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Essentials of multiangle data processing methodology for smoke polluted atmospheres

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USA

CONTENT

- Objectives
- FSL lidar and two methods for lidar data processing
- Determination of the smoke plume/smoke layer heights and dynamics with scanning lidar
- Heterogeneity Height and the Heterogeneity Range-Height Indicators (HHI and HRHI) retrieved from the FSL lidar data measured in the vicinity of wildfires
- Algorithms for determining optical characteristics in horizontally-stratified smoky atmospheres
- Summary

Objective

- During recent decades, an increase in the frequency, duration, and severity of wildland fires throughout the world occurred.
- Remote sensing of smoke plumes in the vicinity of the fires would allow better understanding trajectories, rise, and dispersion of pollutants that affect human health and visibility.
- Mobile scanning lidar is the most appropriate tool for continuous monitoring smoke plumes characteristics and dynamics.
- There is no commonly accepted strategy and methodology of the application of lidar for monitoring smoke plume dynamics and optical characteristics

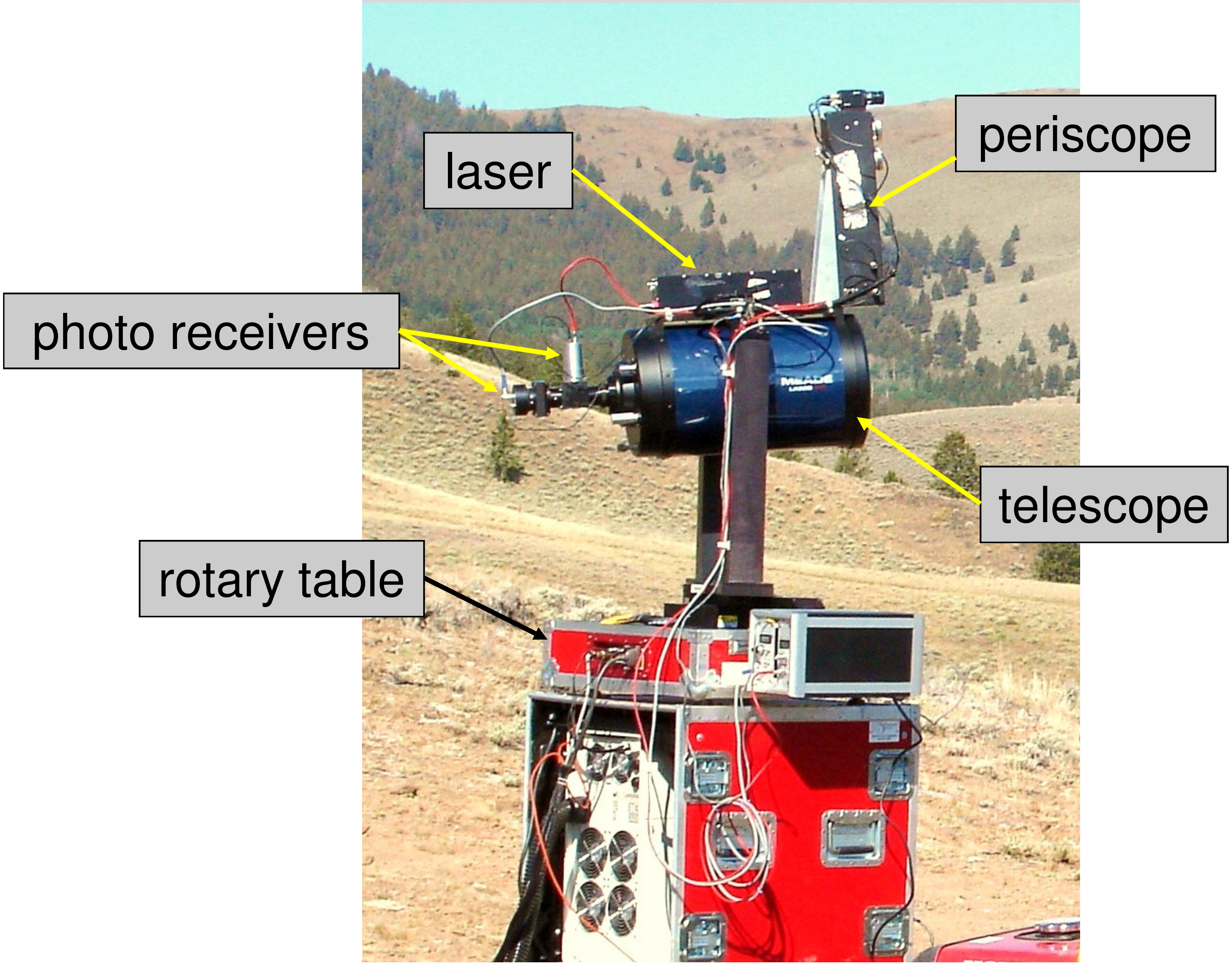
Why lidar?

- Lidar is the only remote sensing instrument capable of obtaining detailed three-dimensional range-resolved information for smoke distributions and dynamics over ranges 10+ km at different wavelengths simultaneously

- Lidar allows continuous monitoring of smoke-polluted atmospheres, providing information about temporal and spatial variation of aerosol properties, plume heights and dynamics, the direction and rate of the smoke plume movement.

- Lidar can operate from a position far outside the burning area with complete safety for the personnel involved.

FSL lidar



FSL mobile laboratory

- Two-wavelength mobile scanning lidar is located in a van
- It operates at 1064 nm and 355 nm wavelengths simultaneously.
- The scanning abilities of the lidar: azimuthal $0^0 – 180^0$, vertical $0^0 – 90^0$

View of a wildfire in Montana (August, 2009)

Courtesy of Steve Baker

Data-processing programs used in the Fire Sciences Laboratory (FSL):

Signals at 1064 nm are used for studying the dynamics of smoke layering and plumes and for determining their heights in time and space

Signals at 355 nm are used to investigate optical characteristics of smoke particulate horizontal layering up to heights of 4+ km.

The lidar-signal inversion yields the vertical profiles of the optical depth, the extinction coefficient, and the lidar ratio

Part I. Essentials of data processing at the 1064 nm wavelength

METHOD

- The lidar signal $P_\Sigma(r)$ with range r is the total of a backscatter signal $P(r)$ and a constant offset B,

$$P_\Sigma(r) = P(r) + B$$

- The conventional lidar-signal transformation:

$$P(r)r^2 = [P_\Sigma(r) - B]r^2$$

- In our alternative method, the original signal $P_\Sigma(r)$ is transformed into function $Y(x)$, which is a sum of two constituents,

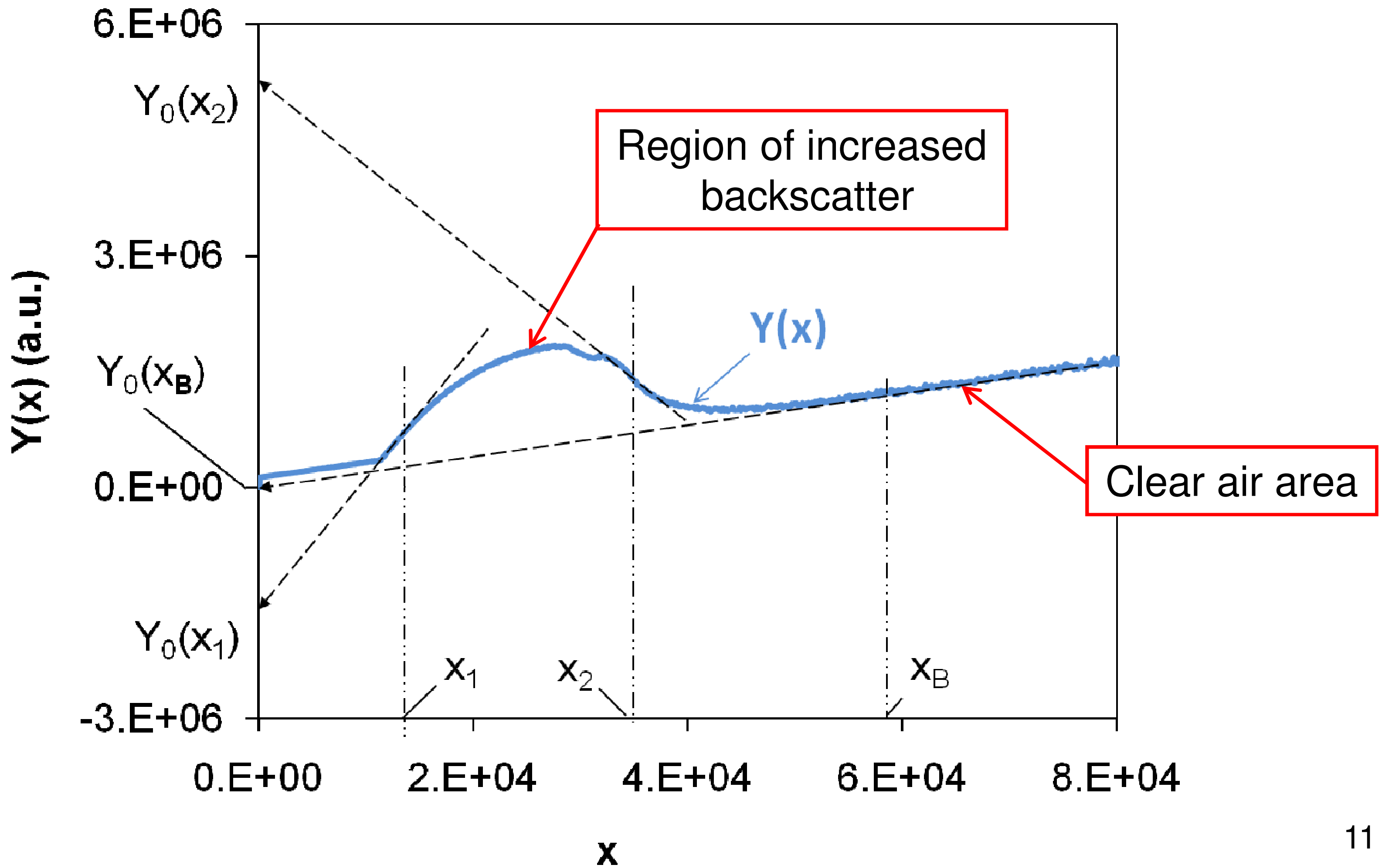
$$Y(x) = P_\Sigma(x)x = P(x)x + Bx$$

where $x = r^2$.

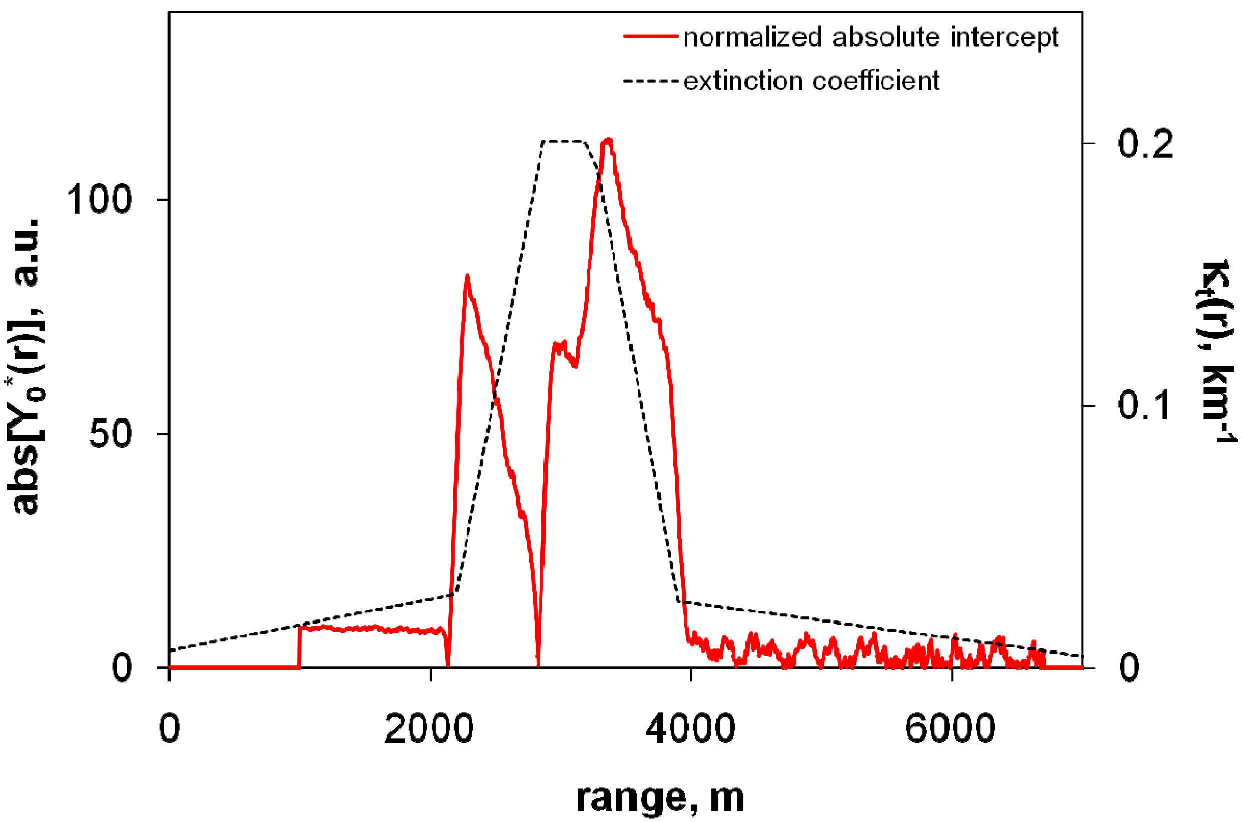
- Then the calculated derivative dY(x)/dx and intercept $Y_o(x)$ are used to determine the regions with high levels of backscattering *)

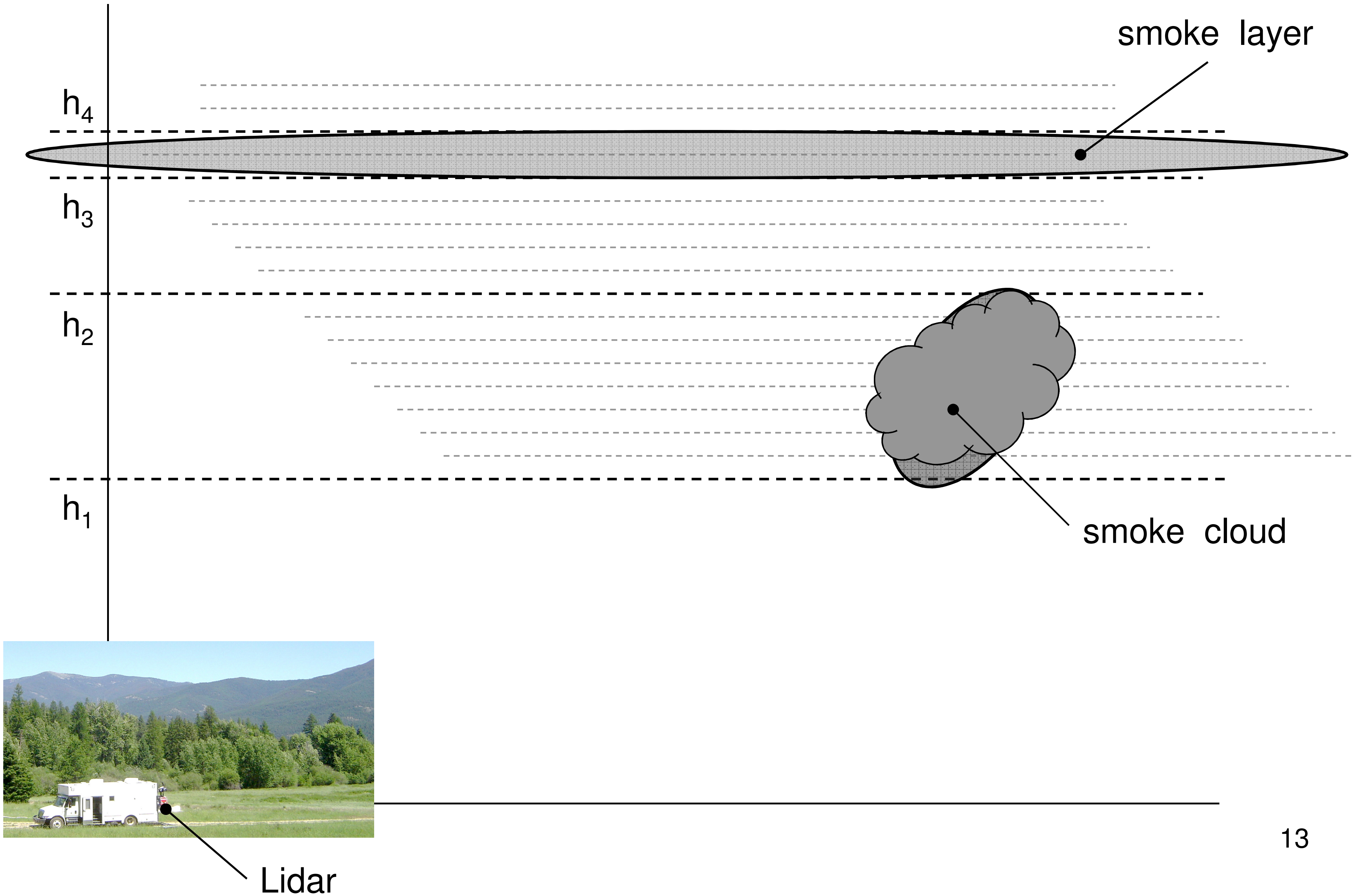
*) V. A. Kovalev et al., "Determination of smoke plume and layer heights using scanning lidar data," Applied Optics, vol. 48, 5287–5294 (2009).

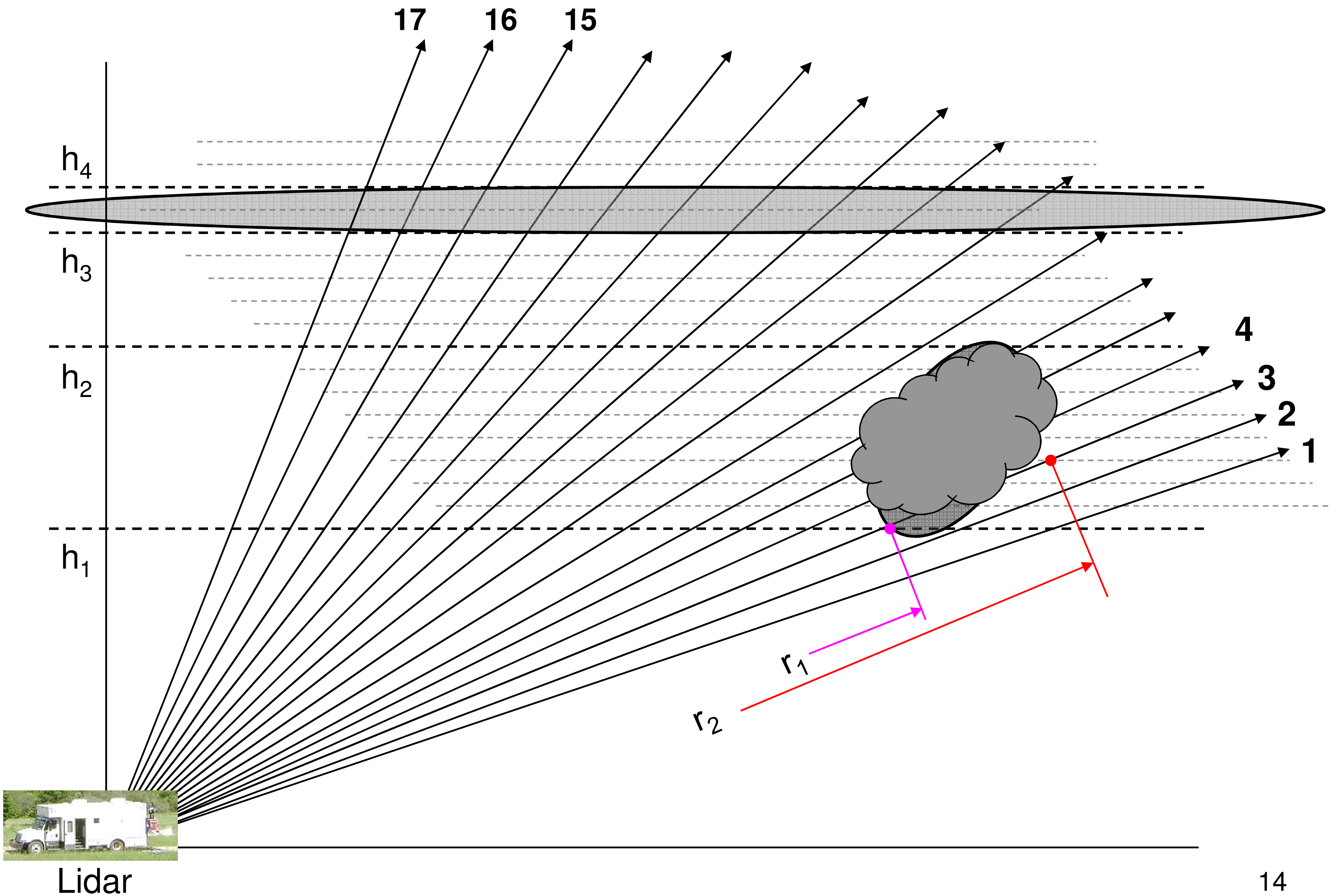
Determination of the intercept $Y_o(x)$

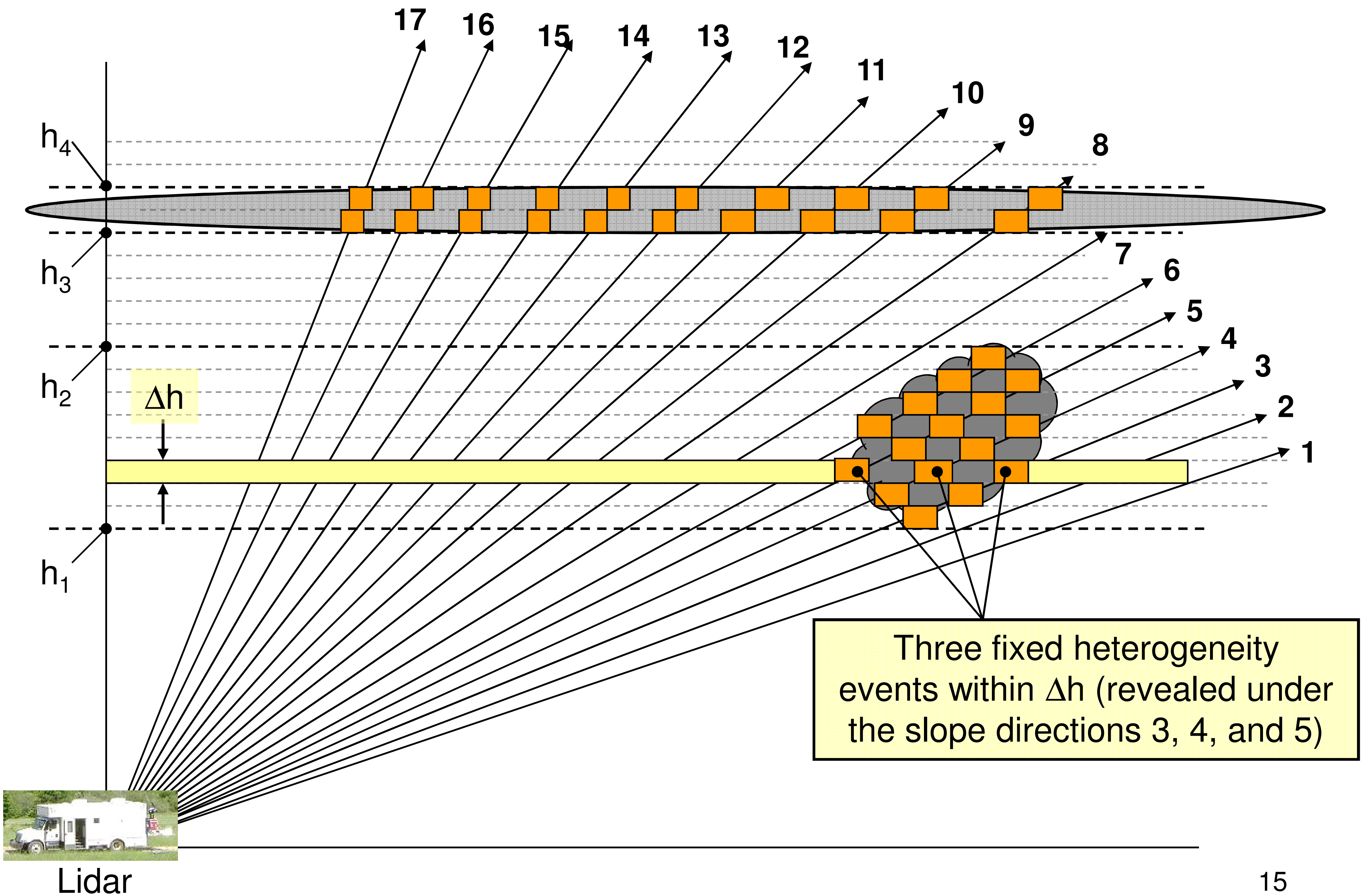


Profile of the smoke-plume extinction coefficient, $\kappa_t(r)$ (the black dotted curve), and the corresponding normalized intercept $|Y_0^*(r)|$



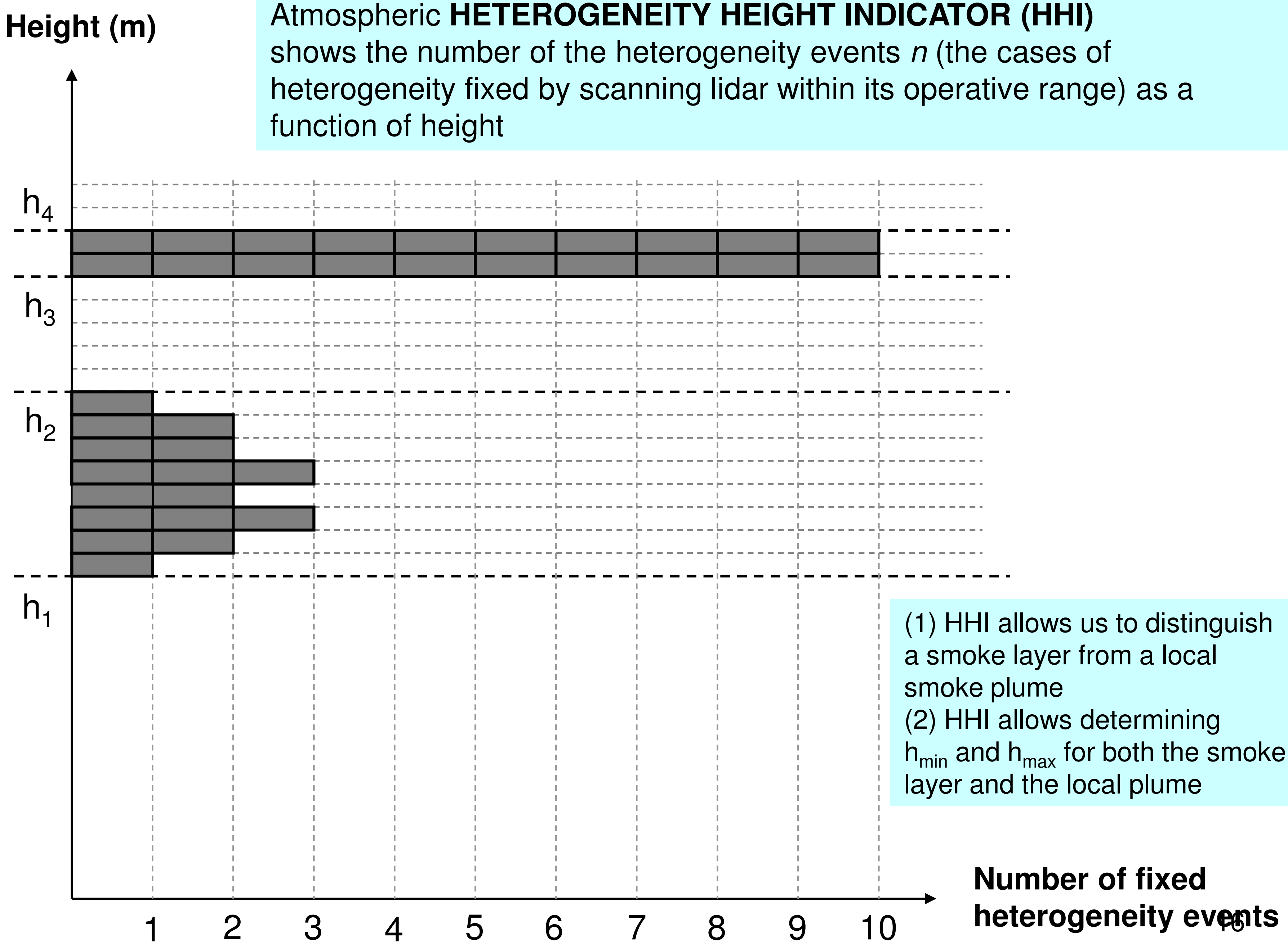

smoke layer
h4
h3
h2
h1
smoke cloud
Lidar


17
16
15
h4
h3
h2
h1
4
3
2
1
r1
r2
Lidar



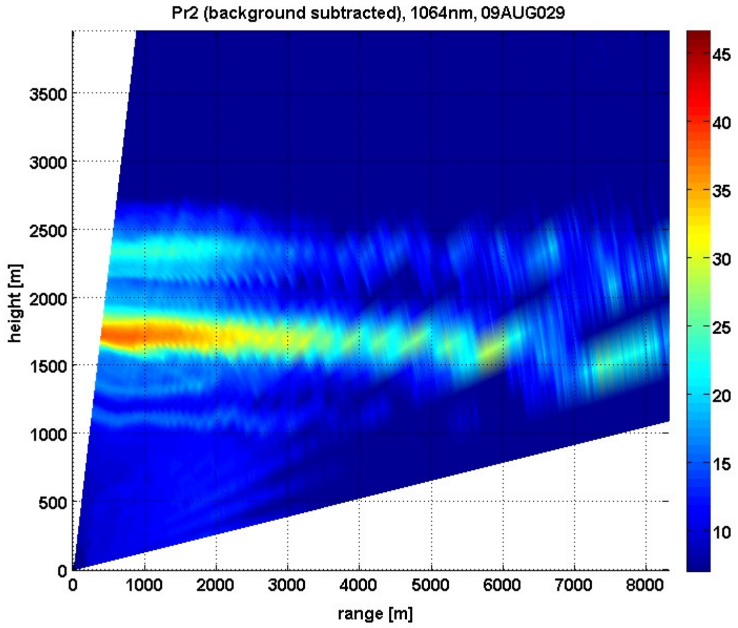
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
h_4
h_3
h_2
Δh
h_1
Three fixed heterogeneity events within Δh (revealed under the slope directions 3, 4, and 5)
Lidar

Atmospheric **HETEROGENEITY HEIGHT INDICATOR (HHI)** shows the number of the heterogeneity events *n* (the cases of heterogeneity fixed by scanning lidar within its operative range) as a function of height

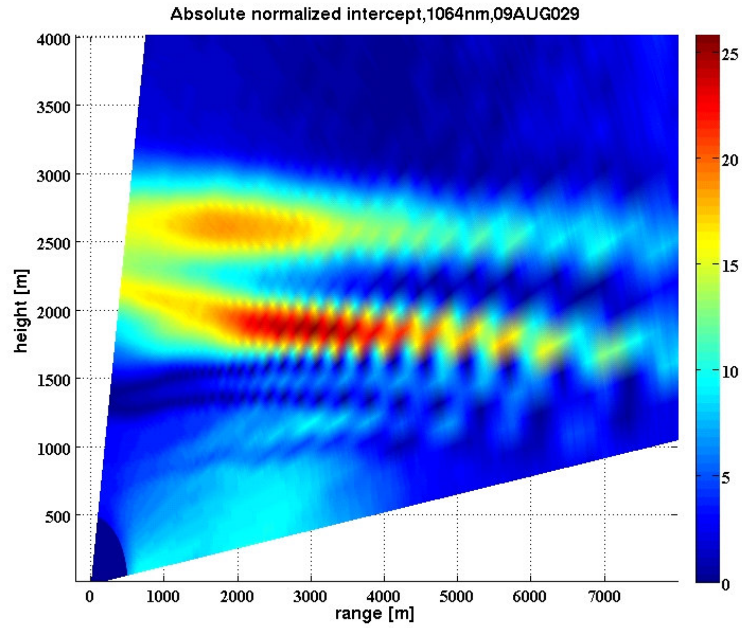


(1) HHI allows us to distinguish a smoke layer from a local smoke plume

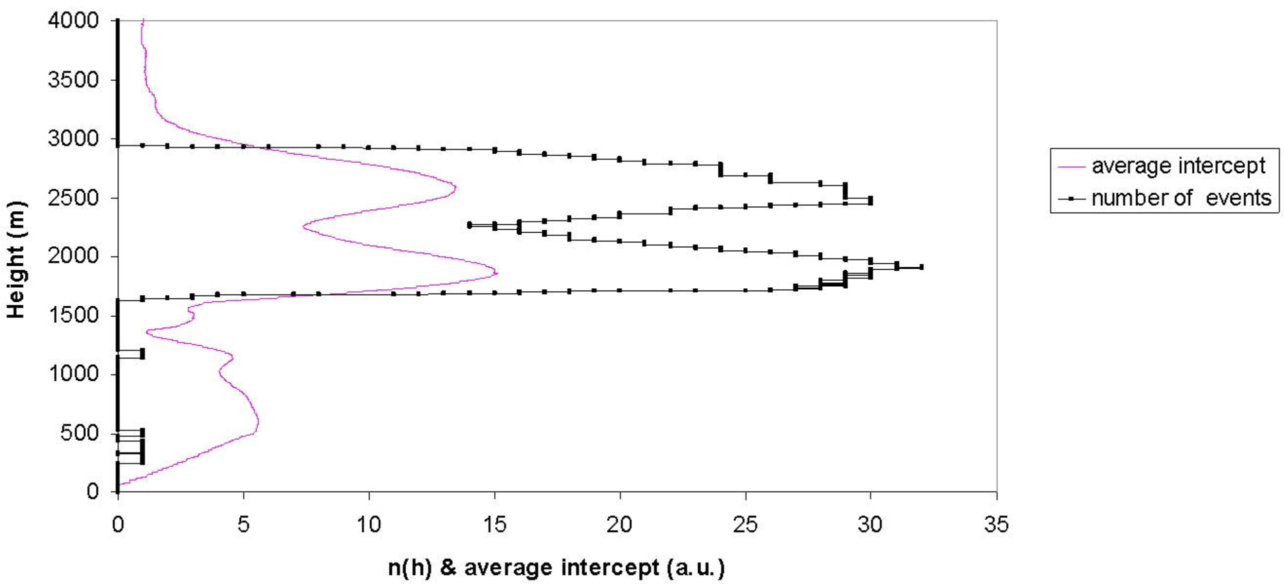
(2) HHI allows determining h_{min} and h_{max} for both the smoke layer and the local plume

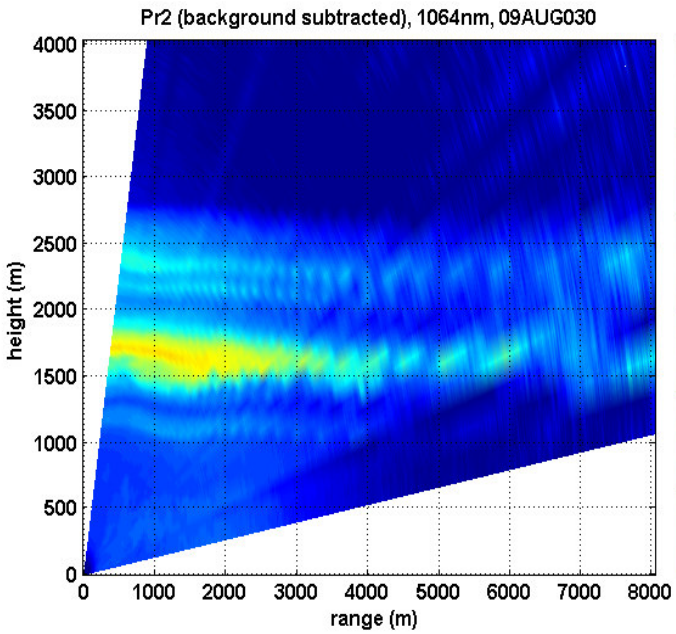


August 9, 2005,
11:24, 1064 nm

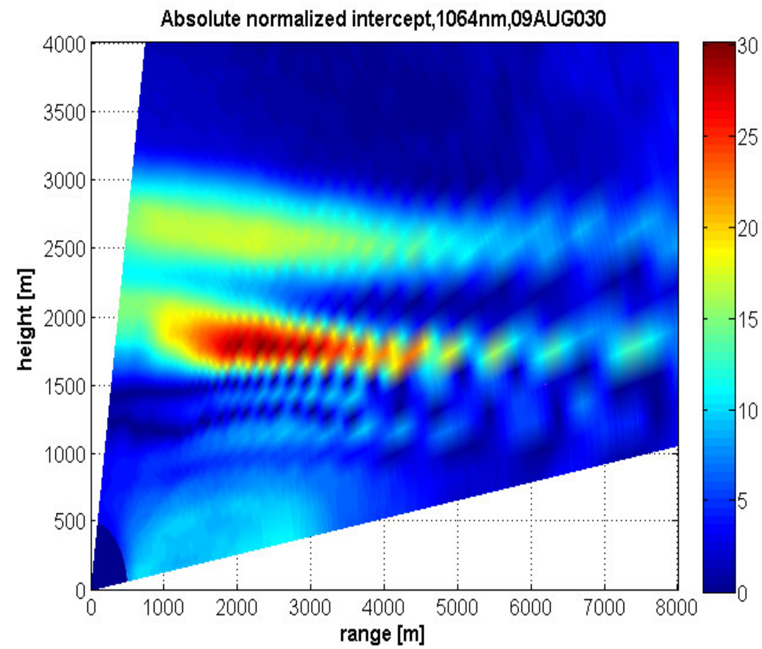


I-90 Wildfire, Montana, USA

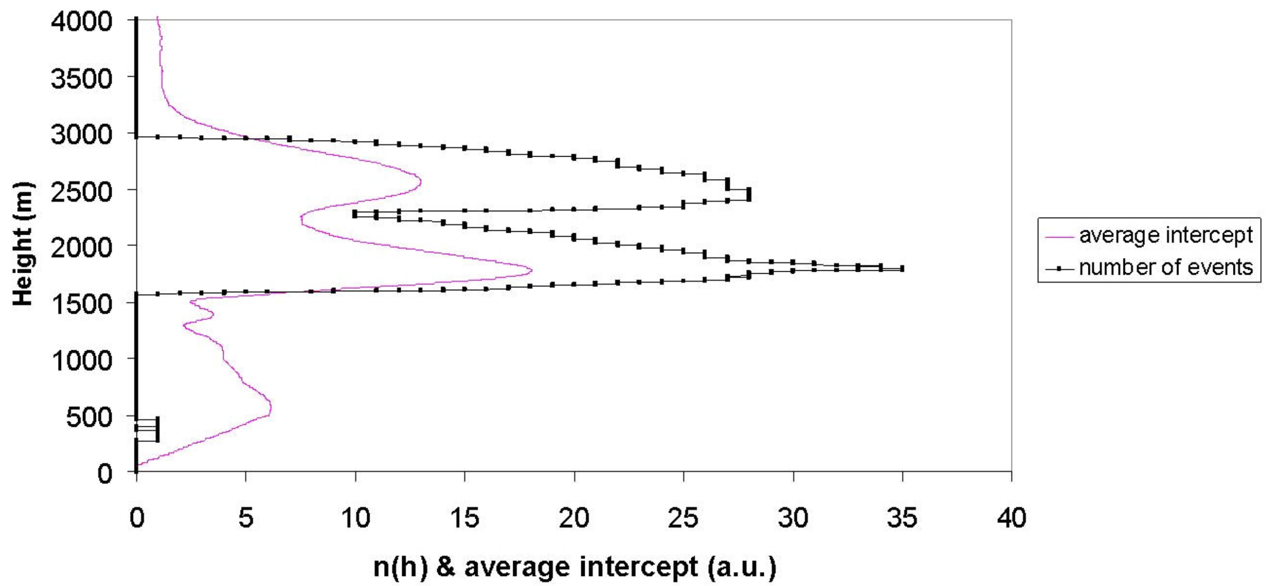


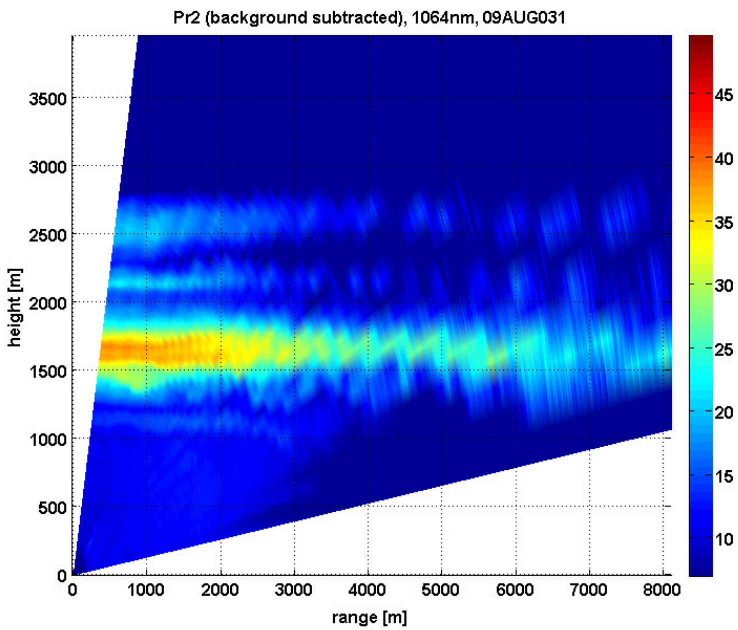


August 9, 2005
11:37, 1064 nm

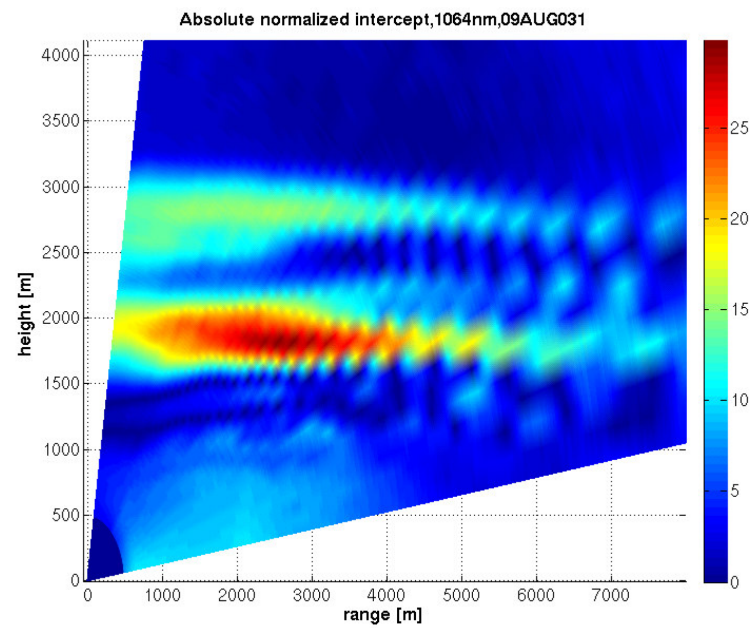


I-90 Wildfire, Montana, USA

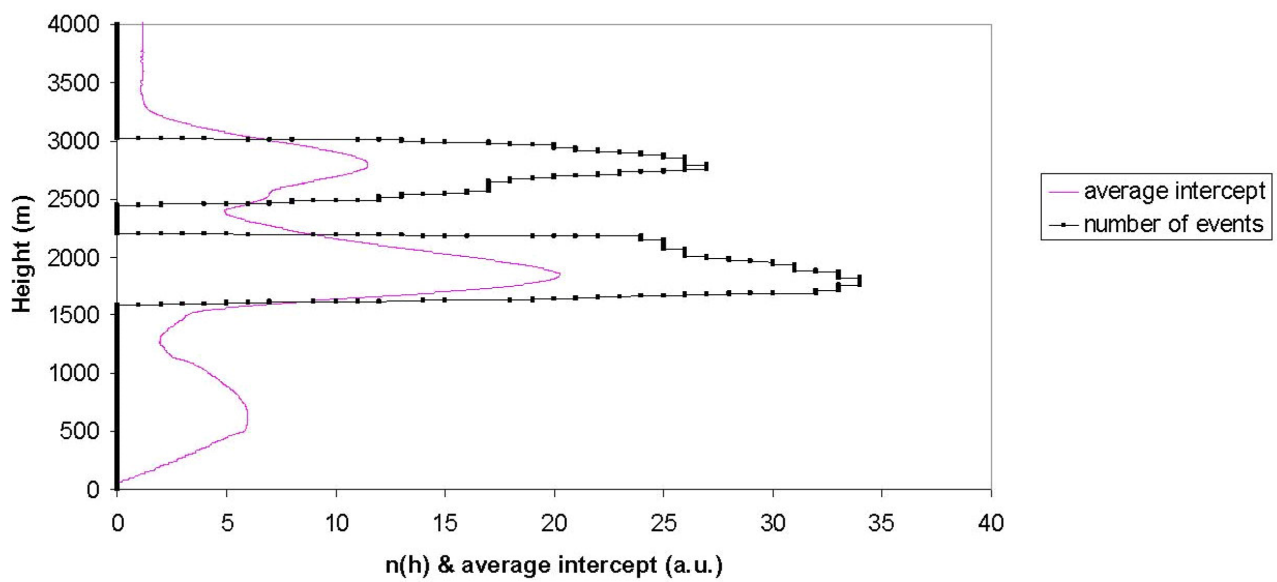


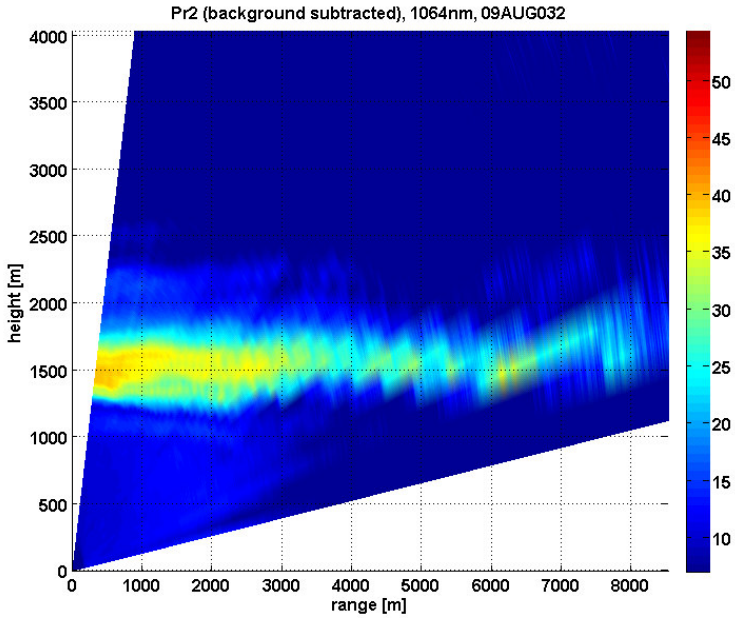


August 9, 2005,
11:52 AM, 1064 nm

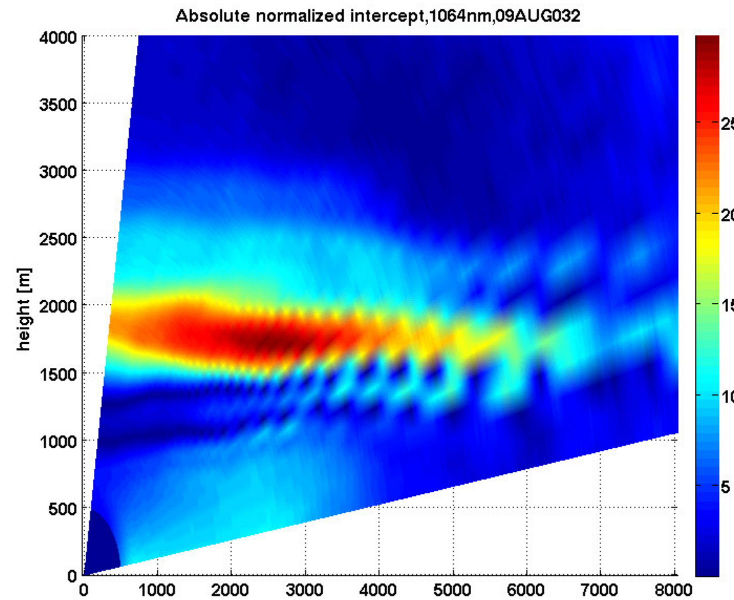


I-90 Wildfire, Montana, USA

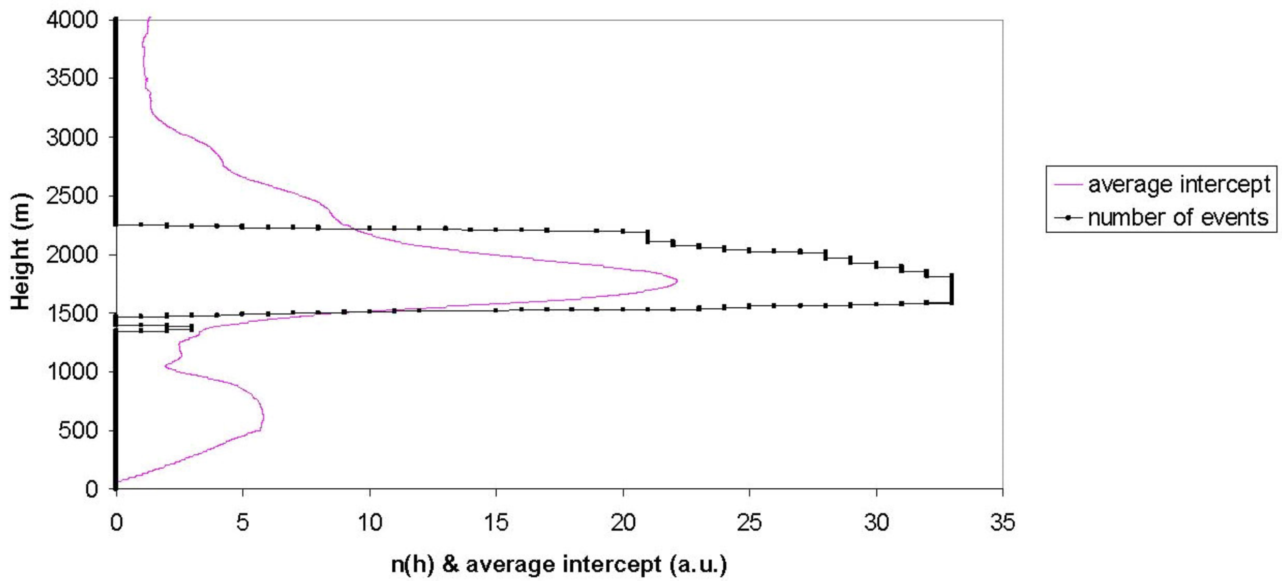


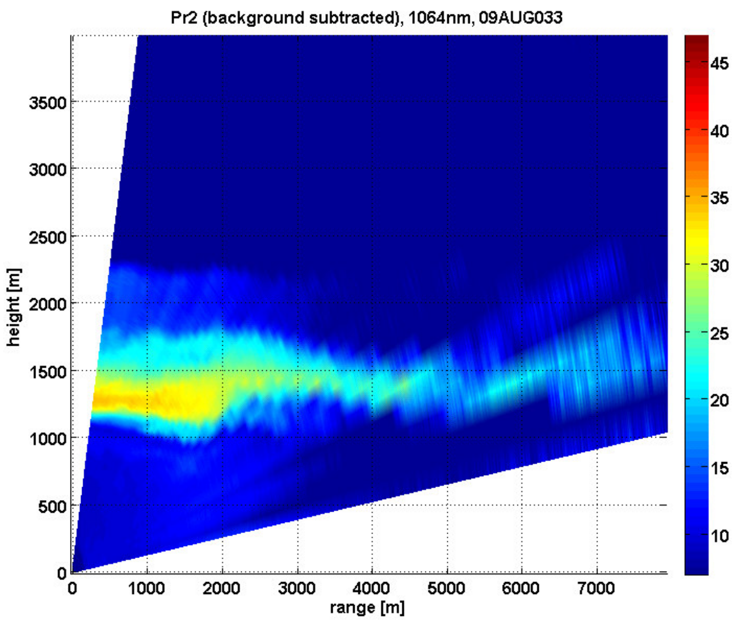


August 9, 2005,
12:08, 1064 nm

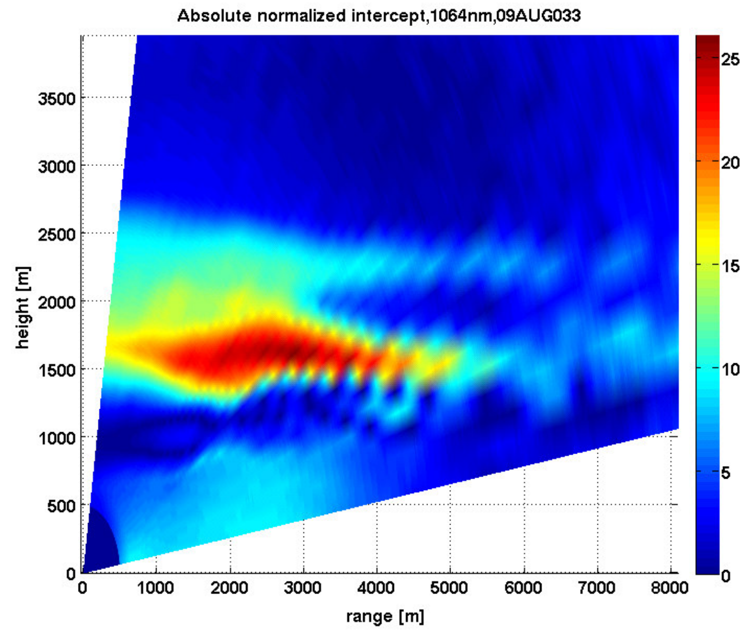


I-90 Wildfire, Montana, USA

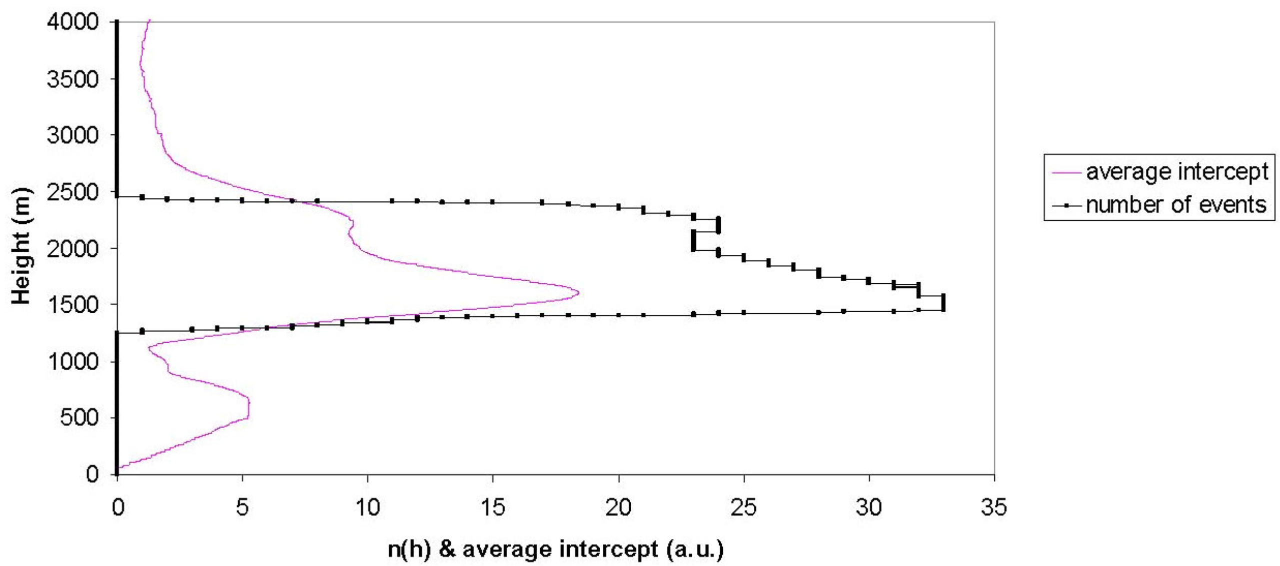




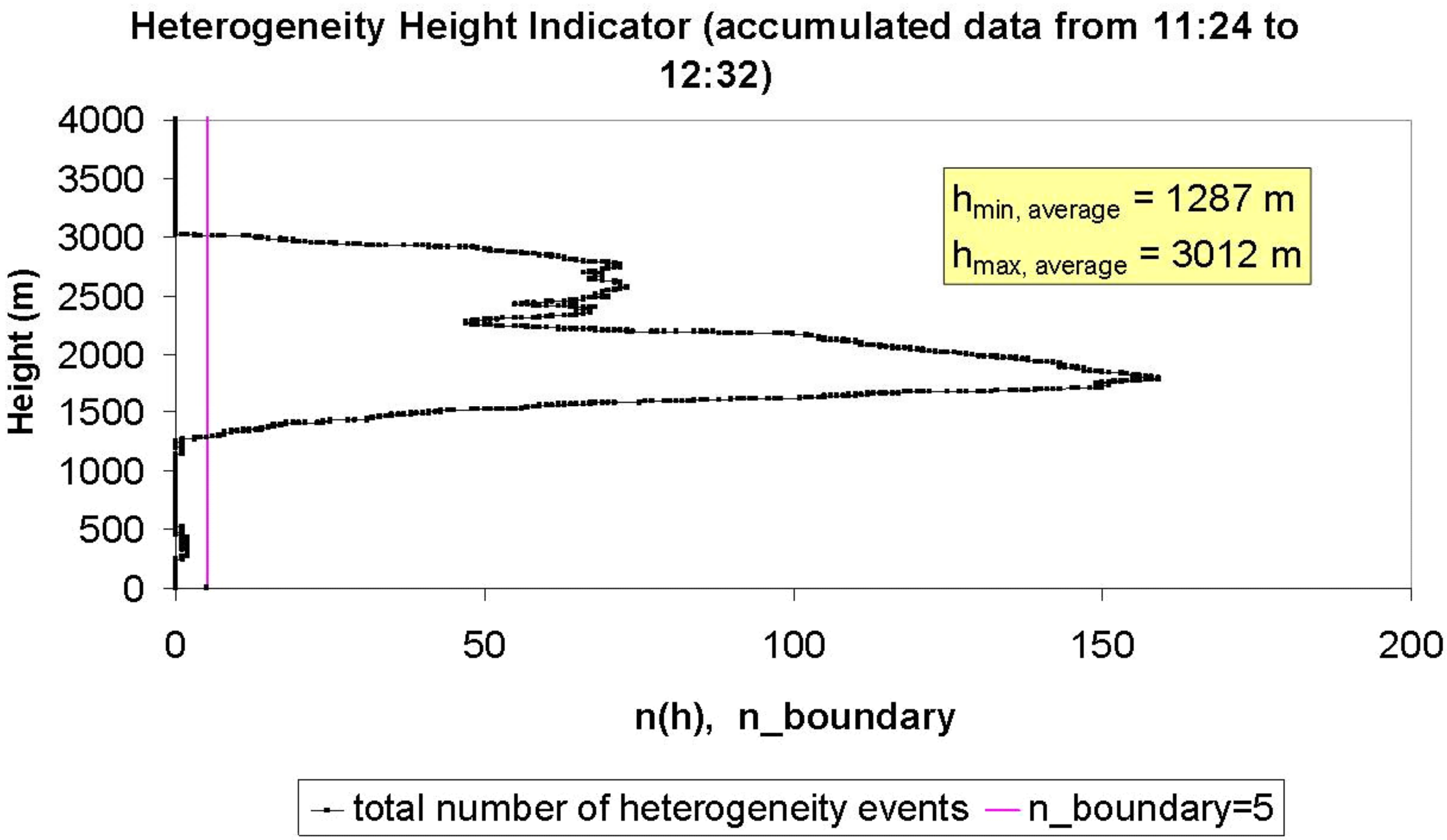
August 9, 2005,
12:32, 1064 nm

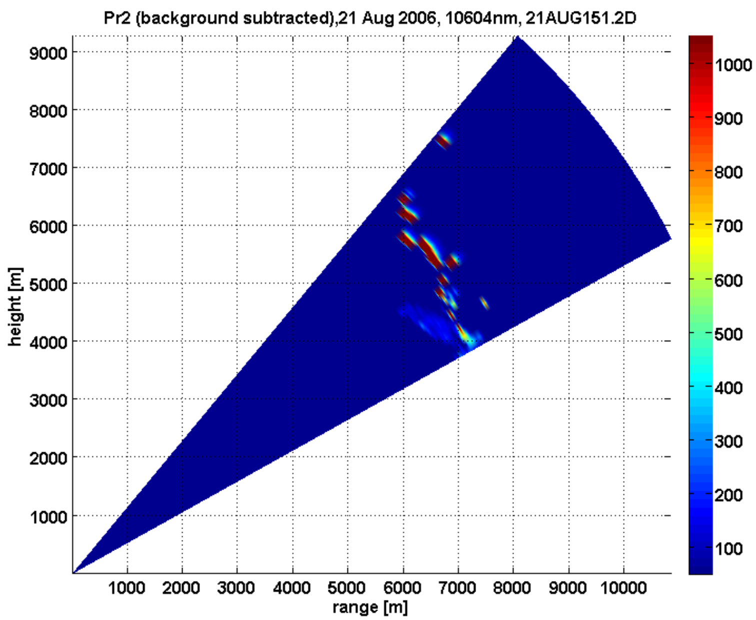


I-90 Wildfire, Montana, USA

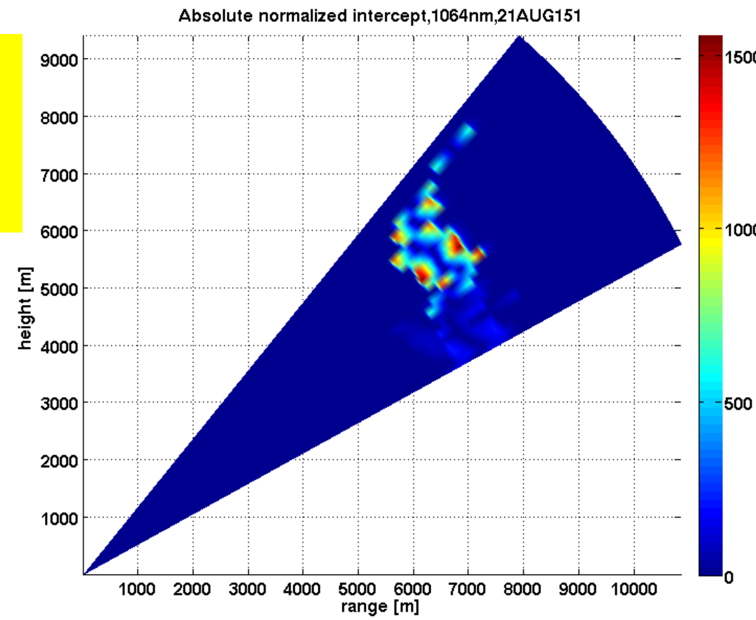


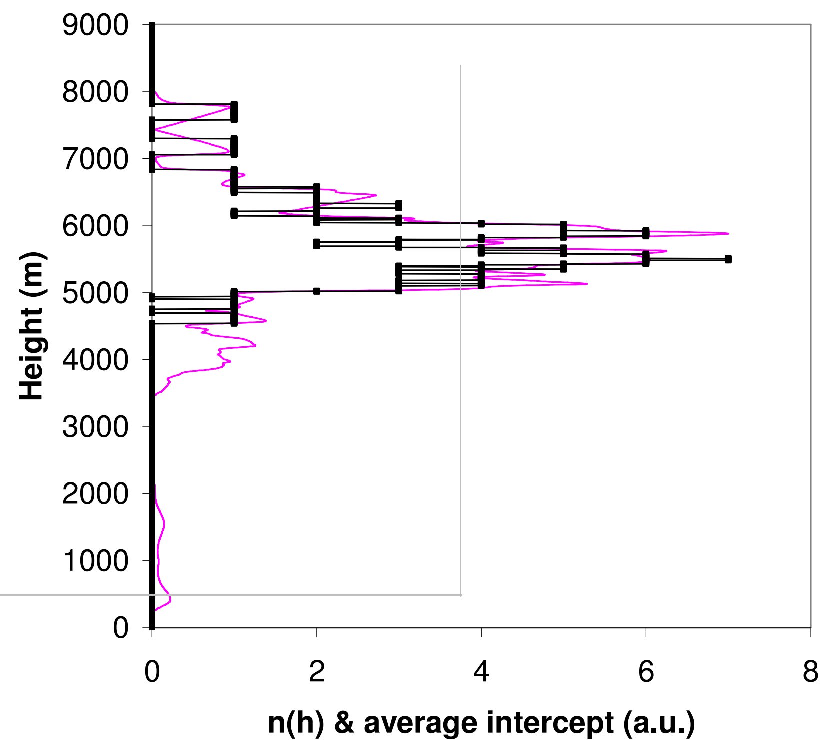
I-90 Wildfire, Montana, USA, August 9, 2005



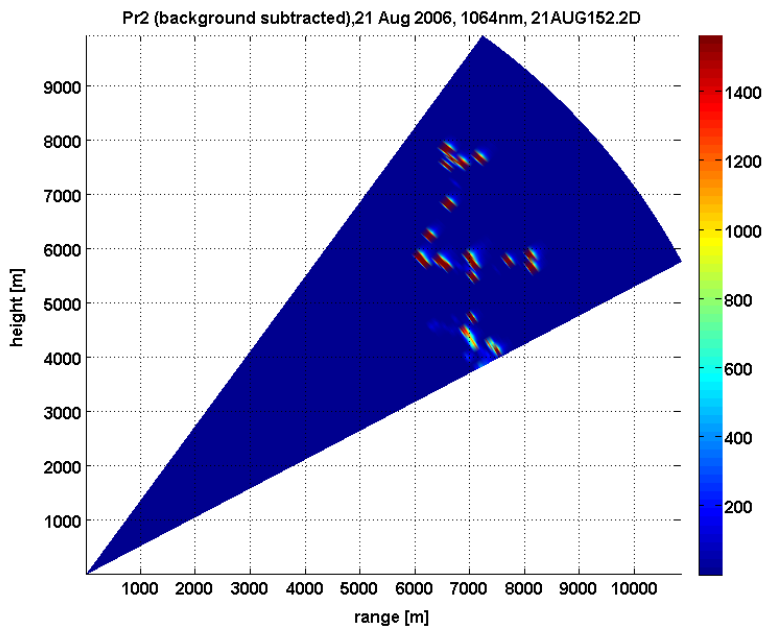


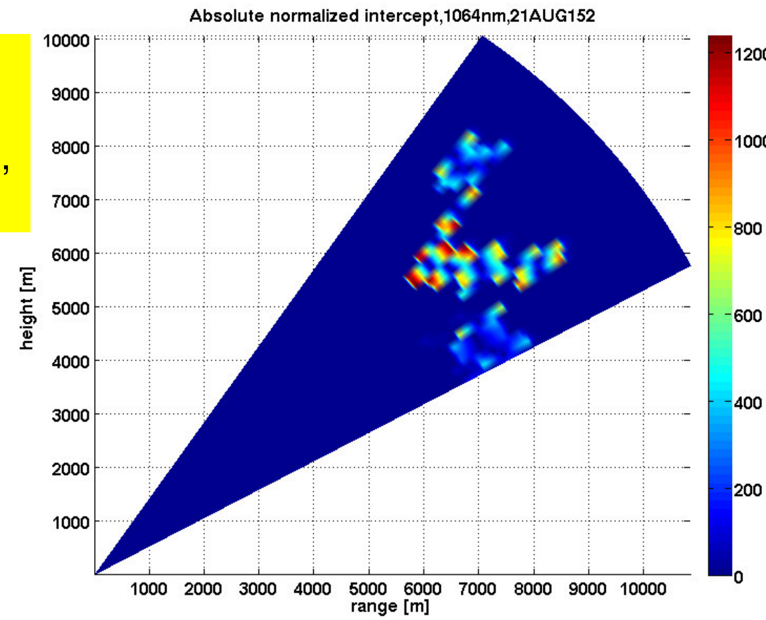
Tripod Fire (Washington)
August 21, 2006,
14:55, 1064 nm

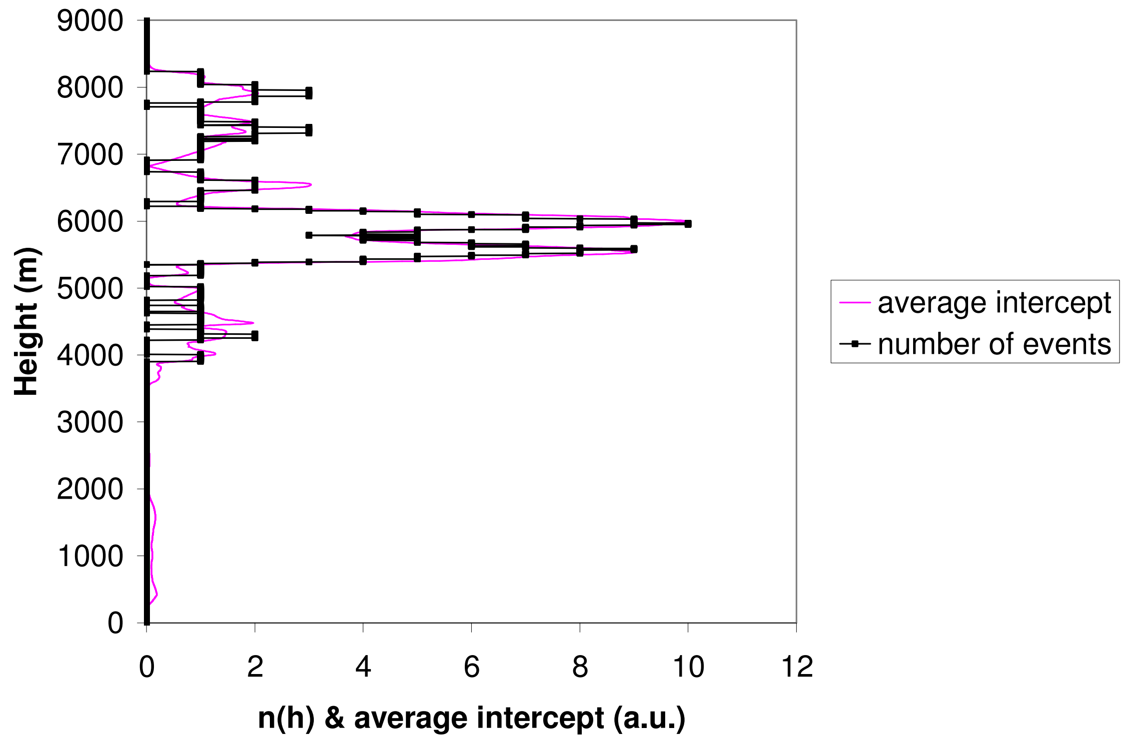


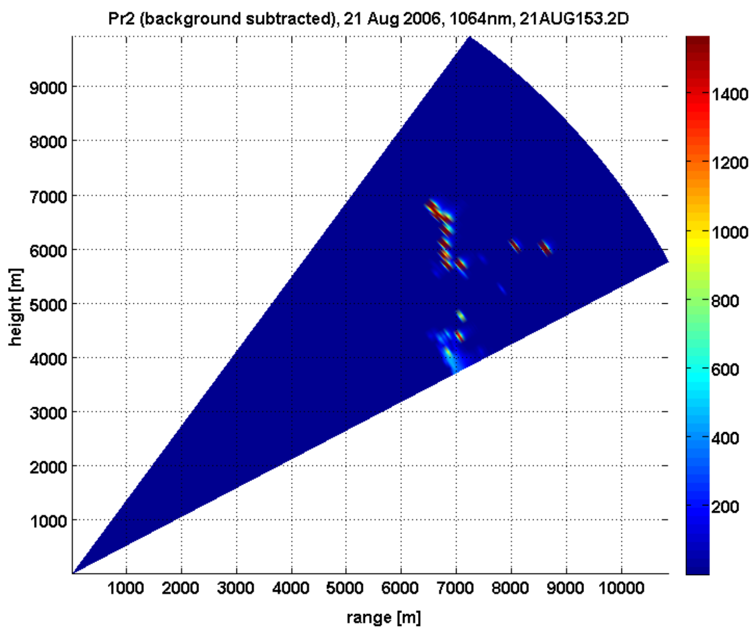


Tripod Fire (Washington)
August 21, 2006, 14:56, 1064 nm



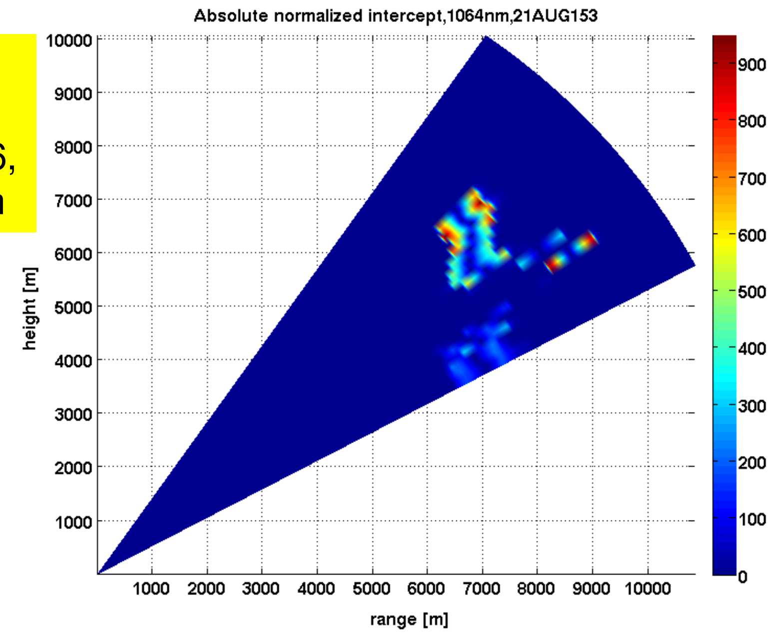


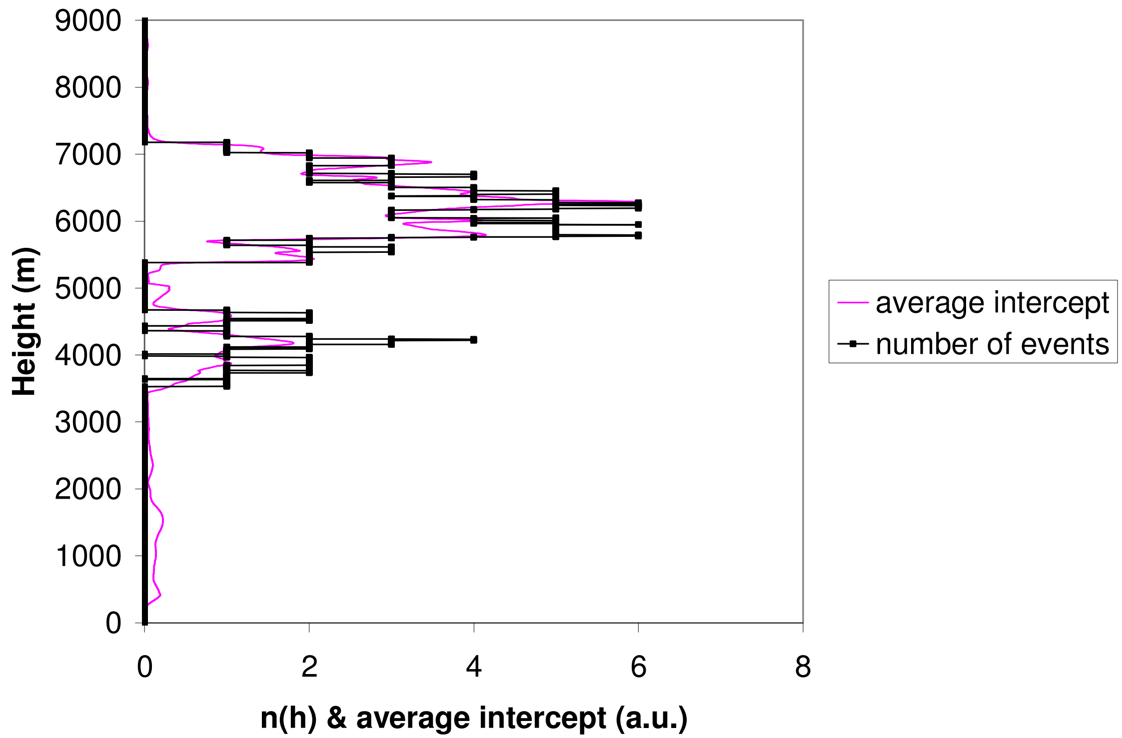




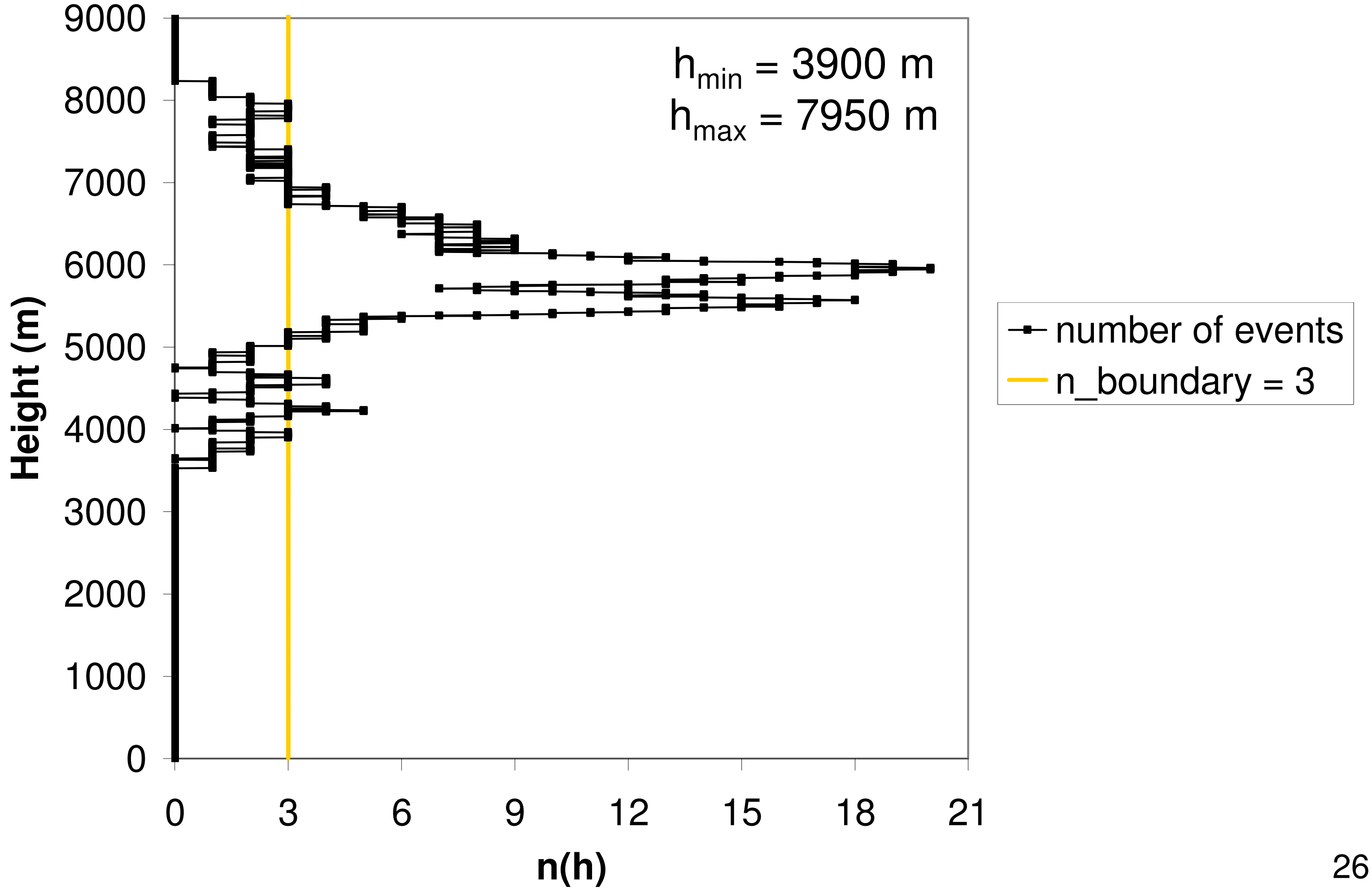
Tripod Fire (Washington)

August 21, 2006, 14:57, 1064 nm



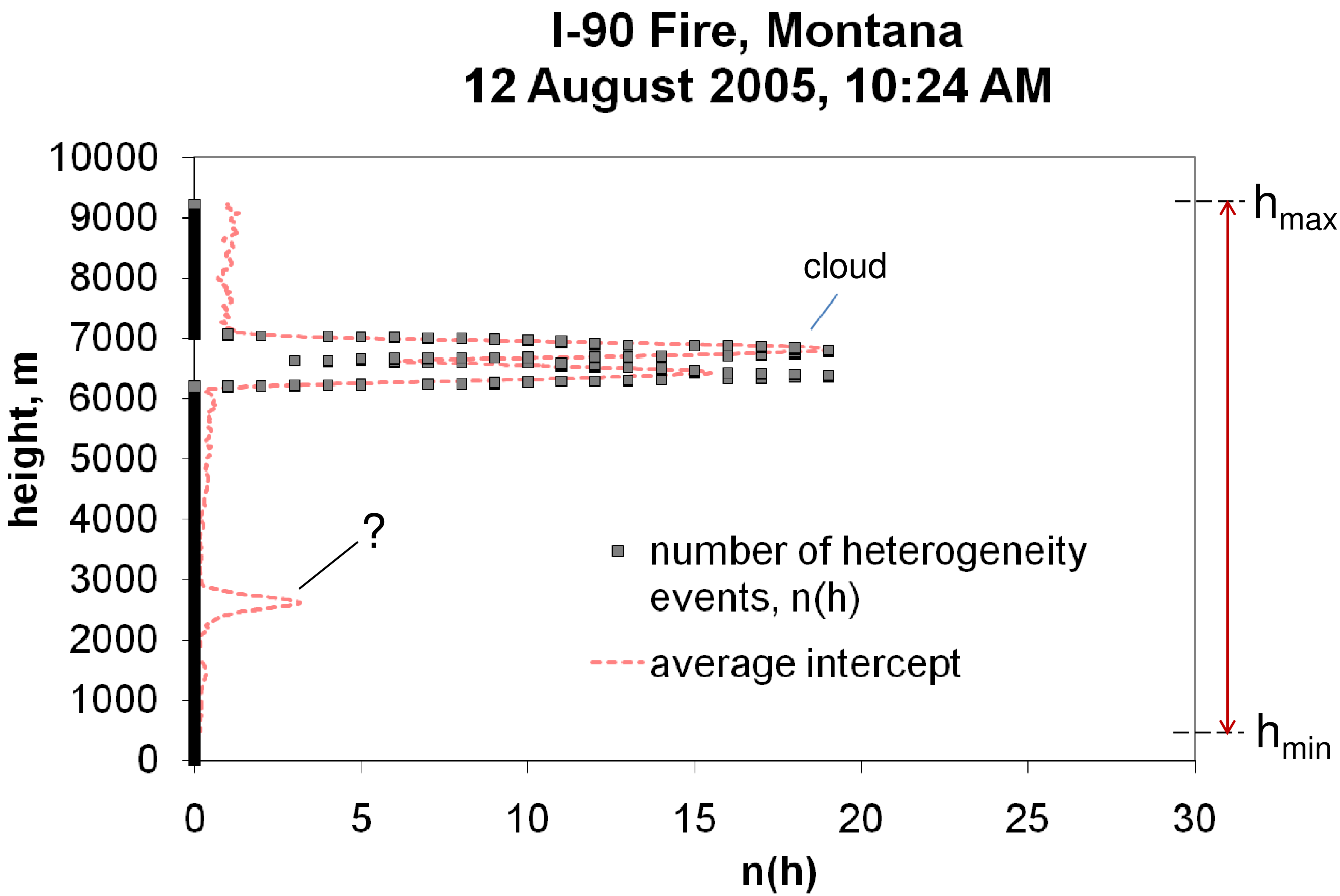


Tripod Fire (Washington)
August 21, 2006,1064 nm
Accumulated data (14:55 – 14:58)

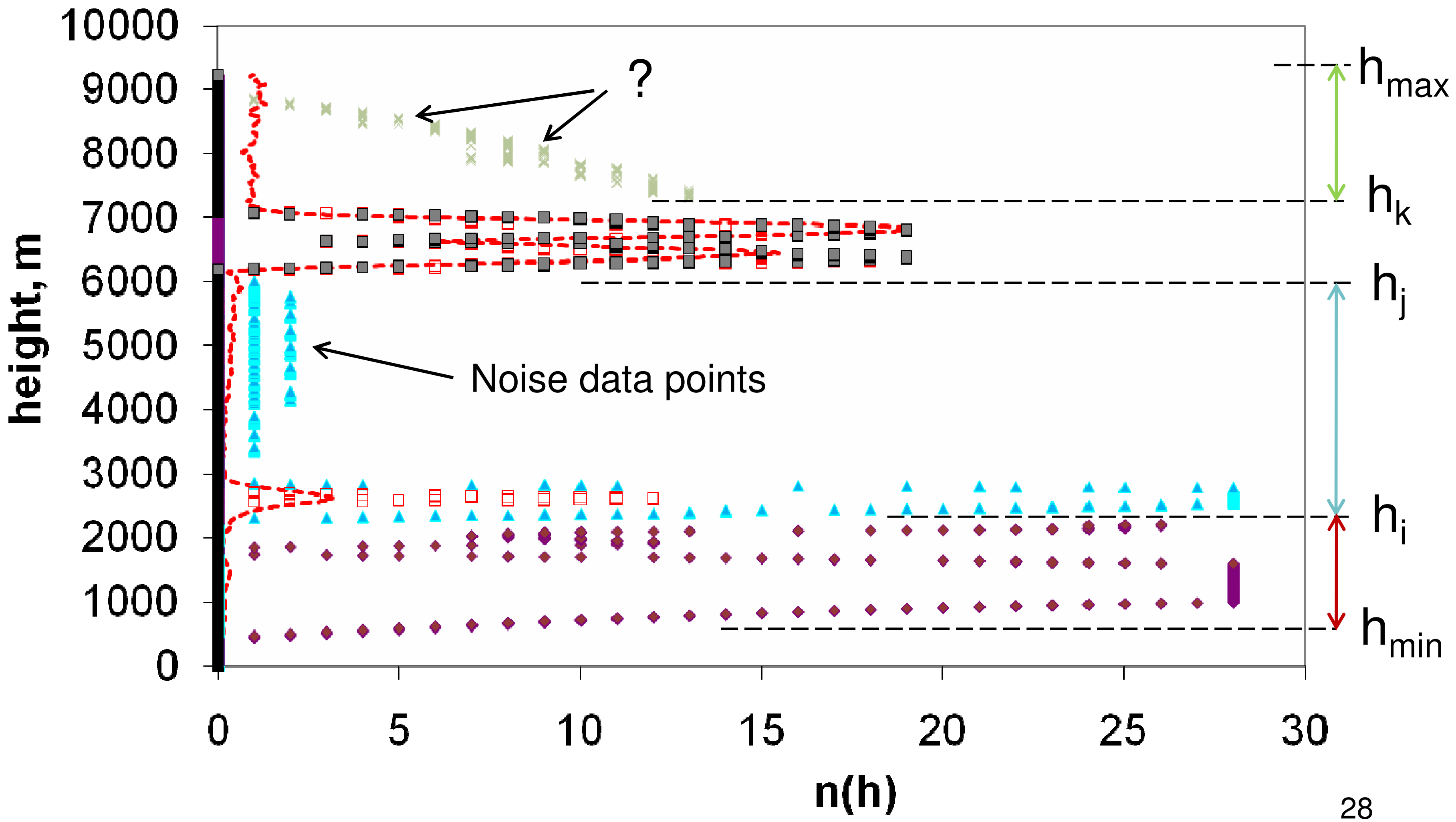


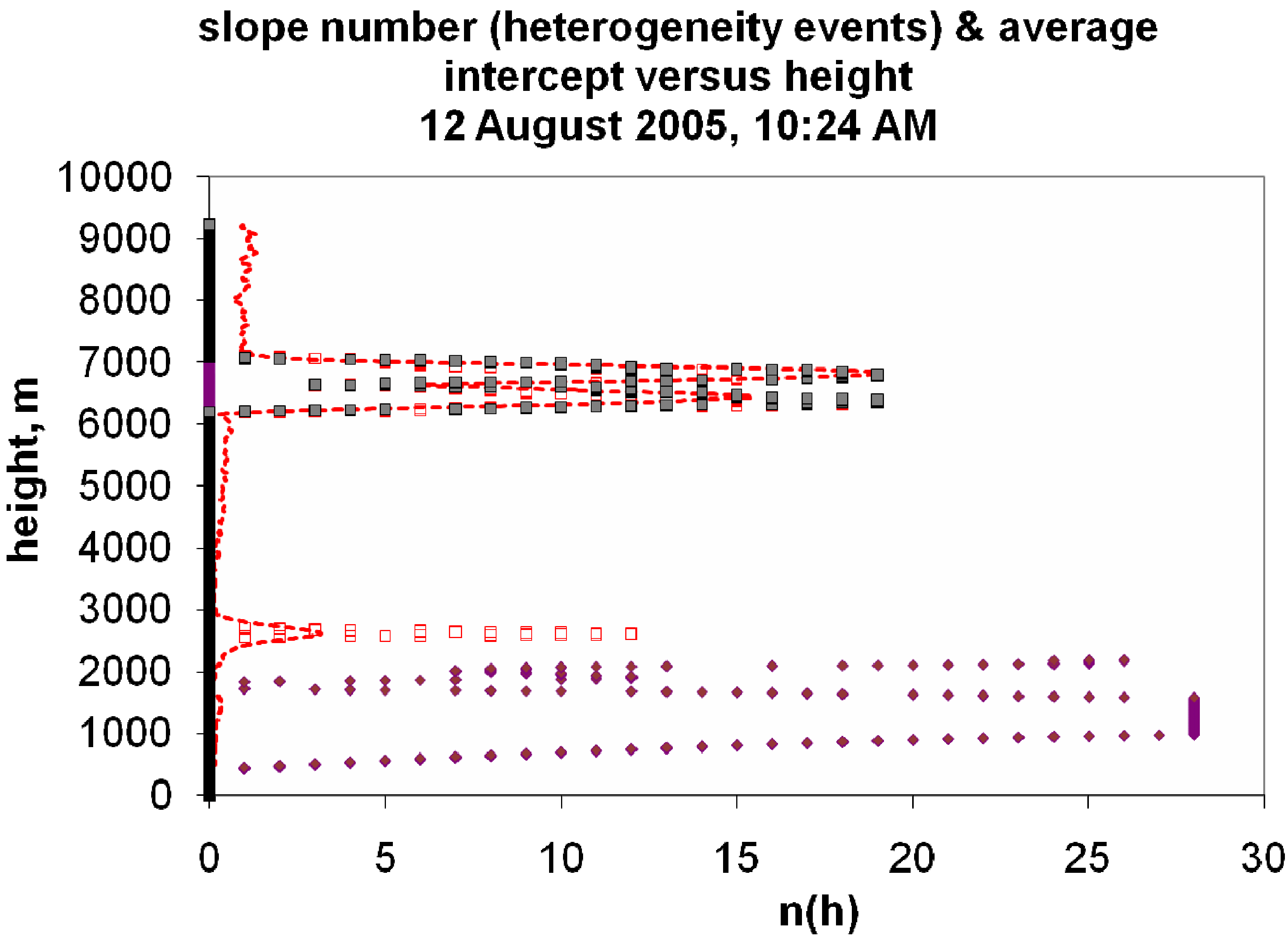
Not normalized intercept

May be helpful for analysis of the detailed vertical profile of HHI



slope number (heterogeneity events) & average intercept versus height
12 August 2005, 10:24 AM



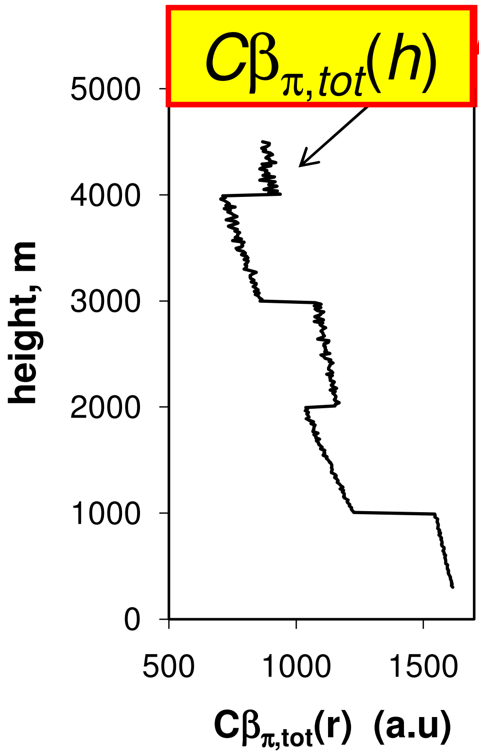


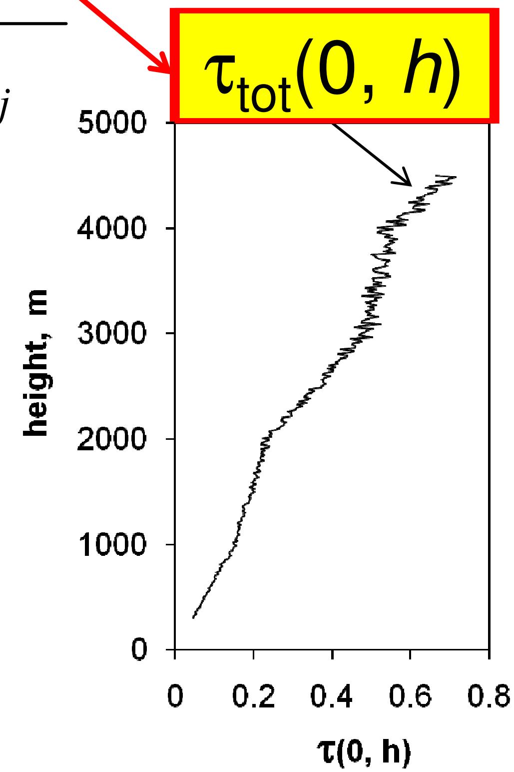
slope number (heterogeneity events) & average
intercept versus height
12 August 2005, 10:24 AM
height, m
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
5
10
15
20
25
30
n(h)

PART II. Investigation of the stratified smoke layering at the 355 nm wavelength

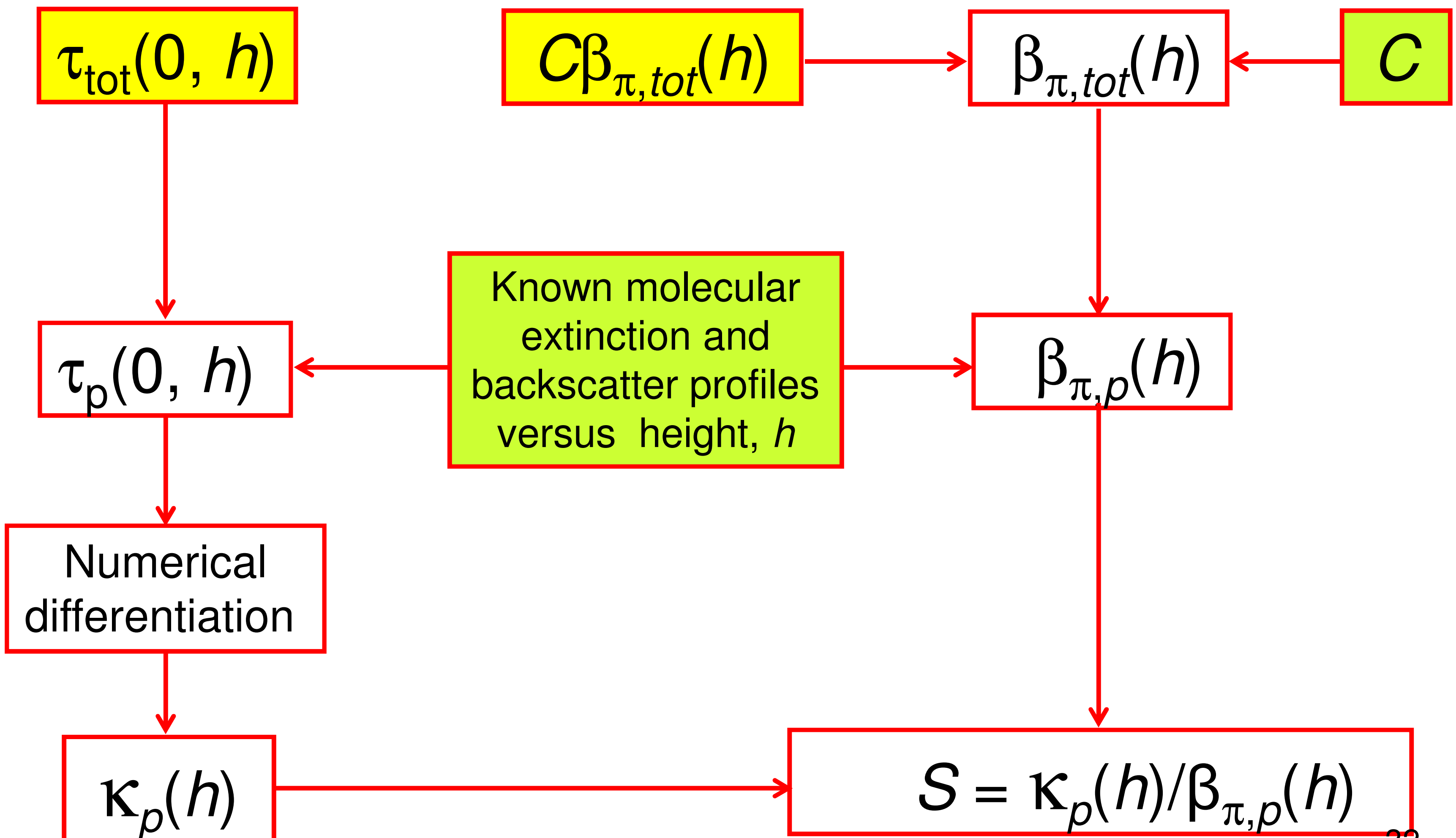
Kano-Hamilton equation:

$$\ln\left[P_j(h)(h/\sin\varphi_j)^2\right] = A(h) - \frac{2\tau_j(0,h)}{\sin\varphi_j}$$

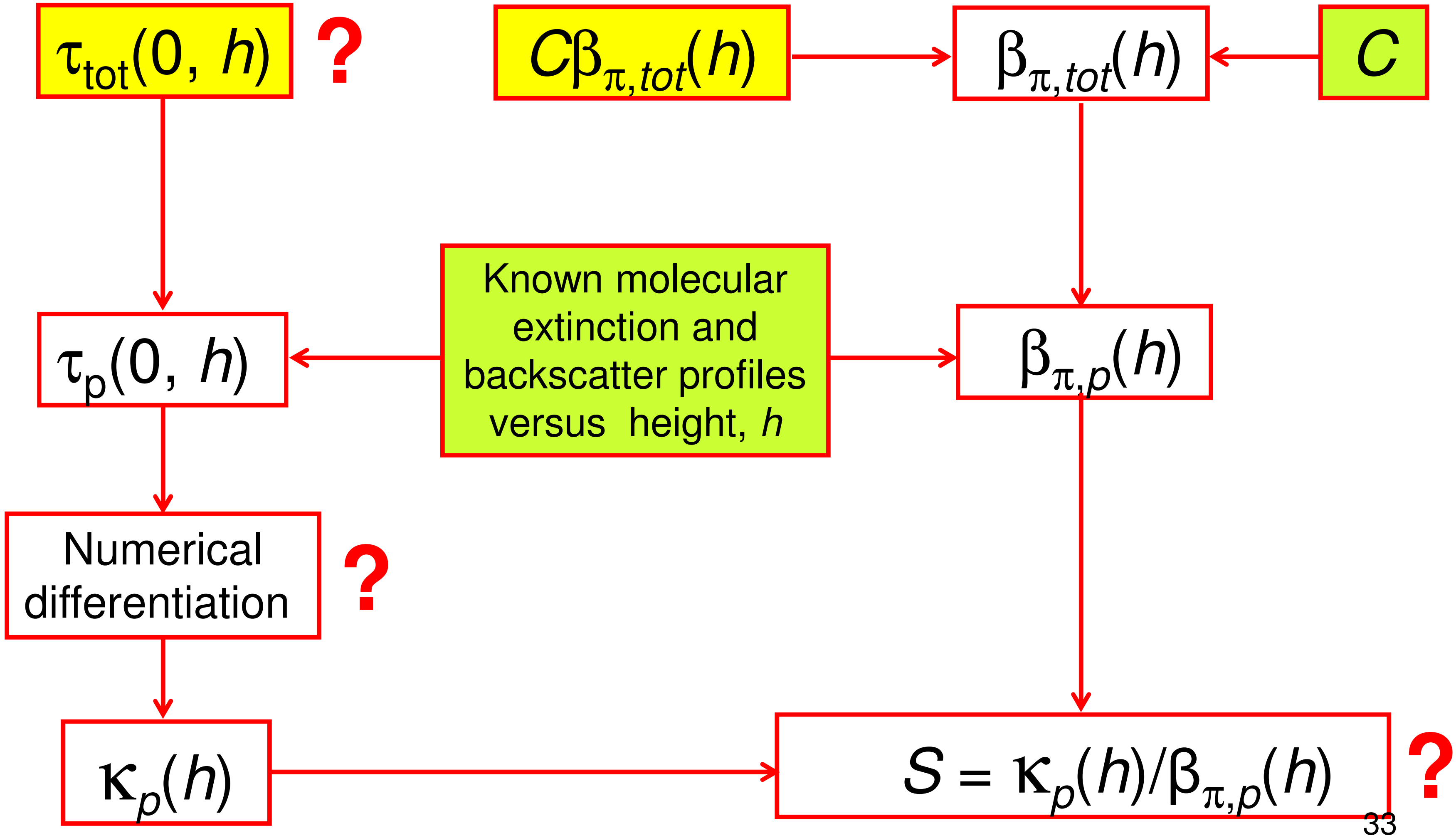




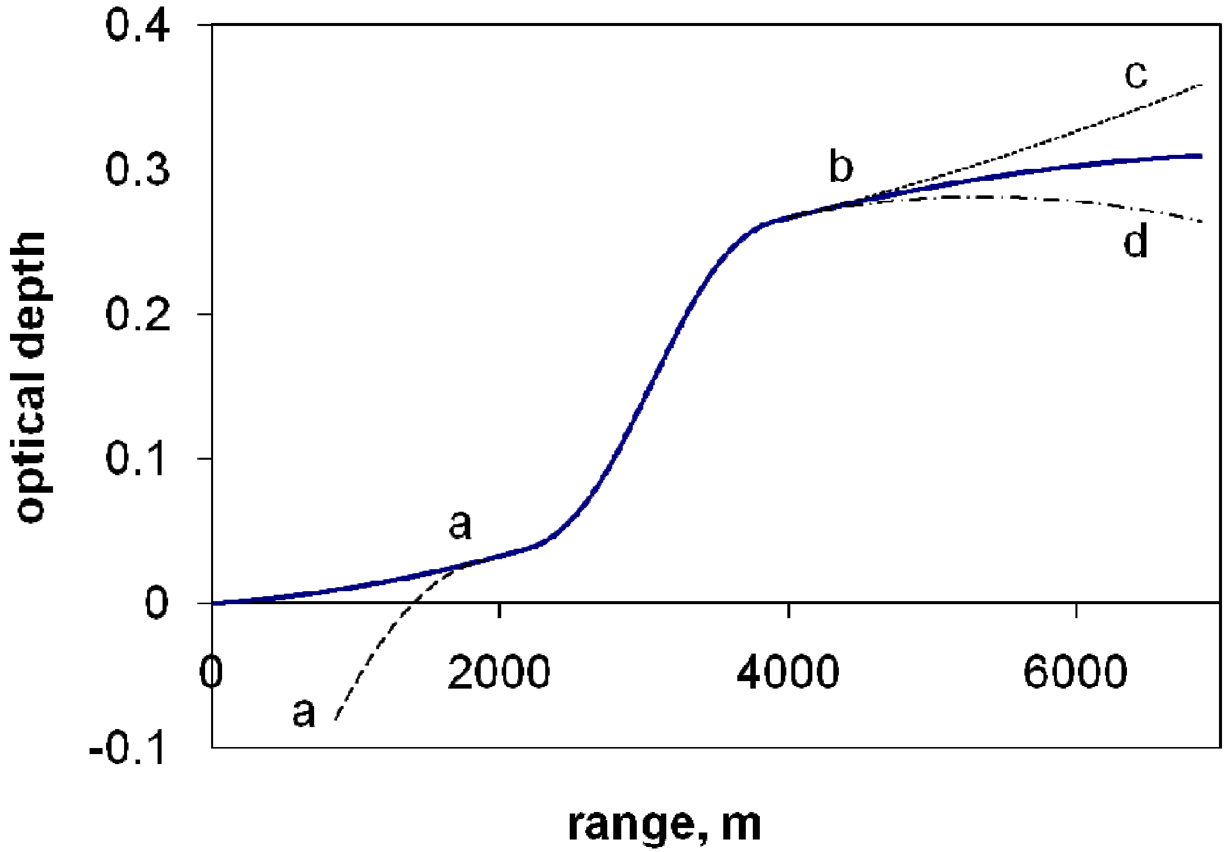
Straightforward retrieval procedure of the particulate extinction coefficient, $\kappa_p(h)$ and the lidar ratio, S



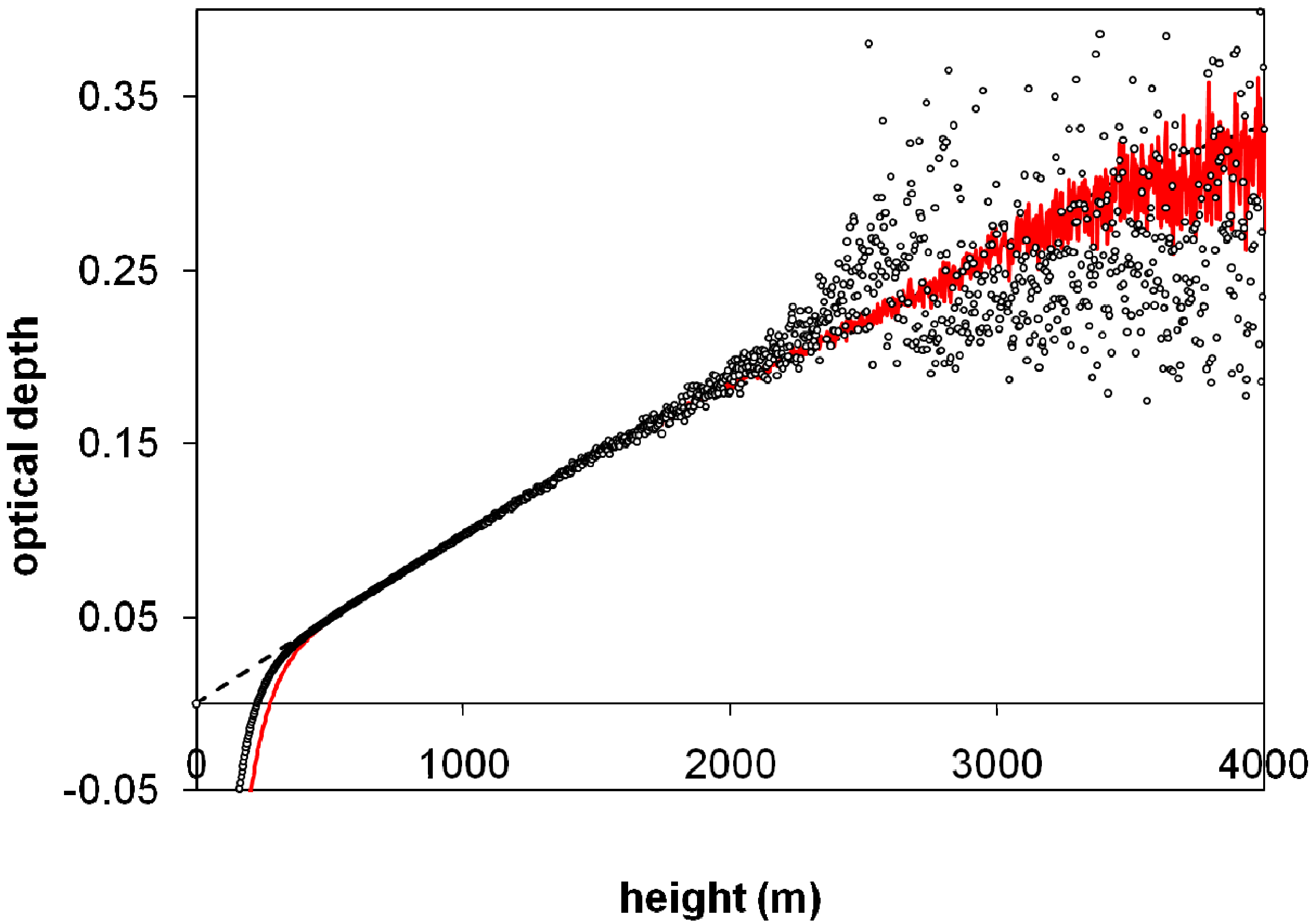
Straightforward retrieval procedure of the particulate extinction coefficient, $\kappa_p(h)$ and the lidar ratio, S



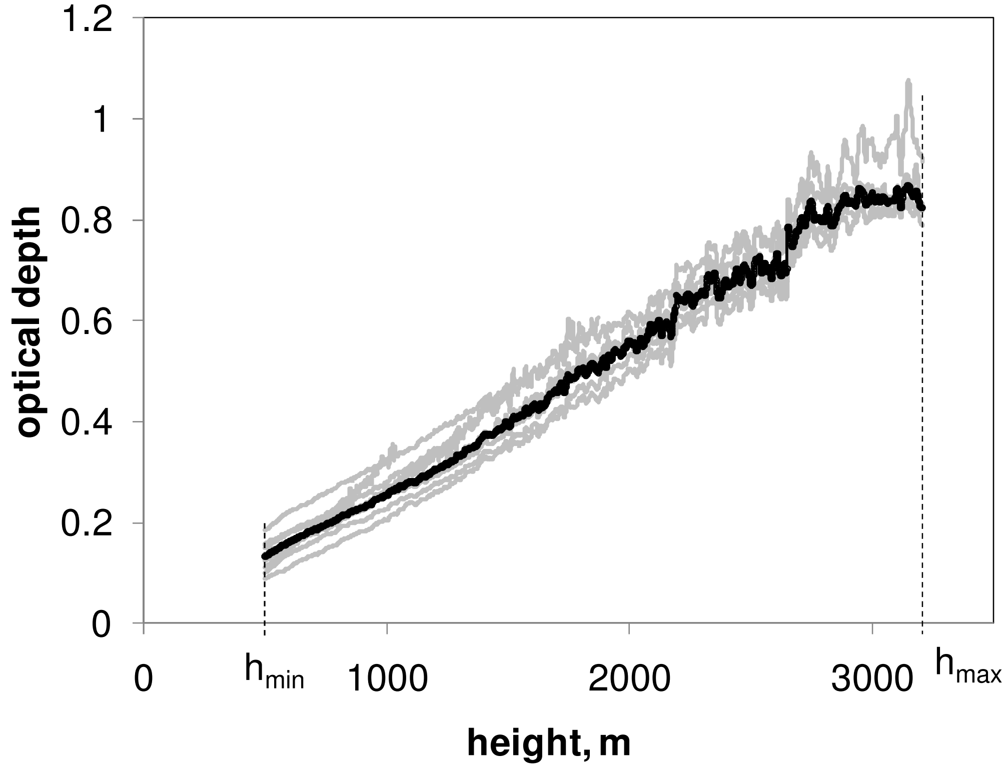
True optical depth (the thick solid curve) and possible near-end (curve *aa*) and far-end (curves bc and *bd*) distortions caused by systematic multiplicative and additive lidar-signal distortions.



OD distortions when using the non-weighted fit (the black circles) and weighted fit (the red curve) in least squares

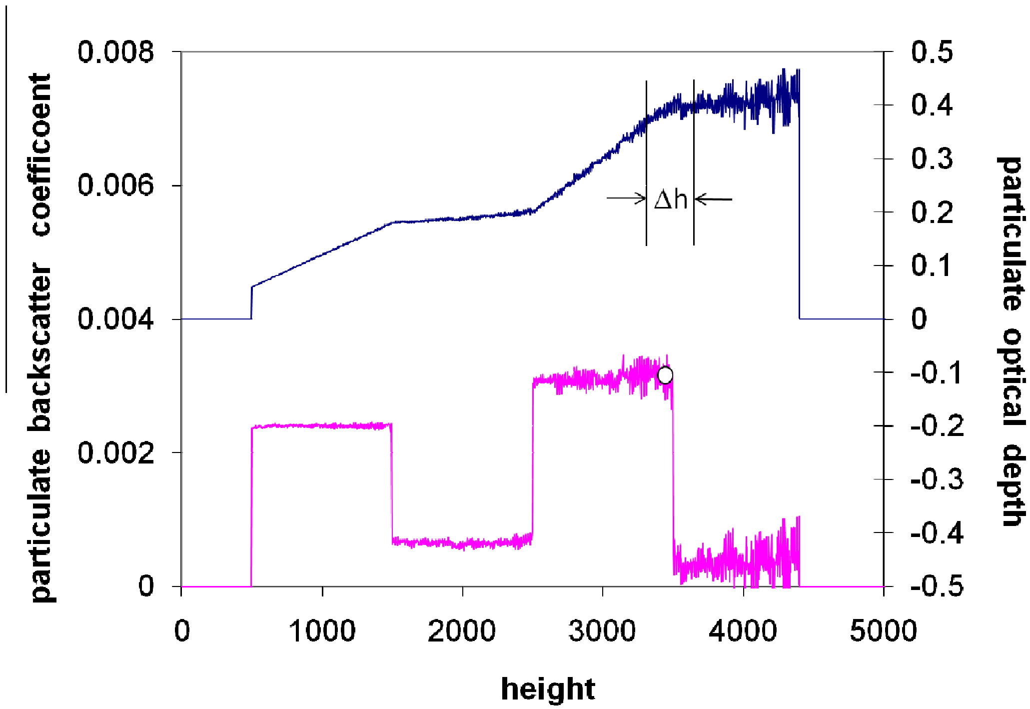


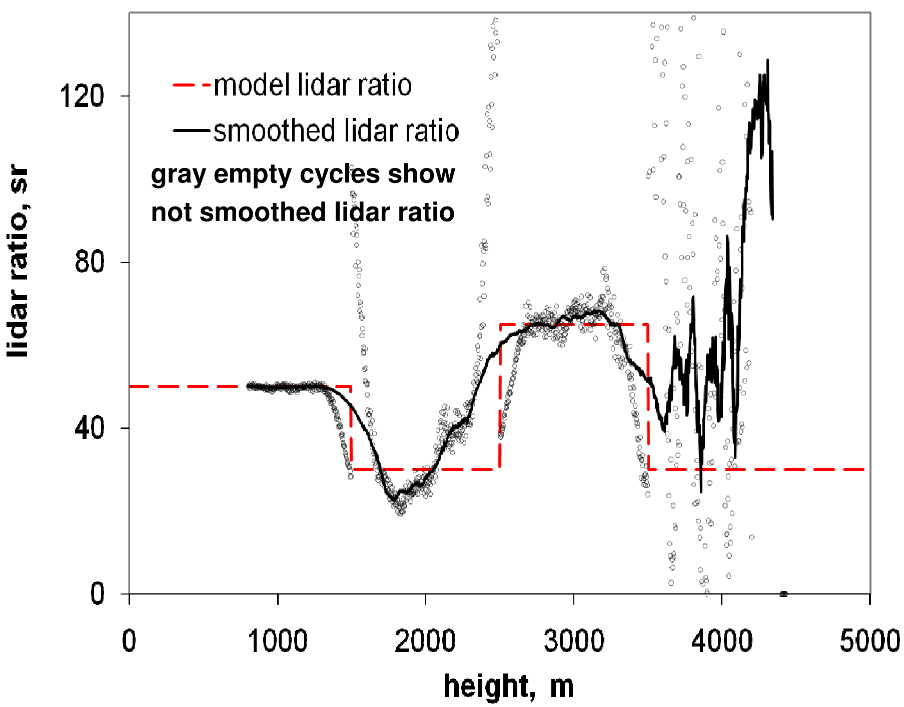
Optical depth profiles obtained from the multiangle measurements made during the Tripod Fire in Washington state in August 2006



- The black thick curve is the optical depth profile, $\tau(0, h)$ retrieved directly from the Kano-Hamilton solution
- The set of the vertical profiles $\tau_1(0, h)$, $\tau_2(0, h)$,… $\tau_j(0, h)$,… $\tau_n(0, h)$, shown as grey thin curves is derived from individual signals with the formula

$$\tau_j(0,h) = 0.5 \sin\varphi_j \left\{ A(h) - \ln\left[P_j(h)(h/\sin\varphi_j)^2 \right] \right\}$$





DISTORTIONS IN THE RETRIEVED LIDAR RATIO WHEN USING FORMULA

$$S = \kappa_p(h)/\beta_{\pi,p}(h) =$$

$$= \frac{d/dh[\tau_p(0,h)]}{\beta_{\pi,p}(h)}$$

Alternative technique for determining the extinction coefficient and the lidar ratio from data of multiangle measurements

The new algorithm determines the particulate extinction coefficient from the backscatter coefficient, $\beta_{\pi,p}(h)$, using the uncertainty boundaries in the retrieved optical depth, $\tau(0, h)$, as a constraint.

The principle that underlies this approach is the assumption that no **sharp** changes in the lidar ratio take place in areas where no **sharp** changes in the extinction coefficient occur. In other words, it is assumed that the sharp changes in the lidar ratio are related with sharp changes in the extinction coefficient.

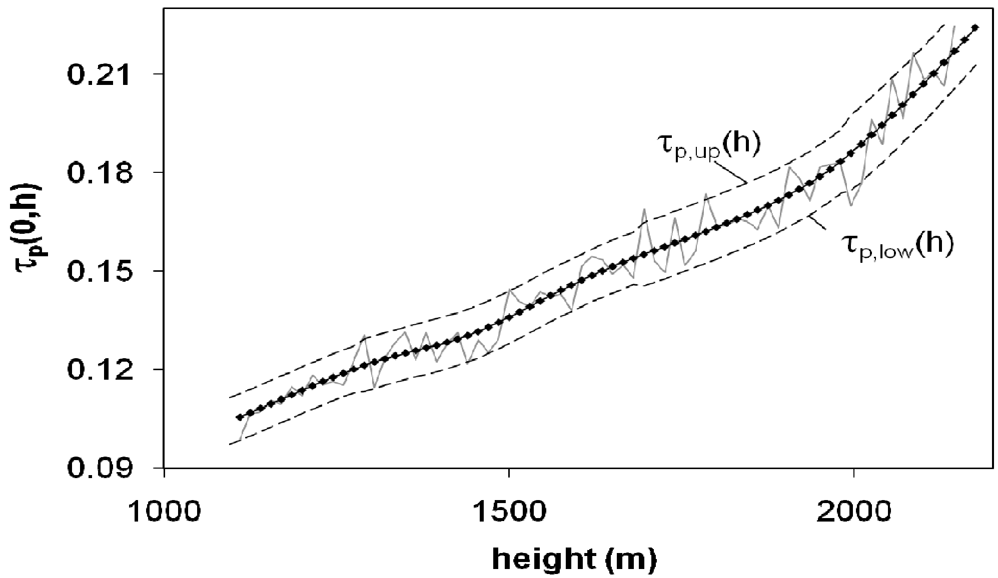
Method

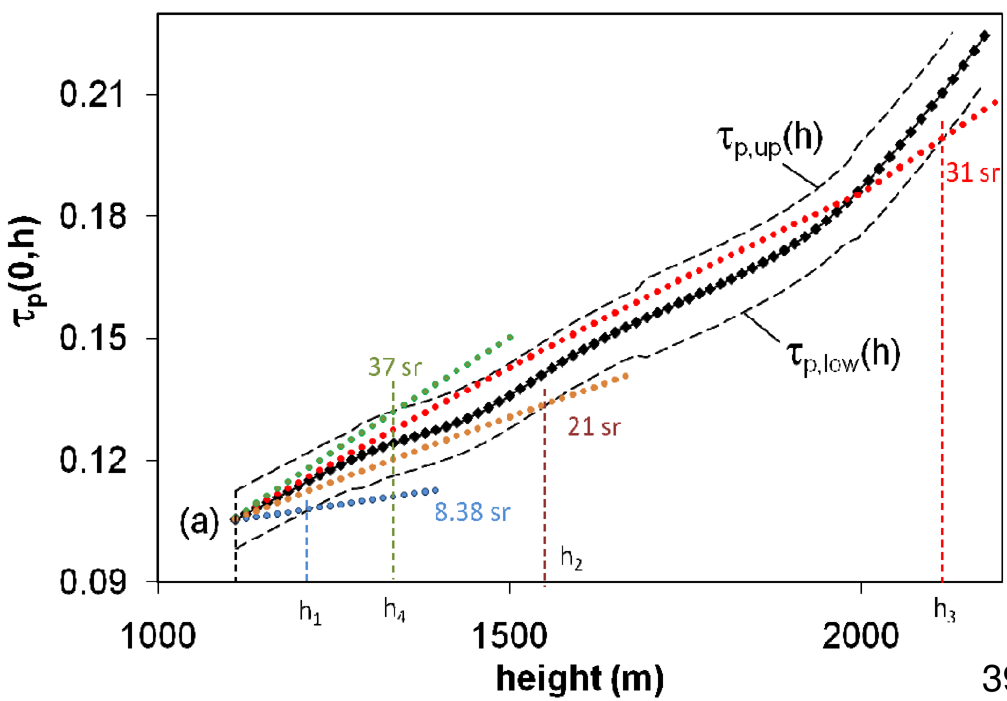
1. Calculate the auxiliary particulate optical depth $\langle\tau_p(h_n, h_m)\rangle$ using the profile of the particulate backscatter extinction coefficient, $\beta_{\pi,p}(h)$ using the formula:

$$\langle\tau_p(h_n,h_m)\rangle = S\int_{h_n}^{h_m}\beta_{\pi,p}(h')dh'$$

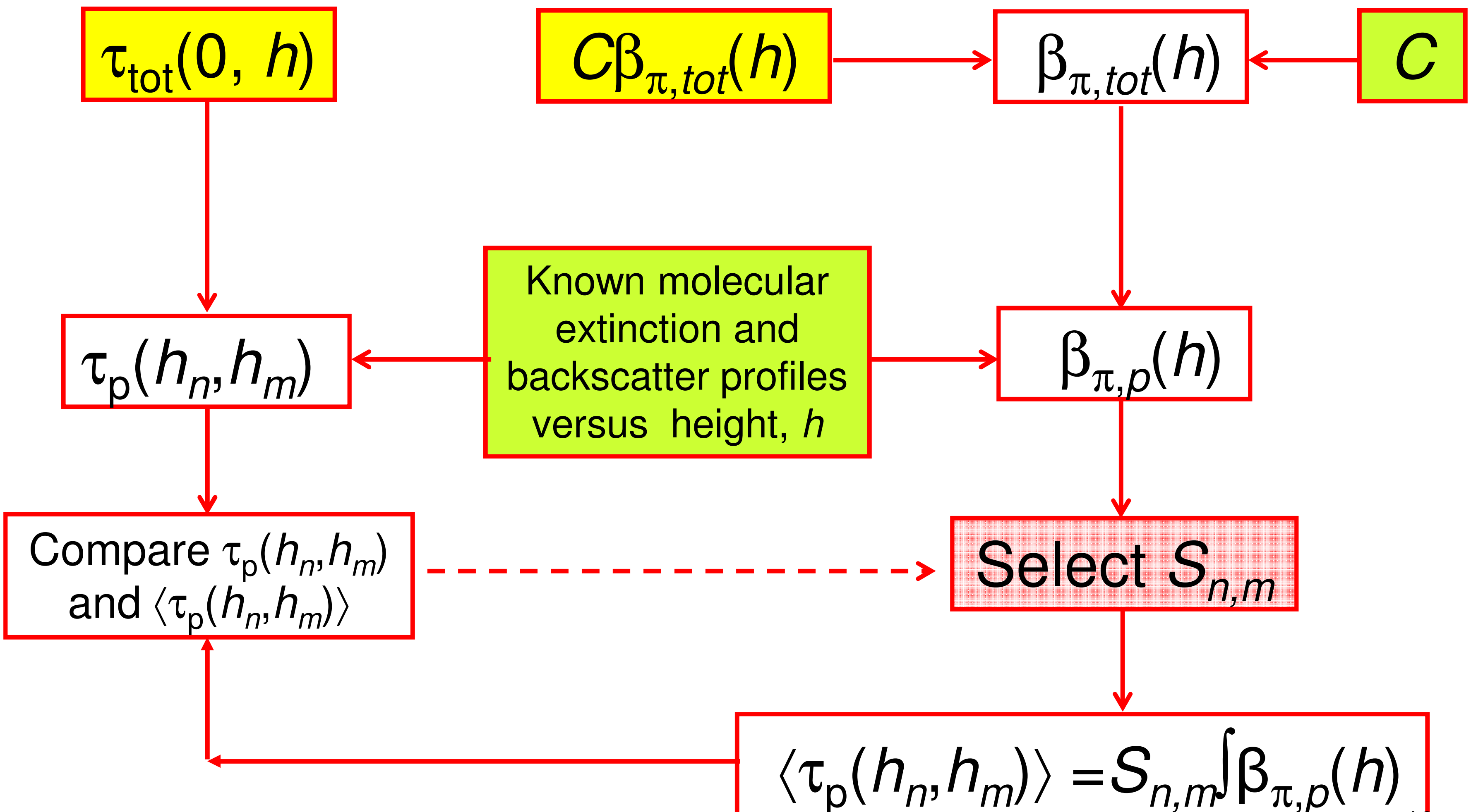
2. Find a column integrated lidar ratio, S, which provides the best match between the above profile, $\langle\tau_p(h_n, h_m)\rangle$ and the profile $\tau_p(h_n, h_m)$, obtained with the Kano-Hamilton solution.

3. Determine the particulate extinction coefficient as the product of S and $\beta_{\pi,p}(h)$.

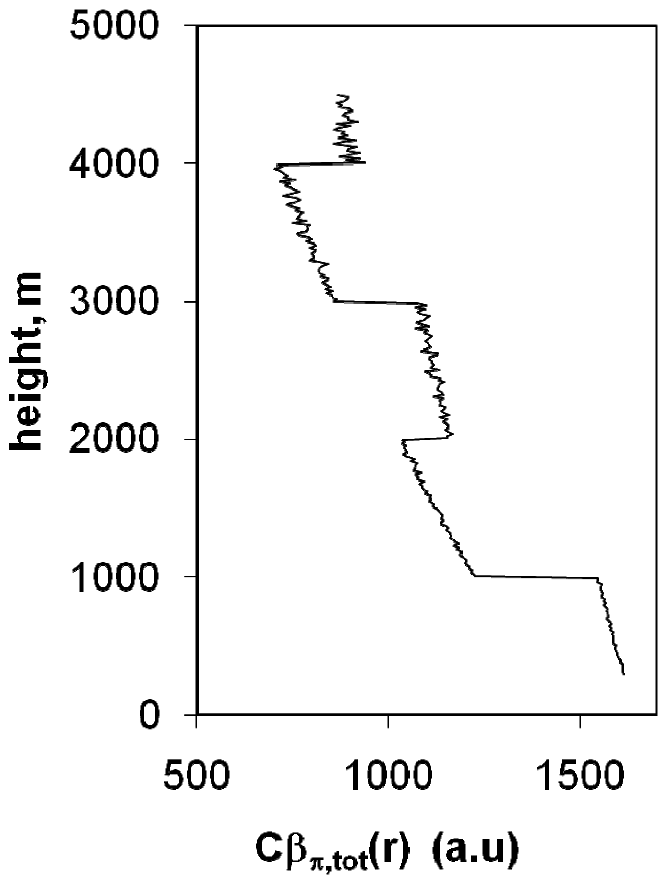


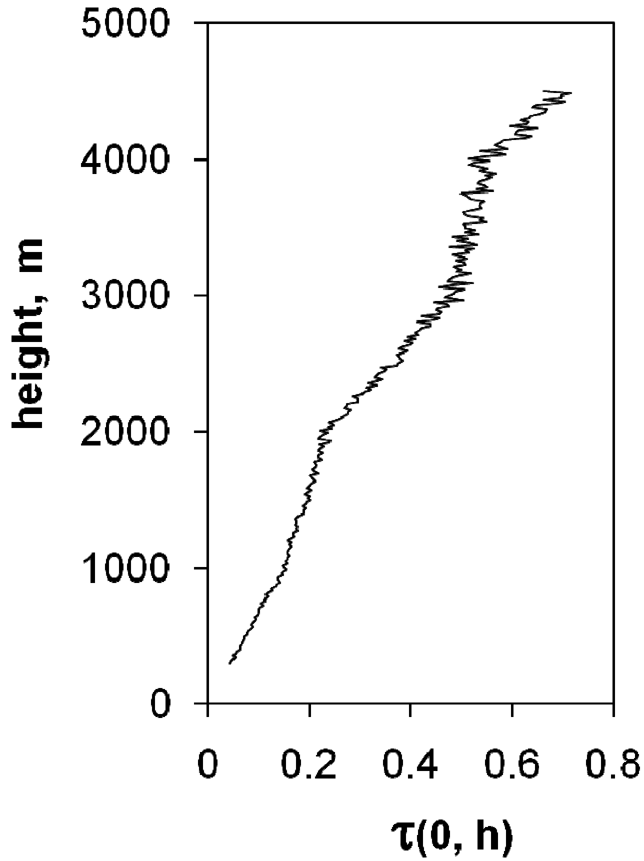


Alternative retrieval procedure of the particulate extinction coefficient, $\kappa_p(h)$ and the lidar ratio, S

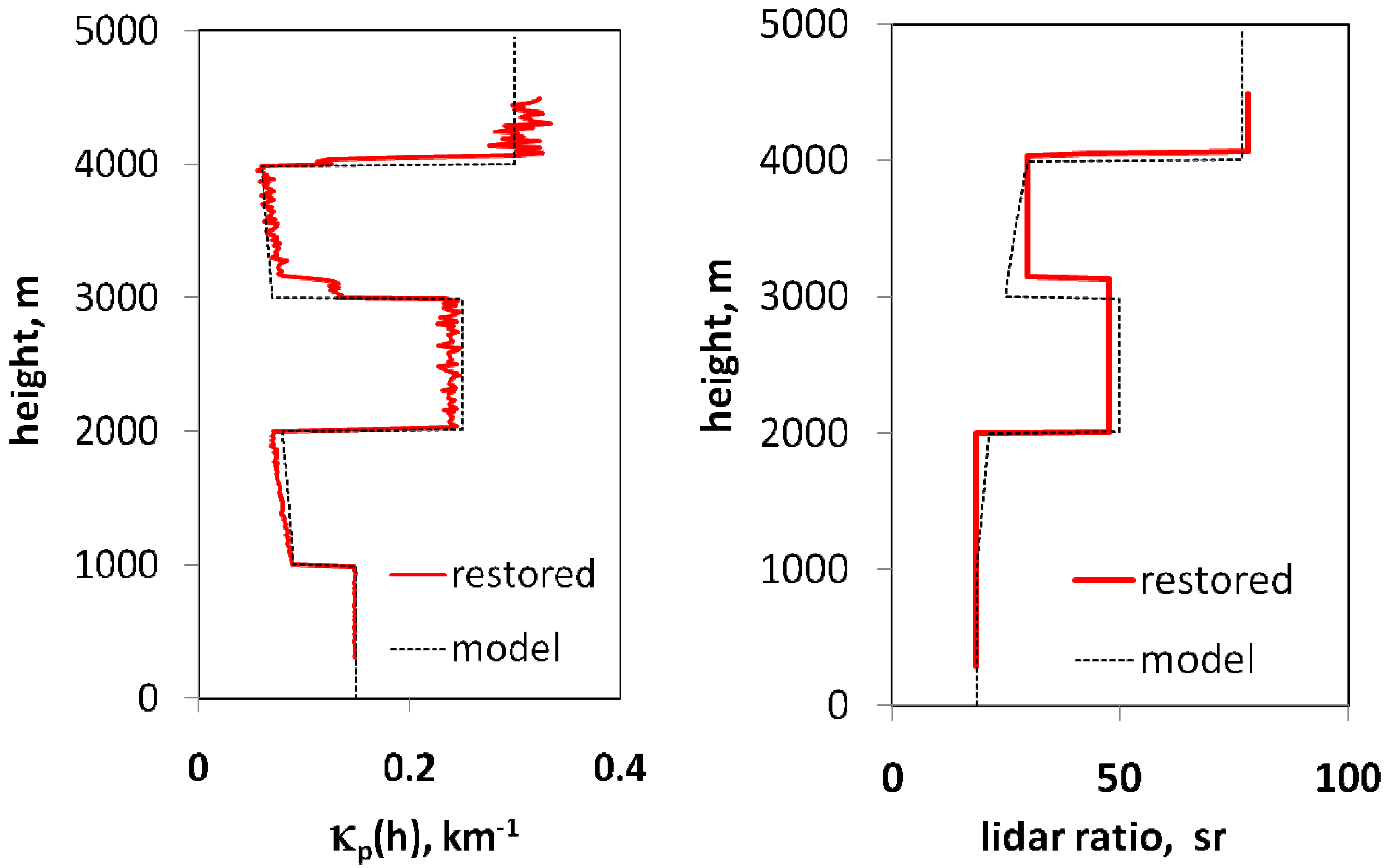


Extracting the extinction coefficient from integrated backscatter coefficient when no accurate estimate of the lidar constant, C, is available
a. Numerical experiment

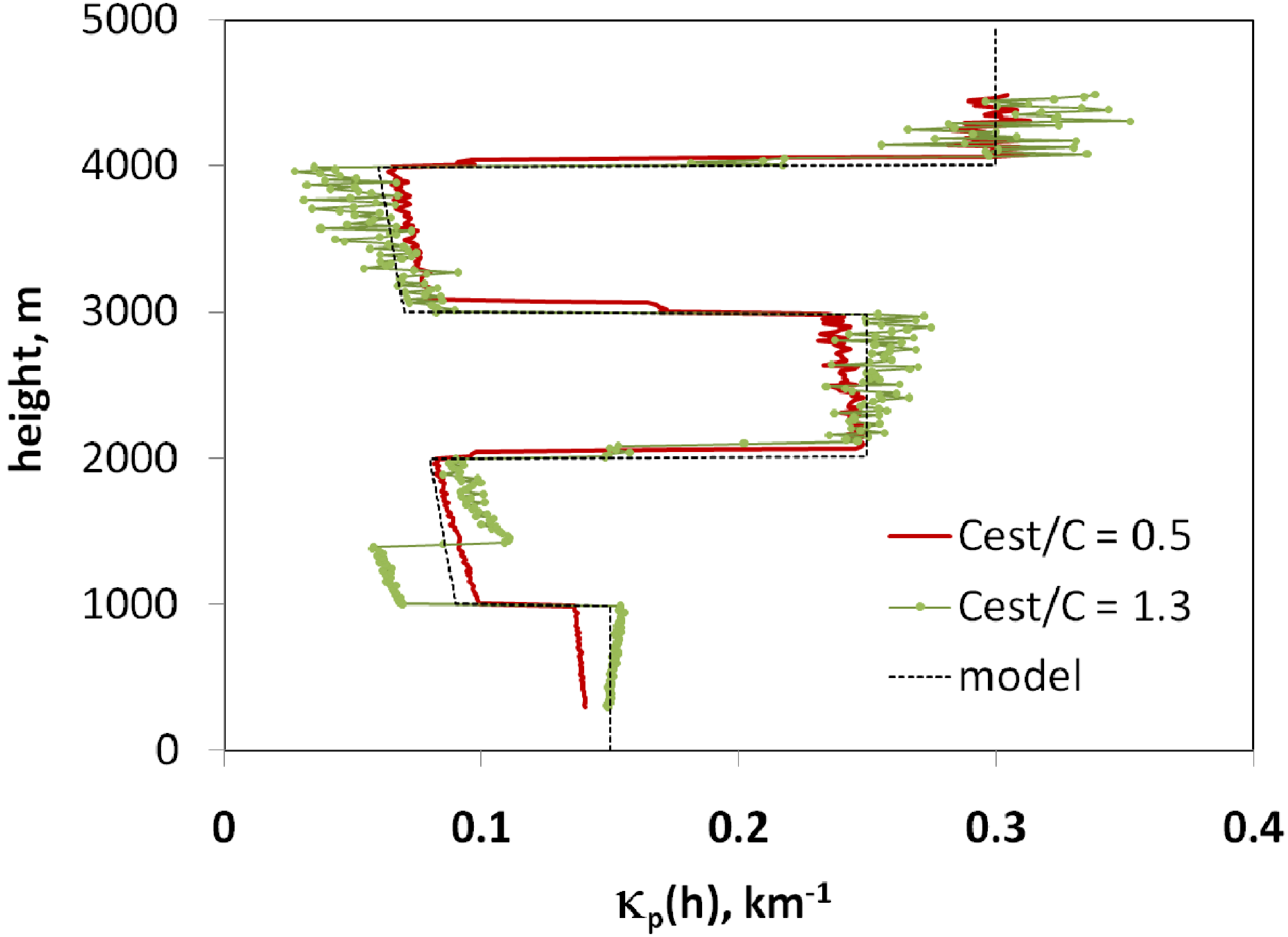




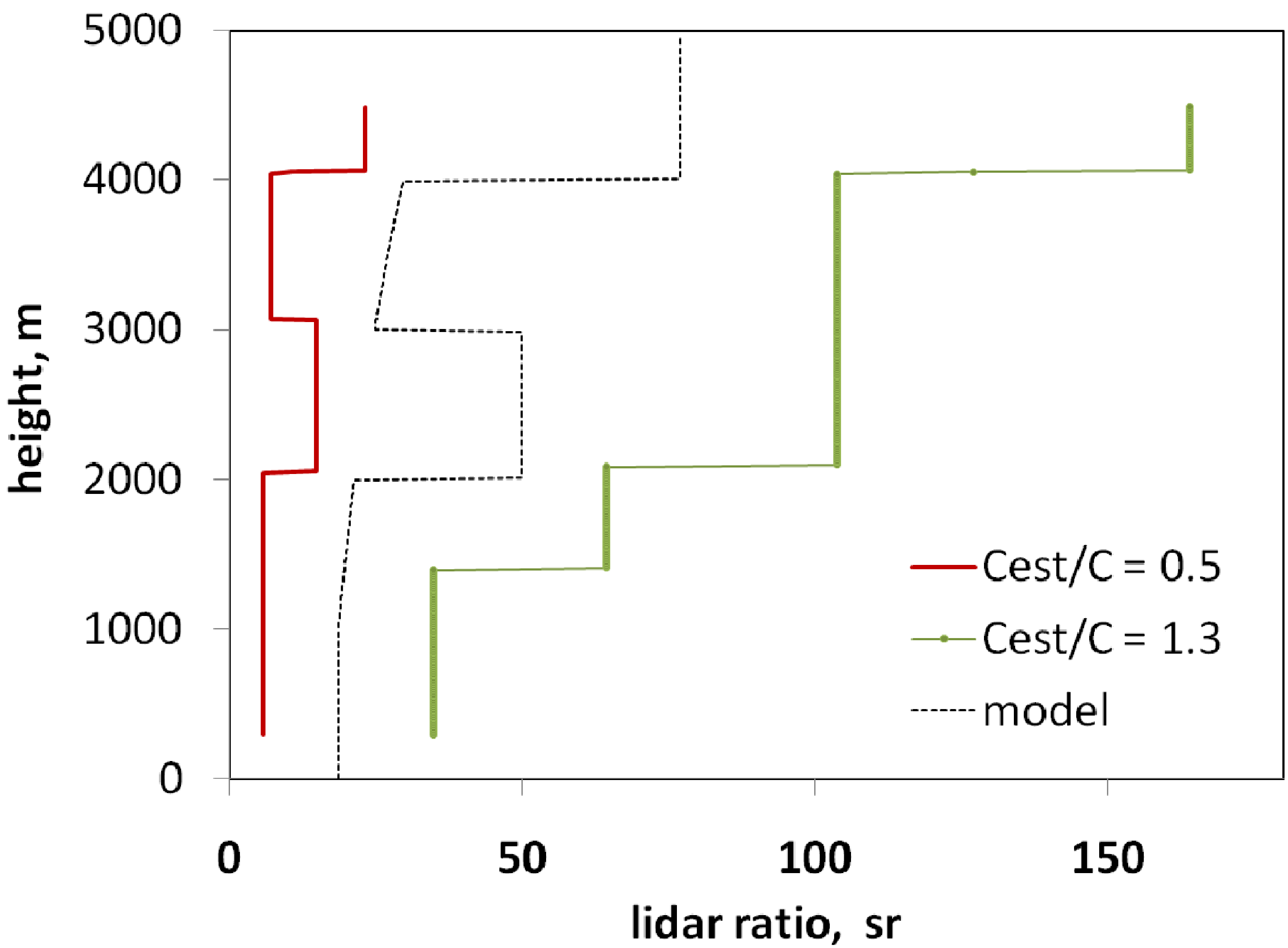
Retrieval results when $C_{est} = C$



Retrieval results when $C_{est} \neq C$

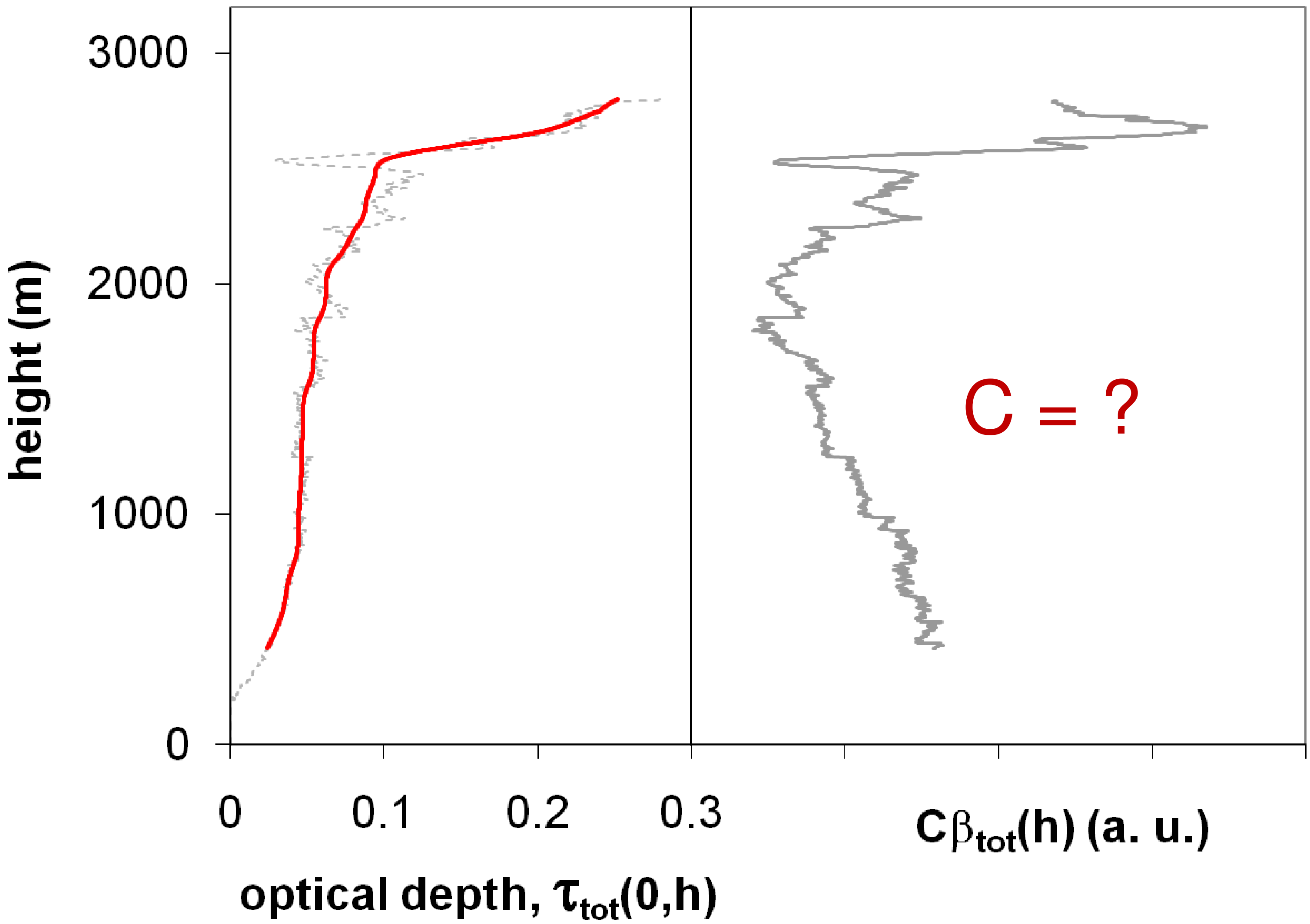


Retrieval results when $C_{est} \neq C$

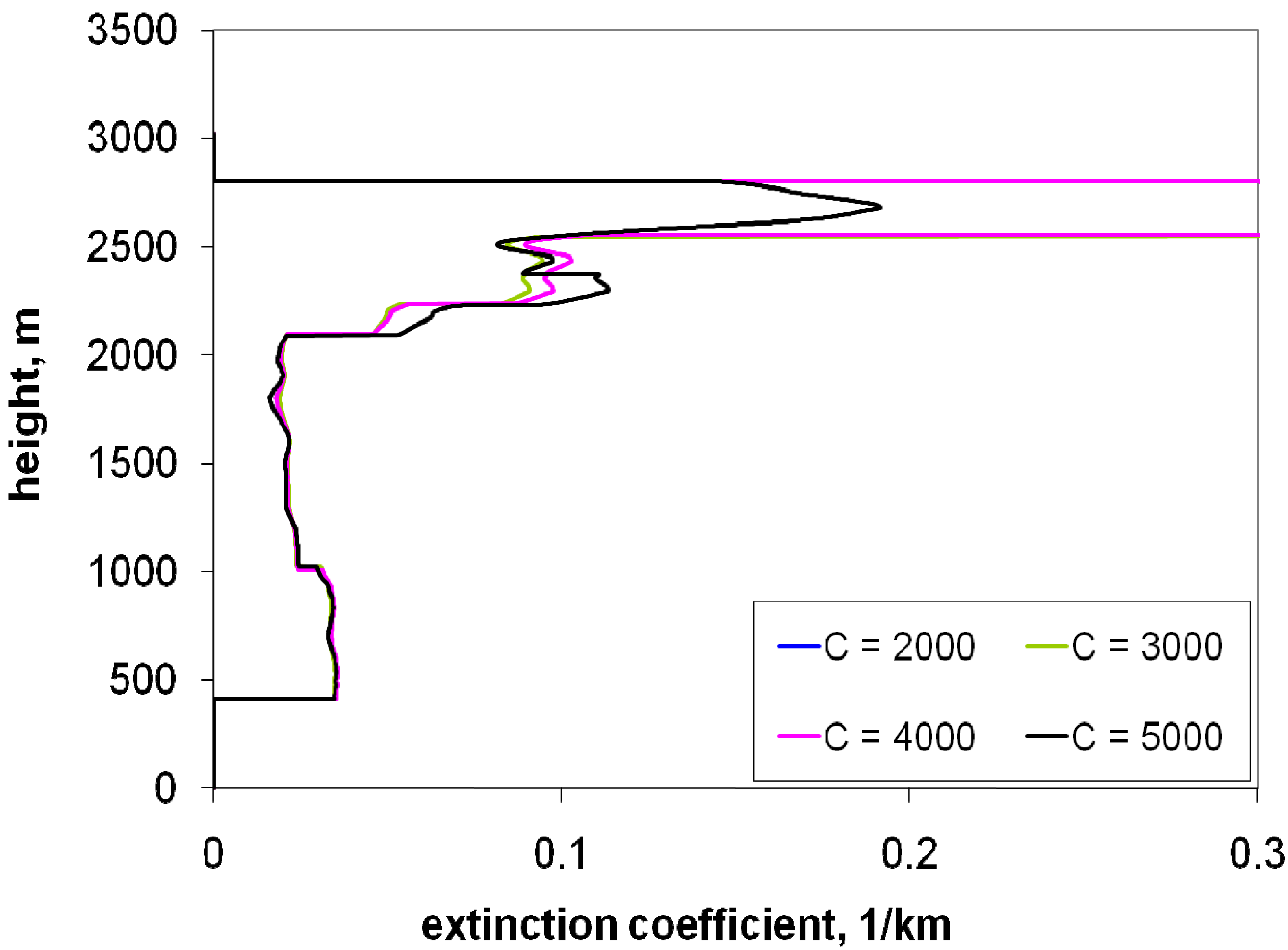


Extracting the extinction coefficient from integrated backscatter coefficient when no accurate estimate of the lidar constant, C, is available
b. Experimental data

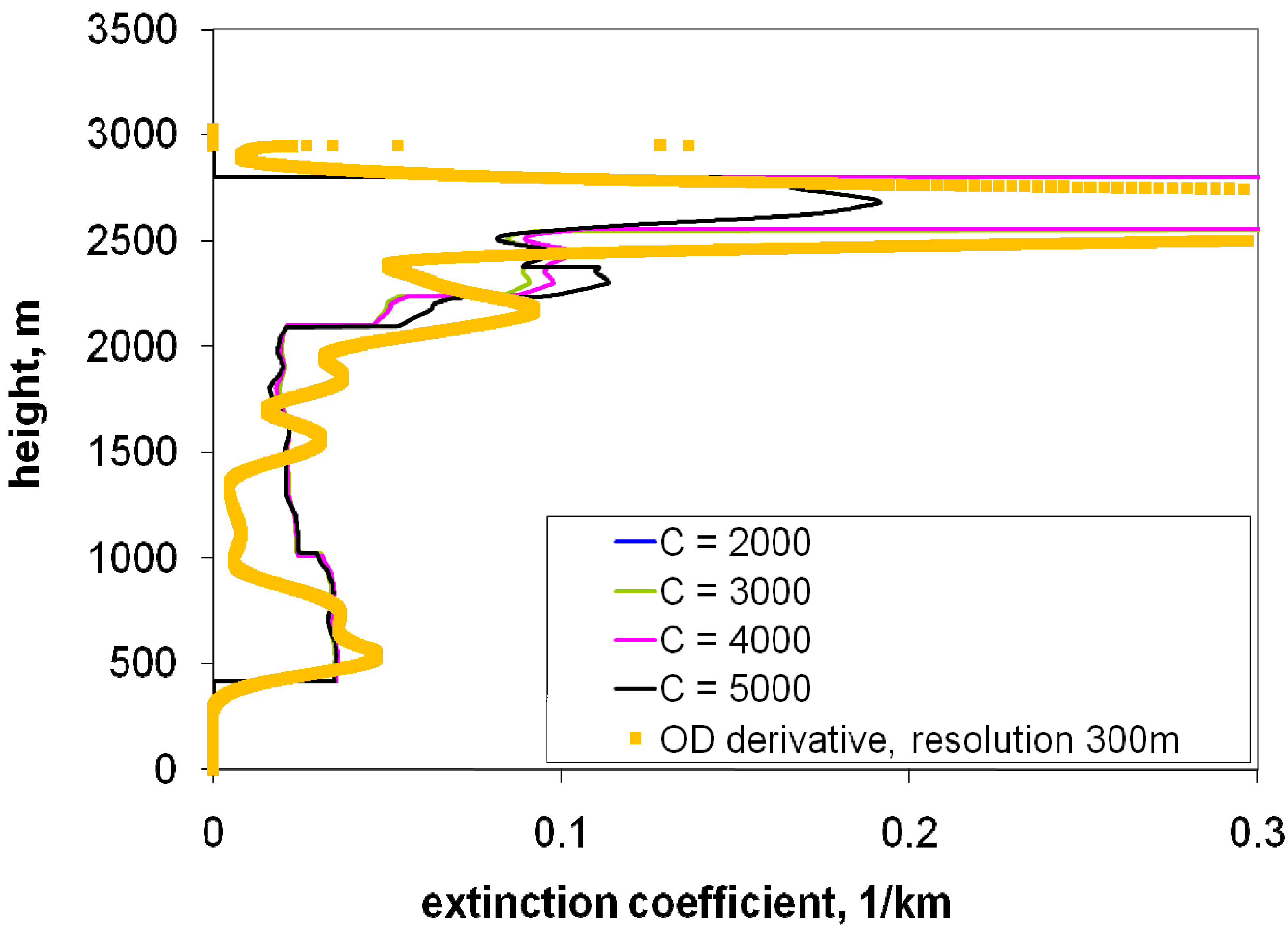
Montana, I-90 fire, August 12, 2005, 09:29AM-09:39AM

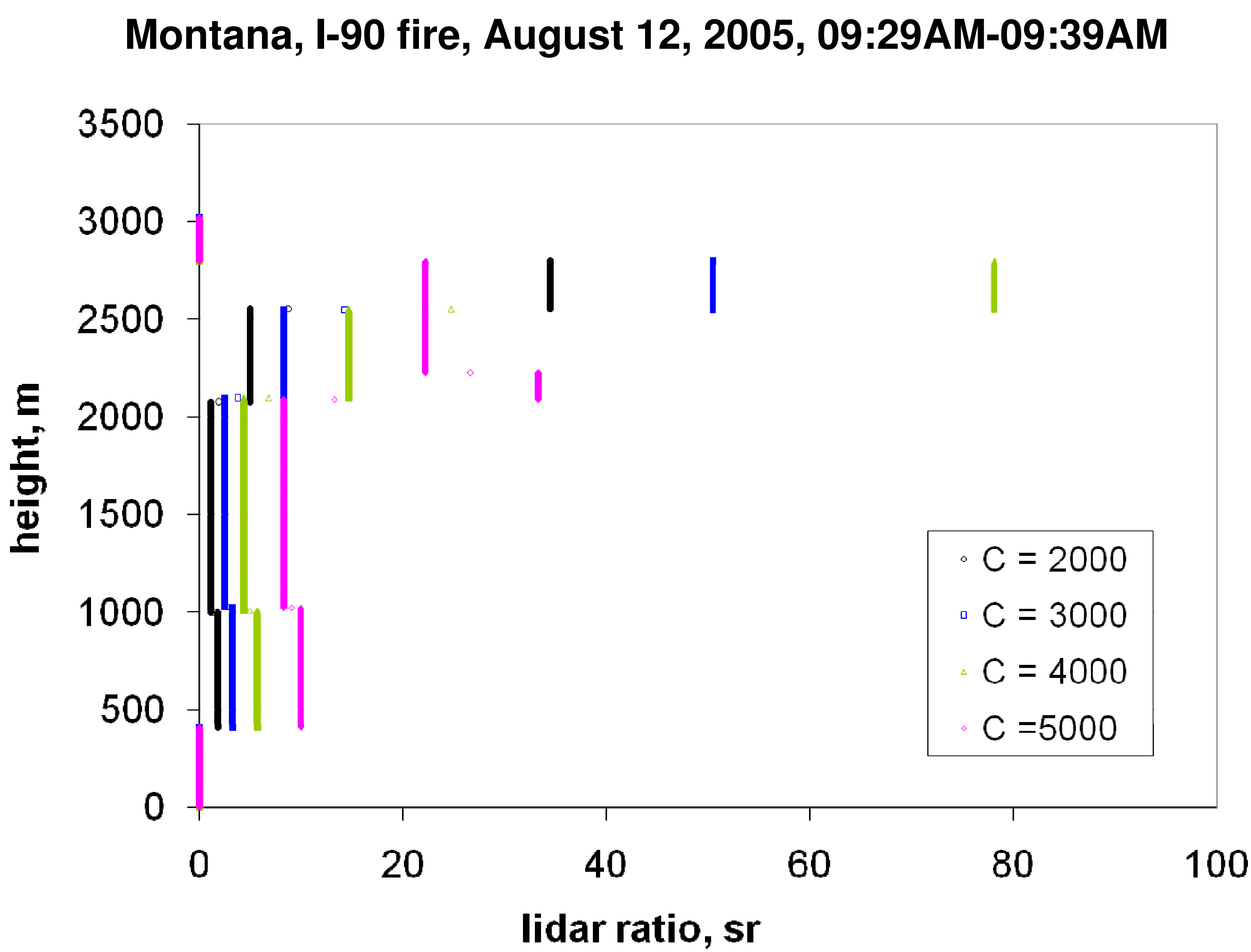


Montana, I-90 fire, August 12, 2005, 09:29AM-09:39AM



Montana, I-90 fire, August 12, 2005, 09:29AM-09:39AM




Montana, I-90 fire, August 12, 2005, 09:29AM-09:39AM
3500
3000
2500
2000
1500
1000
500
0
height, m
0
20
40
60
80
100
lidar ratio, sr
C = 2000
C = 3000
C = 4000
C =5000

SUMMARY

- For smoke-polluted atmospheres, two alternative methods for processing scanning lidar data are used: (a) Investigation of the smoke plume/smoke layer heights and dynamics at the 1064 nm wavelength, and

  (b) Determination of optical characteristics of the searched atmosphere at the 355 nm wavelength.
- Heterogeneity Height Indicator (HHI) allows us to easily determine the heights of smoke plumes and layers and their temporal change using the information obtained for the whole area searched by a scanning lidar
- Atmospheric heterogeneity and lidar-signal systematic distortions in the near- and far-end ranges are dominant factors when determining optical characteristics from lidar multiangle measurements.
- In clear and moderately clear atmospheres, the assumption of a horizontally stratified atmosphere for multiangle measurement can be practical only when the molecular component is relatively large, or at least, comparable with the aerosol component.