun from the open cargo bay of the Space Shuttle as it orbits Earth above the atmosphere. The voltage you measure would be your instrument's extraterrestrial constant. This value depends primarily on the wavelength at which your sun photometer detects light and also on the distance between Earth and the sun. (This distance varies slightly because Earth follows a slightly elliptical, rather than a circular, path around the sun.)

Note that if you really could use a sun photometer outside Earth's atmosphere, you would not have to worry about limiting the field of view. Why? Because outside the atmosphere there are no air molecules or aerosols to scatter sunlight. Hence, your sun photometer will see only direct sunlight.

As a practical matter, sun photometers must be calibrated by inferring the extraterrestrial constant from measurements made at Earth's surface. This is called the "Langley plot" method. These measurements are difficult to take at low elevation sites with variable weather. GLOBE sun photometers are calibrated against reference instruments that have been calibrated using measurements taken at Mauna Loa Observatory, which is widely accepted as one of the best locations for such work.

It is an interesting project to make your own Langley plot calibrations and compare the results with the calibration assigned to your sun photometer. If you would like to do this, contact GLOBE for additional help.

8. Can I make my own sun photometer?

You can purchase a sun photometer kit. Constructing a sun photometer involves soldering some electronic components, which is a skill students need to learn under supervision by someone who has done it before. You can start taking measurements as soon as you have assembled your instrument. However, at some point, you must send your sun photometer to the GLOBE Science Team for calibration before your data can be accepted into the GLOBE Data Archive.

9. How often must I take sun photometer measurements?

The protocol asks that you take measurements every day, weather permitting. In some parts of the world, it is possible to go many days without having weather suitable for taking these measurements. It is highly desirable to have a plan for taking measurements on weekends and during holiday breaks (especially during extended summer holidays).

10. How can I tell whether the sky is clear enough to take sun photometer measurements?

The basic rule is that the sun must not be blocked by clouds during a measurement. It is OK to have clouds near the sun. This can be a difficult decision, because you are never supposed to look directly at the sun. You can look at the sky near the sun by blocking the sun with a book or notebook. An even better idea is to use the comer of a building to block the sun. It is very helpful to wear sunglasses when you make these decisions because they protect your eyes from UV radiation. Orange-tinted sunglasses will help you see faint clouds that might otherwise be invisible.

If you have concerns about a measurement, note them in the *Comments* section of the *Aerosols Data Sheet* when you report the measurement. Thin cirrus clouds are notoriously difficult to detect, but they can dramatically affect sun photometer measurements. If you see cirrus clouds in the hours before or after a measurement, be sure to include that in your sky description.

11. What are aerosols?

Aerosols are liquid or solid particles suspended in air. They range in size from a fraction of a micrometer to a few hundred micrometers. They include smoke, bacteria, salt, pollen, dust, various pollutants, ice, and tiny droplets of water. These particles interact with and scatter sunlight. The degree to which they affect sunlight depends on the wavelength of the light and the size of the aerosols. This kind of particle-light interaction is called Mie scattering, named after the German physicist Gustav Mie, who published the first detailed mathematical description of this phenomenon in the early part of the twentieth century.

12. What is optical thickness?

Optical thickness (or optical depth) describes how much light passes through a material. The amount of light transmitted can be quite small (less than a fraction of 1%) or very large (nearly 100%). The greater the optical thickness, the less light passes through the material. As applied to the atmosphere, aerosol optical thickness (AOT) describes the extent to which aerosols impede the direct transmission of sunlight of a certain wavelength through the atmosphere. In a very clear sky, AOT can have values of 0.05 (about 95% transmission) or less. Very hazy or smoky skies can have AOT values in excess of 1.0 (about 39% transmission).

Percent transmission through the atmosphere is an alternate way to describe the same phenomenon. There is a simple relationship between AOT and transmission expressed as a percentage:

$$\text{transmission (\%)} = 100 \times e^{(-\text{AOT})}$$

Refer to Table AT-AH-1 to see the percent transmission for several values of AOT. Any scientific calculator should have an e^x function key. Try to reproduce one or more of the examples in this table to check if you understand how to use a calculator to convert AOT to percent transmission.

13. What is Beer's Law?

August Beer was a nineteenth-century German physicist who worked in the field of optics. He developed the principle known as Beer's

Law, which explains how the intensity of a beam of light is reduced as it passes through different media. Other nineteenth-century physicists also examined this law and applied it to the transmission of sunlight through the atmosphere. Hence, the equation used to describe how sun photometers work is usually referred to as the Beer/Lambert/Bouguer law. As applied to a sun photometer, Beer's Law is

$$V_o = V(r/r_o)^2\exp\{-m[AOT + Rayleigh(p/p_o)]\}$$

Where r/r_o is Earth-sun distance in astronomical units, m is the relative air mass, AOT is the aerosol optical thickness, Rayleigh is the optical thickness due to Rayleigh scattering, and p/p_o is the ratio of current atmospheric pressure to standard atmospheric pressure (1013.25 mbar). You need to be comfortable with exponential and logarithmic functions before you use this formula to make your own calculations of aerosol optical thickness. Also, you need to know your sun photometer's calibration constants – one value of V_o for each of the two channels – and the Rayleigh coefficients corresponding to each wavelength. If you would like to do this calculation on your own, you will need to obtain the calibration constants and Rayleigh coefficients from GLOBE.

14. What is relative air mass (m)?

Relative air mass (m) is a measure of the amount of atmosphere through which a beam of sunlight travels. At any location or elevation, the relative air mass is 1 when the Sun is directly overhead at solar noon. (**Note:** At any latitude greater than about 23.5 degrees, north or south, the sun is never directly overhead, so the sun can never be observed through a relative air mass of 1.

A simplified formula for relative air mass is

$$m = \frac{1}{\sin(\text{elevation})}$$

where "elevation" is the angle of the sun above the horizon. This calculation is sufficiently accurate for relative air masses up to about 2. Larger values require a more complicated formula that corrects for the curvature of Earth's surface.

15. What is Rayleigh scattering?

Molecules of air scatter sunlight. Air molecules scatter ultraviolet and blue wavelengths much more efficiently than red and infrared wavelengths. (This is why the sky is blue.) This process was first described in the nineteenth century by the Nobel-prize-winning British physicist John William Strutt, the third Baron Rayleigh.

16. How accurate are aerosol measurements made with the GLOBE sun photometer?

The accuracy of sun photometer measurements has been studied for decades by atmospheric scientists, and it remains a topic of some debate. There are some inherent limitations to measuring atmospheric aerosols from Earth's surface, and there are also some limitations imposed by the design of the GLOBE sun photometer.

Measurements made carefully according to the protocols should be accurate to within less than about 0.02 AOT units. For very clear skies, with AOT values of perhaps less than 0.05, this is a significant percentage error. However, even operational "professional" sun photometers claim accuracies of no better than 0.01 AOT units. Thus, the accuracy of measurements made carefully with a GLOBE sun photometer are comparable to measurements made with other sun photometers.

Unlike some other GLOBE measurements, there is no easily accessible standard against which to check the accuracy of AOT calculations. GLOBE aerosol measurements will be subjected to scrutiny by the GLOBE Science Team and others for the foreseeable future. Nevertheless, it is fair to say that GLOBE aerosol measurements can achieve a level of accuracy that can be extremely useful to the atmospheric science community.

17. Will scientists really be interested in my aerosol measurements?

The answer to this question is an only slightly qualified "Yes." Comparatively few sun photometers are in use around the world. Since recent studies have shown that aerosols can block considerable sunlight, thus causing a cooling effect on Earth's climate, there is renewed interest in sun photometer measurements.

Upcoming Earth-monitoring satellite missions will focus on global characteristics of the atmosphere and its constituents. It is essential that reliable ground- based data measurements be available to calibrate satellite instruments and validate their measurements.

GLOBE schools provide the potential to establish a global aerosol monitoring network that is otherwise unattainable. On a regional scale, there is essentially no comprehensive monitoring of aerosols produced naturally by water vapor, naturally occurring forest and brush fires, dust, pollen, gases emitted by plants and trees, sea salt, and volcanic eruptions. The same is true for monitoring aerosols produced by automobile emissions, coal-burning power plants, intentional burning of forests and rangelands, certain industrial and mining operations, and dust from unpaved roads and agricultural fields. Again, GLOBE schools provide the potential for addressing these topics.

Here's the qualification to the "Yes." In most situations, aerosol measurements must be taken in the same place for many months, and even for years, in order to have lasting scientific interest. It is sometimes difficult to keep in mind the long-term value of taking the same measurements day after day. (This is not just a problem for aerosol measurements, of course.) In the case of aerosols, persistence is especially important due to the long time scales required to observe and analyze significant changes in the atmosphere.

What about ground validation measurements for space-based measurements? In this case, even a few accurate ground-based measurements can be valuable. However, it is still important to establish as long a data collection record as possible. This will give scientists confidence in your work, and will establish an aerosol "baseline" for your observing site, against which to evaluate unusual conditions when they occur.

So, the conclusion is: If you follow the protocols and provide careful measurements (especially during the summer), then there is no doubt that scientists will value your contribution now and in the future.

Aerosols Protocol – Looking At the Data

Are the data reasonable?

Perhaps your first thought about determining whether your data are reasonable would be to consider the voltages measured using your sun photometer. This is not as easy as it might seem! A sun photometer converts light from the sun to a voltage; this is what you measure and report to GLOBE. The relationship between the intensity of the light and the voltage produced is determined by the sensitivity of the detectors in your sun photometer (a green or red light emitting diode) and the gain provided by your sun photometer's battery-powered amplifier. This relationship is different for every GLOBE sun photometer, so each instrument has its own calibration constants (one for each of the two channels) that allow aerosol optical thickness to be calculated from the voltages you report.

The GLOBE sun photometer produces a small output voltage even when the sun is not shining on the detector. This "dark voltage," should be small, but how small? GLOBE performs some range checks on both the sunlight and dark voltages. However, reasonable voltages fall within a wide range of values. In some cases, your sun photometer's dark voltage may be only a few tenths of a millivolt. If so, it may display as 0 when you are using a 2 V (or 2000 mV) range setting on your digital voltmeter.

So, it is not easy to predict what "reasonable" voltages are for your sun photometer. However, after you have done the Aerosol Protocol a few times, you will get a good sense of what dark voltages your instrument produces and what sunlight voltages to expect under certain sky conditions. Remember that, generally, these ranges will be different for the green and red channels because of the differences in the detector responses and electronics.

It is much easier to determine whether the aerosol optical thicknesses calculated from your measurements at green and red wavelengths are reasonable. Table AT-AE-2 gives some typical ranges for aerosol optical thickness (AOT).

Table AT-AE-2

Sky condition	Green channel	Red channel
Extremely clear	0.03-0.05	0.02-0.03
Clear	0.05-0.10	0.03-0.07
Somewhat hazy	0.10-0.25	0.07-0.20
Hazy	0.25-0.5	0.02-0.40
Extremely hazy	>0.5	>0.4

The relationship between these numerical values and the sky clarity description (required as part of your data reporting) are only approximate, and may vary depending on local conditions.

Note that red AOT values are typically less than green AOT values. This is due to the fact that typical aerosols scatter green light more efficiently than red light. (The larger the AOT, the more light is being scattered away from the direct beam of sunlight that reaches your sun photometer's detector.) If the red AOT is larger than the green, it is not necessarily wrong, but it is an unusual enough occurrence that it should trigger a closer examination of the conditions under which the measurements were taken.

What do scientists look for in these data?

As noted above, green AOT values are usually higher than red AOT values. When the Science Team looks at your data, they will check that the relationship between the two channels appears reasonable.

The *Aerosols Protocol* requires that you report at least three sets of sun photometer measurements taken within the span of a few minutes. Assuming that you are pointing your sun photometer carefully and consistently toward the sun, differences among the three voltages for each channel are a measure only of the variations in the atmosphere at the time you are taking your measurements. If the differences are large, it may mean that clouds are drifting across the sun while you are taking measurements.

Scientists will also look carefully at cloud cover and type reports and will compare the AOT values calculated from the voltage measurements with reports of sky color and clarity. Cirrus clouds are of particular concern, as they can greatly reduce the transmission of sunlight even when they are almost invisible.

AOT tends to vary seasonally. Warm and humid days in temperate and equatorial climates can produce photochemical smog, especially in urban areas. Consequently, AOT tends to be higher in the summer than in the winter. This seasonal cycle can be difficult to find in GLOBE data, as many GLOBE schools do not report data during summer vacations. Figure AT-AE-1 shows some aerosol data from East Lincoln High School, Denver, NC, USA. Students made some measurements through the spring of 2000 and another class restarted the measurement program in the fall of 2000. Some of the values (especially the very low values) appear to be in error. Although it appears to be the case that warm weather produces higher AOT values, the lack of summertime measurements means that this conclusion cannot really be supported by these limited data.

Note also in Figure AT-AE-1 that there are some very high AOT values recorded in 1999. There are several possible explanations for these values. One possibility is, of course, that these data represent actual very hazy conditions. Another possibility is that students were initially unfamiliar with the sun photometer and recorded sunlight voltages that were too low (which will lead to AOT values that are too high). A third possibility is that there were some clouds between the observer and the sun. The AOT values themselves do not help us choose among these possibilities. The additional information scientists need to make decisions about the quality of sun photometer measurements can be obtained only by looking at all the measurements and their accompanying metadata.

One of the most exciting opportunities for students working with the *Aerosols Protocol* is to compare their measurements with other ground- and satellite-based measurements. Such comparisons can serve both as a check on GLOBE measurements and on the performance of other sun photometers. One source of aerosol data is the Aerosol Robotic Network (AERONET), managed by NASA's Goddard Space Flight Center. This ground-based network has about 100 sun photometers in operation at various locations around the world. The AERONET sun photometers are automated, solar-powered instruments. Their advantage is that they can operate unattended even in remote locations, broadcasting the results of their pre-programmed measurements to satellites, which then beam data to a central ground station for processing. The primary disadvantage of these automated devices is that there is no human observer to make decisions about whether a sun photometer measurement should be made at a particular time. Algorithms are applied to "screen" the measurements for cloud contamination. However, these algorithms are not perfect. They may, for example, suffer from the same lack of ability to distinguish thin cirrus clouds as ground-based observers. Thus, comparisons of automated and manual measurements provide a fascinating and extremely important check on the performance of both systems.

Figure AT-AE-2 shows a comparison of GLOBE sun photometer data with data from AERONET sun photometers. (AERONET data are publicly available online.) AERONET makes measurements every few minutes throughout the day. The GLOBE data sometimes fall near the lower range of AERONET values within a day. A more detailed examination of these data with an expanded time scale (to look at individual days) would clarify the relationship between these two datasets; this would make an excellent student project.

Figure AT-AE-3 shows comparisons between AOT values derived from the MODIS satellite and measurements made by students at East Lincoln High School, Denver, North Carolina, USA. (The MODIS data points are connected with solid lines, but this is only to make the data easier to follow; there is no reason to expect that missing MODIS data would fall along the lines.) Note that the GLOBE data again tend to cluster near the lower MODIS AOT values.

Some of the MODIS values in Figure AT-AE-3 seem very high. Figure AT-AE-4 offers some insight

Figure AT-AE-1: Sun Photometer Data (minimum AOT from a set of three) from East Lincoln High School, Denver, NC,

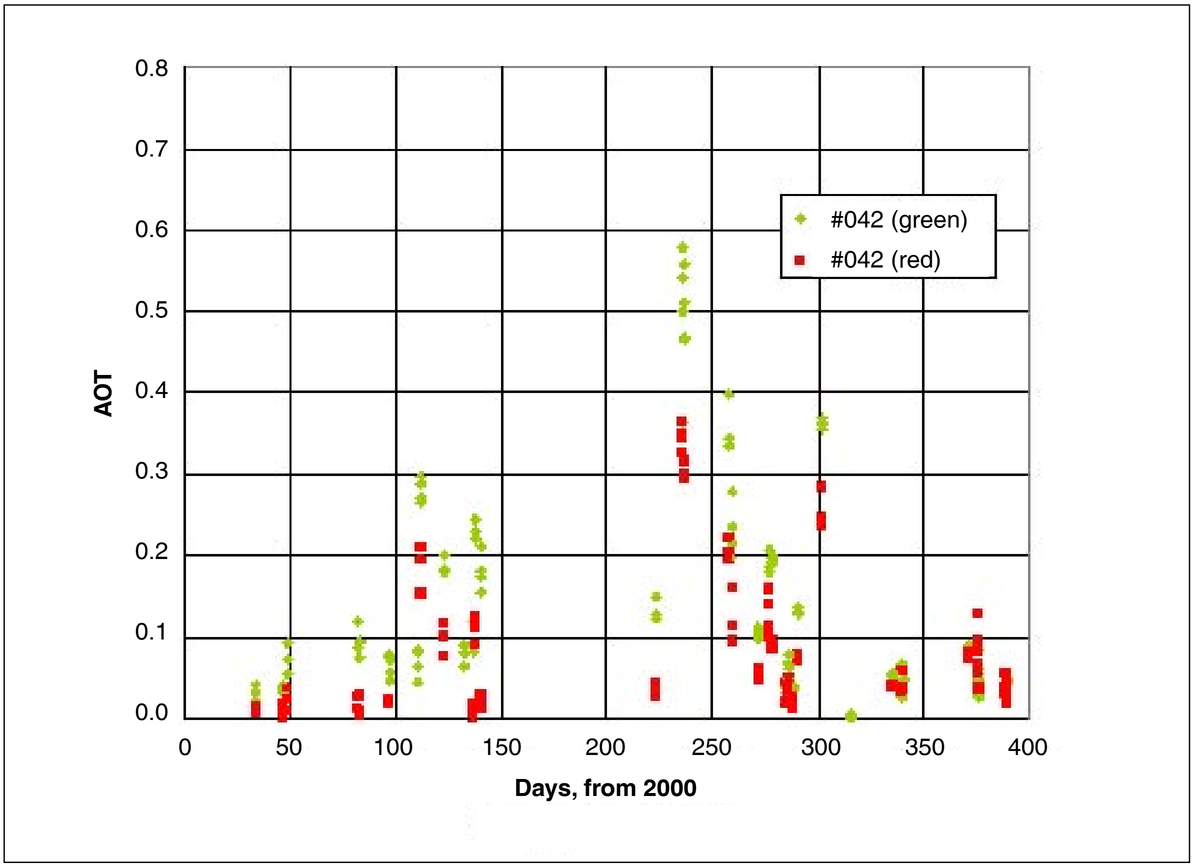


Figure AT-AE-2: Comparison of GLOBE Sun Photometer Measurements Made at Drexel University, Philadelphia, Pennsylvania, USA, with a Nearby AERONET Sun Photometer

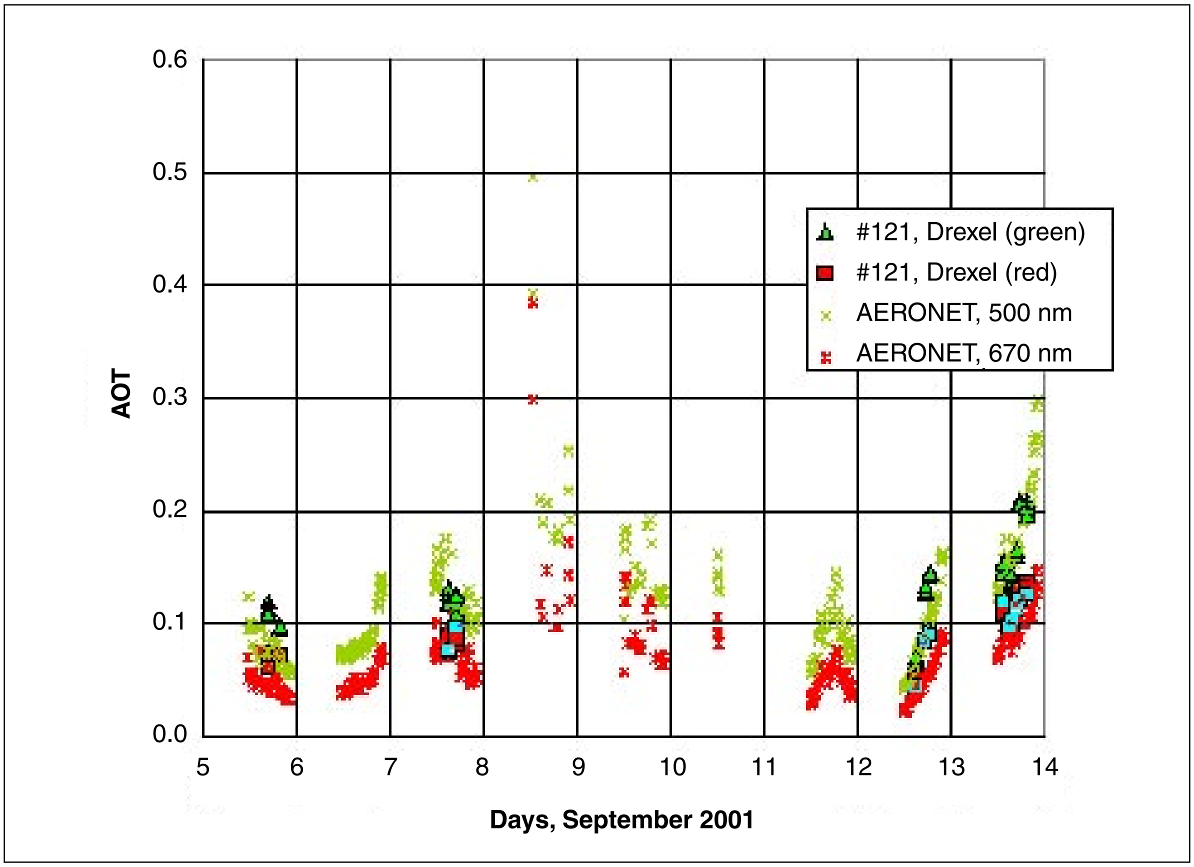


Figure AT-AE-3: Comparison of MODIS Data and GLOBE Sun Photometer Measurements Made at East Lincoln High School, Denver, NC, USA.

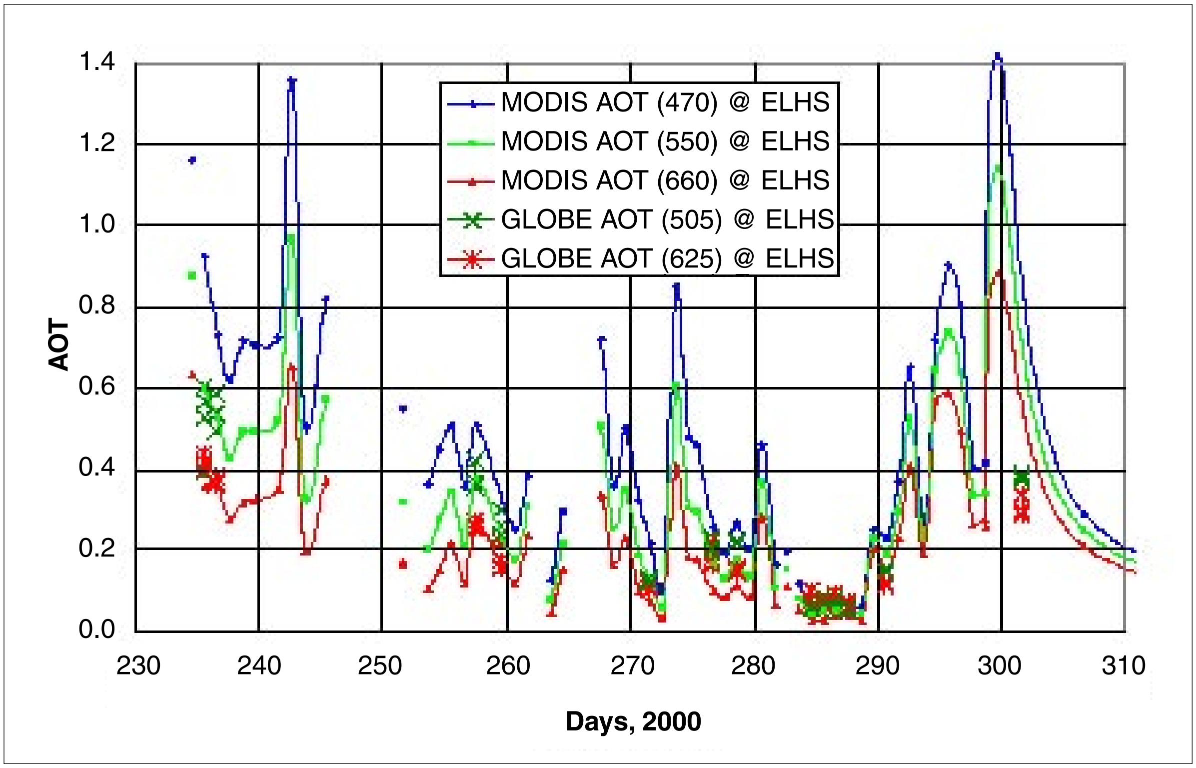
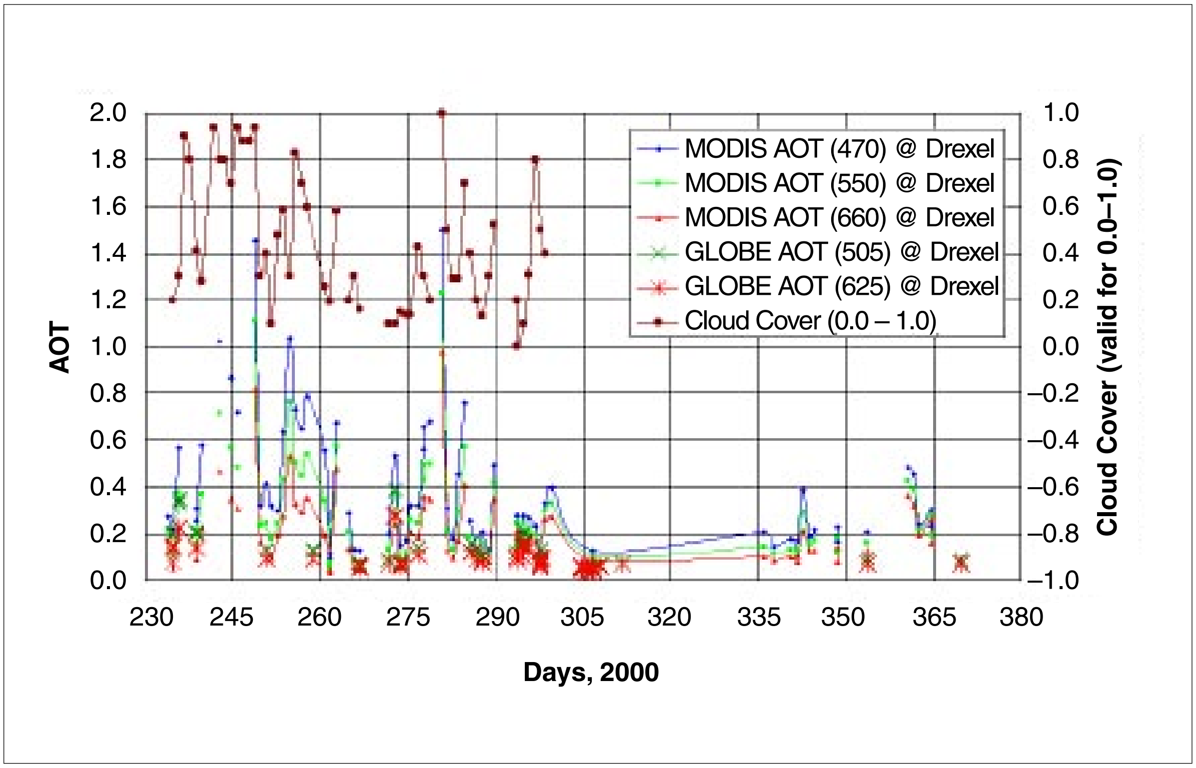


Figure AT-AE-4: Comparison of MODIS Data, GLOBE Sun Photometer Measurements, and Cloud Cover at Drexel University, Philadelphia, Pennsylvania, USA.



into why this might be so. These measurements from Drexel University include the percentage of daytime cloud cover. Clearly, some of the very high MODIS AOT values are associated with cloudy days. Drexel University is located in an urban area with a mixture of water (two rivers flow through Philadelphia), residential and commercial urban development, and green space (a large park). This kind of complicated surface is the most difficult for data reduction algorithms to analyze and the results shown in Figure AT-AE-4 may indicate problems with cloud discrimination over complicated surfaces. Whatever the explanation, Figures AT-AE-3 and AT-AE-4 show clearly the importance of carefully reporting metadata that define the conditions under which sun photometer measurements are taken.

When GLOBE student sun photometer measurements are taken carefully, data such as shown in Figures AT-AE-2, AT-AE-3 and AT-AE-4 can provide valuable information for scientists who are involved in understanding the global distribution of aerosols. The ability of human observers to characterize the circumstances and quality of their measurements provides an opportunity that unattended and satellite-based instruments can never match.

Locally, aerosol optical thickness can be influenced by air quality, season, relative humidity, natural and human-caused events such as volcanoes, forest fires and biomass burning, agricultural activity, windblown dust, and sea spray. All these connections provide many possible sources for student research projects.

Calculating Aerosol Optical Thickness (Advanced Students Only)

When you report voltage measurements from your sun photometer to GLOBE, the aerosol optical thickness (AOT) is calculated and reported. This calculation is too complicated for most GLOBE students to do on their own. However, if you are familiar with logarithmic and exponential equations, you can calculate AOT yourself using the following formula:

$$\text{AOT} = \frac{[\ln(V_o/R^2) - \ln(V - V_{dark}) - a_R(p/p_o)m]}{m}$$

Where:

ln is the natural (base *e*) logarithm

V_o is the calibration constant for your sun photometer. Each channel (red and green) has its own constant, which you can obtain from the GLOBE Web site.

R is the Earth-sun distance expressed in astronomical units (AU). The average Earth-sun distance is 1 AU. This value varies over the course of a year because the Earth's orbit around the sun is not circular. An approximate formula for R is:

$$R = \frac{(1 - \varepsilon^2)}{[1 + \varepsilon \cos(360^\circ \bullet d/365)]}$$

Where ε is the eccentricity of the Earth's orbit, approximately equal to 0.0167, and d is the day of the year. (Eccentricity is a measure of the amount by which the Earth's orbit differs from a circle.) Note that this equation predicts that the minimum value for R occurs at the beginning of the year. The actual minimum Earth-sun distance occurs, in fact, in early January but not on January 1.

V and V_{dark} are the sunlight and dark voltage from your sun photometer.

a_R is the contribution to optical thickness of molecular (Rayleigh) scattering of light in the atmosphere. For the red channel a_R is about 0.05793 and for the green channel it is about 0.13813.

p is the station pressure (the actual barometric pressure) at the time of the measurement.

p_o is standard sea level atmospheric pressure (1013.25 millibars).

m is the relative air mass. Its approximate value is:

m= 1/sin(solar elevation angle)

where solar elevation angle can be obtained from the *Making a Sundial Learning Activity* or by using a clinometer.

When GLOBE calculates AOT, it uses a series of equations to more accurately calculate the Earth-sun distance. For relative air mass, it uses those same astronomical equations to calculate solar position from your longitude and latitude and the time at which you took your measurement. Then it uses the calculated solar elevation angle to calculate relative air mass, using an equation that takes into account the curvature of Earth's atmosphere and the refraction (bending) of light rays as they pass through the atmosphere.

As a consequence of using these more complicated equations, GLOBE's AOT values will not agree exactly with the calculation described here. The smaller the AOT, the greater the difference is likely to be. Consider this example:

Date: July 7, 1999

Sun photometer calibration constant (V_o): 2.073 V

Solar elevation angle: 41°

Station pressure: 1016.0 millibars

Dark voltage: 0.003 V

Sunlight voltage: 1.389 V

Sun photometer channel: green

July 7, 2001, is the 188th day of the year, so:

$R = (1 – 0.0167^2)/[1 + 0.0167 \bullet \cos(360^o \bullet 188/365)] = 1.0166$

The relative air mass is:

$m=1/\sin(41^o) = 1.5243$

Then, aerosol optical thickness is:

$AOT = [\ln(V_o/R^2) - \ln(V - V_{dark}) - a_R(p/p_o)m]/m$

$\ln(V_o) = \ln (2.073/1.01662^2) = \ln(2.00585) = 0.6960$

$\ln(1.389-0.003) = \ln(1.386) = 0.3264$

$a_R(p/p_o)m = (0.1381)(1016/1013.25)(1.5243) = 0.2111$

$AOT = (0.6960 - 0.3264 - 0.2111)/1.5243 = 0.1040$

GLOBE's calculated AOT value for these data is 0.1039, a difference small enough to ignore for these measurements.

In some situations, your AOT value may not agree this well with GLOBE's value. For example, if the solar elevation angle you observe with your solar gnomon is different from the value calculated by GLOBE – then the relative air mass calculated from your observed solar elevation angle will not be accurate. This will cause the AOT calculation to be in error.

AOT can be expressed as the percent of sunlight at a particular wavelength that reaches the Earth's surface after passing through a relative air mass of 1. For this example with the green channel,

$\%\ \text{transmission} = 100 \bullet e^{-AOT} = 100 \bullet e^{-0.1040} = 90.1\%$