Improving an Automated Aerosol Optical Depth Algorithm

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ABSTRACT

Over the past decade, a network of Multifilter Rotating Shadowband Radiometers (MFRSRs) has been monitoring aerosol properties across the nation. Data collected by the MFRSRs could improve climate models, characterize weather events, and correct and validate satellite signals. Before this can happen, the raw data must be processed into useful information, call the aerosol optical depth (AOD). An innovative automated method of computing aerosol optical depth was developed and explained in Augustine and Medina (2003). This method has been further refined in order to increase the accuracy and volume of information retrieved from MFRSR readings. The algorithm was expanded to include five more channels of the MFRSR, from just the previous 500 nm channel. More additions to AOD algorithm include accounting for the variability in the ozone and its affect on AOD and removing data contaminated by clouds. The calibration method was improved, which in turn, improved the error estimation. These changes resulted in superior discrimination of aerosol signals from ozone absorption, molecular scattering, and cloud contamination. These modifications improved the automatic data processing procedures, which result in more accurate and faster AOD data than by the previous hand calculation. The final product is the new aerosol optical depth data. It may be useful in satellite calibration and validation, climate modeling, and climatologic studies.

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Over the past four years, John Augustine, a meteorologist at the National Oceanic and Atmospheric Administration (NOAA) Air Resource Laboratory (ARL), and I have developed a process to calculate Aerosol Optical Depth (AOD) using remote sensing. The goal of calculating AOD is to improve climate models to correct satellite signals, and to validate the accuracy of satellite readings. This AOD calculation process uses data from Multi-Filter Rotating Shadow-band Radiometers (MFRSR) (Harrison et al. 1994) that are deployed in the SURFRAD (Surface Radiation) network (Augustine et al. 2000) to calculate the amount of aerosols. The SURFRAD network monitors the solar radiation budget continuously and provides real time data. SURFRAD consists of seven sights across the continental United States.

Aerosol optical depth is a measure of the total amount of aerosol in a column of the atmosphere. Time series of AOD may be used to detect changes in the total amount of aerosol over a long period of time. Modern robotic spectral solar instruments such as the MFRSRs provide all the raw data necessary to compute AOD as well as the total ozone and water vapor present.

The MFRSRs usually operate in their unattended mode. Thus, their raw data sets sample a wide range of atmospheric conditions, most of which are undesirable for aerosol optical depth analysis. In order to calibrate the MFRSR or to compute AOD, an unobstructed view of the sun is required. Screening MFRSR data for clear sky period was accomplished by applying the clear sky identification algorithm of Long and Ackerman

(2000). The screening process we developed involves the calibration of the MFRSR's six spectral channels over long periods of time, by applying Beer's Law of attenuation through the atmosphere. This process applies a linear fit to the MFRSR data —otherwise known as a calibration Langly plot— which is used to get a calibration value. The calibration values and measurements are then used to compute the AOD for the six channels of the MFRSR. The six channels range in wavelength from about 416 to 936 nm — from the size of molecules to dust partials. Our original automated calibration process, which is for the 500 nm channel only, is summarized in Augustine et al. (2003) and Augustine and Medina (2003). I am proposing to further expand on our calibration process.

In this study, I will be adding absorption and scattering algorithms for the other five MFRSR channels to provide more accurate data sets. I will also incorporate a cloud screening algorithm for the AOD calculations to eliminate any cloud contamination present in the collected data. These additions and improvements will lend to complete automation of ARL's AOD algorithm and accomplish the goals of calculating AOD: to improve climate models, to correct satellite signals, and to validate the accuracy of satellite readings.

METHODS

The first step in the process of expanding ARL's AOD algorithm was to review the existing FORTRAN code, which consists of a calibration program, an AOD calculation program, and a plotting program. This process was accomplished by printing out the syntax for all three programs required by the algorithm. Each program was then examined thoroughly, to regain an understanding of the program's dynamics.

Calibration History

Upon completion of reviewing the code, a calibration history of a test site was constructed. In accordance with past studies, the Table Mountain Test facility was chosen, to create a redundancy and to have a point of reference. The calibration history was completed by researching what instruments were placed at the site and the times they were monitoring. Using this historical information and a linear interpolation program that was written in 2003, we created calibration and error equations. The linear interpolation program performs a linear regression on two-month averages of MFRSR readings and then with time as the independent variable. This produced time-dependent equations in which a fairly accurate calibration value and error value could be computed for any time period of interest. This linear regression technique was completed for both Table Mountain site MFRSR instruments. Next, the slope and intercepts for both the calibration and error equations were entered into a history file. Coding to read and apply all the new information was then added to all three programs associated with the AOD algorithm.

Ozone Absorption

Several other changes needed made to the code to improve the quality of AOD data. A more accurate way of accounting for ozone absorption was also implemented by creating a PERL script. The PERL script acquires the data necessary from Goddard Space Flight Center's website for the specified MFRSR site and time. The data gathered by the PERL script is written to a file, which in turn is run through the ozone equation (Eq.1) in the AOD calculating program. The result is the scattering due to ozone.

$$\tau_{ozone} = ozone\_coeff.\{\frac{total\_ozone(in\,Dobson\,units)}{1000}\} \qquad \text{(Eq. 1)}$$

Molecular Scattering

The next modification was to insert the molecular scattering equation (Eq. 2) into the AOD calculating program in order to compute the correct optical depth value for a given wavelength. By adding the ozone equations and the molecular scattering equation into the AOD calculating program, the AOD algorithm should have become compatible with the MFRSR data.

$$molecular\_scattering = (0.0088)\times\left\{\frac{\lambda}{1000}\right\}^{\left[-4.15+\left(0.2\times\frac{\lambda}{1000}\right)\right]} \qquad \text{(Eq. 2)}$$

$$\lambda = wave\,length\,(in\,nm)$$

Once all the improvements were completed and implemented into the algorithm, an error was discovered in the AOD calculating code. The AOD calculating code was not reading in all the data for every channel. Only the 500 nm wavelength data was being used in the calculations. After correcting this problem, the program was checked for any more oversights. The AOD algorithm was then truly compatible with all the data provided by the MFRSR.

Cloud Screening

The last major step in the development of the AOD algorithm was to add a cloud screening program which would remove cloud contamination from the output files. This required a consultation with an expert in the field of aerosols. Dr. Joe Michalsky, who is the chief of the ARL division in Boulder and helped develop the MFRSR instrument, was asked for a method of removing cloud contamination.

Dr. Michalsky provided an in-depth method of removing cloud contamination by testing the stability of the atmosphere. This was written in the "R" programming language, so it is called the R program. The first step in this process was to eliminate all the aerosol calculations that were obviously caused by clouds. This was accomplished by removing any AOD reading that was over 2. This was the first and largest screening of the new process. The new data was then written into a new input file, which we will refer to as File 1 (J.J. Michalsky, personal communication, July 16, 2004).

The R program cycles File 1 through a series of screening methods to check for stability in the atmosphere. The first of these takes a sequence of 20 points and compute the absolute difference between two consecutive points. It then builds a matrix with this information. The largest deviation in the matrix is then compared to a test deviation of 0.05. If largest deviation is greater than 0.05, then the matrix is cleared. The process is then repeated excluding the first point and continues on to the next sequential 20 points in the file. By iterating this process through until the end of the file, all the passing data is rewritten into another new input file (File 2). File 1 is no longer used. Before going onto the next screening method, the duplicate data in File 2 is removed (J.J. Michalsky, personal communication, July 16, 2004).

The last screening method implements a Lowess fit. This screening method uses a similar process of moving through the data as mentioned above. By applying a Lowess fit to the data, the maximum difference of the Lowess fit is found for every iteration. Meanwhile, a new test deviation is calculated from the original points. The new test deviation is then compared to the maximum difference of the Lowess fit multiplied 0.05. If the new test deviation is less than the Lowess fit multiplied by 0.05, the resultant data is from a stable atmosphere. This is written into another new input file (File 3) and represents all of the times that the data had no cloud contamination. By matching the times from File 3 with the results of the original AOD output file, only the data with no cloud contamination is noted. With the noted data from the AOD output file, results can be plotted using the AOD plot program (J.J. Michalsky, personal communication, July 16, 2004).

Throughout this entire progression, AODs may be found for as often as every two minutes. Amazingly, they are now free from ozone absorption, molecular scattering and cloud contamination. The next step is to validate the AOD's accuracy.

RESULTS AND DISCUSSION

Validation

The progression of removing interference from ozone absorption, molecular scattering, and cloud contamination in calculating AODs must be justified. After the inclusion of the other four wavelengths to the original AOD algorithm, the following plots were recorded for each wavelength. (Figures 1-5).

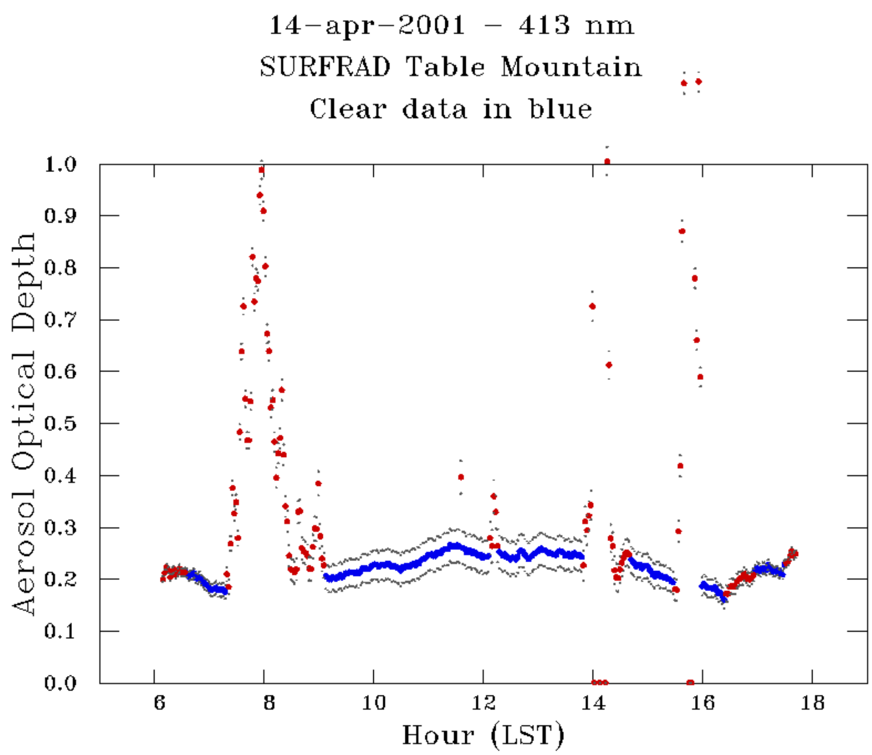

Figure 1: The 413 nm channel visual AOD output of the MFRSR on April 14, 2001

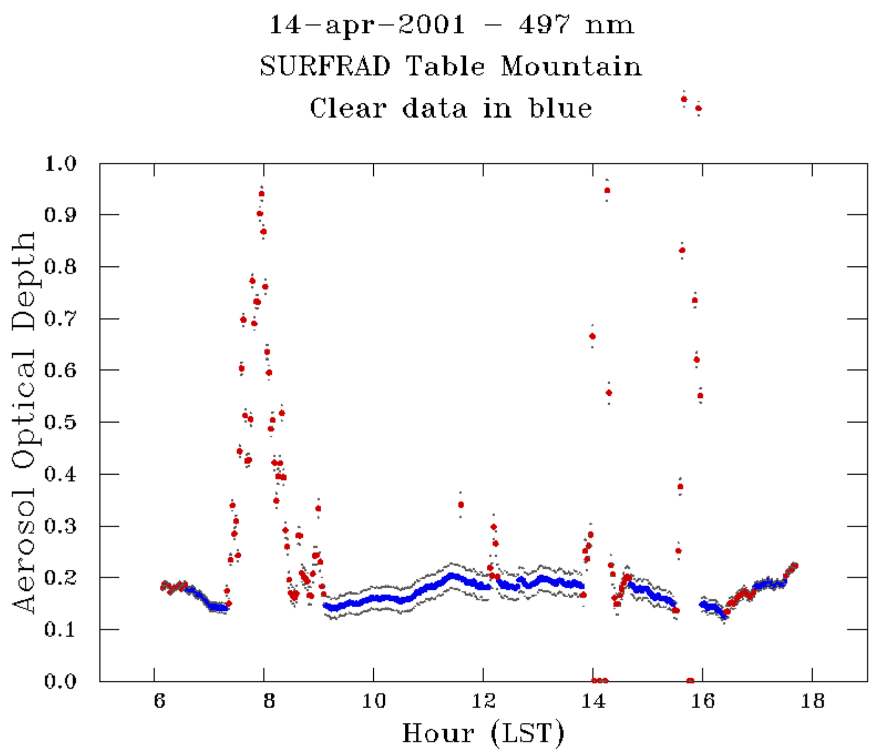

Figure 2: The 497 nm channel visual AOD output of the MFRSR on April 14, 2001

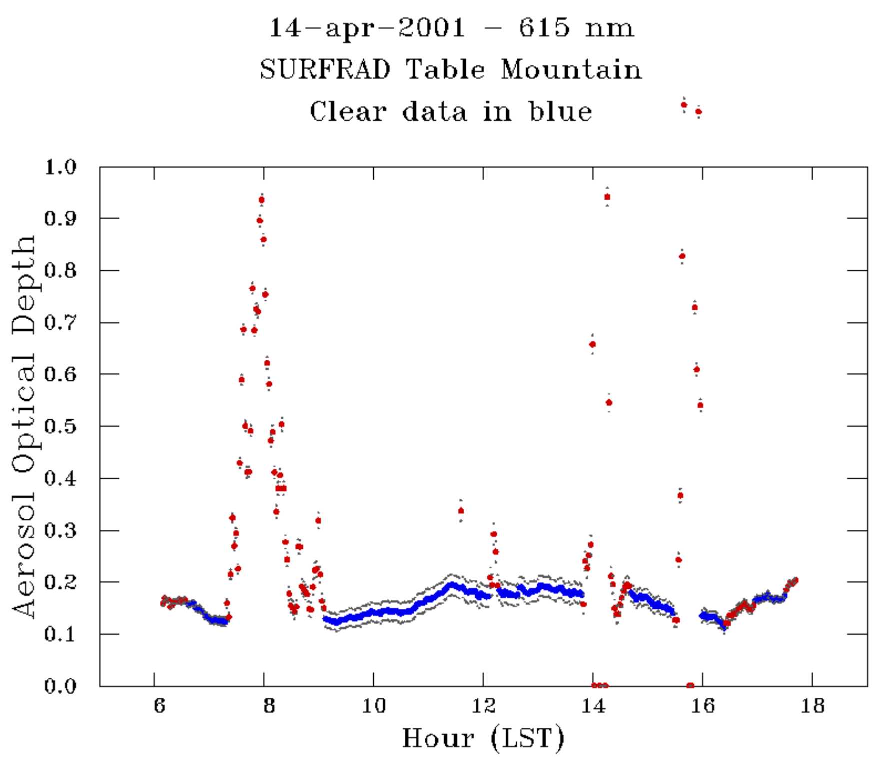

Figure 3: The 615 nm channel visual AOD output of the MFRSR on April 14, 2001

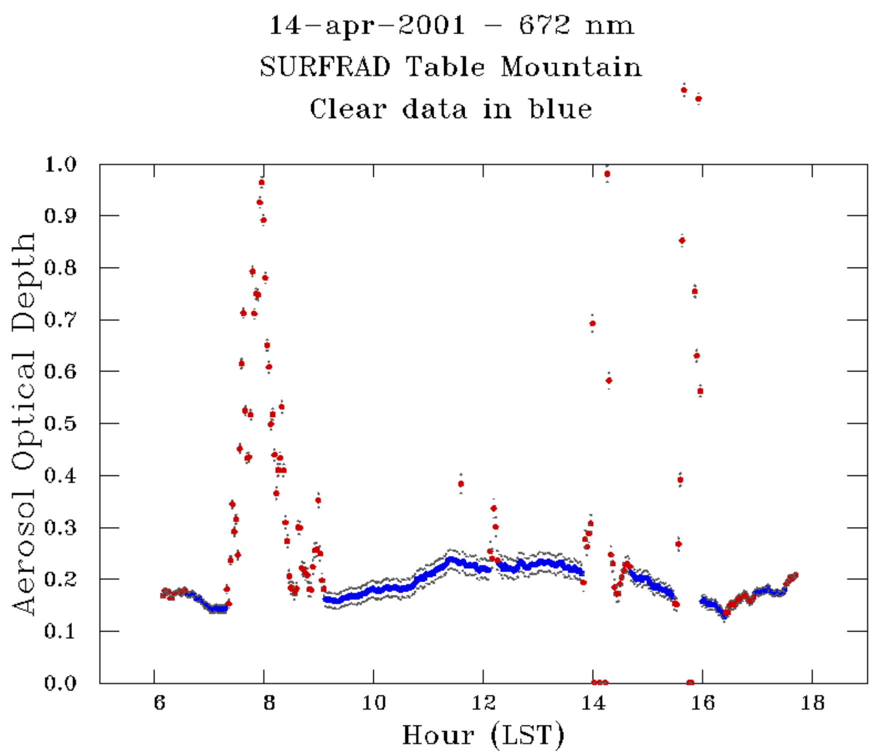

Figure 4: The 672 nm channel visual AOD output of the MFRSR on April 14, 2001

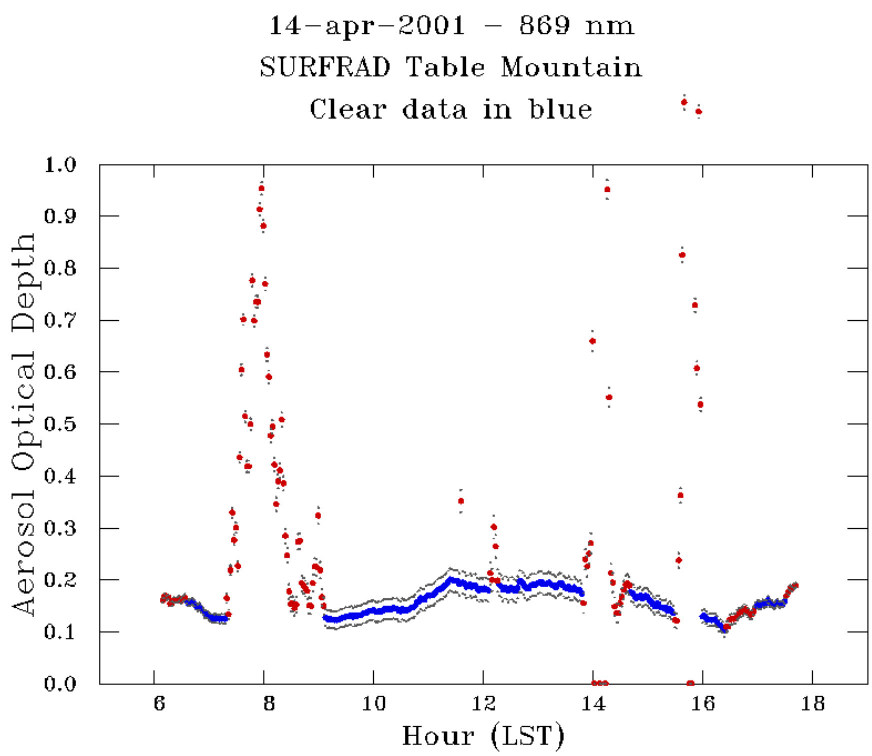

Figure 5: The 869 nm channel visual AOD output of the MFRSR on April 14, 2001

Figures 1 though 5 illustrate final AOD values, with blue showing dots representing cloud free data and red dots representing cloud contaminated data. The blue data was generated by the final AOD algorithm, which removed unnecessary data due to ozone absorption, molecular scattering, and cloud contamination represented.

April 13th and 17th, 2001 were days of noticeably high atmospheric aerosols. The Climate Monitoring & Diagnostics Laboratory (CMDL) data was gathered at the David Skaggs Research facility located approximately 20 miles south of the Table Mountain SURFRAD site. These days were used to evaluate the accuracy of the new additions to the AOD algorithm. The April 2001 plots are shown in Figures 6 and 7. The resultant data from the final AOD algorithm for the same wavelength and time are shown in Figures 8 and 9. The comparison shows that our algorithm is quite accurate and effectively notes cloud contaminated data.

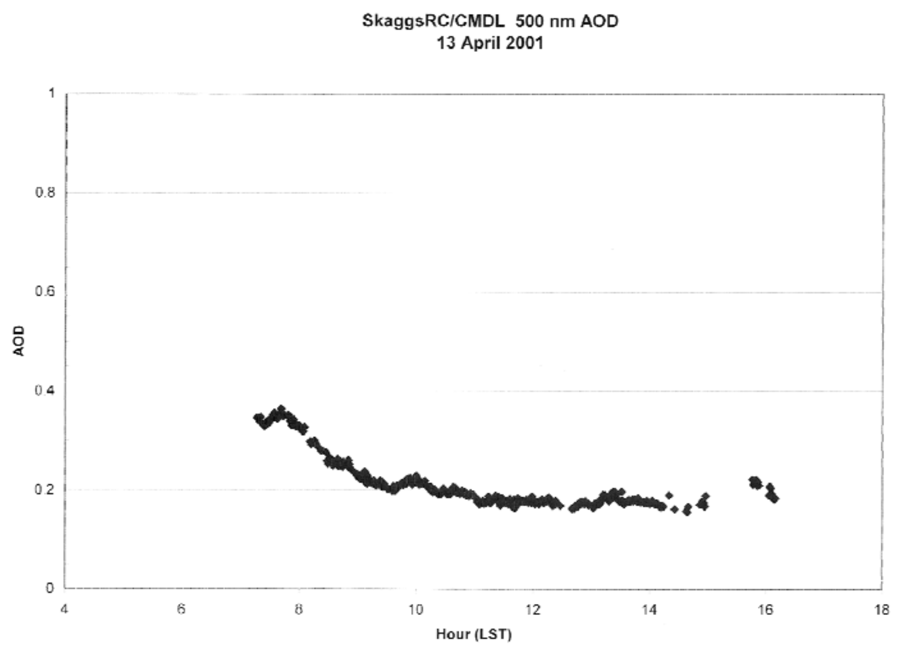

Figure 6: April 13, 2001 cloud screened CMDL AOD data for the 500 nm nominal wavelength

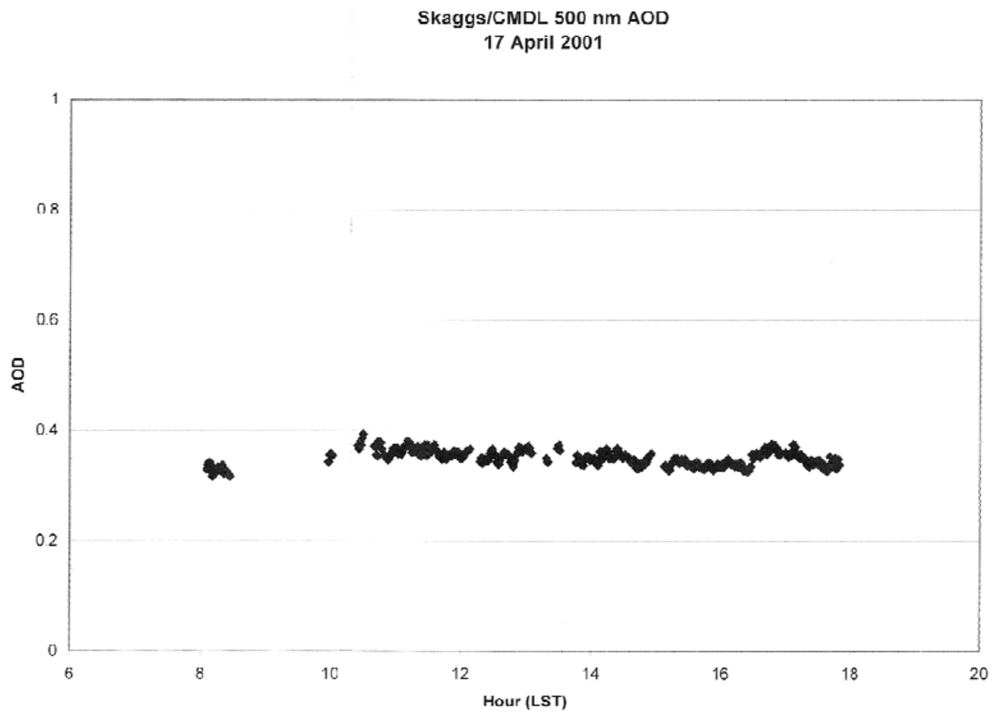

Figure 7: April 17, 2001 cloud screened CMDL AOD data for the 500 nm nominal wavelength

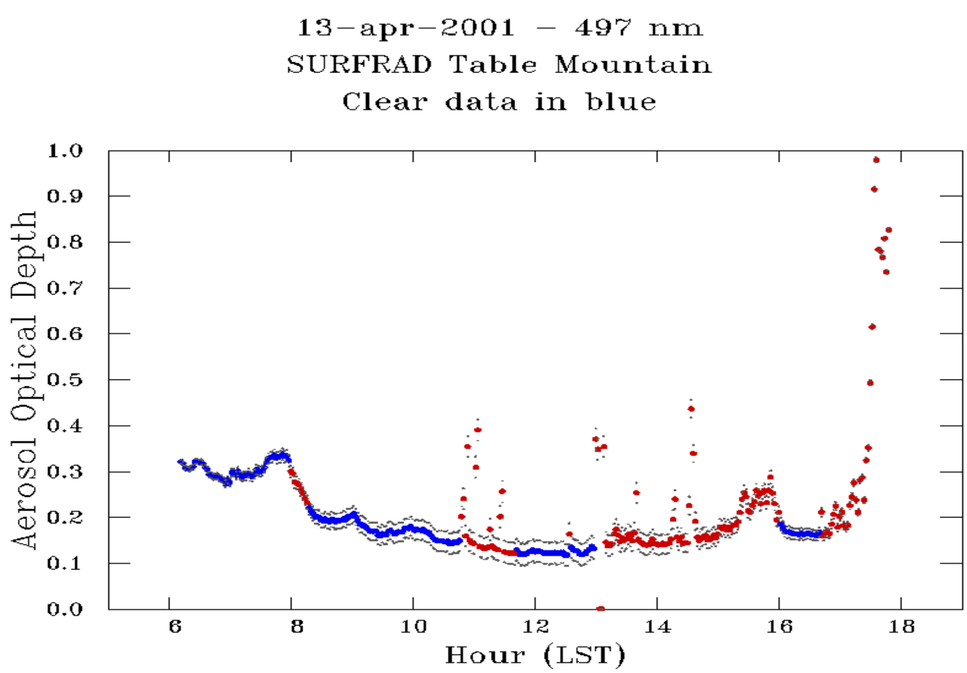

Figure 8: April 13, 2001 cloud screened AOD algorithm data for the 500 nm nominal wavelength

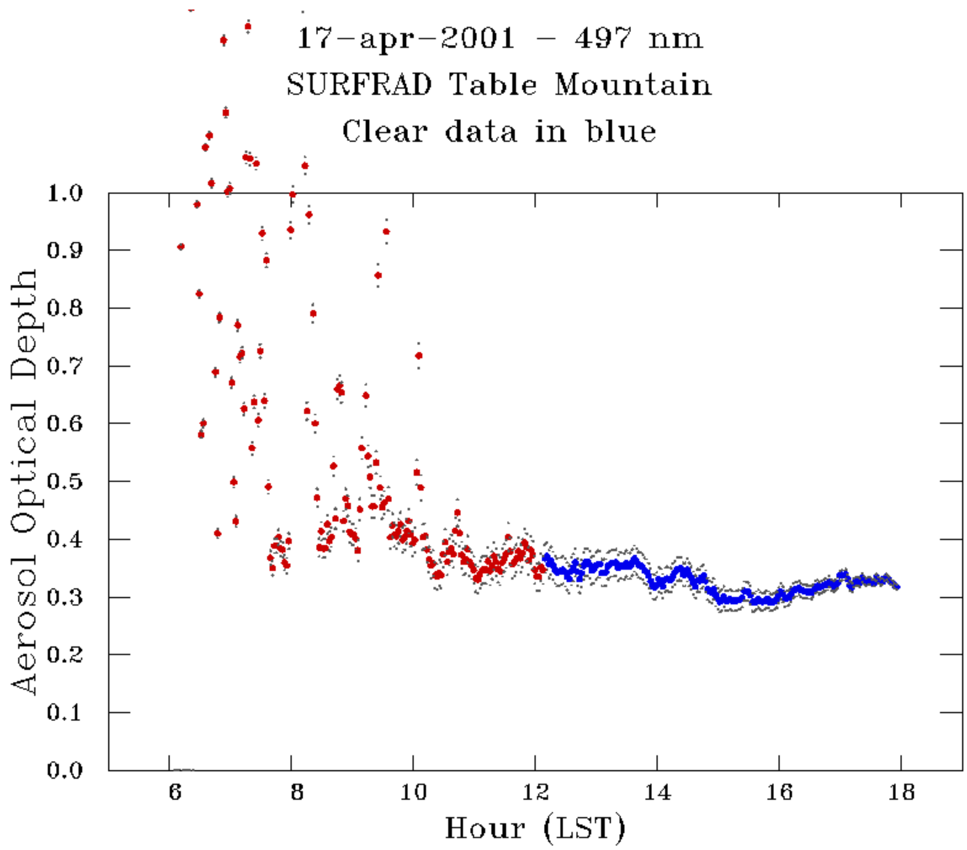

Figure 9: April 17, 2001 cloud screened AOD algorithm data for the 500 nm nominal wavelength

Applications

The finalized data set created by the AOD algorithm has several important applications. The first of these is to provide a point of validation for any satellite, such as NASA's Earth Observing Satellite that measures the Earth's radiation budget. These calculations will also allow the satellites to make necessary corrections to the signals they receive, thereby improving the over all quality of their readings.

The next major use of the AOD algorithm is to improve climate models. The algorithm will provide more accurate and abundant aerosol data to the modeling community, giving them the ability to use this to minimize error caused by assumed aerosol values. The models that are not able to use our data directly will also benefit because of the application to satellites.

The last and possibly most useful application of the data produced by our AOD algorithm is its application in weather simulators. By having a more accurate reading of aerosols, the simulations of the atmosphere will be more accurate. This will allow the National Weather Service (NWS) to better characterize the warning signs of major weather events, thus allowing NWS to better predict and provide advanced warning for potentially hazardous weather events (Orfinger 2002).

The above applications and several other possible users of the SURFRAD data are listed in Table 1. Improving and expanding upon the aerosol calculation process is important to all of these uses and users.

Table 1: Current SURFRAD users

Organizations	Potential Uses
National Centers for Environmental Prediction (NCEP)	Surface physics validation RUC model
	Surface irradiance validation ETA model
National Environmental Satellite, Data, and Information Service (NESDIS)	GOES surface irradiance validation
National Weather Service (NWS)	UV index verification
National Aeronautics and Space Administration (NASA)	EOS satellites' CERES instrument validation
Department of Defense (DOD)	AGROMET validation
European Centre for Medium-Range Weather Forecasts (ECMWF)	Modeled irradiance validation
United States Geological Survey (USGS)	Hydrology modeling validation

Automation

The AOD calculations were automated in order to produce a larger data set and save time on the calculation process. The AOD algorithm will also make the traditional calculations more dynamic. The method of calculating AOD uses several measurements based on location, time of day, and instrument in use. This will increase the accuracy of the results to be used in the applications mentioned previously. The ultimate goal of this process will be to put the finalized product in both numerical and visual form on the SURFRAD ftp site for distribution to any party interested in the data.

REFERENCES

Augustine, J. A., and C. I. Medina 2003: A new automated method of MFRSR-based aerosol optical depth analysis. *Proceedings, 12th Symposium on Meteorological Observations and Instrumentation*, February 9-13, 2003, Long Beach, Cali., CD.

Augustine, J. A., C.R. Cornwall, G. B. Hodges, C. N. Long, C. I. Medina, and J. J. DeLuisi, 2003: An automated method of MFRSR calibration for aerosol optical depth analysis with application to an Asian dust outbreak over the United States, *J. Appl. Meteor.,* **32,** 266-278.

Frogan, B. W., 1988: Sun photometer calibration by the ratio Langley method. *Baseline Atmospheric Program*, B. W. Frogan and P. J. Fraser, Eds., Bureau of Meteorology, 22-26.

Harrison, L., and J. Michalsky, 1994: Objective algorithms for the retrieval of optical depths from ground-based measurements. *Appl. Opt.,* **33,** 5118-5125

Iqbal, Muhammad. <u>An Introduction to Solar Radiation.</u> Vancouver: Academic Press Canada, 1983.

Long, C. N., and T. P. Ackerman, 2000: Identification of clear skies from broadband pyranometer measurements and calculation of downwelling shortwave cloud effects. *J. Geophys. Res. Lett.,* **21,** 999-1002.

Michalsky. J. J., J. A. Schlemmer, W. E. Berkheiser, J. L. Berndt, and L. C. Harrison, 2001: Multiyear measurements of aerosol optical depth in the Atmoshperic Radiation Measurement and Quantitative Links programs. *J. Geophys. Res.,* **106 (D11),** 12 099-12 107.

Orfinger, Becky. “Weather Simulators Prepare Forecasters for the Real Thing.” Rev. Jan 2002. < http://www.disasterrelief.org/Disasters/020116simulator/> (5 Aug. 2004)