Smartphone based Android app for determining UVA aerosol optical depth and direct solar irradiances.

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Abstract

This research describes the development and evaluation of the accuracy and precision of an Android app specifically designed, written and installed on a smartphone for detecting and quantifying incident solar UVA radiation and subsequently, aerosol optical depth at 340 nm and 380 nm. Earlier studies demonstrated that a smartphone image sensor can detect UVA radiation and the responsivity can be calibrated to measured direct solar irradiance. This current research provides the data collection, calibration, processing, calculations and display all on a smartphone. A very strong coefficient of determination of 0.98 was achieved when the digital response was recalibrated and compared to the Microtops sunphotometer direct UVA irradiance observations. The mean percentage discrepancy discrepancy for derived direct solar irradiance was only 4% and 6% for observations at 380 nm and 340 nm respectively, lessening with decreasing solar zenith angle. An 8% mean percent difference discrepancy was observed when comparing aerosol optical depth, also decreasing as solar zenith angle decreases. The results indicate that a specifically designed Android app linking and using a smartphone image sensor, calendar and clock, with additional external narrow bandpass and neutral density filters can be used as a field sensor to evaluate both direct solar UVA irradiance and low aerosol optical depths for areas with low aerosol loads.

Introduction

The most common ground based methods to measure direct solar irradiance and aerosol optical depth involve the use of specialised equipment including sunphotometers and sky radiometers [1][2]. The costs of and accessibility of this equipment often mean that its use, hence the spatial resolution of aerosol data collected is limited. Portable means of ground based measurement, such as the Microtops sunphotometer, while easy to use, are expensive, hence largely inaccessible to the wider community [3].

Smartphone image sensors have been found to have quantifiable sensitivity to ultraviolet A (UVA) (320-400 nm) radiation from both artificial and natural sources

[4][5]. The inclusion of band-pass and neutral density filters are required to prevent saturation and exposure damage of the image sensor. Studies by Igoe et al [5] demonstrated that different brands of smartphone are sensitive at 340 nm and 380 nm wavebands, requiring separate calibration algorithms for each.

Smartphones use the Android programming platform, which can be used by the wider community to write programs, or ‘apps’ that provide a means to link the output obtained from smartphone internal sensors with algorithms that calculate scientific quantities. Smartphone imaging technology and the Android operating system have been recently used in complex applications, including medical, architectural and air visibility studies [6][7].

There have been several apps that have been written to provide solar irradiances. However, these use external data sources and an attached external photosensor [8][9]. An air visibility app has been previously made using the smartphone image sensor and other sensors, focussing on atmospheric turbidity, with the data then sent to a remote server for processing [6]. This research extends previous research and demonstrates that reasonable accuracy for both direct solar irradiance and aerosol optical depth at 340 nm and 380 nm can be obtained with an app collecting, calibrating, processing and calculating the data in the smartphone itself for locations that have low aerosol loading.

Methodology

The smartphone used was an LG Optimus L3, similar to the one used in previous studies by Igoe et al. [5]. The only differences in the previous and present study phone is that the one used in this study has a slightly more advanced Android version (2.3.6 compared to 2.3.3), but the same Android functions work for both. Igoe et al. [5] has previously calibrated the image sensor grayscale (intensity) response (scaled to 255) with respect to direct solar ultraviolet irradiance and aerosol optical depth at 340 nm and 380 nm using data from a Microtops sunphotometer (Model E540, Solar Light). Calibration regression constants were developed for each of the target wavelengths. This study employs the same method of solar image capture as used in [5].

Consistent with the previous research by Igoe et al. [5], the same 380 nm and 340 nm narrowband filters (CVI Melles Griot) were used to discriminate between the two target wavebands, an ND1% neutral density filter (Asahi Spectra) was used to avoid saturation and damage to the image sensor and an additional ND2 neutral density filter (supplied by Bentham Instruments Inc.) was used for the 380 nm observations to prevent saturation.

The image sensor responses needed to be recalibrated to account for any differences in image sensor architecture between the phone used in this study and the one in the earlier study. As the specific information about the image sensor is propriety information and it would be damaging to retrieve the sensor, recalibration of each smartphone was employed. This was achieved through taking measurements calibrated to the data obtained from the Microtops sunphotometer, then comparing the grayscale response to the respective direct irradiance as in Igoe et al. [5] to determine the correct calibration regression constants.

The Android platform requires programming in both Java and XML languages, all algorithms can be written, compiled and tested on an emulator such as Eclipse ADT. The app used in this research has been designed to be as simple as possible, thereby not causing a significant drain on the battery or causing the app to time out. Simplifications will be described where they are made.

XML programming controls the layout and hardware permissions required for an app. The initial screen contains 3 main components:

- A radio box to select the target wavelength (340 nm or 380 nm).
- A text entry box to enter the station elevation in metres.
- A text entry box to enter the station latitude.

To keep the app programming as simple as possible, the user is to enter the latitude and elevation, an alternative method is for these parameters to be detected using the inbuilt GPS and through triangulation of wi-fi signals; however, in field tests performed by the first author, while the latitude was accurate, the elevation was very inaccurate, by up to 1.2 km.

Java algorithms perform all the functions that incorporate input from internal smartphone sensors [10]. Within the Java algorithm are activities, which broadly speaking are tasks that the algorithm performs. To calculate direct irradiance and aerosol optical depth, there are seven main tasks that have been designed and written for this purpose. These tasks are performed in the following sequence:

1. Capturing and retrieving an image (in the default JPEG format). This activity requires the use of the smartphone internal image sensor. This step is achieved by performing a camera intent. Rather than use the full camera functions, a camera intent just opens the camera on button click. The user then can control the parameters and orientation of the camera as they normally would and take the photo. The intent needs to be intercepted and the photo converted to a bitmap array, via a content resolver that exactly determines the location of the stored image.

2. Retrieving grayscale (intensity) data from the captured image. The image taken in the camera intent is retrieved and each pixel is converted to grayscale by equation 1 [11], as all 3 colour channels (red, green and blue) have been found to respond to incident UV radiation [4][5],

   $$Grayscale\ digital\ value = 0.30(red) + 0.59(green) + 0.11(blue) \qquad [1]$$

   The converted pixel digital values are stored as a separate grayscale bitmap array. The average grey response above a common threshold value determined from the calibration data was calculated [5]. The threshold was determined by observing the minimum grey value corresponding to the diameter of the solar disk in images taken for both 340 nm and 380 nm. This threshold value was found to be consistent at an approximate digital number of 20. Although, this is different to the method described by Igoe et al. [5], this approach was employed in the app to reduce the amount of processing required. The thresholded average grey values were similar to the values determined in the previous research.

3. After determining the average grey response, the Sun-Earth distance correction was calculated as is used by the Microtops sunphotometer [3][12]. This activity requires the use of the smartphone internal calendar. This correction is applied to the average grey value as it was in Igoe et al. [5].

4. Calculating the sun position for the date and time of the observation, using the latitude (lat) entered initially and calculations of declination (equation 2) and hour angle (equation 3) based on the date and time [13].

$$decl = 23.45° \sin\left[\frac{360°\,(d-81)}{365}\right] \qquad [2]$$

where *d* is the calendar day of the year.

$$hour\ angle = 15°\,(h-12) \qquad [3]$$

where *h* is the solar hour of the day.

The solar zenith angle (SZA) is calculated by

$$\cos(SZA) = \sin(decl)\cdot\sin(lat) + \cos(decl)\cdot\cos(lat)\cdot\cos(hour\ angle) \qquad [4]$$

This activity requires the use of the internal smartphone clock and calendar. Both the day of the year and hour of the day parameters are internally calculated from the exact time, thus include the fraction of the day and hour at the time of observation respectively.

5. Determination of the station air pressure correction to the Rayleigh optical depth. The Microtops sunphotometer corrects this quantity by multiplying it by the ratio of station air pressure with mean sea level pressure (1013.25 hPa) [3]. Although the most modern smartphones possess a barometric sensor, the LG used in this study did not. Consequently, as a substitute, the barometric formula was used to determine the pressure at the specified elevation (P_z) as in equation 4, valid up to 6 km in elevation [14].

$$P_z = 1013.25e^{\left(-\frac{mgz}{kT}\right)} \qquad [5]$$

The molecular mass of air (m), acceleration due to gravity (g) and absolute temperature (T) are assumed to be constant at 28.95 amu, 9.81 ms^{-2} and 288 K respectively. The Boltzmann constant (k) is 1.3806488 x 10^{-23} m^2 kg s^{-2} K^{-1}. The ratio of air pressure at elevation and mean sea level pressure (1013.25 hPa is used to correct the Rayleigh optical depth [3].

6. Calculation of the natural log of the direct solar ultraviolet irradiance at the selected target wavelength. The average grey value (Y) is multiplied by the 4th power of the cosine of the solar zenith angle (θ_{SZA}) as viewing the sun 'off-axis' (air masses greater than 1) results in the irradiance being subjected to the same trigonometric transformations that occur with field darkening, reducing it by this factor [15]. The Earth-Sun distance correction factor (D) and an additional constant correction factor (C) is also applied for when the target wavelength is 380 nm, to normalise the effects of the additional ND2 neutral density filter [5]. The natural log of this task initially uses the calibration regression constants from Igoe et al. [5] which needed to be tested and recalibrated, using the same method as in [5], to take into account the differences in image sensor architecture and the change in mathematical definition of the average grey value outlined in step 2, to give G' [5]. (m and c are the recalibrated constants):

$$G' = \mathrm{m}\ln(Y\,DC\cos^4\theta_{SZA}) + c \qquad [6]$$

7. Calculation and display of aerosol optical depth using the Beer-Lambert Law [3][5]. The natural log of the same extraterrestrial irradiance ($\ln(I_{0\lambda})$) and the constant values of the sea level base Rayleigh optical depth ($\tau_{R\lambda}$) constants relevant to the target wavelengths used in the Microtops sunphotometer are coded as constants in this activity. Specific aerosol species, including SO_2 and NO_2 are not considered separately [3]. Absorption of O_3 at the target wavelengths are negligible [5].

   The AOD is therefore calculated by (modified from [3]):

$$AOD_{\lambda} = (\ln(I_{0\lambda}) - G') \cdot \cos SZA - \tau_{R\lambda} \cdot \frac{P_z}{P_0} \qquad [7]$$

The tasks and their dependencies are summarised in Figure 1.

<Figure 1>

The calculated values for sun zenith angle, direct UV irradiance and aerosol optical depth are displayed on a dialog box on completion of the calculations for comparison with the Microtops sunphotometer in the initial calibration and follow-up validation observations.

The locations where observations for both calibration and validation tests were made for this research were at private residences in Toowoomba, Queensland (27.56°S 151.96°E, elevation 690 m) and Plainland, Queensland (27.57°S 152.42°E, elevation 80 m). Observations were made on days with clear skies between 9am and noon at both locations during the local winter and early spring. The ambient temperatures during the study varied from 12°C to 23°C (54°F to 74°F). The two sites were selected as they represented separate aerosol environments, Toowoomba situated on top of a range of hills within the Great Dividing Range dominated by continentl aerosols whereas Plainland is a rural centre situated in the middle of the Lockyer Valley, at a lower altitude and closer to the Queensland capital, Brisbane, thus experiences intermittent urban and agricultural aerosols. These locations were selected due to their relatively low elevations and consistent low aerosol loading.

Results and Discussion:

Throughout the observations, the smartphone calculated solar zenith angle only varied from the Microtops by a maximum of 5%. This mean percentage difference discrepancy decreased with decreasing zenith angle down to 0.01%. At solar noon, the values were equivalent; these discrepancies pose a minor error to the subsequent irradiance and aerosol optical depth calculations.

Recalibration

Recalibration of the initial calibration regression constants from [5] served two purposes:

1. To verify the precision of the previous calibration[5].
2. To determine the most accurate regression for the LG Optimus L3, given that the grey values above a threshold are averaged.

Figures 2 and 3 demonstrate the values of cosine grey determined from the app at 340 nm and 380 nm, against the natural log of direct ultraviolet irradiance obtained from the Microtops. The precision for both target wavelengths was very high with correlation coefficients of 0.98. The error bars are the values stated in Igoe et al. [5] and represent one standard deviation from the average grey value. After recalibrating the regression constants, there was a good fit between the smartphone derived cosine grey and the natural log of irradiance derived from observations taken by the Microtops. The same trends in calibration precision occurred in this study as were observed by Igoe et al. [5] for the non-automated measurements.

<Figure 2>

The recalibrated regression at 340 nm was:

$$\ln I_{Microtops} = 0.2821(cosine\ grey) - 1.0339 \tag{6}$$

<Figure 3>

The recalibrated regression at 380 nm was:

$$\ln I_{Microtops} = 0.1804(cosine\ grey) + 0.2462 \tag{7}$$

Validation

The new recalibrated regression constants were tested for accuracy in the two locations and the natural log of direct irradiances and aerosol optical depth observations were compared to those from the Microtops. The comparisons can be seen in Figures 4a, 4b and 5a, 5b respectively. The error bars for the 380 nm waveband comparisons are too small to be seen on the graphs. The scatter of the data may possibly due to intermittent random atmospheric and pixel responsivity fluctuations.

<Figure 4a>

<Figure 4b>

The comparisons were consistent with the results of the non-automated earlier study by Igoe et al. [5]. The 380 nm waveband observations were more accurate and precise than those observed at the 340 nm waveband. The mean percentage difference discrepancies for the 340 nm and 380 nm observations were 6% and 4% respectively.

<Figure 5a>

<Figure 5b>

Generally, in a similar trend to the previous non-automated observations, the 380 nm wavebands demonstrated a greater accuracy and precision than those observed at 340 nm. The aerosol optical depth values demonstrated greater accuracy and precision at lower solar zenith angles, with the greatest deviations occurring at angles of greater than 60°. The mean percentage difference discrepancies for both 340 nm and 380 nm observations were 8%. Inaccuracies also can be due to the presence of subvisible upper level clouds and the increase in error in sun zenith angle calculations.

Conclusion:

The accuracy and precision of a smartphone app developed and written in this research for the automation of the determination of direct solar irradiance and aerosol optical depth at discrete ultraviolet wavebands was demonstrated. Incident solar irradiance and varying aerosol optical depths were evaluated at 340 nm and 380 nm using a specifically designed and written Android app installed on a LG Optimus L3 smartphone. Calibration and validation of the results were consistent with those of previous non-automated research demonstrating that automation of the calculations of the direct solar UVA irradiance and aerosol optical depth are feasible using the internal sensors and the Android programming platform, common in smartphones. This study has shown that with the correct filters and a specific Android app, it is possible to be able to take measurements of UVA direct solar irradiance and low aerosol optical depths.

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Figures

Figure 1: Schematic of Android activities used in the app to determine the direct solar irradiance and aerosol optical depth.

Figure 2: Recalibrated regression comparing the smartphone app derived cosine grey values with the natural log of Microtops measured direct irradiance at 340 nm.

Figure 3: Recalibrated regression comparing the smartphone app derived cosine grey values with the natural log of Microtops measured direct irradiance at 380 nm. The error bars at this target wavelength are too small to be seen.

Figure 4a. Comparison of the natural log of direct irradiances derived from observations from the smartphone app and the Microtops at the 340 nm waveband. The diamonds represent the recalibration data and the circles are the validation data. The line represents an exact match.

Figure 4b. Comparison of the natural log of direct irradiances derived from observations from the smartphone app and the Microtops at the 380 nm waveband.

The diamonds represent the recalibration data and the circles are the validation data. The line represents an exact match. The error bars are too small to be seen in the graph.

Figure 5a. Comparison of the aerosol optical depths derived from observations from the smartphone app and the Microtops at the 340 nm waveband. The diamonds represent the recalibration data and the circles are the validation data. The line represents an exact match.

Figure 5b. Comparison of the aerosol optical depths derived from observations from the smartphone app and the Microtops at the 380 nm waveband. The diamonds represent the recalibration data and the circles are the validation data. The line represents an exact match.

Figure 1

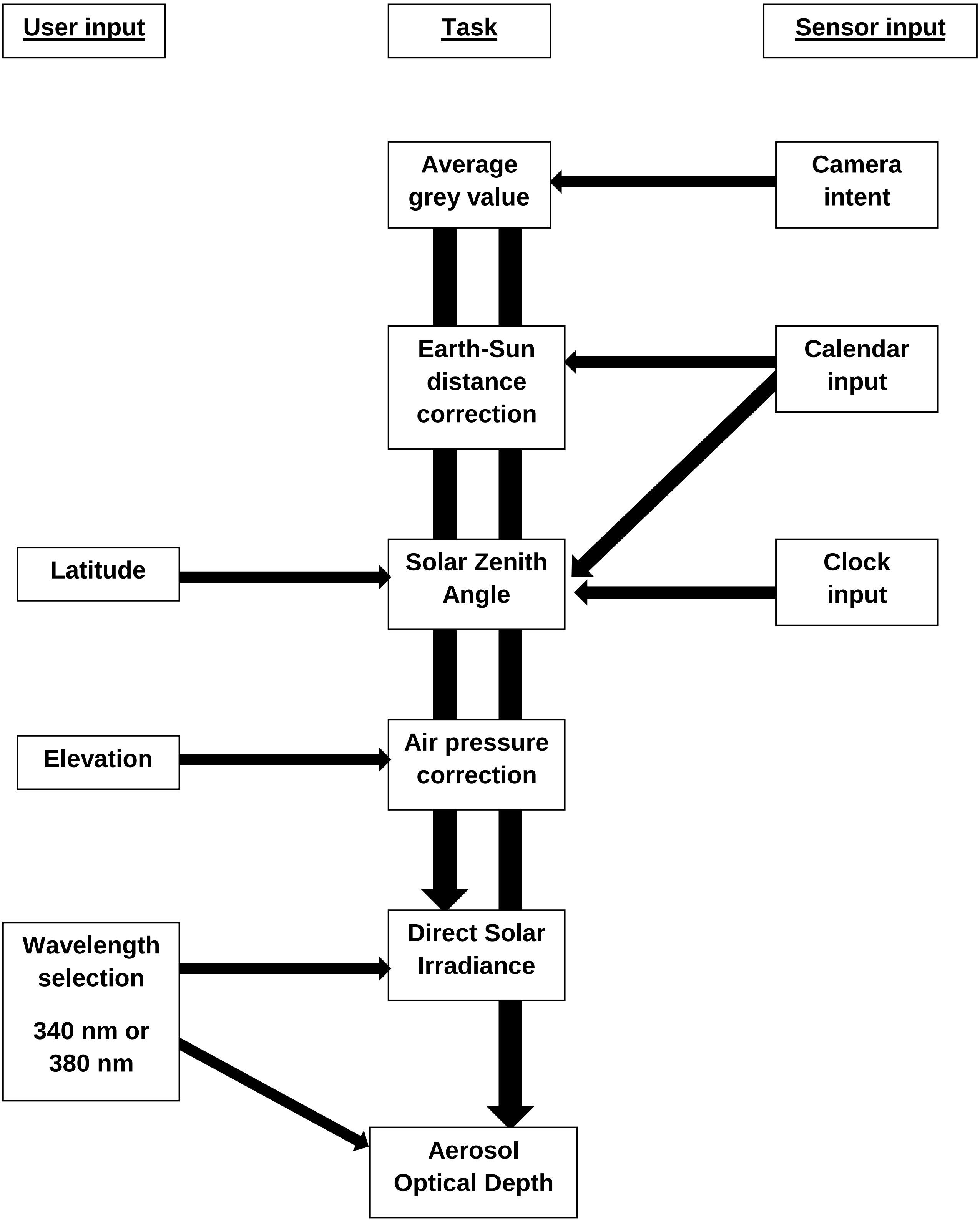
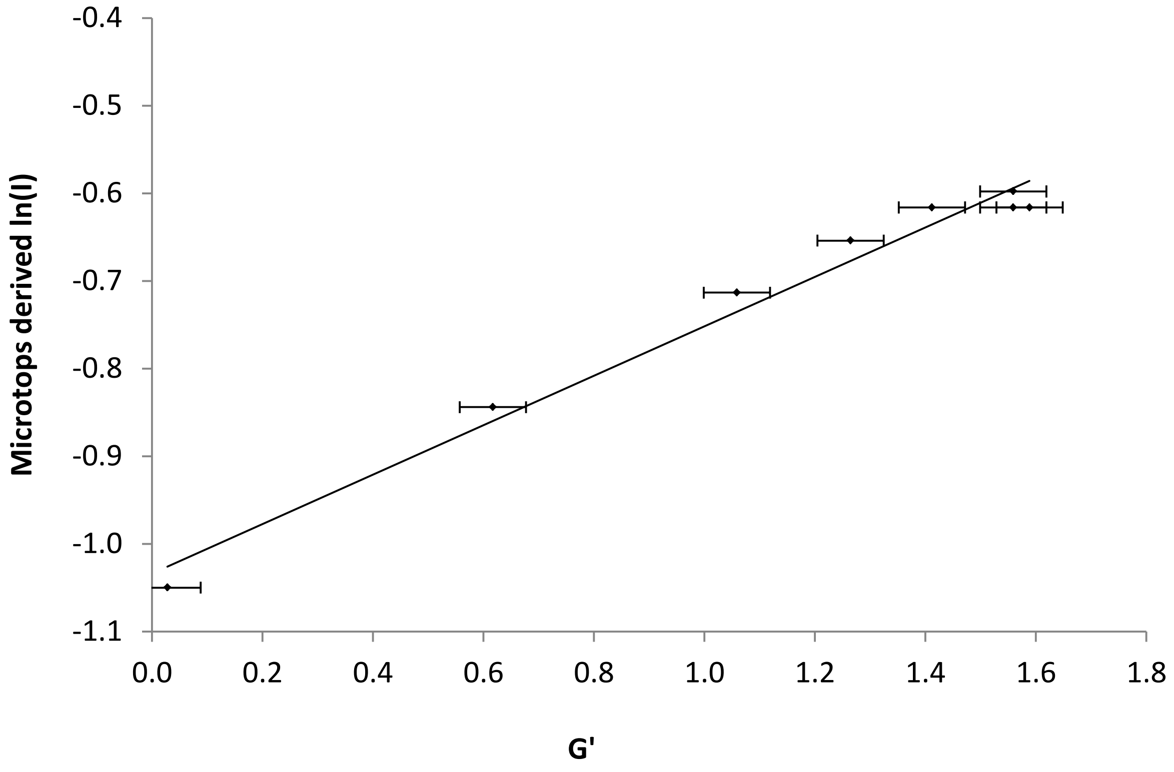

User input
Task
Sensor input
Average grey value
Camera intent
Earth-Sun distance correction
Calendar input
Latitude
Solar Zenith Angle
Clock input
Elevation
Air pressure correction
Wavelength selection
340 nm or 380 nm
Direct Solar Irradiance
Aerosol Optical Depth

Figure 2



Microtops derived ln(I)
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
G'

Figure 3

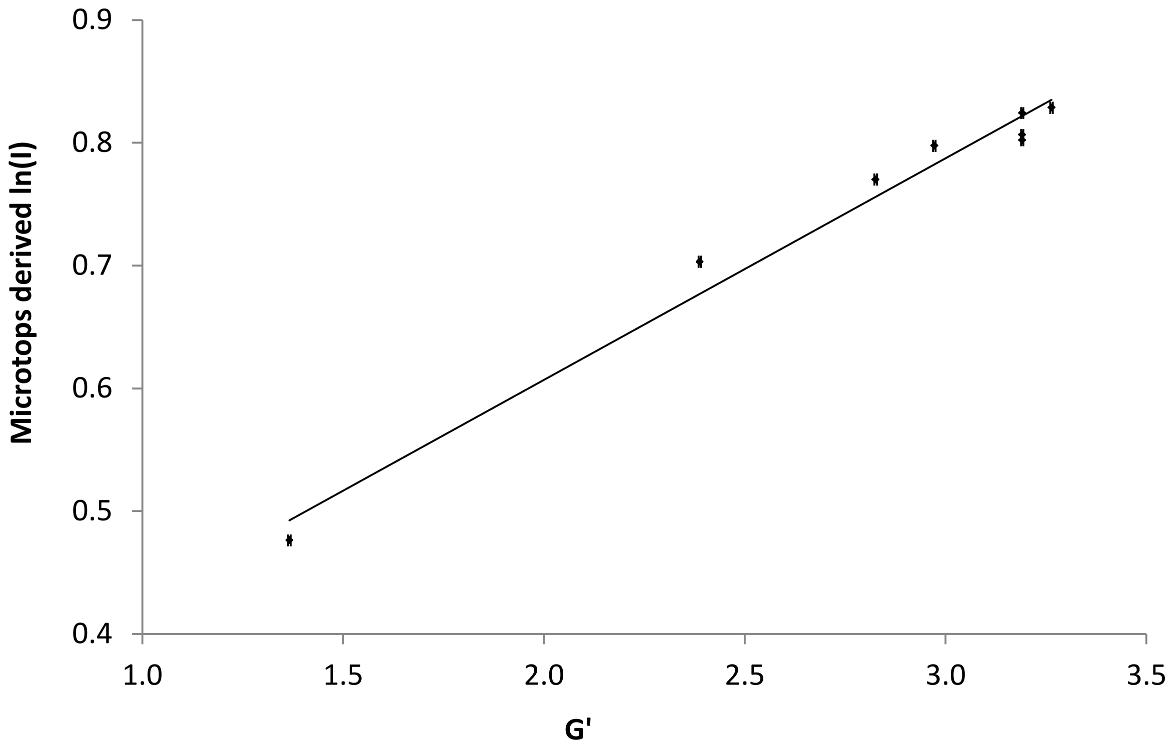


Figure 4a

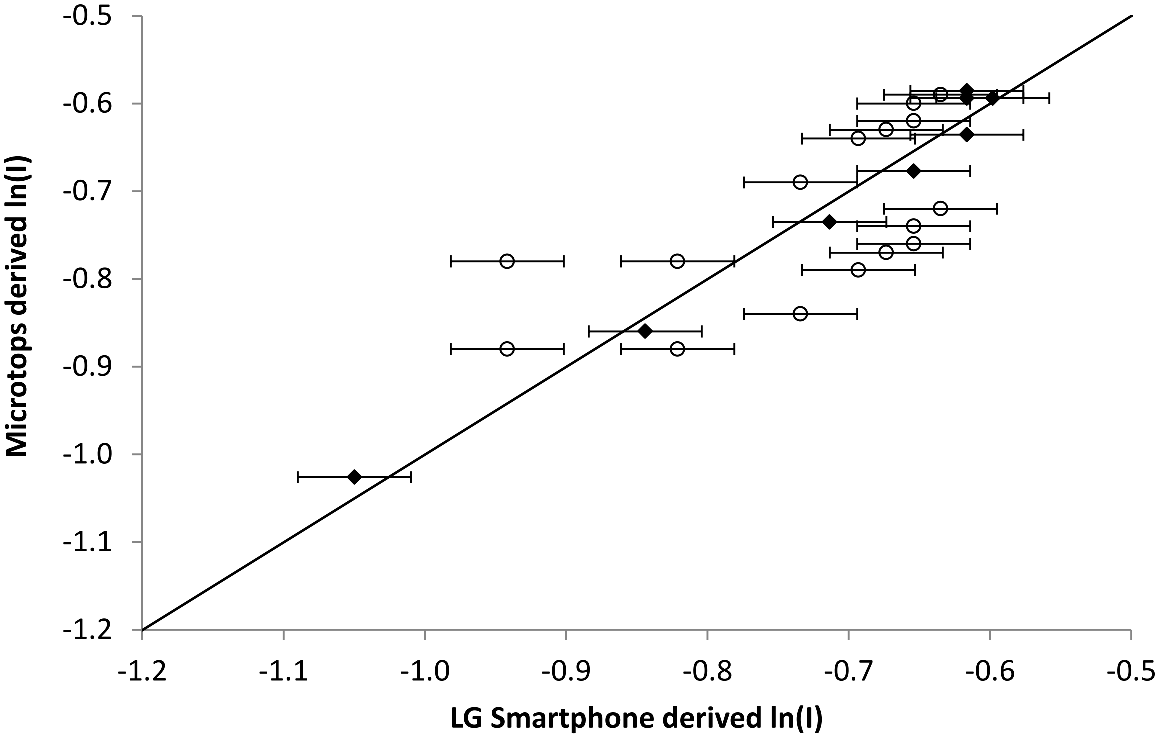
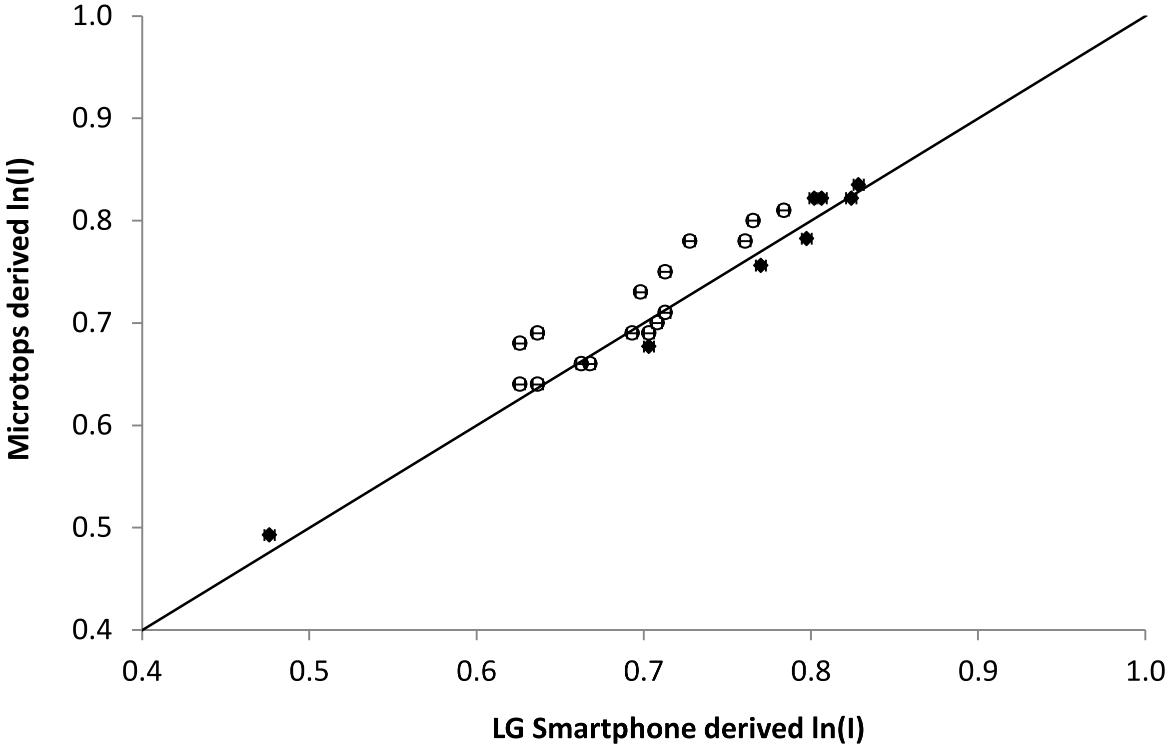

-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
-1.1
-1.2
Microtops derived ln(I)
-1.2
-1.1
-1.0
-0.9
-0.8
-0.7
-0.6
-0.5
LG Smartphone derived ln(I)

Figure 4b



1.0
0.9
0.8
0.7
0.6
0.5
0.4
Microtops derived ln(I)
0.4
0.5
0.6
0.7
0.8
0.9
1.0
LG Smartphone derived ln(I)

Figure 5a

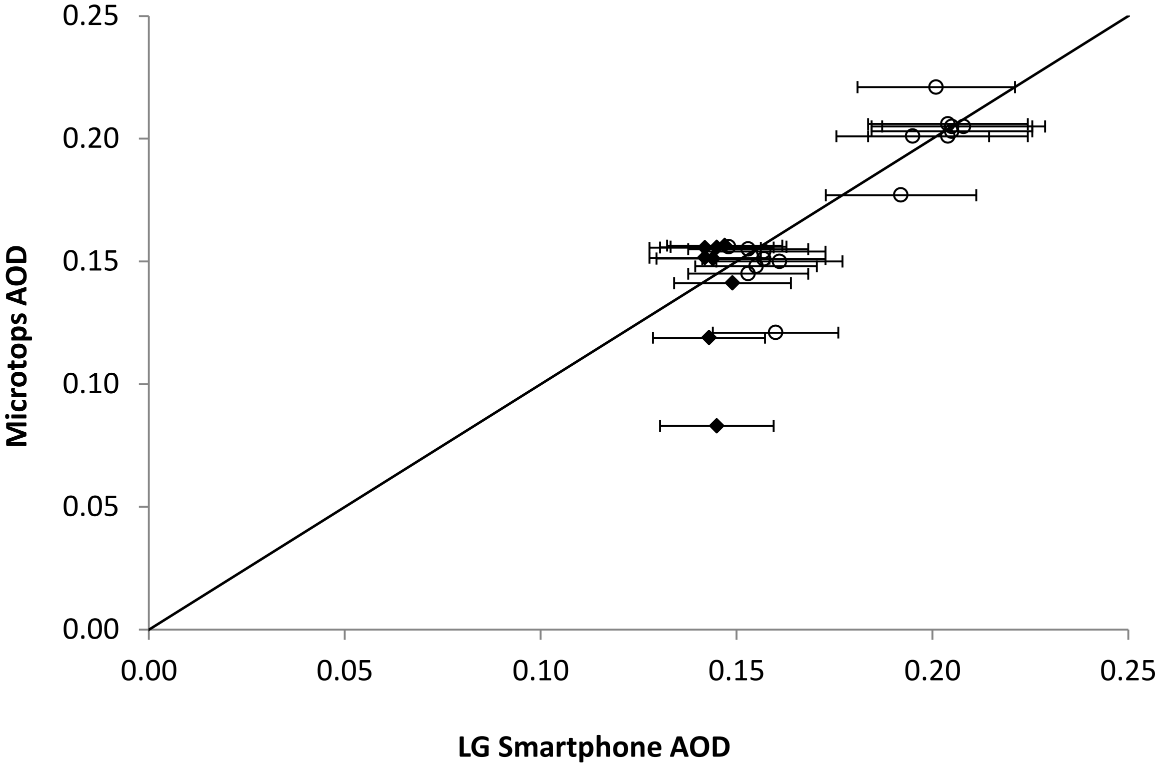
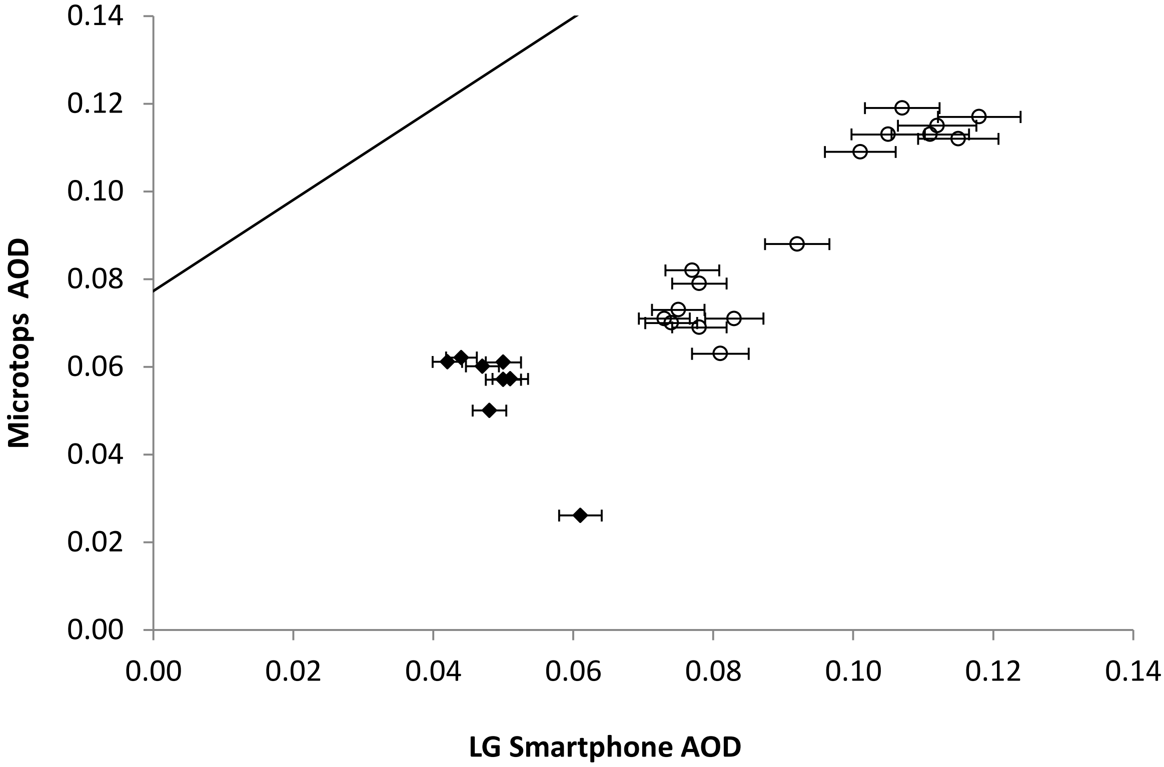

0.25
0.20
0.15
0.10
0.05
0.00
Microtops AOD
0.00
0.05
0.10
0.15
0.20
0.25
LG Smartphone AOD

Figure 5b


0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Microtops AOD
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
LG Smartphone AOD