GENERATION OF ATTENUATION CORRECTED IMAGES FROM LIDAR DATA

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The interpretation of data generated by aerosol backscatter lidars is often facilitated by presentation of RHI and PPI images. These pictures are especially useful in studies of atmospheric boundary layer structure where convective elements, stratifications and aerosol laden plumes can be easily delineated. This paper describes procedures used at the University of Wisconsin to generate lidar images on a color enhanced raster scan display.

The generation of RHI and PPI images from lidar data presents several problems: 1) it is a computer intensive task because each image consists of 10^5 to 10^6 separate pixels, 2) data are acquired in polar coordinates (range, elevation angle) and thus do not map exactly onto the rectangular raster scan coordinates of the picture display, 3) attenuation corrections must be applied to produce a useful image, 4) even after attenuation and range-squared corrections the lidar return amplitudes often vary over a factor of 100 while image displays typically provide less than 32 distinguishable gray levels, 5) real-time display of lidar images is normally required to control data acquisition during experiments.

Different routines are used to form real-time and post-facto displays. Images prepared for publication or detailed analysis are generated using a more sophisticated correction for atmospheric attenuation than is used for the real-time pictures. Except for this difference, which is due to computation time constraints, the image forming routines are identical.

Real-time displays on the UW lidar are formed using the procedures described by Kunkel et al. (J. Applied Meteor., Vol. 16 #12). Each lidar profile is corrected for variations in the transmitted laser energy and for the inverse range-squared signal decrease. The logarithm of the lidar return is then displayed in an A-scope format. A pair of parallel straight lines are shown superimposed on the lidar return. The operator controls the vertical position, the separation and the slope of the displayed lines pairs. The lower line delineates the largest corrected return which will be displayed as black while the upper line indicates the smallest return which will saturate the displayed intensity. Before the lidar return is displayed signal values corresponding to the lower line are subtracted from the signal and the signal values are rescaled such that the distance between the enhancement lines corresponds to 64 levels. The rescaled signal is now used as an index to a color enhancement look-up table. Each element of

the table contains three values corresponding to the mixture of red, green and blue which is to be projected for each rescaled input value. A series of computer subroutines to load the color enhancement tables are available to the operator.

Changing the slope of the enhancement lines corresponds to providing a correction for a spatially invariant attenuation coefficient while changing the separation and the vertical position of the lines provides control of the displayed dynamic range.

The operator selects range and altitude boundaries of the displayed image. The program then computes the ranges at which the last two lidar profiles intersect the near edge of the display area. The lidar data points nearest in range to the intersection points are used to specify two pixels in the image. Any pixels which fall between these two pixels are filled in by linear interpolation. The program then computes the ranges at which the two profiles intersect the next vertical column of pixels and repeats the above process. This is continued until all pixels in the display memory which fall within the pie shaped sector between the last two lidar firing directions are specified.

This real-time display algorithm executes in well under one second per laser shot when run on a digital equipment PDP-11/40. While the pictures produced are excellent for real-time control of experiments and scanning of data tapes, careful examination of the images quickly reveals the limitations of the constant attenuation assumption. Images consisting of a well mixed hazy boundary layer under a much cleaner upper layer force the operator to choose between over-correcting for attenuation in the upper layer or under-correcting in the lower layer. Images containing dense plumes or strong swelling of hydroscopic aerosols at the top of convective cells occasionally show shadows resulting from variations in attenuation. An algorithm based on the Bernoulli solution to the lidar equation is used to improve the attenuation correction when preparing presentation quality pictures. In order to apply this solution, a functional relationship between the extinction cross section and the backscatter cross section must be provided: in addition the extinction cross section must be provided at one point in the data interval. The procedure proposed by Klett (Applied Optics, Vol. 20, #2), where the extinction cross section at large ranges is estimated, works only in the presence of substantial extinction. Because the extinction cross section is usually small in the fair weather boundary layer, the Klett approach is not applicable.

The RHI attenuation correction algorithm first estimates the extinction cross-section profile of the lowest elevation angle shot in the image. In the range interval between 1 and 7.5 kilometers, a least-squares linear fit is matched to the logarithm of the range-squared and energy corrected lidar profile.

The extinction at a data point just out of the overlap region
is estimated, for each lidar return in the image, from:

$$BETA(R,J) = \frac{SIGNAL(R,J)}{LEAST\text{-}SQUARE\ FIT(R)} * SLOPE\ BETA * EXP(2*(TAU(J)-TAU(1)))$$

where:
  BETA(R,J) = extinction at range, R, for J-th lidar return
  SIGNAL (R,J) = energy and range-square corrected lidar return
  TAU(J) = optical depth from lidar to range, R, for J-th return

and where: The value of the estimated optical depth, TAU(J),
is set equal to TAU(1) unless it can be estimated from an imme-
diately preceding image.
     Equation 1 provides a first estimate of the extinction
cross section at one point in each of the lidar profiles which
make up the image. The Bernoulli solution to the lidar
equation is then used to generate first guess values for the
extinction at each point in all profiles. In the relatively
uniform, small extinction conditions normally encountered in
clear air boundary layer studies this procedure provides good
initial values and therefore relatively good first estimates of
the extinction field. However because of the well-known insta-
bilty of the Bernoulli solutions small errors in the initial
guesses will cause substantial errors at longer ranges. Images
produced from these corrected profiles show unacceptable fluc-
tuations between successive lidar shots.
     The corrected data points are now grouped by altitude and
a median filter is applied to each altitude group so as to pro-
vide a median profile of the extinction as a function of alti-
tude. The median profile is very stable in the presence of
errors in the Bernoulli solutions. The median vertical profile
is then used as a guide to correct the initial guesses for each
lidar shot. For each point along each lidar shot, we compute
the correction to the initial guess which would place the point
exactly on the median vertical profile. The initial guess is
then adjusted by the median of the computed corrections for
that shot and the Bernoulli solution is recomputed. This pro-
cess is very stable in the presence of scattering inhomoge-
neities in the individual lidar return.
     The recorrected lidar profiles are once again used to com-
pute a median vertical profile of extinction and the whole pro-
cess is repeated until the maximum change in an initial guess
of any of the returns in the picture is below an operator
supplied threshold value. This procedure converges to produce
an image from 50 lidar returns in ~ 30 seconds of computation
time on the UW lidar VAX 751 computer and attached CSPI mini-
map array processor.

The scattering cross section in the hazy mixed layer is occasionally as much as 100 times as large as it is in the clear stable layer immediately above. If the contrast range of the lidar display is adjusted to accommodate this large dynamic range, small fluctuations in scattering cross section are not visible in either layer and much interesting image detail is lost. Most of this detail is restored by displaying the difference of computed scattering cross section from a background level computed by fitting a smoothing spline to the median vertical profile of scattering cross section.