An Airborne A-Band Spectrometer for Remote Sensing Of Aerosol and Cloud Optical Properties

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ABSTRACT

Atmospheric remote sensing with the O_2 A-band has a relatively long history, but most of these studies were attempting to estimate surface pressure or cloud-top pressure. Recent conceptual studies have demonstrated the potential of spaceborne high spectral resolution O_2 A-band spectrometers for retrieval of aerosol and cloud optical properties. The physical rationale of this new approach is that information on the scattering properties of the atmosphere is embedded in the detailed line structure of the O_2 A-band reflected radiance spectrum. The key to extracting this information is to measure the radiance spectrum at very high spectral resolution. Instrument performance requirement studies indicate that, in addition to high spectral resolution, the successful retrieval of aerosol and cloud properties from A-band radiance spectra will also require high radiometric accuracy, instrument stability, and high signal-to-noise measurements. To experimentally assess the capabilities of this promising new remote sensing application, the NASA Langley Research Center is developing an airborne high spectral resolution A-band spectrometer. The spectrometer uses a plane holographic grating with a folded Littrow geometry to achieve high spectral resolution (0.5 cm^{-1}) and low stray light in a compact package. This instrument will be flown in a series of field campaigns beginning in 2001 to evaluate the overall feasibility of this new technique. Results from these campaigns should be particularly valuable for future spaceborne applications of A-band spectrometers for aerosol and cloud retrievals.

Keywords: Aerosols, clouds, climate, A-band, remote sensing

1. INTRODUCTION

Aerosols and clouds exert an enormous influence on the Earth's solar and thermal radiation budgets and only through a detailed understanding of their role in the climate system will reliable climate simulations be possible. In fact, recent assessments of global climate change by the National Research Council[1] (NRC), the Intergovernmental Panel on Climate Change[2] (IPCC), and NASA agree that the largest uncertainties in our ability to predict future climate change are associated with the radiative effects of aerosols and clouds. These large uncertainties are, in part, due to a limited knowledge of the optical properties of aerosols and clouds on a global scale. A myriad of new sensors and satellite missions is currently being planned to aggressively pursue answers to this major question confronting credible prediction of climate change. However, as noted by the NRC[1], these new measurements may not possess sufficient accuracy to significantly improve predictive capability.

A promising new approach for spaceborne aerosol and cloud remote sensing is the retrieval of aerosol and cloud optical properties from high spectral resolution measurements of reflected sunlight in the oxygen A-band. Although the oxygen A-band has been utilized for a wide variety of remote sensing studies in the past, these studies were primarily focused on the retrieval of cloud top pressure[3,4] or surface pressure[5,6]. O'Brien and Mitchell[7] were among the first to recognize that measurements of reflected sunlight within the O_2 A-band also contain information on the scattering properties of the atmosphere. This study suggested that the information on the optical properties of aerosol or cloud scattering layers is embedded in the detailed line structure of the O_2 A-band, but will only be observable by very high spectral resolution instruments. Recently, Stephens and Heidinger[8] developed the theoretical foundation for retrieval of aerosol and cloud optical properties from high-resolution spectral measurements of O_2 line absorption. In a related paper, Heidinger and Stephens[9] proposed a conceptual approach for retrieval of aerosol and cloud properties from a spaceborne A-band instrument. These two companion studies demonstrated the potential of high spectral resolution A-band spectrometers for the determining the optical properties of scattering layers, such as aerosol or cloud optical depth, aerosol single scatter albedo, and cirrus cloud asymmetry parameter. These conceptual studies, however, argued that a spectral resolution of at least 1 cm^{-1} would be necessary to extract the desired aerosol and cloud particle information from the A-band measurements. This required spectral resolution is significantly higher than exists in current spaceborne A-band spectrometers such as the Global

Ozone Monitoring Experiment[10] (GOME) and significantly higher than considered in past studies. In addition to the high spectral resolution requirement, this technique also demands high signal-to-noise and high radiometric precision, which in turn requires exceptional mechanical and thermal stability of the instrumentation. To date, very limited high-resolution A-band data are available to experimentally assess the feasibility of this new approach, in part due to the technical challenges associated with making these measurements.

The Radiation and Aerosols Branch of NASA's Langley Research Center (LaRC) is developing an airborne A-band spectrometer with the performance specifications necessary to enable the retrieval of aerosol and cloud properties. This spectrometer will serve as a unique science and technology test bed to explore the information content of the O_2 A-band spectra, the instrument performance requirements necessary for these measurements, and the overall feasibility of this new A-band technique for aerosol and cloud retrievals. After comprehensive laboratory characterization and calibration, the A-band spectrometer will be flown on a research aircraft in a series of field measurement campaigns. The experimental data from these field campaigns will serve as the basis for evaluating the capabilities of this instrument and quantifying the accuracy of the A-band retrievals. This new aircraft spectrometer should be a valuable tool for developing future spaceborne applications of A-band spectrometers for remote sensing of aerosol and cloud optical properties.

2. INSTRUMENT DESCRIPTION

The LaRC airborne A-band spectrometer is being designed and fabricated by Ball Aerospace and Technologies Corporation to provide high spectral resolution (0.5 cm^{-1}) radiance measurements of reflected sunlight over the portion of the oxygen A-band spectral region from 13010 to 13110 cm^{-1}. The spectrometer is specifically designed for use in a research aircraft environment and utilizes a plane, holographic grating with a folded Littrow geometry to achieve high spectral resolution in a compact package. The use of the holographic grating allows better stray light rejection than possible with conventional echelle gratings, which is a critical requirement for successful retrievals of aerosol and cloud properties. The spectrometer housing is approximately 102.9 cm x 39.4 cm x 25.4 cm, weighs about 100 lbs., and has three entrance apertures to allow flexibility for aircraft mounting. The CCD electronics are housed in a separate CCD detector interface unit that is approximately 15 cm x 31 cm x 39.1 cm and weighs about 20 lbs. A schematic diagram of the instrument mechanical layout is shown in Figure 1. A plan view of the spectrometer is shown in Figure 2.

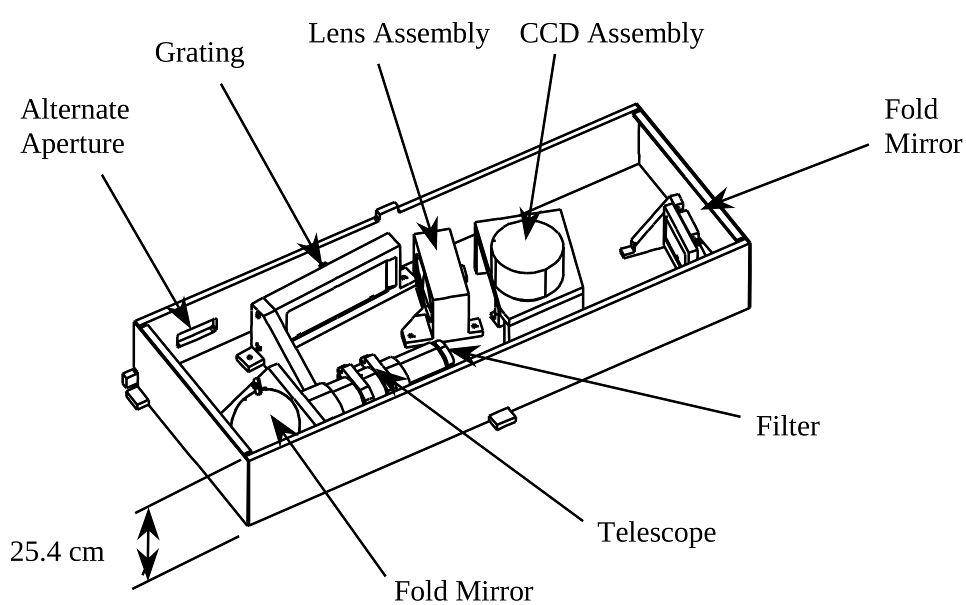


Figure 1. Mechanical layout of LaRC airborne A-band spectrometer.

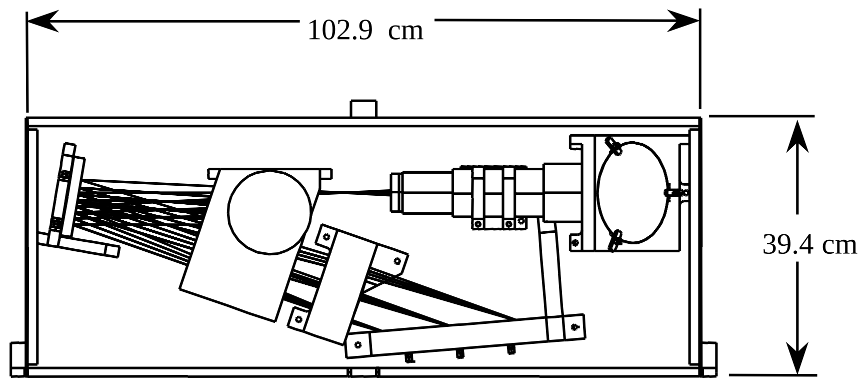


Figure 2. Plan view of the LaRC airborne A-band spectrometer layout.

The entrance slit is the field stop for the aircraft A-band spectrometer. The spectrometer entrance slit is oriented with the slit length in the cross-track direction and the slit width along-track. The cross-track spatial resolution is determined by the image of the slit length on the Earth's surface and the along-track spatial resolution is determined by the aircraft ground speed and integration time. The combination of a 30 μm x 12 mm entrance slit and a 400-mm focal length collecting telescope provides an instantaneous cross-track footprint on the Earth's surface of approximately 300 m at an aircraft altitude of 10 km. The integration time will vary with aircraft speed, but nominally will be 1.5 s for an aircraft ground speed of 200 m/s to yield an along-track spatial resolution of 300 m.

The spectrometer detector is a commercially available two-dimensional scientific CCD spectroscopic array from ISA (ATECCD-2000x800-7). The 2000 x 800 pixel CCD array is back illuminated and air-cooled with a 2-stage TEC. The individual pixels in the array are 15 μm square yielding a total image area of 30 mm x 12 mm. The spectrometer's wavelength dispersion is along the width (2000 pixel dimension) of the CCD array. The width of the spectrometer entrance slit corresponds to 2 pixels, which matches the spectral resolution requirement of 0.5 cm^{-1}. As a result, only about 400 of the available 2000 pixels in the wavelength dimension will actually be utilized to cover the desired 100 cm^{-1} spectral range. A summary of the tentative spectrometer specifications is provided in Table 1.

3. RETRIEVAL APPROACH

The key to retrieval of aerosol and cloud properties from the A-band spectra is the high spectral resolution of the measurements. The high spectral resolution provides a large dynamic range in molecular oxygen absorption that is observed in each measured spectrum. Since molecular oxygen is a well-mixed gas and the dominant absorber in the A-band spectral region, the absorption of scattered sunlight at A-band wavelengths is known for a clear atmosphere. However, the presence of aerosol and cloud scattering layers affect the amount of O_2 absorption by increasing the optical path of the photons as they travel through the atmosphere. The reflected spectral radiances are related to the length and direction of the photon paths in the scattering layer, which are distinct functions of the aerosol/cloud optical properties[10]. Thus, information on the optical depth, angular scattering characteristics, and absorption of scattering layers is imbedded in the shape of the measured O_2 A-band radiance spectrum. Information on the height of the scattering layer is contained in the ratio of the radiances in and out of the deep absorption lines. A conceptual illustration of the sensitivity of nadir viewing A-band measurements to the optical depth and altitude of a scattering layer is shown in Figure 3. As this figure illustrates, a high cloud with an optical depth of 10.0, a mid-level cloud with an optical depth of 1.0, and boundary layer aerosol with an optical depth of 0.1 will produce three distinctly different reflected radiance spectra when observed from above with a high spectral resolution spectrometer. The ability to measure the A-band spectrum at high resolution allows a retrieval to selectively tune out contributions from

Total spectral range	13010 cm^{-1} to 13110 cm^{-1} (762.8 nm to 768.6 nm)
Spectral resolution	0.5 cm^{-1} (29.3 pm)
Total number of spectral samples	> 400
CCD array pixel size	15 μm x 15 μm
Total pixels	2000 wide x 800 high
Grating type	plane, holographic
Digitizer resolution	16 bit
Integration time (nominal)	1.5 s
SNR (SZA=60^o, albedo=0.05)	700

Table 1. Tentative Specifications for LaRC Airborne A-band Spectrometer.

photons scattered by the underlying surface from photons scattered by aerosols or clouds. The retrievals will exploit these sensitivities to estimate the optical properties of the aerosol and cloud layers.

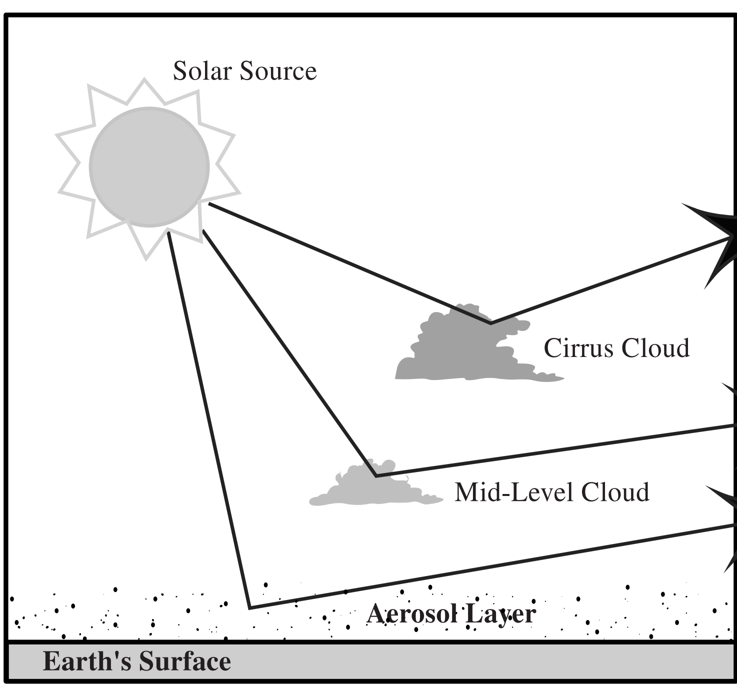
The retrieval approach that we have adopted is based on the optimal estimation method of Rogers[11] and is similar to that utilized by Heidinger and Stephens[9] in their conceptual study. When aerosol or cloud scattering layers are present in the atmosphere, the nature of the A-band radiance spectrum measured at the top of the atmosphere is essentially controlled by six physical parameters:

- aerosol or cloud optical depth, τ
- single scatter albedo, ω_o
- scattering phase function (expressed in terms of an asymmetry parameter, g)
- surface albedo, α_{sfc}
- pressure top of scattering layer, p_t
- pressure thickness of scattering layer, Δp .

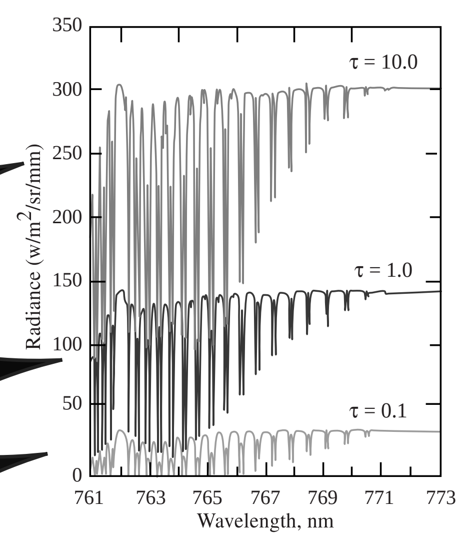
The retrieval algorithm considers a retrieval vector that consists of these six independent variables. The best-fit set of these parameters is determined through a multidimensional minimization of the residuals between the measured A-band spectrum and a modeled spectrum calculated from a forward radiative transfer model with multiple scattering. The solution is obtained iteratively, starting from a set of a priori values for the six parameters.

The information content of the measurements is not sufficient to successfully determine the entire set of retrieval parameters under all conditions and only a subset of these six variables is typically retrieved for a given atmospheric scenario. For instance, clouds scatter conservatively across the A-band spectral region and ω_0 can be assumed to be known (=1) for all cloud retrievals. In addition, the inclusion of simultaneous lidar data can provide accurate information on the altitude and thickness of an aerosol or cloud scattering layer and eliminate these parameters from the retrieval vector. In fact, simulation studies show that incorporation of lidar information into the retrievals as highly accurate a priori estimates of layer top pressure and pressure thickness dramatically increases the accuracy of retrievals performed with A-band radiance spectra alone. An example of the beneficial impact of lidar data on the accuracy of the retrievals is illustrated in Figure 4. To take advantage of the benefits of coincident lidar data to the retrievals, we are evaluating several potential lidar systems to fly in conjunction with the A-band spectrometer. Under this scenario, the aerosol retrievals will focus on aerosol optical depth, single scatter albedo, and surface albedo, while cloud retrievals will target cloud optical depth, asymmetry parameter, and surface albedo.

Simulation studies are underway to explore the retrieval capabilities of the LaRC A-band spectrometer. These studies are based on synthetic A-band spectra produced with an instrument model that incorporates the expected instrument performance specifications for the LaRC A-band spectrometer. Illustrative examples of aerosol optical depth and cirrus cloud optical depth retrievals are shown in Figures 5 and 6, respectively. These figures illustrate the unique capability of this A-band approach to retrieve aerosol and cloud optical depths over both dark ocean surfaces and bright land surfaces where current passive instruments such as MODIS have difficulty. Preliminary simulation studies have shown that it may be possible to retrieve aerosol optical depth to better than 15% accuracy globally for optical depths greater than about 0.2. Cirrus cloud optical depth retrievals may be somewhat more problematic due to uncertain knowledge of the asymmetry parameter. Additional simulation studies are being performed to examine the accuracy of the A-band aerosol single scatter albedo and cirrus asymmetry parameter retrievals. A summary of the principal A-band retrieval parameters and their corresponding accuracy goals are listed in Table 1.



a) A high spectral resolution A-band spectrometer observes reflected sunlight within the oxygen A-band.



b) Observed radiance spectrum depends on optical depth and altitude of scattering layer

Figure 3. Concept for remote sensing of aerosol and cloud optical properties with a high resolution A-band spectrometer.

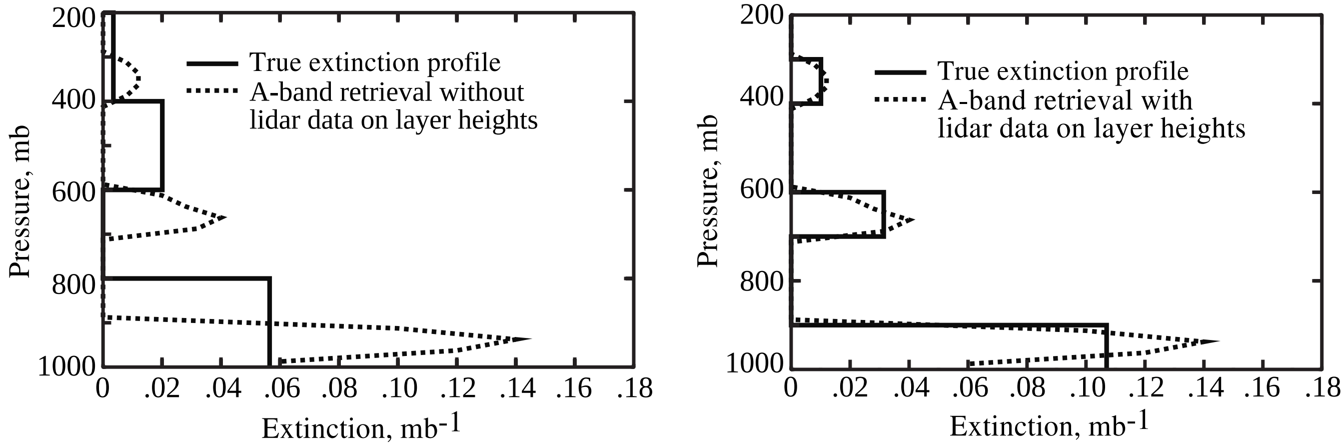


Figure 4. Coincident lidar data provides information on layer height and thickness that improves the accuracy of the A-band retrievals.

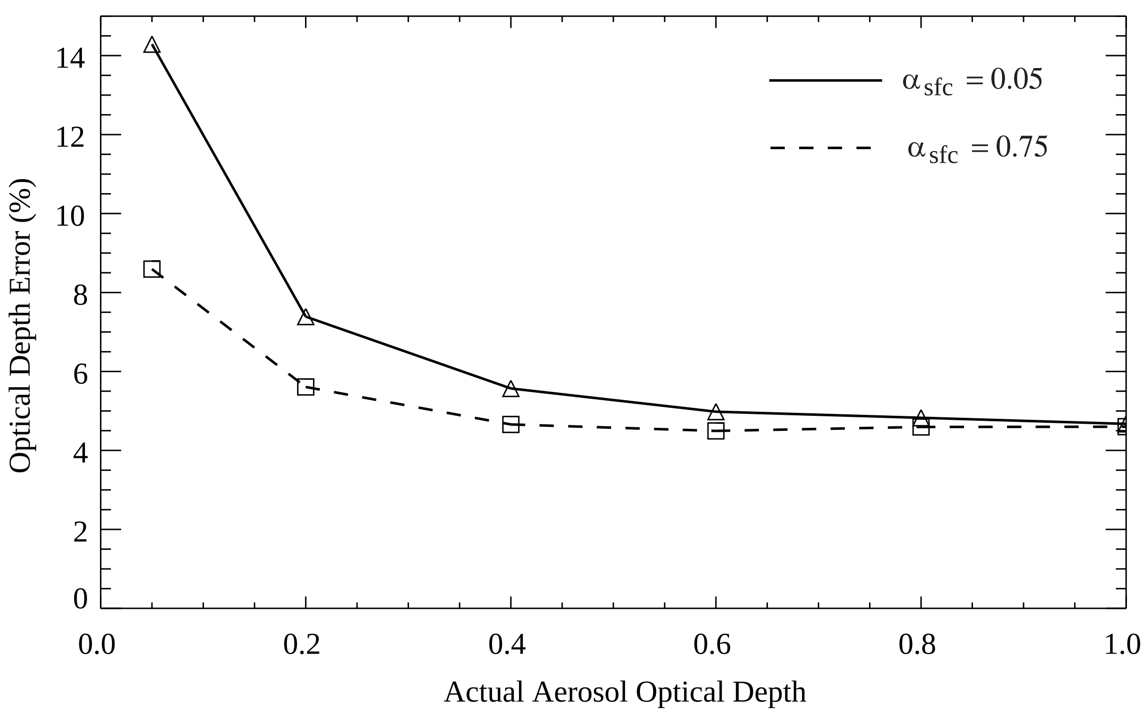


Figure 5. Example of A-band aerosol optical depth retrieval for an aerosol layer placed between the surface and 2.0 km.

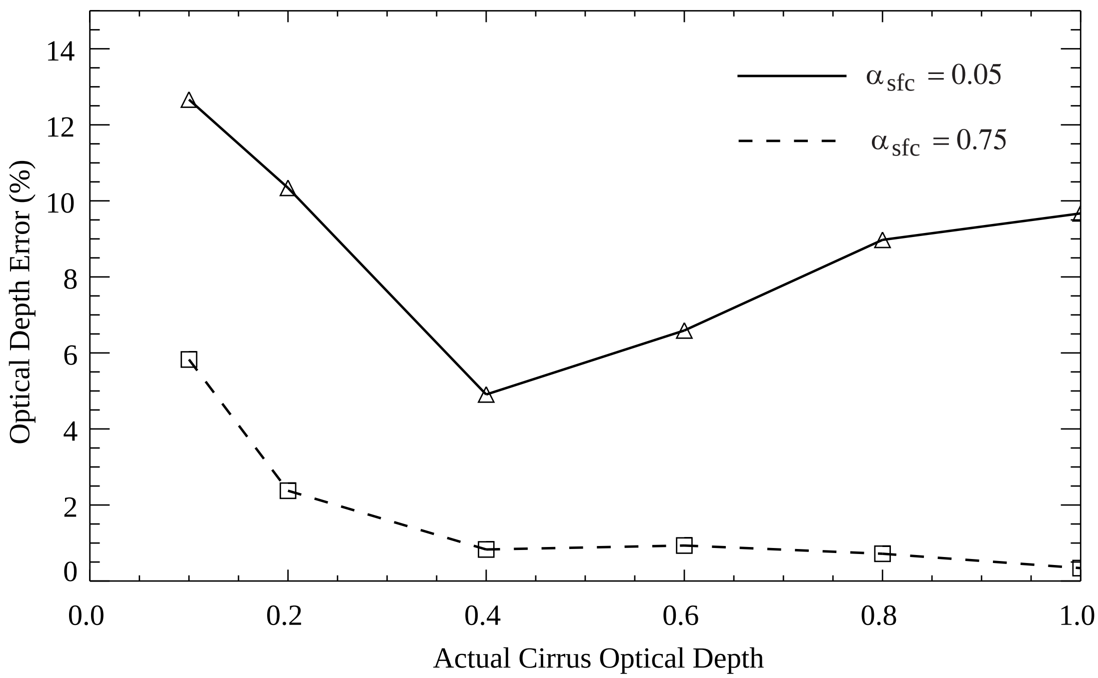


Figure 6. Example of A-band cirrus cloud optical depth retrieval of a cirrus cloud placed between 300 – 400 mb.

Product	Accuracy Goal
Aerosols	
Optical depth, τ_a	15% globally
Single scatter albedo, ω_o	+/- 0.05 for $\tau_a > 0.2$
Clouds	
Optical depth, τ_c	15-30% globally
Cirrus asymmetry parameter, g	0.04

Table 2. Principal A-band spectrometer aerosol and cloud data products and accuracy goals.

4. INSTRUMENT PERFORMANCE REQUIREMENTS

Sensitivity studies were performed to define the performance requirements for the LaRC airborne A-band spectrometer. These studies indicate that the most critical sources of error in the retrievals will be from spectral cross talk, radiometric calibration, and spectral registration. Spectral cross talk refers to the "smoothing" of the measured radiance spectrum that occurs due to a combination of the finite spectral response of the instrument and scattered light from the grating. This is a serious concern for the A-band retrievals because this scattered light results in an apparent "filling in" of the deep oxygen absorption lines with photons from adjacent spectral regions, which will effectively reduce the spectral resolution of the measurements. An example of the effect of spectral cross talk on the A-band radiance spectrum is shown in Figure 7. The left-hand panel shows the shape of a theoretical instrument response function (FWHM = 0.5 cm^{-1}) for various levels spectral cross talk. The scattered light contribution affects the shape of the response function's far wings and is sometimes referred to as the far out-of-band (OOB) or stray light component. In this example, response functions are shown with OOB levels ranging from 10^{-6} to 10^{-2}. The right-hand panel of Figure 7 illustrates the effect the different levels of OOB on the A-band radiance spectrum. For clarity, only a small segment of the A-band spectrum is shown. The thin solid line in the right-hand panel represents the "true" A-band radiance spectrum produced with line-by-line radiative transfer calculations. As the figure illustrates, high levels of scattered light (OOB) significantly smooth and reduce the dynamic range of the radiance spectrum. As levels of OOB drop to 10^{-4} or less, the effect on the radiance spectrum is reduced considerably. The LaRC spectrometer utilizes a holographic grating to reduce the effect of scattered light and is expected to exhibit OOB levels of less than 10^{-4}.

High radiometric accuracy is also important for successful retrievals. Sensitivity studies show that the information content of the A-band spectra depends not only on the measurement resolution, but also on the accuracy of the measurements. Therefore, large instrument calibration errors will effectively reduce the number of independent pieces of information contained in the A-band spectrum. For radiance ratio quantities used in some of the retrievals, calibration errors tend to cancel which will significantly reduce the impact of these errors. In general, however, the A-band measurements must meet or exceed an absolute calibration accuracy of 4-6% for successful retrievals.

Shifts in the spectral registration of the spectrometer are induced by thermal and mechanical instabilities in the instrument. Given the detailed line structure in the A-band, even small errors in the spectral registration will produce dramatic differences between the measured and modeled radiance spectra and lead to significant errors in the retrievals. Fortunately, the combination of high spectral resolution which allows the individual absorption lines within the A-band to be resolved and accurate a priori knowledge of the line center locations from laboratory spectroscopy will permit accurate spectral registration of each measured spectrum. Prototype spectral registration algorithms indicate that spectral registration can be performed to an accuracy of 0.01 $cm^{-1}$and, as a result, spectral registration will not be a significant source of retrieval error.

A comprehensive understanding of the instrument performance and careful instrument calibration will obviously be paramount to the success of A-band aerosol and cloud retrievals. Accordingly, after its delivery to LaRC (scheduled for late 2000), the spectrometer performance will go into a laboratory for full characterization and calibration. Tests will be conducted to document all aspects of instrument performance including instrument throughput, dark current, read noise, linearity, and pixel non-uniformity. Special effort will be also be made to accurately measure the slit function of the spectrometer since preliminary retrieval simulations suggest that accurate knowledge of the slit function is also a key requirement for successful aerosol and cloud retrievals

5. FUTURE FIELD MEASUREMENT CAMPAIGNS

A series of field measurement campaigns are planned to obtain a large volume of A-band spectra from various atmospheric scenarios. The aircraft platform for the LaRC A-band spectrometer will be a Learjet. This aircraft has two down-looking windows for science data collection and has a flight ceiling of approximately 40,000 feet, which will allow it to fly above cirrus cloud layers.

The aircraft measurement campaigns will proceed in two phases. The first phase will be designed to sample single aerosol or cirrus cloud layers in otherwise clear sky conditions to evaluate the optical depth measurement capability of the A-band spectrometer. The aircraft will operate in the vicinity of the Chesapeake Light ocean platform located about 30 km from

LaRC. This platform, which is an active Aerosol RObotic NETwork (AERONET) site and also serves as a Baseline Surface Radiation Network (BSRN) quality site, should provide a valuable data base for correlative comparisons. A second phase of field measurements is planned to evaluate the more challenging aspects of the retrieval problem such as aerosol single scatter albedo. For this phase, we will also obtain in situ measurements to provide some closure to the question of A-band retrieval accuracy.

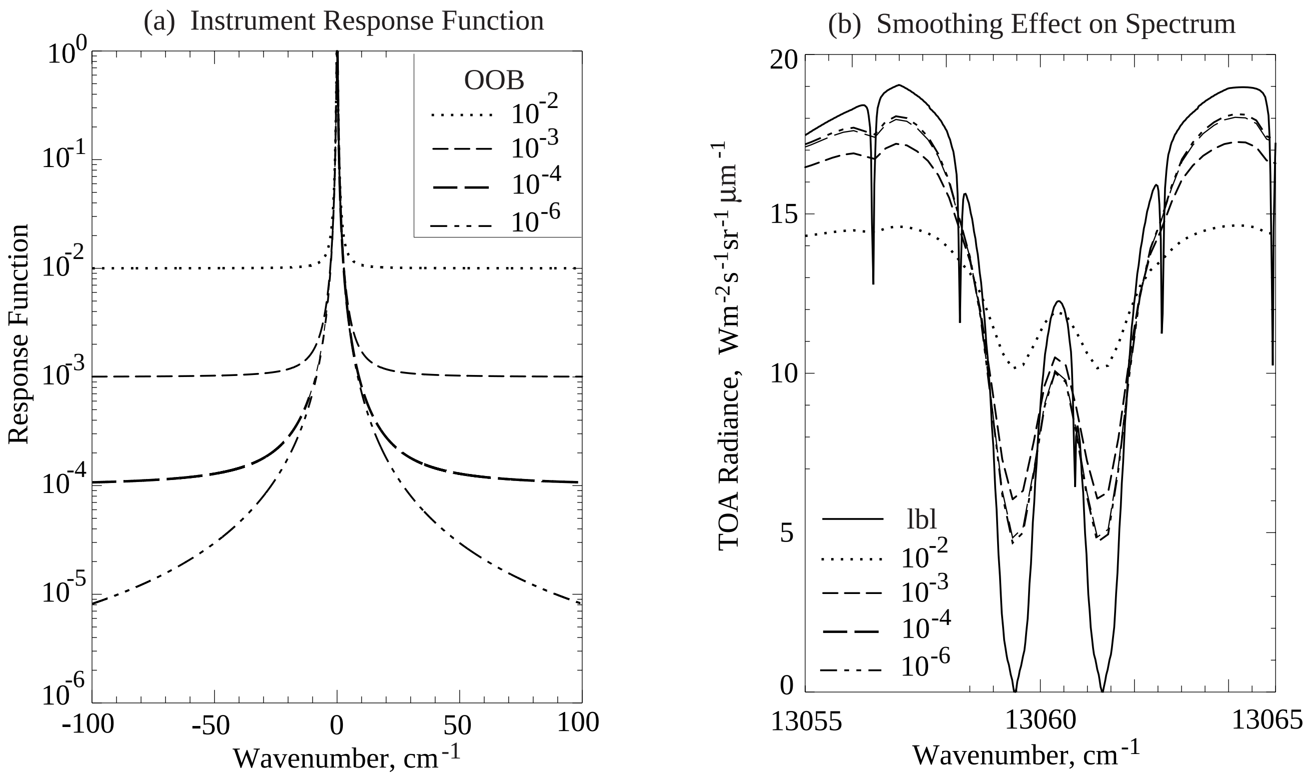


Figure 7. (a) Example of instrument response functions with various levels of spectral cross talk and (b) smoothing effect of spectral cross talk on A-band radiance spectrum.

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