Progress Towards Massively Parallel Smartphone Sunphotometry

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Introduction

In recent years smartphones have become ubiquitous in society. These devices offer unique platforms for remote monitoring applications as they contain advanced processors and communication ability, are equipped with sophisticated sensors (cameras, accelerometers, and GPS), and are consistently located with an end user. In principle, a network of smart-phone-based sun photometers operated by citizen-scientists could offer air-column-integrated information at many locations simultaneously. The purpose of this work is to determine whether the onboard smartphone camera can be used as a detector/ receiver for a sun photometer.

Sunphotometers measure the irradiance of sunlight within narrow wavelength bands that reaches earth's surface. The top-of-the-atmosphere (TOA) solar irradiance can be estimated through construction of a Langley plot, which is a calibration procedure that relates known changes in atmospheric path length (air mass) with observed changes in signals. Once the TOA intensity is known, atmospheric column transmittance (T) and integrated optical depth can be calculated. In principle, if sun photometry data collected with a smart phone could quickly be sent to a central location and automatically processed, environmental monitoring could be performed in nearly real-time on a continental-to-global scale.

Method

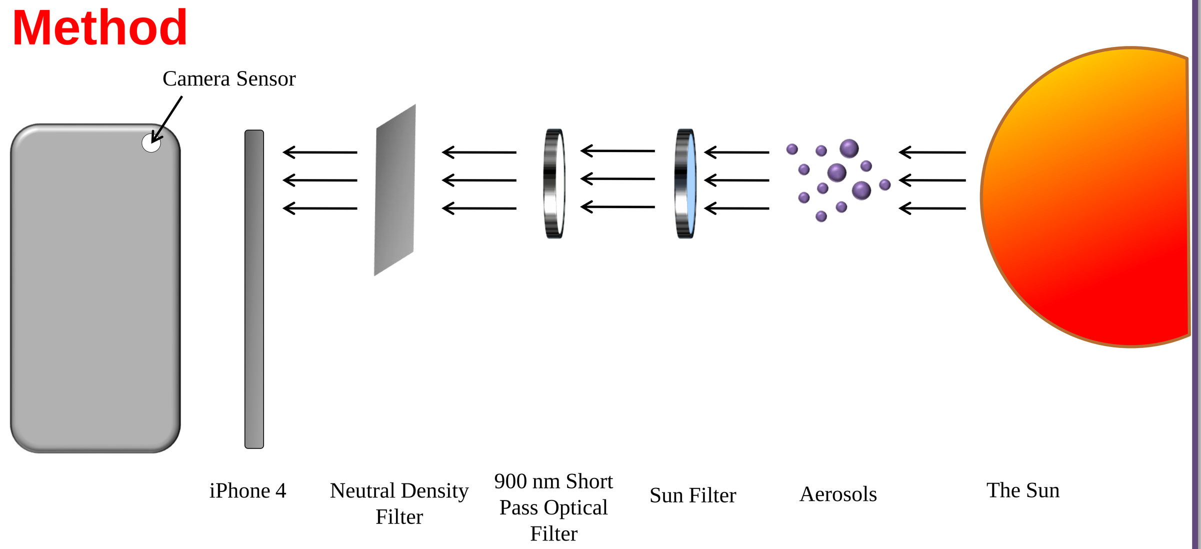

Figure 1. Diagram of Instrument setup for the sunlight measurements. The "sun filters" are band pass filters with spectra as shown in Figure 2. Images were acquired on the iPhone in 645 Pro, a camera app that locks exposure time and ISO setting.

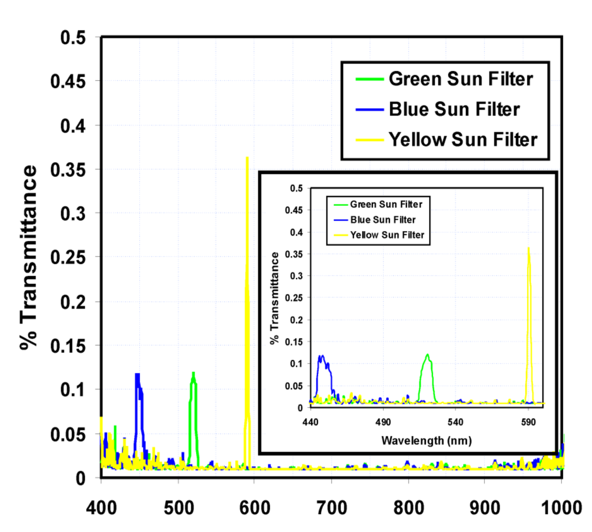

Figure 2. Plot of % Transmittance vs. wavelength for the 3 sun filters used in this study. This data was recorded with a UV-VIS spectrophotometer. Filter band passes were centered around 450, 530, and 590 nm. Low peak transmittance values were required to avoid saturation of the 8-bit detector.

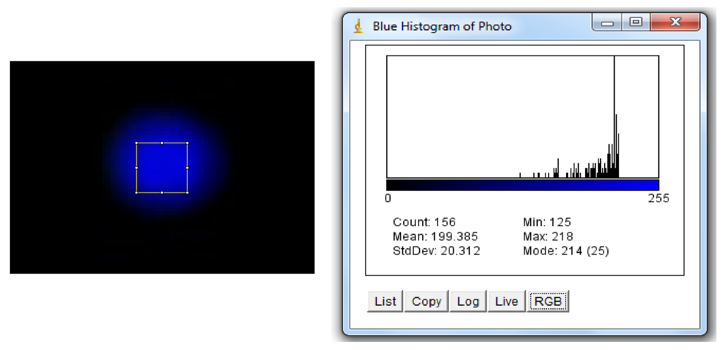

Figure 3. Left – **photo of the sun through the blue sun filter. Right – A histogram of blue channel RGB counts.** Data was processed by using *ImageJ*

Accuracy and Precision of Smartphone Measurements

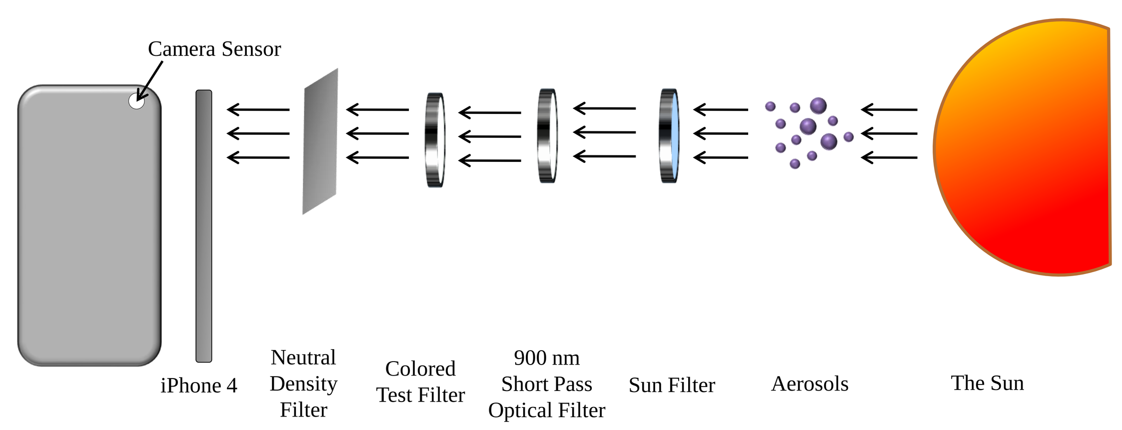

Figure 4. Diagram of Instrument Setup for Accuracy and Precision Measurements

Types of Colored Test Filters
400 nm Long Pass Optical Filter
495 nm Long Pass Optical Filter
550 nm Long Pass Optical Filter
335 - 610 nm Band Pass Optical Filter
"Straw Tint" Plastic Filter
"Chocolate" Plastic Filter
"Dark Steel Blue" Plastic Filter

Table 1. A list of filters used for accuracy and precision testing of smartphone measurements. These filters were used to simulate aerosol loadings. The accepted transmittance of each filter was known, and the smartphone was used to measure a transmittance for comparison data.

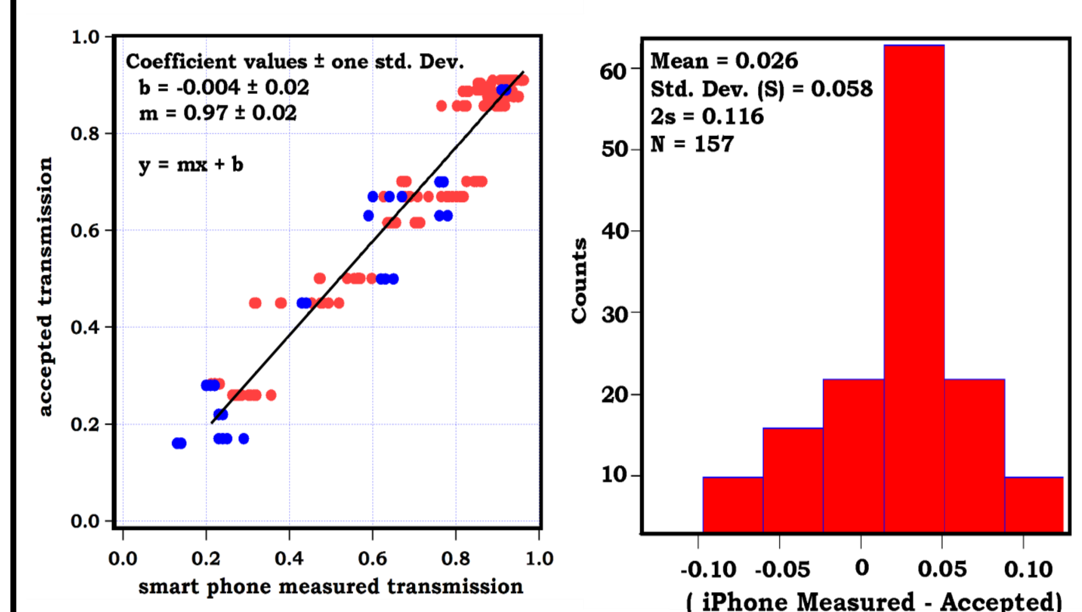

Figure 5. *Left* – Plot of accepted transmittance of a series of colored test filters *vs.* smart phone measured transmittance using the sun (red) and a UV-VIS lamp (blue) as light source. The solid best-fit line was determined by orthogonal distance regression. The slope of the line is close to unity and the intercept near zero indicating good agreement between the measurements made with the smart phone and reference method. *Right* – Histogram of differences between smart phone measured and accepted transmittances for sun data. A slight positive bias is reflected in the data. The calculated standard deviation (*s*) of differences between measurements was 0.058, yielding a 2*s* uncertainty of ±0.116 or 11.6 % T.

Construction of Langley Plots

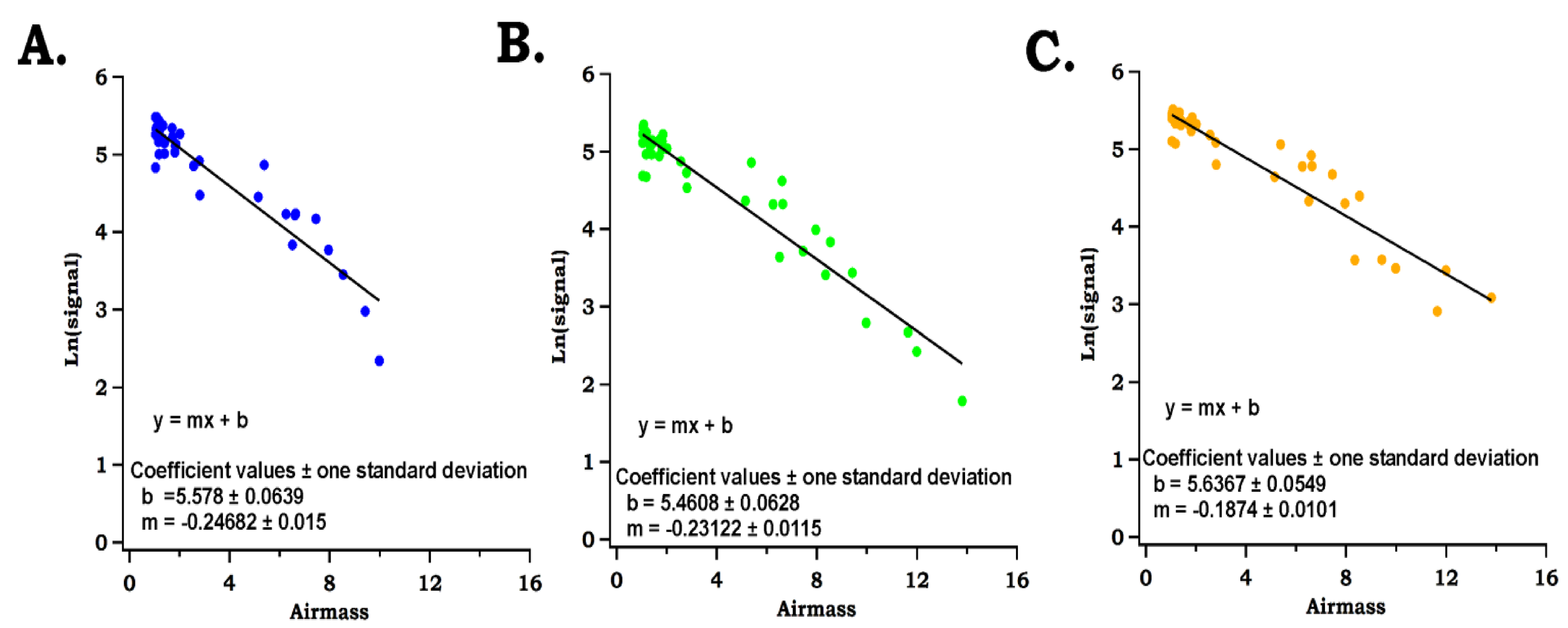

Figure 6. Langley Plots (ln signal vs. air mass) for the blue (A), green (B), and yellow (C) sun filters. The slope of the best-fit lines represent optical loss per unit air mass while the intercept describes the signal expected at the top-of-the-atmosphere (TOA). Best-fit lines determined by orthogonal distance regression.

When the sun is directly overhead (zenith angle = 0), the air mass is equal to z = 1. At dusk and dawn, air mass can exceed 15. If attenuation is caused by a homogeneous atmosphere following the Beer-Lambert law we can write:

$$I(z) = I_0 e^{-mz} \quad (1)$$

Where *I* and I_0 are irradiances at a given wavelength, *z* is air mass, and *m* is a term describing attenuation per unit air mass. Rearranging Eqn. 1 yields:

$$\ln I(z) = \ln I_0 - mz \quad (2)$$

The cosine of the solar zenith angle at any time / date for our location was computed by using the **NOAA solar position calculator** (http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html). Air mass was estimated as the inverse of this value. This estimate is known to be less accurate when the sun is near the horizon (air mass > 10). Also, measurements made near sunrise / sunset are also subject to a higher uncertainty since air mass changes very rapidly at these times, and collecting data for a trial requires a finite amount of time.

Monitoring Changes in Optical Depth

For ambient measurements of optical depth, the observed smart phone sun photometer signals ($I_{observed}$) were determined in Image J and then ratioed to the expected top-of-the atmosphere (I_{TOA}) signal values for each channel obtained via the Langley analysis. This resulted in calculation of atmospheric transmission. Optical depth (o.d.) was then computed via:

$$o.d. = -\ln\left(\frac{I_{observed}}{I_{TOA}}\right) \quad (3)$$

The Angstrom exponent (a) is an empirically derived value used to describe optical attenuation with wavelength. The basic premise is that the trend in atmospheric optical attenuation with wavelength follows a power law of the form:

$$\tau_\lambda = \tau_{\lambda 0}\left(\frac{\lambda}{\lambda_0}\right)^{-\alpha} \quad (4)$$

Where the τ terms represent optical depths at two different wavelengths, and λ and λ_0 represent the two wavelengths considered. The Angstrom exponent (α) describes how rapidly attenuation changes with wavelength. It can reach a maximum value of $\alpha = 4$ for pure Rayleigh scatterers (gas molecules) and can be near zero (or even negative) for very large particles. This is why the clear sky appears blue but a overcast sky appears white or grey.

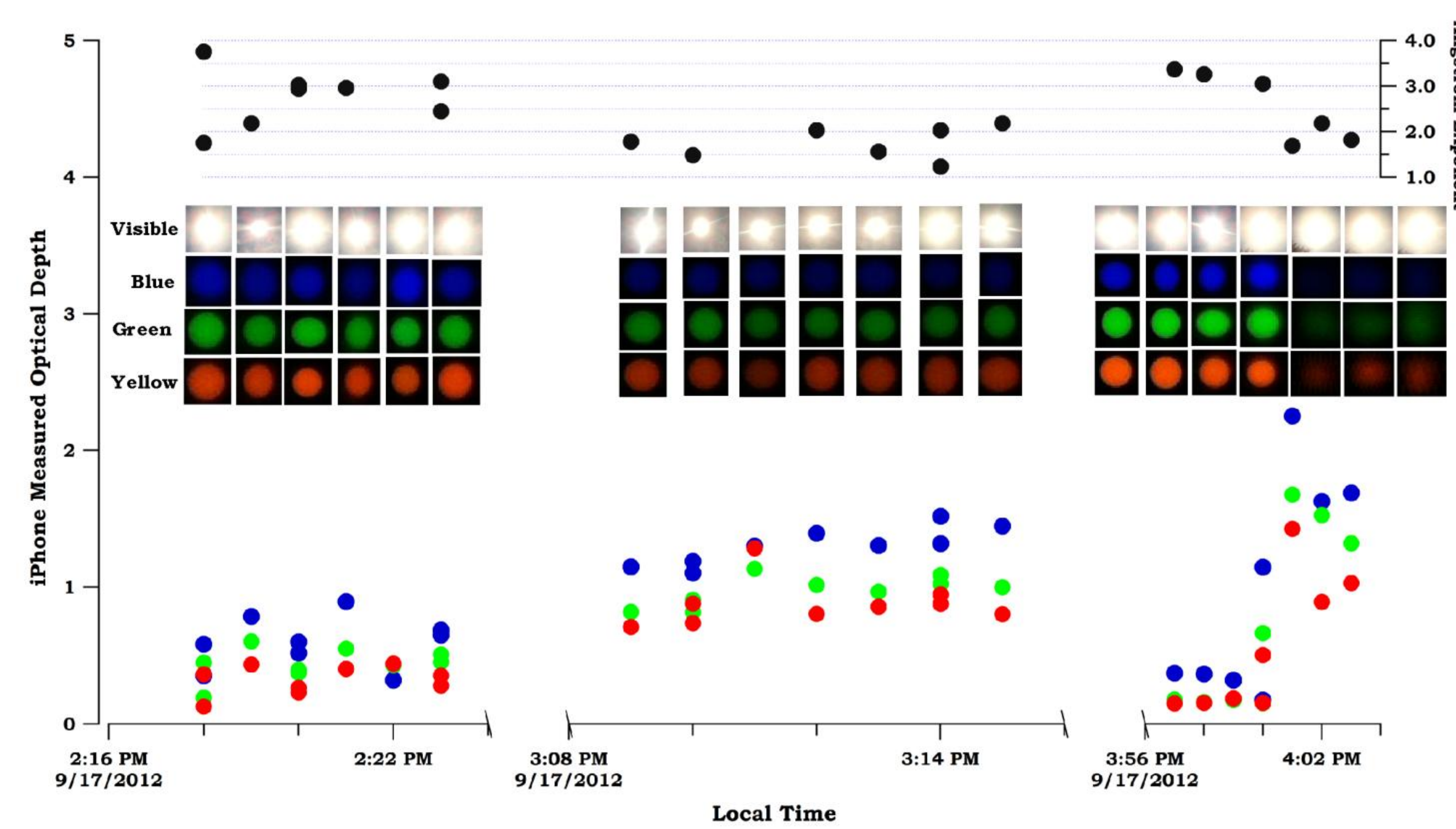

Figure 7. Monitoring atmospheric optical depth and Angstrom exponent at Lubbock, TX during the afternoon of September 17 2012 using the smartphone sun photometer on the blue, green, and yellow channels. September 17 featured a very thin, high-altitude stratus cloud layer that periodically blocked the sun and increased optical depth. This effect is particularly noticeable near 4:00 PM local time when a rapid and large increase in optical depth was observed. This change was accompanied by a reduction in Angstrom exponent by approx. 1 unit which suggests larger particles contribute to the total optical attenuation.

Conclusion & Further Directions

-A common smartphone has been adapted for use as a sun photometer. The uncertainty in optical depth achieved is on the order of 0.12. This is approximately an order of magnitude poorer performance compared to research grade devices. The measurement uncertainty is also similar to the total aerosol optical depths for the continental United States.

-A change in optical depth during the transit of a thin cloud through the optical path between the sun and an observer has been observed. This increase in optical depth corresponded with a decrease in Angstrom extinction exponent. This would be expected for optical attenuation by large water or ice particles of a cloud.

-Further investigations should focus on defining the limit of spectroscopic precision practically achievable with the on-board camera. In addition, new smartphone application software (an app) should be written to serve the specific purposes of the experiment，because at present data analysis is time consuming and complicated.

-Lastly, making narrow band absorption filters from common materials is required to lower the expense of the proposed network.

Acknowledgements

We would like to thank the State of Texas / Texas Tech University for financial support of this project through new investigator start-up funding.