High Spectral Resolution Lidar (HSRL) Measurements of Ice Water Content: Approach and Initial Progress

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Our objective is to demonstrate a new method of remotely determining ice water content in cirrus clouds with the following approach:

HSRL measurements of backscatter cross-section **provide the projected cross-sectional area of particles per unit volume as viewed from the lidar.**

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HSRL measurements of multiple scattering provide information on the shape of the diffraction peak. The angular width is directly related to the cross-sectional area of individual particles. Effective radius and perhaps one additional size distribution parameter can be recover.

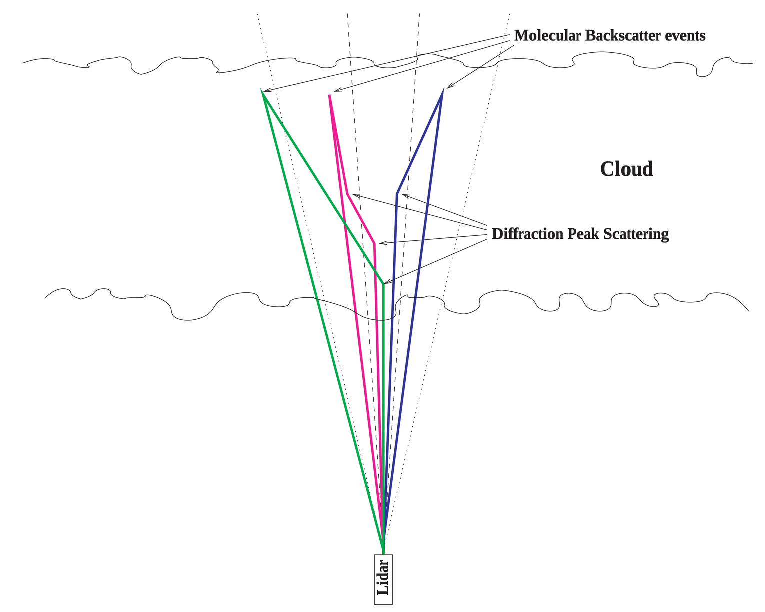
+ Radar cross-section measurements provide the 6th moment of the size distribution when used with the lidar cross section. → Provides gamma distribution of projected area particle size distribution

+ **Assumed projected area volume relationship** → **Provides ice water mass**

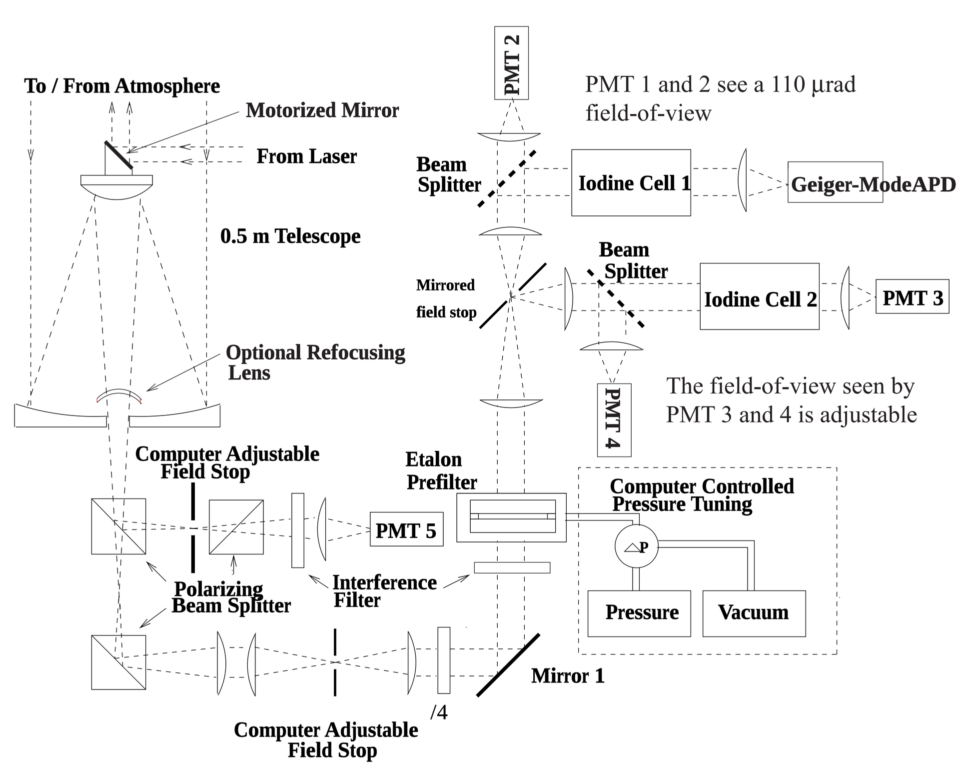
Provides gamma distribution of projected area particle size distribution → Doppler radar measurements of particle fall velocity + **Drag force relationship with assumption about the drag coefficient**

$$F_d = \frac{1}{2}C_0 A\rho_a V^2 + C_0 A\delta_0 V^{\frac{3}{2}}\left(\frac{\rho_a \eta}{D}\right)^{\frac{1}{2}} + \frac{1}{2}C_o A\delta_0^2 V\frac{\eta}{D}$$

→ **Assumed projected area volume relationship** → **Provides ice water mass**



HSRL multiple field of view measurements and a multiple scattering model provide information on forward diffraction peak of the scattering phase function. This is used to derive particle size distribution parmeters. This distribution describes the dimensions of particles projected on a plane perpendicular to the lidar beam. The HSRL is able to isolate photons which have undergone one or more small angle forward scatterings coupled with one molecular backscatter event.



HSRL Receiver Schematic. Gieger-mode APD, and wide-field-of-view channels have been made operational under this grant. The APD has provided a factor of 10 improvement in the sensitivity of this channel.

We have derived a multiple scatter lidar equation describing the ratio of nth order multiple scattering to first order scattering as a function of range (R). This assumes :

1) a log-normal distribution of particles that are large compared to the lidar wavelength, λ.
2) a Gaussian distribution of energy in the transmitted beam with an angular width = $2\rho_l$.
3) a receiver field-of-view = $2\rho_t$.
4) a backscatter phase function $P(\pi,R)$ with an average value of $P_{n\pi}(R)$ for angles near π.
5) A cloud optical depth = τ(R), scattering cross section = β(R)

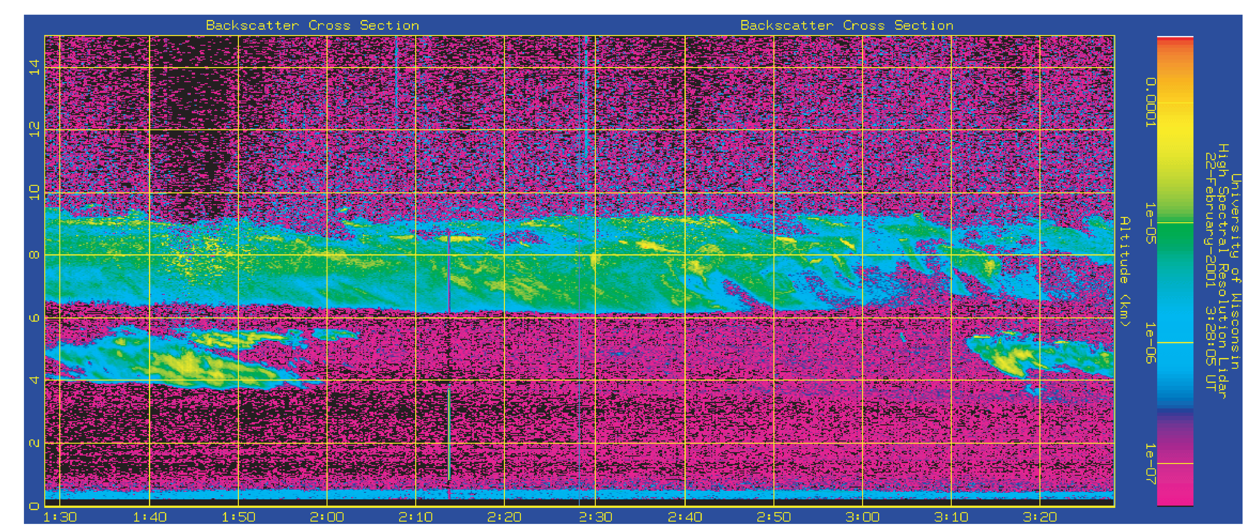
$$\frac{P_n(R)}{P_1(R)} = \frac{P_{n\pi}(R)}{P(\pi,R)}\left[1-\exp(-\frac{\rho_t^2}{\rho_l^2}\right]^{-1}\left\lfloor\frac{\tau^{n-1}}{(n-1)!} - \int_{z_c}^{R}\frac{\beta(z_1)}{\sqrt{\pi}}\int_{-\infty}^{\infty}\exp(-u^2)\cdots\int_{z_{n-2}}^{R}\frac{\beta(z_{n-1})}{\sqrt{\pi}}\int_{-\infty}^{\infty}\exp(-u^2)\exp\left(\frac{-\pi^2\rho_t^2R^2/\lambda^2}{(R-z_1)^2\left(\frac{\exp(-\sqrt{2}\gamma(z_1)u_1-2\gamma(z_1)^2)}{\alpha(z)}\right)+\cdots(R-z_{n-1})^2\left(\frac{\exp(-\sqrt{2}\gamma(z_{n-1})u_{n-1}-2\gamma(z_{n-1})^2)}{\alpha(z)}\right)+\pi^2\rho_l^2R^2/\lambda^2}\right)du'_{n-1}dz_{n-1}du'_{n-2}dz_{n-2}\underset{\mu m}{\ldots}du'_1dz_1\right]$$

Log-normal size distribution:

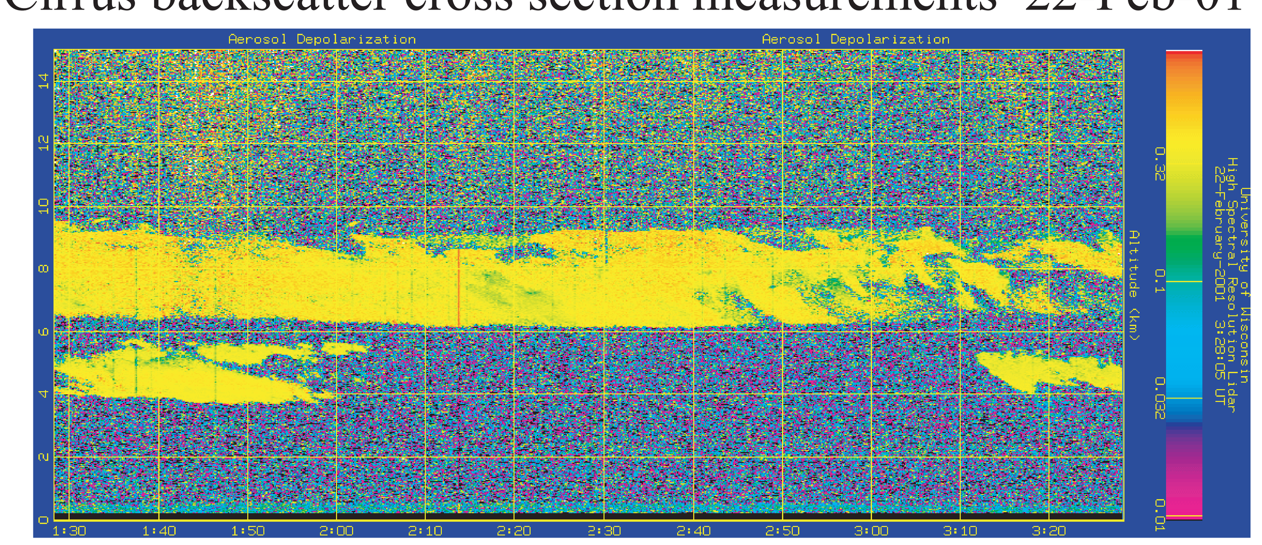
$$n(r,z) = \frac{a(z)}{\sqrt{2}\gamma(z)r}\exp\left(-\frac{1}{2}\left(\frac{\log\left(\frac{r}{\alpha(z)}\right)}{\gamma(z)}\right)^2\right)$$

α can be written in terms of the effective radius:
$\alpha = r_{eff}\exp(-2.5\gamma^2)$

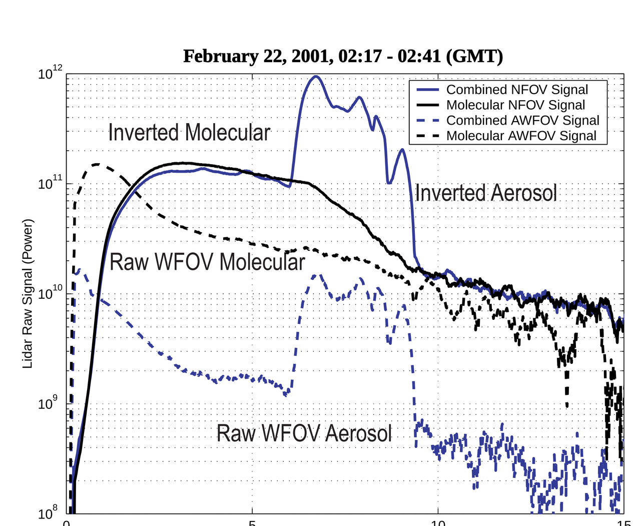
First cirrus particle size measurements using multiple field-of-view molecular backscatter



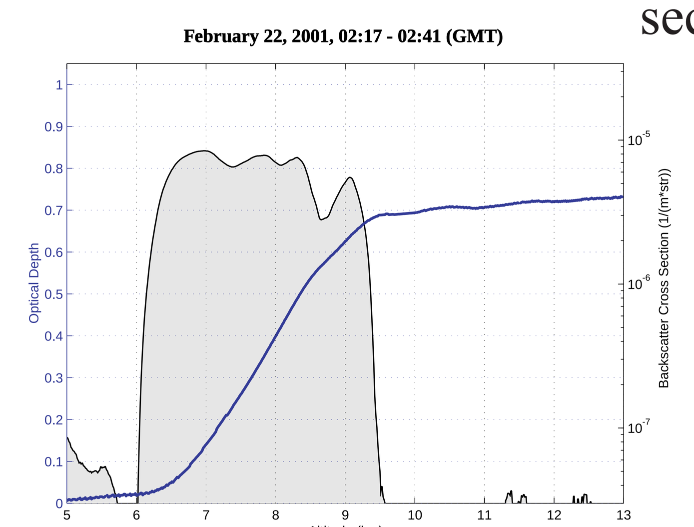
Cirrus backscatter cross section measurements 22-Feb-01



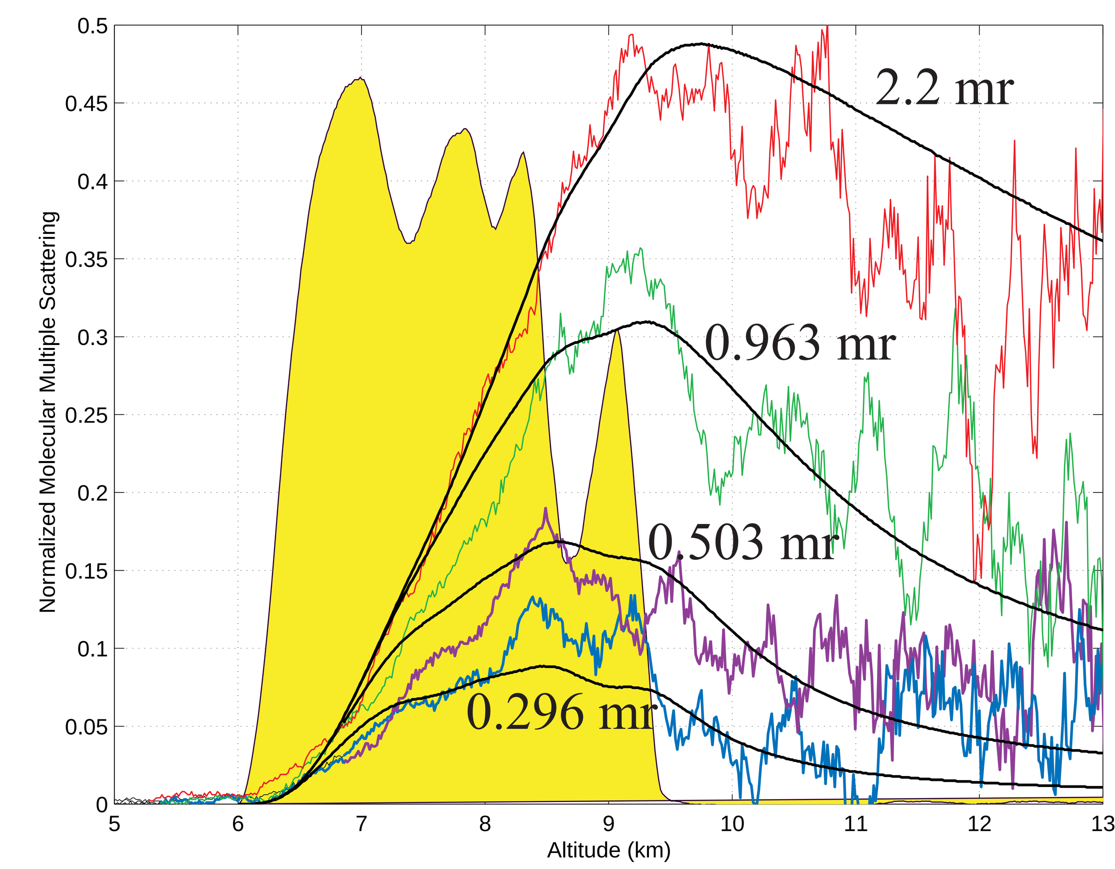
Cirrus cloud depolarization measurements, 22-Feb-01



Measured Lidar returns



Optical depth and backscatter cross section as functions of altitude



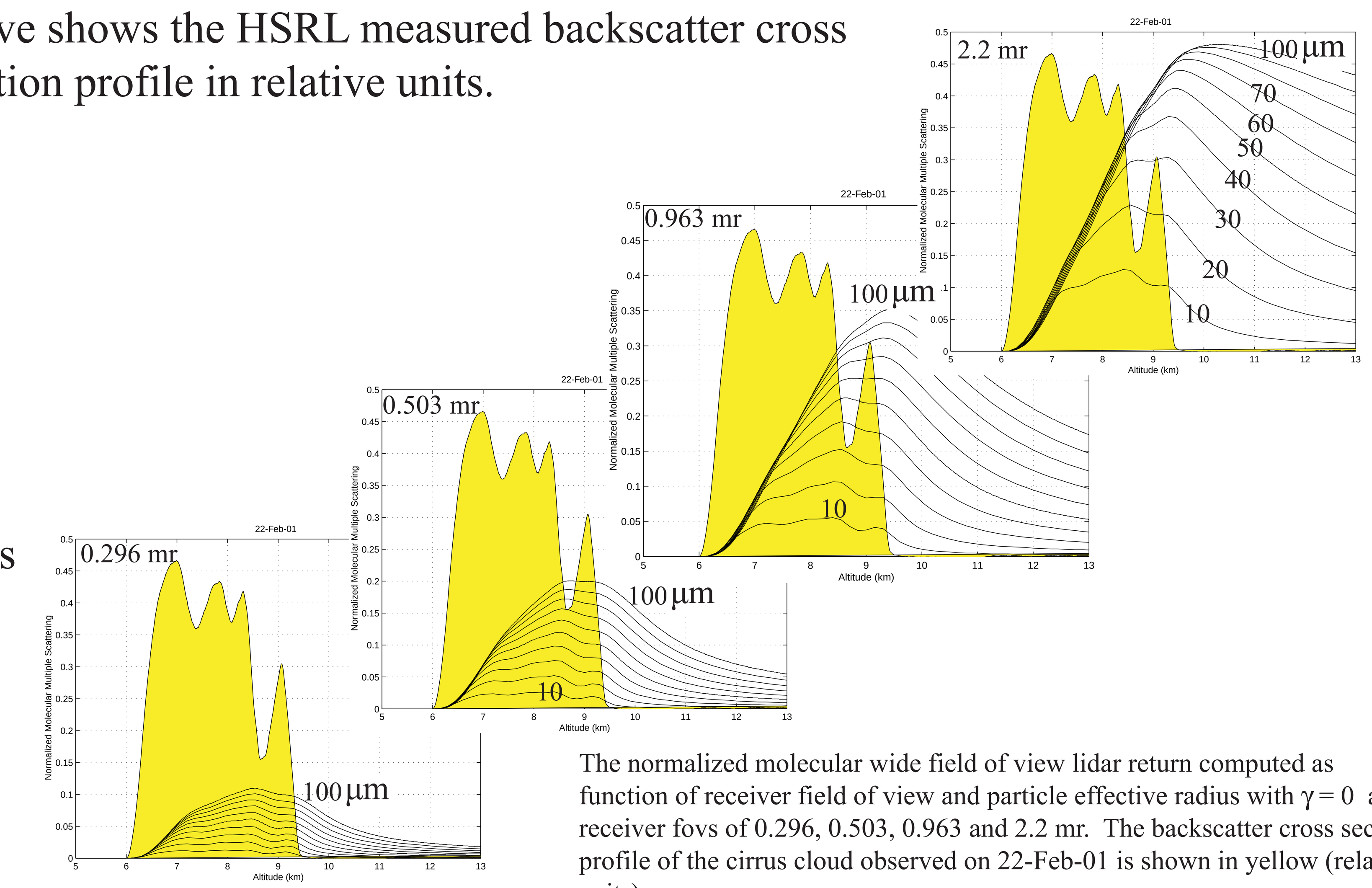
A comparison of the measured multiply scattered molecular lidar return (colored lines) and the model predictions (solid black lines) using an effective radius of 75 microns and γ = 0. The yellow-filled curve shows the HSRL measured backscatter cross section profile in relative units.

Our wide field of view measurements are presented in terms of a normalized return =

$$\frac{\text{WFOV signal-k*(110 μrad FOV molecular signal)}}{\text{(110 urad FOV molecular signal)}}$$

Where: $k = \frac{\text{Clear air WFOV Signal}}{\text{Clear air 110 urad FOV signal}}$

and where WFOV is the molecular wide-field of view channel.



The normalized molecular wide field of view lidar return computed as function of receiver field of view and particle effective radius with γ = 0 and receiver fovs of 0.296, 0.503, 0.963 and 2.2 mr. The backscatter cross section profile of the cirrus cloud observed on 22-Feb-01 is shown in yellow (relative units).