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Stručni rad

DETERMINATION OF THE EFFECT OF AEROSOLS ON DIRECT SOLAR RADIATION WITHIN THE GLOBE PROGRAM

Određivanje utjecaja aerosola na direktno Sunčevo zračenje u okviru GLOBE programa

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Abstract: The paper explains the operating principle of a hand held Sun photometer with light emitting diodes (LED) that was developed for international scientific and educational program "Global Learning and Observation for the Benefit of the Environment" (GLOBE). The performance of GLOBE LED Sun photometer is described and sensitivity of the hand held LED instrument in relation to the photometer with interference filters is discussed. Using of Langley's method to determine extraterrestrial constant of GLOBE LED Sun photometer is discussed. More than 120 GLOBE schools around world are conducting aerosol measurements on daily basis and have reported around 80.000 data on atmospheric optical depth. There are four GLOBE Sun photometers operating in Croatia now, which are used by six schools, so our schools made around 5000 measurements. The data collected to date indicates that the GLOBE LED Sun photometer is capable of meeting its dual purpose of ground and space based data comparison and for use of inquiry based approach to science education in schools.

Key words: aerosols, Sun photometer, extraterrestrial constant, LED, GLOBE

Sažetak: U radu je objašnjen princip rada jednostavnog fotometra sa svjetlećim diodama (light emitting diodes, LED) kao osjetnicima koji je razvijen za potrebe međunarodnog znanstveno-edukacijskog programa „Globalno učenje i opažanje za dobrobit okoliša“ (GLOBE).Opisana su svojstva GLOBE sunčevog fotometra sa svjetlećim diodama i diskutirana je osjetljivost instrumenta u odnosu na fotometre s interferencijskim filterima. Diskutirano je korištenje Langley-jeve metode za određivanje ekstraterestričke konstante GLOBE LED fotometrom. Više od 120 GLOBE škola širom svijeta redovito obavlja mjerenja aerosola i prijavilo je oko 80.000 podataka o atmosferskoj optičkoj debljini. U Hrvatskoj imamo četiri uređaja koje koristi šest škola te su naše škole prikupile oko 5.000 mjerenja. Prikupljeni podaci potvrđuju prikladnost GLOBE LED sunčevog fotometra da se koristi za usporedbu prizemnih i satelitskih podataka i potiče istraživački pristup u nastavi prirodoslovlja u školama.

Ključne riječi: aerosoli, sunčev fotometar, ekstraterestrička konstanta, LED, GLOBE

1. INTRODUCTION

Aerosols, small liquid and solid particles suspended in the atmosphere, have an effect on the energy balance of the atmosphere either by directly scattering and absorbing radiation, by serving as condensation nuclei during cloud formation or by influencing precipitation. Their presence also affects photosynthesis and agricultural production. These same particles that affect climate also impact the quality of the air that we breathe and the health of all living organisms.

"The scattering of energy associated with aerosols is amplified by the fact that some aerosols act as nuclei for cloud droplets and can thereby increase the reflectance of clouds. They also may modify the lifetime of clouds by affecting precipitation. The extent of these mutual effects of aerosols on clouds and of clouds on aerosols are perhaps the single largest unknown in climate change prediction" quoted from NOAA Earth System Research Laboratory (www.esrl.noaa.gov/ research/ themes/aerosols/). Tropospheric aerosol properties and effects exhibit considerable spatial and temporal variability. Contrary to aerosols' influence on weather and climate, few instruments for detecting their presence in the atmosphere are in use around the world.

The practice of measuring aerosols, water vapour and ozone by detecting sunlight traces back a century ago when accurate spectrometers were designed at the Smithsonian Institution's Astrophysical Observatory (Shaw, 1983). A typical instrument will produce an output signal proportional to the solar irradiance within the intended spectral band. The instruments are used to deduce spectral atmospheric transmission, or optical depth, from which the contributions of various atmospheric constituents can be calculated; most commonly aerosol, but water vapor and ozone are also potentially derived.

Aerosol optical depth (AOD) is a quantitative measure of the extinction of solar radiation by aerosol scattering and absorption between the point of observation and the top of the atmosphere. The larger the optical depth at a particular wavelength, the less light of that wavelength reaches Earth's surface. AOD is not directly measurable, but rather must be retrieved from observations of atmospheric spectral transmission. It can be determined from the ground through measurements of the spectral transmission of solar radiation through the atmosphere using Sun photometers (GLOBE teachers guide, 2011). AOD is expressed by a following equation

$$AOD = \frac{\ln(V_0/R^2) - \ln(V - V_{dark}) - a_R(p/p_0)m}{m} \quad (1)$$

where AOD is atmospheric optical depth, V_o is the calibration constant for a device, R is the Earth Sun distance expressed in astronomical units (AU), V and V_{dark} are the sunlight and dark voltage measured by Sun photometer, a_R is the contribution to optical thickness of Rayleigh scattering of light in the atmosphere, p is the station pressure at the time of the measurement, p_0 is standard sea level atmospheric pressure and m is the relative air mass, 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. Recent sun photometers are automated instruments that incorporate a Sun-tracking unit, an appropriate optical system, a spectrally filtering device, a photo detector, and a data acquisition system. A sun photometer should detect a relatively narrow band of optical wavelength since the optical depth of clear sky is strongly wavelength dependant.

For comparison, the spectral discrimination of the traditional photometer is often accomplished with a narrowband interference glass filter which is the source of considerable uncertainty in the typical measurement since they can be subject to unpredictable drift or degradation that can severely affect the quality of measurements. It is such a serious problem that some long term aerosol data series like Background Air Pollution Monitoring Network (BAPMoN) were abandoned as worthless. The World Meteorological Organization (WMO) instigated the Global Atmosphere Watch (GAW) programme in 1989 as a successor to BAPMoN continuously developing new instruments, methods and protocols to collect AOD data of known and assured quality in collaboration with other networks. Besides data quality degradation, the ground based instruments, traditional sun photometers with interference filters, are very expensive and delicate, and unsuitable for deployment in large numbers.

As a result there is virtually no place on earth where adequate monitoring of aerosols is being done at present and scientists have only a limited understanding of the distribution of aerosols in the earth's atmosphere. Some satellites can detect haze and aerosols but not close to the ground. Besides that, great number of qualitative ground based measurements is needed to validate satellite data but the existing networks of ground based sun photometers are sparse.

It is crucial that we improve our understanding of the various processes and feedbacks in the aerosol-cloud-climate system at the full range of temporal and spatial scales. Increasing our understanding of the physical and chemical properties of aerosols is vital for properly assessing their effects on various issues such as human health, air quality and global climate and ultimately establishing effective control strategies.

Information about the concentration, size distribution, and variability of aerosols in the atmosphere and AOD is needed for climate studies, for comparison with satellite data, to track events that alter aerosol concentrations and to understand the global distribution and variability of aerosols.

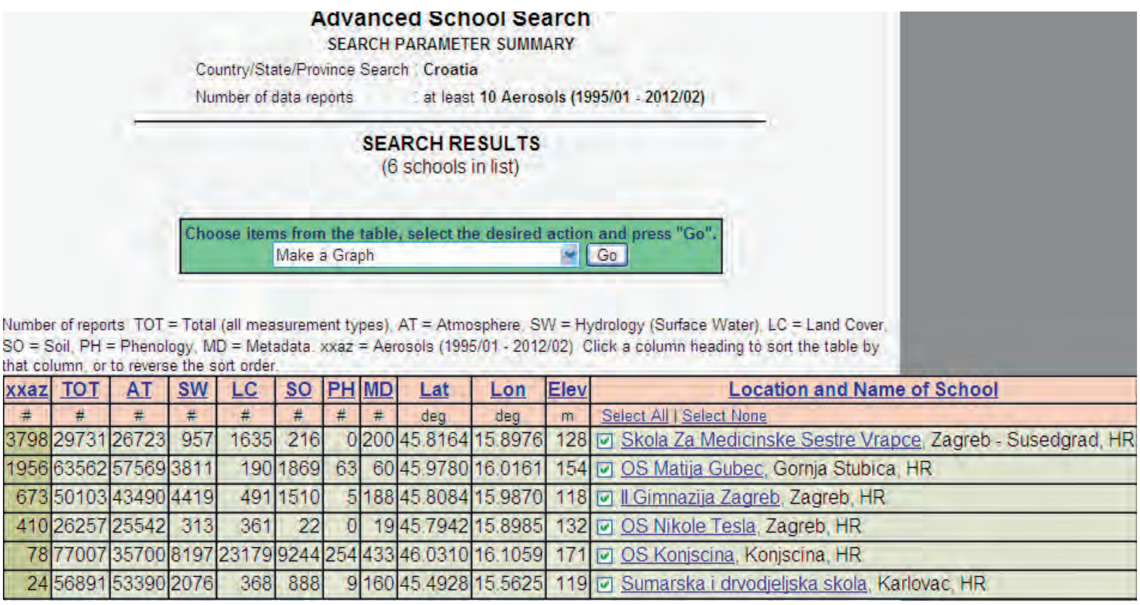
Routine ground based AOD observations are of outmost importance for the calibration and validation of AOD retrievals from satellites. In addition they are necessary to correct for aerosol effects in the retrieval of other satellite products.

New approach to measurement of the intensity in a direct beam of sunlight was applied since 1989 by Forrest Mims III (Mims III, 1992). He devised a filterless method for spectral measurements of the direct solar radiation by using light emitting diodes (LEDs) as spectrally selective photodiodes, a design that greatly improves the long term stability of sun photometers.

This paper describes a new kind of sun photometer based on light emitting diodes as receptors and use of that device as a part of the Global Learning and Observation to Benefit the Environment program (GLOBE). Measurements made by LED sun photometers are presented and the results have been discussed in comparison to the sun photometers with interference filters.

2. HAND HELD GLOBE LED SUN PHOTOMETER

The GLOBE program is a worldwide hands-on, primary and secondary school-based science and education program that started in 1995. GLOBE builds a community of students, teachers and scientists to collaborate on inquiry-based investigations of the environment and the Earth system working in close partnership with NASA, NOAA and NSF Earth System Science Projects (ESSP's) in study and research about the dynamics of Earth's environment. Today, the international GLOBE network has grown to include representatives from 111 participating countries coordinating GLOBE activities that are integrated into their local and regional communities. Croatia joined GLOBE program at the very beginning and is today a respectable member of GLOBE "family" with more than 100


Advanced School Search
SEARCH PARAMETER SUMMARY
Country/State/Province Search : Croatia
Number of data reports : at least 10 Aerosols (1995/01 - 2012/02)

SEARCH RESULTS
(6 schools in list)

Choose items from the table, select the desired action and press "Go".
Make a Graph Go

Number of reports TOT = Total (all measurement types), AT = Atmosphere, SW = Hydrology (Surface Water), LC = Land Cover, SO = Soil, PH = Phenology, MD = Metadata. xxaz = Aerosols (1995/01 - 2012/02) Click a column heading to sort the table by that column, or to reverse the sort order.

xxaz	TOT	AT	SW	LC	SO	PH	MD	Lat	Lon	Elev	Location and Name of School
#	#	#	#	#	#	#	#	deg	deg	m	Select All | Select None
3798	29731	26723	957	1635	216	0	200	45.8164	15.8976	128	Skola Za Medicinske Sestre Vrapce, Zagreb - Susedgrad, HR
1956	63562	57569	3811	190	1869	63	60	45.9780	16.0161	154	OS Matija Gubec, Gornja Stubica, HR
673	50103	43490	4419	491	1510	5	188	45.8084	15.9870	118	II Gimnazija Zagreb, Zagreb, HR
410	26257	25542	313	361	22	0	19	45.7942	15.8985	132	OS Nikole Tesla, Zagreb, HR
78	77007	35700	8197	23179	9244	254	433	46.0310	16.1059	171	OS Konjscina, Konjscina, HR
24	56891	53390	2076	368	888	9	160	45.4928	15.5625	119	Sumarska i drvodjeljska skola, Karlovac, HR

Figure 1. Croatian GLOBE schools that use LED Sun photometers and measure Atmospheric Optical Depth, January 1995 February 2012, number of measurements xxaz, (available on www.globe.gov).

Slika 1. Hrvatske GLOBE škole koje koriste LED sunčev fotometar i mjere optičku debljinu atmosfere, siječanj 1995. veljača 2012., broj mjerenja xxaz (dostupno na www.globe.gov).

Croatian schools involved in the program activities, with six schools that measure the AOD. List of schools that measure AOD is presented on Figure 1.

GLOBE initiated the Haze/Aerosol Project in 1998 to develop hand held LED based Sun photometer to monitor AOD and help scientists interpret measurements made from space, to train teachers and students in their use and to offer the potential for global aerosol monitoring network (Figure 2). Team of scientists and educators, led by David Brooks and Forest Mims III, work since then to accomplish set goals. Reports on project progress were presented each year on GLOBE conferences and are available on www.globe.gov.

A major objective for the Haze/Aerosol project has been to develop a reliable and inexpensive instrument that could be used by scientists, students and others interested in atmospheric aerosol measurements and whose performance can be characterized in a way that is acceptable to the atmospheric science community.

David R. Brooks and Forest Mimms III, GLOBE scientists, developed a two-channel (green and red) hand held LED Sun photometer; produce a protocol for its use; conduct annual calibrations of several reference instruments at Mauna Loa Observatory, Hawaii and transfer calibration to other instruments.

The concept of hand held Sun photometers was pioneered by Volz in 1974. The use of light emitting diodes (LEDs) as inexpensive spectrally selective detectors of light in sun photometers was first described by Mims (Mims III, 1992). LEDs are widely available, inexpensive, require simple electronics, are rugged and have extremely stable optical properties.

GLOBE LED hand held Sun photometer

The GLOBE Sun photometer uses light emitting diodes (as a narrow band receptors), has two channels, each of which is sensitive to a particular wavelength of light — green light at about 505 nanometres (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. Red AOD values are typically less than green AOD values. This is due to the fact that typical aerosols scatter green light more than red light. Data from a single channel enables the calculation of AOD 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 which helps identify the source of the aerosols.

Figure 2. GLOBE LED hand held Sun photometer.

Slika 2. GLOBE LED ručni sunčev fotometar.

Measurements taken with the GLOBE sun photometer are in units of volts. GLOBE Data Server performs the calculations based on the voltage readings submitted by students and return a value of optical depth for students. An example for Aerosol Optical Depth is shown on Figure 3 for GLOBE site, II Grammar school in Zagreb during February - April 2010.

The relation between the intensity of the light and the voltage produced is determined by the sensitivity of the detectors and amplifier. The concept of AOD could be easily understood by younger students when it is expressed in terms of the percentage of light that is transmitted through the atmosphere, and that value is also calculated by GLOBE Data Server after the voltage output of sun photometer according to equation 2.

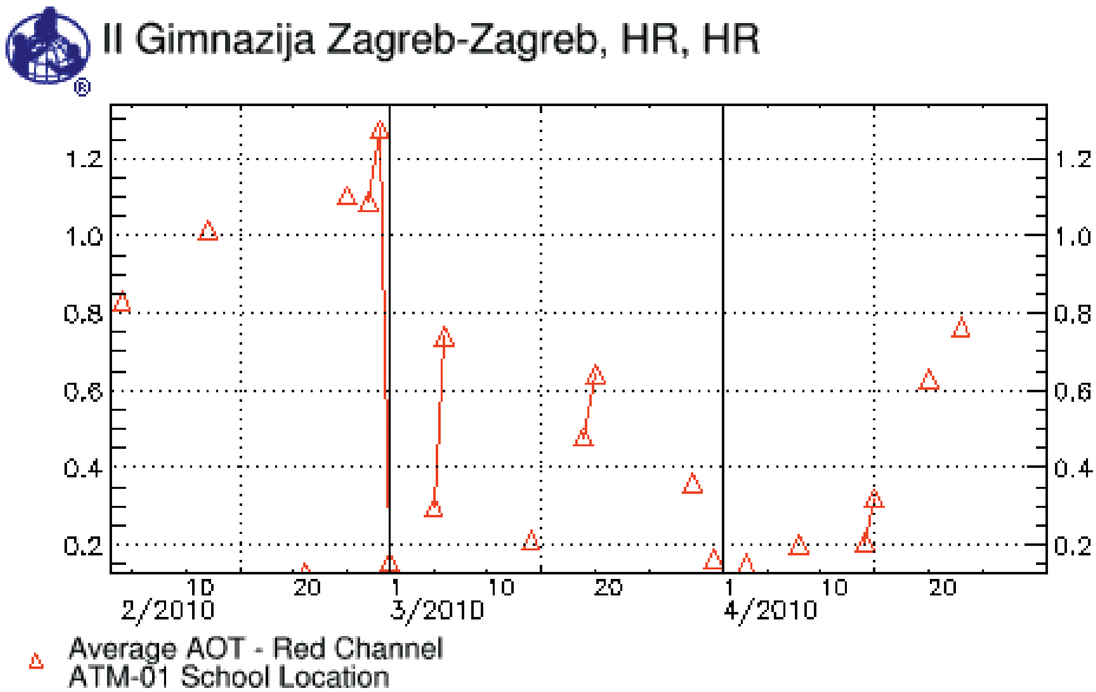


Figure 3. Average Optical thickness-red channel, II Grammar school Zagreb (II Gimnazija Zagreb), February 2010 - April 2010. The x axis features dates and the y axis features the average AOD for red channel.

Slika 3. Srednja optička debljina - crveni spektar, II Gimnazija, Zagreb, veljača 2010. - travanj 2010. Na osi x su datumi, a na y osi srednje vrijednosti optičke debljine atmosfere za crveni spektar.

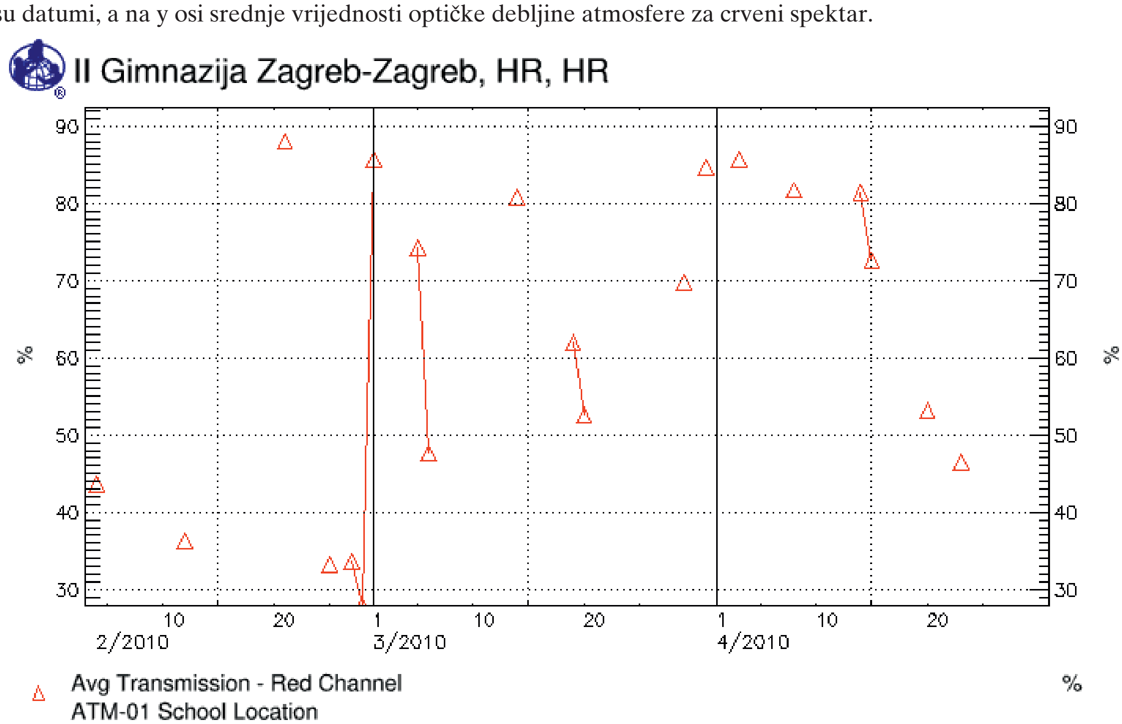


Figure 4: Average Transmission-red channel, II Grammar school Zagreb (II Gimnazija Zagreb), February 2010 - April 2010. The x axis features dates and the y axis features the average atmospheric transmission for red channel.

Slika 4: Prosiječni prijenos-crveni spektar, II Gimnazija Zagreb, veljača 2010. - travanj 2010. Na osi x su datumi, a na osi y prosječni atmosferski prijenos za crveni spektar.

$$\% \text{ transmission} = 100 \cdot e^{-AOD} \quad (2)$$

An example is shown on Figure 4 for illustration.

Older students who are familiar with advanced secondary school algebra can made the calculations on their own according to simplified equations given in the GLOBE guide and so become more familiar with the concept of atmospheric extinction.

As part of the Haze/Aerosol Project a protocol "Observing Visibility and Sky Colour" was also developed. This protocol prepares students for aerosol measurements and help those to investigate how changes in visibility and sky colours are related. The Protocol is suitable for all education levels since its purpose is to observe, document and classify changes in visibility and sky colour over time and to understand the relationship between sky colour, visibility and aerosols in the atmosphere. Students are prepared to carefully observe the atmosphere over a period of days and record their observation. They classify the sky colour using standard categories and record the visibility based on observation of a distant object such as a mountain or a building. Several learning activities are developed that help students to investigate how are changes in visibility and sky colours correlated and to discuss that connection with aerosol concentration in atmosphere.

Croatian primary school Matija Gubec from Gornja Stubica is worldwide recognized as the school that actively participates in the protocol and support ground validation efforts for Earth-observing spacecraft. Children take measurements at specific times, corresponding to spacecraft overflights of their observing site and collaborate with the GLOBE Science Team.

3. DETERMINATION OF THE LED SUN PHOTOMETER EXTRATERRESTRIAL CONSTANT BY LANGLEY METHOD

Despite their many advantages LEDs are not necessary ideal replacements for narrow band interference filters. Their spectral response bandwidth is much greater than that of interference filters and the wavelengths available are limited to those of commercial devices that are designed for other purposes.

Because of LED's relatively wide spectral response there was a challenge for calibration and interpretation. The standard approach to determining a Sun photometer's extraterrestrial constant is the Langley method. The extraterrestrial constant is the total amount of sunlight arriving at the top of the atmosphere. The Langley method assumes a Sun photometer that satisfies the requirements for Beer-Lambert-Bouguer law, namely a direct beam of monochromatic light, although actual instruments detect light over a finite wavelength interval. It is assumed that the monochromatic assumption is still valid for Sun photometers with interference filters (bandwidths of 10 nm or less) but it was questionable whether the same assumption is valid for LED Sun photometers with bandpasses that ranged from about 10 nm to 75 nm (typical bandpasses for green and red LEDs are of 75 nm and 25 nm respectively). While these bandpasses are greater than the 10 nm bandpass of the filters commonly used in sun photometers they regularly show very flat Langley plots. Langley method for Sun photometers requires making measure-

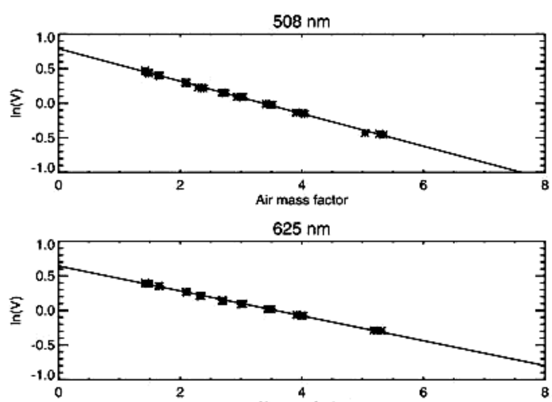


Figure 5. An illustration of a Langley plot according to Boersma 2006 (Langley plot for April 2003 at Koninklijk Nederlands meteorological Instituut, de Bilt, the Netherlands) for top (508 nm) and (bottom) 625 nm. The x axis features the air mass factor, and the y axis features the logarithm of the measured values.

Slika 5. Primjer Langley-jevog dijagrama prema Boersma 2006. (Langley-ev dijagram za travanj 2003. Koninklijk nizozemski meteorološki institut, De Bilt, Nizozemska), za (gore) 508 nm i (dolje) 625 nm. Na osi x je optička masa zraka, a na osi y prirodni logaritam izmjerenih vrijednosti.

ments of direct sunlight with a sun photometer on a very clear day. Data are presented by a graph which coordinates are the natural logarithm of the sun photometer voltage plotted as a function of relative air mass. The data points plotted on a graph will fall along or very near a perfectly straight line. Extending this line to where it crosses the y axis at an air mass of zero will give the ln of the extraterrestrial constant for the instrument. Langley's calibration plot for GLOBE LED Sun photometers were presented in several papers prepared by GLOBE scientific team and other scientists (Brooks 2001, Mims III 1998) and one of the examples is presented on Figure 5.

The very first calibrations of LED sun photometers were made at Seguin Texas, in December 1998, and later at Mauna Loa Observatory, Hawaii on several occasions.

The experiment made by Mims and his team, as well as measurements performed by other scientists show that AOD obtained from the LED detector is consistent with data obtained from Sun photometers with narrowband optical filters.

In order to prepare more LED Sun photometers for GLOBE student network, Langley plot calibrations were performed on a few Sun photometers at Mauna Loa Observatory, Hawaii. Those instruments were then used as reference instruments to transfer calibrations to other Sun photometers. Each GLOBE Sun photometer has its own calibration constant (one for each of the two channels). Air mass is the thickness of the atmosphere through which a beam of sunlight travels. At any sea level location, the air mass is 1 when the Sun is straight over head at solar noon.

4. LEARNING OUTCOMES

As a part of the Haze/Aerosol Project there is a short introduction on theory of atmospheric extinction, optical mass of the atmosphere and AOD calculations. Interactions of electromagnetic waves with molecules and small particles are usually lectured as part of secondary school physics but are rarely explained as everyday atmospheric process, so important for climate and life. The GLOBE Haze/Aerosol project prepare students for field work, hand-on learning activities, and enabled them to participate in scientific projects. As learning outcomes of the Haze/Aerosol activity it is supposed that students understand the concept that the atmosphere prevents part of the sun's light from reaching Earth's surface and they learn what causes hazy skies. As a result of taking part in the Haze/Aerosol activities students will be able to: 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 and recognize and analyze alternative explanations.

Students can construct their own Sun photometer and at some point send it to GLOBE Atmospheric Haze Science Team for calibration before their data can be accepted into the GLOBE Data Archive. Instruments could be also send to some European aerosol calibration centres involved in Global Aerosol Watch operated by World Meteorological Organisation.

Students participating in the GLOBE program are encouraged to compare their measurements with other ground and satellite based measurements. Such comparison can serve both as a check on GLOBE measurements and on the performance of other Sun photometers.

One source of satellite data for comparison is Aerosol Robotic network (AERONET) and the Moderate Resolution Imaging Spectroradiometer (MODIS). AERONET is managed by NASA Goddard Space Flight Centre. The network is ground based, has about 50 automated solar powered instruments and data are publicly available online, so students can use them as a part of their school projects.

More than 120 GLOBE schools around world are conducting aerosol measurements on daily basis and have reported around 80.000 data on AOD since the project started. Network of secondary schools in the Netherland with students routinely measuring AOD at two wavelengths with handheld sun photometers have been established. They have performed more than 400 measurements. Results indicate that GLOBE measurements achieve a precision better than 0.02 AOD for both channels. Besides that the comparison with professional instruments generally shows high correlations.

Data were used to validate MODIS AOD Retrievals over Netherlands. Study shows the potential of secondary school based networks in addition to existing, professional networks that have much less spatial coverage (Boersma 2006).

There are four GLOBE Sun photometers operating in Croatia now and were used by six Croatian schools which made around 5000 measurements. Nursing school Zagreb (Medicinska škola Zagreb) and II Grammar school Zagreb (II Gimnazija Zagreb) prepared together very interesting project on air quality in Zagreb (Aničić J. et al., 2010). They took measurements on the same days and compare the AOD values. Beside that they compare the official data on suspended particles and also use bio indicators as a measure of air quality. High values of AOD, no matter what the cause, may be linked to human health through their influence on respiratory system.

5. CONCLUSION

Handheld GLOBE Sun photometer with light emitting diodes is a new kind of inexpensive instrument that provides much better long term stability than instruments that use expensive, but optically unstable filters. Handheld GLOBE LED Sun photometer that in place of optical interference filters uses photo diodes have significant potential advantages, including low cost, durability and long term optical stability. However their wide spectral response bandwidth poses some challenges in calibration and interpretation. The instruments can be calibrated directly, using widely accepted Langley plot method for extraterrestrial constant calculation, and indirectly against other Sun photometer that use optical filters.

Aerosol measurements made carefully according to the protocol with the GLOBE Sun photometer should be accurate to within less than about 0,02 AOD units. The accuracy of measurements made with a GLOBE Sun photometer is comparable to measurements made with other types of Sun photometers. Even operational "professional" Sun photometers claim accuracies of no better than 0,01 AOD.

Students can make the reliable measurements with the LED based Sun photometers with the results comparable to the conventional filter based instruments even thought their optical properties are significantly different.

Today, several networks use handheld LED Sun photometers as ground base instruments to determine AOD values and validate satellite data according to measurements performed by LED Sun photometers. Besides networks operated by students and volunteers, like GLOBE and The Haze network, some are operated by national weather service or Institutes like The Chinese Sun Haze Meter Network that started in 2004 as the very first standard network established to measure AOD through China (Xin 2007).

The networks are collaborating with Aerosol Robotic Network (AERONET) and the Moderate Resolution Imaging Spectroradiometer (MODIS).

Students can perform high-quality aerosol and water retrievals using LED Sun photometers. The work of D.R. Brooks and F. Mims encourage various organizations to develop hand held LED Sun photometers and publish papers describing their results.

The underlying premise of the GLOBE program is that students motivated by appropriately trained teachers and using detailed written protocols with relatively inexpensive equipment can provide scientifically valuable measurements of environmental parameters. The data collected up to date indicates that the GLOBE LED Sun photometer is capable of meeting its dual purpose of comparing ground and space based data and for use of inquiry based approach to science education in schools.

6. LITERATURE

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