

HSRL

In order to make reliable measurements of the extinction profile the HSRL measures two signals which can be processed to yield separate lidar returns for aerosol and molecular scattering. This separation is possible because the spectrum of the molecular lidar return is Doppler broadened by the thermal motion of the molecules while the slow moving aerosol particles generate negligible spectral broadening. The molecular scattering cross section is a function of molecular density and can be calculated from Rayleigh scattering theory and an independently measured temperature profile. The HSRL then uses molecular scattering as a calibration target which is available at each point in the lidar return.

More detail can be found in the following:

Eloranta, E. W., High Spectral Resolution Lidar in Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere, Klaus Weitkamp editor, Springer Series in Optical Sciences, Springer-Verlag, New York, 2005.

Piironen, P. and E. W. Eloranta, "Demonstration of a High-Spectral-Resolution Lidar based on a Iodine Absorption Filter". Optics Letters, 19, 3, 234-236, 1994.

Piironen, P., "A High Spectral Resolution Lidar Based on an Iodine Absorption Filter", Ph.D. Thesis, University of Joensuu, Department of Physics, Finland, 1994

Eloranta, E. W., I. A. Razenkov, J. P. Garcia, and J. Hedrick, Observations with the University of Wisconsin Arctic High Spectral Resolution Lidar, 22nd International Laser Radar Conference, July 12-16, Matera, Italy.

Razenkov, I. A. ,Eloranta, E. W., J. P. Hedrick, R. E. Holz, R. E. Kuehn and J. P. Garcia, A Spectral Resolution Lidar Designed for Unattended Operation in the Arctic, 21st International Laser Radar Conference, July 8-12, Quebec City, Canada.

Basic HSRL data quantities

Three lidar returns are derived; these are given by the following equations for the photons per unit time incident on the field stop of the receiver. The first equation provides the photon rate due to scattering from molecules(In this equation we have neglected the tiny depolarization component due to Cabannes line scattering of molecules):

$$\frac{dN_m}{dt}(r) = \eta_1 \cdot G(r) \cdot N_0 \frac{c \cdot A_r}{2 \cdot r^2} \beta_m(r) \frac{3}{8\pi} \cdot \exp(-2\tau(r)). \quad (1)$$

The second equation provides the photon rate due to scattering from particulates after transmission through a circular polarizing filter(parallel):

$$\frac{dN_a}{dt}(r) = \eta_1 \cdot G(r) \cdot N_0 \frac{c \cdot A_r}{2 \cdot r^2} \beta_a(r) \left(\frac{P_{11}(\pi, r)}{4\pi} - \frac{P_{44}(\pi, r)}{4\pi} \right) \cdot \exp(-2\tau(r)). \quad (2)$$

The third equation provides the photon rate due to scattering from particles after passing through a circular crossed circular polarizer :

$$\frac{dN_{cp}}{dt}(r) = \eta_1 \cdot G(r) \cdot N_0 \cdot \frac{c \cdot A_r}{2 \cdot r^2} \beta_a(r) \frac{P_{44}(\pi, r)}{4\pi} \cdot \exp(-2\tau(r)). \quad (3)$$

where:

η_1 =Optical transmission of optical elements ahead of field stop

G =Geometric correction for change of telescope focus with range

$N_0 = \frac{E_0}{h\nu}$ =Number of transmitted photons

E_0 =Transmitted energy (J)

h =Plank's constant (J s)

ν =Frequency of transmitted light (Hz)

c =The speed of light (m/s)

A_r =Area of receiving telescope (m²)

r =distance from lidar (m)

β_m =Molecular scattering cross section (1/m)

τ =Optical depth

β_a =Particulate scattering cross section (1/m)

$\frac{P_{ij}(\pi,r)}{4\pi}$ =Elements of the phase matrix for backscattering (1/sr)

The HSRL uses photon counting detectors. The following equations provide the number of photons measured in each channel of the receiver in response to the photon rates predicted by equations 1-3.. The photon count rate measured in the high sensitivity combined channel of the instrument is:

$$\frac{dn_{c-hi}}{dt} = \eta_c \cdot \left(\frac{dNa}{dt}(r) + C_{mc}(r) \cdot \frac{dNm}{dt}(r) \right) + DC_{c-hi} + BL_{c-hi}(r) .$$

When the count rate, $\frac{dn_{c-hi}}{dt}$, exceeds, $M_{threshold}$, (the maximum count rate of the detector) count rates from a lower sensitivity channel are used for the combined count. The photon count rate measured in the low sensitivity combined channel is:

$$\frac{dn_{c-lo}}{dt} = g_{lo} \cdot \eta_c \cdot \left(\frac{dNa}{dt}(r) + C_{mc}(r) \cdot \frac{dNm}{dt}(r) \right) + DC_{c-lo} + BL_{c-lo}(r).$$

The photon count rate measured in the molecular channel is:

$$\frac{dn_m}{dt} = \eta_c \cdot \left(C_{am}(r) \cdot \frac{dNa}{dt}(r) + C_{mm}(r) \cdot \frac{dNm}{dt}(r) \right) + DC_{mol} + BL_m(r).$$

The photon count rate in the cross polarized channel is:

$$\frac{dn_{cp}}{dt} = \eta_c \cdot C_{cp} \cdot \left(\delta_{cp} \cdot \frac{dN_{cp}}{dt}(r) + \delta_m \cdot C_{mc} \cdot \frac{dNm}{dt}(r) \right) + \eta_{cpp} \left(\frac{dN_{c-hi}}{dt} - DC_{c-hi} - BL_{c-hi}(r) \right) + DC_{cp} + BL_{cp}(r).$$

In this equation the $\eta_{cpp}(\dots)$ term describes polarization leakage from the parallel to the cross channel. When the photon rate exceeds the dynamic range of the high sensitivity channel, this term is computed using the low sensitivity combined channel.

The variables used in the above equations are defined as:

η_c =optical transmission of elements in combined channel beyond field stop times quantum efficiency of combined detector.

η_{cpp} =Fraction of the parallel polarization signal leaking into the cross channel.

δ_{cp} =Depolarization due to scattering from particulates.

δ_m =Depolarization of Cabannes line molecular scattering.

g_{lo} =Gain of low sensitivity combined channel relative to the high sensitivity combined channel.

DC_{c-hi} =Dark count in combined high sensitivity channel.

DC_{c-lo} =Dark count in combined low sensitivity channel.

DC_{mol} =Dark count in molecular channel.

DC_{cp} =Dark count in cross polarized channel

$M_{threshold}$ = At combined high channel count rates above this threshold data from the low sensitivity combined channels are used. At this point, the high channel has exceeded its dynamic range and can no longer be corrected for pulse pileup.

The Gieger-mode avalanche photodetectors used in the HSRL are exposed to a strong light pulse scattered from the laser pulse by shared optical elements in the transmit/receive chain. This adds an afterpulse signal to the measured lidar returns. These time decaying baselines (BL_{c-hi} , BL_{c-lo} , BL_m , BL_{cp}) are measured for each detector and must be subtracted along with the dark counts before the data is processed.

The calibration coefficients (C_{mc} , C_{mm} , C_{am} , C_{cp}) provide the detection efficiency of the receiver channels relative to the combined channel response to light with the spectrum of the transmitting laser. They include the optical transmission of all optical elements and filters between the field stop and the respective detectors as well as the quantum efficiency of the respective detectors. The first three of these coefficients are range dependent because the spectral width of molecular scattering is a function of atmospheric temperature.

C_{mc} = Detection efficiency of combined channel to light with the Doppler broadened molecular spectrum.

C_{mm} = Detection efficiency of the molecular channel to light with the Doppler broadened molecular spectrum.

C_{am} = Detection efficiency of the molecular channel to light with the transmitted spectrum.

C_{cp} = Detection efficiency of the cross polarized channel to cross polarized light with the transmitted spectrum.

After correction for pulse pileup, the measured lidar returns $\frac{dn_{c-hi}}{dt}$, $\frac{dn_{c-lo}}{dt}$, $\frac{dn_{mol}}{dt}$, $\frac{dn_{cp}}{dt}$ and the calibration coefficients are used to solve for the received powers in Equations 1 through 3. Equation 1 contains two unknowns: the optical depth between the lidar and the scattering volume, τ , and the molecular scattering cross section, β_m . Molecular scattering is described by the Rayleigh scattering equation and is directly proportional to atmospheric density, ρ :

$$\beta_m(r) = Const \cdot \rho(r)$$

Thus if we define a range-squared, energy corrected molecular lidar return:

$$S_m(r) = \frac{\frac{dN_m}{dt}(r) \cdot r^2}{N_0}$$

$$\ln(S_m(r)) = Const + \ln(G(r)) + \ln(\rho(r)) - 2\tau(r)$$

and using an independently provided temperature profile to compute $\rho(r)$ along with values of $G(r)$ derived from a system calibration, the optical depth between any two ranges, r and r_0 , is given by:

$$\tau(r) - \tau(r_0) = \frac{1}{2} \ln\left(\frac{\rho(r)}{\rho(r_0)}\right) - \frac{1}{2} \ln\left(\frac{S_m(r)}{S_m(r_0)}\right) + \frac{1}{2} \ln\left(\frac{G(r)}{G(r_0)}\right)$$

The average extinction cross section in a layer between r and r_0 can be computed from equation 7:

$$\langle \beta_e(r, r_0) \rangle = \frac{\tau(r) - \tau(r_0)}{r - r_0}$$

Notice that this equation can be used to generate vertical profiles of the extinction cross section; however, the vertical resolution will be dictated by the minimum layer thickness required to detect differences in optical depth.

The ratio of the aerosol lidar return to the molecular return provides the lidar backscatter ratio:

$$R(r) = \frac{\frac{dN_a}{dt}(r)}{\frac{dN_m}{dt}(r)} = \frac{2\beta_a(r) \cdot P(\pi, r)}{3\beta_m(r)}$$

The lidar backscatter ratio, and the molecular backscatter cross section derived using an independently measured temperature profile, can be used to calculate the aerosol backscatter cross section:

$$\beta_a(r) \frac{P(\pi, r)}{4\pi} = R(r) \cdot \beta_m(r) \frac{3}{8\pi}$$

and the ratio of the layer average aerosol backscatter cross section to the layer average aerosol extinction cross section provides the average backscatter phase function between r and r_0 times the single scatter albedo, $a(r)$:

$$\langle \frac{P(\pi,r)}{4\pi} \cdot a(r) \rangle = \langle \beta_a(r, r_0) \rangle / \langle \beta_e(r, r_0) \rangle$$

For water and ice clouds (and many aerosols) the single scatter albedo at the 532 nm wavelength of the HSRL is very close to unity; thus equation 10 provides the backscatter phase function.

The HSRL provides measurements of circular depolarization. Depolarization measurements allow discrimination between water and ice clouds. The circular depolarization ratio is given by:

$$\delta_c(r) = \frac{dN_{cp}(r)/dt}{dN_a(r)/dt} = \frac{P_{44}(\pi,r)}{P_{11}(\pi,r) - P_{44}(\pi,r)}$$

Most users are more familiar with the linear depolarization ratio, δ_l ; for a vertically pointing lidar it can be computed from the circular depolarization ratio:

$$\delta_l(r) = \frac{\delta_c(r)}{2 + \delta_c(r)}$$

Some important variables contained in our NetCDF files

The NetCDF files contain a very complete record of the raw data, calibration and supplementary data used to derive processed HSRL data. Here we present a small subset of the variables. Other variables are documented in the NetCDF files.

times are provided as 8 element vectors:

time_vector(year,month,day,hour,min,sec,milliseconds,microseconds)

For convenience, times are also provide as a base time with offsets:

int base_time ; long_name = "Base seconds since Unix Epoch" ; units = "seconds since 1970-01-01 00:00:00 UTC" ;

double time_offset(time) ; long_name = "Time offset from base_time" ; units = "seconds since start of file" ;

r = float altitude(altitude) ; long_name = "Height above lidar" ; units = "meters" ;

$\tau(r) - \tau(o)$ = float od(time, altitude) ; long_name = "Optical depth of particulate" ; units = " " ;

β_a = float beta_a_backscat(time, altitude) ; long_name = "Particulate backscatter cross section per unit volume" ; units = "1/(m sr)"

float std_beta_a_backscat(time, altitude) ; long_name = "Std dev of backscat cross section (photon counting)" ; units = "1/(m sr)" ;

β_m = float profile_beta_m(altitude) ; long_name = "Raob molecular scattering cross section profile" ; units = "1/meter" ;

δ_c = float depol(time, altitude) ; long_name = "Circular depolarization ratio for particulate" ; description = "left circular return divided by right circular return" ; units = " " ;

Times at which new calibration are introduced are stored in new_cal_times. Each successive entry holds a time_vector marking the time at which a new calibration is introduced and new_cal_trigger provides the reason for a new calibration:

short new_cal_times(calibration, time_vector) ; new_cal_times:long_name = "Time of Calibration Change" ; description = "New raob or system calibration data triggered recalibration" ;

byte new_cal_trigger(calibration) ; new_cal_trigger:long_name = "Trigger of Calibration Change" ; description = "reason for recalibration" ; bit_0 = "radiosonde profile" ; bit_1 = "i2 scan" ; bit_2 = "geometry" ;

$G(r)$ =float geo_cor(calibration, altitude) ; long_name = "Overlap correction" ; description = "Geometric overlap correction averaged to requested altitude resolution" ; units = " " ;

C_{mc} =float Cmc(calibration, altitude) ; Cmc:long_name = "Molecular in Combined Calibration" ;

C_{mm} =float Cmm(calibration, altitude) ; Cmm:long_name = "Molecular in Molecular Calibration" ;

C_{am} =float Cam(calibration, altitude) ; Cam:long_name = "Aerosol in Molecular Calibration" ;

g_{lo} =float combined_gain(calibration) ; combined_gain:long_name = "Combined Gain Factor" ; combined_gain:description = "Low Gain level * Factor ~ High Gain level" ;

$M_{threshold}$ =float combined_merge_threshhold(calibration) ; combined_merge_threshhold:long_name = "Combined Merge Threshold" ;