INEXPENSIVE SUN PHOTOMETERS FOR MONITORING THE ATMOSPHERE

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ABSTRACT

In response to global issues of air quality and climate change, and to the need to improve the quality of science education, inexpensive atmosphere monitoring instruments have been developed that are suitable for use by teachers, students, and other non-specialists. These instruments have both pedagogical and scientific value, as they can be deployed in spatially dense networks that are not practical for much more expensive research-quality instruments. Light emitting diodes can sometimes be used as spectrally selective detectors for such instruments. These devices are very inexpensive, optically stable, and virtually indestructible. The design of visible light sun photometers for measuring aerosol optical thickness and near-IR sun photometers for measuring total atmospheric column water vapor is described. Calibration and data collection protocol issues dominate the development of such instruments. Extensive experience in the field demonstrates that students and teachers, working in collaboration with scientists, can calibrate instruments and use them to collect valuable, scientifically reliable data about atmospheric properties. Several examples of student-collected data are shown.

KEYWORDS: aerosols, air quality, instrument design, optical thickness, science education, sun photometry

1. INTRODUCTION

This work is based on two considerations:

1. The need to respond to air quality and climate change as global issues;
2. The need to improve Earth science education by providing opportunities for collaborative partnerships among scientists, teachers, and students.

The circulation of the atmosphere means that many environmental quality issues must be considered on regional and global scales. Increasing production of aerosols is both a local and regional problem. Air quality is decreasing in many parts of the world. Especially in rapidly developing countries, it is difficult to impose strict pollution control measures on industrial and transportation sectors that are responding to the demands of economic expansion. When economic development is successful, rising standards of living increase demands on resources and increase per capita power consumption – a major contributor to anthropogenic climate change.

Remote sensing and imaging of the Earth/Atmosphere system have dramatically and conclusively demonstrated the global nature of these problems. Local and regional aerosols, both natural and manmade, are transported around the globe. Saharan dust and smoke from sub-Saharan biomass burning travel westward across the Atlantic to the Caribbean, Central America and the southern United States. Dust, smoke, and industrial pollution from Asia travel eastward across the Pacific. In large cities in the United States, where monitored surface ozone levels form the basis for regulatory action by the Environmental Protection Agency, the number of non-complying ozone days may be increased significantly not by local activity, but by the transport of air pollution from hundreds of kilometers away. The global distribution and transport of water vapor, and its relationship to other air quality issues, is still poorly understood. These kinds of problems are exacerbated by the increased power consumption resulting from growing populations and rising standards of living. Developing countries may not have the infrastructure and resources needed to control emissions. Industrialized countries are slow to exercise leadership in the development of sustainable energy sources that are needed even now to limit spiraling fossil fuel consumption, and will become essential later in this century.

Because of the strong links among the atmosphere, surface air quality, human health, and quality of life, it is essential to involve the public, and especially teachers and students, with the underlying science that provides the means of understanding and dealing with these issues. Earth and atmospheric science provide many opportunities for scientific and educational collaborations, as many of the concepts and questions can be understood at least qualitatively by non-specialists. The challenge is to enable students and teachers to be *participants* in the science process and not just *observers*. Work with the GLOBE Program (an international environmental science and education program, see www.globe.gov) since 1998 has shown these kinds of authentic science partnerships to be entirely feasible. In addition to supporting standard meteorological and hydrological measurements, GLOBE and the United States' National Aeronautics and Space Administration (NASA) also sponsored development of several inexpensive atmosphere monitoring instruments that are suitable for use by teachers, students, and other non-specialists. These include a handheld two-channel visible light sun photometer for measuring aerosol optical thickness, a two-channel near-IR sun photometer for measuring total column water vapor, a UV-A radiometer/sun photometer, and a silicon solar cell-based pyranometer for measuring insolation at Earth's surface. The first two of these are discussed in this paper.

The challenge for sun photometry is that research-quality instruments are very expensive and require ongoing maintenance. The Aerosol Robotic Network (AERONET) [1] is the only truly global sun photometer network. The approximately 150 AERONET instruments, which cost approximately US$25,000 each, are distributed worldwide but still provide only a very coarse-resolution view of global distribution and transport of aerosols and water vapor. Both the initial cost of research-quality sun photometers and the ongoing cost of maintaining them are prohibitive for truly global monitoring. One way to provide more detail – for example, to provide spatially dense coverage within a small region of interest – is to develop a network that includes much less expensive sun photometers that can be used and maintained by teachers, students, and other non-specialists, and whose performance can be monitored by ongoing comparisons against more expensive instruments.

It is true that highly industrialized countries often already have extensive air quality monitoring capabilities that can be locally dense. However, in the United States, for example, these capabilities are intended primarily for regulatory rather than scientific purposes. That is, the purpose of surface air quality monitoring is primarily to determine the degree of compliance with air quality standards. While these data may be useful for enhanced understanding of air quality at Earth's surface, they do not necessarily address broader questions of scientific interest – total column amounts of atmospheric constituents and their regional transport, for example. Hence, there remains a great need for collaborations among scientists, teachers, and students that *can* address these issues.

2. MATERIALS AND METHODS

2.1 Instrument Design Considerations

The primary design consideration for inexpensive atmospheric monitoring instruments is the cost and optical performance of their detectors. The two-channel visible light sun photometer shown in Figure 1 uses green and red light emitting diodes (LEDs) as spectrally selective detectors. This ingenious application of LEDs to sun photometry was first described by Mims [2]. LEDs are not ideal detectors for sun photometry, because of their relatively wide spectral response. The spectral response characteristics of LEDs are always different from their emission spectra (which are readily available from manufacturers) and must be measured directly. The detector spectral responses for the sun photometer design shown in Figure 1 are given in Figure 2. Testing of many LEDs during the development of this instrument has shown that, while the current output from a batch of identical LEDs can vary significantly from sample to sample, the differences in spectral response are not significant. Brooks and Mims [3] have shown how to assign an effective wavelength for determining aerosol optical thickness (AOT), as a substitute for the monochromatic assumption that can be made for filtered detectors with response bandwidths of only a few nanometers. Several years of field experience demonstrate conclusively that this substitution is valid, that LED-based sun photometers can be can be calibrated against research-quality instruments such as the CIMEL sun photometers used by AERONET, and that they can be used for high-quality measurements of AOT. In contrast to the interference filters and photodetectors used in more expensive sun photometers, LEDs are inexpensive, virtually indestructible, and optically stable. These characteristics make LEDs ideal for student use and for measurements in spatially dense networks, and more than overcome their potential disadvantages. Detailed data collection protocols are essential, as these detectors do exhibit some temperature sensitivity.

For near-IR water vapor sun photometers [4], the case for LED detectors is less clear because the significant temperature sensitivity of some otherwise suitable LEDs precludes their effective use. As an alternative, it is possible to purchase relatively inexpensive filtered photodiodes (less than US$20) at appropriate wavelengths. Water vapor transmission through the atmosphere and the normalized spectral response of some possible detectors is shown in Figure 3. One successful water vapor instrument design uses a 940 nm filter, centered over a strong water vapor absorption band, and an LED whose response peaks at about 825 nm. The LED response overlaps a much weaker water vapor absorption band, but still provides sufficient sensitivity, with minimal temperature sensitivity, to changes in column water vapor. This LED can be replaced with a filtered photodiode at 870 nm, but this has not been shown to provide significant improvements in instrument performance. The long-term performance of these filter-based instruments must be monitored carefully.

3. RESULTS AND DISCUSSION

3.1 Calibrating LED-Based Sun Photometers

Calibration is especially important for these inexpensive instruments. For several years, the GLOBE Program sponsored yearly calibration of one or two visible light reference sun photometers at Mauna Loa Observatory, using the well-known Langley plot method. This is the generally accepted “absolute” calibration method for sun photometers and MLO is the premier site for such work because of its stable meteorology. Instruments for use in the field, identical to the reference instruments, are then calibrated by collecting data side-by-side and forcing the derived aerosol optical thickness values to agree. This method has been implemented successfully for several hundred sun photometers produced for the GLOBE Program. Figure 4 shows AOT values derived from student data collected at the Ramey School, Aguadila, Puerto Rico, USA, from an LED-based sun photometer previously calibrated against an identical MLO reference instrument, compared with cloud-screened AOT values from an AERONET site in La Parguera, Puerto Rico, about 60 km to the south. Average ozone optical thickness corrections of -0.01 and -0.03 are applied to the 505-nm and 625-nm optical thickness values. The AERONET data use climatological average modeled ozone corrections, but the differences are minor.

These data show good qualitative agreement but, considering the distance between the two sites, there is no justification for more quantitative comparisons. The high AOT values may be caused by Saharan dust blowing across the Caribbean, a common occurrence often noted in the data submitted from the Ramey School (as determined from aviation reports and other sources). The high LED sun photometer AOT values around day 30 are questionable, as are the very low values occurring throughout the year. Additional qualitative information provided with the raw data from these instruments, including cloud cover and type, sky color, and horizontal visibility, can be used to assess the quality of the data.

When AOT data are to be compared with AERONET data, it is reasonable to calibrate LED-based sun photometers directly against an AERONET sun photometer. Figure 5 shows such a data set from NASA's Goddard Space Flight Center, the home of the AERONET project and the place where the reference AERONET sun photometers are maintained. These data were collected by secondary school students in April, 2006.

Figure 5 illustrates the opportunities and some potential problems for such an approach. The handheld sun photometer had already been independently calibrated against an MLO reference instrument. Using this calibration, the agreement of the 505-nm channel with AERONET's 500-nm channel is excellent – even the AERONET AOT values are considered to be no more accurate than about 0.005-0.010 AOT units. The red channel data show the effects of sunlight heating the red LED detector, which is more temperature-sensitive than the green channel. The higher the detector temperature, the higher the channel's output voltage and the lower the derived AOT. In this case, student observers were told by their teacher to "be very careful with these important measurements." As a result, they took much longer to record a set of five green/red voltage pairs than would normally be the case. This entire process should take no more than two or three minutes, but instead took three times as long. So, although the original case temperature was maintained within prescribed limits (20-25°C) at the start of each measurement set, the detector heated considerably during each data collection period. Despite this potential problem, multiple readings during each "measurement" are still considered essential to provide a quality control check on meteorological conditions and observer proficiency.

The agreement for both channels could easily be improved by making sure that data collectors are aware of the importance of controlling heating of the LED detectors, and by adjusting the calibration coefficients to force better agreement with the AERONET values. The wavelength differences can be taken into account by calculating AERONET Ångstrom coefficients and adjusting the AERONET AOTs to the LED sun photometer wavelengths. This is more important for the red channel because of the larger wavelength difference – 625 *vs* 675 nm.

Another way of characterizing the performance of LED sun photometers is to compare independently calibrated instruments against each other. Figure 6 shows 2005 AOT data from an elementary school in Arkansas, USA. These students often report simultaneous or nearly simultaneous data from several sun photometers. Considering that Figure 6 represents *all* data submitted, without any additional quality control criteria being applied, these two instruments are in excellent agreement. The differences at high AOT values may be due not to calibration differences between the two instruments, but to variable cirrus cloud contamination of the direct view of the sun. This would explain the relatively high AOT values and would affect those values whenever the measurements were not made at exactly the same time.

3.2 Calibrating Handheld Water Vapor Sun Photometers

Water vapor instruments present a more difficult calibration challenge than sun photometers used for optical depth measurements. Although it is possible, in principle, to calibrate such a water vapor sun photometer using radiative transfer models and a thorough characterization of an instrument's optical and electronic performance, such an undertaking would not be feasible for large numbers of inexpensive instruments. Instead, calibrations must be based on comparisons with independently derived total column water vapor values. Two possible sources are the water vapor product from AERONET and water vapor retrievals from Global Positioning Satellite Meteorology (GPS-MET) sites [5], of which there are several hundred in the United States. For water vapor instruments with identical detectors and electronics, the output of each channel will still vary from instrument to instrument, because of differences in the electronic gain and detector current output. A single calibration constant can account for these differences and can be used to relate the ratio of the two IR channels to total column water vapor [6]. Then, field instruments can be calibrated using side-by-side measurements with a reference instrument, as is done for the visible light sun photometers.

A teacher and students at the Ramey School, Aquadila, Puerto Rico, calibrated a water vapor instrument in 2004 against a nearby GPS-MET site at Isabela, Puerto Rico (less than 10 km away), and have provided measurements since that time. Figure 7 shows water vapor derived from these measurements along with all GPS-MET water vapor data from Isabela during 2005. Note that the sun photometer measurements closely track the GPS-MET data and provide some water vapor data during times when the Isabela site was out of operation. Regression analysis of Ramey School water vapor values against the closest (in time) GPS-MET site value, whenever both sources are available, yields a variance $r^2 = 0.971$ with standard error = 0.177 for 2005 data and $r^2 = 0.967$ and s.e. = 0.246 for 2006 data. In 2006, the handheld instrument water vapor values tend to be a little higher than the corresponding GPS-MET data, which accounts for the slight decrease in r^2 and increase in s.e. and which suggest that this instrument may need to be recalibrated. It is a reasonable expectation even for a research-quality instrument to require recalibration after two years. If a calibration drift is confirmed for this instrument, the most likely cause is a change in the transmission of the near-IR filter relative to the LED.

4. DISCUSSION AND CONCLUSIONS

This paper has shown that it is entirely feasible to design relatively inexpensive (~US$100) atmosphere monitoring instruments that can be used by teachers, students, and other non-specialists and that produce reliable, scientifically valuable data. In addition to their pedagogical value, science applications for simple handheld instruments include ground validation for space-based measurements and for other situations where spatially dense measurements can provide data that are not practical to obtain with large numbers of research-quality instruments.

LEDs and other inexpensive detectors, as used in the visible light and near-IR sun photometers described in this paper, can be applied to other instruments as well [7]. A UV-A radiometer/sun photometer has been developed that uses a blue-emitting LED with a strong spectral response peak at 372 nm. This instrument was designed for validating algorithms developed for deriving column ozone and UV radiation at Earth's surfaced based on measurements from the Ozone Monitoring Instrument (OMI) on NASA's Aura spacecraft. A UV-A measurement provides a way of monitoring spatial and temporal variability of UV radiation at a wavelength where ozone absorption is insignificant; this allows separation of ozone variability from other sources of variability such as aerosols and cloud cover.

An inexpensive silicon solar cell-based pyranometer, similar to commercial pyranometers widely used for agricultural and environmental monitoring, can be built for less than US$20. A four-channel radiometer that can be rotated 180° to measure incoming and reflected radiation uses the same red and green LED detectors as the two-channel visible light sun photometer, the near-IR LED used in the water vapor sun photometer, and a small silicon solar cell; it can be built for less than US$50. This instrument gives an ideal "hands on" introduction to multispectral radiometry, and can also provide scientifically interesting data about variability in surface reflectance.

There remains within the scientific community some skepticism about the value of student-collected data using "homemade" instruments. The best way to counter this skepticism is to implement rigorous and well-documented calibration and maintenance programs and to present data, as in this paper, that have not been "sanitized." Calibration issues also apply to professional instruments, but are easy to overlook because they are included in the higher initial cost of such instruments. Recalibration and maintenance can be expensive and disruptive, so it is often the case that even high-quality commercial atmosphere monitoring instruments are not well-maintained.

Other concerns include protecting instruments that are not necessarily weatherproof, uncompensated temperature sensitivity, and *ad hoc* data collection procedures. However, these concerns can be addressed by using detailed written data collection protocols and by providing thorough training for motivated observers. The value of building and calibrating instruments with some obvious design constraints, and then characterizing their performance, cannot be overestimated. Even at the university level, there remains a great need for students to understand the instruments they use. Highly developed instrumentation with automated data collection and digital storage systems can mask the underlying realities of measurements in an analog world – realities that can never be ignored even with the most expensive instruments.

In developing countries with little infrastructure in place for environmental monitoring, the inexpensive approaches described here have a significance that extends far beyond their pedagogical value. With proper guidance of motivated students, teachers, and other non-specialists, networks of inexpensive instruments can be used alongside just a few research-quality instruments to build a high-quality monitoring network that addresses national environmental monitoring priorities and provides real benefits for all participants.

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Figure 1. Two-channel visible light sun Photometer with LED detectors.

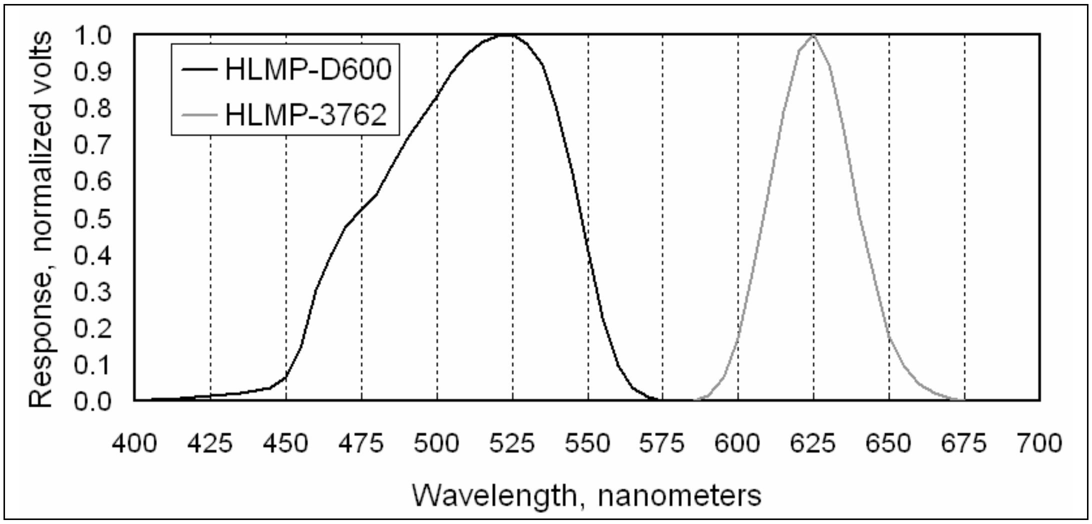

Figure 2. Spectral response of green and red LEDs used as detectors in visible light sun photometers.

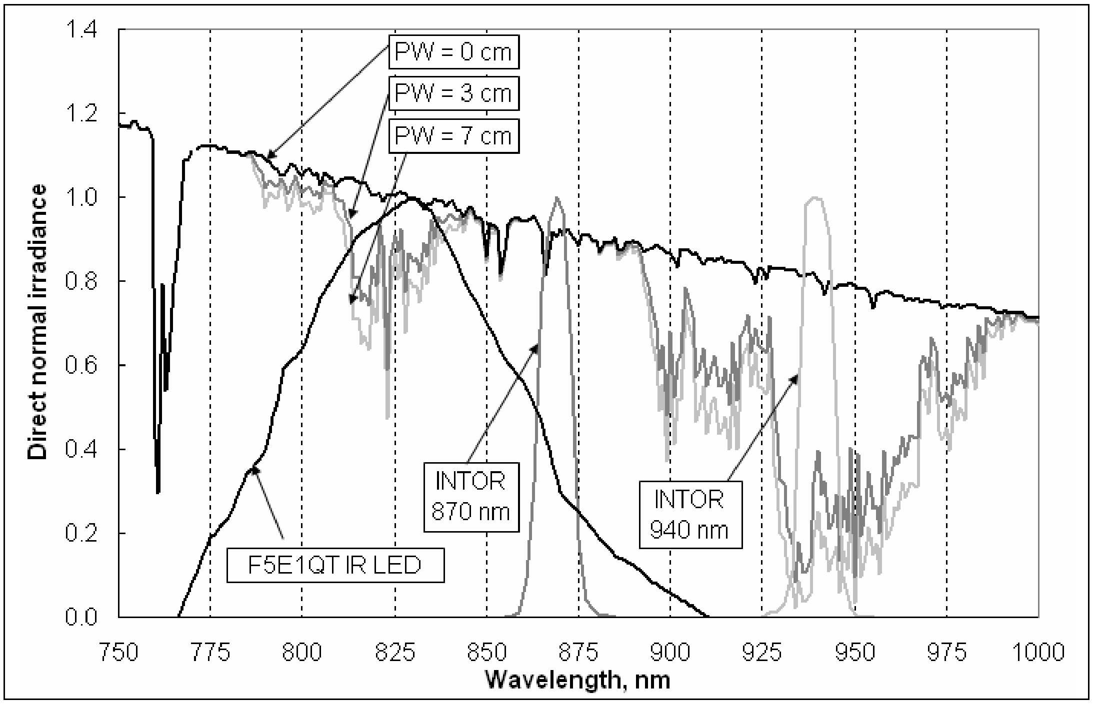

Figure 3. Water vapor transmission through the atmosphere and spectral response of possible near-IR detectors.

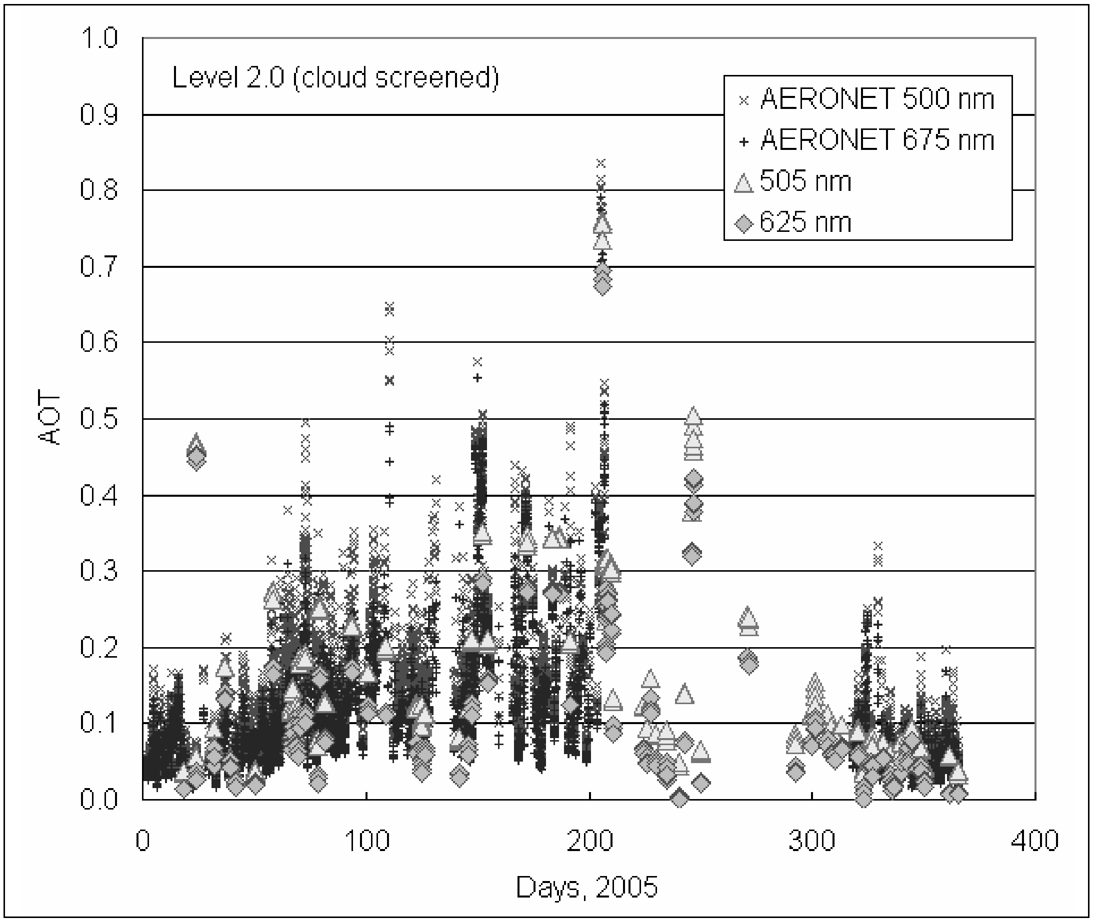

Figure 4. 2005 AOT data from AERONET site, La Parguera, Puerto Rico, USA, and LED sun photometer from Ramey School, Aguadila, Puerto Rico, USA.

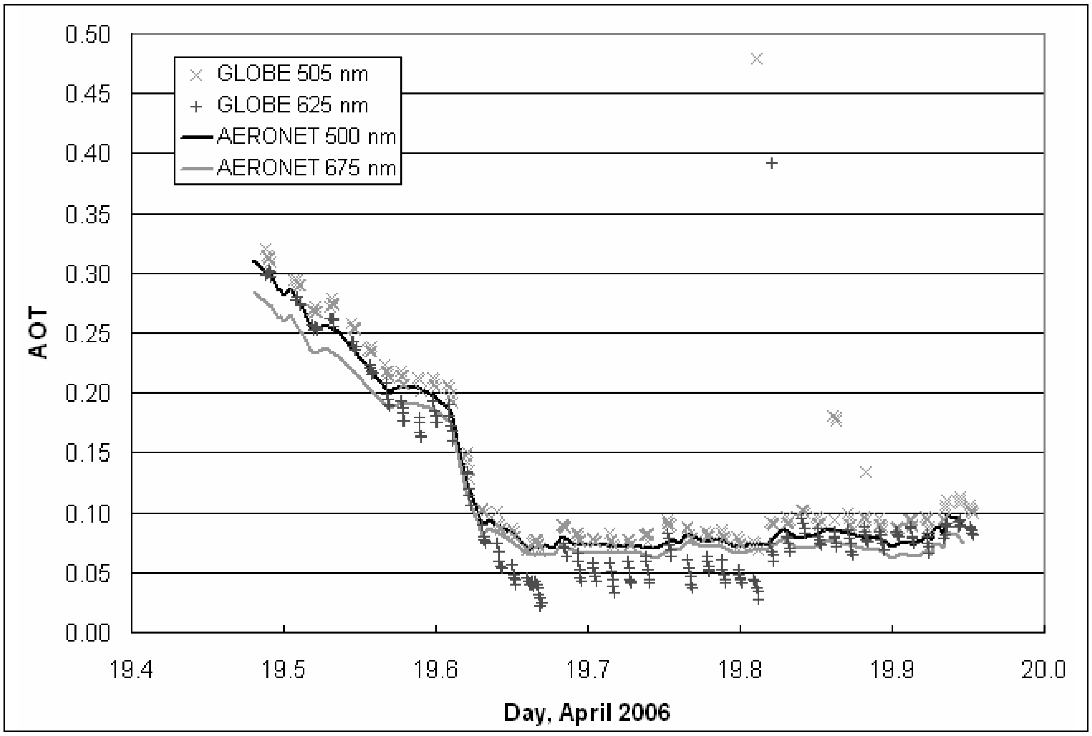

Figure 5. Student measurements with previously calibrated LED sun photometer, compared to AERONET data at National Aeronautics and Space Administration, Goddard Space Flight Center, USA.

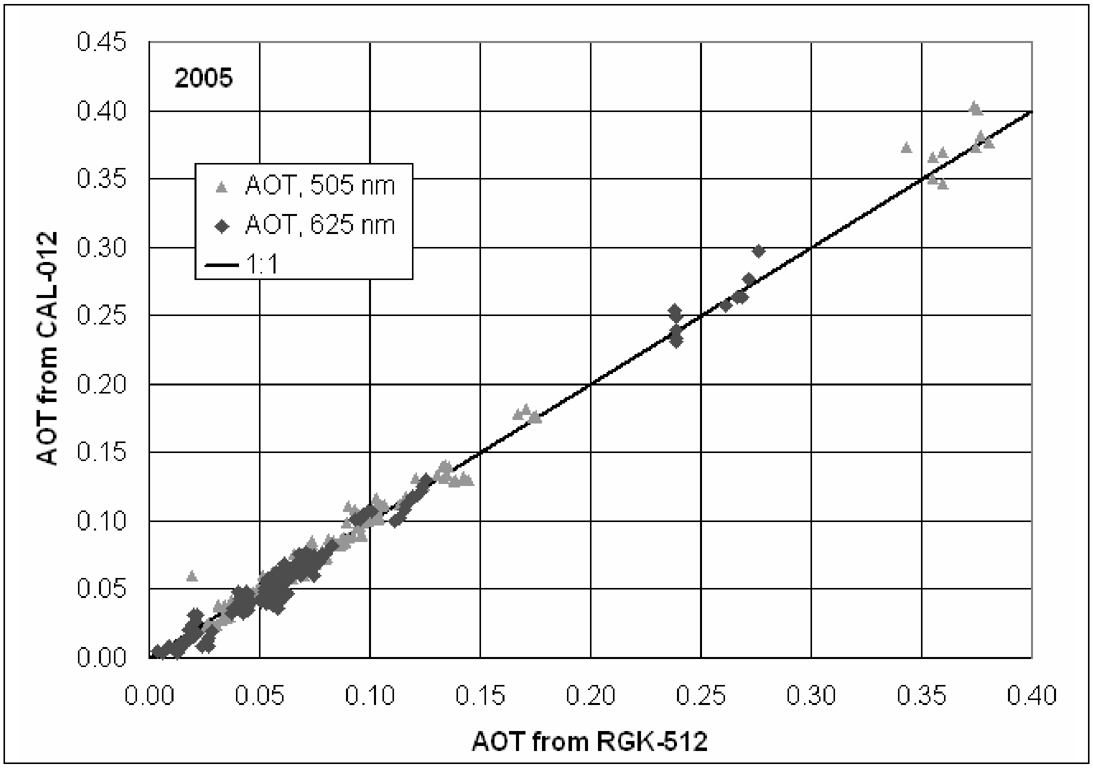

Figure 6. Comparison of two LED sun photometers from elementary school students in Arkansas, USA.

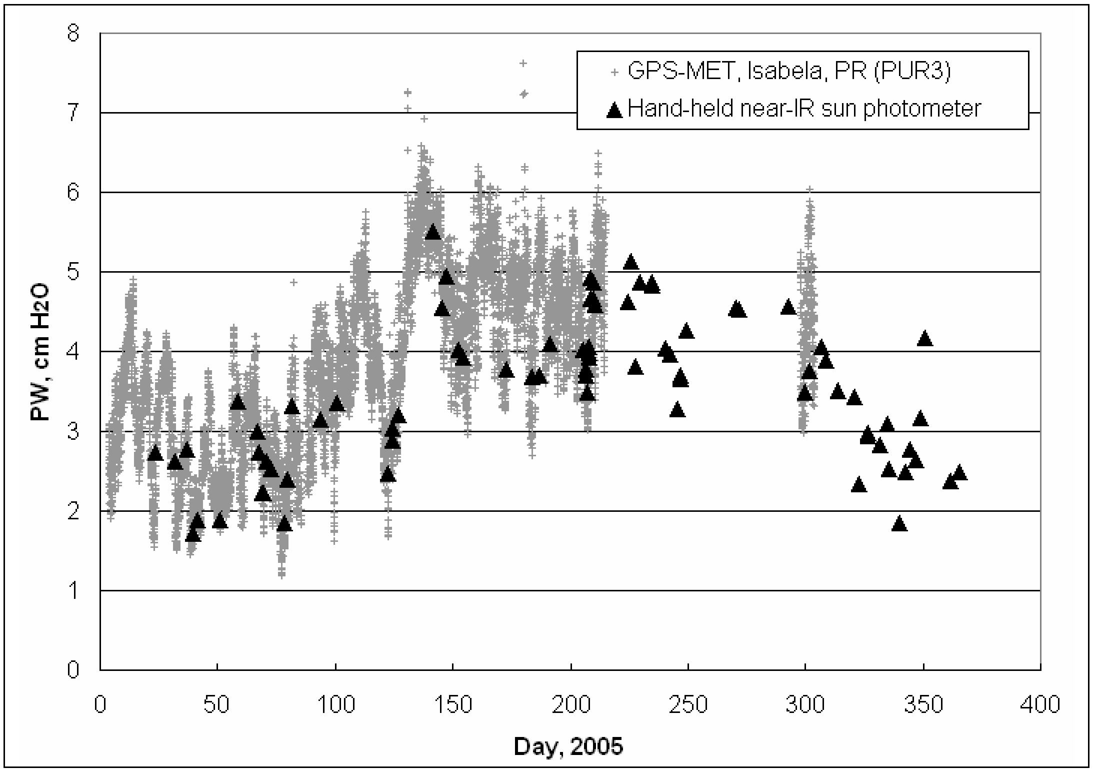

Figure 7. Water vapor data from GPS-MET site at Isabela, Puerto Rico and near-IR sun photometer-derived water vapor from Aguadila, Puerto Rico.