

THE USE OF THE ARM WSI TO ESTIMATE THE ATMOSPHERIC OPTICAL DEPTH AT NIGHT

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ABSTRACT

Broadband observations of starlight with a whole sky imager are used for determining the nighttime aerosol optical depth. The main difficulty in such measurements consists of accurately separating the star flux value from the non-stellar diffuse light. The monochromatic extinction at the ground due to aerosols is extracted from heterochromatic measurements. The total error is between 2.6 and 3% rms. Comparison with aerosol optical depth measured by other methods shows good agreement.

yield an accurate value of the aerosol optical depth. An inter-play exists between the different spectral output of stars, known from their Morgan-Keenan spectral type, and the aerosol spectral opacity. The wavelength-dependent aerosol optical depth (AOD) is modeled following a well-known empirical law, $(AOD = \beta \lambda^{-\alpha})$, where “alpha” is the Angstrom exponent and “beta” is the turbidity parameter. The AOD obtained at the center of the observing bandwidth, between 500 and 600 nm, is the most reliable monochromatic parameter, constructed from a heterochromatic measurement.

1. MEASUREMENT TECHNIQUE

The whole sky imager (WSI) observes the night sky vault with exposure times of 1 minute, and does not compensate for Earth’s rotation. Digital images with stars visible simultaneously are used to infer star irradiance at the ground. Sequences of images taken as the stars pass through different altitudes above the horizon are used to infer aerosol optical depth variation during the night.

The star irradiance is inferred by an “On/off” technique, as the amount of radiation above the sky background, geometrically associable with the star center position (known from catalog) and with the spread of the star profile over a few pixels, which is due to the compounded effects of turbulence, diurnal rotation during the exposure time and multi-wavelength nature of the observation. The sky background value for a particular star, defined as value of the sky without the star present in it, is observable “as is” only when the star is close to the zenith direction, otherwise it is “enhanced” by atmospheric scattering of night-sky extended sources and by observational geometry.

The difficulties inherent for observations with WSI are the high sky background, the low resolution (poor separation between stars) and coarse pixelization of star profiles (undersampling). Approximately 120 stars, not all present simultaneously on the sky, were measured on 300 clear nights from 1998 to 2003.

2. HETEROCHROMATICITY

When applied to WSI measurements, which are made at wavelengths between 400 and 900 nm, simple monochromatic Langley plots, as those derived with monochromatic observations with photometers, do not

3. TEMPORAL/SPATIAL VARIABILITY

Rather than trying to obtain the optical thickness value towards each star direction, the method used in this study assumes that all irradiances from stars visible at the same time can be used to obtain the AOD, that is, the optical thickness in the vertical direction. This AOD should be comparable with the same amount determined with more precise methods, as the nighttime LIDAR. The comparison holds during the majority of nights measured because the aerosol spatial coherence distance, of a little under 200 km (Anderson et al, 2003), is also the maximum WSI observable distance, measured on an aerosol layer at 5 km height above the ground, between directions of stars situated as low as 3 degrees elevation above the horizon, on the opposite ends of a big meridian circle.

4. NON-STELLAR DIFFUSE BACKGROUND

At low elevations, stellar irradiance value is more difficult to assess, because of the diffuse scattered light, which has non-stellar origin (airglow emission, integrated starlight of non-resolved stars and zodiacal light), but also because of the molecular and aerosol scattering of the airglow, and of the other extended sources. A correction for irradiances of stars observed at low elevations is used. Principally, the sky background value is computed as the median pixel in an elliptical aperture placed on the sky such that more pixels covering the same zenith angle to be included, that is, an elliptical aperture with the larger axis perpendicular on the diameter of the lens; this step allows the most probable value per pixel of the air scattered airglow at that zenith distance to be included. Secondly, an atlas of sky brightness (Leinert et al, 1998) is used to

account for the part, in the sky median pixel value, that represents the airglow multiple scattering on air molecules.

5. WSI EQUATION

For a given star, the wavelength averaged irradiance F_i is given by equation (1),

$$F_i(\theta) = F_{0555} \int_{\lambda_i} f_0(\lambda, \text{class}) R(\lambda) T_{\text{gases}}(\theta) T_{\text{aerosols}}(\theta) d\lambda$$

where F_{0555} is the 555nm top of atmosphere monochromatic flux; T_1 is the monochromatic transmissivity; θ is the zenith angle; R_i is normalized instrument response function and $f(\lambda, \text{class})$ is the normalized spectrum for the Morgan-Keenan class and luminosity classification of the star (i.e., F_{0i}/F_{0555}); $T_{\text{aerosols}} = \exp(-X \tau)$ and $\tau = \text{AOD} = \beta \lambda^{-\alpha}$.

Using an iterative method (Kythe and Puri, 2002) with an a priori knowledge of atmospheric gases opacity, and a first guess for aerosol parameters ($\beta = 0.001$ and $\alpha = 0.1$), all the possible pairs of different colored star irradiances measured at the same moment are reduced to find the best transmission correction factor and best effective wavelength, in the atmospheric filter, for their color.

6. AEROSOL OPTICAL DEPTH COMPUTATION UNCERTAINTY

Uncertainties in the instrument calibration, background corrections, absolute flux of the individual stars, and the gaseous transmittance uncertainties govern the absolute accuracy of the aerosol estimation. The compounded effect of different errors introduced in the AOD computation (Musat, 2004) by the method used is given in the Table 1.

Table 1. Errors in AOD computation from WSI star irradiances.

Uncertainties:	Random	Systematic
Absolute Flux calibration constant		0.5%
Star flux accuracy (includes error from dark current subtraction, readnoise, digitization noise, flatfield division and bias subtraction for the CCD frame)	< 0.03 rms	
Solid angle per pixel	0.71%	
Pixel surface projection on constant height layer	0.22%	
Background sky correction (for large zenith angle only)		0.26%
Vega monochromatic flux	$0.002 \cdot 10^{-7}$ mW/m ² /nm rms	
Catalog Magnitude	0.01mag	
Numerical integration		10^{-12}
Monochromatic absolute flux (other stars)		1%
Star calibrated measurement (CM)	1.11%(Vega) 1.37% (other stars)	
Relative airmass (<84 deg.zenith)	< 0.065%	
LOWTRAN model sensitivity (without aerosols)		0.72%
Kernel	0.72%	
Per step iteration (from CM & Kernel)	(1.32-1.55)%	
Convergence error		10^{-5}
AOD at centre of bandpass	(2.6-3.1)%	

Fig.1 shows a sequence of AOD from the Sun photometer CIMEL (500nm, daytime) and WSI (night) for 17-24 Aug.1998, while Fig.2 presents Raman Lidar AOD

(355nm,line), in comparison with AOD at 355nm (diamond symbol) simulated from the WSI measurement, for 14-16 Dec.1998.

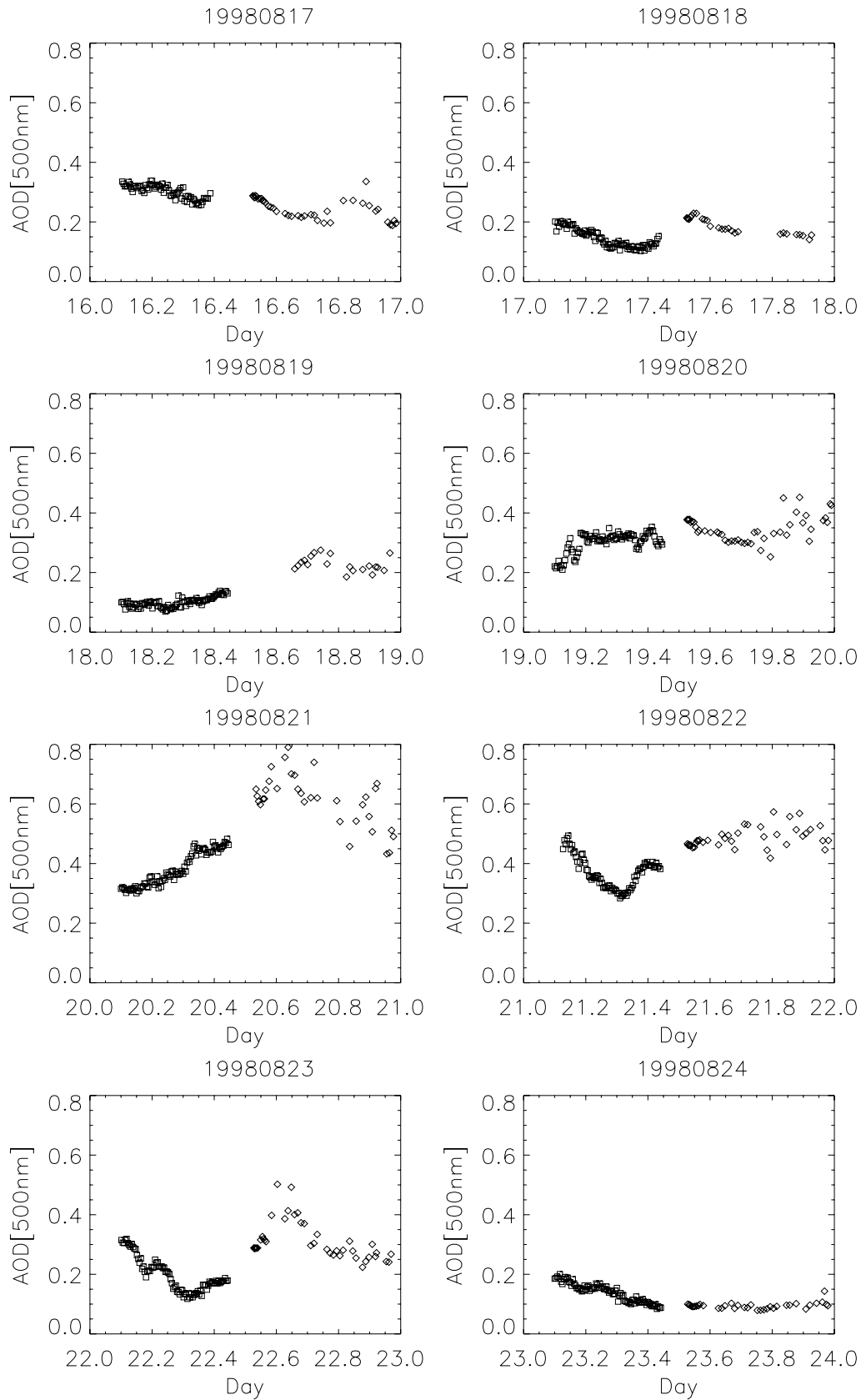


Fig.1 From left to right, from top to bottom, a sequence of AOD from the Sun photometer CIMEL (500nm, square symbol, daytime) and WSI (500 nm, diamond symbol, nighttime) for 17-24 Aug.1998.

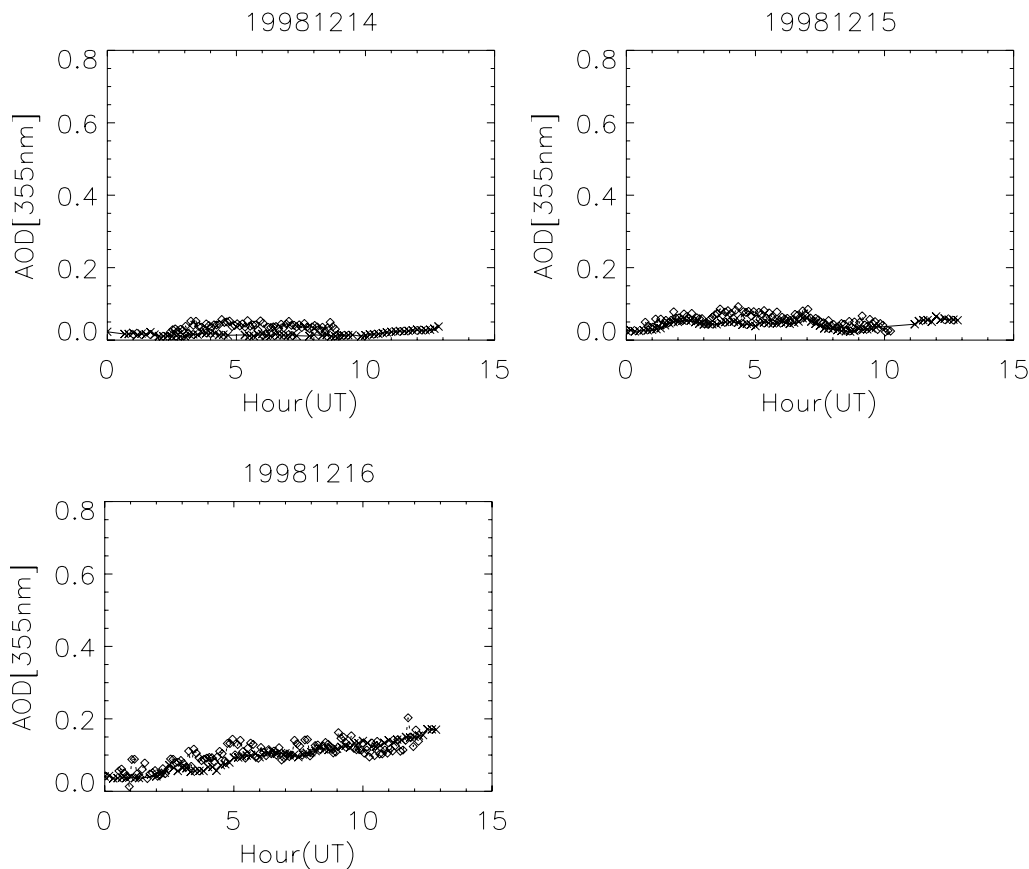


Fig.2 Aerosol optical depth from Raman Lidar at 355nm (line), and the same AOD at 355nm (diamond symbol) simulated from the WSI measurement, for 14-16 Dec.1998.

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