A Small Inexpensive (<$10K) Spectrometer System For Measuring Radiance And Irradiance From 275 To 525 Nm At 0.5 Nm Steps.

We have recently developed a small spectrometer system for measuring total column NO_2 in the atmosphere from direct sun radiances. The same system can be adapted to measure sky radiances and total irradiance as a function of wavelength. The current configuration measures at better than 0.5 nm spectral resolution between 275 and 525 nm. Key to the accuracy of the instrument is maintaining a nearly constant temperature for the spectrometer during its operation. We found that a temperature of about $20^{o}\pm2^{o}C$ is sufficient for the high precision work needed for deriving NO_2. For just UV irradiance and radiance, the thermal stability could be relaxes to $\pm3^{o}C$ for about 5% precision assuming a laboratory calibration to a NIST lamp standard.

1.0 Spectral Sampling and Averaging

One of the motivations for using an linear array detector spectrometer is to overcome the effects of spectral under-sampling and atmospheric change during a measurement that is inherent in the use of a Brewer spectrometer. For this purpose we have deployed a small 1024 element Avantes CMOS diode array spectrometer that is capable of simultaneously measuring sun irradiances from 275 to 525 nm at a spectral resolution of 0.4 nm with ~3X oversampling (3 pixels per resolution width $\Delta\lambda = 0.4$ nm). Radiometric and wavelength stability are achieved by maintaining temperature stability (within $2^{o}C$) and by measuring the dark current for all 1024 elements after every NO_2 measurement (~ every 20 seconds). For cloud-free fields of view FOV, 2500 spectra are obtained every 20 seconds and averaged together to reduce random noise at a readout rate >125 Hz. The dark current measurements are similarly averaged.

Table 1 PAN-1 Spectrometer Characteristics

Spectral range	270-500nm
Pixel pitch	25 μm
Pixel size	25 x 500 μm
Sensitivity	30 Counts/ μW
Peak wavelength	500nm
S/N	2000:1
Spectral resolution	0.5nm
A/D resolution	14 bit
Number of lines(Grating)	1200 mm^{-1}
Slit range (265 – 500 nm)	42 - 52μm
Integration time	4ms- 5s

In section 2, we provide a detailed description of the technical characteristics of PAN-1, with emphasis on those necessary for the NO_2 measurement. Because there is a moderate strength H_2O band in the vicinity of 441 nm, we solve simultaneously for NO_2 and H_2O column content after correcting for the presence of O_2:O_2 absorption. The result of the spectral fitting is a high precision measure of the water vapor column, which we compare to the corresponding precipitable water content from a co-located CIMEL using the 940 nm filter channel based on the method described by Schmid et al. [2001].

In section 3, a brief analysis of the first direct-sun irradiance data obtained using PAN-1 is presented and applied to the retrieval of aerosol optical thickness, NO_2, and H_2O column amounts over a highly populated and industrialized urban area, Thessaloniki, Greece. The results are compared with co-located aerosol and H_2O measurements by an AERONET CIMEL sun and sky photometer, a UV-MFRSR

(Multifilter Rotating Shadowband Radiometer), and NO_2 measurements from a Mark-III Brewer double-grating monochromator.

2.0 PAN-1 Instrument Description

The PAN-1 system spectrometer (Figure 1A and 2) is an Avantes symmetrical Czerny-Turner optical design with a focal length of 75 mm, a diffraction grating covering a spectral range from $\lambda = 275$ to 525 nm with a spectral resolution of 0.4 nm, a slit of 50 microns, and a low noise 1024 element Hamamatsu CMOS linear array that has no hot pixels. The spectrometer is connected to the sensor head (Figures 1B and 2) by a 10-meter fused silicate single-core fiber optic cable such that the transmitted light fills the 50-micron slit. Use of a fiber optic cable permits the temperature sensitive spectrometer to be stored away from the sun in an off-the-shelf insulated thermoelectric cooler capable of maintaining the temperature within 20±2°C. The temperature is constantly monitored with a wireless credit-card sized thermometer every 2 minutes so that the results can be corrected for small temperature changes. The wireless thermometer stores 8000 data points before it needs to be downloaded to a computer.

When viewing the direct sun, the sensor head has a multiply baffled collimating tube with a 1.6° FOV. Light that passes through the collimator then goes through a filter wheel assembly that contains two UV band-pass filters used for ozone measurements, an open hole, and a blocked region for measuring dark current after each measurement. In addition, there is a circuit board for controlling the filter wheel and sun-tracking device through an RS-232 serial computer interface. A quartz window constitutes the first optical element, which protects the internal optical and electrical components from rain, dust, and humidity.

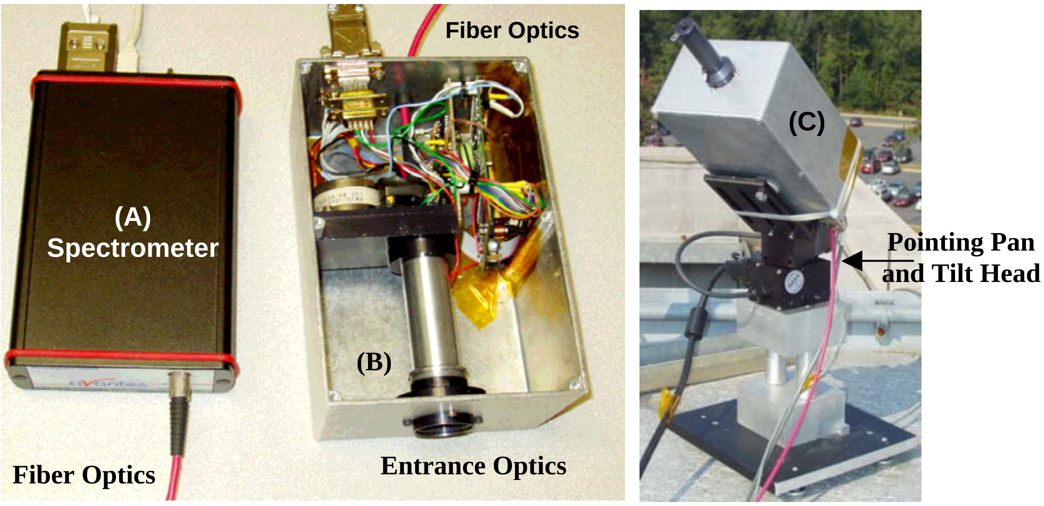

Figure 1: (A) The PAN-1 small 1024 element CMOS spectrometer with fiber optics coupling to (B) control electronics box, entrance optics, rotating filter wheel and shutter. (C) Field mounted fore optics and precision pan and tilt head with 0.01 degree pointing accuracy. The aluminium box shown mounted on the Pan-Tilt head in 1C weighs less than 1 kg.

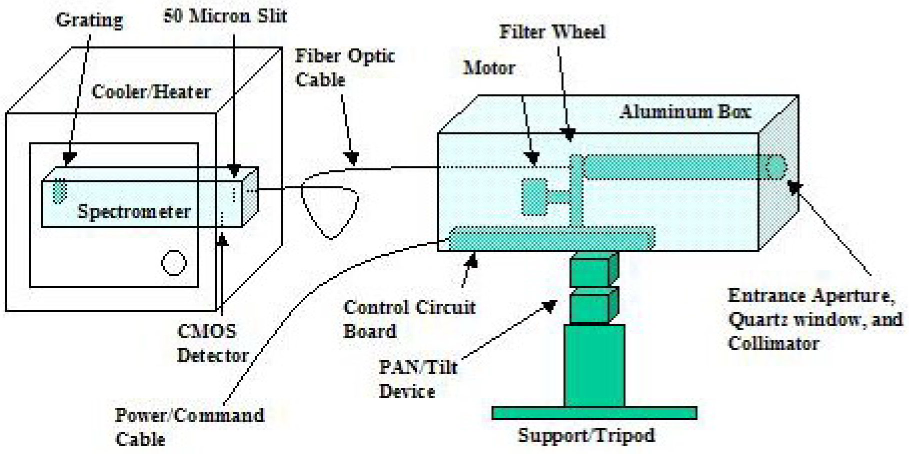

Figure 2 Block Diagram of PANDORA system showing the spectrometer in an environmental cabinet connected to the front-end optics and filter wheel assembly by a 10 meter looped fiber optic cable.

The front-end optical assembly is mounted on a precision pan-tilt tracking device (Figures 6C and 7, from Directed Perceptions) capable of approximately 0.01^{o} pointing accuracy. The position of the center of the sun is calculated from ephemeris coordinates, corrected by detecting the sun's limb and triangulating to the center. The front-end optics and tracking unit are mounted on a steel plate connected to a heavy-duty tripod. The steel plate is leveled to approximately 0.1^{o} using a digital leveling device.

3. Estimate of PANDORA Errors

Measurements of direct-sun irradiances were made at the city of Thessaloniki, in Greece (latitude 40.5^{o} North, longitude 22.9^{o} East). The instruments were set up on an elevated platform on top of the Aristotle University Physics building, about 60 meters above sea level, as part of the July 2006 Greek-EU Scout-O3 campaign. After instrument setup, a Brewer, PAN-1, UV-MFRSR, and a CIMEL made measurements throughout the day from 13 July to 23 July under all sky conditions. All four instruments measured 2 out of 3 aerosol parameters (optical depth, Angstrom coefficient, and absorption coefficient) in different ways, the Brewer and PAN-1 measured NO_2, PAN-1 and the CIMEL measured H_2O, and the Brewer and the UV-MFRSR measured O_3. PAN-1 also measured O_3, but these data have not yet been processed, since they require a laboratory calibration of the UV bandpass filter.

The measurements of interest are those mainly related to NO_2, with the measurements of other gases and aerosols serving as auxiliary data. The auxiliary data permits us to remove Rayleigh scattering, aerosol effects, and ozone absorption, leaving the NO_2 residual in the data as described in Cede et al. [2006].

For most of the day, the measured values of the PAN-1 AOD and a track those measured by the CIMEL sunphotometer at the same wavelength (440 nm). In addition, we show the same parameters measured by the Brewer at 363 nm. There are periods where the PAN-1 values are quite different than those from the CIMEL caused by a sun-tracking algorithm error that did not track the center of the sun. This results in a small apparent intensity reduction that is indistinguishable from having additional aerosol in the atmosphere. The error is particularly apparent in a, which has greater sensitivity to pointing errors than AOD. The small pointing error does not affect the spectral fitting technique for NO_2 and H_2O, since these are fits to relative values at different wavelengths that does not change the peak to trough ratios for a given amount of NO_2 or H_2O in the atmosphere.

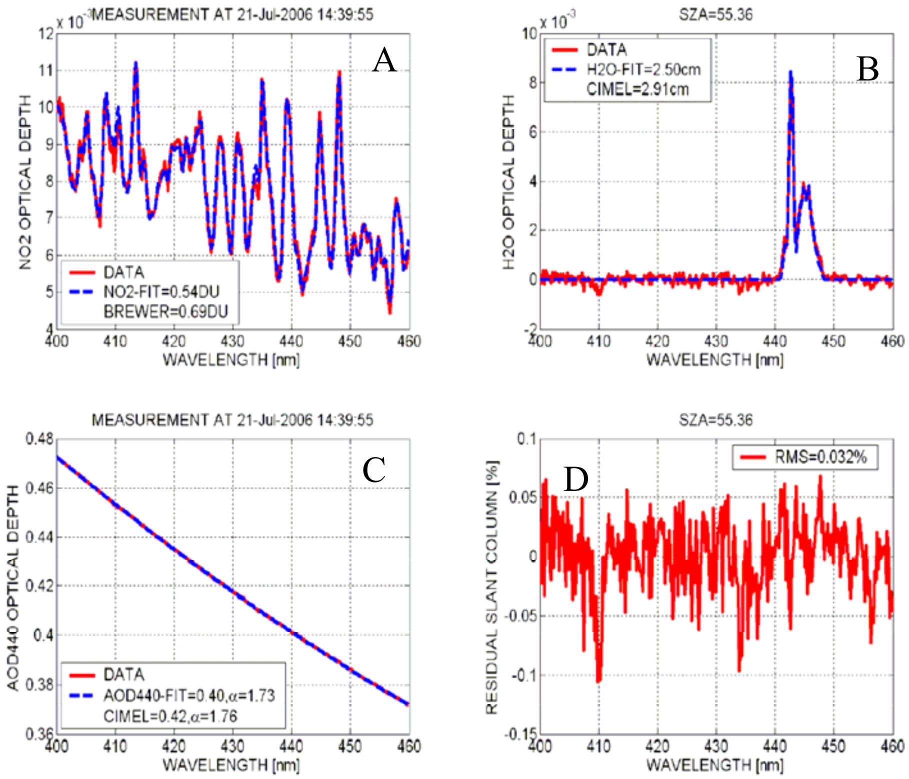

Figure 3: Sample solution for NO_2 and H_2O at Thessaloniki for 21 July 2006 at 14:39:55
(A) NO_2 optical depth from radiative transfer calculations (blue dashes) and from measured radiances (red), (B) water optical depth, and (C) aerosol optical thickness at 440 nm derived from the PAN-1 data and a radiative transfer calculation, and (D) Residual slant column for retrieved NO_2 from the differences between the data in 9A.

Figure 3A shows the computed optical depth (blue) for 0.54±0.01 DU of NO_2 compared to the optical depth (red) estimated from the measured solar irradiances for 21 July 2006 at 14:39:55. The PAN-1 NO_2 uncertainty is estimated from the 0.03% (1 standard deviation) in the NO_2 residuals in Figure 9D. At the same time, the Brewer spectrometer measured 0.69±0.5 DU. Figure 9B shows the amount of water vapor in the atmosphere to be 2.5 cm compared to the simultaneously measured CIMEL value of 2.91 cm at 940±5 nm.

Figure 3C shows the measured aerosol optical depth as a function of wavelength fitted by a quadratic smoothing function. Figure 3D shows the residuals in NO_2 slant column formed by taking the difference between the values obtained from the measured radiances and those calculated from the laboratory absorption cross sections in Figure

3A. This shows that the PAN-1 noise (±0.01 DU of NO_2) is negligible, and only systematic errors need to be considered.

More work needs to be done to develop a weather resistant field version that does not need much daily care. For sites where there is no nearby building within about 20 meters, a rugged PC inside a weather-resistant box is needed. Similarly, the temperature-controlled box must also be weather resistant. Since it operates at about 70^oF ($\sim 20^oC$), the operating temperature is within the range of thermoelectric coolers and strip heaters for most sites and all seasons. Only the fiber optic cable and sensor head is exposed directly to light and weather.

Because of our success with these devices, it is recommended that further development be done to produce a field instrument system at low cost (<$10K) compared to current commercial spectrometer and broadband instruments.

Current costs:

1. Spectrometer	$3500	
2. Precision tracking head	$2500	
3. Cooling/Heating Box	$200	
4. 20 meter fiber optic cable	$400	
5. Tripod	$125	
6. Computer	$1000	
7. Temperature sensor	$125	
8. Portable Carrying case	$125	
9. Software	$free	
10. PC weather case	$150	
11. Diffuser for Irradiance	$200	
12. Sensor-Head Assembly	$500	(This could run up to $1000 for NO_2)
‘Total	$8825	

Item 2 is not needed for Irradiance
Item 12 is greatly simplified for Irradiance

It is advised that a symmetric Czerny-Turner system be used, since the slit function is much easier to characterize for high precision work.