Proceedings of 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington, USA
Published by the International Association of Wildland Fire, Birmingham, Alabama, USA

# Validation of smoke plume rise models using ground based lidar

Cyle E Wold[A,B], Shawn Urbanski[A], Vladimir Kovalev[A], Alexander Petkov[A], Wei Min Hao[A]

[A] U.S. Forest Service, RMRS Fire Sciences Laboratory, Missoula, MT 59808, USA.
[B] Corresponding author. E-mail: cwold@fs.fed.us

**Abstract**
Biomass fires can significantly degrade regional air quality. Plume rise height is one of the critical factors determining the impact of fire emissions on air quality. Plume rise models are used to prescribe the vertical distribution of fire emissions which are critical input for smoke dispersion and air quality models. The poor state of model evaluation is due in large part to a lack of appropriate observational datasets. We have initiated a research project to address this critical observation gap. A ground-based, mobile elastic scanning lidar (**li**ght **d**etection **a**nd **r**anging) instrument and data-processing methodology have been developed at the Missoula Fire Science Laboratory to study the three-dimensional plume dynamics and the optical properties of smoke particles over large prescribed fires and wildfires. The lidar measurements are being used to validate several plume rise models, including the Briggs equations which are used in VSMOKE and other smoke management tools. We present the validation results and provide recommendations regarding application of the models to wildland fire.

## Introduction

Tightening standards governing air quality have increased the pressure on land management agencies to address the air quality impact of wildland fire use and prescribed burning. Land management agencies need rigorously tested, accurate models to quantify the contribution of fire emissions to air pollution and visibility impairment.

Accurately describing and predicting smoke plumes and subsequent smoke transport is a major uncertainty in determining the impact of fire emissions on air quality. While many smoke plume models exist, few smoke plume observational datasets are available to properly validate these models and quantitatively assess their uncertainties, biases, and application limits.

We have initiated a research project to acquire the data needed for evaluation of plume rise and smoke dispersion models. The project deploys a ground based, mobile lidar and an airborne instrument package to investigate smoke plume dynamics, smoke aerosol distribution and chemical composition in and around active wildfires and large prescribed fires. Multiple wildland fires have been investigated over a two year period to measure plume rise and smoke transport over a wide range of meteorological, fire activity, fuel, and terrain conditions.

We have developed a new lidar data processing technique based on the concept of the Atmospheric Heterogeneity Height Indicator (AHHI) that enables the automatic determination of plume heights and the processing of large volumes of data (Kovalev *et al.* 2010).

## Instrumentation

### *Lidar*

Lidar measurements were made using a mobile, Q switched Nd:YAG scanning elastic lidar operating at wavelengths 1064 nm and 355 nm with 98 mJ and 45 mJ energy, respectively. The receiver section of the lidar consists of a 10 in. UV enhanced Schmidt-Cassegrain telescope with two detectors – a cooled, IR enhanced, avalanche photodiode for detection of the 1064 nm signal and a photomultiplier tube for detection of the 355 nm signal. The lidar scan range is 0° - 180° in azimuth and 0° - 90° in elevation.

*Aircraft*
The Forest Service Region 1 Cessna 206 was equipped with a Radiance Research M903 single wavelength nephelometer, a LICOR LI-6262 $CO_2/H_2O$ analyzer and a grab bag system for gas collection and later Gas Chromatograph analysis. Mass concentration of the particles with an aerodynamic diameter < 2.5 micron (an EPA criteria pollutant, PM2.5), is derived from the nephelometer scattering results using the calibration equation $C_{PM2.5}$ = 0.2148 (±0.0092) μg $m^{-2}$ x $B_{scat}$ $m^{-1}$. The calibration was derived by sampling smoke in the lab and then correlating the integrated scattering of the nephelometer with the particulate weights collected on co-located filter samples.

## Lidar data processing

*The normalized intercept function*
In principle, lidar can easily detect the boundary between different atmospheric layers and discriminate the regions of smoke and clear atmosphere. However, the identification of the exact boundary location of smoke layers and plumes where the dispersion processes create a continuous transition zone between the heterogeneous areas and clear air presents a significant challenge. The smoke plume density, its concentrations, the level of heterogeneity and the smoke dispersion are extremely variable and depend heavily on the distance of the smoke plume from the fire source.

The absence of unique criteria for determining the boundary between the smoke plume and clear-air areas when it is poorly defined is the principal issue of any range-resolved remote sensing technique. No standard definition of such a boundary exists. When determining the boundary, the most common approach is to use some relative, rather than absolute characteristic. For example, one can select the boundary location as the area where the examined parameter of the interest, e.g., the square-range-corrected lidar signal, decreases from a maximum value down to a fixed, user-defined level. However, there is no way to establish a standard value for this level which would be acceptable for all cases.

An improved data processing methodology has been developed for the use of vertical lidar scans in areas of smoke plumes for extracting information about the plume heights and their spatial and temporal changes. The initial transformation of the lidar signal is as follows.

The recorded lidar signal, $P_\Sigma(r)$ is the sum of the range-dependent backscatter signal, $P(r)$ at the range $r$ and the range-independent offset, $B$, the background component of the lidar signal and the electronic offset,

$$P_\Sigma(r) = P(r) + B\,. \qquad (1)$$

This signal is transformed in the auxiliary function $Y(x)$, defined as,

$$Y(x) = P_\Sigma(x)x = [P(x) + B]x\,, \qquad (2)$$

where $x = r^2$ is the new independent variable. The sliding derivative of this function, d*Y*/d*x*, is calculated and the intercept point of each local slope fit of the function with the vertical axis is found and normalized. The intercept function versus *x* is found as,

$$Y_0(x) = Y(x) - \frac{dY}{dx}x\,. \qquad (3)$$

The retrieval technique that is used here for processing the measurement data of both scanning and one-directional lidar is based on determining the so-called normalized intercept function (Kovalev *et al.* 2009). The normalized intercept function is defined as,

$$Y_{0,norm}(x) = \frac{Y_0(x)}{x + \Delta}\,, \qquad (4)$$

where Δ is a user-defined positive non-zero constant whose value can range from 0.02 - 0.05 of the maximum value of the variable *x* over the selected range.

For the scanning lidar, the absolute value of the normalized function under the slope direction φ is calculated as a function of height, $h = r \sin \varphi$, giving

$$F(h, \varphi) = \left|Y_{0,norm}(h, \varphi)\right|. \qquad (5)$$

*Determining the maximal height of a smoke plume using the AHHI*

The concept of the Atmospheric Heterogeneity Height Indicator (AHHI), used in this measurement methodology, has been introduced in the study by Kovalev *et al.* (2009). The AHHI is a histogram showing the number of heterogeneity events determined for consecutive height intervals. It defines the heights where the heterogeneity events were fixed and the number of events observed at those heights. The AHHI enables large volumes of lidar data to be analyzed providing an accurate time series profile of smoke-plume heights.

Fig. 1 shows graphically the principal behind the AHHI. The basic principal behind this new lidar-data processing method is the same as for any other method used to determine atmospheric heterogeneity - to identify ranges where increased gradients in the backscatter signal exist. This new method, though, does not require initial separation of the background component, *B*, in the recorded lidar signal [Eq. (1)]. In order to determine smoke layer and plume heights and to monitor their changes over time, the lidar signal transformation described in Kovalev *et al.* (2010) is utilized.

(a) (b)

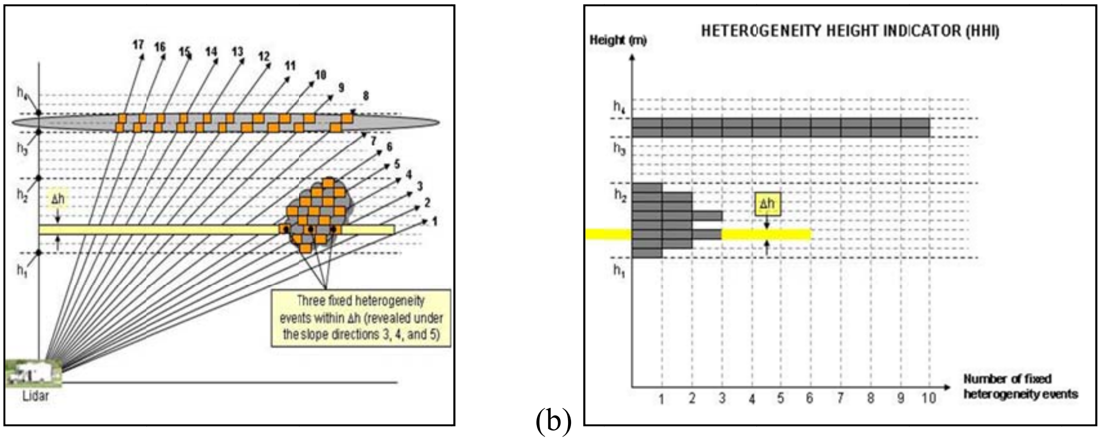


**Fig. 1.** (a) Principle of determining the locations with increased backscatter gradient in the atmospheric lidar signals. The thin lines show the scanned slope directions, and the filled rectangles are the areas with increased backscatter. (b)The Atmospheric Heterogeneity Height Indicator (AHHI), a histogram which shows a number of heterogeneity events defined by scanning lidar at the consecutive height intervals.

Using Eq. (5), the function $F_i(h, \varphi)$ is determined for each slope direction φ and the maximum function, $F_{max}$, for the above set of functions is found. The local heterogeneity event is considered as being true at the locations where the function $F_i(h, \varphi)$ reaches some user established threshold, χ, relative to $F_{max}$ (Kovalev *et al.* 2009). Using such a histogram, one can determine the location and the maximal height of the region with the increased heterogeneity that corresponds to the selected $\chi$. The smoke-plume maximum height is defined as the height where the plume presence can be discriminated from noise in the lidar data. In the example of the experimental data presented in Fig. 2, the AHHI identifies the maximal height of the plume at 2700 m.

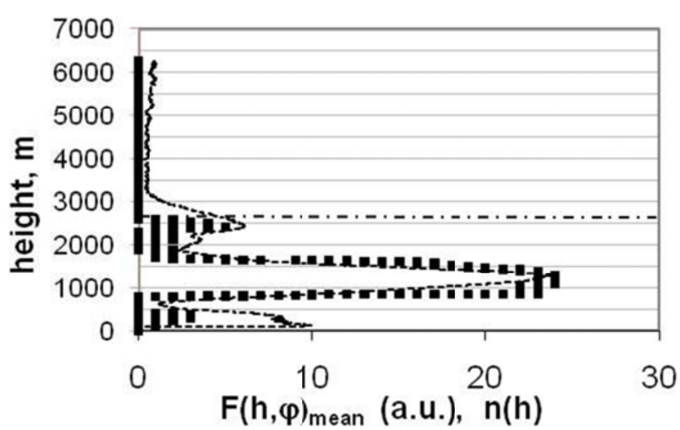

**Fig. 2** . Plot of the AHHI (the filled squares) overlaid with the mean normalized intercept function (the dotted curve) showing three regions of polluted air from ground level to 3000 m, a region of polluted air from ground level to 700 m and regions of smoke from 700 m to 1900 m and from 2000 m to 3000 m. The AHHI identifies the height of the upper boundary of the smoke plume at 2700 m, indicated by the horizontal dashed line.

**Plume rise models**

Seven plume rise models comprising three categories are investigated, two Briggs equation based models, three empirical models and a one dimensional time dependent entrainment model.

FEPS (Anderson et al., 2004) and VSMOKE (Lavdas 1996) use modified Briggs equation based plume rise models. These computer programs use atmospheric stability and buoyancy flux values to choose between multiple built in models. Because the atmosphere stability was neutral to unstable on August 27, 2009 and the buoyancy flux was greater than 51.602, the Briggs equation used by FEPS and VSMOKE to determine plume rise on that day is,

$$H = \frac{38.7F^{3/5}}{W} \qquad (6)$$

where H is the plume rise in meters, F is the buoyancy flux and W is the transport wind velocity in $ms^{-1}$ (Anderson *et al.* 2004; Lavdas 1996).

FEPS and the Harrison and Hardy models (H_H 1992 and H_H 2002) use empirical plume rise models based on inputs of fire energy release rate (Harrison and Hardy 1992; Hardy 2010). FEPS uses fuel consumption rate as a surrogate for energy release rate while the fire energy release rate is directly input into the Harrison and Hardy models. FEPS determines the minimum and maximum plume rise in meters using the empirical models,

$$H_{min} = 4000 - \left[\frac{4000}{e^1} e^{\left(1-\frac{A}{400}\right)}\right] \qquad (7)$$

$$H_{max} = 8000 - \left[\frac{8000}{e^1} e^{\left(1-\frac{A}{400}\right)}\right] \qquad (8)$$

where A is the fuel consumption rate in acres per hour. The Harrison and Hardy empirical models give the maximum plume rise in km using,

$$H = 1.54\sqrt{Q} - 0.276 \qquad (9)$$

$$H = 1403Q^{0.36} \qquad (10)$$

where Q is the fire heat release in GigaWatts.

PLUMP is a one-dimensional, time-dependent, entrainment model that neglects the effects of wind and uses input soundings of pressure, temperature and dew point along with either fuel loading or energy release rate to predict plume rise (Latham 1994).

**Kootenai Creek case study**

We investigated the smoke plume characteristics of the Kootenai Creek Fire in the Bitterroot Valley, Montana, USA over several days during July and August of 2009. Between mid-July and early September, the fire burned 2,000 ha of conifer forest.

Fig. 3 shows the schematic of the method used to obtain lidar transects of the plume. For the Kootenai Creek study the lidar vertical scan corresponding to 130° azimuth is used for comparison with the modeled plume rise. The 130° azimuth scan transects the plume approximately 12 km from the fire and 2 km downwind of where the aircraft sampled the plume.

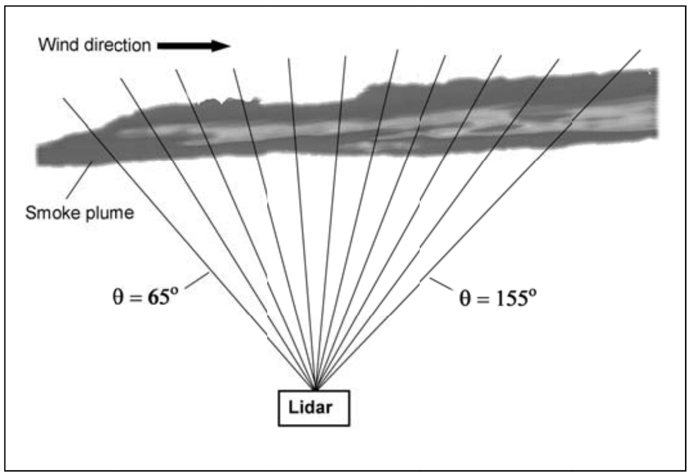


**Fig. 3.** Schematic of data collection with the vertically scanning lidar during the Kootenai Creek fire in Montana during July and August 2009. The thin lines show the scanned azimuthal directions. (The sector 45° - 65°, which overlaps the wildfire site, is not shown).

Fig. 4 shows a time series of smoke plume profiles obtained from the Kootenai Creek Fire on August 27, 2009 between the hours of 14:30 and 17:00. These profiles were constructed from vertical lidar scans taken of the smoke plume at the lidar's 130° azimuth and show relative smoke-concentration variations. Overlaid on the smoke plume profiles are the AHHI histograms and the AHHI determined plume height.

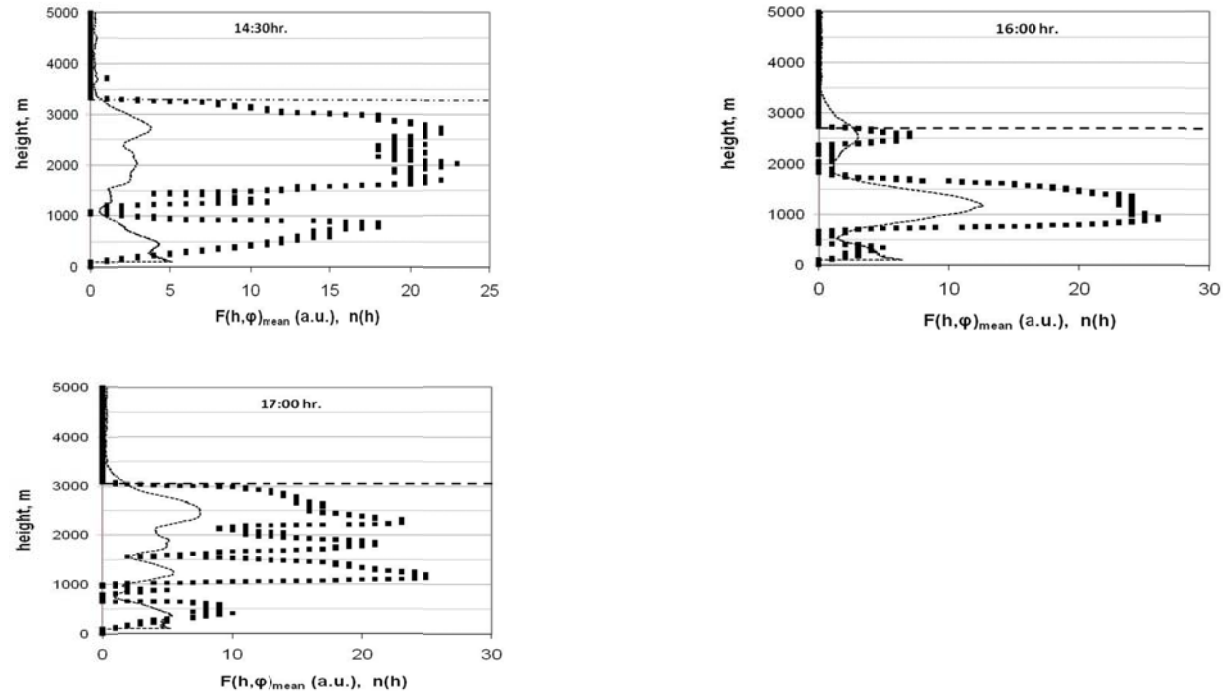


**Fig. 4.** Lidar vertical scan time series showing the mean normalized intercept function (thin sold line) of the smoke plume overlaid with the AHHI histogram (the filled squares). The horizontal dashed line indicates the AHHI determined smoke plume height.

Fig. 5 and 6 show aerosol (PM2.5) mass concentrations measured during aircraft penetrations of the smoke plume approximately 10 km downwind of the active fire at approximately 16:00 on August 27, 2009. Fig. 5 shows a vertical profile of the aerosol mass concentration when the aircraft made a spiraling decent into the downwind plume. The upper smoke plume boundary can be clearly seen at ≈2790 m AGL.

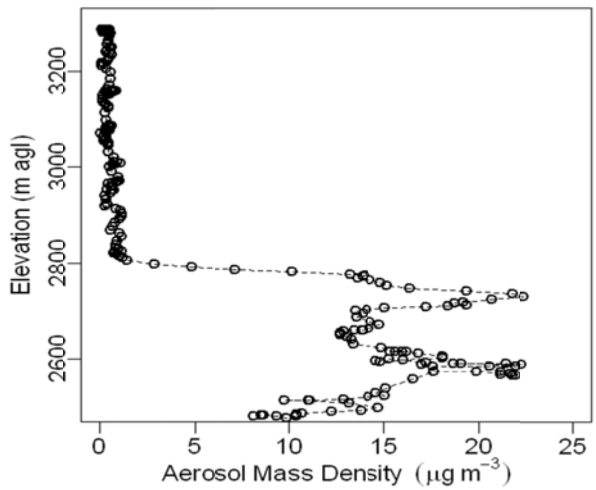


**Fig. 5.** Vertical profile of aerosol mass concentration measured ≈10 km downwind of the Kootenai Creek Fire. The vertical profile identifies the top of the smoke plume located ≈2790 m AGL.

Comparing the Fig. 4, 16:00 lidar vertical scan with the vertical profile in Fig. 5, the AHHI determined plume height agrees well with the aircraft measured plume height at 2790 m. Fig. 6 shows the aerosol mass concentration of the plume at 1900 m AGL and 2500 m AGL, measured when the aircraft flew two transects of the plume approximately 30 km in length and perpendicular to the transport wind direction. Comparing the Fig. 4, 16:00 lidar vertical scan

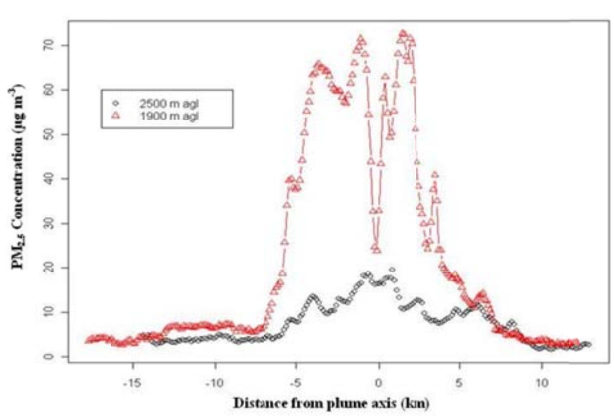


**Fig. 6.** Airborne measurements of aerosol concentration downwind of the Kootenai Creek fire on august 27, 2009. The aircraft flight path consisted of two 30 km segments, oriented perpendicular to the transport winds (i.e. the direction of the plume's flow and located ≈10 km downwind of the active fire.

with the Fig. 6 aircraft horizontal transects, the lidar backscatter profile tracks the corresponding aerosol mass concentrations measured by the airborne instruments.

Fig. 7 compares the plume rise models' predicted plume heights with the lidar measured heights at the Kootenai Creek Fire during the period from 12:30 to 17:00 on August 27, 2009. In all cases the plume rise models underreported the plume height determined by the AHHI algorithm.

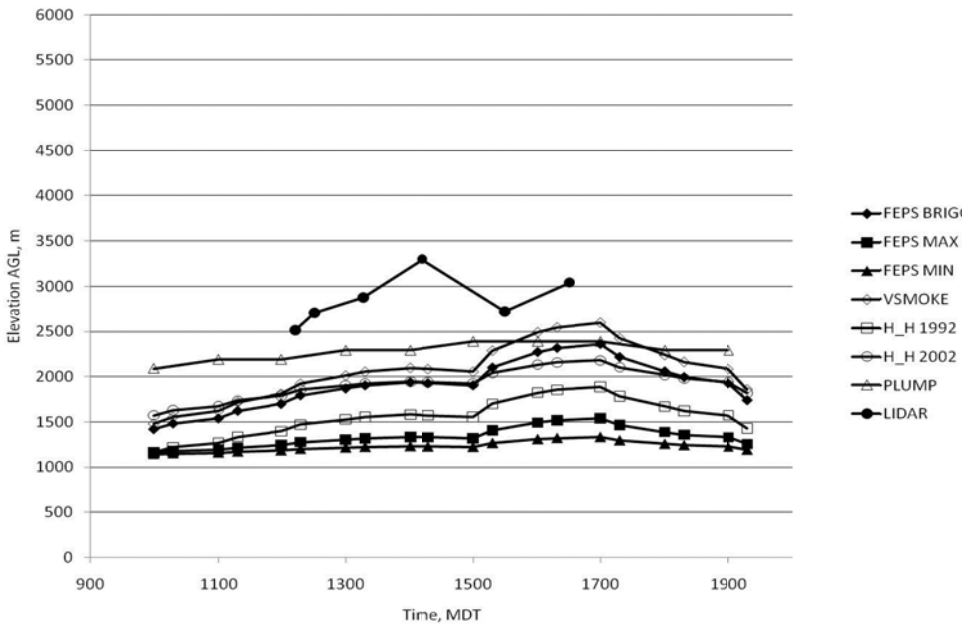


**Fig. 7.** Comparison of modeled smoke plume heights with heights determined by the lidar AHHI algorithm at the Kootenai Creek Fire on August 27, 2009.

The Briggs equation based models produced similar plume height predictions with the maximum difference of 239 m occurring at 17:00; the variations in the predictions of the two models is due to the manner in which they handle the transport winds, the transport winds on August 27, 2009 were approximately 4 $ms^{-1}$ and this is the value used by the VSMOKE model, FEPS sets the transport wind minimum at 5 $ms^{-1}$ and used that value, consequently the plume rise prediction of FEPS is lower than that of VSMOKE.

The maximum difference between the empirical plume rise models was 847 m and occurred at 17:00. The H_H 2002 model most closely agreed with the Briggs based models, underreporting the VSMOKE model by 420 m at 17:00.

In general, the PLUMP model performed better than the other models.

Comparison of the plume profiles in Fig. 4 with the predicted plume heights shown in Fig. 7 indicates that, although the predicted plume heights underreport the maximum smoke plume boundaries measured by the lidar, the predicted plume heights lie at approximately the same height as the lidar maximum backscatter and at presumably the maximum particulate concentrations in the plume.

## Summary

To acquire the data needed for evaluation of plume rise and smoke dispersion models, a research project has been initiated. The project deploys a ground based, mobile lidar and an airborne instrument package to investigate smoke plume dynamics, aerosol distribution, and chemical composition in smoke-polluted atmospheres.

The new lidar AHHI algorithm was developed, which successfully detects the maximal smoke plume boundary and automates the process of smoke plume boundary detection, enabling the ready processing of large volumes of data from many prescribed and wild fires.

The AHHI algorithm and the airborne instruments agree on the maximal smoke plume height of the Kootenai Creek Fire at 16:00 on August 27, 2009. The lidar measured smoke plume profiles are in good agreement with the profiles of the PM2.5 concentrations measured by the airborne instruments.

All plume rise models investigated underreported the AHHI determined smoke plume height for the Kootenai Creek Fire on August 27, 2009. The PLUMP model predicted heights were generally closer to the AHHI determined heights than all other models. FEPS and VSMOKE use Briggs equation based models and predicted heights close to those of the PLUMP model. FEPS and VSMOKE compared closely with each other, the difference resulting from the manner in which the two programs deal with transport wind, FEPS having a set minimum wind speed while VSMOKE does not. The H_H 2002 empirical model performed as well as the FEPS Briggs equation based model, all of the empirical models significantly underreported the measured maximum plume height.

While the plume rise models underreported the AHHI determined maximal smoke plume height, their predicted heights appear to correlate with the maximum particulate concentration heights detected by the lidar and measured by the airborne instruments.

## Acknowledgements

This research project was funded by the Joint Fire Sciences Program (Project Number 08-1-6-09). We would like to thank USFS Region 1 Aviation for supporting the airborne portion of our research project.

## References

Anderson GK, Sandberg DV, Norheim RA (2004) ‘Fire Emission Production Simulator (FEPS) User’s Guide.’ Version 1.0.

Hardy C, (2010) Personal communication.

Harrison H, Hardy C (1992) Plume rise from prescribed fires: model and data. In Proceedings ‘1992 annual meeting of the Pacific Northwest International Section, Air and Waste Management Association,’ 11-13 November, 1992; Bellevue, WA. (Air and Waste Management Association: Pittsburgh, PA)

Kovalev VA, Petkov A, Wold C, Hao WM, (2011) Lidar monitoring of the regions of intense backscatter with not well-defined boundaries. *Applied Optics* **50** (1), xx-xx

Kovalev VA, Petkov A, Wold C, Urbanski S, Hao WM, (2009) Determination of smoke plume and layer heights using scanning lidar data. *Applied Optics* **48**, 5287-5294.

Latham DJ (1994) ‘PLUMP: a Plume Predictor and Cloud Model for Fire Managers.’ USDA Forest Service, Intermountain Research Station General Technical Report INT-GTR-314.

Lavdas LG (1996) 'Program VSMOKE – User's Manual.' USDA Forest Service, Southern Research Station General Technical Report SRS-GTR-6.