RETRIEVAL OF THE DIURNAL VARIABILITY OF TROPOSPHERIC OZONE PROFILES, AEROSOL PROPERTIES, AND OTHER TRACE GAS AMOUNTS USING GROUND-BASED SPECTROMETERS

Proposal Submitted to:

Science Mission Directorate

Global Ground-based Trace Gas
and Aerosol Measurements
&
Measurements, Modeling, and
Analysis under the Radiation
Sciences Program

Solicitation: NNH06ZDA001N-ACRM

National Aeronautics and Space Administration
Washington D.C.

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ABSTRACT

This proposal is for obtaining and analyzing hourly radiance data from a new tropospheric and stratospheric ozone profiling technique to understand the relationship between variations in trace gas (e.g., NO_2) and ozone amounts in the troposphere and their impacts on air quality. The procedure used to derive ozone profiles requires that we also simultaneously derive information on other trace gas amounts (NO_2, HCHO, and SO_2) and aerosol optical properties. The result of this effort will be the first automated, passive measurements of hourly tropospheric ozone variability as a function of altitude combined with measured stratospheric profile information, hourly trace gas, and aerosol amounts. We propose to finish the development, optimization, and validation of the new technique for measuring temporal variation of the vertical distribution of tropospheric and stratospheric ozone amounts. The technique is designed as an alternative to either balloon sondes or lidars that are too expensive to obtain hourly data over long periods, and is a significant improvement over the traditional Umkehr method of obtaining stratospheric ozone profiles. As part of this proposal we will develop an automated passive remote sounding network from selected ground-based instruments using existing worldwide Brewer spectrometers. Each selected Brewer spectrometer will be modified by its owner to match the new capabilities of the current operational GSFC modified Brewer spectrometer from supplied engineering drawings, parts lists, and algorithms. We also propose to complete the development of an existing inexpensive (<$10K) portable spectrometer system (spectrometer, pointing device, temperature control chamber, fore-optics, and electronics) so that it can perform many of the same measurements as the Brewer spectrometer. Minor modifications of our technique for application to this small spectrometer system will allow for retrievals of ozone profiles, trace gas amounts, and aerosol properties at any location (e.g., deploying copies at AERONET sites over land or onboard an ocean vessel). The resulting data will be readily available to NASA and the rest of the scientific community for satellite validation (e.g., the current AURA/OMI and future NPOESS) and for bounding tropospheric photochemical models, and will provide a unique dataset for studying the evolution of tropospheric ozone, trace gases, and aerosols and their impacts on climate and air quality at each location where the method is applied.

1. SUMMARY OF PERSONNEL AND WORK EFFORTS

Name	Time %/Yr	Responsibilities	ORG
Dr. Jay Herman, PI	25	Overall responsibility for management, algorithms, and data analysis.	GSFC
Dr. Nader Abuhassan, Co-I	25	CCD Spectrometer scientist	SSAI
Dr. Alexander Cede, Co-I	25	Brewer Spectrometer scientist	SSAI
Dr. Nickolay Krotkov, Co-I	25	Radiative transfer and data analysis + aerosol validation	UMBC
Dr. Maria Tzortziou, Co-I	50	Data and radiative transfer analysis, ozone retrieval	UMCP

GSFC	Goddard Space Flight Center
SSAI	Science Systems and Applications Inc.
UMCP	University of Maryland, College Park
UMBC	University of Maryland, Baltimore County

2. SCIENTIFIC / TECHNICAL / MANAGEMENT SECTION

2. 1. INTRODUCTION

2. 1. 1. Purpose of Proposed Research

We propose to develop and optimize a new technique for measuring temporal variation of the vertical distribution of tropospheric and stratospheric ozone amounts using an existing network of ground-based Brewer spectrometers. As part of the procedure used to derive ozone, we simultaneously derive information on other trace gas amounts (NO_2, HCHO, and SO_2) and aerosol optical properties. The proposed measurements are in support of the following NASA objectives,*"Atmospheric composition determines air quality and affects weather, climate, and critical constituents such as ozone… NASA's research for furthering our understanding of atmospheric composition is geared to providing an improved prognostic capability for the recovery of stratospheric ozone and its impacts on surface ultraviolet radiation, the evolution of greenhouse gases and their impacts on climate, and the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality"*. The result of this effort will be **the first automated, passive measurements of diurnal tropospheric ozone variability as a function of altitude combined with measured stratospheric profile information**. The resulting data will be readily available to NASA and the rest of the scientific community for satellite validation (e.g., AURA/OMI), for bounding tropospheric photochemical models, and will provide a unique dataset ***for studying the evolution of tropospheric ozone and aerosols and their impacts on climate and air quality*** at each location where the method is applied.

Measurement of tropospheric ozone (O_3), either from satellites or from the ground, is a difficult problem of intense scientific interest. Tropospheric O_3 is the major ingredient in urban smog that continues to pose a health risk to a large percentage of the US population. Nearly 100 major cities in the United States are periodically exposed to concentrations of ozone that exceed EPA health-based air-quality standards. Tropospheric ozone amounts and vertical distributions show strong seasonal and diurnal variability for each location, especially in polluted areas (e.g., Los Angeles, Atlanta, and Washington, DC). In contrast, mid-latitude stratospheric O_3 (altitude > ~20 km) usually remains relatively constant throughout each day, but has a well-defined seasonal variation typical of the location's latitude as has been determined from SBUV and SAGE satellite data. Nadir-view satellite data (SBUV, OMI, GOME) usually has little sensitivity to lower tropospheric ozone changes and cannot report on diurnal changes, or in the case of SAGE solar occultation data, is made highly uncertain by the presence of aerosols and clouds and has very sparse time coverage at any given location.

Determining the diurnal or seasonal changes in tropospheric ozone concentrations and distributions from the ground has been difficult mainly because of the high cost and complexity characterizing current measurement techniques. Two main techniques have been available for measuring tropospheric ozone in the altitude range 1 to 20 km: 1) In-situ sensing from balloon sondes and aircraft, and 2) remote sensing using an ozone lidar. Balloon sondes (0 to 30 km) and aircraft (1 – 10 km) are impractical and expensive for the required hourly measurements of ozone every day (balloon sondes are several hundred dollars each, not including launch-site labor). Ozone lidars can make frequent measurements of the upper troposphere and stratosphere (5 km to 50 km) with excellent altitude resolution (~100 meters). However, there are only a few operational tropospheric ozone lidars because they are expensive to construct (~$500,000) and maintain.

This proposal is for the development of an ozone profiling technique as a new alternative to either balloon sondes or lidars that is based on automated passive remote sounding from the ground using an existing network of Brewer spectrometers. As part of the method, retrievals are made for ozone profiles, aerosol properties, and trace-gas amounts. The method is capable of retrieving ozone profiles from 0 to 50 km with about 5 km altitude resolution in the troposphere. Our retrieval algorithm uses an optimal estimation technique [Rodgers, 2000]applied to ground based observations of sky radiances measured at 6 selected UV wavelengths, multiple viewing angles, for different solar zenith angles, every 15 minutes to one hour, during the day. For this purpose, we have modified an existing double-grating Brewer spectrometer to remove instrumental polarization sensitivity so that we can measure absolute radiances at many angles and measure the polarization state of the atmosphere in the presence of aerosols [see Figure 1 and Cede et al., 2006a and 2006b].

We are also proposing to complete development of an inexpensive portable CCD spectrometer system that can perform many of the same measurements as the Brewer spectrometer. Minor modifications of our technique for application to the CCD spectrometer system will allow for retrievals of ozone profiles, trace gas amounts, and aerosol data at any location (e.g., at AERONET sites over land and onboard an ocean vessel).

The optimal estimation method has been used in previous theory-only studies for retrieval of ozone profile information from synthetic downwelling UV spectral irradiance [Liu et al., 2006; Guo et al., 2006]. However, this is the first study where such a method is directly designed for application to the real atmosphere (ozone, aerosols, and trace gases), and to a specific class of ground-based spectrometers that operate at more than 50 stations worldwide. We have more than two years of measured radiance data suitable for determining ozone profiles at the Goddard Space Flight Center in Maryland. The proposed work builds on current research performed by our group and is based on preliminary results indicating the validity of the technique.

Proposal Objectives and Goals:

The primary objectives of this proposal are:

Science:

(1) Determine the hourly and day-to-day variability of tropospheric ozone at several different sites in the US, Europe, and other locations as a measure of tropospheric pollution levels.
(2) Examine differences and correlations in tropospheric ozone and NO_2 variability at different sites to investigate the underlying chemical and dynamical processes used in photochemical models,
(3) Determine aerosol optical properties in the UV as a further measure of air quality and to help estimate the amount of UV reaching the surface from satellite measurements,
(4) Perform satellite data validation for AURA/OMI and SBUV ozone profiling, trace gas amounts (e.g., NO_2), and aerosol properties.
(5) Provide an accurate atmospheric correction for coastal region satellite estimated water-leaving radiances including ozone, aerosol, and NO_2 absorption.

Instruments and algorithms:

(6) Complete development and validation of our optimal estimation algorithm for the retrieval of tropospheric ozone profile information and simultaneous measurements of trace gas amounts and aerosol properties from Brewer measurements;
(7) Obtain O_3 profile data at multiple sites;
(8) Demonstrate that similar analysis can be obtained from a small portable inexpensive CCD spectrometer system (less than $10,000);
(9) Transfer the technology to the existing worldwide network of presently unmodified double-grating Brewer Spectrometers;
(10) Transfer the CCD spectrometer system design to a number of sites, especially in the Southern Hemisphere where data coverage is currently extremely sparse.

Initial results have already been obtained and published for NO_2 comparisons with satellite data [Cede et al., 2006b]. During the period of performance, at least two new relatively inexpensive CCD spectrometers will be deployed at strategic AERONET sites to extend the existing data capabilities for aerosols, NO_2, and O_3, and to provide a wider geographical distribution of satellite validation sites. Advantage will be taken of the existing worldwide Brewer network to make measurements of tropospheric ozone and trace gases. This program is already started for NO_2 with two sites, one in Reading, England and the other in Thessaloniki, Greece. Domestically, there is interest in both the NO_2 and O_3 measurements from the Environmental Protection Agency (using their Brewer spectrometers) and from the US Department of Agriculture (for deployment of the small inexpensive CCD spectrometer system).

2. 1. 2. Background - Technical Overview

Tropospheric O_3 is a critical atmospheric species that drives much of the photochemistry in the lower atmosphere, and is an important health-affecting component of smog. In addition to regulating the oxidation capacity of the troposphere and influencing background levels of trace chemicals, O_3 is an important greenhouse gas, affecting radiative balance and global climate. Increased ground-level ozone concentrations are toxic, posing serious threats to agriculture productivity and human health. Breathing ozone can irritate air passages, reduce lung function, aggravate asthma, and inflame and damage the cells lining the lungs. In addition to tropospheric O_3, trace gases such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and formaldehyde (HCHO) in the troposphere also contribute to radiative forcing and have important implications for human and environmental health. Understanding the factors that influence the hourly variations and spatial distributions of these pollutants is important for predicting their impacts on climate and air quality, and protecting human health.

Recent analysis of data obtained from space-borne ozone monitoring instruments such as TOMS and AURA-OMI has shown that it is possible to obtain some information on tropospheric ozone, trace gas, and aerosol amounts from satellite observations, but with considerable uncertainties. For these data, ground-based validation is essential to drive improvements in satellite retrieval algorithms. Because of their much higher spatial resolution, ground-based observations can provide critical information for quantifying the role of ozone, trace gases, and aerosols on local and regional environmental degradation that are not accessible to satellites. To understand tropospheric processes governing the amount of ozone in the atmosphere and its effects on surface UV radiation and photochemistry we need at least hourly measurements of the tropospheric ozone vertical distribution. Because of greater molecular and aerosol scattering in the lower atmosphere, a given quantity of tropospheric ozone is more effective in attenuating UV-B than an equal amount of ozone in the stratosphere [Brühl and Crutzen, 1989] for low to moderate solar zenith angles [Krotkov et al 1998].

The work described in this proposal is for the development and implementation of a new technique that will provide **the first automated, passive measurements of diurnal and seasonal tropospheric ozone variability as a function of altitude combined with stratospheric profile information.** The algorithm needed to derive ozone profiles is based on a Rodgers optimal estimation (i.e. maximum likelihood, ML) method [Rodgers, 2000; Liu et al., 2006] as opposed to stratospheric only Umkehr technique [Petropavlovskih, 2005] and analysis of real and synthetic data based on the pseudo-spherical radiative transfer programs, including both polarization and aerosol effects. The proposed method is directly designed for a specific class of ground-based spectrometers (i.e. the uniquely modified Brewer instrument shown in Figure 1) for which we have more than two years of sky-radiance data. Preliminary results by our group (see Section 2.3.4) indicate that minimization of residuals in the ML method provides information on both ozone and aerosol properties (305 to 340 nm), but requires knowledge of NO_2 amounts from the Brewer's direct-sun measurements to obtain the correct aerosol single-scattering albedo (absorption) in the 340 to 360 nm range [Cede et al., 2006b]. **Therefore, in addition to stratospheric and tropospheric ozone variability, application of the proposed technique will obtain simultaneous information on temporal behavior and spatial**

distribution of chemically and radiatively important trace gases (NO_2, SO_2, HCHO) and aerosol properties (particle size, optical depth, and absorption).

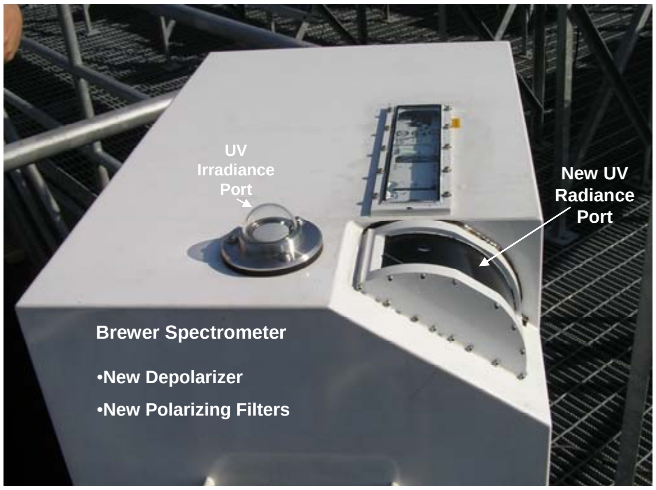


Figure 1: A photograph of the modified Mark III double Brewer spectrometer showing the curved radiance entrance port on the lower right.

In its various models, the Brewer spectrometer [Kerr et al., 1985] has been available for the past 25 years as a means of making accurate measurements of irradiance and radiances that can in turn be used to derive column ozone and SO_2 [Kerr et al., 1988]. Our version, the Mark-III Brewer double–grating spectrometer, has also been used to derive more accurate total column ozone and SO_2 (300 – 310 nm) with the advantage of a very low level of internally scattered light (~10^{-8}) at the short UV wavelengths. The low scattered light capability would make the Mark III Brewer ideal for measuring sky radiance except for the problem of polarization sensitivity related to the grating and to the flat quartz window (Fresnel effect) covering the entrance port [Cede et al., 2006a].Measurements of global (~2π steradian) UV irradiance are made through a diffuser mounted on top of the instrument (see Figure 1) and solar irradiance by directly viewing the sun using a narrow field of view radiance port. We have modified the Brewer (see Figure 1) to eliminate both sources of polarization sensitivity by introducing a depolarizer in front of the grating and by installing a curved quartz window such that incident radiances observed by the spectrometer are always perpendicular to the window surface. Once the spectrometer is made insensitive to polarization caused by atmospheric Rayleigh scattering, sky-radiance data can be used to derive ozone profiles and aerosol optical properties. We will also attempt to derive more aerosol information from the Brewer data (optical depth, single-scattering albedo, particle size, and plume height) by using 3 new polarizing analysis filters installed in front of the depolarizer to completely determine the Stokes vector. The Brewer spectrometer at GSFC is always operated in conjunction with Cimel sunphotometers and a UV-MFRSR (UV shadowband) for validation of aerosol parameters and total column ozone [Cede et al., 2006b].

2. 1. 3. Basis in NRA

The research we propose is related to NASA’s strategic goal and Science objective (as stated in the latest version of its Strategic Plan) to: *“Conduct a program of research and technology development to advance Earth observation from space, improve scientific understanding, and demonstrate new technologies with the potential to improve future operational systems”*. This proposal addresses the goal through much needed satellite validation of data and algorithms for critical measurements in the troposphere.

The NRA specifically states, *“The research strategy in atmospheric composition encompasses an end-to-end approach for instrument design, data collection, analysis, interpretation, and prognostic studies. NASA expects to provide the necessary monitoring and evaluation tools to assess the effects of climate change and air quality forecasts that take into account the feedbacks between local, regional, and global air quality and global climate change. Drawing on global observations from space, augmented by suborbital and* ***ground-based*** *measurements, NASA is uniquely poised to address these issues.”*

In particular, this proposal addresses the specific goals of the first principal area of research solicited here, *"for measurements that contribute to ongoing, global, long-term data records of atmospheric trace gases and aerosols"*. According to the NRA: *"proposals that utilize the measurements together with inverse modeling to examine the atmospheric burden of anthropogenic and naturally occurring* ***ozone- and climate-related trace gases*** *are of particular interest"*. One of the key objectives of this call is "*documentation of global distributions and* ***temporal behaviors of chemically and radiatively important gases***". In addition, the proposed work responds to this NRA call for "*proposals that* ***utilize aerosol measurements together with inverse modeling to estimate aerosol properties*** *such as aerosol size distribution, single scattering albedo, aerosol vertical distribution*".

2. 2. RESEARCH OBJECTIVES AND WORK STATEMENT

Research Objectives: We are proposing to measure tropospheric ozone profiles at least once per hour throughout each partly cloudy or clear-sky day, to measure stratospheric ozone profiles at least once per day, combined with aerosol characteristics (particle size, optical depth, and absorption) and trace gas amounts at least once per hour. For this purpose we will use measured radiances and polarization components from our modified Brewer double monochromator (Figure 1) and from our newly built CCD spectrometer system (Figure 2), and will extend our recently developed algorithms for determining ozone profiles and aerosol characteristics. We will develop the correlation between tropospheric ozone variability, changes in trace gas amounts, and aerosol amounts using photochemical models at GSFC. A Statement of Work is in the two tables below.

Year	Statement of Work (Years 1 and 2)
1	**1. Continue ongoing Brewer measurements at GSFC and start the data analysis to obtain a 2-year record of tropospheric ozone profiles from measured radiances.** **2. Move the Brewer and CCD instrument to sites with balloon-sonde campaigns to validate the ozone profile retrievals.** **3. Acquire and implement a new solar and sky tracker for the CCD spectrometer.** **4. Extend development of the ozone profile algorithm to detect and correct for aerosols using the existing Brewer polarization analysis capabilities.** **5. Assist other locations to modify their Brewer spectrometers.** **6. Extend the validation of AURA/OMI data to include trace gases, aerosols, and tropospheric ozone amounts.** **7. Build and test one operational small spectrometer system based on the existing prototype (shown in Figure 2).**
2	**1. Modify the ozone and trace gas algorithm to take advantage of the full spectrum available with the CCD spectrometer 305 to 500 nm.** **2. Extend the number of trace gases beyond NO_2 and SO_2 to include glyoxal (CHOCHO), formaldehyde (HCHO) using the CCD spectrometer.** **3. Build and implement the CCD system at 2 selected AERONET sites.** **4. Make available a full parts list, control software, and algorithms for implementing the CCD spectrometer package at other sites.** **5. Obtain an accurate atmospheric correction for water leaving radiances in coastal waters for use in improved satellite retrievals of chlorophyll and CDOM.**

We intend to distribute the operating software for the Brewer spectrometer and algorithms to a number of existing Brewer sites throughout the world. We will also distribute the plans for modifying the Brewer (depolarizer, polarizing filters, new entrance window, and software with duplication cost less than $6K), and the plans for the CCD instrument system (spectrometer, solar tracker and sky pointer, thermal control system, optical system, and computer software with duplication cost less than $10K). The goal is to create a worldwide network for satellite validation and scientific investigation at no additional cost for NASA.

Year	Statement of Work (Years 3 and 4)
3	**1. Complete development of the algorithms to obtain the aerosol particle size distribution, single scattering albedo and optical depth using the polarization measurements from the Brewer spectrometer. Improve the polarization accuracy of the Brewer spectrometer.** **2. Modify the CCD spectrometer with a depolarizer as the first optical element before the grating and add polarization filters to compare with the Brewer polarization measurements.** **3. Develop satellite data validation capability at various sites around the world in cooperation with other organizations that have implemented the changes to their Brewer spectrometers or CCD spectrometer systems.** **4. Correct the NO_2 retrieval for the presence of water vapor.** **5. Obtain an accurate "air-mass" correction at different locations for AURA/OMI satellite retrievals of trace gas amounts.**
4	**1. Analyze and publish the data obtained from various instruments.** **2. Modify the CDD spectrometer system for better SNR and lower stray light.** **3. Improve the inversion algorithm to obtain simultaneous solutions for trace gases, aerosols, ozone profiles, and total column ozone.** **4. Conduct additional field campaigns in cooperation with AERONET and other international validation campaigns.** **5. Compare the Brewer and small spectrometer aerosol properties with those derived from the UV-shadowband and Cimel sunphotometer.** **6. Incorporate the results into photochemical models to further understand the relation between tropospheric trace gas amounts and ozone.**

2. 3. TECHNICAL APPROACH AND METHODOLOGY

2. 3. 1 Description of Ground Based Instruments

The main instruments for making the proposed measurements are a Brewer double-grating spectrometer, 283 to 364 nm with 0.5 nm resolution, operating in its radiance-measuring mode, and a small CCD spectrometer operating from 280 to 550 nm with 0.5 nm resolution and 3X over-sampling. The advantage of using the Brewer spectrometer for trace-gas retrieval is its excellent radiometric and wavelength stability needed to remove the Solar Fraunhofer line structure to permit detection of the small residual underlying trace-gas absorption spectra. The CCD spectrometer system has the advantage of being able to measure all wavelengths simultaneously in a small easily portable system. The particular CCD spectrometer we have chosen (Avantes) has been tested to show it has adequate stability for trace-gas determination with appropriate calibration and temperature stabilization (1^oC) techniques. The Brewer and CCD measurement data sets consist of 1) direct-sun irradiances, 2) sky radiances in the principal plane, 3) polarization measurements of the Stokes vector from the sky radiances, and 4) ancillary data sets from a UV-Shadowband instrument and Cimel sunphotometer used for validating total ozone and aerosol measurements.

Brewer Double Monochromator: Ozone measurements are routinely performed at Goddard Space Flight Center (GSFC), Greenbelt, Maryland, USA (38.98°N, 76.83°W, 90m a.s.l.), using a MK3 Brewer spectrometer [*Kerr et al.*, 1985]. Our instrument, Brewer #171, has a wavelength range from 282.6 to 363.6nm and a triangular slit function with full width half maximum from 0.47nm to 0.67nm that decreases with wavelength. Brewer #171 is a double monochromator with very low internal stray light ($<10^{-8}$), and, therefore, ideal for measurements in the ultraviolet (UV), especially for wavelengths less than 310nm, which we use for ozone (O_3) and sulfur dioxide (SO_2) retrievals. Raw counts from the Brewer are converted to 'effective count rates', which includes corrections for the dark count. Internal attenuation filters are used to adjust the intensity, the dead time of the photomultiplier tube, and the instrument's temperature dependence. The narrow field of view port of Brewer #171 is regularly absolutely calibrated in our laboratory in the same way as described by *Kazadzis et al.* [2005]. The Brewer is internally temperature stabilized to permit automatic operation in a wide variety of weather conditions.

The Brewer can operate either in a 'wavelength scanning mode', where the gratings are moved and any wavelength can be selected, or in a 'slit-mask mode', which allows nearly simultaneous measurements of 6 wavelengths that are about 3 nm apart using a fixed grating position. In the slit-mask mode the measured signals are obtained from multiple runs over all 6 wavelengths with 0.11 seconds integration time for each wavelength.

For total column amounts of ozone and trace gases (SO_2 and NO_2), the Brewer is operated in direct-sun viewing mode using our newly developed sun-centroiding algorithm. The column NO_2 algorithm and comparison with SCIAMACHY satellite data are discussed in a published paper (Cede et al., 2006b) and is the subject of a previous proposal. Numerous authors have discussed Brewer spectrometer column ozone and SO_2 algorithms based on the use of 6 wavelengths in the range from 300 to 320 nm such that the central wavelength of each channel falls on the maxima and minima of the ozone absorption cross section.

CCD spectrometer: The CCD system consists of an Avantes fiber optic spectrometer, Figure 2A, that is connected to an electronics control box with a 6-position filter wheel (Open, Opaque, 280-315nm-Bandpass, Polarizer-1 Polarizer-2, and Polarizer-3) (Figure 2B), and mounted on a computer controlled sun-tracker and sky-scanner (~0.01 arcsecond pointing accuracy) (Figure 2C). The spectrometer is temperature stabilized (within 1^oC) inside of a small enclosure. To further minimize instrumental variability, the dark current is measured in between each radiance measurement using the opaque filter wheel setting. Wavelength calibration is maintained by using mercury lamps and by an analysis of the solar Fraunhofer line structure. Because of stray light at short wavelengths (290-305nm), intrinsic in a short-path single grating design, SO_2 retrieval may not be practical. We are testing the system to see if SO_2 retrieval is possible by inserting a UV bandpass filter (280 – 315 nm), with a sharp cutoff at 320 nm, to greatly reduce stray light. The CCD system has already successfully measured NO_2 in direct-sun mode and will acquire sky-radiance data for measuring O_3 profiles. Part of the work in this

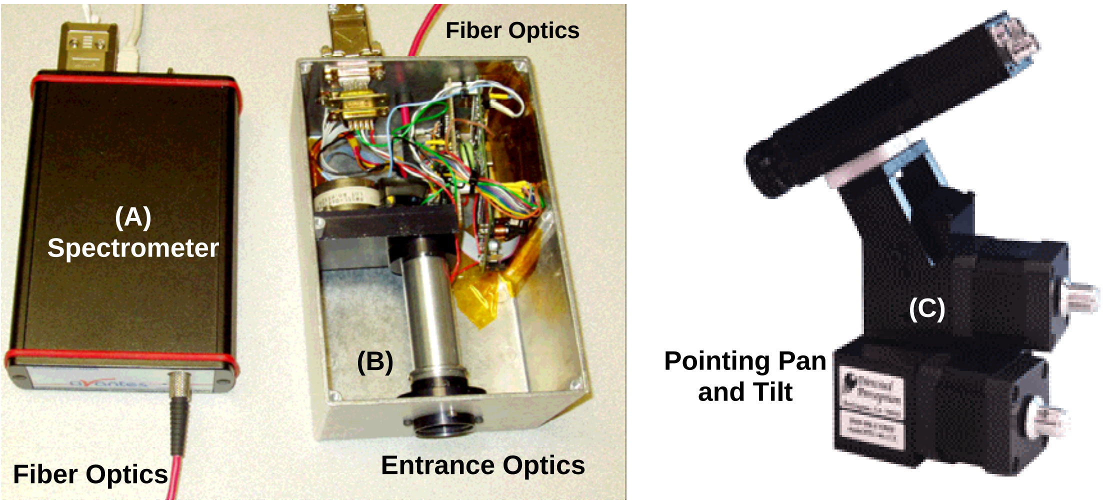


Figure 2: (A) Small CCD spectrometer with fiber optics coupling to (B) control electronics box, entrance optics, rotating filter wheel and shutter. (C) Precision pan and tilt head with 0.01 degree pointing accuracy. The system, including the portable temperature control chamber (±1^oC) is less than $10K to duplicate. The entire system is weather resistant to permit automatic operation.

proposal is to perform the data analysis to demonstrate that the highly portable CCD spectrometer system (<~$10K, weight ~8 kg) can also obtain ozone profiles that are comparable to the more expensive Brewer spectrometer (more than $220K, weight ~50 kg). When successful, this system design shown in Figure 2 will be offered to sites that do not currently have a Brewer spectrometer (e.g., most AERONET sites).

In Figure 2, items 2A (~$3500) and 2C (~$2500) have been borrowed from another project for development purposes, and have to be purchased specifically for this project and long-term usage. Item 2B has been constructed at GSFC and is available for this project. Item 2B still requires polarization filters (~$100) identical to those used in the Brewer, and additional full system calibration for absolute radiance measurements. The 280-to-315 nm UV bandpass filter (~$800) has also been borrowed for testing and would have to be acquired as part of this project.

2. 3. 2. Ozone Profile Inversion Algorithm

The inversion strategy for ozone profile retrieval is to simultaneously fit Brewer spectral and angular sky radiance measurements in the solar principal plane constrained by the nearly simultaneous Brewer total column ozone (TCO) measurement. To stabilize our retrievals we used a-priori O_3 profile information based on a climatological database derived by combining SAGE II and MLS satellite data with data from balloon ozonesondes [McPeters and Labow, in press]. This ozone climatology was produced for use with the Version-8 Total Ozone Mapping Spectrometer (TOMS) and Solar Backscatter Ultraviolet (SBUV) retrieval algorithms.

The basic equations used in the tropospheric ozone inversion algorithm are:

$$\begin{cases} N_{\_meas}(\lambda,\theta) = N_{\_\mathrm{mod}el}(\lambda\;;\theta\;;\Omega) + \varepsilon_N(\lambda) & \text{[1a]} \\ TCO \;= \sum\limits_l \omega_l \;+ \varepsilon_{TCO} & \text{[1b]} \\ \omega_{\_a_l} = \omega_l \;+ \varepsilon_a & \text{[1c]} \end{cases}$$

where, $N_{meas}(\lambda,\theta)$ and $N_{model}(\lambda,\theta,\Omega)$ are Brewer measured and model calculated N-values of sky radiance in the principal plane at wavelength λ, with vertical view angle θ and ozone profile Ω; N values were estimated as $N(\lambda,\theta)$=-100$\log_{10}\cdot(I\cdot(\lambda,\theta)/F\ )$, where I and F the absolute sky radiance and solar irradiance (ATLAS-3 SUSIM solar spectrum convolved with the Brewer slit function and corrected to the actual Sun-Earth distance), respectively; TCO is the total column ozone amount derived from Brewer direct sun measurement [Cede et al., 2005]; $\Omega=\{\omega_l\}$ is the forward model ozone profile, where ω_l is ozone amount in Umkehr layer l (l = 1,..,L) and $\omega_{\_\alpha l}$ is the a-priori estimate of the layer ozone amount in Umkehr layer l. Equation [1a] describes fitting Brewer sky measurements using a forward radiative transfer model for a specified atmosphere and an error term ε_N. The second equation [1b] constrains the profile total column ozone amount with the Brewer TCO measurement. Since the TCO measurement is made in direct-sun mode, it is practically independent of the ozone profile shape and has an error term ε_{TOC}. Equation [1c] describes a-priori knowledge of ozone profile statistics with an a-priori error, ε_α, estimated based on the climatological ozone database. In our retrievals, direct-sun and sky radiance are limited to view angles < 77^o due to edge effects from the Brewer instrument input window. In designing the retrieval, we minimize systematic N-value errors (both from the model and measurements) by taking spectral N value ratios to 320nm and assuming that residual random errors have a Gaussian distribution about the mean with known covariance matrices, **S**. We seek the unique ozone profile solution, described as a profile (state) vector of ozone amounts in standard Umkehr layers, that provides the best overall fit of all 3 equations in system (1) in a least-squares sense. To constrain the retrieval to only positive ozone amounts, we redefine the state vector as natural logarithms of the layer ozone amounts: $\mathbf{x}_o = [\mathbf{x_j}] = [\ln(\omega_j)]$, for j=0 to L.

To achieve the statistically optimum solution with random noise optimization we solve equations (1) using the Maximum Likelihood (ML) approach [Rodgers, 2000]. Combining Brewer sky measurements with the total column ozone (TCO) into a single measurement vector, **y**, Eq. [1] can be re-written in Rodgers [2000] notation:

$$\mathbf{y} = \mathbf{f}\ (\mathbf{x}) + \boldsymbol{\varepsilon}_y \qquad [2a]$$

$$\mathbf{x}^a = \mathbf{x} + \boldsymbol{\varepsilon}_a \qquad [2b]$$

where ε_y is the error in the measurement vector **y**, and ε_a is the error in the a-priori ozone profile $\mathbf{x}^a$. According to the ML approach, the statistically best solution that can be derived from all given data is a vector x_o corresponding to the minimum of the following quadratic form:

$$\Psi(\mathbf{x}) = (\mathbf{y} - \mathbf{f}(\mathbf{x}))^T\ W_y^{-1}\ (\mathbf{y} - \mathbf{f}(\mathbf{x})) + \gamma\ (\mathbf{x}^a - \mathbf{x})^T\ W_a^{-1}\ (\mathbf{x}^a - \mathbf{x}) \qquad [3]$$

where $W_y^{-1} = \sigma^2_{TCO} S^{-1}_y$ and $W_a^{-1} = \sigma^2_a S^{-1}_a$ are weight matrices, with S_y and S_a the covariance matrices for the measurement vector y and the apriori ozone profile, respectively, σ^2_{TCO} the variance in TCO measured error, σ^2_a the minimum layer variance in a-priori O_3 profile, and γ is a weight coefficient (Lagrange multiplier). The minimization of **Ψ(x)** is implemented iteratively using a linear approximation of **f(x)** based on Taylor series at each iteration step:

$$\mathbf{x}^{p+1} = \mathbf{x}^p - t_p \Delta \mathbf{x}^p \qquad [4]$$

where $\Delta\mathbf{x}^p$ is a linear estimator for the ozone profile correction at each iteration step p and t_p is a Levenberg-Marquardt multiplier. This multiplier is used to provide monotonic convergence, and is typically smaller than 1 ($t_p<1$). The linear correction $\Delta\mathbf{x}^p \approx \mathbf{x}_0 - \mathbf{x}^p$ is found by finding the minimum of the linearized quadratic form [3] given by solution of the so-called normal equation system:

$$\left(\mathbf{K}^T_{\mathbf{x}^p} W_y^{-1} \mathbf{K}_{\mathbf{x}^p} + \gamma\ W_a^{-1}\right)\ \Delta\mathbf{x}^p = \mathbf{K}^T_{\mathbf{x}^p} W_y^{-1}\left(\mathbf{y} - \mathbf{f}(\mathbf{x}^p)\right) + \gamma\ W_a^{-1}(\mathbf{x}^a - \mathbf{x}^p) \qquad [5]$$

where, $\{K_{x^p}\}_{i,j} = (\{\partial\mathbf{f}(\mathbf{x})\}_i) \backslash \partial\mathbf{x}_j\ |_{\mathbf{x}^p}$ is the weighting function matrix of the partial derivatives (Jacobian) [Rodgers, 2000] in the near vicinity of the vector $\mathbf{x}^p$. The partial derivative elements for **K** are re-calculated numerically at each iteration step by finite differencing model calculated N_i values for each ozone layer. Iterations continue until the convergence is satisfied when the norm of the vector $\Delta\mathbf{x}^p$ (difference between iterations) is less than a certain threshold value.

The averaging Kernel matrix **A** is defined as sensitivity of the retrieved state $\mathbf{x}'$ to true state $\mathbf{x}_o$ and provides useful analysis of the information content of the retrieval at each altitude node point [Rodgers, 2000]. We estimated **A** from:

$$\mathbf{A} = d\mathbf{x}'/d\mathbf{x}_o = \left(\mathbf{K}^T_{\mathbf{x}_0}\ W_y^{-1}\ \mathbf{K}_{\mathbf{x}_0} + \gamma\ \cdot W_a^{-1}\right)^{-1} \cdot (\mathbf{K}^T_{\mathbf{x}_0}\ W_y^{-1}\ \mathbf{K}_{\mathbf{x}_0}) \qquad [6]$$

The trace of the Averaging Kernel Matrix, DFS = Trace(A), gives the degrees of freedom for signal (DFS), or an estimate of the number independent pieces of retrieved information. DFS is inversely related to the FWHM(A) (full width at half maximum) of the peaks of A. An example of estimated averaging Kernel Matrix is discussed in the results section (2.3.4). The retrieval errors are estimated according to Rodgers [2000] equation [3.9] and also estimated numerically using a Monte Carlo noise propagation study.

2.3.3 Trace Gas Measurements

Trace gas column amounts, other than SO_2, are retrieved using direct-sun observations with a 2^o FOV in the wavelength range 320 to 440 nm (320 to 360 nm for the Brewer spectrometer). The retrieval algorithm is a version of the DOAS (Differential Optical Absorption Spectroscopy) technique applied to 6 wavelengths for the Brewer and many more wavelengths for the CCD spectrometer. The method, its calibration, and measurement results are described in complete detail in our recent publication [Cede et al., 2006b]. The direct-sun method does not have the large airmass error (50 to 100%) associated with traditional zenith-sky DOAS, and our calibration technique removes the error down to the residual representing stratospheric NO_2 (about 0.2 DU) compared to tropospheric measurements ranging up to 3DU.

2. 3. 4. Preliminary Ozone Retrieval Results

Preliminary results by our group (see below) show that the proposed technique performs well for a wide range of solar zenith angles, showing that the method can be applied to derive information on diurnal variability of tropospheric ozone. Moreover, our preliminary results show that minimization of residuals in the Maximum Likelihood method obtains both ozone and aerosol information (305 to 320 nm), but requires knowledge of NO_2 amounts from the Brewer's direct-sun measurements to obtain the correct aerosol single- scattering albedo (absorption) in the 340 to 360 nm range [Cede et al., 2006b]. The derived aerosol amounts and optical properties will be validated with the Cimel sunphotometer and UV-shadowband.

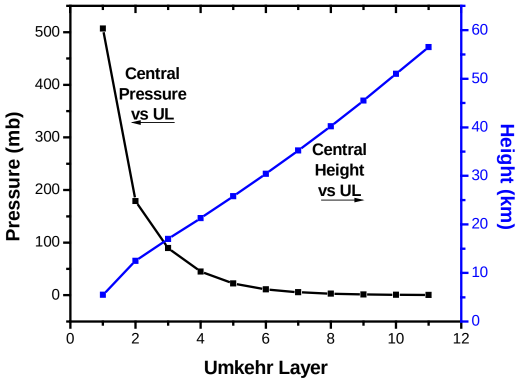


Figure 3: Umkher layers vs pressure and altitude at the center of the layer [Tranchant and Vincent, 2000]

The ozone retrievals are obtained at 11 Umkehr layers corresponding to an altitude range of about 1 to 57 km, each located at half the pressure of the preceding layer (Figure 3). This layering scheme is similar to previous retrievals from the zenith-sky Umkehr technique and for the SBUV (Solar Backscatter Ultraviolet) satellite retrieval methods. The proposed method is a significant improvement over the traditional Umkehr approach to obtaining stratospheric ozone profiles, since the measurement takes only two minutes instead of a few hours each day by using multiple wavelengths and look angles in place of multiple solar zenith angles.

2.3.4.1 Retrieval of diurnal ozone variability

To test the method, model runs were performed for solar zenith angles in the range 35-75^o using an input O_3 profile ("true"). Ground-based measurements of radiation fields (measurement vector ***y***) were simulated by running the TOMRAD forward RT (radiative transfer) code [Dave, 1964] for a pure Rayleigh atmosphere with total column ozone TCO = 325 DU (2 different cases of a "true" O_3 profile are shown in Figure 4), and neglecting aerosols and clouds. To simulate Brewer data, model runs were performed for the specific instrumental characteristics of the Brewer spectrometer including known instrumental uncertainties. Radiances were estimated at the 6 Brewer UV wavelengths (λ = 303, 306, 310, 313, 316, 320 nm) and 5 selected Brewer viewing angles (θ_{view} = 0, 18, 36, 54, 72^o) in the solar principal plane. The ozone absorption coefficients [*Bass and Paur*, 1984] and the Rayleigh scattering coefficients and depolarization factors [*Bates* 1984] were averaged using measured Brewer slit functions.

Random errors, of the order of the random noise observed in the actual Brewer data, were applied to the synthetic measurement vector. To remove possible constant errors and biases from the dataset, N values were normalized to measurements at 320 nm. Because forward scattering within the solar aureole affects the accuracy of the measurements, retrievals were performed only at the anti-sun direction (azimuth = 180^o). Data can be used from the sun-side as long as the FOV is at least 6^o away from the sun direction.

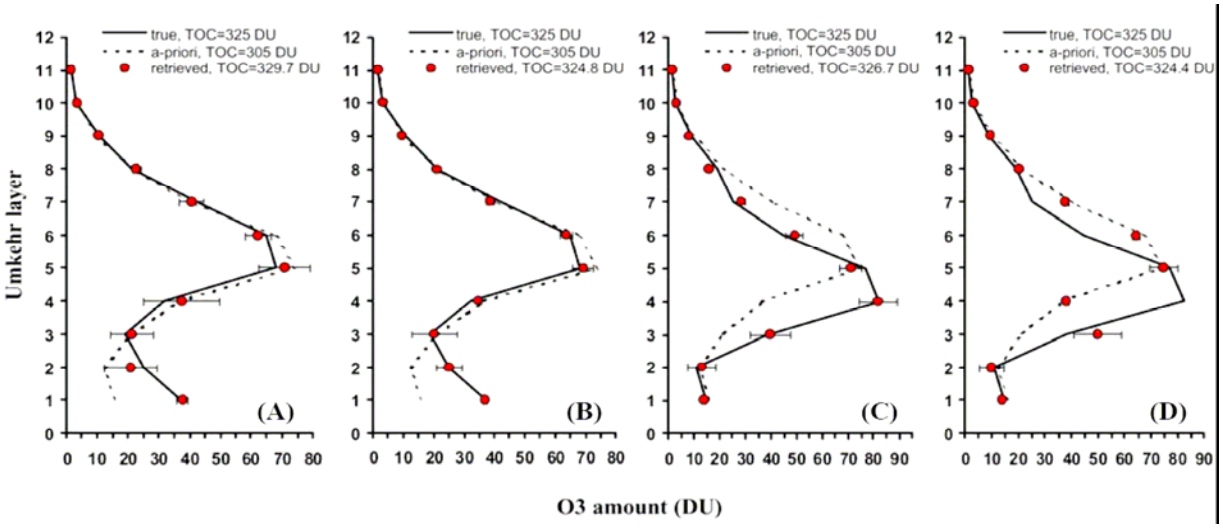


Figure 4: "True" (solid line), a-priori (dotted line), and retrieved (solid circles) O_3 profiles for Case 1 "true" O3 at (A) sza=75^o and (B) sza=45^o, and for Case 2 "true" O3 at (C) sza=75^o and (D) sza=45^o.

To stabilize our retrievals we used an a-priori O_3 profile based on a climatological database derived by combining SAGE II and MLS satellite data with data from balloon sondes [McPeters and Labow, in press] ("a-priori" ozone profile in Figure 4). Information on the total column ozone (TCO) amount (a parameter measured by the Brewer) was also used to constrain our retrievals. Uncertainties in the a-priori and the total ozone amount were estimated based on the ozone climatological dataset and the Brewer TCO measurements, respectively, and were included in the retrieval. The "true", a-priori, and retrieved O_3 profiles are shown in Figure 4 for 2 cases of "true" O3 profiles and for retrievals at 2 different solar zenith angles (sza=45 and 75^o). The Averaging Kernel matrices are shown in Figure 5 for Case 1. Very similar results were obtained for Case 2.

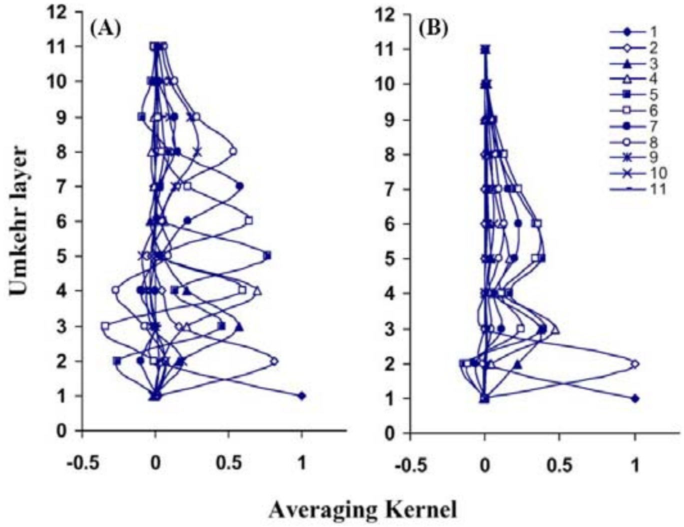


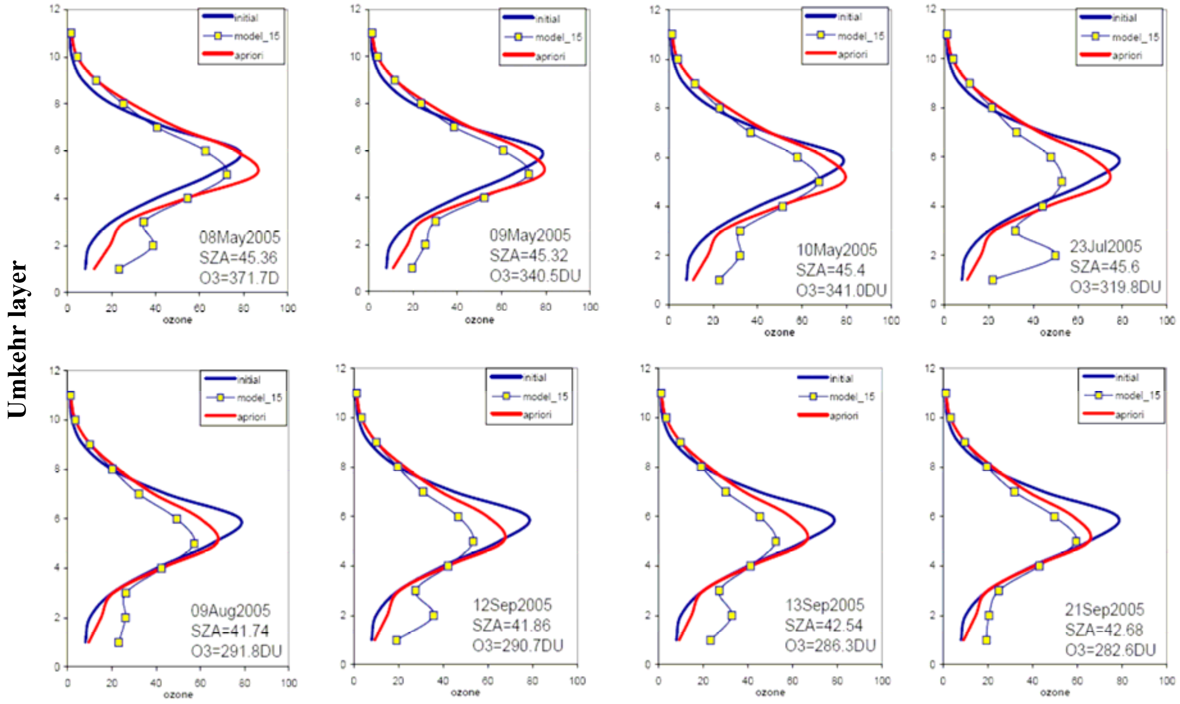
Figure 5: Averaging Kernels for Case 1 "true" O3 at (A) sza=75^o, (B) sza= 45^o. Very similar results were obtained for the Case 2 O3 profile.

The Averaging Kernel (Figure 5) provides an estimate of the amount of information in a given altitude range, and should have at least one peak for the layer corresponding to each retrieved layer value. The widths of the peaks are a measure of the spatial resolution inherent in the data, and can be used to estimate the optimal number of layer node points used in the inversion. The current inversion uses a spatial grid fixed by the 11 classical ozone Umkher layers and results in an altitude resolution of about 7 km in the troposphere. The retrieval could use approximately 1 to 3 layer node points per Averaging Kernel peak, or about 20 layers increasing the resolution to about 5 km. Features in the profile that are wider than the FWHM(A) will be resolved in the retrieval, but features that are finer than the peaks will be averaged out of the retrieved profile.

From Figure 4a, 4c, and 5a it is evident that midlatitude retrievals at sza=75^o (early in the morning and late in the evening) provide very good information on upper-tropospheric and stratospheric ozone. Once the stratospheric ozone is determined, it is assumed that the stratosphere is approximately constant throughout the day so that hourly variation in the troposphere can be estimated. Figures 4b, 4d and 5b show that at lower solar zenith angles the model becomes very sensitive on tropospheric ozone. For retrievals at sza=45^o, Umkehr layers 1 to 3 span the troposphere and are well resolved, especially layers 1 and 2 (see averaging kernel in Figure 5). This means that we can expect a resolved ozone point near the surface, at about 7 km, at about 15 km, and at about 20 km.

2.3.4.2 Application of proposed technique to Brewer data

In addition to the studies using synthetic datasets, we applied our retrieval to real data obtained by the modified double grating Brewer spectrometer operating at GSFC. The instrument was set up on an elevated platform on top of a building about 21 meters above the ground or about 100 meters above sea level. There are no nearby obstructions or significantly reflective surfaces near the spectrometer. The ozone profile retrievals are shown in Figure 6.



model-15: convergence was achieved in 15 iterations or less

Figure 6: Ozone retrievals from Brewer radiance data obtained at GSFC for 8 clear-sky days with SZA between 40^o and 46^o and measured total ozone amounts from 282.6 to 371.7 DU. Shown are the a-priori constraint profile (red), the initial guess profile (black), and the retrieved ozone profile (squares).

2.3.4.3 Effect of Aerosols on Ozone Profile Retrievals

The O_3 profiles derived using measured Brewer data seem reasonable (squares in Figure 6). However, closer analysis revealed that, even during relatively clear days (e.g. AOD around 0.2 at 500 nm and ~0.4 at 310nm), aerosols have a large effect on the tropospheric ozone retrievals. Figure 7(a) shows an example of the residuals between the N-values, $N=-100\mathrm{Log}_{10}$(measured radiance/solar irradiance), measured by the Brewer and the N-values estimated by the model for the retrieved O_3 profile when no aerosols were included in the retrieval. The residuals were: (i) significantly larger than expected based on the measurement errors, (ii) large at all wavelengths, and (iii) strongly dependent on viewing angle. The magnitude and shape of the residuals were very similar to the magnitude and shape of the residuals estimated when we ran our aerosol-free retrieval (Figure 7b) using a simulated Brewer dataset obtained for a model atmosphere that included a small amount of absorbing aerosols (the University of Arizona forward RT code was used in this case for $\mathrm{AOD}_{(500\ \mathrm{nm})} = 0.175$, and $\mathrm{SSA}_{(340\ \mathrm{nm})} = 0.92$).

We then modified the retrieval to include an aerosol correction using measurements of aerosol optical depth (AOD), single-scattering albedo (SSA), and particle size distribution (PSD) obtained by a CIMEL spectrophotometer operating at the same location as our Brewer instrument (AERONET data, GSFC site). The CIMEL aerosol parameters (340 to 440 nm) were used as a first guess for the aerosol correction needed for 305 to 320 nm. UV-shadowband

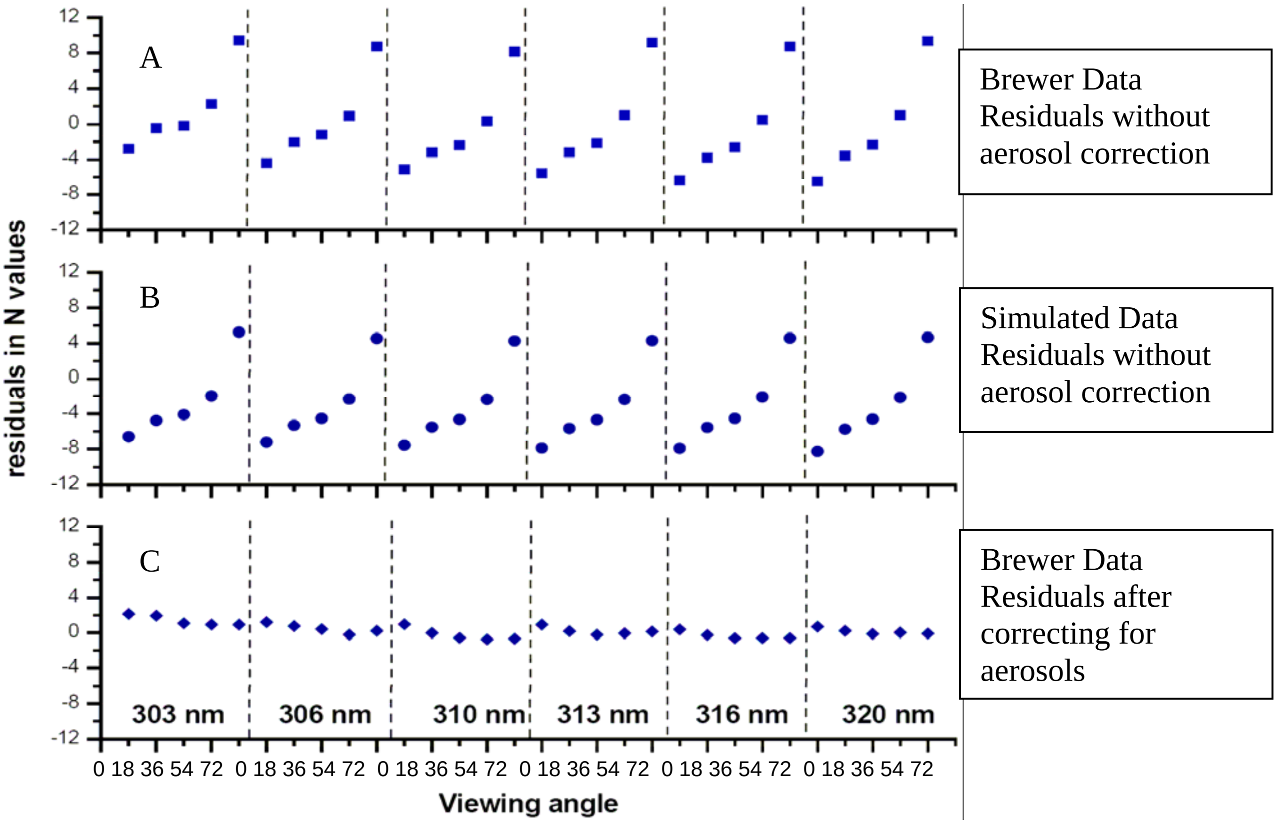


Figure 7: Residuals in N values (each point corresponds to specific vertical angle (zenith on the left to 72 on the right) and wavelength shown in lower panel) (a) between Brewer data and model calculations without correction for aerosol effect; (b) between simulated Brewer data for an atmosphere that included aerosols and model estimations without correction for aerosol effect; (c) between Brewer data and model estimations after correcting for the effect of aerosols.

measurements provide adjustments to the CIMEL SSA and AOD that greatly reduced the residuals between measured and calculated N values (Figure 7(c)) in the O_3 profile retrieval. The PSD, AOD, and SSA can be obtained from the Brewer 340 - 360 nm direct sun and multiple-angle sky radiance measurements, where ozone absorption is negligible. The amount of NO_2 must be simultaneously determined to correct for its absorption, which otherwise creates an error in the aerosol SSA [Cede et al., 2006b]. The AOD is obtained from direct-sun observations, permitting the SSA [Krotkov et al 2005c; Cede et al., 2006b] to be independently determined from sky radiances. The PSD will be obtained from an AERONET Cimel until the Brewer algorithm is validated. The slope of the residuals (Figure 7) is sensitive to all three measured aerosol parameters.

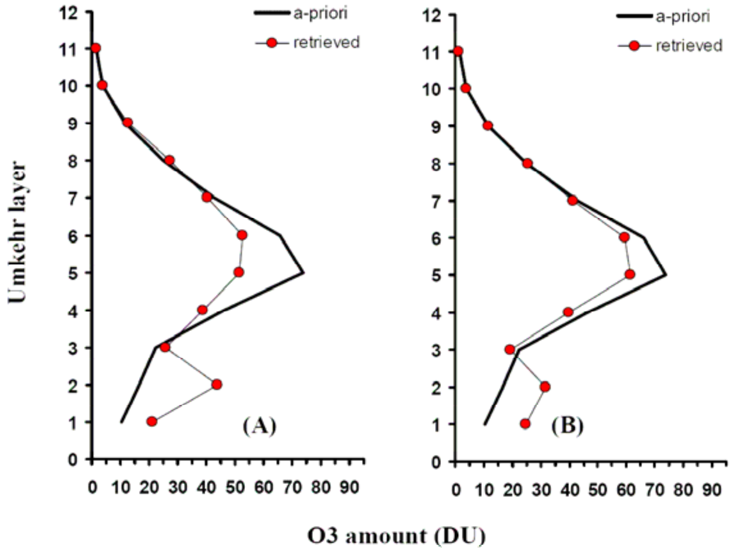


Figure 8: Brewer retrieval (A) no aerosol correction, (B) with aerosol correction

The effect of including aerosol and NO_2 absorption in the ozone retrieval algorithm is shown in Figure 8. Figure 8a shows the ozone profile retrieval corresponding to the residuals shown in Figure 7a, where the presence of aerosols in the atmosphere was neglected. Figure 8b shows the ozone profile retrieval corresponding to the residuals shown in Figure 7c, where the aerosol amounts derived from the CIMEL and UV-shadowband data, modified slightly to minimize the residuals, are included in the retrieval algorithm. The differences are significant in the ozone peak values in Umkehr layers 5 and 6, and in the troposphere in layer 2. ***As part of the proposed work we will incorporate the aerosol retrieval into the maximum likelihood ozone algorithm so that ozone and aerosol properties are retrieved simultaneously using the Cimel derived aerosol properties as a starting point.***

Aerosols: We currently make several measurements of aerosol properties with the Brewer spectrometer that should yield independent measures of AOD, PSD, SSA, and plume height. These are, AOD from direct sun attenuation, PSD from measurements of the solar aureole with a variable FOV from 1^o to 5^o, measurements of the SSA using sky radiances at multiple view angles, both polarized and unpolarized, from 320 to 360 nm combined with the measured PSD and AOD. Polarization measurements also give an estimate of the plume height in addition to the AOD and SSA. In the near future these measurements will be validated against Cimel sunphotometers (AERONET) and the UV-shadowband [Cede et al., 2006b; Krotkov et al., 2005a;b]. Similar measurements will be made with the small CCD spectrometer.

Validation: Currently, there has been no means of validating the existing Brewer ozone profile data set obtained at GSFC. That is, until this summer (August 2006) when there is a nearby (4 km) balloon ozone-sonde campaign. Our preliminary results (both simulated and real Brewer data) suggest that the retrieved profiles are reasonable and self-consistent, the method is stable, and the retrieval is sensitive to stratospheric ozone amounts (for sza=75^o and larger), and is sensitive to the amount of ozone in the troposphere (i.e. 3 lowest Umkehr layers) at sza smaller than 60^o.

2.4 SUMMARY

The ozone, trace gas, and aerosol retrievals presented in this proposal are based on extensive preliminary analysis for O_3 profiles and on previously published work (aerosols and trace gases) [Cede et al., 2006a,b]. The proposed work is to:

1. Develop a new algorithm for the Brewer spectrometer that simultaneously solves for all of the necessary parameters needed to obtain tropospheric and stratospheric ozone profiles.
2. Complete the hardware development of the small CCD spectrometer and the necessary modified algorithm.
3. Obtain the diurnal variation of tropospheric ozone at GSFC and other sites, and relate this variation to the amounts of NO_2 and aerosol.
4. Use the atmospheric data to validate satellite retrievals (AURA/OMI and SBUV-2) of aerosol parameters, tropospheric and stratospheric ozone, and NO_2.
5. Transfer the designs for the Brewer modifications and the CCD spectrometer system of other sites in the US and other locations in the world (e.g., Europe and selected AERONET sites) to form a network of tropospheric ozone measurement sites that are useful for atmospheric analysis and satellite validation.

2.5 IMPACT OF THE PROPOSED WORK

The results from this work will be the first remote sensing passive simultaneous retrieval of the diurnal changes in tropospheric ozone profiles, trace gas amounts, and aerosol properties. The retrievals will provide the first practical technique for hourly tropospheric ozone profile measurements every day at a number of existing Brewer spectrometer sites and several AERONET sites. Deployment of the instrumentation and application of the retrieval technique to the Brewer and small CCD spectrometers will lead to a network of stations suitable for understanding the interaction between diurnally varying tropospheric ozone amounts, aerosols, and trace gases (e.g., NO_2) under a variety of different local conditions. Incorporation of these results into atmospheric chemistry models will place constraints on the dynamics and chemistry rates, especially the tropospheric photolysis rates such as J_{NO2}. The results will also provide much needed validation of the current AURA/OMI and future NPOESS ozone profiling and trace gas measurements.

2.6 REFERENCES

Bass, A.M., and R.J. Paur, The ultraviolet cross-sections of ozone, I, Measurements, in Atmospheric Ozone, in Ozone Symposium (1984: Halkidiki, Greece): Atmospheric Ozone, edited by C.Z.Zeferos, and A.Ghaz, p.606-616, D.Reidel, Hingham, Mass., 1985.

Bates, D.R., Rayleigh Scattering by Air, *Planet. Sp. Sci*., 32, 785-790, 1984.

Brühl, C. and P. J. Crutzen, On the Disproportionate Role of Tropospheric Ozone as a Filter Against Solar UV-B Radiation. *Geophysical Research Letters,* Vol. 16, pp. 703-706, 1989.

Cede, A., and J. Herman, Measurements of O_3, SO_2, NO_2 and HCHO column amounts using a Brewer spectrometer, in Ultraviolet Ground- and Space-based measurements, Models, and Effects V, July 31 to August 1, 2005, San Diego, USA, Proceedings of SPIE Vol. 5886, Pages 7-15, SPIE-The International Society for Optical Engineering, G. Bernhard, J. R. Slusser, J.R. Herman, W. Gao, and G. Bernhard Editors, 2005.

Cede, A., S. Kazadzis, M. Kowalewski, A. Bais, N. Kouremeti, M. Blumthaler, and J. Herman, Correction of direct irradiance measurements of Brewer spectrophotometers due to the effect of internal polarization, Geophys. Res. Lett., 33 (2), L02806, doi: 10.1029/2005GL024860, 2006a.

Cede, A., J. Herman, A. Richter, N. Krotkov, and J. Burrows, Measurements of nitrogen dioxide total column amounts using a Brewer double spectrometer in direct Sun mode, J. Geophys. Res., 111, D05304, doi:10.1029/2005JD006585, 2006b.

Dave , J.V., Meaning of successive iteration of the auxiliary equation of radiative transfer, *Astrophys. J.*,140, 1292-1,303, 1964.

Guo, X., V. Natraj, D. R. Feldman, R. J. D. Spurr, Run-Lie Shia, S. P. Sander, Y.Yung, Retrieval of ozone profile from ground-based measurements with polarization: A synthetic study, in press, JSQRT, 2006.

Kazadzis, S., A. Bais, N. Kouremeti, E. Gerasopoulos, K. Garane, M. Blumthaler, B. Schallhart, and A. Cede, Direct spectral measurements with a Brewer spectroradiometer: Absolute calibration and aerosol optical depth retrieval, *Applied Optics*, 44(9), 1681– 1690, 2005

Kerr, J. B., C. T. McElroy, D. I. Wardle, R. A. Olafson, and W. F. J. Evans, The automated Brewer spectrophotometer, in *Atmospheric Ozone: Proceedings of the Quadrennial Ozone Symposium*, edited by C. S. Zerefos and A. Ghazi, pp. 396–401, Springer, New York, 1985.

Kerr, J.B., I.A. Asbridge, and W.F.J. Evans, Intercomparison of total ozone measured by the Brewer and Dobson spectrophotometers at Toronto, J. Geophys. Res., 93, 11,129-11,140, 1988.

Krotkov,N.A., P. K. Bhartia, J. R. Herman, V. Fioletov, and J. Kerr, Satellite estimation of spectral surface UV irradiance in the presence of tropospheric aerosols 1. Cloud-free case, J. Geophys. Res. 103(D8), 8779-8793, 1998.

Krotkov, N.A., P.K. Bhartia, J.Herman, Jim Slusser, G. Scott, G. Janson, G. Labow, T. Eck, and B. Holben, Aerosol UV absorption experiment (2002 to 2004): 1. UV-MFRSR calibration and intercomparison with CIMEL sunphotometers, Opt. Eng., 44 (4), *Opt. Eng*., *44* (4), 141004, doi:10.1117/1.1886818, 2005a.

Krotkov, N.A., P.K. Bhartia, J.Herman, Jim Slusser, G. Scott, G. Labow, A. Vasilkov, T. Eck, O. Dubovik, and B. Holben, Aerosol UV absorption experiment (2002 04): 2. Absorption optical thickness, refractive index, and single scattering albedo, Opt. Eng., *44(4)*, 041005, doi:10.1117/1.1886819, 2005b.

Krotkov, N., J. Herman, A. Cede, G. Labow (2005), Partitioning between aerosol and NO2 absorption in the UVA, in *Ultraviolet Ground- and Space-based Measurements, Models, and Effects V*, edited by Germar Bernhard, James R. Slusser, Jay R. Herman, Wei Gao, Proceedings of SPIE, 5886, (SPIE , Bellingham, WA, 2005), 588601, 2005c

Liu X., Chance K., Sioris C.E., Newchurch M. J., and Kurosu T.P., Tropospheric ozone profiles from a ground-based ultraviolet spectrometer: a new retrieval method, *Applied Optics*, Vol. 45, No. 10, 2352-2359, 2006.

McPeters R.D., Labow G.J., Logan J.A., Ozone Climatological Profiles for Satellite Retrieval Algorithms, JGR, in press, 2006.

Petropavlovskikh I., P. K. Bhartia, J. DeLuisi, New Umkehr ozone profile retrieval algorithm optimized for climatological studies, Geophys. Res. Lett., 32, L16808, doi:10.1029/2005GL023323, 2005.

Rodgers, Clive, Inverse methods for Atmospheric Sounding: Theory and Practice, World Scientific Publishing Company, 2000.

Tranchant, B. J. S. and A. P. Vincent, Statistical interpolation of ozone measurements from satellite data (TOMS, SBUV and SAGE II) using the kriging method, Ann. Geophysicae 18, 666±678 (2000) Ó EGS ± Springer-Verlag 2000.

3. MANAGEMENT APPROACH

Dr. Jay Herman, PI The PI will have overall responsibility for algorithms, instrument operation, data acquisition, and validation of AURA trace gas (NO_2, SO_2, O_3) amounts, aerosol properties, and UV irradiance and the overall management of the project. This will include the arrangements for remote site campaigns and coordination with other ongoing AURA validation and science team projects. He will make arrangements for getting other sites to install the modifications to their Brewer spectrometers, arrange support for installation and inversion algorithms, and organize joint measuring programs for satellite validation. Dr. Herman will be responsible for archiving all data and data analysis, and making it available to the AURA science team and other interested investigators. He will also write at least one refereed journal publication on the results of the proposed study.

Dr. Alexander Cede CoI Dr. Cede will be responsible for the operation of the Brewer spectrometer, obtaining and archiving its data, continuing the development of the algorithms and error analysis, and arranging for data acquisition such that comparison with AURA data is optimum. Dr. Cede will be responsible for acquiring the trace gas amounts of NO_2, SO_2, and O_3. He will also acquire the CIMEL and MPL data as processed by AERONET and MPLNET, and make sure that the data quality is good. Working with other CoI's, he will combine the Brewer data with the UV-MFRSR data to internally verify the measured aerosol properties and ozone amounts.

Dr. Nickolay Krotkov CoI Dr. Krotkov will be responsible for the operation and acquisition of data from the UV-MFRSR in conjunction with other members of the proposal team. He will work closely with Dr. Cede to combine data from the CIMEL, MPL, UV-MFRSR, and Brewer to produce aerosol properties that are valid for both visible and UV wavelength ranges. He will obtain ozone amounts and UV-irradiances from both the Brewer and UV-MFRSR and will internally verify the data before using it for AURA validation. He will also help develop the theoretical basis for the inversion algorithm used to derive tropospheric and stratospheric ozone profiles from the Brewer spectrometer and small spectrometer data.

Dr. Maria Tzortziou CoI Dr Tzortziou will be responsible for the theoretical and practical development and optimization of the tropospheric O_3 retrieval algorithm. She will be responsible for performing the data inversions to derive simultaneous solutions for hourly values of tropospheric and stratospheric ozone, NO_2, aerosols, and other trace gases from the Brewer and small spectrometers.

Dr. Nader Abuhassan, CoI Dr. Abuhassan will be responsible for completing the development of the small spectrometer hardware and control software so that a complete temperature controlled operating system is available. He will then be responsible for building the 3 final operating versions of the small spectrometer based on the existing prototype. Dr. Abuhassan will also participate in the data analysis of the measured spectra so as to produce tropospheric and stratospheric ozone values and trace gas amounts.

4. FACILITIES AND EQUIPMENT

We currently have a modified double Brewer with 2 years of field use since the modifications, a modified UV-shadowband (UV-MFRSR) with 1 year of operation, a Cimel sunphotometer with several years of operation, and a partly completed prototype of the small spectrometer system with 2 months of operation. We have access to the AERONET instruments and facilities.

All four of the proposed instruments are calibrated and operating at GSFC. The modifications to the Brewer spectrometer are complete and tested. The addition of the 440 nm channel to the UV-MFRSR has been completed, tested, and been in operation for over 1 year.

The facilities include calibration laboratories with large spherical diffuse light sources using NIST FEL lamps, laser calibration facilities (HeNe and dye lasers), and various support equipment for calibration. A small amount of additional laboratory equipment will have to be purchased (~$2000/year) consisting of calibration lamps, small electronics, and small optical components.

We have a 4-KW portable gasoline generator for use at remote sites, if needed, along with portable PC's suitable for data logging.

Computation facilities include 3 Linux high-speed quad-processor data computer/servers with 18 terabytes of data storage, and several high speed Windows PCs.

5. **BUDGET JUSTIFICATION**

Category	**Amount**	**Justification FY2007**
1. Direct Labor Salary Overhead	**$226,653** 161,254 99,399	The labor includes Dr Jay Herman (PI) scientist 25% (salary $xx,864) and 4 Co-I's. Dr. Alexander Cede scientist 25% (salary $xx,550) Dr. Nader Abuhassan scientist engineer 25% (salary $xx,200) Programmer (50%) (salary $xx,500) Dr. Maria Tzortziou scientist 50% (salary $xx,624) Dr. Nickolas Krotkov scientist 25% (salary $xx,516)
2. Other Direct Costs (Total)	**$44600**	
Equipment	$15,600	Spectrometer and accessories $3500 Pointing Mechanism & Controller $3200 Filter Wheel Assembly & Electronics $1200 Optical Assembly $1500 Laboratory Instrument Control Software $800 Spectrometer Base, Mounting Hardware, Misc. $400 Brewer Spectrometer Maintenance $3000 Laboratory Calibration Equipment $2000 The parts listed above are to assemble a complete portable temperature controlled spectrometer system capable of measuring from 280 to 500 nm including UV bandpass filters (280 to 329 nm and 280 to 380 nm) and 3 polarization filters
Travel Domestic Foreign	$21,000 6,000 15,000	Total for meetings and field campaigns. 1 or 2 science meetings plus 1 domestic campaign and 1 foreign campaign
Other Materials Publication	$8,000 3,000 5,000	The materials are miscellaneous laboratory materials and other small items incidental to developing, analyzing, and maintaining instrumentation. Acquisition will be by small purchases as needed. It is assumed that there will be two publications per year in refereed journals.
3. F & A (Total) Mandatory Institutional Costs	**$35,895** 8,125 27,771	Research and Development Multiple Support Directorate Assessment including Branch and Division
4. Other Costs	0	
Subtotal	$341,148	Sum of Bolded amounts.
Cost Sharing	0	
Total	$341,148	Sum of Bolded amounts.

The detailed budget above is for obtaining the radiance data from the Brewer spectrometer and deriving tropospheric ozone variability throughout each day. In addition, the NO2 amounts and aerosol properties will be derived simultaneously. This is the major portion of the proposed effort involving the PI and 3 of the Co-I's. One of the Co-I's will complete the construction and testing of the first of three small spectrometers based on an already developed prototype small spectrometer system. This includes operating the spectrometer to obtain science data for NO2 ozone and aerosols, and comparison with equivalent data obtained from the Brewer spectrometer. The data obtained will also be compared with the suite of instruments operating simultaneously at GSFC and with AURA/OMI satellite data. The small spectrometer will also be deployed on field campaigns along with the Brewer, UV Shadowband, and Cimel sunphotometer to further validate the results. The entire team will participate in this effort. The remaining two small spectrometer systems will be constructed during the 2nd year (FY08) for deployment at AERONET sites other than GSFC. At least 1 paper will be published.

Category	Amount	Justification FY2008
1. Direct Labor Salary Overhead	**$272,819** 168,820 103,999	The labor includes Dr Jay Herman (PI) scientist 25% (salary $xx,864) and 4 Co-I's. Dr. Alexander Cede scientist 25% (salary $xx,550) Dr. Nader Abuhassan scientist engineer 25% (salary $xx,200) Programmer (50%) (salary $xx,500) Dr. Maria Tzortziou scientist 50% (salary $xx,624) Dr. Nickolas Krotkov scientist 25% (salary $xx,516)
2. Other Direct Costs (Total)	**$53,600**	
Equipment	$24,600	Spectrometer and accessories $3500 Pointing Mechanism & Controller $3200 Filter Wheel Assembly & Electronics $1200 Optical Assembly $1500 Spectrometer Base, Mounting Hardware, Misc. $400 2nd spectrometer system as above $9800 Brewer Spectrometer Maintenance $3000 Laboratory Calibration Equipment $2000 The parts listed above are to assemble 2 complete portable temperature controlled spectrometer systems capable of measuring from 280 to 500 nm including UV bandpass filters (280 to 329 nm and 280 to 380 nm) and 3 polarization filters
Travel Domestic Foreign	$21,000 6,000 15,000	Total for meetings and field campaigns. 1 or 2 science meetings plus 1 domestic campaign and 1 foreign campaign
Other Materials Publication	$8,000 3,000 5,000	The materials are miscellaneous laboratory materials and other small items incidental to developing, analyzing, and maintaining instrumentation. Acquisition will be by small purchases as needed. It is assumed that there will be two publications per year in refereed journals.
3. F & A (Total) Mandatory Institutional Costs	**$38,691** 8,856 29,835	 Research and Development Multiple Support Directorate Assessment including Branch and Division
4. Other Costs	0	
Subtotal	$365,110	Sum of Bolded amounts.
Cost Sharing	0	
Total	$365,110	Sum of Bolded amounts.

The next year, FY09 is for continuation of data analysis of field campaigns, intercomparison of data from all spectrometers and supporting instruments (CIMEL sunphotometer and UV shadowband spectroradiometer), and for comparison with various satellite data sets (e.g., TES, AURA/OMI). Full characterization of all instruments will be performed in FY08 and FY09, including radiometric analysis, determination of angular response, and wavelength calibration as part of the maintenance. At least 2 papers will be published.

Category	Amount	Justification FY2009
1. Direct Labor Salary Overhead	**$2285,601** 176,747 108,854	The labor includes Dr Jay Herman (PI) scientist 25% (salary $xx,864) and 4 Co-I's. Dr. Alexander Cede scientist 25% (salary $xx,550) Dr. Nader Abuhassan scientist engineer 25% (salary $xx,200) Programmer (50%) (salary $xx,500) Dr. Maria Tzortziou scientist 50% (salary $xx,624) Dr. Nickolas Krotkov scientist 25% (salary $xx,516)
2. Other Direct Costs (Total)	**$34,000**	
Equipment	$5,000	Brewer Spectrometer Maintenance $3000 Laboratory Calibration Equipment $2000 Part of the Brewer maintenance is for the installation of an improved depolarizer and polarizing filters. A new master curved window holder will be machined, 3-d scanned, and copied at low cost in high-density plastic for use at other sites with a double Brewer.
Travel Domestic Foreign	$21,000 6,000 15,000	Total for meetings and field campaigns. 1 or 2 science meetings plus 1 domestic campaign and 1 foreign campaign
Other Materials Publication	$8,000 3,000 5,000	The materials are miscellaneous laboratory materials and other small items incidental to developing, analyzing, and maintaining instrumentation. Acquisition will be by small purchases as needed. It is assumed that there will be two publications per year in refereed journals.
3. F & A (Total) Mandatory Institutional Costs	**$39,348** 10,426 28,922	 Research and Development Multiple Support Directorate Assessment including Branch and Division
4. Other Costs	0	
Subtotal	$358,950	Sum of Bolded amounts.
Cost Sharing	0	
Total	$358,950	Sum of Bolded amounts.

The final year, FY10, will be spent in field campaigns, data validation exercises, improving the inversion algorithms, improving the calibration, and reprocessing all of the data, if needed. During the FY08 and FY09 we expect to distribute the modifications and new software for the Brewer spectrometers to various interested sites in the US, Europe, Asia, and South America where there are double Brewers. We will also distribute the inversion algorithm. In addition, we will make available the design plans for the small spectrometer built entirely from standard commercially available parts, and will distribute all operating and data inversion software to interested sites to set up worldwide network of observers for tropospheric trace gases and aerosols. During FY10 we will continue to distribute the plans for Brewer modifications, and the small spectrometer as well analyzing data from all of the various sites that have adopted the new instruments and Brewer modifications. At this point there should be a significant small network of observing instruments capable of measuring tropospheric ozone, aerosols, and other trace gases.

Category	Amount	Justification FY2010
1. Direct Labor Salary Overhead	**$299,753** 185,051 114,701	The labor includes Dr Jay Herman (PI) scientist 25% (salary $xx,864) and 4 Co-I’s. Dr. Alexander Cede scientist 25% (salary $xx,550) Dr. Nader Abuhassan scientist engineer 25% (salary $xx,200) Programmer (50%) (salary $xx,500) Dr. Maria Tzortziou scientist 50% (salary $xx,624) Dr. Nickolas Krotkov scientist 25% (salary $xx,516)
2. Other Direct Costs (Total)	**$34,000**	
Equipment	$5,000	Brewer Spectrometer Maintenance $3000 Laboratory Calibration Equipment $2000 Part of the Brewer maintenance is for the installation of an improved depolarizer and polarizing filters. A new master curved window holder will be machined, 3-d scanned, and copied at low cost in high-density plastic for use at other sites with a double Brewer.
Travel Domestic Foreign	$21,000 6,000 15,000	Total for meetings and field campaigns. 1 or 2 science meetings plus 1 domestic campaign and 1 foreign campaign
Other Materials Publication	$8,000 3,000 5,000	The materials are miscellaneous laboratory materials and other small items incidental to developing, analyzing, and maintaining instrumentation. Acquisition will be by small purchases as needed. It is assumed that there will be two publications per year in refereed journals.
3. F & A (Total) Mandatory Institutional Costs	**$38,222** 10,849 30,224	Research and Development Multiple Support Directorate Assessment including Branch and Division
4. Other Costs	0	
Subtotal	$374,826	Sum of Bolded amounts.
Cost Sharing	0	
Total	$374,826	Sum of Bolded amounts.

4-year total	$1,440,035

6. BIOGRAPHICAL SKETCHES

Dr Jay R. Herman PI (NASA/GSFC)

RESEARCH AREA EXPERIENCE:	Ion chemistry, earth ionosphere, planetary ionospheres, radio wave propagation in plasmas, stratospheric chemistry and modeling, radiative transfer, atmospheric spectroscopy, uv solar flux measurements, ozone inversion algorithms, and long-term ozone trend analysis, volcanic aerosols, tropospheric trace gas detection, physical oceanography.
PRESENT POSITION	Principal Investigator Proposed JANUS Mission Project
	Project Scientist DSCOVR Mission
	Principal Investigator UV and aerosol from satellite data
	Principal Investigator Ground-based Measurements Project for UV, Aerosols, and Trace Gases
	Principal Investigator L-2 SVIP Interferometer/Spectrometer
	Principal Investigator Ocean Radiation
	Atmospheric Chemistry and Dynamics Branch, NASA/Goddard Space Flight Center, Code 613.3 Greenbelt, MD 20771 USA
EDUCATION:	1959 - B.S. - Physics, with minor in mathematics, (obtained with high honor) Clarkson College, Potsdam, New York
	1963 - M.S. - Physics, Penn. State Univ., State College, PA
	1965 - Ph.D. - Physics, Penn. State Univ., State College, PA
PREVIOUS POSITIONS:	Principal Investigator for FM-5 TOMS Project
	Principal Investigator for TOMS/Meteor Project
	Principal Investigator Atmos. Chem. Model
	1960 - 1961 Solid State Devices Engineer, I.B.M., Poughkeepsie, New York
	1965 - 1967 National Academy of Sciences Research Associate
	1967 - 1970 NASA/GSFC, Ionospheric Physics
	1970 - 1975 NASA/GSFC, Planetary Atmospheres, Radiative Transfer
	1976 - 1986 NASA/GSFC, Principal Investigator, Stratospheric photochemical modeling and physics.
	Solar UV Data Analysis and Solar Spectroscopy
	1986 - 1990 NASA/GSFC TOMS/SBUV Ozone Data Analysis and TOMS Recalibration
	1991 - TOMS Lead Scientist for Data Acquisition and Analysis.

Recent Refereed Publications (2003 –2006)

1. Arola, A.; Kaurola, J.; Koskinen, L.; Tanskanen, A.; Tikkanen, T.; Taalas, P.; Herman, J. R.; Krotkov, N.; Fioletov, V., A new approach to estimating the albedo for snow-covered surfaces in the satellite UV method, JGR., Vol. 108, No. D17, 4531, 10.1029/2003JD003492, 2003.
2. Hsu, N.C., J.R. Herman, Si-Chee Tsay, Radiative impacts from biomass burning in the presence of clouds during boreal spring in southeast Asia, Geophys. Res. Lett. VOL. 30, NO. 5, 1224, doi:10.1029/2002GL016485, 2003.
3. Hsu, N. Christina, Si-Chee Tsay, Michael D. King, Jay R. Herman, and Brent N. Holben, Aerosol Retrievals Over Bright-Reflecting Source Regions, accepted, *IEEE Trans. Geosci. Remote Sens, 42, 557-560, 2004.*
4. Cede, A., E. Luccini, R.D. Piacentini, L. Nuñez, M. Blumthaler, and J. Herman, TOMS-derived erythemal irradiance versus measurements at the stations of the Argentine UV Monitoring Network, J. Geophys. Res., 109 (D8), D08109, 10.1029/2004JD004519, 2004
5. Fioletov, V.E., M. G. Kimlin, N. Krotkov, L. J. B. McArthur1, J. B. Kerr, D. I. Wardle, J.R. Herman, R. Meltzer, T. W. Mathews1 and J. Kaurola , UV index climatology over North America from ground-based and satellite estimates, *J. Geophys. Res.*, 109, D22308, doi:10.1029/2004JD004820, 2004.
6. Krotkov, P.K. Bhartia and J.R.Herman, Jim Slusser, Gwen Scott, G. Labow T. F. Eck,and B. N. Holben, UV aerosol absorption experiment (2002-04): 1. UV-MFRSR calibration and performance at GSFC, Optical Engineering 44(4), 041004, 2005.
7. Krotkov, P.K. Bhartia and J.R.Herman, Jim Slusser, Gwen, Scott, G. Labow T. F. Eck,and B. N. Holben, Aerosol UV absorption experiment (2002-04): 2. Absorption optical thickness and single scattering albedo, Opt. Eng., 44, 4, 041005, 2005
8. Vasilkov, A.P., J.R. Herman, Z. Ahmad, M. Kahru, and G. Mitchell, Assessment of the ultraviolet radiation field in ocean waters from space-based measurements and full radiative transfer calculations, Opt. Eng. 44, 2863-2869, 2005.
9. Ahmad, Z. J.R. Herman, A. Vasilkov, N. Krotkov, M. Tzortziou, G. Mitchell, M. Kahru, Seasonal climatology of UV irradiances in the ocean, submitted, Applied Optics, 2004.
10. Meloni, D., A. di Sarra, J. R. Herman, F. Monteleone, and S. Piacentino, Comparison of ground-based and TOMS erythemal UV doses at the island of Lampedusa in the period 1998-2003: the role of tropospheric aerosols, J. Geophys. Res., 110, D01202, doi:10.1029/2004JD005283, 2005.
11. Tzortziou, Maria, Jay R. Herman, Ajit Subramaniam, Patrick J. Neale, Charles L Gallegos and Lawrence W. Jr Harding, Optical properties and radiation in the Chesapeake Bay estuarine waters: An in-water optical closure experiment, submitted to J. Geophys. Res., 2005.
12. Patra, P.K., S. K. Behera, J. R. Herman, S. Maksyutov, H. Akimoto, T. Yamagata, The Indian summer monsoon rainfall: interplay of coupled dynamics, radiation and cloud microphysics, Atmos. Chem. Phys. Discuss, 5, 2879-2895, 2005.
13. Fromm, Michael, R. Bevilacqua, R. Sevranckx, J. Rosen, J.P. Thayer, J. Herman, and D. larko, Pryo-cumulonimbus, injection of smoke to the stratosphere: Observations and impact of a super blowup in northwestern Canada on 3-4 August 1998, J. Geophys. Res., 110, D08205, doi:101029/2004JD005350, 2005.
14. Arola, Antti, Stelios Kazadzis, Nickolay Krotkov, Alkis Bais, Julian Grobner, and Jay R. Herman, Assessment of TOMS UV bias due to absorbing aerosols, J. Geophys. Res., VOL. 110, D23211, doi:10.1029/2005JD005913, 2005.
15. Tanskanen, A., N. Krotkov, J.R. Herman, and P.K. Bhartia, “A. Arola, Surface UV Irradiance from OMI, IEEE, TGRS AURA,” special issue, 44, 1267-1271, 2005.
16. Cede, Alexander, M. Kowalewski, Stelios Kazadzis, Alkis Bais, Natalia Kouremeti, Mario Blumthaler, and Jay Herman, Solar zenith angle effect for direct-sun measurements of Brewer spectrophotometers due to polarization, Geophysical Research Letters, Vol. 33, L02806, doi:10.1029/2005GL024860, 2006.
17. Cede, Alexander, Jay Herman, Andreas Richter, Nickolay Krotkov and John Burrows, Measurements of Nitrogen Dioxide Total Column Amounts at Goddard Space Flight Center Using a Brewer Spectrometer in Direct Sun Mode, accepted, Journal Of Geophysical Research, Vol. 111, D05304, doi:10.1029/2005JD006585, 2006.
18. Antón, M., V.E. Cachorro, J.M. Vilaplana, N.A. Krotkov, A. Serrano, C. Toledano, B. de la Morena, J.R. Herman, Toms Retrievals Of Erythemal-Cie Uv Irradiance And Daily Cie Doses Compared With Brewer Ground-Based Measurements At El Arenosillo (Spain)' submitted JGR as Manuscript # 2006JD007254, 2006.

Dr. Maria Tzortziou, CoI

RESEARCH AREA EXPERIENCE:	Radiative transfer in ocean and atmosphere; Bio-optics of coastal waters; UV, Aerosols, Ozone remote sensing; Remote sensing of Case 2 waters
PRESENT POSITION	Research Associate - Earth Science System Interdisciplinary Center, University of Maryland at College Park
EDUCATION:	1997 B.S. Physics (with high honor), Aristotle University, Greece 1999 M.Sc. Environmental Physics (with high honor), Aristotle University, Greece 2001 M.Sc. Meteorology, University of Maryland College Park (UMCP) 2004 Ph.D. Ocean and Atmospheric Sciences, UMCP
PREVIOUS POSITIONS:	2004-2005 Post-doctoral Fellow - Smithsonian Institution, Smithsonian Environmental Research Center (SERC), MD 1999-2004 Graduate Research Assistant - University of Maryland, UMCP 2001-2003 Pre-doctoral Fellow - Smithsonian Institution, SERC 1998 Visiting Scientist - NASA, Goddard Space Flight Center 1997-1999 Graduate Research Assistant - Aristotle University, Greece, Dept of Physics, Laboratory of Atmospheric Physics. 1996-1997 Research assistant - Aristotle University of Thessaloniki, Dept of Physics, Laboratory of Atmospheric Physics.
RECENT PUBLICATIONS	Tzortziou M., J. Herman, C. Gallegos, P.Neale, A. Subramaniam, L. Harding, and Z. Ahmad, “Bio-Optics of the Chesapeake Bay from Measurements and Radiative Transfer Closure”, Estuarine Coastal and Shelf Science, 68,348-362, 2006. Zerefos C, Syrakov D, Ganev K, Vasaras A, Kourtidis K, Tzortziou M, Prodanova M, Dimitrova R, Georgieva E, Yordanov D, and Miloshev N, “Study of the pollution exchange between Bulgaria and northern Greece”, International Journal of Environment and pollution, 22 (1-2): 163-185 2004 Formenti P, O.Boucher, T.Reiner, D. Sprung, M. Andreae, M. Wendisch, H. Wex, D. Kindred, M.Tzortziou, A. Vasaras, and C. Zerefos “The STAAARTE-MED 1998 airborne measurements over the Aegean Sea:II. Aerosol scattering and absorption, and radiative calculations”, JGR, Vol 107, No D21, 2002 Formenti, P., T. Reiner, D. Sprung, M. O. Andreae, M. Wendisch, H. Wex, D. Kindred, K. Dewey, J. Kent, M. Tzortziou, A. Vasaras, and C. Zerefos, “The STAAARTE-MED 1998 summer airborne measurements over the Aegean Sea: I. Aerosol particles and trace gases”, JGR, Vol 107, No D21, 2002 Zerefos C., D. Balis, M. Tzortziou, A. Bais, K. Tourpali C. Meleti, G. Bernhard and J. Herman, "A note on the interannual variations of UV-B erythemal doses and solar irradiance from ground-based and satellite observations", Annales Geophysicae 19: 115-120, 2001 Zerefos C., K. Ganev, K. Kourtidis, M. Tzortziou, A. Vasaras, E. Syrakov, “On the origin of SO_2 above Northern Greece”, GRL, Vol. 27, 3, 365-368, 2000 Ahmad Z., Herman J.R.,Vasilkov A., Tzortziou M.,Mitchell G., Kahru M., “Seasonal variation of UV radiation in the ocean under clear and cloudy conditions”, Proc. SPIE Vol. 5156, p. 63-73, UV Ground- and Space-based Measurements, Models, and Effects III; Slusser, Herman & Gao; Eds., 2003.

Dr. Nader Abuhassan, CoI

RESEARCH AREA EXPERIENCE:	Over 16 years of experience in Industry, National and International Research Centers. Actively participated in the design, development and scientific validation of several instruments and radiation sensors for remote sensing of greenhouse gases and monitoring of atmosphere optical properties.
PRESENT POSITION	Sr. Scientist/Engineer at Science Systems & Applications Inc.
EDUCATION:	1991-1995Ph.D. Development of a Portable Multi-spectral Infrared Radiometer, first applications. Department of Physics at the University Pierre and Marie Curie, Paris 6, France (Financial support for the project was provided by the French Space Agency 93/CNES/373 and Cimel Electronique). 1990-1991 DESS Geophysics, (Post Graduate), University Pierre and Marie Curie, Paris6, France. 1986-1987 French language Certification, University of Paris 5 (La Sorbonne), France.Diploma of Electronic Engineering, Damascus University, Faculty of Electrical Engineering, Syria, 1979-1983.
PREVIOUS POSITIONS:	2000- present SSAI Sr. staff Scientist/Engineer supporting the Atmospheric Chemistry &Dynamics branch at NASA/GSFC. 1997-2000 SSAI Sr. staff Scientist/Engineer - Sensor Systems supporting the Aeronet Network. at NASA/GSFC. 2000 Ciena Corporation Sr. Engineer -10GHZ Transceiver. 1991-1997 Cimel Electronique R&D Engineer Paris, France 1988-1990 CNRS visiting Scientist /Engineer at the French National Research Center (CNRS\CRG).
RECENT PUBLICATIONS	“Solar Viewing Interferometer Prototype”,Richard G. Lyon, Jay R. Herman,Nader Abuhassan, Cathy T. Marx, Semion Kizhner, Julie Crooke, RonaldToland, Albert Mariano, Cheryl Salerno, Gary Brown, Tony Cazeau, SPIEAstronomical Telescopes and Instrumentation, June 21-25, 2004, Glasgow Scotland. ·Analysis of the performance characteristics of the five-channel Microtops II sun photometer formeasuring Aerosol Optical Thickness and Precipitable Water Vapor.Charles Ichoku , Robert Levy , Yoram J. Kaufman , Lorraine A.Remer , Rong-Rong Li ,Vanderlei J. Martins , Brent N. Holben , NaderAbuhassan, Ilya Slutsker, Thomas F. Eck ,Christophe Pietras , IGR.2001. ·Aerosol optical properties climatology at selected globally distributed sites fromAERONET Holben, B.N., O.Dubovik, A.Smirnov, T.F.Eck, N.Abuhassan,I.Slutsker,W.Newcomb, D.Tanre, Y.Kaufman, N.T.O'Neill, M.King and T.Nakajima, The CCSR COE Symposium/3rd Aerosol-Cloud Remote SensingWorkshop, Kyoto, Japan, December 1-3, 1999. Mineral dust optical properties on the AERONET (Aerosol Robotic Network)sites Smirnov, A., B.N.Holben, O.Dubovik, T.F.Eck, I.Slutsker, andN.Abuhassan,,IGARSS99, Hamburg, Germany, June 26-July 3, 1999.

Dr. Nickolay Krotkov, CoI

RESEARCH AREA EXPERIENCE:

Geophysics, Atmospheric and Oceanic optics; Theory and numerical methods in Radiative transfer; Ultraviolet and visible passive remote sensing of the Earth (atmosphere, oceans, and volcanic plumes monitoring). Satellite and ground based passive spectral data analysis and inversions (aerosols and minor gases). Theoretical work experience includes radiative transfer modeling of the polarization effects of the scattered solar radiation in the atmosphere-ocean system, as applied to passive spectral and polarization remote sensing of the atmospheric gases, aerosols and natural waters. Research on the retrieval of the aerosol absorption properties in UV using a combination of ground based passive radiometers and spectrometers.

PRESENT POSITION

2000- Senior Research Scientist, Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County

EDUCATION:

1983 B.S. Physics, Moscow Institute of Physics and Technology (MIPT)
1985 M.S. Remote Sensing, MIPT
1990 Ph.D. Oceanography, P.P.Shirshov Institute of Oceanology, Russian Academy of Sciences

PREVIOUS POSITIONS:

1996-2000 Principal Scientist, Raytheon ITSS Co
1994-1996 Research Associate, UMD College Park
1993-1994 Reaserch Associate, Universities Space Research Association, NASA/GSFC
1990-1992 Research Associate, Central Aerological Observatory, Dolgoprudny, Russia
1986-1990 Graduate Research Assistant, Graduate student, Moscow Institute of Physics and Technology, Dolprudny, Russia

RECENT PUBLICATIONS

Krotkov, N, A. , S. A. Carn, A.J. Krueger, P.K. Bhartia, K. Yang, Band residual difference algorithm for retrieval of SO2 from the AURA Ozone Monitoring Instrument (OMI), *IEEE Transactions on Geoscience and Remote Sensing, AURA special issue*, 44(5), 1259-1266, doi:10.1109/TGRS.2005.861932, 2006

Tanskanen, A., N. Krotkov, J.R. Herman, P.K. Bhartia, A. Arola, Surface UV Irradiance from OMI, *IEEE Transactions on Geoscience and Remote Sensing, AURA special issue*, 44(5), 1267-1271, doi:10.1109/TGRS.2005.861932, 2006.

Krotkov, N.A., P.K. Bhartia, J.Herman, J. Slusser, G. Scott, G. Janson, G. Labow, T. Eck, and B. Holben, Aerosol UV absorption closure experiment (2002 –04): 1. UV-MFRSR calibration and performance at GSFC, Opt. Eng., 44,4, 2005

Krotkov, N.A., P.K. Bhartia, J.Herman, J. Slusser, G. Scott, G. Labow, A. Vasilkov, T. Eck, O. Dubovik, and B. Holben, Aerosol UV absorption closure experiment (2002 –04): 2. Absorption optical thickness and single scattering albedo, Opt. Eng.,44(4), 2005.

Dr. Alexander Cede, CoI

RESEARCH AREA EXPERIENCE:

Calibration of (spectro) radiometers, Radiative transfer, UV irradiance at the Earth’s surface, Aerosols, Cloud studies, Atmospheric spectroscopy

PRESENT POSITION

Scientist at Science Systems & Applications Inc., since 2002 and now at University of Maryland ESSIC

EDUCATION:

1996 M.S. Physics, University of Innsbruck, Austria
2001 Ph.D. Physics, University of Innsbruck, Austria

PREVIOUS POSITIONS:

1994-1996 Laboratory Assistant at Institute of Medical Physics, University of Innsbruck, Austria
1997-1999 Scholarship of the “Skin Cancer Foundation” of Argentina
2000 Scientist at “Mag. Ing. Schreder – Calibrations, Measurements, Softwaresolutions”
2001-2002 Scientist Institute of Medical Physics, University of Innsbruck, Austria

RECENT PUBLICATIONS

Cede, A., and J. Herman, Measurements of O3, SO2, NO2 and HCHO column amounts using a Brewer spectrometer, in Ultraviolet Ground- and Space-based measurements, Models, and Effects V, July 31 to August 1, 2005, San Diego, USA, Proceedings of SPIE Vol. 5886, Pages 7-15, SPIE-The International Society for Optical Engineering, G. Bernhard, J. R. Slusser, J.R. Herman, W. Gao, and G. Bernhard Editors, 2005.

Cede, A., S. Kazadzis, M. Kowalewski, A. Bais, N. Kouremeti, M. Blumthaler, and J. Herman, Correction of direct irradiance measurements of Brewer spectrophotometers due to the effect of internal polarization, Geophys. Res. Lett., 33 (2), L02806, doi: 10.1029/2005GL024860, 2006a.

Cede, A., J. Herman, A. Richter, N. Krotkov, and J. Burrows, Measurements of nitrogen dioxide total column amounts using a Brewer double spectrometer in direct Sun mode, J. Geophys. Res., 111, D05304, doi:10.1029/2005JD006585, 2006b.

Cede, A., B. Bojkov, J. Herman, M. Wenig, E. Bucsela, E. Celarier, and J. Gleason, Validation of OMI Vertical Column NO2 with Brewer Direct Sun Measurements, in preparation, 2006c.

Cede, A., E. Luccini, R.D. Piacentini, L. Nuñez, M. Blumthaler, and J. Herman, TOMS-derived erythemal irradiance versus measurements at the stations of the Argentine UV Monitoring Network, J. Geophys. Res., 109 (D8), D08109, 10.1029/2004JD004519, 2004.

Cede, A., G. Labow, M. Kowalewski, N. Krotkov and O. Dubovik, Deriving aerosol parameters from absolute UV sky radiance measurements using a Brewer double spectrometer, in Ultraviolet Ground- and Space-based measurements, Models, and Effects III, 4-6 August 2003, San Diego, USA, Proceedings of SPIE Vol. 5156, Pages 323-329, SPIE-The International Society for Optical Engineering, J. R. Slusser, J.R. Herman, and W. Gao Editors, 2003.

7. CURRENT AND PENDING SUPPORT				
OTHER SUPPORT	Source of Support	Award Amount and Period of Performance	Person-Months and Level of Effort (PM/Year)	Project Title and Short Abstract (50 words or less)
Dr. Herman PI				
PI **Year 2 of 3**	NNH04Z YS004N	$1070K FY2005 to FY2007	3 PM/Year	**OMI Validation and Analysis of NO_2, HCHO, and SO_2**
PI **Pending**	NNH04Z YS004N	$706K FY2006 to FY2008	3 PM/Year	**Ocean Atmospheric Correction 340 – 440 nm**
Dr. Krotkov Co-I				
Co-I **Year 2 of 3**	NNH04Z YS004N	$1070K FY2005 to FY2007	3 PM/Year	**OMI Validation and Analysis of NO_2, HCHO, and SO_2**
PI	NNH05Z DA001N -AC	$801784 FY2006 to FY2008	6 PM/Year	**Mapping SO2 emissions with Aura/OMI**
Dr. Cede Co-I				
Co-I **Year 2 of 3**	NNH04Z YS004N	$1070K FY2005 to FY2007	6 PM/Year	**OMI Validation and Analysis of NO_2, HCHO, and SO_2**
Dr. Tzortziou Co-I				
Co-I **Pending**	NNH04Z YS004N	$706K FY2006 to FY2008	6 PM/Year	**Ocean Atmospheric Correction 340 – 440 nm**
Dr. Abuhassan Co-I				
	N/A			
Pending = Proposal Awarded, but not yet funded				