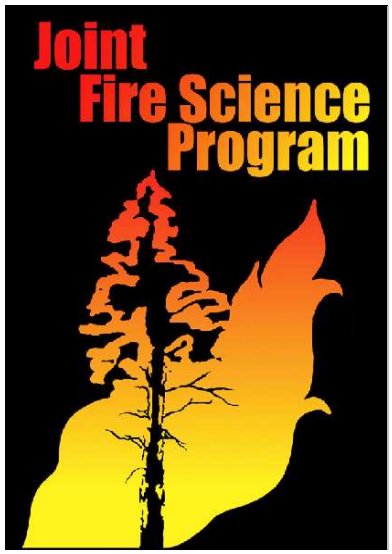

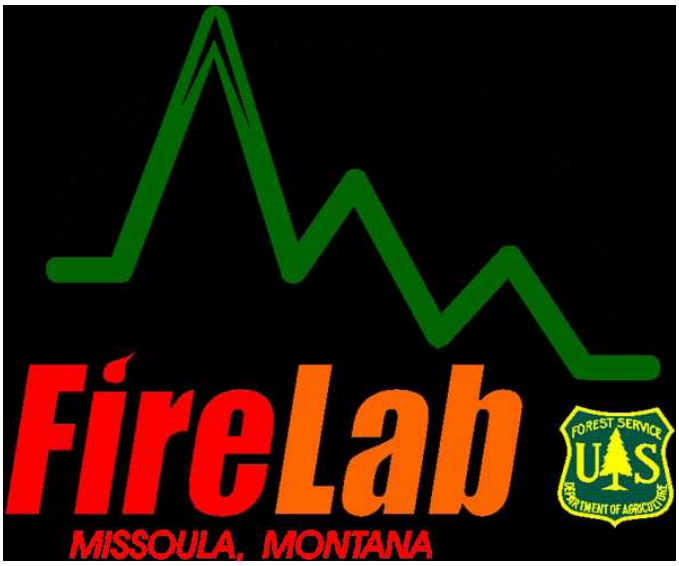

Real-Time Monitoring of the Three-Dimensional Distribution of Smoke Aerosol Levels from Prescribed Fires and Wildfires

Final Report for JFSP Project 04-1-1-04

April 28, 2008

Principal Investigators:
Vladimir Kovalev and Wei Min Hao
(406) 329-4862, vkovalev@fs.fed.us

Executive Summary

The goal of the project was to fulfill a thorough investigation of (1) the potential and limitations of the remote sensing lidar technique when operating in smoky polluted atmospheres, and (2) the ability of lidar in providing the accurate real-time information on smoke plume dynamics, optical properties, and microphysics in the vicinity of wildfires and prescribed burns. An improved measurement methodology and data processing techniques were developed for analyzing data obtained with the elastic scanning lidar and the auxiliary in situ instrumentation when working in smoke-polluted atmosphere. The improved measurement methodology included: (i) a new lidar-data inversion method, which allowed significant reduction of random and systematic distortions in the optical-depth and extinction-coefficient profiles retrieved from lidar data; (ii) a new near-end calibration method for elastic lidar operating in a multiangle mode.

The above technique was used for processing data obtained by the FSL scanning lidar operated in a combined vertical-azimuthal mode in smoke-polluted atmospheres. It allowed the investigation of smoke plumes and extended horizontal smoke layering created by atmospheric inversion in the vicinity of large wildfires. The lidar measurements close to the wildfires revealed numerous cases of such a horizontally stratified multilayer atmosphere.

The FSL lidar was successfully used for the determination of smoke plume dispersion, its spatial boundaries and top heights, and their changes with time. These experiments confirmed that lidar together with the auxiliary in situ instrumentation can provide critical information on plume heights and aerosol levels to validate smoke-dispersion models.

Our experiments confirmed that lidar is an invaluable tool that can provide the following types of measurements:
1) Vertical scans of smoke plumes and smoke layers. These measurements can give information on the height of the plume top and bottom, and their variations with time.
2) Vertical profiles of smoke optical depth, extinction and backscatter coefficients from the surface up through the plume top. Such combined information would allow one to make an estimation of vertical smoke-plume concentration and its temporal behavior during day and night.
3) Continuous time series monitoring of smoke layers in the vicinity of strong wildfires allowing the behavior of these layers and their evolution to be characterized in the morning, evening, daytime, and overnight.

Table of Contents

	Executive summary	2
	Table of contents	3
1	Introduction	4
2	FSL lidar measurements in smoke-polluted atmospheres: overview	5
2.1	Lidar measurements of smoke plumes dynamics in areas of prescribed burns: lessons we learned	6
2.2	Lidar measurements of plume heights in the vicinity of intense wildfires	8
3	Issues and solutions for the multiangle lidar measurement of smoke particulate optical characteristics	13
3.1	Development of the measurement methodology for scanning lidar operating in a multiangle mode	14
3.2	Modernization of the signal inversion algorithm	15
3.3	Concept of the lidar near-end calibration	17
4	Determination of the smoke particulate concentration: issues and solutions	18
4.1	Optical and mass concentration measurements of the smoke particulate matter using the combustion facilities at the FSL	19
4.2	Sources of the uncertainty in the transition from the particulate optical parameters to the particulate mass concentration	19
5	Summary: What information on the smoke particulate matter can be obtained with the FSL research-grade lidar and what cannot	21
6	Deliverables	22
7	References	23
	Appendix 1. Lidar and supplemental in situ instrumentation	28
	Appendix 2. Publications	30
	Appendix 3. Presentations	31

1. Introduction

The objective of this project was to develop and implement the most practical ground-based remote-sensing technologies for the measurement of smoke particulate characteristics for monitoring smoke-plume dynamics in real-time. The project was focused on obtaining and documenting information on the smoke plume rise and dispersion and the investigation of the three-dimensional distribution of smoke particulate concentration in areas around and close to prescribed fires and wildfires. The project objectives have been achieved by using the most advanced remotely sensed, fast-response Light Detection And Ranging (lidar) and a set of in-situ optical instrumentation. The information on changes in particulate levels enables fire and air quality managers to assess smoke effects on visibility and public health in near real-time. Such measurements can also provide critical information on plume heights and aerosol levels to validate smoke dispersion models operated by the Forest Service Consortia for Advanced Modeling of Meteorology and Smoke (FCAMMS).

This project was to produce the following results:

1. Science-based information on the three-dimensional distribution of smoke particulate concentration and dispersion in the atmospheres polluted by wildland fires.
2. Monitoring of air quality in smoke polluted atmospheres adjacent to severe wildfires, including diurnal and daily spatial variation of aerosol levels, and plume heights and dynamics.
3. Determination of smoke aerosol levels and their temporal change in the vicinity of fire.
4. Investigation of the dependencies between the optical characteristics of smoke particulates and their mass concentration to provide the estimates of the concentration levels of PM-2.5 and PM-10.
5. Profiles of the vertical distribution of smoke plumes and particulate levels from prescribed fires.
6. Critical data needed to validate smoke dispersion models, particularly data on smoke plume heights, dispersion, and ground level aerosol concentrations, for adjusting the FCAMMS smoke dispersion models.

To achieve these goals, the following studies and investigation have been planned and fulfilled:

I. Development of a lidar measurement strategy for determining the optical characteristics of smoke plume particulates in smoke-polluted atmospheres.
II. Development and experimental testing of the most effective lidar signal-inversion algorithms and the corresponding lidar software for determining the optical characteristics of smoke plume particulates and the spatial boundaries of the smoke plume rise and dispersion.
III. Experimental tests of the lidar measurement technology in smoke–polluted atmospheres in the vicinity of wildfires and the prescribed burns.

2. FSL Lidar Measurements in Smoke-Polluted Atmospheres: Overview

In 2004, a mobile research-grade lidar instrument for smoke measurements was assembled and delivered to the FSL from the University of Iowa. After preliminary tests, the lidar has been utilized for smoke-particulate measurements in smoke-polluted atmospheres. The two-wavelength lidar simultaneously operates at two wavelengths (355 nm and 1064 nm). The scanning capabilities of the lidar allow changing the searching direction rapidly through 180^0 horizontally and 90^0 vertically (Appendix 1). The operating range of the lidar extends from the minimal measurement range of, approximately, 1 km up to 5 - 10 km, depending on atmospheric conditions. Initially, lidar test measurements were made in clear atmospheres near Missoula. These test measurements allowed examining lidar data distortions and their influence on the measurement accuracy of the optical parameters of interests. Based on the investigation, routine test procedures for the lidar and special calibration methods were developed.

Fig. 1. The Forest Service scanning lidar in a mobile laboratory.

During the prior two years, in 2004 and 2005, the multiangle measurement strategy and the corresponding software were developed and tested. The software allowed (a) reading raw data from the scanning-lidar data control software, (b) performing signal corrections, and (c) calculating the vertical optical depth and the relative backscatter coefficient profiles as a function of height. During the next two years, this technique was improved,

and in addition, new and effective algorithms were developed that allowed one to effectively invert the above profiles into the profiles of the extinction coefficient and the column-integrated extinction-to-backscatter ratio (the lidar ratio).

The concrete tasks of our investigations in smoky-polluted atmospheres were as follows:
1. Monitoring smoke's three-dimensional distribution and dynamics over fire areas and the determination of smoke-plume variability and heights.
2. Validation of algorithms for determining optical properties of the smoke particulates.
3. Determining vertical profiles of the smoke distribution and their temporal changes up to heights ~ 4 - 5 km
4. Obtaining experience in lidar operation and use in the conditions surrounding wildfires.

2.1. Lidar Measurements of Smoke Plume Dynamics in Areas of Prescribed Burns: Lessons We Learned

In the very beginning of our studies, we focused on lidar measurements of smoke plumes near the areas of prescribed burns. We located the lidar and the other instrumentation outside the fire area at the distances of 1 – 1.5 km from the prescribed fire boundaries. The lidar typically operated in the azimuthal scanning mode over a range of fixed slope directions. The in-situ optical instrumentation (a nephelometer and particulate sizers) located at the lidar measurement site was used to provide reference data for the lidar signal calibration (Kovalev, 2003 and 2003a; Kovalev et al., 2004).

The first experiment in which the smoke plume optical characteristics were measured at both lidar wavelengths was performed in 2004. In these measurements, a TSI 3563 three-wavelength nephelometer and a Mikron TH 2700 Infrared camera were used as auxiliary instrumentation. The newly developed lidar-data processing software was used to process the multiangle lidar data, resulting in two-dimensional images of the areas with maximal smoke plume concentrations. Later a new simple and robust algorithm was developed for determining three-dimensional smoke-plume boundaries from the measured set of lidar signals (Kovalev et al., 2005). The most important advantage of this algorithm in comparison with the others was that it was relatively insensitive to significant changes in the intensity of the lidar backscatter signals at the smoke boundaries. The efficacy of this algorithm was validated with lidar experimental data obtained during the prescribed burn near Dillon, Montana, on 23 April 2004 [Fig. 2(a)]. An example of the two-dimensional lidar scan at 1064 nm with marked smoke boundaries is shown in Figs. 2(b). Here the color scale shows the relative intensity of smoke backscattering, and the areas of the densest smoke show as dark red. The near-edge smoke boundaries retrieved with the above algorithm are shown as blue dashes. The intensity of backscattering at the smoke boundaries in the smoke-polluted area ranged by a factor of 50; however, this did not prevent obtaining the well-defined boundaries of smoke.

Fig. 2 (a). Lidar smoke measurements from a sage burn in western Montana used to test the new method for smoke boundary determination.

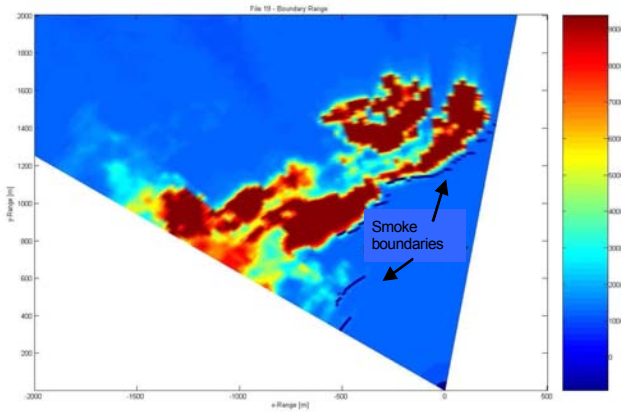

Fig. 2 (b). Results of the determination of smoke-plume boundaries from signals of the azimuthally scanning lidar. The color scale shows the relative level of backscattering. Dark red colors show the areas of the densest smokes.

To meet our objectives, we monitored the dynamics and temporal evolution of local plumes and the change in their heights. However, during prescribed burns, the dense smoke plumes of interest existed only for short periods and quickly dispersed because of wind. Usually, the smoke plumes close to the fires were laid low over by the wind. Accordingly, the heights of the smoke plumes measured by the lidar depended on the distance of the lidar measurement site from the burn and on the wind direction. Quite often, the wind blew in the opposite direction, making it impossible to continuously monitor the smoke with lidar.

The analysis of the measurement results, obtained with lidar in areas close to the prescribed burns, led us to conclude that the potential of the remote sensing technique, such as lidar, cannot be properly utilized in the case of temporarily short and quite local prescribed burns. In such measurements, lidar cannot yield the required information because of the following issues: First, the particulate emission level created by prescribed burn is too low to form a stable smoke configuration that could be reliably monitored by lidar. The smoke-polluted area is local and relatively small; it is not adequate for the lidar searching abilities. In addition, the boundaries of the smoke-polluted area continuously change. The rapid changes of the spatial boundaries of the smoke polluted area and smoke-plume concentration during the flaming phase of combustion and relatively short periods of the smoldering phase create an unstable (non-stationary) atmosphere, which does not allow applying any temporal averaging of the lidar signals; accordingly, the

measurement accuracy of any derived parameters of smoke particulates is poor. Second, the most intense plumes originating in the prescribed fires are not lofted and propagated with wind, but are relatively close to the ground and then dispersed. Therefore, the lidar measurement requires pointing the laser beam as close to ground as possible, starting with small elevation angles, generally less than ~10^o. Meanwhile, it is always an issue to find the measurement site where the lidar "can see" the smoke plume, that is, where the lidar beam will not hit trees, buildings, hills, etc. during azimuthal scanning. Third, the right selection of the measurement site for the planned prescribed burn is always an issue because the wind direction is uncertain, and accordingly, the exact direction of the smoke propagation during the future burn is unpredictable. Quite often, the smoke plume propagates away from the lidar at low altitude where the lidar is unable to monitor. In other cases, the smoke plume propagates directly towards the lidar measurement site. In this case, the smoke plumes immediately enter the lidar non-operative zone (~ 1000 m), where the lidar-signal inversion is impossible (due to the incomplete overlap of the transmitted laser beam and the receiver's telescope field of view). Meanwhile, any relocation of the mobile lidar from one to another measurement site (even if such an alternative site was preliminary found) requires, at least 2 – 3 hours, and is not realistic because of a short duration of a prescribed burn. Thus, in areas of small prescribed burns, the useful information that can be extracted from lidar signals is minimal.

2.2. Lidar Measurements of Plume Heights in the Vicinity of Intense Wildfires

Lidar measurements in smoky-polluted atmospheres and the measurement data analysis led us to the conclusion that the most valuable information about the smoke particulate matter and smoke plume dynamics could be obtained in the vicinity of large wildfires, extended in space and time. In such cases, the quality of the lidar data does not depend so dramatically on the selection of the measurement site as in prescribed burn. Moreover, because of the large levels of smoke-particulate emission, lidar can successfully operate at distances of ~ 10 – 15 miles and more from active flaming. There is no need to locate lidar close to the active burn, as should be done in a prescribed burn.

The list of the locations and dates where the FSL lidar was used to measure the characteristics of the smoke plumes in the vicinity of large wildfires is given in Table 1.

Table 1. Locations and dates of the lidar measurements in the vicinity of wildfires

Fire	Date	Location	Instruments deployed:
Bull Fire (New Mexico)	6/29/2005	Elevation 7821 ft 33.45217^o N 108.24865^o W	Lidar, FRM, 3-Wavelength Nephelometer, SMPS Particle Sizer (6/29 - 6/30), APS Particle Sizer (6/29 - 6/30)
	6/30/2005	Elevation 7662 ft 33.4463^o N 108.23125^o W	
	7/1/2005	Elevation 7502 ft 33.42077^o N 108.15887^o W	

	7//2/2005	Elevation 7328 ft 33.41914^{o} N 108.14234^{o} W	
I-90 Fire (Montana)	8/9/2005 8/10/2005 8/11/2005 8/12/2005 8/15/2005 8/16/2005	Elevation 3166 ft 47.04287 ^{o} N 114.34856^{o} W	Lidar, 3-Wavelength Nephelometer
Woodchuck Fire (Montana)	7/27/2006	Elevation 3722 ft 46.65941^{o} N 114.00485^{o} W	Same
Gash Creek Fire **(**Montana)	8/2/2006 8/3/2006	Elevation 3523 ft 46.37875^{o} N 114.16246^{o} W	Same
Potato Fire (Idaho)	8/13/2006 8/14/2006	Elevation 7080 ft 44.49443^{o} N 114.33318^{o} W	Same
Tripod Complex Fire (Washington)	8/19/2006 8/20/2006	Elevation 1875 ft 48.47967^{o} N 120.18995^{o} W	Same
Tripod Complex Fire (Washington)	8/21/2006	Elevation 4908 ft 48.59794^{o} N 119.74074^{o} W	Same
Derby Fire (Montana)	9/09/2006 9/10/2006	Elevation 5658 ft 45.65223 ^{o} N 109.93209^{o} W	Same

When measuring wildfire smoke plumes with lidar, extremely different situations may be encountered. Accordingly, different measurement technologies should be applied for data processing, depending on the smoke heterogeneity and the dispersion level, the smoke plume density, the concentration levels, the spatial location and spread of smoke polluted areas, etc. In general, we identified three situations that were met during our measurements:

1. Dense fire plumes over large wildfires and in their near vicinity (Tripod Complex Fire, Winthrop, Washington).
2. Separate local fire plumes scattered within some wildfire area (GILA WFU ncident in New Mexico).
3. Highly dispersed smoke haze downwind far from of large fires (Tripod Complex Fire, Okanogan, Washington).

Among the most interesting cases of smoke-plume monitoring in the vicinity of the wildfires, three large wildfires yielded the most interesting data: Bull Fire in New Mexico, I-90 Fire in Montana (both in 2005), and Tripod Complex Fire in Washington

in 2006. Accordingly, the analysis below is focused on lidar measurement results obtained from these wildfires.

In June 2005, the lidar was deployed to the Bull Fire in the Black Range Complex in New Mexico's Gila National Forest as part of the Blue Sky RAINS effort. Diffuse smoke and smoke plume data were gathered during the four days of deployment. These measurements were accompanied with measurements made with a three-wavelength TSI nephelometer, a Radiance Research integrating nephelometer, a scanning mobility particle sizer (SMPS), and an aerodynamic particle size spectrometer (APS). However, the ground measurements with this in situ instrumentation provided some informative data only during early morning hours, when the temperature inversion held the smoke particulates on and close to the ground. Immediately after sunrise, the inversion weakened and disappeared, the smokes rose up, and the ground-based instrumentation operated in clear air conditions. As smoke plumes spontaneously appear and disappear, our lidar measurements were focused on investigating smoke plume dynamics and determining their heights. In Table 2, some results of the plume height measurements obtained from the lidar vertical scans at 1064 nm during Bull Fire are presented. As in the table, the range of the fixed maximal heights at the Bull Fire varied from ~ 1 km to ~ 4 km. Later, working in the vicinity of more heavy wildfires, we measured smoke plumes at much higher altitudes.

Table 2. Example of the lidar height plume measurements at Bull Fire, New Mexico

30-Jun-2005	Time	Max Elevation, (deg)	Azimuth	Range resolution (m)	Max Plume Height (m)	Distance from Lidar (m)
File 081	16:35	50	156	6	965	1150
File 086	16:40	50	159	6	1040	1330
File 087	16:41	50	159	6	1025	1520
File 134	17:30	50	158	6	970	1242
File 135	17:32	10	70	6	965	1240
2-Jul-2005						
File 132	13:07	54	139	6	3980	3460
File 133	13:08	54	139	6	4030	4030
File 134	13:09	54	139	6	4150	4445

In August 2006, the lidar was deployed to the wildfires in Montana, Idaho and Washington states. The most interesting data were measured during Tripod Complex Fire in Washington. During three days, from 19 to 21 August we measured vertical profiles of the smoke haze distribution, their temporal changes, and smoke-plume heights. A smoke plume scanned by the lidar on 21 August, 2006 at Tripod Complex Fire (Okanogan, WA) is shown in Fig. 3. During the time available for the measurement (12 min during which the smoke top was not screened by the terrain), the mean height of the top of the plume above the lidar was 7416 m (24,333 feet); the maximum measured height was 8165 m (26,788 feet).

Fig. 3. A smoke plume monitored by the FSL lidar at Tripod Complex Fire (Okanogan, WA) on 21 August 2006. The mean height of the top of the smoke was 7416 m and the maximum fixed height was 8165 m AGL.

To illustrate abilities of the lidar to monitor temporal changes in smoke particulate loading in the troposphere, we present below a set of vertical profiles of the backscatter signals, measured by the FSL lidar in August 2005, when the lidar was deployed to I-90 Fire in Montana. An extremely large number of local wildfires scattered over a large area during this period (Fig. 4). These scattered fires created numerous and intense smoke layers at different heights, which could be monitored far from the active flaming area up until at least midday, during the six days of deployment.

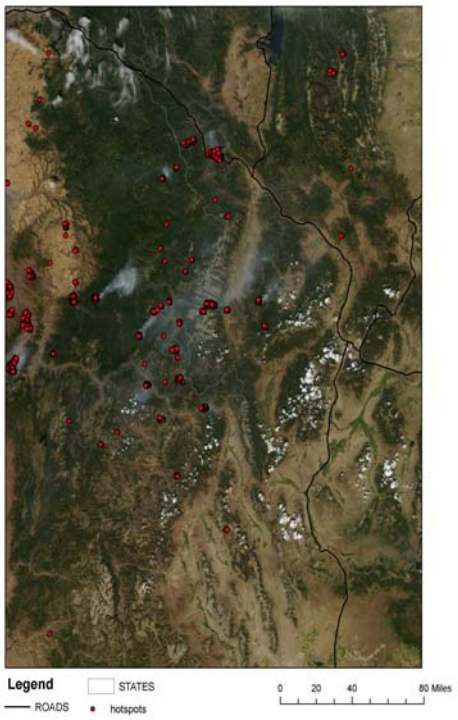

Fig. 4. Western Montana Fires on August 15, 2005, 14:40 MDT from satellite data.

In Fig. 5, a series of two-dimensional images of the vertical scans measured at wavelength 1064 nm are shown. These images were obtained on August 12, 2005, during the period from 9:17AM to 12:11 PM. The lidar scans shown in the figure were made at approximately one-hour intervals. The same as in Fig. 2(b), the color scale shows the intensity of the range-corrected backscatter signals in relative units. Smoke plume layers are seen as red and green horizontal structures. Note that initially, between 9:17 AM and 10:21 AM only one intense smoke layer existed over the altitudes from approximately 2200 m to 2900 m; almost no smoke pollution was observed

below it (Fig.5, two upper plots). One hour later, a thick smoke polluted layer appeared at the lower heights, located over the heights of ~700 – 2000 m (Fig. 5, two bottom plots).

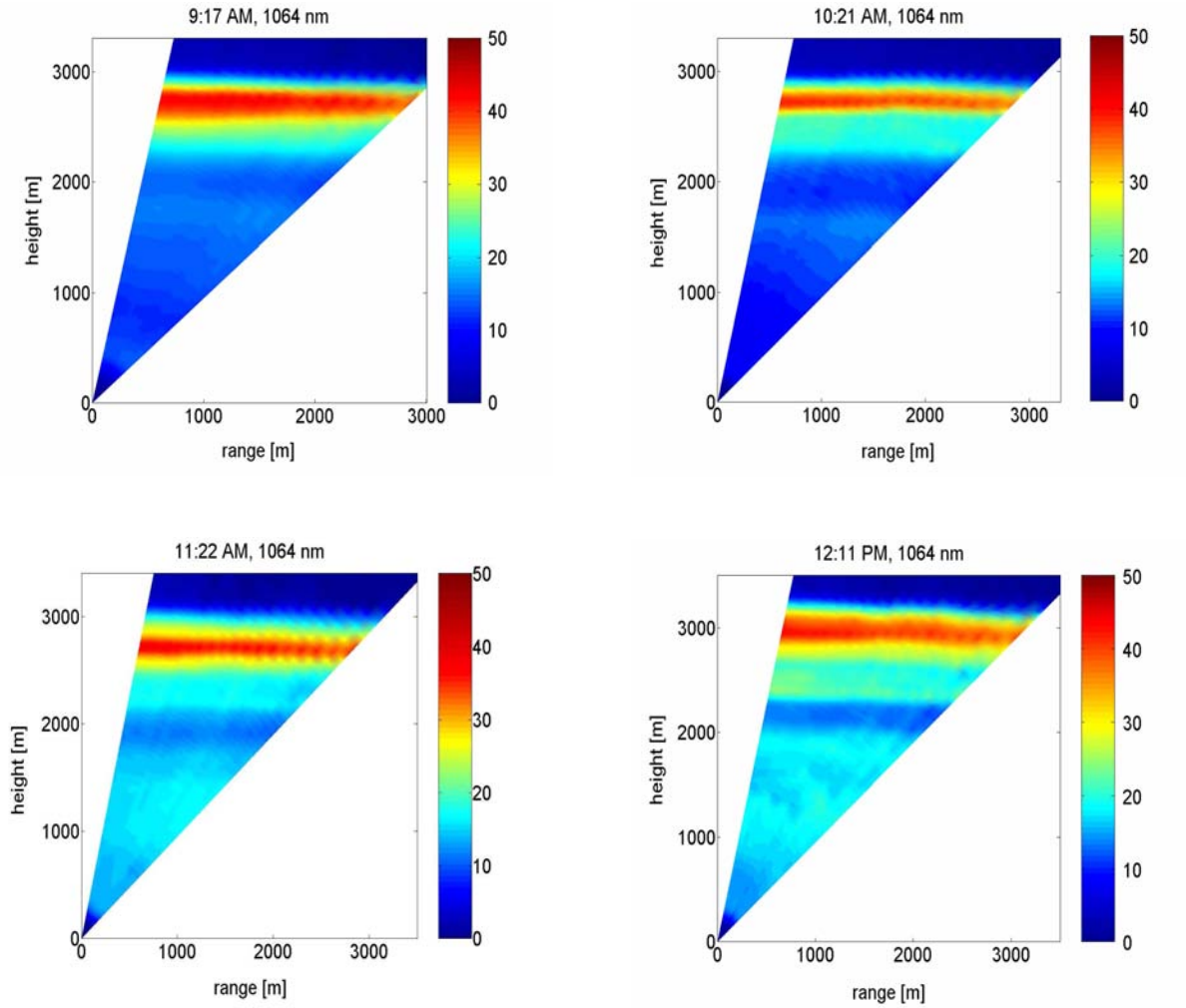

Fig. 5. Examples of the vertical lidar scans obtained over a temporal interval of approximately three hours in the vicinity of the Montana I-90 Fire on August 12, 2005. The color scale shows the relative level of backscattering. The blue colors show clear-air areas, the green and red colors show areas and layers polluted by smoke particulates. Note a significant transport of the smoke particulates down to heights below 2000 m in the bottom figures.

Our two-year measurements showed that such an atmospheric structure is typical in the vicinity of large wildfires. The measured profiles show well-defined smoke horizontal layering, located mostly at the heights of ~ 2000 - 3000 m. Such layers are typical in smoke-polluted atmospheres, when the morning inversion positions the smoke in a layer located above the planetary layer, and solar heating of the layer maintains the temperature inversion (Taubman et al., 2003). Finally, the inversion weakens, and the smoke layer

disperses. In some cases, strong downdrafts transport the smoke particulates downward worsening visibility and air quality on the ground level.

The different optical situations we encountered in the vicinity of wildfires required the development of different measurement technologies and lidar inversion algorithms for the extraction the smoke-particulate optical parameters of interest. As known (Müller, et al., 1999), to invert these optical data into particulate microphysical properties, the initial optical data must be obtained with an accuracy of better than 10-20%. Therefore, the development, validation, and improvement of the measurement technologies and corresponding software, which would allow reaching the required inversion accuracy, were the principal tasks during the fulfillment of the project.

3. Issues and Solutions for the Multiangle Lidar Measurement of Smoke Particulate Optical Characteristics

In the two years of 2005 and 2006, the lidar measurements in smoky atmospheres led us to conclude that the lidar searching in the vicinity of strong wildfires was much more informative and provided much more information on smoke particulate characteristics than those made in the vicinity of prescribed burns. The properly organized and fulfilled lidar searching in the vicinity of large wildfires could potentially provide valuable information on smoke plume dynamics and concentrations. However, before this could be achieved, the principal questions had to be answered, particularly: (1) What would be an optimal strategy and methodology when performing the lidar remote measurement in smoky atmospheres, and (2) What inversion algorithms had to be used to get the required information on the particulate optical properties in smoky polluted atmospheres.

The principal issue when utilizing elastic lidar for routine atmospheric measurements is an uncertainty of the solution for the elastic-lidar equation. The uncertainty is caused by the presence of two unknown functions (the extinction and the backscatter coefficients) in this equation. In order to separate these parameters of interest, a profile of the extinction-to-backscatter ratio (or the lidar ratio) should be known. Generally, it is not known, and therefore, is selected a priori. This specific is the main source of measurement error when searching the atmosphere with elastic lidar. The Kano-Hamilton multiangle data-processing technique (Kano, 1968; Hamilton, 1969), which applies the layer-integrated form of the angle-dependent lidar equation, is the only method that allows one to avoid the a priori selection of the ratio. However, the practical utilization of this technique requires a horizontally stratified atmosphere. Accordingly, the use of the lidar multiangle solution is impeded by three aggravating factors.

The first factor is the quite common atmospheric heterogeneity. Therefore, the classic multiangle methods often yield poor inversion results (Spinhirne et al., 1980; Russel and Livingston, 1984; Rothermal and Jones, 1985, are rarely used in lidar measurements. Although the real atmosphere is heterogeneous, in most cases the horizontal variability is significantly less than vertical changes in the aerosol loading. Therefore, the assumption of horizontal homogeneity is still more reasonable than the assumption of a height-

independent backscatter-to-extinction ratio (or lidar ratio), which is used in most one-directional, vertical elastic-lidar measurements.

The second factor is systematic distortion in any measured lidar signal. It significantly worsens the inversion accuracy of the retrieved extinction-coefficient profiles both in the near and far end of the lidar measurement range (Kovalev, 2004). The multiangle solution is extremely sensitive even to minor systematic distortions in inverted data (Kovalev and Eichinger, 2004; Kovalev et. al., 2007a).

Finally, the third aggravating factor is a deficiency in the inversion method of extracting the extinction coefficient from multiangle data, which is based on the numerical differentiation of the extremely noisy experimental data.

These three factors significantly impede the application of the multiangle measurement mode; therefore, they were the focus of the investigation of the FSL lidar team during the fulfillment of the project. A special measurement and data-processing technology was developed and tested; it allowed addressing the above issues.

3.1. Development of Measurement Methodology for the Scanning Lidar Operating in a Multiangle Mode

During conventional vertical scanning in a fixed azimuthal direction, any local cloud or smoke plume that intersects the line of scanning can distort measurement data. This significantly worsens the measurement accuracy, especially in areas close to wildfires. When using the conventional method of azimuthally fixed searching, the only option is to stop the measurement and wait until the cloud moves (under the condition that the wind blows in the "right" direction). Therefore, we had to modify the Kano-Hamilton method. In our modified variant, wide azimuthal scans and stepped slope scans were combined to reduce the influence of the atmospheric heterogeneity (Fig. 6). The implementation of

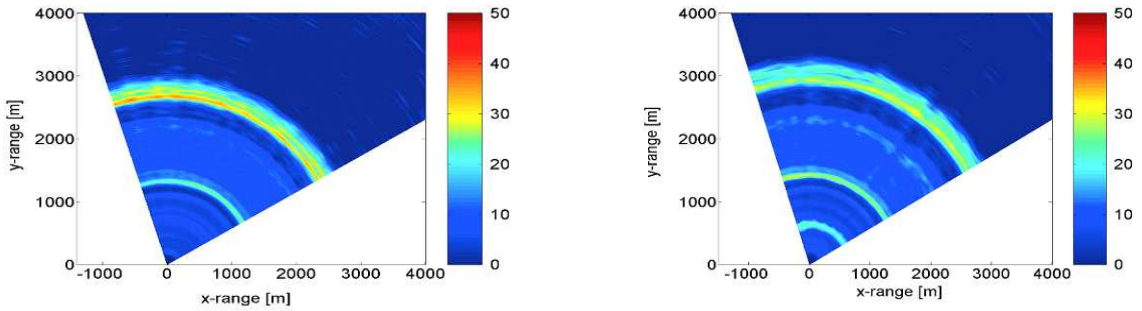

Fig. 6. Azimuthal scans measured at fixed elevation angles at 1064 nm in August 15, 2005. (a) 9:35 AM, Azimuth 30:3:110, Elevation 58°, and (b) 10:18 AM, Azimuth 30:3:110, Elevation 49°. The green and yellow arcs are multiple smoke-plume layering.

wide azimuthal scanning allowed us to exclude "bad" data by using the standard statistical analysis of the recorded signals measured at fixed slopes

The methodology was initially tested during six days between 28 February and 6 April 2005 at the Fire Sciences Laboratory test site located approximately 30 km west of Missoula, Montana. The measurements were made with two scanning lidars (FSL and Johns Hopkins University), which operated at the wavelengths 1064 nm and 355 nm, and at 1064 nm, 532 nm, and 355 nm, respectively. The experiments were made under clear atmospheric conditions, when the influence of atmospheric heterogeneity and instrumental random and systematic distortions on the measurement accuracy is most severe. The purpose of this study was to analyze and improve the classic Kano-Hamilton method for multiangle data obtained with an elastic lidar (Adam at el., 2007).

It is generally agreed that the inaccuracy of multiangle measurements takes place mainly due to atmospheric heterogeneity. Our analysis revealed that the problem is more cumbersome. We established that even minor instrumental errors that are often ignored could significantly worsen the accuracy of multiangle measurement methodology. This specific significantly impedes the use of the multiangle method even in an ideal homogeneous atmosphere. The method had to be improved in order be applied to experimental data in smoky atmospheres.

The application of the modified Kano-Hamilton method to experimental data obtained in clear atmospheres at different wavelengths also showed that the lidar signals measured at the shorter wavelength, 355 nm, yield much more accurate inversion results than those measured at longer wavelengths. The application of the method to the data from the 532 nm and 1064 nm channels yielded worse inversion results because these data were much more sensitive to the heterogeneity of particulate loading. In addition, the signal-to-noise ratio for the signals at 1064 nm was much worse than for the signals at 355 nm; accordingly, the total measurement range for the signal at 1064 nm was much shorter than that at 355 nm. The lidar measurements at 532 nm are more promising and we believe that this wavelength can also be used in multiangle measurements.

We tested three different wavelengths simultaneously for the multiangle method and experimentally corroborated that the shortest wavelength should be preferably used for the measurements even in clear atmospheres. This is true in spite of worsening the measurement accuracy of the particulate component due to the presence of a large molecular component. The large contribution of the molecular component (and accordingly, larger errors in the retrieved particulate component) is an unavoidable for this method. Our measurements also confirmed that the longer wavelengths provide much larger (in clear atmospheres, too large) errors in the retrieved particulate optical depth.

3.2. Modernization of the Signal Inversion Algorithm

The retrieval of the optical parameters of interest, the extinction coefficient and the backscatter-to-extinction or lidar ratio, in the multiangle method is a two-step procedure. During the first step, the slope and the intercept of the linear fit of the Kano-Hamilton

function are determined. The slope is proportional to the vertical optical depth and the intercept is proportional to the total backscattering. The second-step inversion procedure includes the extraction of the profiles of the particulate extinction coefficient and the lidar ratio (or the reversed value, the backscatter-to-extinction ratio). The extraction of these functions, which are key parameters related with the levels of smoke concentrations, are the most challenging operations due to the numerical differentiation of noisy profiles of the optical depth, obtained after fulfillment of the first-step inversion the lidar data. A large number of studies have been devoted to this issue (e.g., Whiteman, 1999; Rocadenbosch et al., 2000; Volkov et al., 2002; Rocadenbosch et al., 2004; Kovalev, 2002 and 2006; Kovalev et al., 2004), however, the issue has not been completely solved.

During this project, a new method was developed for improving the accuracy of the inversion of optical-depth and backscattering-coefficient profiles obtained from the multiangle mode lidar data from smoky atmospheres (Kovalev, et al., 2007b and 2007c). The extinction coefficient is retrieved from the profile of the backscattering coefficient rather than from the optical depth. The new method determines a stepwise profile of the column-integrated lidar ratio that provides the best match of the initial (inverted) profile of the optical depth to that extracted from the backscatter-coefficient profile. Two possible variants of this methodology were analyzed; in both cases, the retrieval of the extinction coefficient is made without using numerical differentiation. This method significantly reduces the level of random noise in the retrieved lidar ratio and extinction coefficient. Accordingly, the more accurate extinction coefficient and lidar ratio will then facilitate determining accurate values of the particulate concentration in smoke plumes.

In Fig. 7(a), an example of the lidar measurement results at 355 nm is shown. The measurement data were obtained in a smoky atmosphere in the vicinity of I-90 Fire on August 9, 2005. The vertical profiles of the particulate backscatter coefficient, shown at the left side of the figure and the particulate optical depth shown as the black dotted curve on the right side are used for the inversions. The dashed curves show the optical-depth uncertainty boundaries. The red curve is the corrected optical depth profile calculated using the derived extinction coefficient. The inversion result is shown in Figs. 7(b) and 7(c).

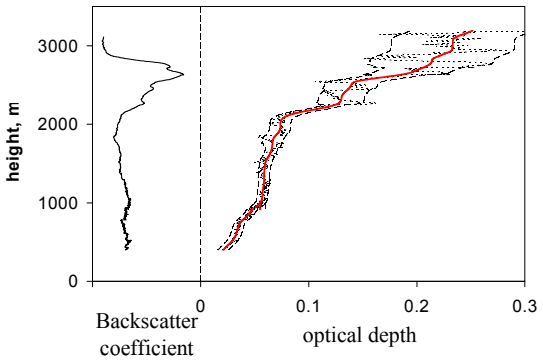

Fig. 7(a). The vertical profiles of the particulate backscatter coefficient (the left side) and the particulate optical depth (the black dotted curve on the right side) derived from the lidar signals and used for the retrieval the extinction coefficient and the column-integrated lidar ratios shown in Figs. 7(b) and 7(c), respectively.

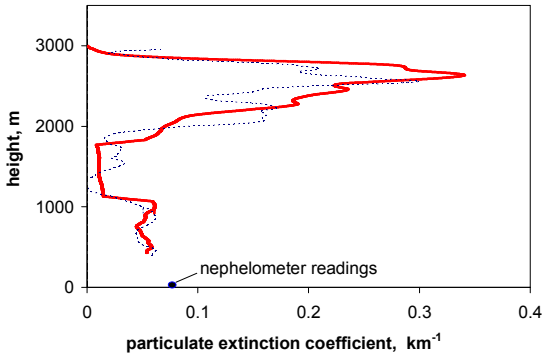

Fig. 7(b). The vertical profile of the particulate extinction coefficient obtained with the new method developed at the FSL (the red thick curve) and that obtained with the conventional method (the dotted curve).

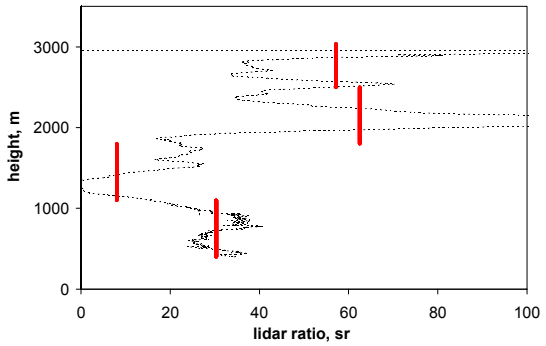

Fig. 7(c). The stepwise column integrated lidar ratio (the thick red lines) and the vertical profile of the lidar ratio extracted using the conventional method (the dotted curve).

We developed the lidar measurement methodology and the inversion algorithms that provide accurate profiles of the optical depth, the particulate extinction coefficient, and the backscatter-to-extinction ratio (or its reversed value, the lidar ratio). Although this task proved to be much more time-consuming than we expected, the FSL lidar team successfully fulfilled it. However, the next task, the transition from smoke-plume optical parameters to the smoke-particulate mass concentrations met significant difficulties, not related directly with specifics of the lidar measurements.

3.3. Concept of the Lidar Near-End Calibration

The determination of the vertical profiles of the smoke-particulate backscatter and extinction coefficient requires the determination of the lidar calibration constant. The most common way to achieve this purpose is the far-end lidar calibration, which is based on the assumption of the aerosol-free atmosphere at high altitudes. When such a calibration was possible, this approach was used in our multiangle measurements (Kovalev et al., 2007a and 2007b). However, the far-end lidar calibration has two significant drawbacks. First, the selection of the height of the aerosol-free area is rarely possible based on our knowledge. Generally, no reliable information is available and selection of the reference point for the calibration is based on indirect factors. Second, the lidar signals at the far-end, used for the calculation of the constant, have a poor signal-to-noise ratio and increased levels of systematic distortions. An additional drawback appears

when working in smoky-polluted atmospheres close to wildfires. In such highly polluted areas, the existence of the clear-air zones at the far-end lidar measurement range becomes problematic.

The most promising way to solve this issue would be the replacement of the far-end lidar calibration, in which the solution constant is found using the assumption of an aerosol-free atmosphere, with a near-end calibration. In this case, a reference point where the appropriate information is available is required within the near-end zone. The concept and the methodology of the lidar near-end calibration for scanning lidar were recently developed in the FSL. It requires the utilization of a special nephelometer, which should be located at the lidar measurement site (Wold et al., 2008). In this case, the near-end lidar signals with minimal systematic distortions and a good signal-to-noise ratio can be used for such a calibration. Obviously, no aerosol-free areas, the same as no assumptions on the existing atmospheric properties are required for the near-end calibration.

To implement the near-end calibration, a special in situ instrument, a ground-based fast-response backscatter nephelometer is required similar to that used by Doherty et al., (1999), and Anderson et al., (2000). Unfortunately, such instrumentation is not commercially available. Furthermore, as follows from our concept of the lidar calibration, an open-path backscatter nephelometer will be more preferable for this task rather than that used in the above-cited studies. The first experimental setup, the open-path backscatter nephelometer, which operates at 355 nm, is currently developed and will be tested during the future lidar use in the vicinity of fires.

4. Determination of the Smoke Particulate Concentration: Issues and Solutions

In September 2006, EPA revised the 1997 National Ambient Air Quality Standards (NAAQS) for particulate matter. These standards tightened the 24-hour fine particle mass PM2.5 standard, reducing it down to 35 $\mu g/m^3$, and retained the existing 24-hour PM10 standard of 150 $\mu g/m^3$. These EPA standards, regulating particulate matter, define PM2.5 as the mass less than 2.5 μm in diameter measured by the Federal Reference Method (FRM). To determine the level of particulate matter, the gravimetric analysis of filters sampled over a ~24 h period is used. The determination of PM2.5 is a manual method; it cannot be used to provide real-time analysis. To achieve real-time monitoring of PM2.5, continuous and automatic particulate-matter monitoring technologies must be used. During the past decades, a set of commercially available instrumentation has been developed which presumably provides the required real-time measurements of particulate matter. Unfortunately, at this time no such instrumentation for such continuous, real-time monitoring of particulate matter is certified. This significantly impedes our task of the adaptation of such a methodology for continuous monitoring of particulate mass concentrations for the lidar measurement technique.

4.1. Optical and Mass Concentration Measurements of the Smoke Particulate Matter Using the Combustion Facilities at the FSL

During the spring of 2006 and 2007, extensive optical and mass concentration measurements of smoke particulate matter were performed using the FSL combustion facilities. The goal of the controlled laboratory combustion of different wildland fuels was to investigate and characterize smoke particulate and gas emissions from wildland fires. The studies included the measurement of such properties of burning emissions as light scattering, light absorption, and mass concentration and their changes during the flaming and smoldering combustion phases. For these measurements, the most advanced techniques were used. These included different types of the nephelometers, aerosol mass spectrometers, a 7-wavelength aethalometer, a 2-wavelength photoacoustic instrument, filter samplers, and other instrumentation. The studies were performed by research teams from the National Park Service, the US Forest Service, Colorado State University, Desert Research Institute (Reno, NV), U.S. Environmental Protection Agency, University of Colorado, University of Nevada at Reno, Aerodyne Research, Inc., Montana State University, and Lawrence Berkley Labs.

In addition to the above experiments, comprehensive analyses of experimental data, previously obtained in the same combustion facility at the FSL, have been completed and published (Chen at el., 2006 and 2007).

Laboratory-controlled fires are extremely useful for investigating the effects of individual parameters (e.g., fuel, moisture, combustion phase, etc.) on the emission factors. However, they do not fully anticipate or reproduce the complex real-world fires. Therefore, special field experiments will be performed with direct sampling of emissions from prescribed burns during the spring of 2008, where the lidar and a set of auxiliary in situ instrumentation, including the open-air backscatter nephelometer, will be used.

4.2. Sources of the Uncertainty in the Transition from the Particulate Optical Parameters to the Particulate Mass Concentration

After new technologies for automated, continuous monitoring of the mass concentration and the corresponding in situ instrumentation became commercially available, a large number of investigations were made. The goal of these investigations was to clarify the accuracy of the results that might be provided with this commercially available but not standardized instrumentation. Numerous studies were performed where the mass concentration measured by the continuously operating instruments and that determined by the Federal Reference Method were compared. These comparisons revealed discrepancies, sometimes significant, in the results obtained with the FRM and the continuous methods (Lee et al., 2005; Reesa et. al, 2004; Tohno and Hitcenberger, 2000; Dvonch J. T. et al., 2000). Similar discrepancies in the measurement results were obtained when comparing the mass concentrations measured by different types of the continuously operating instrumentation (Weingartner et al., 2003; Arnott et al., 2003; Moosmüller et al., 2001).

The increase in wildfire intensity and their influence on potential climate changes has excited the lidar community to investigate the application of the lidar technique to measure smoke particulates. As compared to the above in situ instrumentation, lidar has a great advantage and large potential for remote sensing of smoke particulates over extended areas. This is due to the possibility that the instrument is capable of measuring smoke optical characteristics and simultaneously characterizing both the scattering and absorption properties of smoke particulates over distances up to 10 -12 km.

Early attempts to apply lidar for smoke-concentration measurements were made as long ago as in the early eighties (e. g., Jennings and R. G. Pinnick, 1980; Ezcurra et al., 1985). More recently, a set of studies were made in which the relationship between the lidar-derived optical parameters and microphysical characteristics of the particulate matter were investigated (Del Guasta, 2002; Ferguson et al., 2003; Cheng et al, 2006; Del Guasta et al., 2007; Pesch and Oderbolz, 2007; Shinozuka et.al, 2007; Wilkerson et al., 2007). However, the results obtained in these studies are preliminary. They are based on insufficient statistics and cannot be used for routine smoke measurements.

The basic issue in utilizing lidar for mass concentration measurement is as follows: As with any optical instrument, the lidar methodology for continuous measurement of the particulate mass concentration must be based on some reliable relationships between light scattering and the mass concentration. As mentioned, the transition from the optical parameters of the aerosol particulates to their mass concentration is difficult problem which has not been solved. The currently available optical instrumentation is still not able to provide the reliable measurement of particulate mass concentration with an acceptable accuracy.

The basic, unsolved issues of the above transition are as follows (Bohren and Huffman, 1983; Bergstrom et al., 2002; Del Guasta, 2002; Nessler et al., 2005; Lee et al., 2005; Andreae and Gelencser, 2006; Sun et al., 2007):

(1) The retrieval of particulate microphysical parameters from optical data is based on an inversion algorithm that includes Fredholm integral equations of the first kind. This difficult problem is exacerbated by the fact that the measurable optical parameters stromgly depend on the number of particulates and their size distribution rather than on the quantity of interest, the mass concentration of PM2.5 and PM10.

(2) The carbonaceous particulates originating in wildfires increase the absorption component in the measured light extinction. The absorption component is related with the concentration of black carbon, and thus, this quantity should be determined. Meanwhile, the accurate determination of the absorption component through the measurement of light scattering is always difficult, sometimes even impossible.

(3) The discovery of the light-absorbing carbon that is not black, the so-called “brown carbon” made it imperative to reconsider the components that make up light-absorbing matter [Andreae and Gelencser, 2006; Sun et al., 2007). This discovery also forced researchers to investigate the carbonaceous particulate concentration, focusing their

studies on multiwavelength rather than on single-wavelength measurements (Lewis et al., 2007, in print). This issue impedes a comprehensive investigation of practical dependencies between optical characteristics of the smoke plume particulates, derived with lidar, and the mass concentration extracted from the reference instrumentation.

5. Summary: What Information about Smoke Particulate Matter Can Be Obtained With the FSL Research-Grade Lidar and Future Tasks

When lidar is utilized for searching the atmosphere, three levels of data processing can be used, yielding different levels of information:

(1) The Level 1 investigates the shape of the backscatter signal when scanning smoke plumes. It does not require signal inversion; however, all components of the measured signal not related with the laser backscattered light are removed, the backscatter signal is square-range corrected, and the near and the far end boundary ranges (heights) within which the information is not distorted are established. This level is required to obtain information on smoke plume dynamics, the spatial and temporal changes of the smoke layering, and smoke plume heights.

(2) The Level 2 requires signal inversion; the inversion is made using the backscatter signals obtained with Level 1 in the multiangle mode. The retrieved information includes the vertical profiles of the optical depth, the backscatter and extinction coefficients, and the backscatter-to-extinction ratio.

(3) The Level 3 is reached when the information on the optical properties of aerosol (smoke) particulates is transformed into information on the microphysical properties of the particulates (e.g., the particulate number and mass concentration, the size distribution, etc.).

Our current measurement methodology and inversion algorithms allow us to extract from our lidar measurement data the information at Level 1 and 2. To provide good accuracy of the inverted data at Level 2, the data of the supplementary in situ instrumentation, located at the lidar measurement site, is used. The in situ instrumentation consists mainly of a commercially available three-wavelength integrating nephelometer, TSI, model 3563, and periodically, the scanning mobility particle sizer. However, to achieve the better inversion accuracy of the scanning lidar data, additional in situ instrumentation is required. This instrumentation is needed for the operative lidar calibration, which requires the knowledge of a reference value of the backscatter coefficient. Currently such instrumentation is not commercially available. We have developed a new principle of near-end calibration for the scanning lidar, and are now in the process of development of a special research-grade backscatter nephelometer.

As stated above, there exists no theoretical basis that would provide the reliable information needed for Level 3, at least when using aerosol optical characteristics derived from single wavelength. Single, one-functional relationships (e.g., relationship between the mass concentration and the optical depth or between the mass concentration and the

extinction coefficient) cannot provide acceptable accuracy for the determination of mass concentration. Up until now, no unique and practically usable dependencies have been established between the optical and microphysical characteristics, such as the mass concentration of black and brown carbon. This issue can only be solved by establishing statistically ensured, empirical dependencies that allow the transition from optical parameters measured by lidar at different wavelengths to mass concentration of carbonaceous particulates. The improved accuracy at Level 3 can be achieved only if some number of optical characteristics of the smoke aerosol at different wavelengths is related to the particulate concentration (Müller et al., 1999, 2000, and 2001; Veselovskii et al., 2002 and 2005).

The implementation of additional auxiliary instrumentation, which operates while fulfilling lidar scanning, will facilitate the determination of smoke aerosol levels and their temporal change on ground level, including populated areas and areas near fire camps.

6. Deliverables

Proposed	**Accomplished/Status**
Develop the lidar-measurement technology to determine the three-dimensional distribution of smoke particulate matter concentration in the atmospheres polluted by the wildland fire	The methodology for the continuous lidar operation in the combined azimuthal/slope multiangle measurement mode was developed. The corresponding inversion algorithms and software were implemented which allowed determining the optical characteristics of the smoke plume particulates, their spatial boundaries, and the presence and basic optical properties of the horizontally-extended smoke layering in the atmospheres polluted by the wildland fire.
Develop the technology to measure smoke plumes heights, dynamics, and dispersion in areas of wildfires and prescribed burns to validate smoke dispersion models	An improved algorithm and the corresponding lidar software for determining the spatial boundaries of the smoke plume rise and dispersion were developed and tested in areas of wildfires and prescribed burns.
Monitoring the optical situation in smoke polluted atmospheres adjacent to severe wildfires, including diurnal and daily spatial variation of aerosol levels, and plume heights and dynamics	Monitoring of the optical properties in smoke polluted atmospheres adjacent to severe wildfires were made in New Mexico (Bull Fire), Montana (I-90 Fire, Woodchuck Fire, Gash Creek Fire), Idaho (Potato Fire), and Washington (Tripod Complex Fire, Derby Fire).

Investigation of the dependencies between the optical characteristics of the smoke particulates and their mass concentration to provide estimates of the levels of PM-2.5 and PM-10	In 2006 and 2007, optical and mass measurements of the smoke particulate matter were performed using the FSL combustion facilities. A comprehensive analysis of the experimental data previously obtained in these combustion facilities were completed and published.
None	A new method of a near-end calibration for the scanning lidar was developed, and a research-grade backscatter nephelometer for the calibration has been developed.
Publications	Appendix 2
Presentations	Appendix 3
Final Presentation and Publication	Oral presentation and the paper in Proceedings of the SPIE International Symposium on Optical Engineering. Section Remote Sensing on Fire: Science and Application, 10-14 August, 2008, San Diego, CA, USA

7. References

Adam, M., "Development of lidar techniques to estimate atmospheric optical properties", Ph. D. Dissertation, John Hopkins University, 2005.

Adam, M., V. Kovalev, C. Wold, J. Newton, M. Pahlow, Wei Min Hao, and M. Parlange, "Application of the Kano-Hamilton multiangle inversion method in clear atmospheres," *J. Atmosph. Oceanic Technol.,* **24**, 2014-2028, 2007.

Anderson, T. L., S. J. Masonis, D. S. Covert, R. J. Charlson, and M. J. Rood, "In situ measurement of aerosol-to-backscatter ratio at a polluted continental site," *J. Geoph. Res*., **105**, No. D22, 26907-26915, 2000.

Andreae, M. O. and A. Gelencser, "Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols," *Atmos. Chem. Phys*., **6**, 3131-3148, 2006.

Arnott, W. P., H. Moosmuller, P.J. Sheridan, J. A. Ogren, R. Raspet, W. V. Slaton, J. L. Hand, S. M. Kreidenweis, and J. L. Collett Jr., "Photoacoustic and filter-based ambient aerosol light absorption measurements: Instrument comparisons and the role of relative humidity," *Journ. Geoph. Res.*, **108(D1)**, 4034, doi:10.1029/2002JD002165, 2003.

Bergstrom, R. W., P. B. Russell, and P. Hignett, "Wavelength dependence of the absorption of black carbon particles:Prediction and results from the TARFOX experimentand implications for the aerosol single scattering albedo," *Journ. Atmosph. Sci*., **59(3)**, 567-577, 2002.

Bohren, C. F. and D. R. Huffman, "Absorption and scattering of light by small particles," Wiley Science Paperback Series, 1998.

Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and Wei Min Hao, "Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles," *Environ. Sci. Technol*., vol. 41, 4317-4325, 2007.

Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and Wei Min Hao, "Particle emissions from laboratory combustion of wildland fuels: In situ optical and mass measurements," *Geophis. Res. Letters,* vol. 33, L04803, doi:10.1029/2005GL024838, 2006.

Cheng, A. Y. S., A. Viseu, R. L. M. Chan, K. S. Tam, and K. I. Lam, "Studies of urban aerosol in Macao using a horizontal Mie lidar," ," in Proceedings of the *Twenty Third International Laser Radar Conference* (ILRC23), Nara, Japan, 643-646, 2006.

Del Guasta, M., "Daily cycles in urban aerosols observed in Florence (Italy) by means of an automatic 532-1064 nm lidar," *Atmosph. Environ.*, **36**, 2853-2865, 2002.

Del Guasta, M., F. Castagnoli, M. Baldi, and V. Venturi, "An automatic, low-cost telemetric lidar for continuous monitoring of urban aerosols in the surface layer," *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing*, Proceedings of SPIE **6750**, 6750OL-1 – 67500L-9, 2007.

Doherty, S., T. L. Anderson, and R. J. Charlson, "Measurement of the lidar ratio for atmospheric aerosols using a 180^0-backscatter nephelometer," *Applied Optics*, **38**, 1823-1832, 1999.

Dvonch, J. T., F. J. Marsik, G. J. Keeler, T. G. Robins, F. Yip, and M. Morishita, "Field comparison of TM2.5 TEOM and TM2.5 manual filter-based measurement methods in urban atmospheres," *J. Atmos. Sci*., **31**, S190-S191, 2000.

Ezcurra, A., B.Benech, P. V. Dinh, and J. L. Lesne, "Investigation of a 1000 mw smoke plume by means of a 1.064 μm lidar. -1. Lidar calibration procedure from in situ aerosol measurements and vertical lidar shots," *Atmosph. Environ.*, **19**, 1125-1133, 1985.

Ferguson, S. A., R. L. Collins, J. Ruthford, and M. Fukuda, "Vertical distribution of nighttime smoke following a wildland biomass fire in boreal Alaska," *J. Geoph. Res*., **108(D23)**, 4743, doi:10.1029/2002JD003324, 2003.

Hamilton, P. M. "Lidar measurement of backscatter and attenuation of atmospheric aerosol," *Atmos. Environ.*, **3**, 221-223, 1969.

Jennings, S. G. and R. G. Pinnick, "Relationships between visible extinction, absorption, and mass concentration of carbonaceous smokes," *Atmosph. Environ.*, **14**, 1123-1129,

1980.

Kano, M., “On the determination of backscattered and extinction coefficient of the atmosphere by using laser radar,” *Papers Meteorol. and Geophys.*, **19**, 121-129, 1968.

Kovalev, V. A., “Stable near-end solution of the lidar equation for clear atmospheres,” *Applied Optics*, **42**, 585-591, 2003.

Kovalev, V. A., “Near-end solution for lidar signals that includes a multiple scattering component,” *Applied Optics*, **42**, 7215-7224, 2003a.

Kovalev, V. A., “Distortions of the extinction coefficient profile caused by systematic errors in lidar data,” *Applied Optics*, **43**, 3191-3198, 2004.

Kovalev, V. A. and W. E. Eichinger, *Elastic lidar. Theory, practice, and analysis methods*, J. Wiley & Sons Inc., 615 p., 2004.

Kovalev, V. A., R. A. Susott, and Wei Min Hao. “Inversion of lidar signals from dense smokes contaminated with multiple scattering”; in *Laser Radar Technology for Remote Sensing*, Proceedings of SPIE **5240**, 214-222, 2004.

Kovalev, V. A., J. Newton, C. Wold, and Wei Min Hao “Simple algorithm to determine the near-edge smoke boundaries with scanning lidar,” *Applied Optics*, **44**, 1761-1768, 2005.

Kovalev, V. A., “Determination of slope in lidar data using a duplicate of the inverted function,” *Applied Optics*, **45**, 8781-8789, 2006.

Kovalev, V. A., W. M. Hao, C. Wold, and M. Adam, "Experimental method for the examination of systematic distortions in lidar data," *Applied Optics*, **46**, 6710-6718, 2007a.

Kovalev, V. A., Wei Min Hao, and C. Wold, “Determination of the particulate extinction-coefficient profile and the column-integrated lidar ratios using the backscatter-coefficient and optical-depth profiles,” *Applied Optics*, **46**, 8627-8634, 2007b.

Kovalev, V. A., C. Wold, Wei Min Hao, and B. Nordgren, ”Improved methodology for the retrieval of the particulate extinction coefficient and lidar ratio from the lidar multiangle measurement,” in *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing*, Proceedings of SPIE **6750**, 67501B-1 - 67501B-9, 2007c.

Lagrosas , N., H. Kuze, N. Takeuchi, S. Fukagawa, G. Bagtasa, Y. Yoshii, S. Naito, and M. Yabuki, “Correlation study between suspended particulate matter and portable automated lidar data,” *J. Aerosol Sci.*, **36**, 439-454, 2005.

Lee, J. H., P. H. Hopke, T. M. Holsen, and A. V. Polissar, "Evaluation of continuous and filter-based methods for measurimg PM2.5 mass concentration," *Aerosol Sci. & Technol.*, **39**, 290-303, 2005.

Lewis, K., W. P. Arnott, H. Moosmüller, and C. E. Wold, "Strong spectral variation of biomass smoke light absorption and single scattering albedo observed with a novel dual wavelength photoacoustic instrument," Submitted to *Journ. Geophys. Res.,* 2007.

Müller, D., U. Wandinger, and A. Ansmann, "Microphysical particle parameters from extinction and backscatter lidar data by inversion with regularization: simulation," *Applied Optics*, **38**, 2358-2368, 1999.

Müller, D., F. Wagner, U. Wandinger, A. Ansmann, M. Wendisch, D. Althausen, and W. von Hoyningen-Huene, "Microphysical particle parameters from extinction and backscatter lidar data by inversion with regularization: experiment," *Applied Optics*, **39**, 1879-1892, 2000.

Müller, D., U. Wandinger, D. Althausen, and F. Wagner, "Comprehensive particle characterization from three-wavelength Raman-lidar observations: case study," *Applied Optics*, **40**, 4863-4869, 2001.

Moosmüller, H., W. P., Arnott, C. F. Rogers, J. L. Bowen, J. A. Gillies, W. P. Pierson, J. F. Collins, T. D. Durbin, and J. M. Norbeck, " Time resolved characterization of diesel particulate emissions. 2. Instruments for particle mass measurements," *Environ. Sci. Technol*., 781-787, 2001.

Nessler, R., E. Weingartner, and U. Baltensperger, "Effect of humidity on aerosol light absorption and its implications for extinction and the single scattering albedo illustrated for a site in the lower free atmosphere," *Journ. Aerosol Sci.*, **36**, 958-972, 2005.

Pesch, M and D. C. Oderbolz, "Calibrating a backscatter lidar for continuous measurements of PM2.5," in *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing*, Proceedings of SPIE **6750**(19), 2007 (in print).

Reesa, S. L., A. L. Robinson, A. Khlystovd, C. O. Stanierd and S.N. Pandisb, "Mass balance closure and the Federal Reference Method for PM2.5 in Pittsburgh, Pennsylvania," *Atmos. Environ.*, **38**, No. 20, 3305-3318, 2004.

Rocadenbosch, F., A. Comeron, and L. Albiol, "Statistics of the slope-method estimator," *Applied Optics*, **39**, 6049-6057, 2000.

Rocadenbosch, F., M. Sicard, and A. Comeron, "Automated variable-resolution algorithm for Raman extinstion retrieval," In: Proceedings of ILRC22, *Lidar Remote Sensing in Atmospheric and Earth Sciences*, Matera, Italy, 2004.

Rothermal, J. and W. Jones, "Ground-based measurements of atmospheric backscatter and absorption using coherent CO2 lidar," *Applied Optics*, **24**, 3487-3496, 1985.

Russel, P. B., and J. M. Livingston, "Slant-lidar aerosol extinction measurements and their relation to measured and calculated albedo changes," *J. Clim. Appl. Meteorol.*, **23**, 1204-1221, 1984.

Shinozuka, Y., et.al, "Aircraft profiles of aerosol microphysics and optical properties over North America: Aerosol optical depth and its association with PM2.5 and water uptake," *J. Geoph. Res.,* 112, D12S20, doi:10.1029/2006JD007918, 2007.

Spinhirne, J. D., J. A. Reagan, and B. M. Herman, "Vertical distribution of aerosol extinction cross section and inference of aerosol imaginary index in the troposphere by lidar technique," *J. Appl. Meteorol.*, 19, 426-438, 1980.

Sun, H., L. Biedermann, and T. C. Bond, "Color of brown carbon: A model for ultraviolet and visible light absorption by organic carbon aerosol," *Geophys. Res. Letters*, **34**, doi:10.1029/2007GL029797.

Taubman, B. F., et al., Smoke over haze: Aircraft observations of chemical and optical properties and the effects of heating rates and stability, J. Geoph. Res., 109, DO2206, doi:10.1029/2003JD003898.

Tohno, S. and R. Hitcenberger, "Comparison of ambient carbon particulate monitor and filter sampling for black carbon measurement, *J. Atmos. Sci*., **31**, S315-S316, 2000.

Veselovskii, I., A. Kolgotin, V. Griaznov, D. Müller, U. Wandinger, and D. N. Whiteman, "Inversion with regularization for the retrieval of tropospheric aerosol parameters from multiwavelength lidar sounding," *Applied Optics*, **41**, 3685-3699, 2002.

Veselovskii, I., A. Kolgotin, D. Müller, and D. N. Whiteman, "Information content of multiwavelength lidar data with respect to microphysical particle properties derived from eigenvalue analusis," *Applied Optics*, **44**, 5292-5303, 2005.

Volkov, S. N., B. V. Kaul, and D. I. Shelefontuk, "Optimal method of linear regression in laser remote sensing," *Applied Optics*, **41**, 5078-5083, 2002.

Weingartner, E., H. Saathoff, M. Schnaiter, N. Streit, B. Bitnar, and U. Baltensperger, "Absorption of light by soot particles:determination of the absorption coefficient by means of aethalometers," *J. Aerosol Sci.*, **34**, 1445-1463, 2003.

Whiteman, D. N., "Application of statistical methods to the determination of slope in lidar data," *Applied Optics***, 15**, 3360-3369, 1999.

Wilkerson, T. D., G. E. Bingham, V. V. Zavyalov, C. Marchant, J. M. Anderson, and L. P. Andrew, "AGLITE: a multiwavelength lidar for measuring particle sizes,

concentrations and fluxes emitted from agricultural operations," *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing*, Proceedings of SPIE **6750**, 6750O1-1 – 6750O1-12, 2007.

Wold, C., V. A. Kovalev, and Wei Min Hao, "Backscatter nephelometer to calibrate scanning lidar," submitted in Proceedings of ILRC24, 2008.

Appendices

Appendix 1. Lidar and Supplemental In Situ Instrumentation

The FSL mobile laboratory is equipped with the remote sensing instrument (lidar) and a set of the data-point measurement instrumentation that provides the flexibility and mobility to deploy a field monitoring operation. It includes the following instrumentation:

Lidar

Fig. 8. FSL scanning lidar

The FSL mobile lidar is a small scanning lidar that uses elastic backscattering to obtain the relative distribution and properties of smoke particulate and the amount of atmospheric attenuation. The lidar operates at the wavelengths 355 nm and 1064 nm and allows to conduct research related to smoke plume dynamics, propagation, and properties.

The elements of the lidar are shown in Fig. 8. A short-pulsed Nd:YAG laser (1) operating at 355 nm and 1064 nm is used as the light source. The laser is attached to the top of a Cassegrain telescope (2). The laser beam is emitted parallel to the telescope after going through a periscope (3), so that the effective exit aperture is a certain distance (0.41 m) apart from the center of the telescope. The periscope simplifies the alignment of the laser beam and increases the distance at which the laser beam overlaps the telescope field of view, thus increasing the total measurement range. The telescope-laser system is able to turn rapidly through 180° horizontally and 90° vertically using computer-controlled motors incorporated into the telescope mount (4). The lidar can be operated during day and night.

Due to its compactness and portability, the lidar can easily be deployed to the field site of interest. The scanning capabilities can be categorized as follows:

- Two-dimensional spatial scan: An image ("slice") of relative aerosol concentration is developed from individual lidar lines of sight (horizontal or vertical).

- Three-dimensional spatial scan: A series of horizontal scans at different elevation angles in a given region of the atmosphere.
- Time-domain scan: Represents data collected from a single line of sight for particular scan duration.

The lidar system specifications are given in Table 3.

Table3. JHU lidar system specifications.

Laser	BigSky laser, model CFR400; Q-switched Nd:YAG with 98mJ (1064nm), and 45mJ (355nm); 30 Hz repetition rate; 8 ns pulse duration; 1 mrad beam divergence;
Telescope	Cassegrain f/10, 10 in. diameter, 5mrad FOV (Meade LX200)
Detector	1064 nm - IR-enhanced Si avalanche photodiode; 355 nm – photomultiplier.
Digitizer	Dual 12-bit 125 MHz, dual channel (Signatec PDA12A)
Minimal range resolution	1.2 m
Incomplete overlap length	~ 1000 m
Scanning system	Azimuth rotary stage (180:1), stepper motors & encoders, elevation right angle reducer (100:1), AT6400 controller (Compumotor)

In Situ Instrumentation

1. Three-wavelength integrating nephelometer (TSI, model 3563) at 450, 550 and 700 nm wavelengths with the angular integration of the scattered light
2. Single-wavelength integrating nephelometer (Radiance Research, model 903) for determining scattering coefficient at the wavelength 530 nm
3. Scanning mobility particle sizer (SMPS) (TSI, model 3936 L25) for measuring submicron aerosol size distributions in the diameter range of 0.01-1 μm

Appendix 2. Publications:

Papers:

- V. A. Kovalev, Wei Min Hao, and C. Wold, "Determination of the particulate extinction-coefficient profile and the column-integrated lidar ratios using the backscatter-coefficient and optical-depth profiles," *Applied Optics*, vol. 46, 8627-8634, 2007.

- M. Adam, V. Kovalev, C. Wold, J. Newton, M. Pahlow, Wei Min Hao, and M. Parlange, "Application of the Kano-Hamilton multiangle inversion method in clear atmospheres," *J. Atmosph. Oceanic Technol.*, vol. 24, 2014 -2028, 2007.

- V. A. Kovalev, W. M. Hao, C. Wold, and M. Adam, "Experimental method for the examination of systematic distortions in lidar data," *Applied Optics***,** vol. 46, 6710-6718, 2007.

- Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and Wei Min Hao, "Emissions from Laboratory Combustion of Wildland Fuels: Emission Factors and Source Profiles," *Environ. Sci. Technol*., vol. 41, 4317-4325, 2007.

- V. Kovalev, "Determination of slope in lidar data using a duplicate of the inverted function," *Applied Optics*, vol. 45, No. 34, pp. 8781-8789, 2006.

- Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and Wei Min Hao, "Particle emissions from laboratory combustion of wildland fuels: In situ optical and mass measurements," *Geophis. Res. Letters,* vol. 33, L04803, doi:10.1029/2005GL024838, 2006.

- V. A. Kovalev, J. Newton, C. Wold, and Wei Min Hao "Simple algorithm to determine the near-edge smoke boundaries with scanning lidar," *Applied Optics*, vol. 44, 1761-1768, 2005.

Proceedings

- V. Kovalev, C. Wold, Wei Min Hao, and B. Nordgren, "Improved methodology for the retrieval of the particulate extinction coefficient and lidar ratio from the lidar multiangle measurement," *Lidar Technologies, Techniques, and Measurements for Atmospheric Remote Sensing*, Proceedings of SPIE **6750**, 67501B-1 - 67501B-9, 2007.

- V. A. Kovalev, C. Wold, J. Newton, and Wei Min Hao, "Determination of extinction coefficient profiles from multiangle lidar data using a 'clone' of the optical depth," in Proceedings of the Twenty Third International Laser Radar Conference (ILRC23), Nara, Japan, 283-286, 2006.

- V. A. Kovalev, C. Wold, J. Newton, and Wei Min Hao, "Combination of one-directional and multiangle data processing techniques to reduce uncertainty in the elastic lidar measurement data," in *Laser Radar Techniques for Atmospheric Sensing*, Proceedings of SPIE **5575**, 2004.

Appendix 3. Presentations:

- V. Kovalev, C. Wold, Wei Min Hao, and B. Nordgren, "Improved methodology for the retrieval of the particulate extinction coefficient and lidar ratio," Presentation at the SPIE Europe Remote Sensing Conference," Florence, Italy, 17-20 September 2007.

- V. Kovalev, J. Newton, C. Wold, and Wei Min Hao, "Determination of extinction coefficient profiles from multiangle lidar data using a duplicate ('clone') of the optical depth," Presentation at the ILRC23, Nara, Japan, 24 - 28 July, 2006.

- W. M. Hao, V.A. Kovalev, J.O. Newton, C.E. Wold, "Lidar - advanced technology for measuring smoke plume properties, boundaries and heights," Presentation at the JFSP Workshop, 2006.

- W. M. Hao, V. Kovalev, and S. P. Urbanski , "Air Quality forecasting using real-time modis data and lidar's plume measurements," Presentation at the Jet Propulsion Laboratory, Pasadena, CA, 2005.

- V. A. Kovalev, C. Wold, J. Newton, and Wei Min Hao, "Combination of one-directional and multiangle data processing techniques to reduce uncertainty in the elastic lidar measurement data," Presentation at the SPIE Remote Sensing Conference, Maspalomas, Gran Canaria, Spain, 14-16 September 2004.