A CLOSURE EXPERIMENT: PREDICTION AND MEASUREMENT OF DIRECT-NORMAL SOLAR IRRADIANCE AT THE ARM SITE

R. N. Halthore [1], S. E. Schwartz [1], J. J. Michalsky [2], M. H. Bergin [1,3], R. A. Ferrare [4], B. N. Holben [4], and H. M. ten Brink [5]

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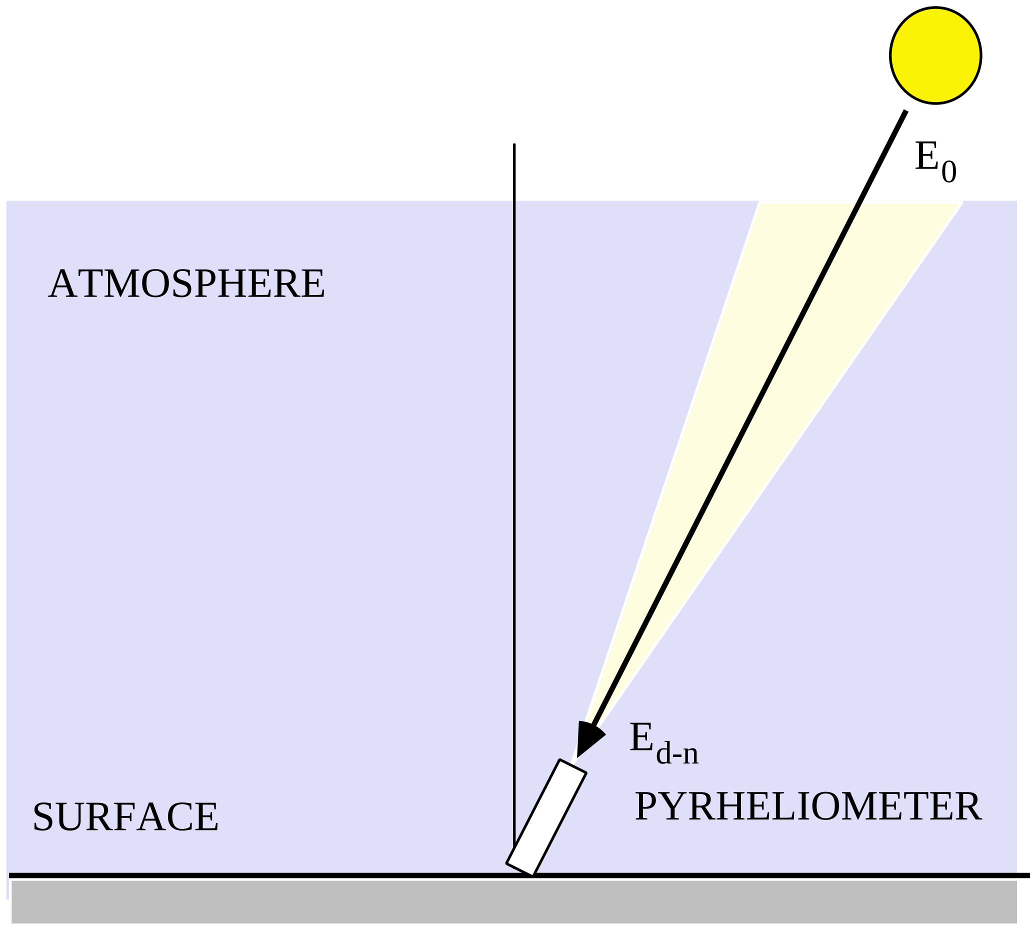
Abstract: *Eos, Trans. Amer. Geophys. Un.* **77**, (No. 46, Supplement) F74 (1996).

1. Department of Applied Science, Brookhaven National Laboratory, Upton New York.
2. Atmospheric Sciences Research Center, State University of New York, Albany, New York.
3. Climate Monitoring and Diagnostics Laboratory, NOAA, Boulder, Colorado.
4. Goddard Space Flight Center, NASA, Greenbelt, Maryland.
5. Netherlands Energy Research Foundation, Petten, The Netherlands.

ABSTRACT

Multi-Filter Rotating Shadowband Radiometers (MFRSRs) are employed at the Department of Energy's Atmospheric Radiation Measurement (ARM) sites to measure the total and diffuse hemispherical-surface irradiance in seven bands from 0.3 to 1.1 µm. The direct-normal solar irradiance is obtained as the difference of the total and diffuse components divided by the cosine of the solar zenith angle and corrected for the angular response of the instrument. Based on absolute calibration of the sensors using the Langley method or versions thereof, the atmospheric transmission is evaluated in these bands to determine aerosol optical thickness (AOT) and water vapor column abundance, the most variable components of the atmosphere that affect radiative transfer. To establish a level of confidence in these measurements, they are compared to the corresponding quantities derived from sunphotometers. Independent measurements of water column abundance are also available from microwave radiometers and radiosondes. A comparison between all these different quantities and types of measurement will be presented for three periods--April 1994, October 1995, and April 1996. Calibration methods and their uncertainties will be discussed. Comparison of the sunphotometer and MFRSR derived values showed that the AOTs were generally within the expected uncertainty of ±0.02, but the nature of disagreement, namely systematic differences dependent on airmass, showed that factors other than calibration uncertainty may be important. The radiative transfer model MODTRAN-3 is used to predict the direct surface solar irradiance in the wavelength range 0.3 - 5.0 µm, using as input, the MFRSR measurement of AOT with its wavelength dependence, radiosonde measurements for atmospheric characterization, and ozone and carbon-dioxide abundance from climatology. The closure experiment consists of comparing the MODTRAN-3 predicted value with the direct-normal shortwave irradiance measured by a calibrated pyrheliometer. Results show that the model overpredicts the measured value by 2 % (or 15 W m^{-2} in a measured value of 850 W m^{-2} on October 18, 1995 at 1835 UT during the ARESE period. Factors that affect this comparison are pyrheliometer calibration, aerosol optical thickness, and loading and absorption of trace gases. An analysis of the impact of each on this comparison will be presented.

WHAT IS DIRECT-NORMAL SOLAR IRRADIANCE?



$E_{d-n} = E_0 T$

E_{d-n} = measured direct normal solar irradiance

E_0 = direct normal solar irradiance

T = atmospheric transmittance

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MOTIVATION

- ARM goals - closure experiments.
- Clear-Sky absorption problem - is there a problem?

Why Direct-Normal Solar Irradiance (DNSI)?

- Simple atmospheric radiation quantity that depends on the atmospheric transmittance and extra-terrestrial solar irradiance.
- It does not depend on the details of light extinction - whether scattering or absorption.
- It can be measured accurately by a simple device such as a pyrheliometer that has relatively narrow field-of-view encompassing the Sun.

APPROACH

- Use Normal Incidence Pyrheliometer (NIP) to obtain measured value of DNSI. Estimate the expected uncertainties.

- Use MODTRAN-3 to predict DNSI and compare. As input use field measured quantities of atmospheric transmission and constituents.

- Perform sensitivity analyses by varying any or all the input parameters to determine quantities that must be accurately measured for good closure.

INPUT PARAMETERS

- Aerosol Optical Thickness (AOT) as measured by a Multi-Filter Rotating Shadowband Radiometer (MFRSR) or a sun photometer.
- Pressure, Temperature, and Relative Humidity from radiosonde measurements.
- Ozone and other minor gases from Climatology.

Is the determination of AOT from DNSI using MFRSR or a sun photometer incestuous?

No, because:

- Calibration of MFRSR and sun photometer is done independently through the Langley plot method.
- AOT is derived only in specific "narrow" bands throughout the visible and near-IR spectrum.

LANGLEY PLOT METHOD FOR CALCULATING AOT

Bouguer's Law: (for channels without water vapor)

$$E_{\mathrm{d-n}} = (E_0 / R^2)\exp(-m\tau)$$

E_0 = Solar Irradiance (in wavelength band) at 1 a.u.

R = Solar Distance in a.u.

m = number of airmasses in optical path, $m \approx \sec\theta_0$.

Instrument Response:

$$V_{\mathrm{d-n}} = (V_0 / R^2)\exp\left[-(m\tau)_{\mathrm{Rayleigh}} - (m\tau)_{\mathrm{ozone}} - (m\tau)_{\mathrm{aerosol}})\right]$$

(At high solar zenith angle, m values are different for each attenuation because of variable refraction effects at different altitudes).

$$\ln V_{\mathrm{d-n}} - (m\tau)_{\mathrm{Rayleigh}} - (m\tau)_{\mathrm{ozone}} = \ln(V_0 / R^2) - (m\tau)_{\mathrm{aerosol}}$$

Langley Plot: Plot of left hand side vs. m_{aerosol}.

Langley Intercept: Extrapolation of Langley plot to $m = 0$ to obtain $\ln(V_0 / R^2)$.

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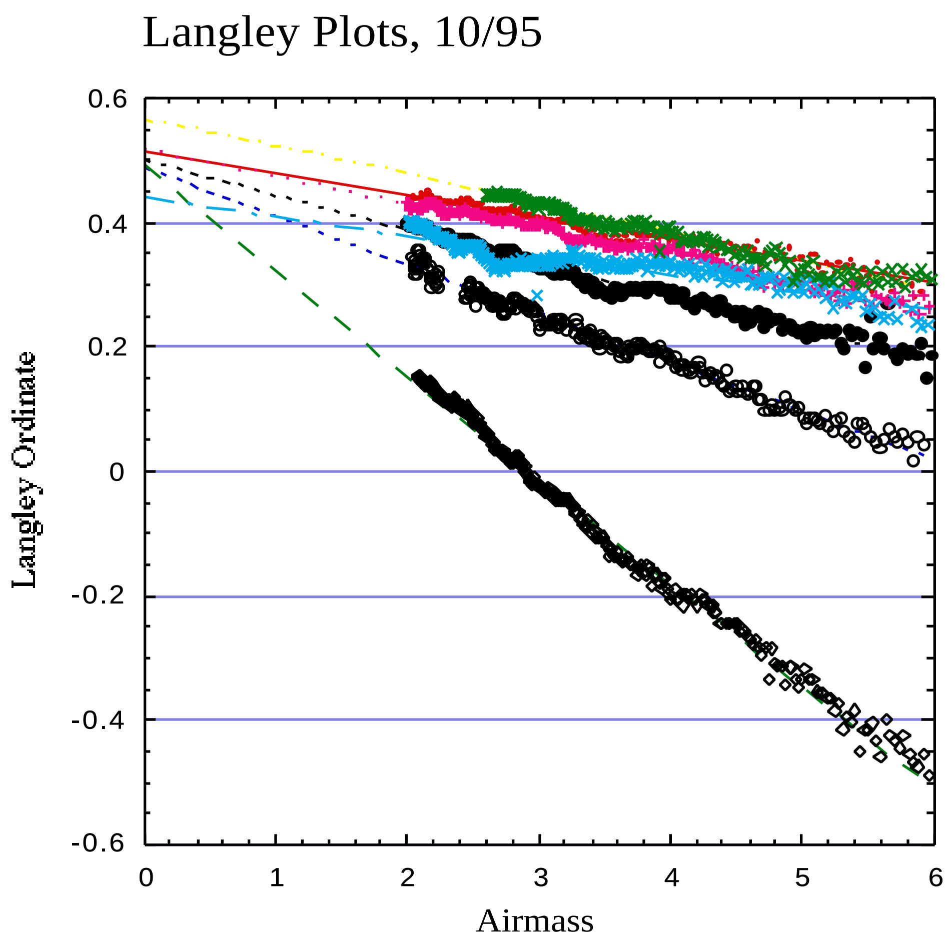
LANGLEY PLOTS



Langley intercept V_0 is derived from selected plots exhibiting maximum linearity (constant aerosol properties during morning or evening).

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AEROSOL OPTICAL THICKNESS

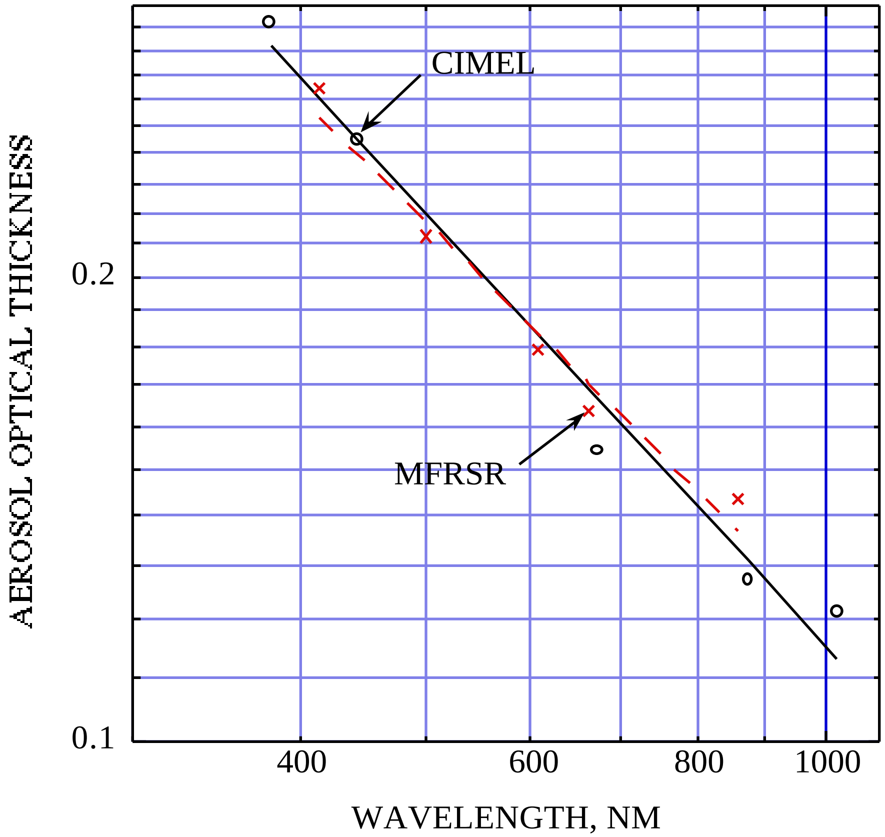
$$\tau_{\mathrm{aerosol}} = \frac{1}{m_{\mathrm{a}}}\left[\ln(V_0 / R^2) - \ln V_{\mathrm{d-n}} - (m\tau)_{\mathrm{Rayleigh}} - (m\tau)_{\mathrm{ozone}}\right]$$

Error in estimate of aerosol optical thickness:

Under assumption that all other contributions to error are small, uncertainty in aerosol optical thickness is dominated by uncertainty in V_0:

$$\Delta\tau_{\mathrm{aerosol}} = \frac{1}{m_{\mathrm{a}}}\frac{\Delta V_0}{V_0}$$

ÅNGSTRÖM PLOTS SHOWING DEPENDENCE OF AOT ON WAVELENGTH



Note close agreement in magnitude of AOT and slope (Ångström exponent) between Cimel sunphotometer and Multi-Filter Rotating Shadowband Radiometer (MFRSR).

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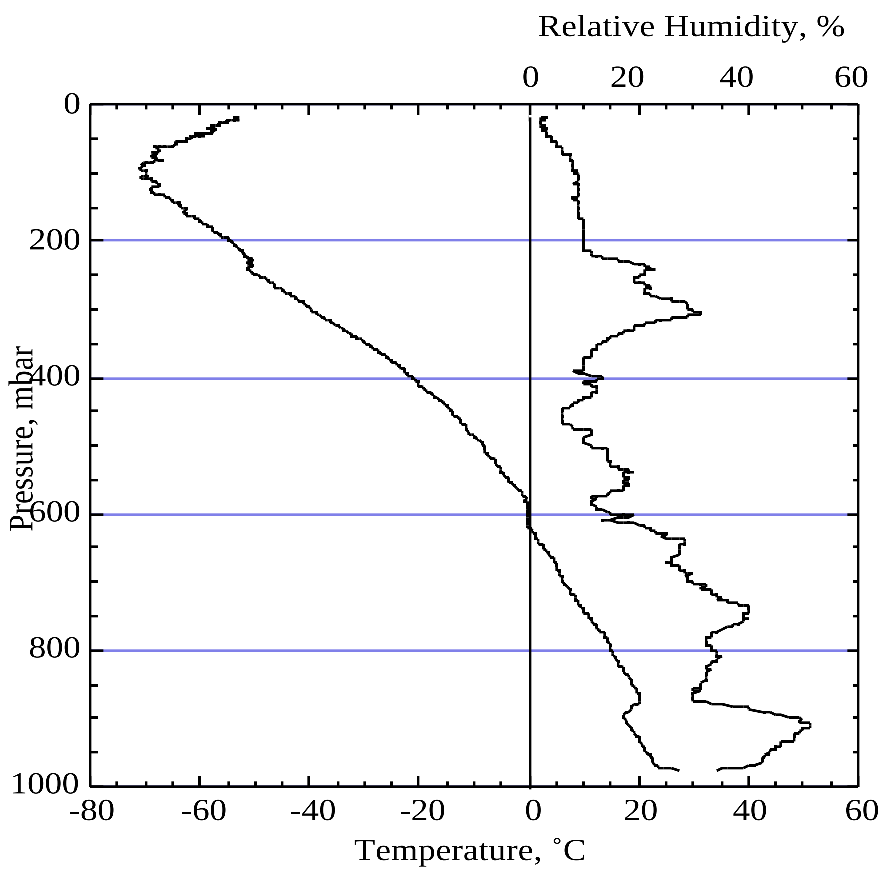
EXAMPLE OF TEMPERATURE AND RH SOUNDING USED AS INPUT TO MODEL



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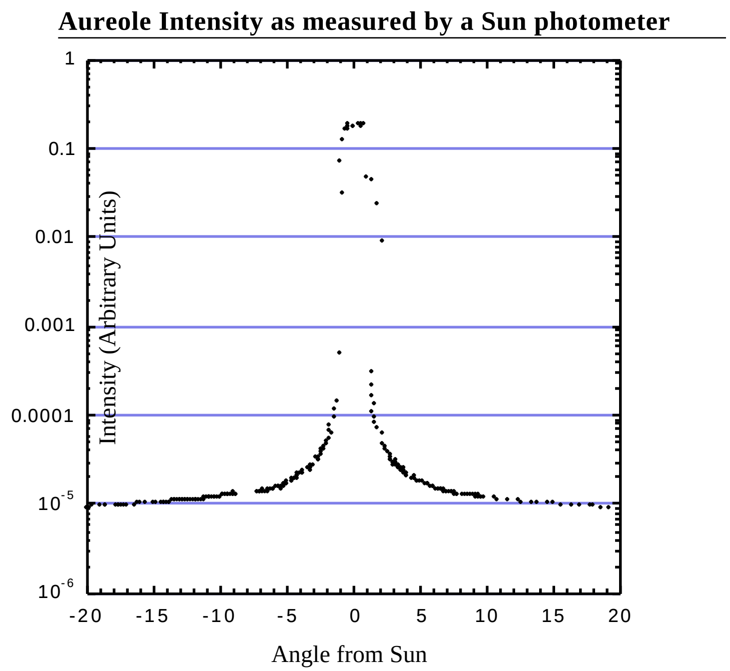
RESULTS

Date	Pyrheliometer Measured Irradiance W/m²	MODTRAN-3 Estimated Irradiance W/m²	Difference (%) W/m²
10/18/95	866 ± 9	882	15 (1.7%)
4/18/96	833 ± 8	857	23 (2.8%)

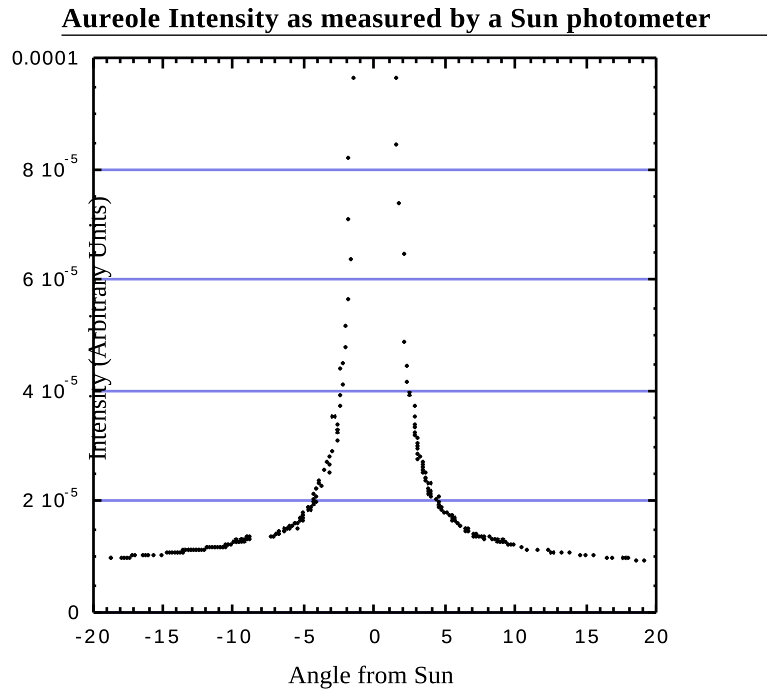
- In addition to DNSI, Normal Incidence Pyrheliometer (NIP) measures aureole brightness, which is estimated here to be as great as 1%.

INFLUENCE OF SMALL ANGLE SCATTERING ON PYRHELIOMETER SIGNAL

Logarithmic plot



Linear Plot



Scans across solar disk with a narrow field of view sunphotometer (1.5˚ FOV) indicate ~ 1% contamination by aureole sky brightness in the pyrheliometer signal (5˚ FOV).

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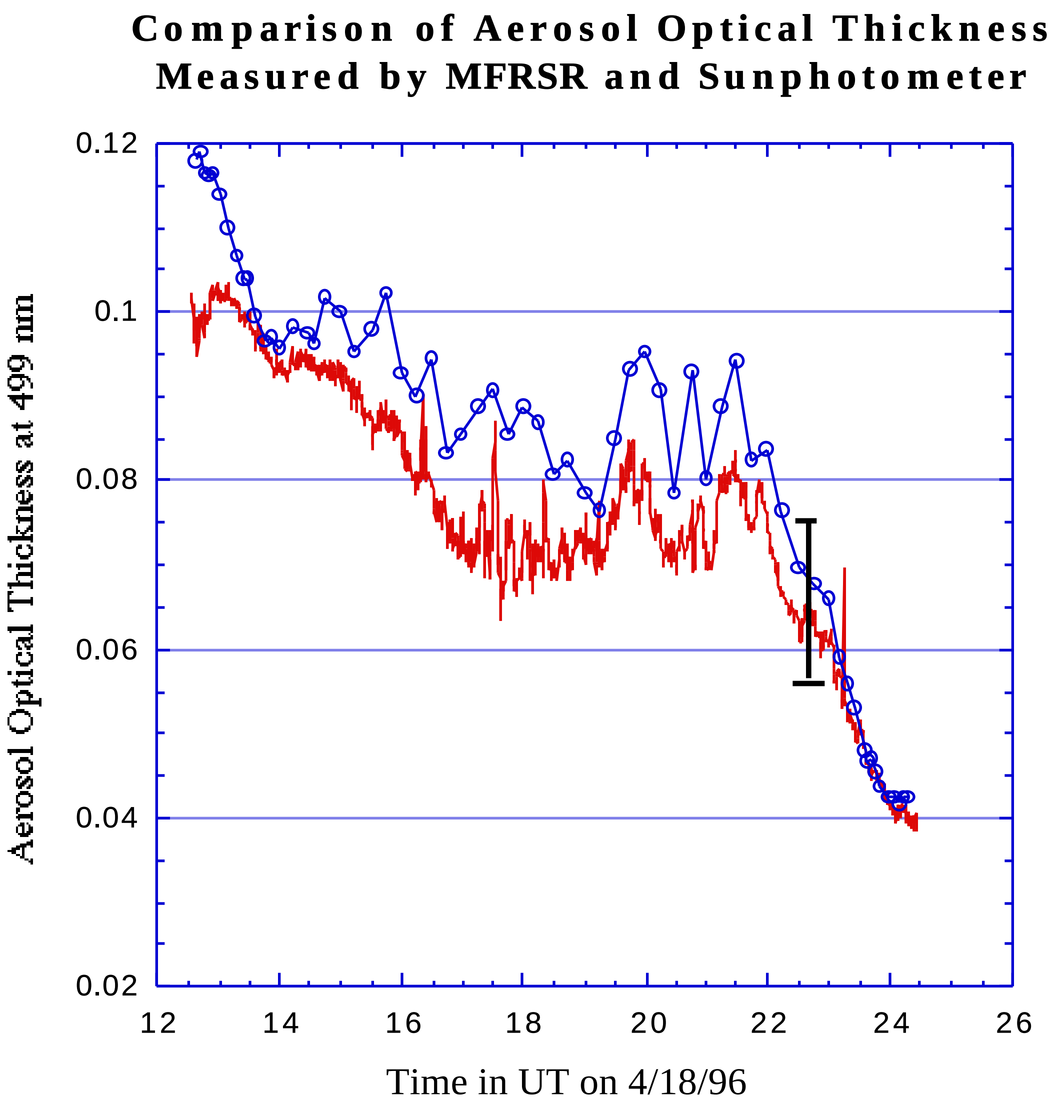
SENSITIVITY ANALYSIS

Date: 4/18/96. Solar Irradiance: 1355 W/m^2

Item	AOT 550	Precipitable Water cm	Ångström exponent	Predicted Irradiance W/m^2
Pyrheliometer				833 ± 8(Measured) 825 ± 8(Corrected)
Baseline	0.066	0.73	1.3	857
AOT	0.076	0.73	1.3	843
PW	0.066	0.80	1.3	853
Ångström Exponent	0.066	0.73	1.5	858
AOT & PW	0.076	0.80	1.3	839



Comparison of aerosol optical thickness (AOT) derived from a sunphotometer (Cimel) and a Multi-Filter Rotating Shadowband Radiometer (MFRSR) on April 18, 1996 at the CART ARM site in Oklahoma.

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COMPARISON OF AOT FROM SUNPHOTOMETER AND MFRSR

- Agreement is generally excellent, within combined uncertainty.

- Slight trend in the difference, i.e., decrease over the course of the day, is attributed to error in MFRSR alignment.

- The two instruments measure fundamentally different atmospheric radiation quantities.

- The two instruments are ***independently calibrated*** by the Langley plot procedure.

- Sunphotometer is calibrated at a mountain site; MFRSR is calibrated at the CART site, by careful screening of suitable days in April, 1996.

CONCLUSIONS

- Models over-predict the measured DNSI values by about 2 - 3%.

- Uncertainty in the measured vertical AOT of about 0.01 results in a 1.6% uncertainty in DNSI at a solar zenith angle of 60° and this is the maximum effect.

- A 10% increase in water column abundance decreases the DNSI by 0.46%

- Even assuming that the atmospheric transmission measurement uncertainties of 0.01 in AOT and 10% in PW always exist as an unknown bias in any closure experiment including this one, the amount of overprediction by MODTRAN-3 here shows that there may be a clear-sky absorption problem.

NECESSARY FUTURE WORK

- Measurement of AOT and PW by a number of instruments employing different methods to reduce the uncertainties in atmospheric transmission measurement.

- Use of narrow field of view (~1°) pyrheliometer with improved solar tracking, preferably with a 4-quadrant detector in active feedback loop.