Full Polarization Observations of Oriented Ice Crystals and Rain by the NCAR GV High Spectral Resolution Lidar

Matthew Hayman, Scott Spuler, Bruce Morley
National Center for Atmospheric Research

17th AMS Conference on Meteorological Observation and Instrumentation

June 12, 2014

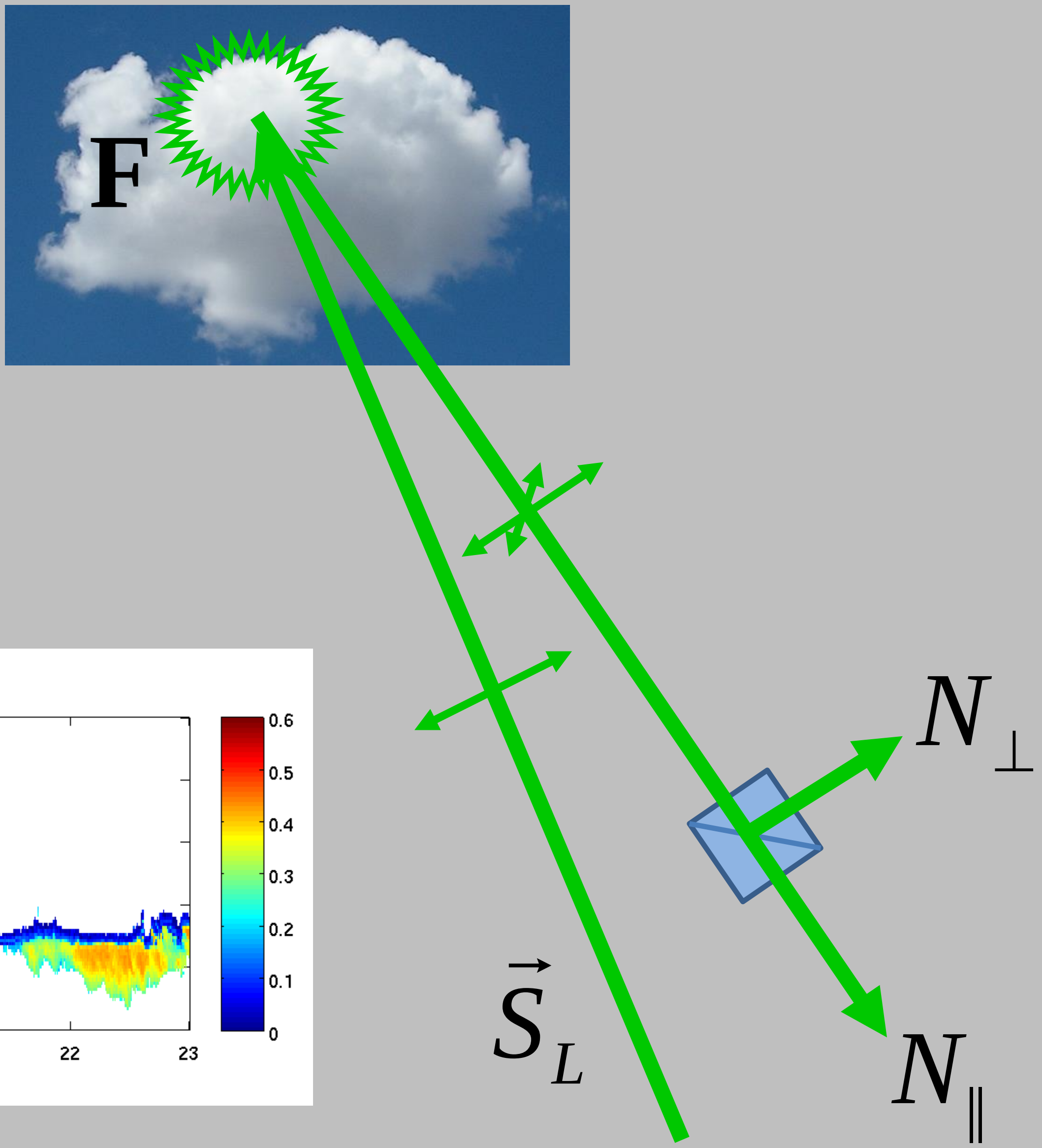
Polarization Lidar Parameters

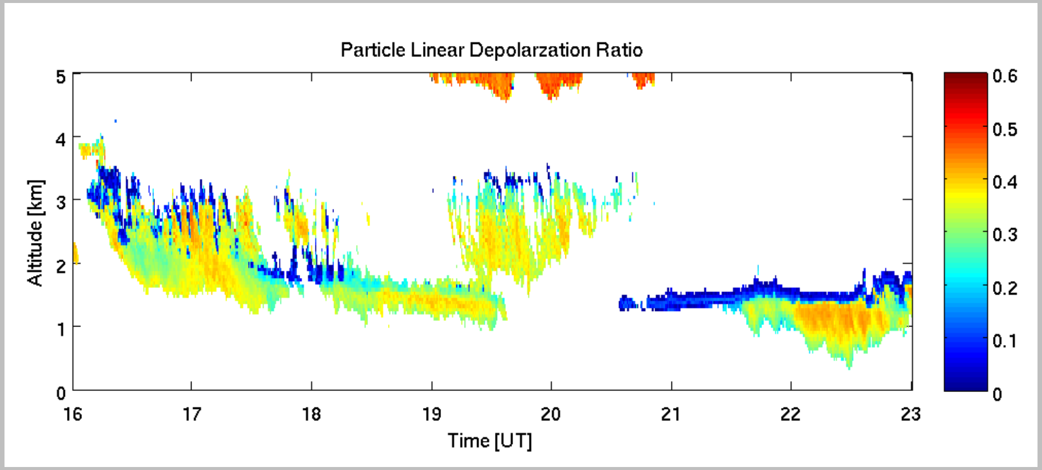
Total Backscatter

$$N = N_{\perp} + N_{\parallel}$$

Depolarization Ratio

$$\delta = \frac{N_{\perp}}{N_{\parallel}}$$

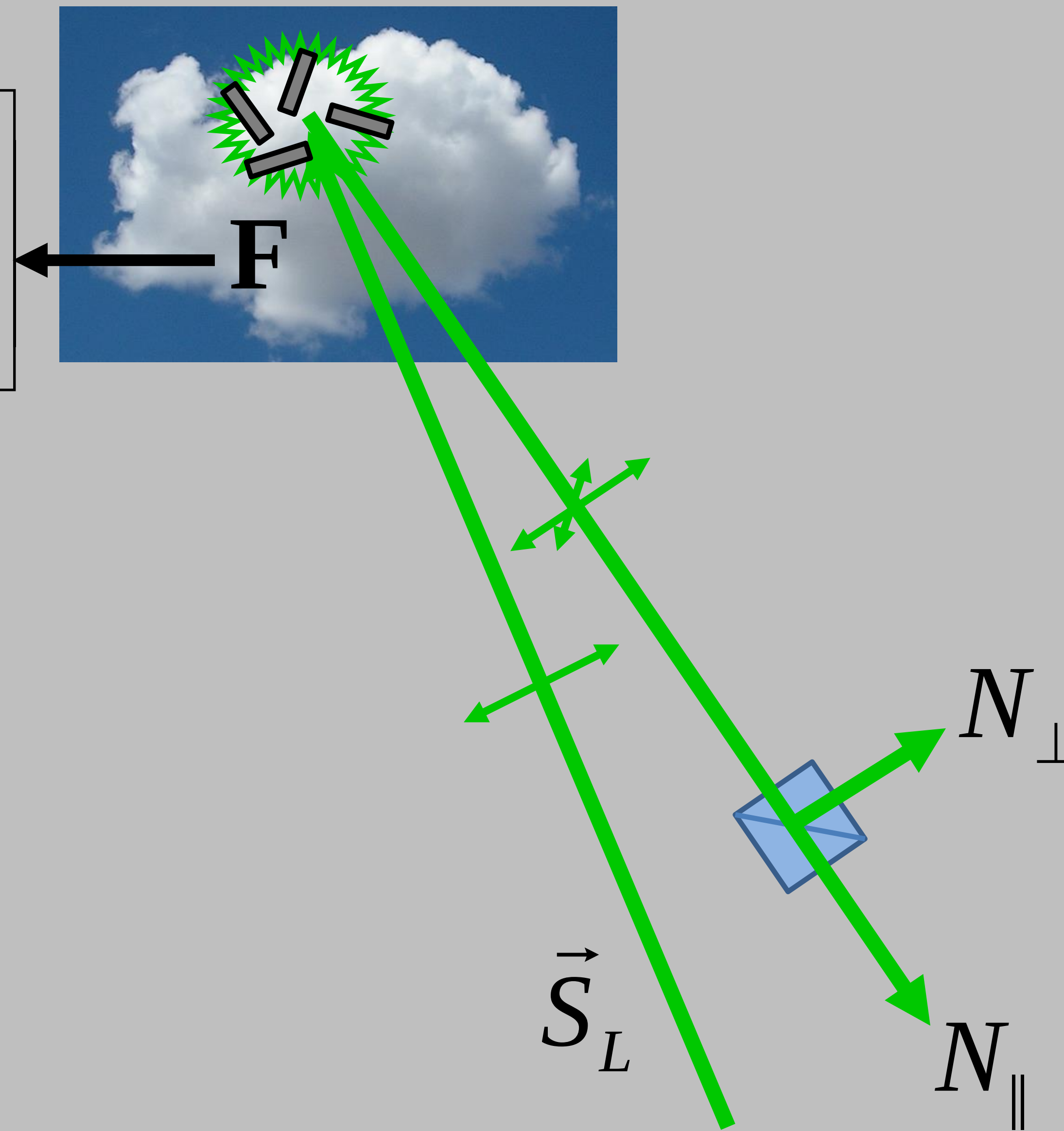




Backscattering by randomly oriented particles

Two degrees of freedom

$$\mathbf{F}(\pi) = \beta \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{bmatrix}$$



Linear Depolarization Ratio

$$\delta_L = \frac{N_{\perp}}{N_{\parallel}} = \frac{d}{2-d}$$

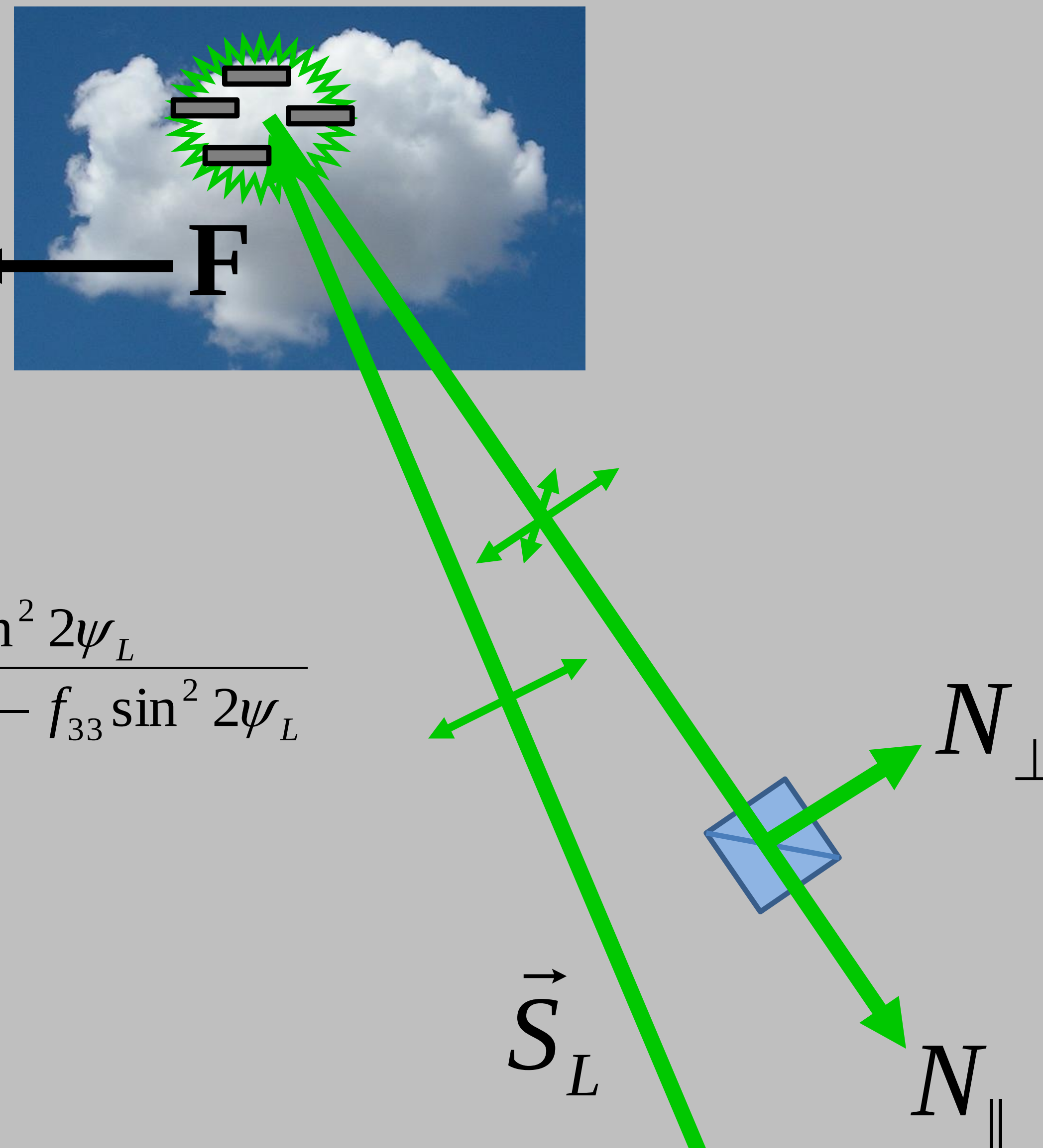
Circular Depolarization Ratio

$$\delta_C = \frac{N_{\perp}}{N_{\parallel}} = \frac{d}{1-d}$$

Backscattering by oriented particles

Six degrees of freedom

$$\mathbf{F}(\vec{k}_i,-\vec{k}_i)=\beta\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$



Linear Depolarization Ratio

$$\delta_L=\frac{1-f_{22}\cos^2 2\psi_L+f_{33}\sin^2 2\psi_L}{1+2f_{12}\cos 2\psi_L+f_{22}\cos^2 2\psi_L-f_{33}\sin^2 2\psi_L}$$

Circular Depolarization Ratio

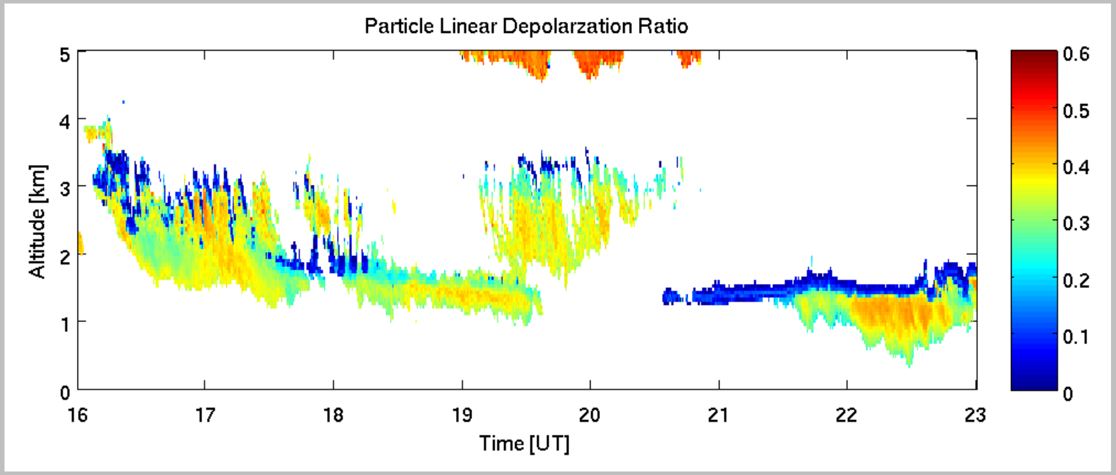
$$\delta_C=\frac{1+f_{44}}{1-f_{44}}$$

Implicit assumption of random orientation

"Assuming the volume consists of randomly oriented, axially symmetric particles…"

Unless stated otherwise, analysis of polarization lidar data ***ALWAYS*** assumes that the particles are randomly oriented.

No diagnostic for influence of oriented particles



Oriented ice particles make a great "gotcha"

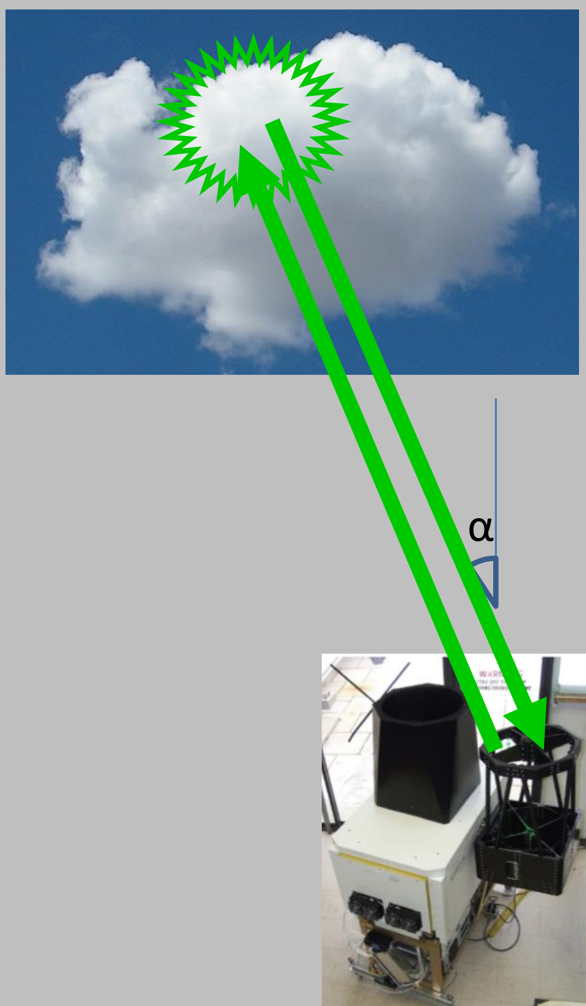
Don't like someone's polarization lidar data?

Suggest oriented particles are corrupting the data

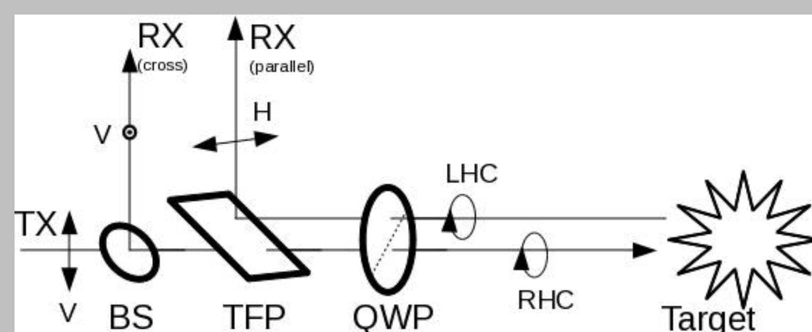
HSRL started measuring the full scattering matrix in Spring 2012

Operated it three tilt angles:

α = 4° (minimum angle)	Summer 2013
α = 22°	Summer 2012, Fall 2012
α = 32°	Summer 2012, Winter 2012



HSRL Specifications:
Wavelength: 532 nm
Max Range Resolution: 7.5 m (30 m typical)
Time Resolution: 0.5 s (20 s for full matrix)
RX Aperture: 40 cm
TX Power: 400 mW @ 4kHz
Coaxial TX/RX



See *Hayman et. al, Opt. Express 2012.*

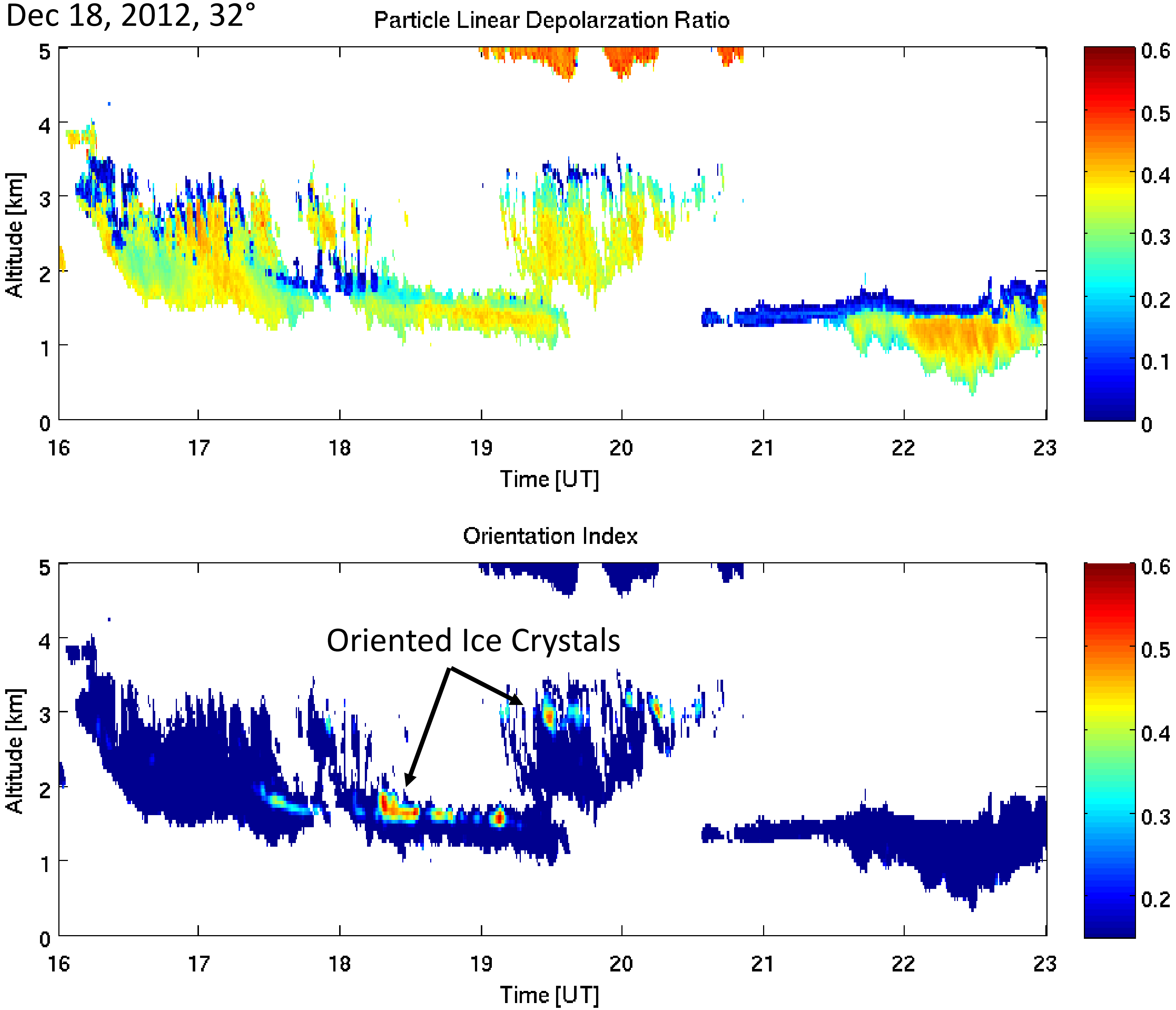
$$\mathbf{F}(\vec{k}_i, -\vec{k}_i) = \begin{bmatrix} ? & ? & 0 & 0 \\ ? & ? & 0 & 0 \\ 0 & 0 & ? & ? \\ 0 & 0 & ? & ? \end{bmatrix}$$

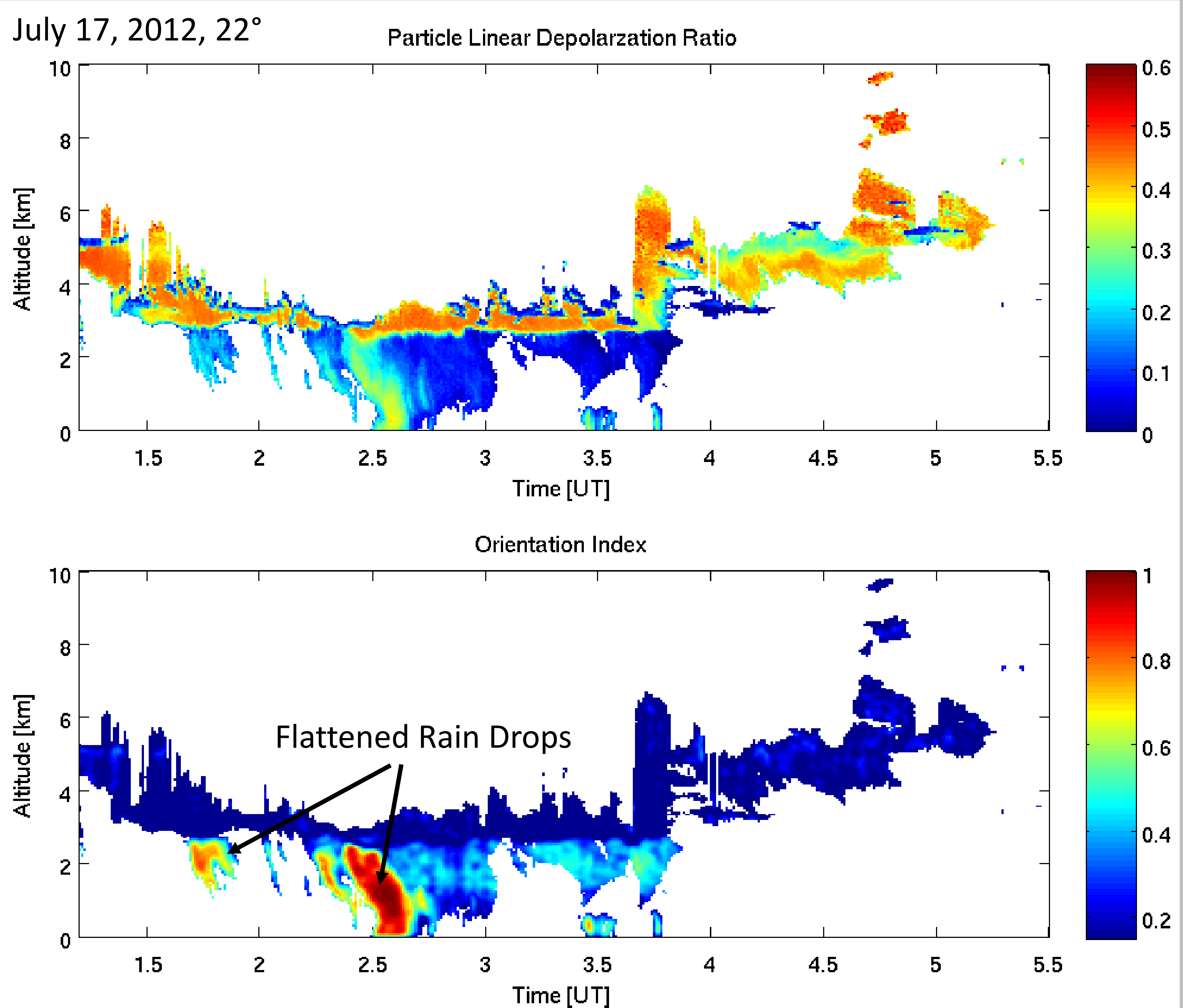
What does an atmospheric oriented scattering matrix look like?

What observations can safely assume randomly oriented particles?

One paper published on the subject: *Kaul et. al, Appl. Opt. 2004*

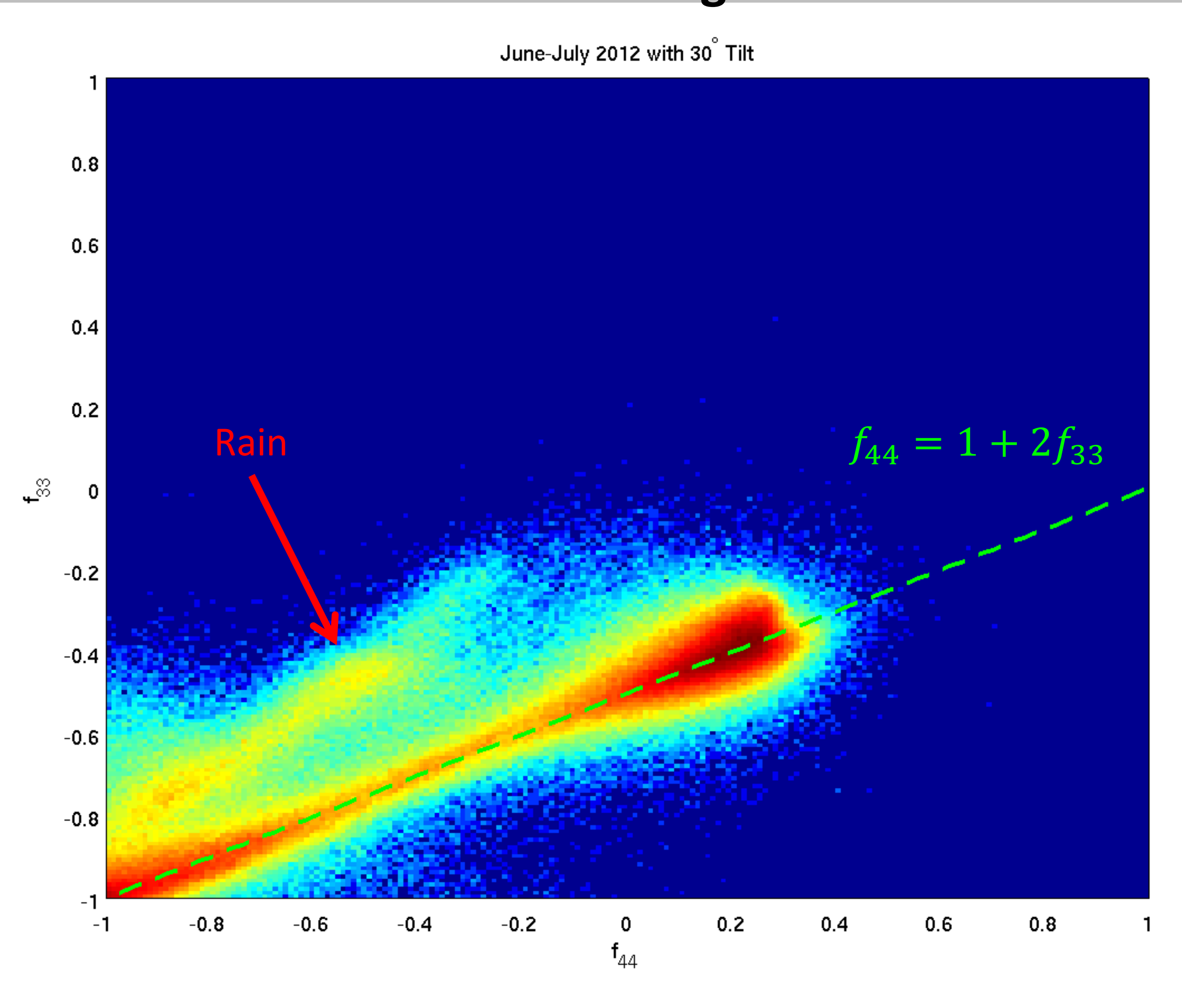
Dec 18, 2012, 32°





July 17, 2012, 22°
Particle Linear Depolarzation Ratio
Altitude [km]
Time [UT]
Orientation Index
Altitude [km]
Time [UT]
Flattened Rain Drops

Total Cloud Observations Histogram

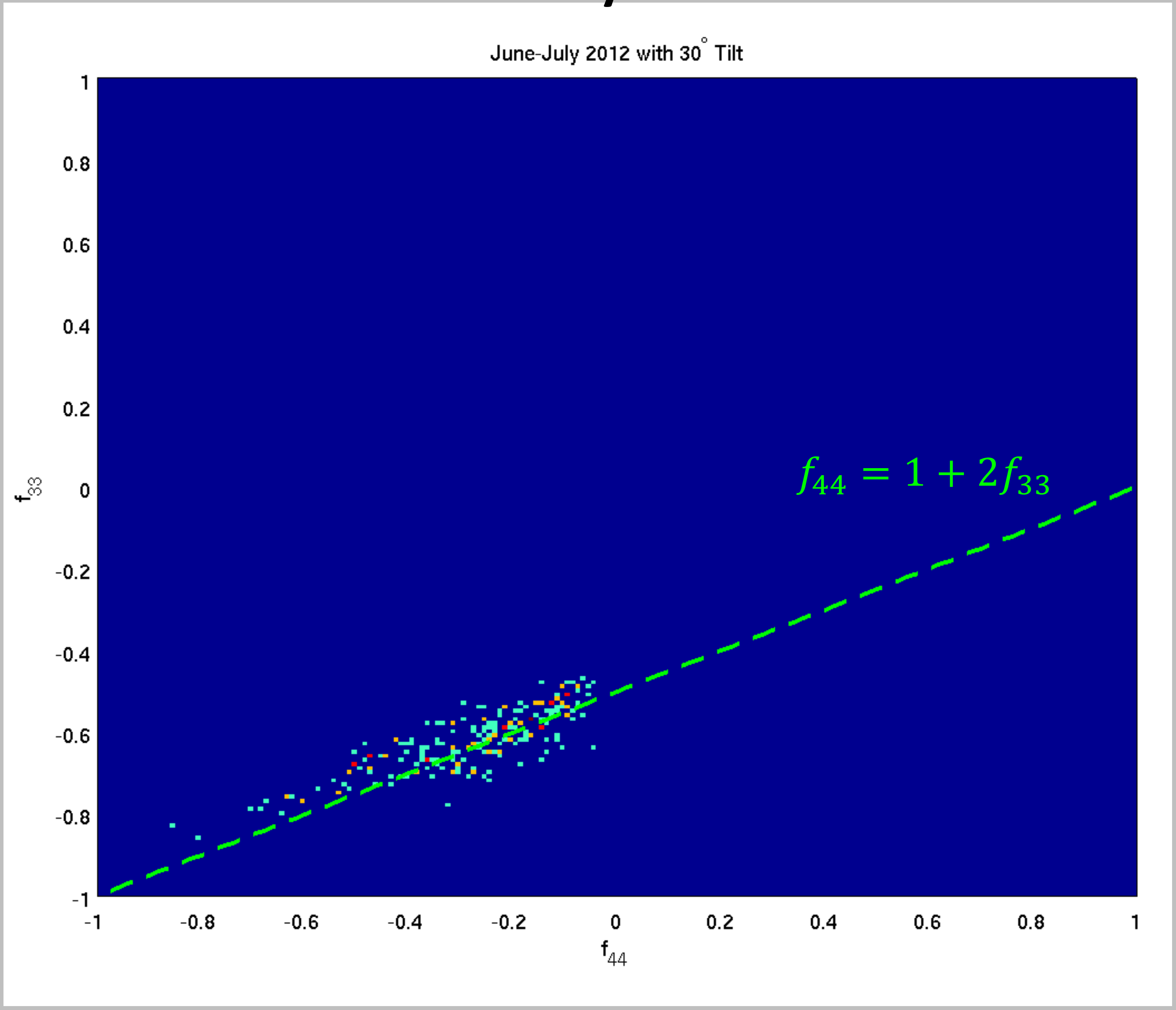


$$\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{bmatrix}$$

See *Hayman et. al, Opt. Express In Review.*

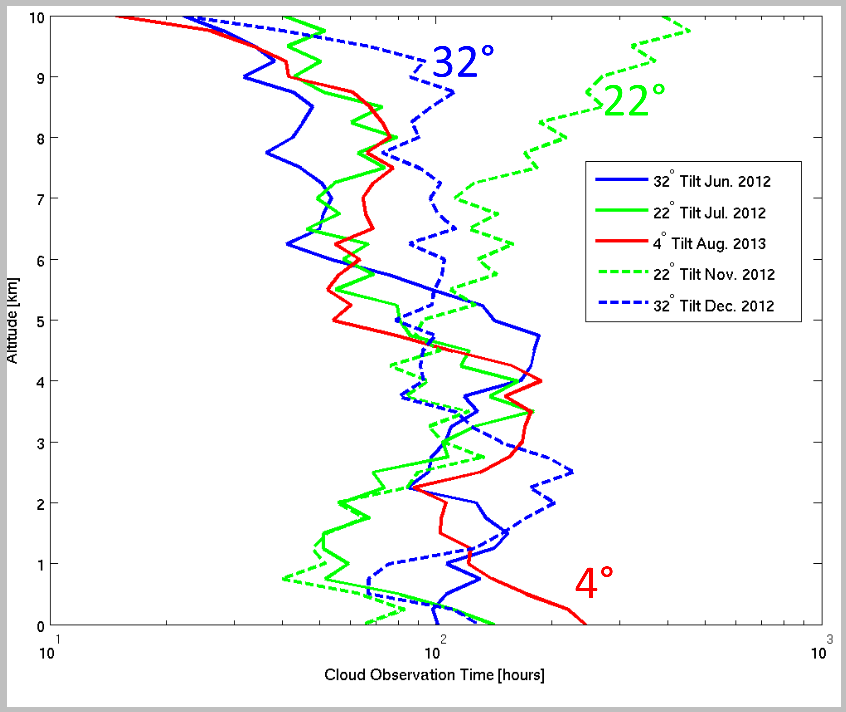
Filtered for Oriented Ice Crystals

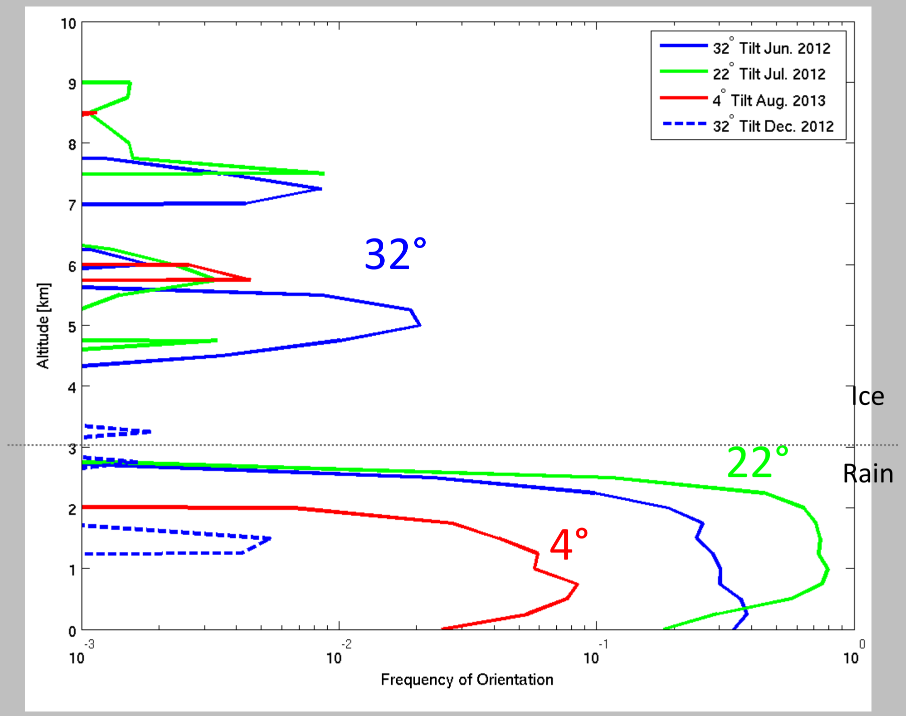


$$\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-d & 0 & 0 \\ 0 & 0 & d-1 & 0 \\ 0 & 0 & 0 & 2d-1 \end{bmatrix}$$

How often do oriented signatures appear in polarization lidar data?

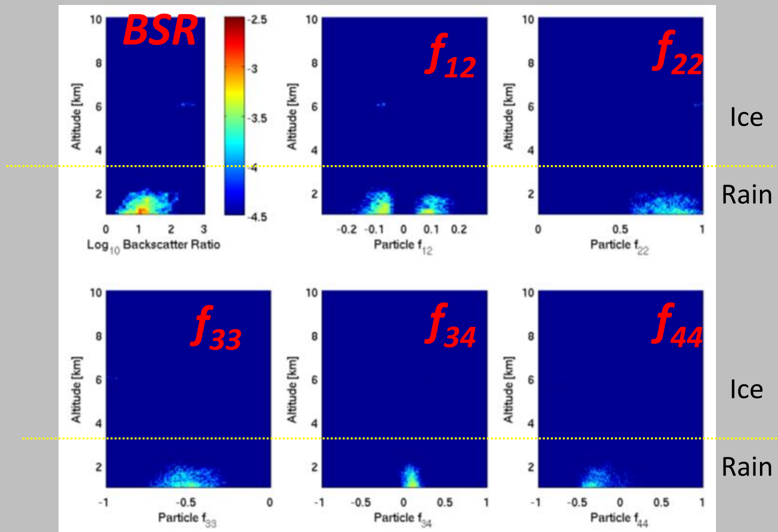




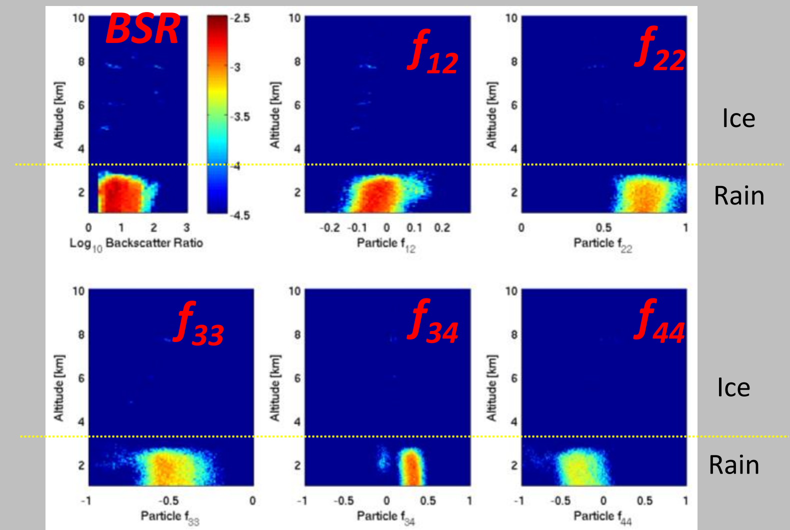
Oriented rain is frequently observed at all tilt angles
Oriented ice crystals are most frequently observed at 32° tilt

See *Hayman et. al, Opt. Express In Review.*

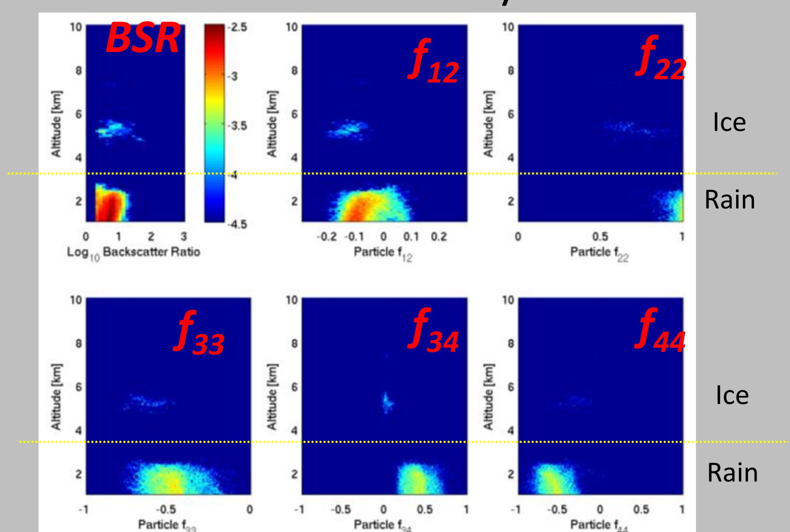
4° Tilt – 50 days



22° Tilt – 56 days



32° Tilt – 28 days



$$\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$

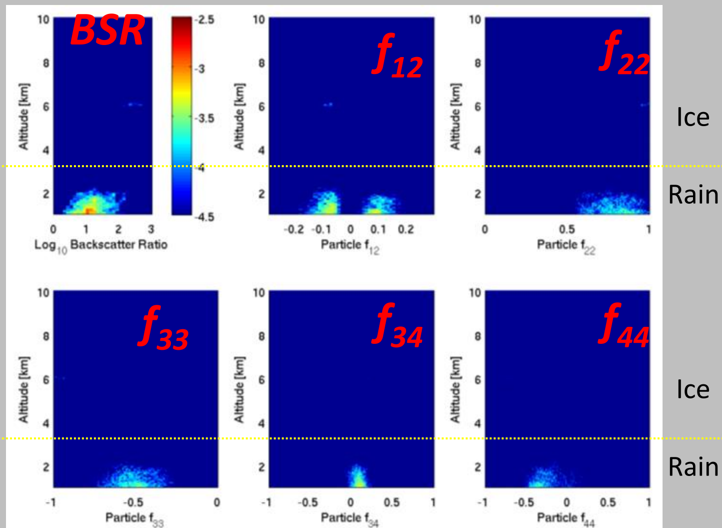
Ice Crystals Conditions:

Typically virga when lidar is tilted near 30°

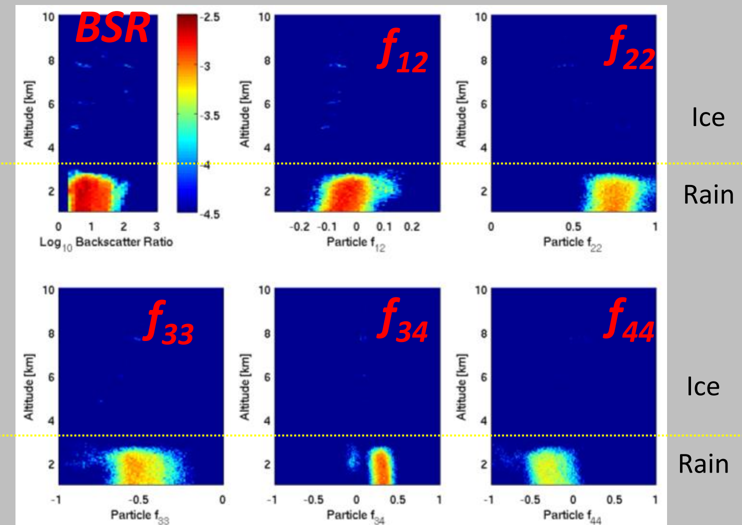
- $-0.2 < f_{12} < -0.05$
- $f_{34} \approx 0$
- $f_{44} = 1-2f_{22} = 1+2f_{33}$

See *Hayman et. al, Opt. Express In Review.*

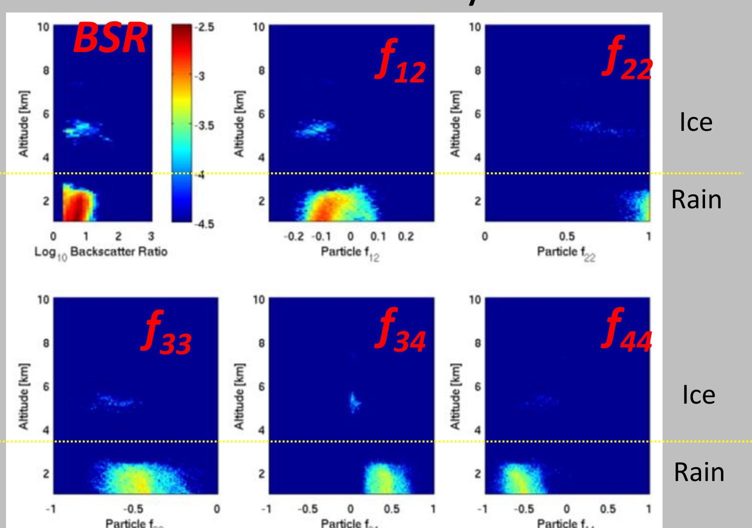
4° Tilt – 50 days



22° Tilt – 56 days



32° Tilt – 28 days



$$\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$

Oriented Rain Conditions:
Most rain (all tilt angles)

- $-0.2 < f_{12} < 0.15$
- $0 < f_{34} < 0.6$
- $f_{44} \neq 1-2f_{22} \neq 1+2f_{33}$

See *Hayman et. al, Opt. Express In Review.*

- What polarization lidar observations can safely assume randomly oriented particles?
  - Most ice cloud observations, particularly at near zenith pointing angles
  - Never rain regardless of pointing angle

- What does an atmospheric oriented scattering matrix look like?
  - Ice crystals
    - Significant diattenuation (f_{12})
    - Little or no retardance (f_{34})
    - Dependent diagonal terms
  - Rain
    - Large diattenuation (f_{12})
    - Large retardance (f_{34})
    - Independent diagonal terms

$$\begin{bmatrix} 1 & f_{12} & 0 & 0 \\ f_{12} & f_{22} & 0 & 0 \\ 0 & 0 & f_{33} & f_{34} \\ 0 & 0 & -f_{34} & f_{44} \end{bmatrix}$$