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Design and performance of the COOPS sun photometer

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DESIGN AND PERFORMANCE OF THE COOPS SUN PHOTOMETER

A Thesis

Presented to

The Faculty of Moss Landing Marine Laboratories

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

Luke Valentine Beatman

December 2006

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ABSTRACT

DESIGN AND PERFORMANCE OF THE COOPS SUN PHOTOMETER

by Luke Valentine Beatman

The scattering of light in the atmosphere by aerosols has significant implications to the measurement of ocean color by satellite. Determining the effects of this scattering by measuring aerosol optical thickness (τ_a) and sky radiance requires a Sun Photometer. The COOPS Sun photometer was designed and constructed using a commercially available two channel CCD spectrometer, tracking telescope, and Gershun Tubes fabricated at Moss Landing Marine Laboratories. The instrument was then calibrated using the high altitude Langley method. The performance of COOPS was evaluated using an industry standard CIMEL CE 318N (serial #59) as a reference. Measurements of τ_a by both instruments were compared and the results show deviations as a function of wavelength, channel, and day of measurement. COOPS was accurate to within 2% for select sequences of measurements at 440 nm while measurements at the longer wavelengths of 675 and 870 nm showed potential for similar accuracy. The development and evaluation of the COOPS determined that a commercially available spectrometer coupled with a tracking telescope could be an effective tool in measuring τ_a .

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Introduction

The measurement of physical, biological, and geological properties of the Earth's surface from above the atmosphere began in the early 1970's and continues today. Seasat was launched in 1978 as the first satellite specifically designed for and dedicated to ocean surveillance (Robinson, 1985). The primary instrument installed on Seasat was a radiometer operating in the microwave region of the electromagnetic spectrum to avoid missing measurements due to clouds. Information was recovered about surface temperature, surface roughness, sea surface height, and ocean waves for a period of three months before a power failure ended the satellite's lifetime. In the same year of 1978 a radiometer was installed on one of the Nimbus series satellites with the intent of measuring ocean color in the visible part of the electromagnetic spectrum. This instrument, The Coastal Zone Color Scanner, has supplied a wealth of synoptic views of the color of large areas of the world's ocean, at a spatial resolution greater than one kilometer (Robinson, 1985). Measurements of the color of the ocean surface at visible wavelengths have been used to monitor phytoplankton pigment concentration as an indication of primary production. A continuous time series of phytoplankton pigment concentration on a global scale is integral to our understanding of carbon and nutrient cycles and their impact on climate change.

As with any newly developed scientific technology, challenges remain that must be addressed. At visible wavelengths of the electromagnetic spectrum, typically 90% of

the top of the atmosphere (TOA) signal is composed of photons that have not interacted with the seawater and therefore do not contain information on water composition or color (Schwindling and Deschamps, 1998). To accurately determine the phytoplankton pigment concentration, or more specifically chlorophyll concentration, an atmospheric correction technique must be employed. Critical to the development of an accurate atmospheric correction technique is the *insitu* measurement of water-leaving radiance and subsequent determination of chlorophyll concentration. Designed for this purpose, MOBY (Marine Optical Buoy) is an optical buoy package that has monitored water-leaving radiance off the coast of Lanai, Hawaii since 1980. The measurements of water-leaving radiance from MOBY are used as ground truth for the determinations of water-leaving radiances by a number of ocean color satellites including SeaWiFS, MODIS-Terra and MODIS-Aqua. The spectral differences between the *insitu* measurement of water-leaving radiance by MOBY and the remotely measured water-leaving radiance by satellites are a result of atmospheric absorption, emission, and scattering. This absorption, emission, and scattering can be measured directly with a Sun photometer. This study was an attempt to use inexpensive instrumentation to design, calibrate, and evaluate a Sun photometer using measurements of one of the key atmospheric correction parameters related to aerosols: τ_a .

Currently, the atmospheric correction scheme relies heavily on standard atmospheric models to approximate the spectral radiance resulting from absorption, emission, and scattering by atmospheric molecules and aerosols. The prediction of

radiance from a standard atmosphere, one consisting of only air molecules, can be almost exactly calculated using Rayleigh scattering theory. Complications due to scattering and absorption by aerosols require the use of aerosol models in an atmospheric correction scheme. Not all measurements by satellites require atmospheric correction for aerosols, however for measurements of radiance at visible wavelengths, atmospheric correction for the effects of aerosols is critical. A fundamental aspect of atmospheric correction is the assumption that a negligible amount of light is radiated from the ocean surface at the red end of the visible spectrum. Using this assumption and the absorption properties of both the Earth's and Sun's atmospheres, the ocean color community has agreed upon a select set of wavelengths at which to measure radiance. For example, one of the most successful ocean color satellites to date is SeaWiFS, measuring the upwelling radiance of the ocean at 411, 443, 490, 510, 555, 670, 765, and 865 nm.

Any liquid or solid particle suspended in the Earth's atmosphere is considered an aerosol. Aerosols can be characterized many different ways including, but not limited to, size, sources, location, and primary or secondary formation. A common system of size classification divides aerosols into three size ranges or modes, namely the nucleation mode (0.0001 - 0.1 μm), accumulation mode (0.1 - 1 μm), and coarse mode (>1 μm) (Jacobson, 1999). Another way to describe aerosols is by the source, natural or anthropogenic. On a global average the naturally produced aerosols outnumber the anthropogenic aerosols by many orders of magnitude but on a local scale anthropogenic aerosols can become more significant (Jacobson, 1999). Some of the most common

naturally produced aerosols are from the ocean and volcanoes. Breaking waves onshore and whitecaps offshore cause sea salt particles to become airborne and their distribution is then controlled by the physical processes governing atmospheric circulation, including diffusion, advection, and convection. Most of the sea salt aerosols remain in the lower atmosphere or troposphere (0 - 15 km) while aerosols generated by volcanic eruptions can be propelled into the stratosphere (15-50 km.) Other natural aerosols include dust, smoke, pollen, spores, plant and animal fragments, bacteria, fungi, and viruses.

The majority of anthropogenic aerosols are produced by some form of combustion. Fossil fuel burning automobiles and power plants are the most significant sources and are particularly important in developed nations, whereas biomass burning can be more significant in undeveloped nations. The combustion of organic molecules produces both primary and secondary aerosols. Primary aerosols refer to those that are directly injected into the atmosphere and do not rely on chemical or physical processes for their existence. An example of a primary aerosol resulting from fossil fuel combustion would be an elemental carbon particle or soot. The burning of fossil fuels produces precursor gases that can become aerosols at a later time. These are known as secondary aerosols. Some examples of these precursor gases are species of sulfur and nitrogen compounds including sulfur dioxide (SO_2), nitrogen monoxide (NO), and nitrogen dioxide (NO_2). Another significant precursor gas occurring naturally is dimethyl sulfide (DMS) resulting from the biological activity of phytoplankton (Hewitt and Jackson, 2003).

Due to the size of an average aerosol, local weather has a dominating effect on the concentration and distribution of aerosols at any one location. Prevailing winds are most important in distributing aerosols away from a point source such as a fossil fuel power plant while rain can wash aerosols out of the air decreasing concentrations. For secondary aerosols, not only local weather, but large scale atmospheric dynamics and sunlight play a role in their formation, concentration and distribution. All these factors affect aerosols making their temporal and spatial distribution highly variable.

The definition of an aerosol is somewhat flexible in that it includes any solid or liquid particle suspended in a gas. This flexibility translates to a wide variety of effects attributable to aerosols from effects on human health to radiative transfer and the global heat budget. In relation to human health, aerosols can be particularly threatening to those with preexisting lung or respiratory conditions. Submicron aerosols have the potential to penetrate the deepest part of the human lungs and cause or exacerbate asthma, respiratory disease and heart disease (Jacobson, 1999). These problems are most common in urban areas where anthropogenic aerosols can reach high concentrations.

In the context of this study, the effects of aerosols on the transfer of radiation and the global heat budget are most interesting. It has long been known that aerosols attenuate the amount of light reaching the Earth's surface. This fact has important consequences on the global heat budget directly affecting the climate. Studies of the direct effects of aerosols on climate have revealed three facts about scattering and absorption of solar radiation. First, aerosols backscatter a fraction of the incoming solar

radiation, second, some aerosols absorb solar radiation and reemit infrared radiation, and lastly, all aerosols absorb and reemit earth's infrared radiation (Jacobson, 1999). This variety of pathways for radiation and how it relates to a satellite is illustrated in Figure 1.

A more complicated effect of aerosols on the global heat budget is through their intimate relationship with clouds. Aerosols are critical to the existence of clouds as condensation nuclei, a surface necessary for the condensation of water vapor. The more aerosols available to the atmosphere the more potential for the condensation of water vapor and resulting cloud formations.

Figure 1: Radiance entering the detector of a satellite comes from multiple sources. Here the most significant sources are shown including the Sun, clouds, aerosols, and the surface of the ocean. Figure modified from pg. 45 in Stewart, 1985.

Clouds are strong reflectors of solar radiation and are therefore important in the global heat budget. This relationship between aerosols and clouds and the effects of clouds on radiation are both poorly understood and are the subject of much ongoing research (Jin *et al.*, 2005, Brennan *et al.*, 2005, Koren *et al.*, 2004).

The transmission of light through the atmosphere can be approximated using the Lambert-Beer law, which describes the relation between monochromatic direct solar

$$\frac{I}{I_o} = e^{-kz} \quad (1)$$

radiation at the Earth's surface, I , and zero airmass incident solar radiation at the top of the atmosphere, I_o . Airmass is the path length through the atmosphere between the Sun and an observer on the Earth's surface. The direct solar radiation is a function of altitude, z , and the properties of the atmosphere that determine the attenuation coefficient, k , which τ_a contributes to (Shaw *et al.*, 1973). Other significant attenuators accounted for in atmospheric correction include pure air, which causes Rayleigh scattering, and ozone. The optical thickness attributable to air and ozone are designated in Equation 2 by τ_R and τ_o respectively. The product of kz in Equations 1 and 2 is the total optical thickness.

$$kz \approx \tau_R + \tau_o + \tau_a \quad (2)$$

The application of this concept will be discussed in the methods section. Zero airmass represents the conditions above the Earth's atmosphere. The minimum value for airmass at the Earth's surface is one and corresponds to the shortest path length through the atmosphere with the sun at zenith.

In the context of satellite oceanography and measuring ocean color from space, τ_a is necessary to calculate the radiance received at the sensor due to the effects of aerosols. This radiance is only one component of the overall radiance received by the sensor but it is the most difficult to determine. Because of this difficulty the calculation of τ_a for the purposes of satellite oceanography is based on numerical models. These models rely on atmospheric radiative transfer theory and a database of measurements, dating back to 1973. The standard model in the atmospheric correction community is that of Shettle and Fenn (1979).

With the importance of aerosols to ocean color, climate, and human health, there are ongoing efforts to measure τ_a throughout the world. AERONET (Aerosol Robotic Network), a program funded by NASA, is a global effort to monitor aerosols (Holben *et al.* 1998). AERONET has distributed a commercially available Sun photometer, manufactured by CIMEL Electronique, to hundreds of locations, one of which was Moss Landing Marine Labs (MLML) in Moss Landing California. The AERONET project aims to maintain a worldwide network of CIMEL Sun photometers with the purpose of understanding aerosols and their effects on radiative transfer through validating satellite retrievals of τ_a (Holben *et al.*, 1998). AERONET's deployment of a CIMEL at MLML

provided an opportunity to evaluate the performance of an alternative instrument, the Celestron/Ocean Optics Sun photometer (COOPS).

Within the context of this thesis, the COOPS Sun photometer was designed and built at MLML using commercially available components including a spectrometer and solar tracking telescope. For collecting optics, two Gershun tubes were machined and interfaced to the spectrometer using 1mm fiber optic cables. The characterization of COOPS required experiments designed to measure the solid angle of the Gershun tubes and the linearity of the response of the spectrometer. The calibration of COOPS required a high altitude Langley plot for the measurement of τ_a and the absolute radiance calibrations for measuring sky radiance (Schmid and Wehrli, 1995). The high altitude Langley plot was performed at Heavenly Mountain in South Lake Tahoe, California. The absolute radiance calibration was performed at MLML using two NIST traceable standards, one irradiance and one radiance. The experiments to determine the linearity of the spectrometer and the field of view (fov) of both Gershun tubes were also performed at MLML. After calibration the instrument package was deployed at MLML for the purpose of evaluating the precision and accuracy of measurements of τ_a , using the CIMEL as a reference. The performance of the two independent channels of COOPS at the wavelengths of the CIMEL (440 nm, 675 nm, 870 nm) was determined and analyzed. The methods explaining the details of this work are presented in the next section. This is followed by a presentation of results of the experiments and a discussion of these results and implications on measuring τ_a . The goal of this work was to determine whether a

commercially available spectrometer combined with a solar tracking telescope can be an effective tool in measuring τ_a .

Methods

Measuring the effects of aerosols on the transmission of light through the atmosphere requires a Sun photometer, which usually consists of a spectrometer coupled with a solar tracking mechanism controlled by a preprogrammed measurement protocol. That protocol typically includes measurements of the Sun's intensity, used to calculate direct atmospheric transmittance, coincidental with sky radiance measurements at predetermined angles relative to the Sun's position. Direct atmospheric transmittance measurements are subsequently processed to yield values of τ_a while sky radiance measurements are necessary to determine the angular dependence of scattered light. For this study, the COOPS Sun photometer was designed, characterized, calibrated and evaluated at MLML. The CIMEL CE 318N, the Sun photometer used by the AERONET network, was used as a reference by comparing coincidental measurements of aerosol optical thickness determining the precision and accuracy of COOPS.

Design and Construction

The COOPS Sun photometer is comprised of three independent mechanisms, a Celestron NexStar 5 tracking telescope, an Ocean Optics SD2000 spectrometer coupled with an Ocean Optics SAD 500 analog to digital converter, interfaced with fiber optic cable to a collecting optic or Gershun tube, designed and machined at MLML (Fig. 2).

Figure 2: The COOPS Sun photometer is the combination of a 2-channel Ocean Optics spectrometer interfaced by optical fibers to Gershun tubes machined at MLML, and the Celestron Nexstar 5. The telescope and spectrometer can be powered with either sealed lead acid batteries or ac line voltage. Also shown is a thermometer for monitoring the temperature of the spectrograph and a computer for data acquisition.

The Celestron NexStar 5 tracking telescope is a Schmidt-Cassegrain Catadioptric design with a 5 inch aperture and tracking capabilities. The purpose of the telescope was to provide a reliable mechanism for centering the Gershun tubes of the COOPS instrument on the Sun while measuring direct atmospheric transmittance. The tracking ability of the Celestron was helpful in keeping the telescope centered on the Sun making only minor adjustments in altitude or azimuth necessary prior to each measurement. The

telescope was controlled through a built in keypad to perform an initial alignment sequence and pointing adjustments. The Celestron was used with a solar filter effectively blocking 99.999% of the incoming light and a Plossl 25mm eyepiece resulting in a field of view (fov) of 1.04 degrees. The telescope was not used for radiometric measurements.

The Ocean Optics SD2000 spectrometer is a 12-bit linear silicon charged coupled device (CCD) measuring at 2048 discrete wavelengths from 350 to 1000 nm on two independent channels. Integration times (i.t.) of 5 to 65535 ms are available. The operation of any CCD is dependent on the photoelectric effect. The photoelectric effect is the generation of electrons when a photon strikes a metal (Halliday and Resnick, 1988). When incident photons of wavelength shorter than 1 micrometer break the covalent bonds of the silicon wafers in the CCD assembly a voltage is generated (Photometrics Ltd., 1992). The spectrometer's output voltage is converted by the SAD500 into a digital count corresponding to the signal intensity. The instrument as sold by the manufacturer comes uncalibrated. To measure absolute values of radiance or irradiance the instrument must be calibrated accordingly using radiance or irradiance calibration standards. The SD2000 was calibrated for measuring absolute radiance with two independent NIST traceable calibration sources, one irradiance standard and one radiance standard. The SD2000 while integrated to the COOPS was also calibrated as a Sun photometer using the high altitude Langley method (Schmid and Wehrli, 1995).

The Ocean Optics SD2000 accepts an optical signal through a one millimeter diameter fiber optic cable with a standard sub-miniature version A (SMA) 905 connector

on both ends. The transmission of the fiber optic cables was between 200 and 750 nm. Two different Gershun tubes were constructed for the two independent channels of the SD2000 by William Watson, a student at MLML. The Gershun tube limits the accepting angle of the system to a narrow cone of light, or solid angle. A typical Gershun tube has a cylindrical barrel and a series of baffles within the barrel (Fig. 3). A hole is machined in each baffle terminating in a knife edge to minimize reflections. The purpose of the barrel is to prevent light reaching the detector from outside a predetermined solid angle.

Figure 3: Collecting optics of the COOPS Sun photometer. The design of Gershun tube 2 (bottom) is significantly different than Gershun tube 1 because of the differences in baffles and the fov. Gershun tube 1 used baffles machined at MLML that were a consistent diameter whereas Gershun tube 2 used precision pinholes ranging from 200 to 1000 microns.

The series of baffles within the barrel block scattered light that enters the Gershun tube from any angle outside the preferred solid angle. The first Gershun tube manufactured was for channel one and was a relatively simple design. The main barrel was machined out of black Delron plastic with an outside diameter of 2.54 cm, an inside diameter of 1.91 cm and an overall length of 6.60 cm. A shorter barrel was machined also from black Delron plastic with an outside diameter of 3.05 cm, an inside diameter of 2.54 cm and an overall length of 2.79 cm. The purpose of the shorter barrel is to hold filters if necessary and connect the main barrel of the Gershun tube to the fiber optic cables. Next, a series of baffles were machined all terminating in a knife edge at a hole in the center. The diameter of the hole in each of the five baffles was approximately 0.51 cm. The final product was then assembled by sliding the baffles into the barrel and sealing the end with an o-ring. The design objective for Gershun tube 1 was a fov of 4 degrees. Gershun tube 2 was a more complicated design with tapering baffles (Fig. 3 inset). Similarly, Gershun tube 2 was made from two cylindrical barrels. The main barrel was again machined from black Delron plastic with an outside diameter of 2.54 cm, an inside diameter of 1.91 cm and an overall length of 6.60 cm. Again a shorter barrel with the purpose of holding filters and interfacing the fiber was machined with an outside diameter of 3.05 cm, an inside diameter of 2.54 cm and an overall length of 2.79 cm. The primary differences between the two Gershun tubes were the baffles and the fov. Gershun tube 2 used five precision pinholes purchased from Edmund Optics as baffles. The diameters of the pinholes used were 200, 400, 600, 800, and 1000 microns. Spacers were machined as

precisely as possible to position the precision pinholes at predetermined distances relative to the front of the fiber. This design theoretically would reject off-axis light better than Gershun tube 1 because the baffle is not a consistent size but is matched with the diameter of the solid angle at that position. Because the diameters of the precision pinholes were much smaller than the holes in the baffles used in Gershun tube 1 the pinholes are relatively much closer to the front of the fiber. The rest of the main barrel has a threaded plastic sleeve inside also machined from black Delron plastic. The inside diameter of the sleeve is large enough so as not to limit the fov of the Gershun tube and threaded in an attempt to reject and attenuate off axis light. The design objective for Gershun tube 2 was a fov of 3 degrees.

After construction of the Gershun tubes, preliminary measurements of direct atmospheric transmission were saturated at the lowest integration time available by the SAD500. Two filters were purchased for each channel of the SD2000 from Edmund Optics. Because Gershun tube 1 had a larger fov, two filters, a 13% neutral density filter and an opal glass diffuser were needed. For Gershun tube 2 only an opal glass diffuser was necessary. The percent transmission of the filters used in the Gershun tubes is plotted in Figure 4. The measurement of the transmission was performed at Dr. Sue Carter's lab in UCSC using an N+K Spectrometer.

Figure 4: Percent transmission of the filters used in the Gershun tubes. The upper axis shows the percent transmission as a function of wavelength for the opal glass diffuser used in Gershun tube 1 and 2. The lower axis shows the transmission of the 13% neutral density filter used in Gershun tube 1.

Solid Angle Determination (1)

To fully characterize the COOPS, the actual fov of both Gershun tubes was determined experimentally. This was done with two different experiments. The first involved projecting a stable light source, Ocean Optics LS-1, through a fiber connected to the Gershun tube onto a smooth surface (Fig. 5). The distance from the front of the fiber

to the surface, d , was measured using a digital caliper/micrometer. The diameter of the circle of light projected was also measured with the digital caliper and the resulting area, A , was calculated. The solid angle, Ω , in steradians (sr) of the Gershun tube was then determined by a linear regression according to Equation 3. Measurements were made at 8 different distances between 125 and 415 mm.

$$\Omega = A / d^2 \quad (3)$$

Solid Angle Determination (2)

The second solid angle measurement employed a laser as a static beam of light. The Gershun tube was connected to the SD2000 spectrometer using fiber optic cable, and the optical axis aligned with the path of the laser at 5 distances between 100 and 500 mm (Fig. 6). When the laser is within the fov of the Gershun tube the SD2000 measurement shows a distinct peak at 530 nm, the wavelength of the laser (Fig. 7). The position of the Gershun tube was measured starting from well outside the beam of light projected by the laser. Then the Gershun tube was moved laterally in steps of 1 millimeter while making measurements with the SD2000. At the first and last discernable indication of the laser in the measurement, the position of the Gershun tube was recorded. The difference between these two positions corresponds to the diameter of the fov of the Gershun tube. Again the measured data of area and distance was linearly regressed yielding a solid angle estimate for the Gershun tube.

Figure 5: First experiment designed to measure the solid angle of both Gershun tubes. Essential components included the Ocean Optics LS1-cal, the fiber optic cable, a smooth surface for projection, and the digital caliper/micrometer.

Figure 6: Second experiment designed to measure the solid angle of both Gershun tubes. On the ruler track in the foreground is the laser and in the background is the Gershun tube interfaced to the Ocean Optics SD2000 spectrometer at the right. The solid angle was determined by recording the first and last discernable signal due to the laser at the spectrometer as the Gershun tube was moved laterally in 1mm increments.

Figure 7: Measurement of the laser using the Ocean Optics SD2000 and the MATLAB data acquisition software. The spectrum shows a distinct peak at 530 nm when the laser is within the fov of the Gershun tube.

This study began with the composition of an entire set of low level functions written in MATLAB to control the Ocean Optics SAD500 analog to digital converter acting as an interface between the SD2000 spectrometer and the computer. These low level functions were then assembled into a script with a graphical user interface (GUI) to simplify SD2000 operation (Fig. 8). The script allows the user to control the communication parameters of the instrument including which serial port will be used at

what baud rate as well as the operating parameters of the measurement including integration time, boxcar averaging, which pixels to transmit, and active channel. Within the GUI there are two graphs, one for each channel, that display any scans made with the instrument. When the user is satisfied with the set of scans on the graph they may save those scans to a self describing MLdbase binary file.

Standard Operating Procedure

A typical data acquisition session with the COOPS Sun photometer began with the alignment procedure for the Celestron NexStar 5. The Celestron offers two different alignment procedures, a two star alignment and an auto alignment. The auto alignment procedure was used because of the lack of visible alignment stars during the day. The first step in the alignment procedure, leveling the tripod, was not documented in the Celestron manual but was important in achieving a good alignment and tracking capability, and was practiced before every measurement series. The next step was to level the optical tube and point it towards true north. Then using the keypad of the Celestron, the current date and time were entered. The next information necessary for a proper alignment was the latitude and longitude of the site acquired from nautical charts. After entering the latitude and longitude, the NexStar 5 points to an alignment star and final adjustments were made in altitude and azimuth. At this point the NexStar 5 has the ability to find the Sun or thousands of other celestial objects. The final step to ensure proper tracking was to set the tracking mode to “altitude/azimuth” and the tracking rate to

“solar.” The function of the telescope within the Sun photometer system was to ensure accurate and precise pointing capability. The Gershun tubes were attached to the optical tube of the scope using an aluminum channel and Velcro. The aluminum channel had mounted on it a piece of black Delron plastic with two holes in it machined to match the outside diameter of the Gershun tubes. One major requirement necessary for this system to work was that the optical axis of the Gershun tubes was parallel to the optical axis of the telescope. The fov of the telescope was 1.04 degrees when using the 25 mm eyepiece and the fov of the smallest Gershun tube was 4 degrees, therefore if when viewing the Sun through the eyepiece the entire solar disk was within the fov of the telescope the user must assume the entire solar disk was within the fov of the Gershun tube. A typical measurement was made beginning with a dark scan, accomplished by capping the end of the Gershun tube with a piece of black Delron plastic and taking a measurement. All measurements were preceded and followed by dark scans. After making the initial dark scan, the user looked through the eyepiece of the telescope to ensure it is centered on the Sun. The light scans were then taken typically in sets of 5 or 10 followed by another dark scan. Using the GUI, the user then saved a file that includes some limited amount of information about the scan. Typically this included the measurement site, detector temperature, sky conditions, and other notes the user wishes to include in the file.

Figure 8: Graphical user interface designed for the COOPS Sun Photometer.

A Sun photometer is typically used to measure direct atmospheric transmittance through a range of air masses, while measuring sky radiances at a set of predetermined angles relative to the Sun's position. Air mass can be understood as a path length through the Earth's atmosphere between a subject's position and the Sun and is therefore a function of the Sun's elevation. During this study, only direct atmospheric transmittance was measured. From those measurements, τ_a was derived according to the method outlined in Shaw *et al.* (1973). The measurement of direct atmospheric transmittance

through a range of air masses is known as the Langley method and was used at a high altitude mountain site to calibrate the COOPS Sun photometer. The Langley method is also valuable in that it allows a determination of τ_a without a calibration, but the accuracy of the determined τ_a depends on the stability of the atmosphere. The calibration of the Sun photometer using high altitude measurements allows instantaneous measurements of τ_a . τ_a and the Angstrom exponent are two parameters that describe the optical state of the atmosphere with respect to aerosols. The Angstrom exponent is an exponent that expresses the spectral dependence of τ_a with the wavelength of incident light (Eqn. 9). While the values of τ_a are directly related to the aerosol concentration, the Angstrom exponent characterizes the wavelength dependence of τ_a , and thus the aerosol size (Schwindling and Deschamps, 1998). Based on the size of the aerosols conclusions can be made about their type or source.

High Altitude Calibration

In this study the Langley method was practiced in two distinct environments, Heavenly Mountain in South Lake Tahoe, California and Moss Landing, California. Measurements at Heavenly Mountain were necessary for the calibration of the COOPS Sun photometer and the subsequent measurement of instantaneous τ_a . High altitude transmittance measurements have significantly less variability than measurements in the lower atmosphere, leading to a better determination of the calibration constants. Two trips to Heavenly Mountain were made in August and October of 2002. In August

measurements were made for 5 consecutive days starting on the 6th. The morning of the 6th was spent surveying the mountain for access to possible measurement sites with power and an unobstructed view of the sky. No sites offered views of both sunrise and sunset so measurements were made at two different locations: the gondola top-station (latitude: 38.935° N, longitude: 119.910° W, elevation: 2804 m) in the morning and the gondola mid-station (latitude: 38.940° N, longitude: 119.919° W, elevation: 2780 m) in the evening. Using a differential GPS the location of both stations was recorded for use in calculations. Ambient temperature and air pressure were recorded for use in calculations by a Kestrel 4000 portable weather station. Five individual Langley series were recorded with COOPS channel 1 and 8 with channel 2. Measurements were made every five minutes between air masses of 2 and 6 or when the Sun was between the elevations of 10 and 30 degrees. Unfortunately, the data from the August campaign were taken incorrectly by not adjusting integration time in between measurements. In October another attempt at a high altitude calibration was made but the weather was poor. Correctly integrated measurements were made on only one day: the morning and the evening of August 22nd, 2002.

The result of a high altitude calibration is known as $F_0(\lambda)$, the extra-terrestrial flux as a function of wavelength. This constant is defined in the context of a modified Lambert-Beer Law describing the relation between air mass and incident solar radiation

$$F(\lambda, z) = \left(\frac{r_m}{r}\right)^2 F_0(\lambda) \exp[-M(z)\tau(\lambda)] + F_d(\lambda, z) \quad (4)$$

where $F(\lambda, z)$ is observed ground level solar flux at wavelength λ and solar zenith angle z , r and r_m are the earth-sun distance at the time of observation and mean earth-sun distance respectively, and $F_0(\lambda)$ is the directly transmitted solar flux at wavelength λ and mean earth-Sun distance, at zero air mass (Shaw *et al.*, 1973). The term $M(z)$ is atmospheric air mass relative to the vertical position, and $\tau(\lambda)$ is the total optical depth at wavelength λ . The last term in the equation $F_d(\lambda, z)$ is the diffusely scattered flux at wavelength λ entering the radiometer and is assumed negligible in this context because of the relative insignificance when compared to direct sunlight. $F_0(\lambda)$ must be determined for all wavelengths and channels being used. $F_0(\lambda)$ was calculated as the y intercept of the natural log of the instrument's output as a function of air mass, and can be thought of as the value the instrument would read if it were outside the Earth's atmosphere (Shaw *et al.*, 1973). $F_0(\lambda)$ was calculated for both channels of the COOPS Sun photometer at the wavelengths of the CIMEL instrument, 870, 670, and 440 nm. For the purpose of making direct comparisons of τ_a measured by the COOPS and CIMEL instruments, the filter transmissions of the CIMEL were acquired from the AERONET organization and applied to all data measured by the COOPS. All measurements were processed by taking the average of all light scans and subtracting the average of all dark

scans and dividing by the integration time (i.t.) used for the measurement. This quantity is referred to as *countadj* in Equation 5.

$$countadj = \frac{\overline{lightscans(\lambda)} - \overline{darkscans(\lambda)}}{i.t.} \quad (5)$$

The time of the measurements was converted into universal time coordinated (UTC), used to calculate the Sun's zenith angle and azimuth according to Wilson, 1980. The solar zenith angle, θ , as calculated by Wilson was used to calculate the air mass, M , according to equation 6 from Kasten, 1966. Figure 9 shows the increase of airmass with solar zenith angle, according to this equation.

$$M = 1/\cos(\theta) + .15 * (93.885 - \theta)^{-1.253} \quad (6)$$

This algorithm was updated in 1989 by Kasten and Young to more accurately calculate airmass at high zenith angles. For the Langley plots in this study measurements were limited to airmasses below 6, consistent with methods outlined in Holben *et al.* 1998, therefore the updated algorithm was unnecessary.

An extensive data set was collected at MLML in Moss Landing, California between December 2, 2002 and October 14, 2004. MLML is at the center of Monterey Bay in Moss Landing California at 121.787° W, 36.795° N, and observations were made at an elevation of 18 m. A concrete patio on the west side of the main lab at MLML

offered the necessary views of the setting Sun and power for the instruments. A total of 25 Langley series were recorded all in the afternoon/evening. Measurements were made every 5 minutes between air masses of 2 and 6. Three of these Langley series were coincidental with measurements made by the CIMEL and will serve as a comparison to quantify the precision and accuracy of the COOPS instrument.

Figure 9: Airmass as a function of solar zenith angle. Values were calculated using an algorithm from Kasten 1966.

Aerosol Optical Thickness Measurements

The measurement of direct atmospheric transmittance allows a calculation of instantaneous total atmospheric optical thickness. The total atmospheric optical thickness, $\tau(\lambda)$, may be approximated by adding three components, Rayleigh optical thickness, $\tau_R(\lambda)$, ozone optical thickness, $\tau_O(\lambda)$, and aerosol optical thickness, $\tau_a(\lambda)$ (Schmid and Wehrli, 1995).

$$\tau(\lambda) = \tau_R(\lambda) + \tau_O(\lambda) + \tau_a(\lambda) \quad (7)$$

τ_a is calculated by subtracting the Rayleigh optical thickness and ozone optical thickness from the total atmospheric optical thickness. To be consistent with AERONET data processing routines the Rayleigh optical thickness was calculated based on Penndorf, (1957) and the value of ozone optical thickness was based on London (1967). As with the high altitude measurements, countadj was calculated and converted to atmospheric optical thickness using the calibration constants from the Heavenly data set and Equation 8, the logarithmic form of Equation 4.

$$\ln F(\lambda, z) = 2 \ln(r_m / r) + \ln F_0(\lambda) - M(z)\tau(\lambda) \quad (8)$$

Upon determination of τ_a at a specific wavelength, the Angstrom Exponent, α , can be used to quantify the spectral dependence of τ_a with Equation 9 (Robinson, 1985), where τ_λ and τ_{λ_0} are the aerosol optical thickness' at the wavelengths of interest, λ and λ_0 .

$$\tau_\lambda = \tau_{\lambda_0} \left(\frac{\lambda}{\lambda_0} \right)^{-\alpha} \quad (9)$$

Radiance Calibration

For the COOPS Sun photometer to measure sky radiance the system must be absolutely calibrated with a known radiance standard. This calibration was performed with two different methods and the results of each calibration compared. Any absolute radiometric calibration requires the system to be calibrated in the same configuration as is used in the field. This requirement presented a significant challenge because both calibration sources were of relatively low intensity requiring unreasonably long integration times. Therefore a piece-part calibration technique was applied. This piece-part calibration technique involved calibrating the system terminated with a bare fiber and separately characterizing the Gershun tube by measuring the fov, and the percent transmission of the filters used.

The first method of radiance calibration used a NIST traceable OL220M standard of spectral irradiance purchased from Optronics Laboratories. In order to realize the high accuracy assigned to the OL220M it was necessary to control the current supplied to the

lamp to 0.01 amps. An OL65A programmable DC current supply was also purchased from Optronics Laboratories for this purpose. In principle, measuring and calibrating radiance requires that the illumination source be completely diffuse and larger than the fov of the collecting optics. To diffuse the light from the OL220M, an OL25RS diffuse reflectance standard was used. The output of the OL220M, as documented by the calibration file, is in terms of irradiance and is specific to a distance of 50 cm. Therefore, the reflectance plaque was placed at a distance of 50 cm from the OL220M and the surface was oriented at zero degrees to intercept as much of the output of the OL220M as possible. The bare fiber has a fov of 22 degrees. To overfill the fov, the fiber needed to be placed close ($< 2\text{cm.}$) to the OL25RS (Fig. 10). To verify the fov of the fiber was within the boundaries of the reflecting surface of the OL25RS, a light source, Ocean Optics LS1, was projected through the fiber onto the OL25RS. Another consideration in the placement of the fiber was not to shadow the reflectance plaque. Once the physical orientation of the lamp, fiber, and reflectance plaque was determined the lamp was allowed to warm up for 20 minutes. After the lamp warms, a dark measurement was made before and after 10 light measurements. The resulting $\text{count}_{\text{adj}}$ was calculated as before by taking the mean of all light measurements and subtracting the mean of all dark measurements and dividing the result by integration time. The spectral function defining a radiometric calibration is known as a system response (SR) and is calculated by dividing the specified radiance output of the calibration standard by the instrument

output. To calculate a *SR* for radiance for all pixels of the SD2000, the irradiance values of the OL220M were converted to radiance according to Equation 10,

$$L(\lambda) = \frac{R(\lambda) * E(\lambda) * \cos(\theta)}{\pi} \quad (10)$$

where $L(\lambda)$ and $E(\lambda)$ are spectral radiance and spectral irradiance respectively, $R(\lambda)$ is the spectral reflectance of the plaque and θ is the viewing angle between the irradiance source and the reflectance plaque (Sanders, 1997). The resulting values of radiance, and the reflectance values of the OL25RS were interpolated to the discrete wavelengths of the Ocean Optics SD2000. The *SR* was then calculated as the lamp's output converted to radiance divided by the instrument output, *countadj*, according to Equation 11.

$$SR = \frac{L(\lambda)}{countadj} \quad (11)$$

Figure 10: Absolute radiance calibration using a NIST traceable OL220M irradiance standard and OL25RS reflectance standard. The OL220M was powered by the Optronics OL65A programmable dc current supply. A piece of black fabric was placed on top of the optical bench while making measurements to avoid unwanted reflections.

The second method used to calibrate the COOPS Sun photometer for measuring radiance involved the help of Mike Feinholz and Stephanie Flora, members of the MOBY team. This calibration used an Optronics Laboratories OL420. The OL420 is a low light level integrating sphere radiance calibration standard with an exit port producing a known radiance (Fig. 11). The OL420 was powered by the OL65DS power supply capable of controlling the current to 0.01 amps. The bare fiber was positioned 1 cm from the exit

port and dark measurements were made before and after light measurements. The countadj was calculated and divided by the output of the OL420, interpolated to the wavelengths of the SD2000, to produce a system response.

Non-Linearity Study

In an effort to further characterize the SD2000, tests of the linearity of the response were performed over an integration time range of 5 to 130 ms. The method used to test linearity was developed from an Ocean Optics algorithm (Ocean Optics, personal communication). A necessary requirement for testing linearity is maintaining a stable light field. This was achieved by using the Optronics Laboratories OL65A supplying a current of 6.5 amps to a GE200W Quartzline Lamp. This lamp was chosen because it is used by Optronics Laboratories for a NIST traceable irradiance standard. Before the lamp was used it was "seasoned", or current was applied for 15 hours as recommended by Optronics Laboratories. The fiber was focused on the OL25RS at a 45 degree angle and positioned as not to shadow the reflectance plaque. The distance between the lamp and plaque was adjusted so the integration time of 130 ms, corresponding to the longest integration time used in the field, caused saturation. After allowing the lamp to stabilize for 20 minutes, measurements of the OL25RS at 80 ms were recorded in order to monitor the performance of the lamp throughout the time necessary to complete the experiment. Only light measurements were recorded for all

integration times between 5 and 130 ms. After half of the measurements and upon completion, scans of the lamp at 80 ms were made in order to verify stability.

Figure 11: Absolute radiance calibration using the Optronics OL420 by the MOBY team in Honolulu, Hawaii. The OL420 is a low light level integrating sphere radiance calibration standard with an exit port producing a known radiance. Picture here is the Gershun tube interfaced to the Ocean Optics SD2000 (not shown) viewing the exit port of the OL420.

Twenty two pixels were chosen for analysis, 11 pixels that were saturated at 130 milliseconds and 11 that were not. The algorithm creates two sets of data for counts and counts per second (CPS) for all pixels and integration times. The data for counts were then sorted and the indexes of those sorted data are applied to the data for CPS. All values of CPS were then normalized by dividing by the maximum CPS yielding values between 0 and 1. Then CPS as a function of counts for each pixel was regressed using a 7th order polynomial consistent with the Ocean Optics algorithm. The value of the polynomial at each count should then be applied to all digital counts for all successive measurements in an effort to correct for the non-linear response of the instrument.

Comparison to CIMEL

Upon completion of the characterization and calibration of the COOPS Sun photometer, measurements of τ_a were made at MLML to compare to coincidental measurements made by one of the AERONET CIMEL Sun photometers. The direct comparison of τ_a between the two instruments required that the sampling times of the COOPS be interpolated to the sampling times of the CIMEL. After the interpolation, the absolute difference and percent differences in τ_a were calculated and the agreement was analyzed based on channel, wavelength, and the day of the measurement series.

Results and Discussion

The results of this study are presented in two sections. The first section discusses the characterization and calibration of the COOPS Sun photometer requiring experiments to determine the solid angle of the collector or Gershun tube, the linear response of both channels of the spectrometer, the system response of two independent radiance calibrations, and finally the calibration constants resulting from high altitude Langley plots. These experiments were necessary for the measurement of two radiometric quantities, direct atmospheric transmission, and sky radiance. Only measurements of direct atmospheric transmission were collected but the results of the calibration for both measurements will be shown and discussed. The second section presents the application of the characterization and calibration yielding measurements of τ_a . Whenever possible, measurements made with the COOPS Sun photometer were compared to one of the AERONET network of Sun photometers manufactured by CIMEL International.

Characterization and Calibration of COOPS

Experiments necessary to measure sky radiance include the determination of the solid angle of the Gershun tube and an absolute radiance calibration for the system terminating in a bare fiber. The collecting optics of the COOPS Sun photometer were a pair of Gershun tubes manufactured at MLML. The solid angle of each Gershun tube was measured with two independent experiments discussed in the methods section. In

Figures 12 and 13 the solid angle ω is shown with the error of the regression calculated at a 95% confidence interval. Based on these errors experiment 1 was more precise. While the solid angle of Gershun tube 1 determined by both experiments agreed within the calculated error, the solid angle of Gershun tube 2 did not. Therefore, the solid angle of Gershun tube 1 will be accepted as an average of the two values, 0.0051 sr. The value of the solid angle of Gershun tube 2 determined by experiment 1 was 0.0039 ± 0.00014 sr but because the two values determined by the experiments did not agree, the value of ω for Gershun tube 2 remains unknown. For the sake of further analysis, the solid angle of Gershun tube 2, determined by experiment 1, will be used. These solid angles correspond to planar angles of 4.6° and 4.0° for Gershun tubes 1 and 2 respectively.

Experiment 2 failed for at least two reasons. First, the position of the Gershun tube relative to the laser could only be determined to a precision of 1 mm. A 1 mm error in this measurement changed the determination of ω by 90%. Secondly, the diameter of the laser was too large. These issues could be resolved with a precision slit placed in front of the laser and with a more precise positioning method than the meter stick used, pictured in Figure 6 in the methods section. With these improvements, experiment 2 should produce better results because there are fewer measurements involved.

Figure 12: A regression of measured data resulting from solid angle measurements for exp. 1 of both Gershun tubes. A light source was projected through the Gershun tube onto a smooth surface. The resulting area of the light and the distance from the screen were measured. These values were linearly regressed giving the results seen here. The errors associated with the regressions for experiment 1 are less than those for experiment 2. For Gershun tube 1 the solid angle determined by both experiments agrees within the error but not for Gershun tube 2.

Figure 13: A regression of measured data resulting from solid angle measurements for exp. 2 of both Gershun tubes. Experiment 2 used a laser as a static line of light while the Gershun tube was moved laterally across the beam making measurements with the spectrometer. At the first and last signal corresponding to the laser, the position of the Gershun tube was recorded. The distance between these two positions and the distance from the laser to the Gershun tube was measured. This procedure was practiced at 5 different distances between the laser and Gershun tube and the values were linearly regressed giving the results seen here.

Figure 14: The radiance system response for COOPS determined by two independent experiments. The MOBY system response was generated using a NIST traceable radiance standard and the Optronics system response was generated using a NIST traceable irradiance standard with a reflectance plaque.

Calibration of the spectrometer for the measurement of absolute radiance was performed with two independent experiments. The results of each calibration were calculated as a system response and the two system responses are plotted together in Figure 14 and listed in the Appendix. The system response was defined in equation 11 of the methods section. The ratio of the system responses was calculated to show agreement as a function of wavelength and this ratio is presented in Figure 15. All experiments were performed for both channels with almost identical results, therefore Figures 14 and 15 and the Appendix show results from channel 1 only.

For wavelengths between 400 nm and 700 nm the two calibrations agree within 5% (Fig.15). For wavelengths beyond 700 nm the agreement is near 10%. This agreement is quite remarkable considering the fundamental differences in the calibration method. In the practical application of radiometry, 5% agreement between calibrations is often acceptable in the measurement of absolute radiance. Beyond 700 nm, the Optronics system response is significantly lower than the MOBY system response. This result can be best understood by considering the calibration equipment used for each method.

The MOBY radiance calibration used an integrating sphere radiance source. This instrument has many advantages over reflecting an irradiance source off a reflectance plaque. In particular, the integrating sphere has the ability to control the radiance field whereas using a reflectance plaque subjects the radiance field to reflections that are considered light contamination. A system response is calculated as the output of the calibration source divided by the output of the detector as shown in Equation 11 in the

methods section. If the output of the detector is treated as a constant in the denominator of the system response one can begin to understand the source of the divergence in system responses starting at 700 nm. A significant amount of light can reflect off any available surface and subsequently reflect off the reflectance plaque contributing to the total radiance. Therefore, the actual radiance leaving the reflectance plaque is greater than the radiance as specified by the manufacturer. This effect is especially important in

Figure 15: The ratio of system responses calculated from two independent calibrations. The agreement between the two calibrations is remarkable considering the significant differences in the methods used.

small spaces but could be avoided by calibrating outdoors. The result of this effect increases the radiance leaving the plaque causing an underestimation of the system response. This underestimation is greatest towards the red end of the spectrum. The spectral dependence of the underestimation is due to the differences in the output of the two calibration sources, shown in Figure 16. Because the output of the OL220M is greatest in the red portion of the spectrum, one would expect the contamination of the radiance field and subsequent underestimation of the system response to be greatest in that region. For these reasons, the MOBY absolute radiance calibration is probably the better of the two and should be used for any subsequent radiance measurements.

Measuring instantaneous τ_a requires the execution of a high altitude Langley plot for calibration. The theoretical basis of the Langley plot is discussed in the methods section. On October 22 of 2002, two high altitude Langley plots were performed, one in the morning and one in the evening. The results of these measurements at the wavelengths of 440, 500, 675 and 870 nm for both channels are shown in Figures 17 through 20, respectively. There are significant features of these plots that require explanation. The first characteristic consistent at all wavelengths is the output of the instrument is less for ch.2 than ch.1. The two channels of the Ocean Optics SD2000 are completely independent so the relatively low output of ch.2 at all wavelengths can be explained as an inherent property of the ch.2 CCD. This conclusion is supported by the fact that measurements of a stable light field in the lab with ch.2 consistently use a higher integration time than identical measurements with ch.1. The conclusion here is that ch.1

is simply more sensitive. Another feature that can be seen in the plots as well as Table 1 is the errors of the regressions are consistently worse for ch.1. This can be explained by the differences in the fov of the Gershun tubes and the concept of direct versus scattered light.

Figure 16: Absolute output of the two calibration sources compared. The OL420 is a low light level integrating sphere radiance standard. This particular source is vigorously characterized by NIST because it is used for calibrating radiometers as components to MOBY. The OL220M is a lower wattage irradiance standard that was reflected off of a reflectance plaque to produce a calculated radiance.

Figure 17: High altitude Langley plot for channel 1 and 2 of COOPS on the morning and evening of Oct. 22, 2002 at 440 nm.

The design of the collecting optics of Sun photometers represents a compromise between limiting atmospheric scattered light in high turbidity conditions and pointing requirements (Schmid and Wehrli, 1995). Any Sun photometer measures both direct and scattered light, because the fov, typically between 1.3° and 4°, is larger than that of the Sun (0.5°). Scattered light, when measuring direct atmospheric transmission, is a known source of error that can be significant, depending on sky conditions. An instrument with a smaller fov will reject more skylight than one with a larger fov and will therefore make more precise measurements with less variability. Considering that ch.1 has a fov that is significantly larger than ch.2 it follows that ch.1 will see more variability in the measurements due to less rejection of skylight. This source of variability can be seen quite clearly at 675 and 870 nm (Figs.19 and 20) and to a lesser extent at 440 and 500 nm (Figs. 17 and 18).

Another significant result is the negative correlation between the r^2 value of the regressions and wavelength (Fig. 21). This can be explained by considering the relative values of light and dark scans. While the dark scan values are independent of wavelength the light scan values are dependent on wavelength for two reasons; the nature of the solar spectrum and the response of the detector. At longer wavelengths, this dependence affects the value of the light scans rendering them less significant relative to corresponding dark scans. The increased relative significance of dark scans adds variability to the measurements at longer wavelengths and results in the poor r^2 values at 870 and 675 nm (Fig. 21).

Figure 18: High altitude Langley plot for channel 1 and 2 of COOPS on the morning and evening of Oct. 22, 2002 at 500 nm.

Figure 19: High altitude Langley plot for channel 1 and 2 of COOPS on the morning and evening of Oct. 22, 2002 at 675 nm.

Figure 20: High altitude Langley plot for channel 1 and 2 of COOPS on the morning and evening of Oct. 22, 2002 at 870 nm.

Figure 21: All four high altitude Langley plots show a negative correlation between the r squared value of the regression and wavelength.

The y-intercept of a high altitude Langley plot gives the calibration constants for a particular wavelength. Table 1 lists these constants for the morning and afternoon Langley plots for both channels.

Table 1: Calibration constants for both channels and calibrations of the COOPS Sun photometer. The units of countadj are defined by Equation 3 in the method section.

Wavelength(nm)	870	675	500	440
ch.1am(countadj)	2.084±0.061	4.745±0.048	5.650±0.020	4.042±0.026
ch.1pm(countadj)	2.057±0.090	4.750±0.127	5.623±0.058	4.061±0.045
% difference	1.3%	0.1%	0.5%	0.5%
ch.2am(countadj)	1.307±0.031	3.573±0.018	4.335±0.012	3.164±0.015
ch.2pm(countadj)	1.314±0.032	3.610±0.033	4.392±0.039	3.258±0.041
% difference	0.6%	1.0%	1.3%	2.9%

At all wavelengths except for 870 nm, the differences in calibration constants are smaller for ch.1 than ch.2. This may be explained by considering the differences in the fov of the two instruments and the relation of fov to pointing accuracy. Absolutely necessary to measuring direct atmospheric transmittance is the centering of the Gershun tube on the Sun. In the case of the CIMEL this is accomplished by an active quadrant detector that measures the relative intensities in four quadrants of the image and adjusts the alignment of the instrument until these intensities are balanced. Because the COOPS Sun

photometer was not equipped with a quadrant detector, one could not be absolutely sure that the Sun was centered in the fov of both Gershun tubes. Considering ch. 2 has a fov that is significantly less than the fov of ch.1, the alignment of ch.1 is not as critical and the chance of the Sun being within the fov is greater. While this larger fov has effectively been shown to increase variability in measurements, it apparently has advantages in that it doesn't require as accurate an alignment. It is reasonable to assume that the alignment of the Gershun tubes played a significant part in the agreement between calibration constants and the reproducibility of the alignment between Langley plots is superior for ch.1. The calibration constants shown in Table 1 were determined by linear regression calculated at a 95% confidence interval. In all cases for ch.1 the calibration constants agree within the calculated precision, therefore the average was accepted as the final result and used to calculate τ_a . For ch.2, the calibration constants agree within the calculated precision at the wavelengths of 870 and 675 nm but not at 500 and 440 nm. Therefore the calibration constants for ch.2 of COOPS at 500 and 440 nm remain unknown. For the sake of further analysis the mean of the constants for ch.2 at 500 and 440 was used.

Another significant result apparent in Table 1 is the errors of the calibration constants associated with the morning measurements are, in every case, less than those for the afternoon measurements. This can be explained by the fact that the atmosphere is typically more stable in the morning than the afternoon.

Linearity

Part of the characterization of the COOPS Sun photometer necessary for measurements of sky radiance, direct atmospheric transmittance, and any other radiometric measurements, included an experiment to measure the linearity of the response of both channels. The algorithm used for this experiment was adopted from Ocean Optics and described in the methods section. Ocean Optics tests linearity for only one pixel and assumes that the results apply to all other pixels. Using the Ocean Optics algorithm, linearity was tested for a selection of pixels to verify this assumption. Figures 22 and 23 show the normalized response of channels 1 and 2 respectively, as a function of digital count for the selection of pixels. Also in these figures, plotted in black, is the normalized response of both channels as determined by Ocean Optics at the time of purchase.

The difference in corrections for the selection of pixels, as determined by this experiment, is within 1%, affirming the assumption made by Ocean Optics. The differences between the corrections determined by Ocean Optics and those determined by the current study are near 1% at all digital counts below 4000 and approach 2% above 4000. As a general rule, users of this spectrometer should not use an integration time resulting in digital counts above 75% of saturation. Because 4000 digital counts is only 95 less than saturation for a 12-bit instrument (4095) this 2% difference at 4000 counts in the linearity correction is not a concern.

Figure 22: The non-linear response of a selection of pixels from channel 1 of the SD2000. The Y-axis is normalized counts per second. Plotted in black is the 7th order polynomial regression by Ocean Optics to determine the non-linearity correction at the time of purchase. The other colors each represent an individual pixel, 20 in all were analyzed for response linearity.

Figure 23: The non-linear response of a selection of pixels from channel 2 of the SD2000. The Y-axis is normalized counts per second. Plotted in black is the 7th order polynomial regression by Ocean Optics to determine the non-linearity correction at the time of purchase. The other colors each represent an individual pixel, 20 in all were analyzed for response linearity.

The linearity corrections as determined by the current study for all pixels are consistently greater than those calculated by Ocean Optics. This discrepancy can be explained by inspecting the residuals of the current experiment and comparing them with the residuals resulting from the Ocean Optics experiment shown in Figure 24. For the Ocean Optics experiment the values of the residuals were significantly smaller. These smaller residuals can be explained by either a more stable detector or a more stable light source. The power supply and lamp used for the evaluation were more than adequate therefore it is more likely that the detector is not as stable as it was when Ocean Optics performed the experiment. As a direct result of the detector being less stable, and the nature of the Ocean Optics algorithm, the corrections determined by Ocean Optics are smaller by 1-2 %. The results of the current study are comparable (within 1%) to the results of the Ocean Optics experiment and the regression statistics of the Ocean Optics experiments are superior, therefore nonlinearity corrections as determined by Ocean Optics should be applied to any subsequent measurements.

Comparison to CIMEL

The calibration and characterization of the COOPS Sun photometer was a necessary step for measuring τ_a . To determine the performance of the COOPS Sun photometer in terms of accuracy and precision, all measurements were compared to coincidental measurements of τ_a by the CIMEL stationed at MLML, part of the AERONET Network of Sun photometers.

Figure 24: The residuals from a regression of counts per second vs. counts for both non-linearity experiments. The upper plot shows residuals from Ocean Optics at the time of purchase. The lower plot shows residuals from a more recent non-linearity experiment, in which the non-linearity was calculated for more than one pixel. The results for both channels were nearly identical therefore these graphs represent channel 1 only.

The results of comparing coincidental measurements of τ_a were calculated as percent differences between the two channels of the COOPS and the CIMEL. These differences were calculated for three Langley series on the mornings of the 12th, 13th, and 14th of October 2004 recorded at MLML. The comparison of COOPS with CIMEL shows deviations as a function of channel, day, and wavelength.

To evaluate the performance of COOPS as a function of channel, the measurements of τ_a at 440 nm were used. Figure 25 shows the values of τ_a at 440 nm for all three days as measured by both instruments. This Figure shows large deviations in the percent difference between the values of τ_a at 440 nm measured by CIMEL and COOPS channel 2, while channel 1 agrees reasonably well ($\pm 10\%$). It is apparent from Figure 25 that ch.2 routinely underestimates τ_a which is most likely a result of being out of calibration. The consistency with which ch.2 underestimates τ_a suggests a positive change in the amount of light accepted by the system between the date of calibration and measurement. Considering the apertures of the baffles used in Gershun tube 2 (200 – 1000 microns), only a small change in the position of any one of the 5 baffles could cause a significant change in the percent transmission and the resulting determination of τ_a . Another possibility is a change in the alignment of the Gershun tube. Almost two years passed between the time of calibration and measurement, therefore either is a realistic possibility. Figure 26 represents the best agreement in terms of wavelength for ch.2. At 675 nm ch.2 deviates even further from CIMEL, between 20 and 50%, at 870 nm the differences are between 0 and 100% (Fig. 29, Fig. 31).

Figure 25: τ_a at 440 nm measured by CIMEL and both channels of COOPS. The measurement of τ_a at 440 nm by the COOPS instrument was the most accurate and precise when compared to the CIMEL, relative to the other wavelengths of 675 and 870 nm.

Figure 26: Percent difference in τ_a at 440 nm as measured by CIMEL and both channels of COOPS.

Figure 27: The absolute value of τ_a measured by COOPS channel 2 on Oct. 14th. τ_a measured by COOPS channel 2 is significantly different than the values measured by CIMEL. However, there does seem to be agreement between COOPS channel 2 and CIMEL in monitoring temporal changes in τ_a .

While the absolute value of τ_a measured by ch.2 is significantly different than the value measured by the CIMEL, there does appear to be some agreement with the CIMEL in monitoring temporal changes in τ_a (Fig. 27). The ability of COOPS ch.2 to monitor temporal changes in τ_a , while the absolute values are significantly different, supports the conclusion that the instrument was out of calibration at the time of the measurement but could accurately measure τ_a if another calibration were performed.

To evaluate the performance of COOPS on the basis of day, again the measurements of τ_a at 440 nm were used. The mean percent difference of all measurements for both 440 and 870 nm on the 12th is the highest and on the 14th, the least (Table 2). An anomaly is present at 675 nm where the mean percent difference is highest on the 12th but least on the 13th. This trend seen at 440 and 870 nm is believed to be caused by disassembly of the instrument between measurement sequences.

Table 2: The mean percent difference between measurements of τ_a by COOPS and CIMEL for all three days and wavelengths. At 870 and 440 nm the measurements by COOPS were most accurate on the 14th and least accurate on the 12th. At 675 nm the measurements were least accurate on the 12th but most accurate on the 13th.

Wavelength(nm)	870	675	440
Oct. 12, 2004	242.9 %	29.0 %	13.2 %
Oct. 13, 2004	153.8 %	7.0 %	4.2 %
Oct 14, 2004	135.8 %	15.2 %	1.9 %

To evaluate the performance of COOPS on the basis of wavelength, the measurements of τ_a by ch. 1 were used. For all three days, the agreement between CIMEL and COOPS ch.1 is greatest at 440 nm and worst at 870 nm (Table 2). Two factors contribute to these trends, the spectral transmission of the fibers (200 – 750 nm) and the operating wavelengths of the SD2000 CCD (350 – 1000 nm). At 870 nm the fibers are limiting the amount of light reaching the detector resulting in overestimates of τ_a , seen as relatively large positive percent differences in column 1 of Table 2. The wavelength of 440 nm is well within the operating wavelengths of the fibers and the detector resulting in relatively accurate estimates of τ_a , as seen in column 3 of Table 2. To speculate about the accuracy of measurements of τ_a at 675 nm, it is possible that the fibers were again limiting the signal. The exact spectral transmission of the fibers from Ocean Optics was not available.

As previously mentioned, the success of the COOPS instrument was heavily dependant on the day of the measurement, on the 14th of October, at 440nm the agreement between COOPS ch.1 and CIMEL is excellent, a mean percent difference of 1.9% (Table 2.) The agreement for COOPS ch.1 on this day is shown in the bottom axis of Figure 26. An encouraging feature of this plot is the percent differences for successive measurements are equally distributed above and below zero. This symmetry about zero represents a characteristic of an instrument that has been properly calibrated for that wavelength. In contrast, the percent differences at 870 nm between COOPS ch.1 and CIMEL are consistently positive, representing an overestimation of τ_a (Fig. 31). This is

consistent with using a fiber having a transmission between 200 and 750 nm. An insufficient amount of light reaching the detector as a result of the limited transmission of the fiber renders as a higher than realistic value for τ_a .

Figure 28: Coincidental measurements of τ_a at 675 nm by CIMEL and both channels of COOPS.

Figure 29: Percent difference in τ_a at 675 nm measured by CIMEL and both channels of COOPS.

Figure 30: Coincidental measurements of τ_a at 870 nm by CIMEL and both channels of COOPS.

Figure 31: Percent difference in τ_a at 870 nm measured by CIMEL and both channels of COOPS. The apparent accuracy of COOPS ch.2 on October 12th and 13th is believed to be coincidence resulting from using a fiber with the wrong transmission and a physical change in the Gershun tube between calibration and measurement.

Summary and Conclusions

The development, calibration, and characterization of the COOPS Sun photometer provided valuable insight into the requirements for measuring sky radiance and τ_a accurately and precisely. The COOPS Sun photometer was the integration of an Ocean Optics SD2000 two channel spectrometer, a Celestron Nexstar 5 telescope, and Gershun tubes machined at MLML. There were distinctive problems and benefits of the spectrometer, the telescope, and the COOPS system as a whole that are worth noting.

The Celestron Nexstar 5 was well suited to providing the tracking mechanism necessary to measure τ_a and sky radiance. The telescope's ability to track the Sun was a function of the quality of the alignment procedure. When properly aligned the scope was capable of tracking the Sun for hours. The tracking mechanism was used only to keep the Sun in the general area while a certain amount of fine tuning was necessary before an actual measurement was made. In the interest of developing COOPS further, the Celestron could be fully programmed and controlled using the built in RS-232 interface. A script written for controlling the Celestron would be a significant improvement to the system and would qualify the Celestron as more than adequate for a fully functional Sun photometer. If the COOPS system was to be deployed for an extended period of time, it would necessary to protect the scope from weather. Without some modification or weatherproofing the telescope would certainly degrade quickly depending on conditions.

The Ocean Optics SD2000 spectrometer when used as a Sun photometer has one distinctive advantage over the CIMEL and any other filter Sun photometer. The SD2000 was a linear CCD instrument with a resolution of 0.3 nm. This high resolution allows one to compare measurements of either sky radiance or τ_a to measurements made by any other instrument as long as the filter functions of that instrument are available. This was practiced in comparing the measurements of COOPS to the CIMEL. The two distinct channels of the SD2000 were advantageous in determining the effects of different fields of view on the calibration of the Sun photometer. These two channels could have been used differently by configuring one to measure sky radiance and the other to measure direct atmospheric transmittance. The SD2000 was a compact instrument that could be encapsulated for weatherproofing and temperature maintenance allowing for prolonged deployment and better management of dark counts. Perhaps one of the biggest advantages of using the SD2000 was the price, at \$4000, a fraction of the cost of an alternative spectrometer that would be integrated into a Sun Photometer. The Celestron Nexstar 5 was approximately \$1000 and additional components needed would be another \$1000 bringing the total for the COOPS to \$6000. For reference, a CIMEL costs approximately \$28,000 (Holben, personal communication).

One of the problems with the SD2000 was the mating of the fibers to the spectrometer. This process was not repeatable and should not be trusted depending on the intended measurements. Ideally, after calibration, the spectrometer/fiber/Gershun tube assembly would never be disassembled. The bandwidth of the fibers was too small.

At the time of purchase Ocean Optics offered two types of fibers and both were purchased, UV-VIS and VIS-NIR. Depending on which fibers were used, the shorter or longer wavelengths of the CIMEL could not be measured, namely 440 or 870 nm. Ocean Optics now sells fibers with a bandwidth of 400 – 2100 nm.

A few successes and failures of the COOPS system should be mentioned. Assuming a proper calibration with fibers of a proper bandwidth, COOPS has significant potential to accurately and precisely measure τ_a . This ability was most apparent on October 14, 2004 at the wavelength of 440 nm (Fig. 26, bottom plot) when the mean percent difference was less than 2%. There is no reason to assume that measurements at the longer wavelengths of 500, 675, and 870 nm could not be as precise and accurate. The ability to measure sky radiance was not determined.

The COOPS instrument failed at longer wavelengths due to user inexperience and the limited bandwidth of the fibers. For COOPS to be a fully functional automated Sun photometer additional work would need to be invested in writing scripts to simultaneously control the telescope and the spectrometer. For the purpose of focusing the instrument on the Sun, a quadrant detector could be used, or a MATLAB script could determine the orientation of the scope corresponding to the strongest signal received by the spectrometer. With these additional modifications COOPS could be deployed for an all day measurement series.

The spectrometer/fiber/Gershun tube assembly should not be disassembled without a subsequent calibration. This assembly would be awkward to handle and

transport and the mounting of the Gershun tubes on the optical tube of the telescope would have to be repeatable, otherwise the current calibration would be erroneous. The repeatability of this mounting procedure was not tested.

Unfortunately because of the disruption of the channel 2 Gershun tube between the time of calibration and measurement, the effects of different fov on measurements of τ_a could not be determined. However, there were apparently significant effects of the different fields of view on the calibration measurements. The channel with a larger fov made measurements with more variability as one would expect because of the influence of skylight. Both channels had fov that were too large by accepted standards of 1-3°. While the large fov increases variability it does not require as accurate pointing capability which may have been significant considering the COOPS had no quadrant detector. Further research is required to understand the effects of different fov on the calibration coefficients determined from high altitude Langley plots as well as measurements of τ_a and sky radiance.

One conclusion important to the field of Sun photometry as well as any other field involving radiometric measurements was the remarkable agreement between the two different methods of absolute radiance calibration. Any absolute radiometric calibration requires a NIST traceable standard lamp. For this study, radiance calibration was performed using a radiance standard as well as an irradiance standard combined with a reflectance plaque. The results showed agreement within 5% for the two methods between 400 and 700 nm, and agreement within 10% above 700 nm. As a result of

calibrating with an irradiance standard in a small room, there was significant contamination of the light radiating from the plaque resulting in an underestimation of the system response above 700 nm. This lack of agreement above 700 nm could be addressed by attempting the same calibration outdoors on a dark night.

In conclusion, the COOPS Sun photometer showed significant potential to be an economical, portable, automated instrument with the ability to accurately and precisely measure τ_a . This approach to measuring τ_a could potentially fill a niche between handheld Sun photometers requiring constant attention and a CIMEL which can be deployed for months at a time.

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Appendix

Radiance System Response for COOPS in $\mu\text{W}\cdot\text{s}/\text{cm}^2\cdot\text{nm}\cdot\text{sr}\cdot\text{counts}$

Wavelength (nm)	MOBY	Optronics	Ratio
400.27	0.0547	0.0535	0.97776
405.26	0.0485	0.0486	1.00293
410.25	0.0441	0.0451	1.02206
415.23	0.0429	0.0437	1.01797
420.21	0.0404	0.0404	1.00181
425.18	0.0373	0.0367	0.98315
430.14	0.0346	0.0346	0.99962
435.10	0.0319	0.0319	0.99876
440.05	0.0301	0.0295	0.97909
445.34	0.0282	0.0278	0.98564
450.28	0.0278	0.0270	0.96887
455.21	0.0264	0.0253	0.95799
460.13	0.0249	0.0241	0.96774
465.05	0.0223	0.0214	0.95990
470.31	0.0188	0.0179	0.95041
475.21	0.0156	0.0150	0.96265
480.11	0.0130	0.0125	0.96202
485.35	0.0112	0.0107	0.95908
490.23	0.0100	0.0096	0.96406
495.10	0.0094	0.0091	0.97266
500.32	0.0091	0.0089	0.98120
505.18	0.0089	0.0088	0.98507
510.04	0.0089	0.0088	0.99490
515.23	0.0089	0.0090	1.00520
520.07	0.0088	0.0089	1.01006
525.25	0.0088	0.0090	1.01509
530.07	0.0088	0.0090	1.02036
535.23	0.0088	0.0090	1.02353
540.04	0.0088	0.0091	1.03095
545.19	0.0092	0.0094	1.03132
550.33	0.0092	0.0095	1.03569
555.11	0.0094	0.0097	1.03819
560.23	0.0097	0.0101	1.03611
565.01	0.0099	0.0103	1.04057
570.11	0.0101	0.0105	1.04091
575.21	0.0105	0.0109	1.03549
580.29	0.0107	0.0111	1.03558
585.03	0.0109	0.0113	1.03510
590.11	0.0111	0.0116	1.03952
595.17	0.0114	0.0118	1.03928
600.22	0.0118	0.0123	1.03791
605.27	0.0121	0.0125	1.03255
610.30	0.0126	0.0130	1.02805
615.33	0.0131	0.0135	1.03002
620.01	0.0134	0.0138	1.02928

Radiance System Response for COOPS in $\mu\text{W}\cdot\text{s}/\text{cm}^2\cdot\text{nm}\cdot\text{sr}\cdot\text{counts}$ (cont.)

Wavelength (nm)	MOBY	Optronics	Ratio
625.02	0.0140	0.0143	1.02099
630.02	0.0147	0.0149	1.01546
635.01	0.0149	0.0152	1.01700
640.33	0.0156	0.0157	1.01222
645.30	0.0163	0.0164	1.00929
650.27	0.0169	0.0170	1.00687
655.22	0.0175	0.0176	1.00390
660.16	0.0184	0.0183	0.99516
665.10	0.0191	0.0190	0.99539
670.03	0.0203	0.0200	0.98507
675.27	0.0213	0.0209	0.98135
680.18	0.0223	0.0218	0.97944
685.08	0.0239	0.0232	0.97184
690.29	0.0247	0.0239	0.96904
695.17	0.0260	0.0250	0.96282
700.04	0.0274	0.0264	0.96262
705.22	0.0290	0.0276	0.95022
710.07	0.0298	0.0281	0.94411
715.23	0.0318	0.0298	0.93933
720.05	0.0334	0.0312	0.93343
725.19	0.0355	0.0332	0.93413
730.00	0.0372	0.0345	0.92732
735.12	0.0395	0.0365	0.92418
740.22	0.0418	0.0383	0.91770
745.00	0.0444	0.0406	0.91288
750.08	0.0471	0.0430	0.91335
755.16	0.0508	0.0464	0.91298
760.22	0.0549	0.0498	0.90686
765.27	0.0590	0.0538	0.91096
770.30	0.0632	0.0571	0.90274
775.02	0.0668	0.0607	0.90877
780.03	0.0716	0.0646	0.90237
785.03	0.0742	0.0680	0.91603
790.02	0.0779	0.0712	0.91337
795.00	0.0810	0.0738	0.91204
800.28	0.0867	0.0781	0.90153
805.23	0.0917	0.0823	0.89739
810.18	0.0971	0.0878	0.90426
815.11	0.1045	0.0950	0.90889
820.02	0.1106	0.1004	0.90790
825.24	0.1192	0.1062	0.89124
830.13	0.1292	0.1150	0.89034
835.01	0.1373	0.1221	0.88943
840.18	0.1491	0.1334	0.89461
845.03	0.1578	0.1404	0.88946
850.18	0.1717	0.1512	0.88093
855.01	0.1839	0.1629	0.88601

Radiance System Response for COOPS in $\mu\text{W}\cdot\text{s}/\text{cm}^2\cdot\text{nm}\cdot\text{sr}\cdot\text{counts}$ (cont.)

Wavelength (nm)	MOBY	Optronics	Ratio
860.12	0.1983	0.1777	0.89609
865.23	0.2152	0.1906	0.88551
870.02	0.2344	0.2124	0.90619
875.09	0.2562	0.2288	0.89276
880.15	0.2829	0.2547	0.90001
885.20	0.3039	0.2703	0.88933
890.23	0.3183	0.2809	0.88264
895.24	0.3305	0.2999	0.90740
900.24	0.3463	0.3131	0.90414