The uncertainties in surface altimetry of space-borne lidar measurements caused by unknown size (and shape) of ice particles

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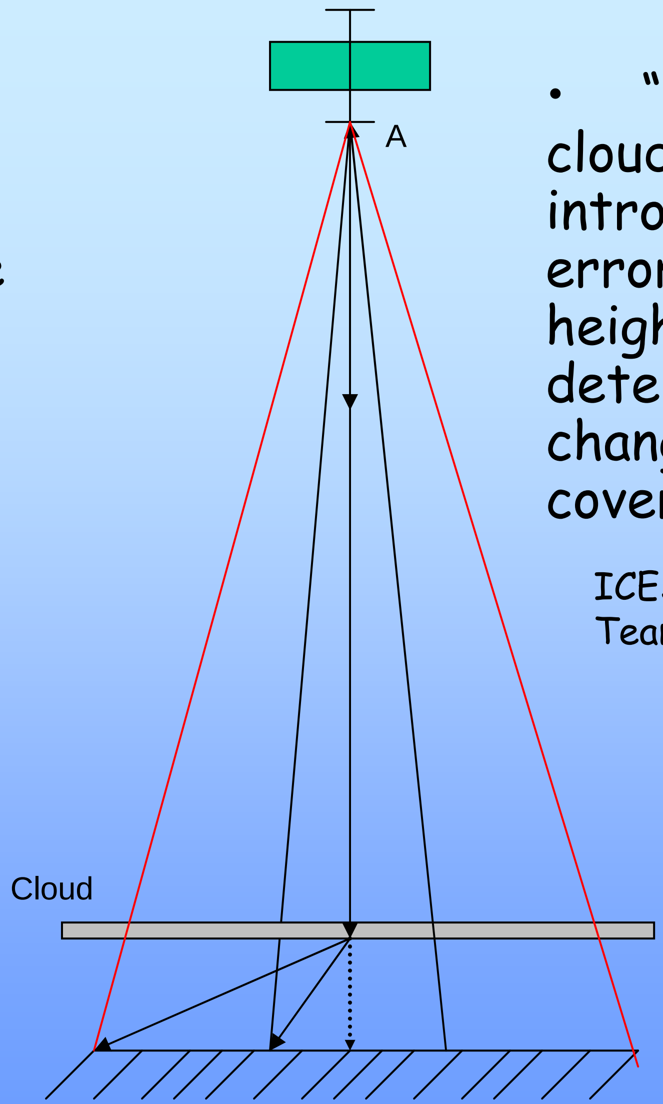
Motivation

- "… forward scattering of the laser light from clouds and aerosols increases the path length, thus making the surface appear farther from the satellite."

- The residual bias "imposed by undetected cloud scattering is at the decimeter, not centimeter level."

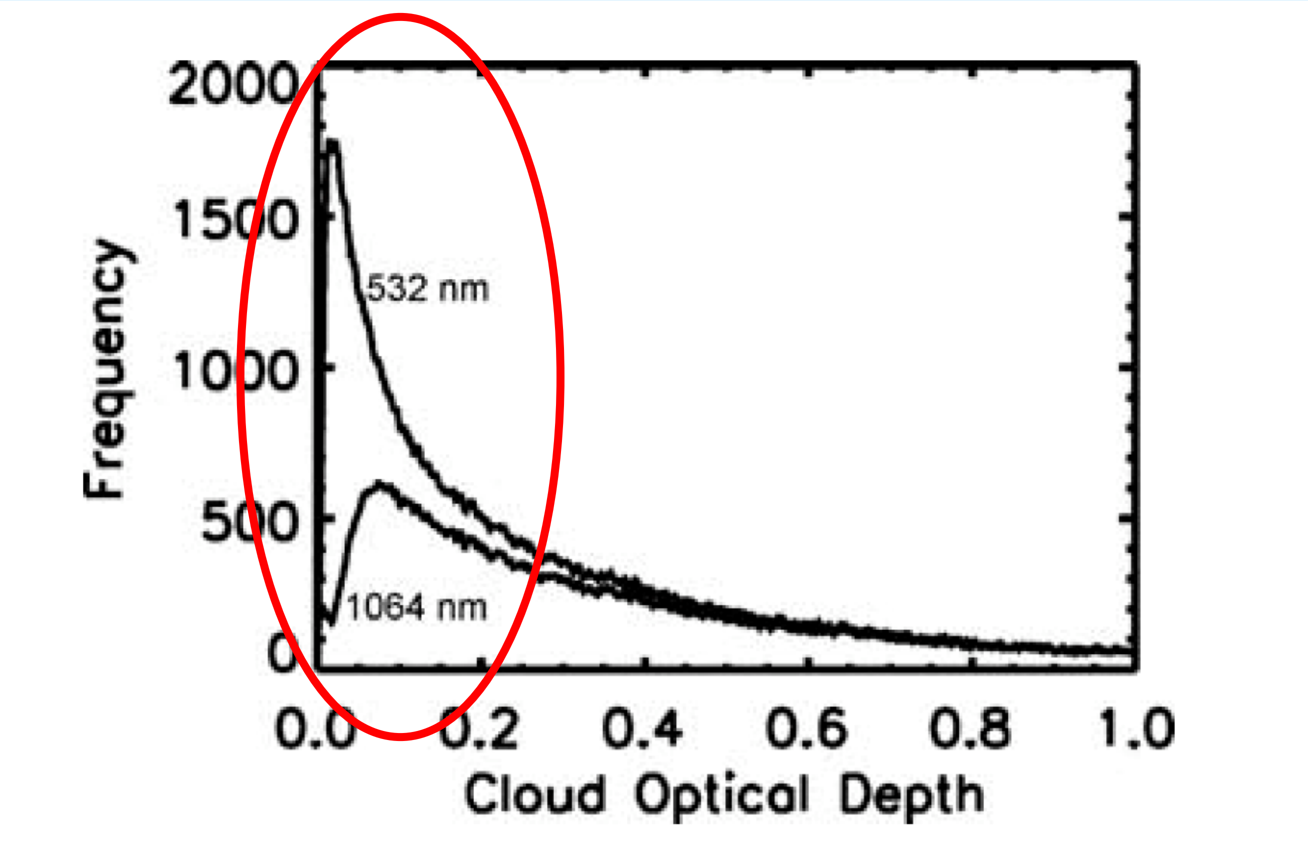
ICESat II workshop report, 2007



- "A bias from cloud scattering introduces an error to surface height *change* detection due to changes in cloud cover."

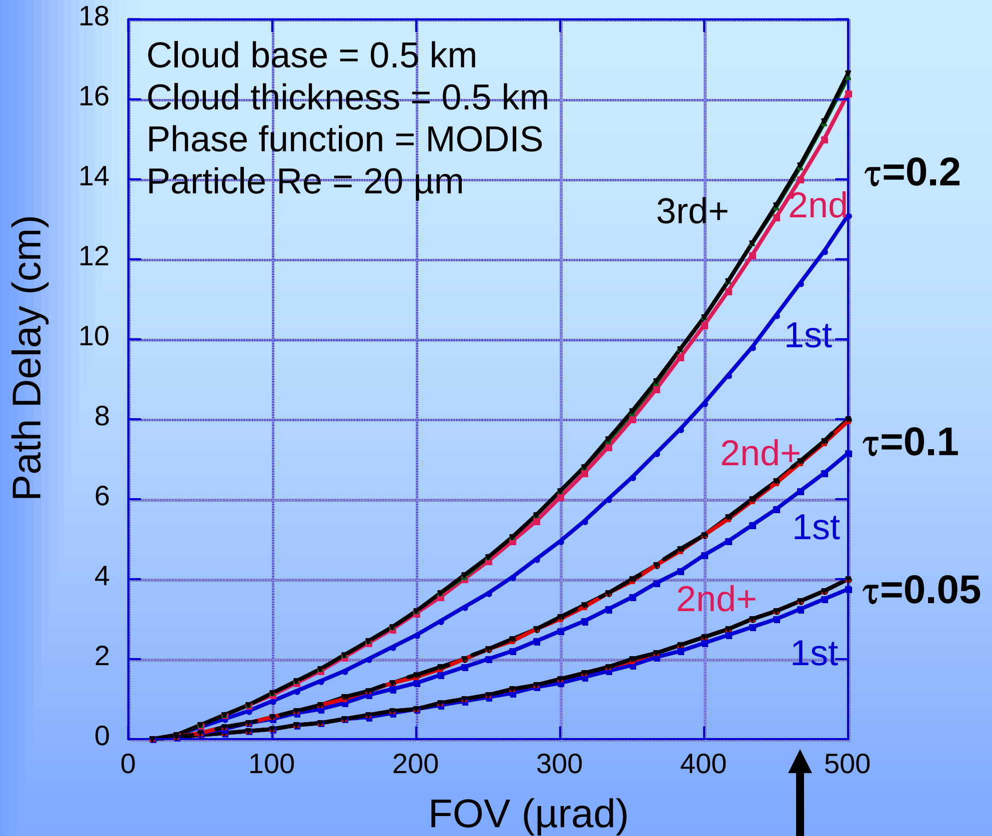
ICESat II Science Team report, 2008

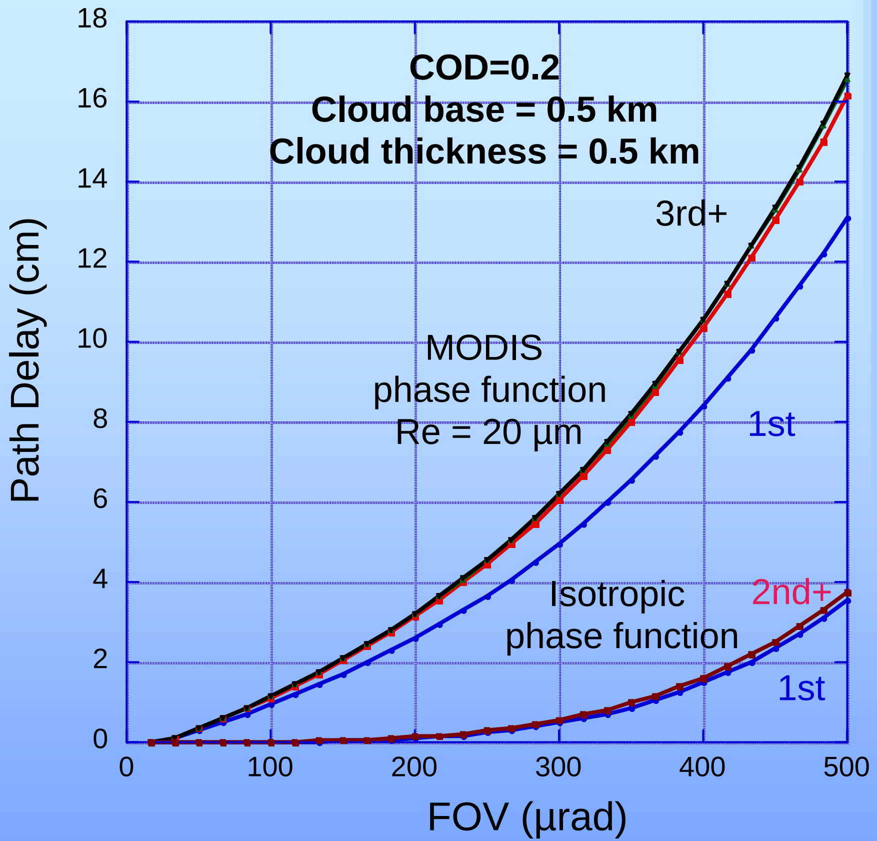
Clouds missed by the 1064 nm channel
(from Spinhirne et al., 2005)



The relative frequency of COD retrieved from the 532-nm channel together with clouds detected by the 1064-nm channel.

Scattering order: forward-scattering and isotropic phase functions



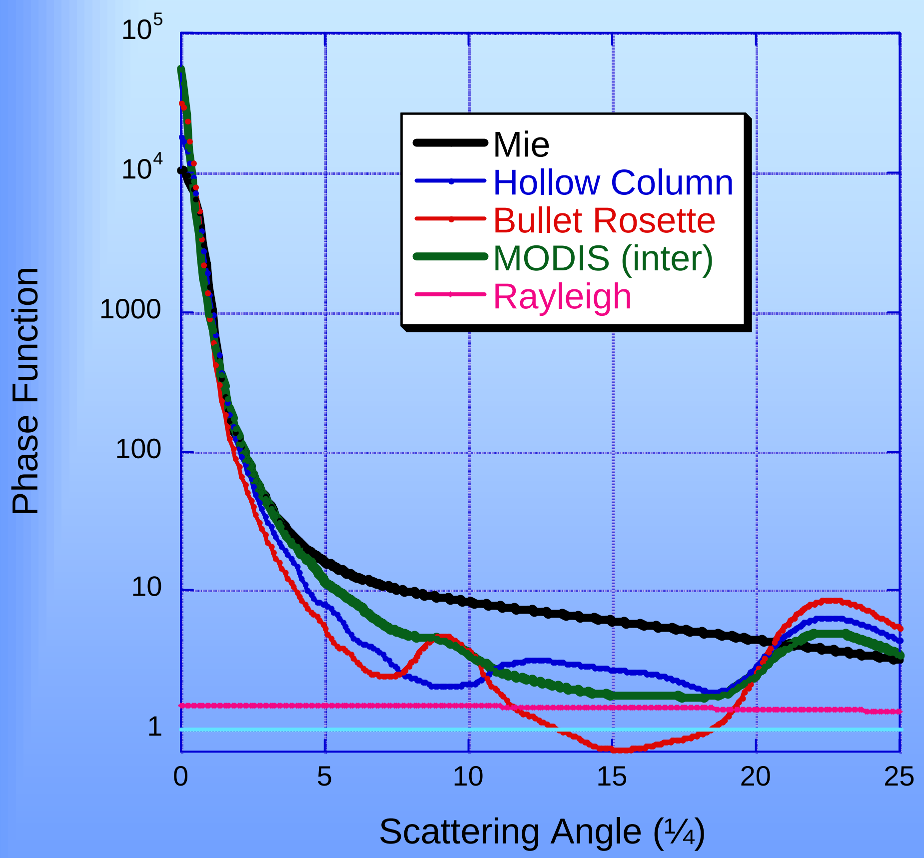


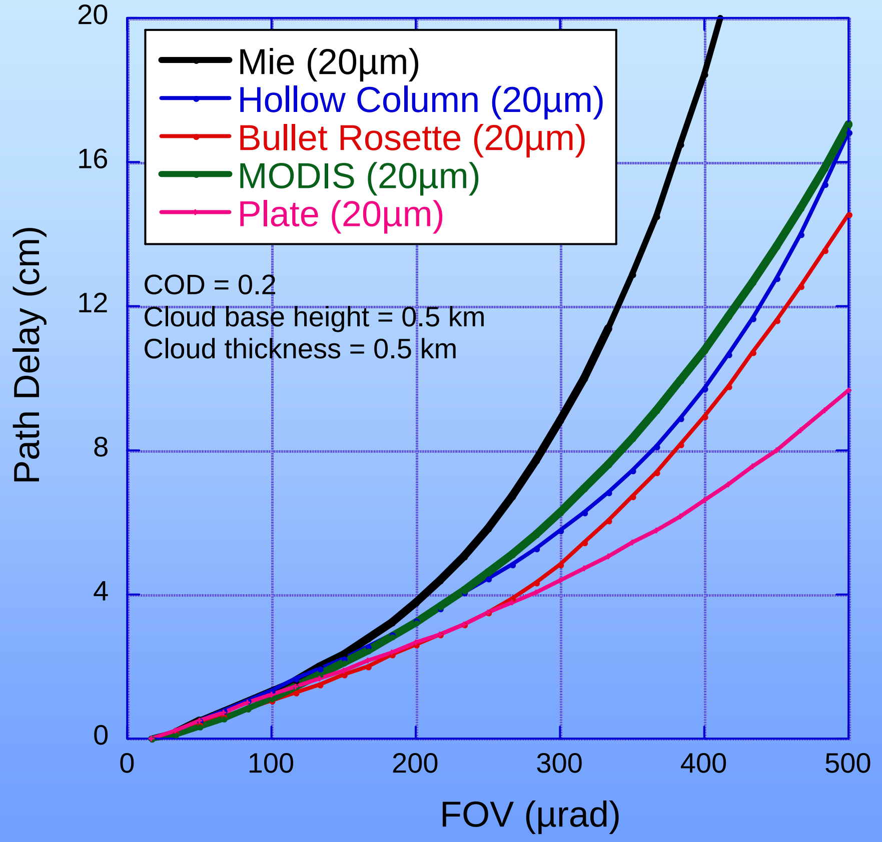
Different COD

The current GLAS FOV: 485µrad = 285m

Forward-scattering and isotropic phase functions

Effect of particle shape on the range delay



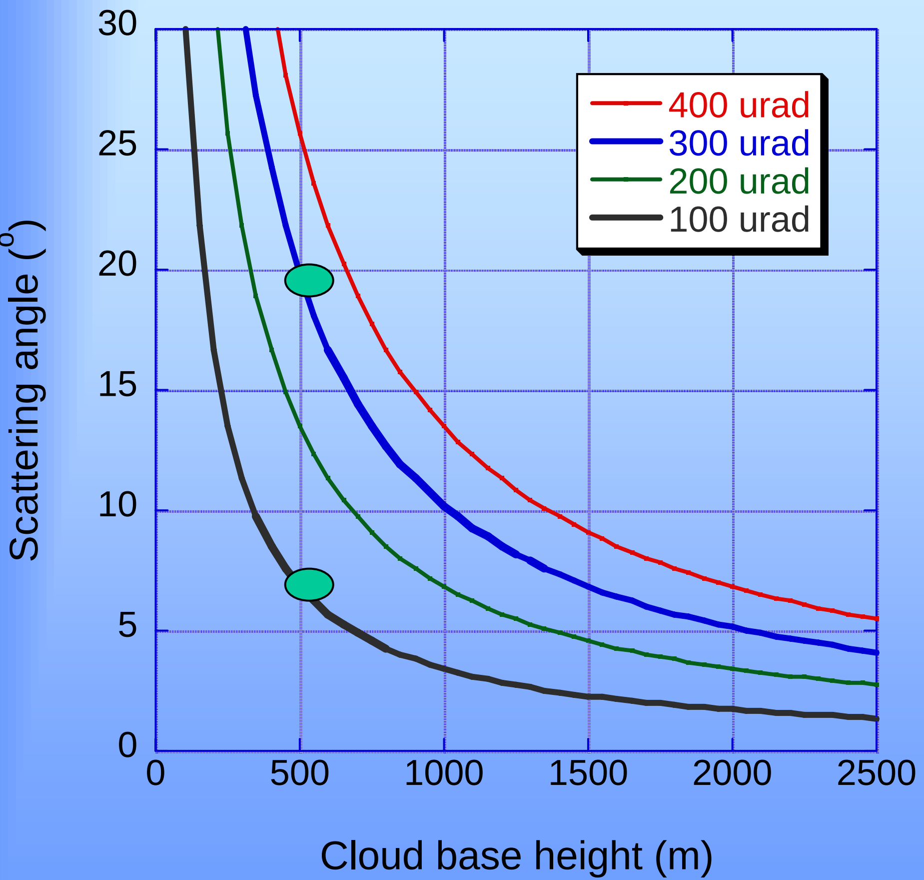


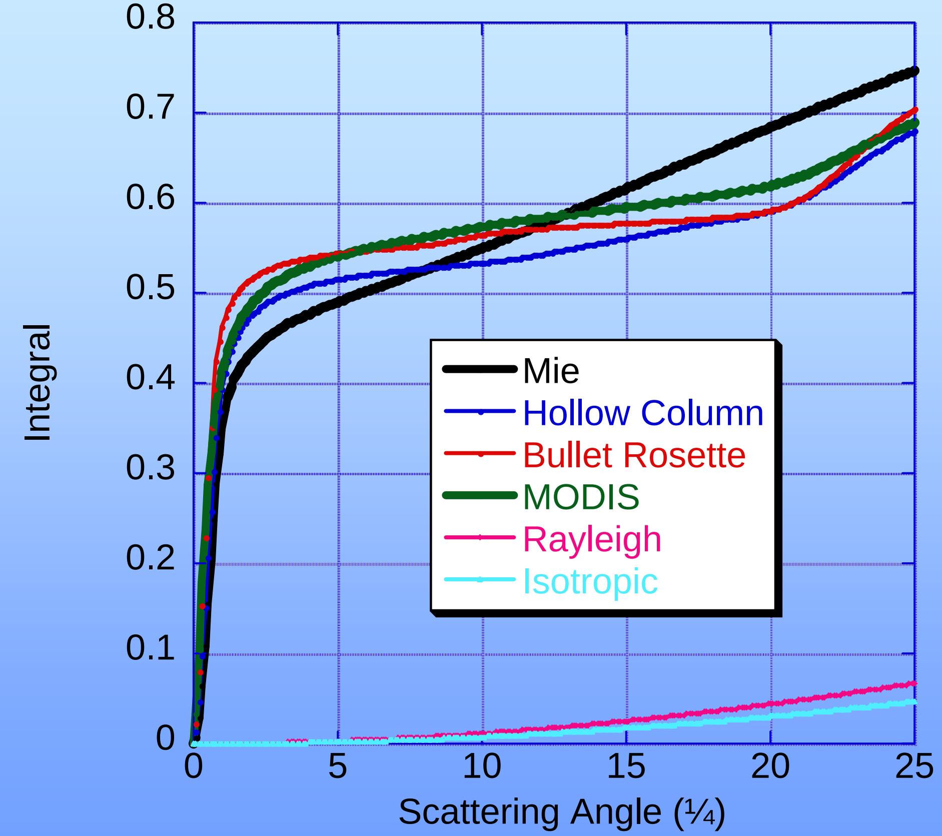
for 100 µrad 1.0-1.5 cm; for 300 µrad 4-6 cm

What scattering angles need to be accounted for as a function of FOV and CBH

Scattering Angle inside FOV

$$p(\theta) = \frac{1}{2}\int_0^{\theta} P(\theta')\sin\theta' d\theta'$$





If clouds are between 0.5 and 1 km, for FOV=100μrad θ<7° is important while for FOV=300μrad θ<20°

Blowing Snow

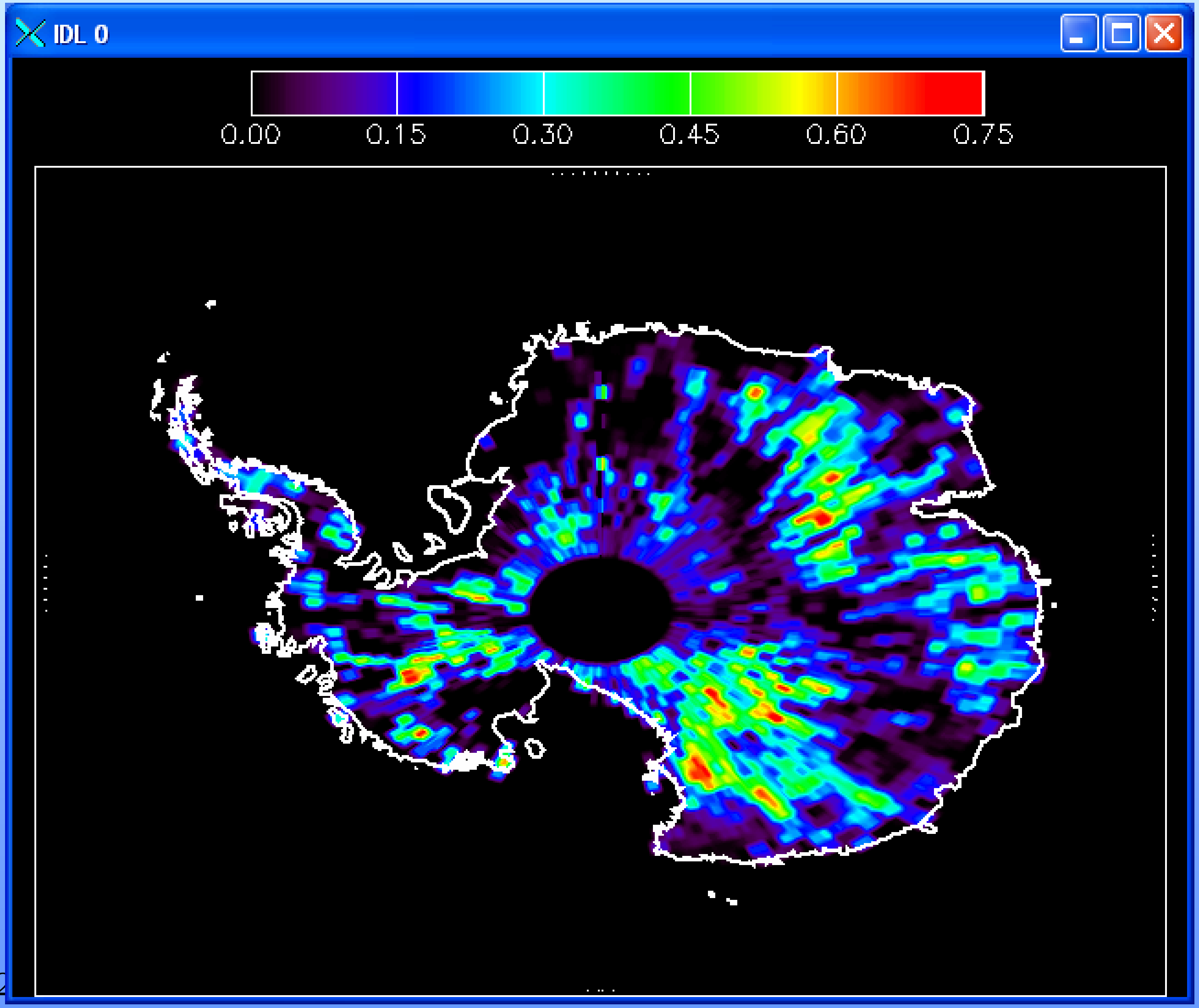
Why should we care about blowing snow?

from Steve Palm's ICESat Science Team presentation

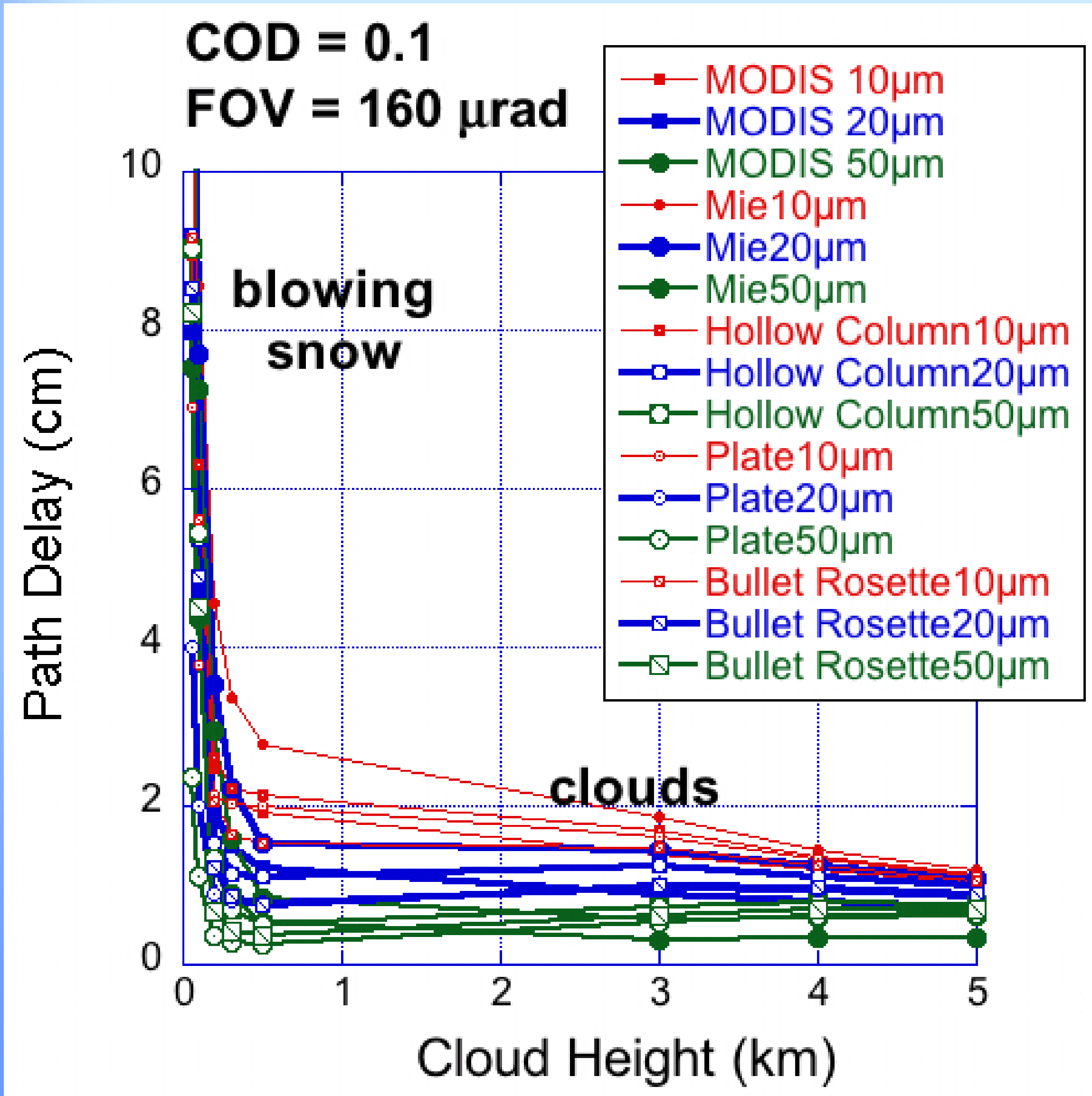
- Antarctic Ice Sheet Mass Balance
- Forward Scattering Effect on Altimetry

Blowing Snow Frequency October 1 – 24, 2003

from Steve Palm's ICESat Science Team presentation



The uncertainties in range delay for FOV=160 μrad

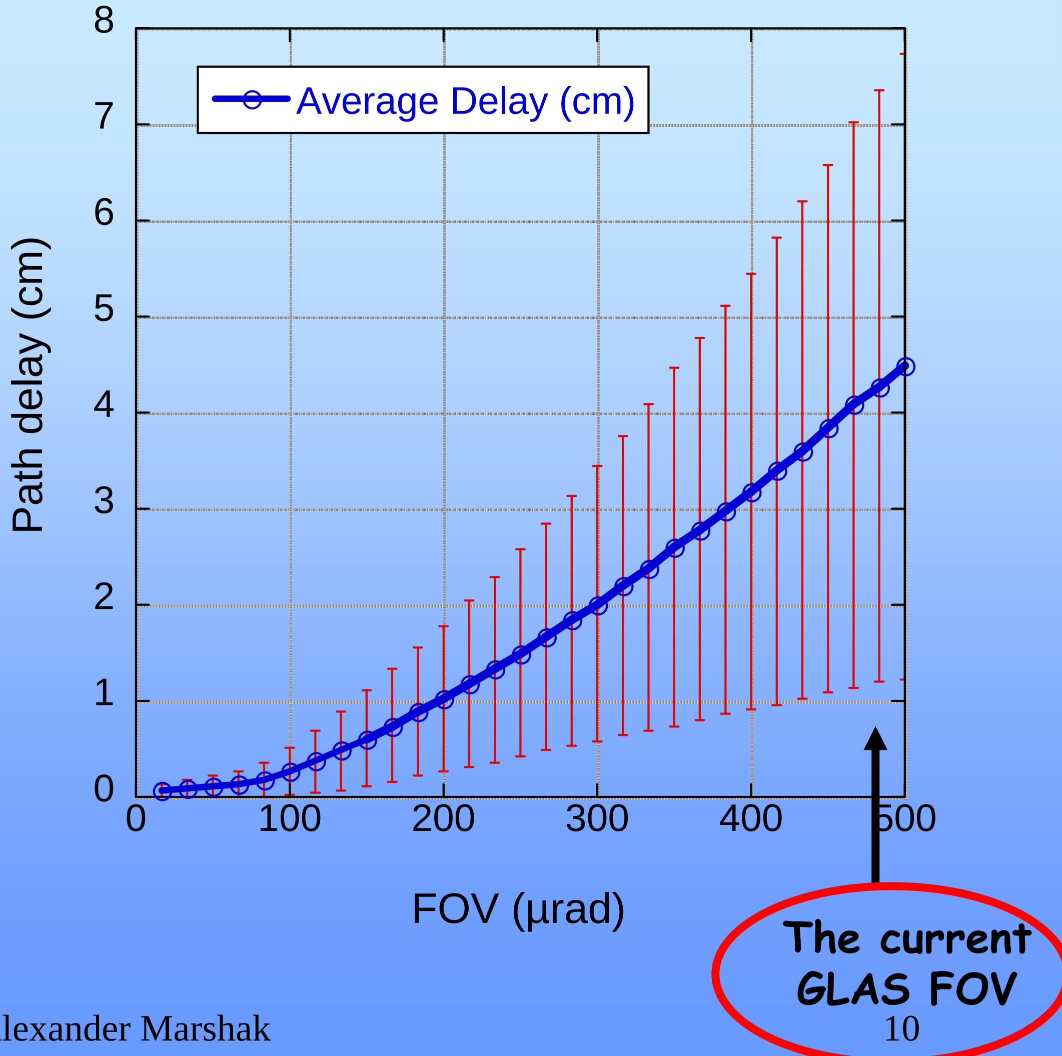


Size and shape of ice crystals varies

Expected path delay

$$I(\Delta\psi) = \iiint p_1(h_b,\tau)p_2(\tau)p_3(r_{eff})\, L(h_b,\tau,r_{eff};\Delta\psi)\, dr_{eff}\, d\tau\, dh_b$$

- $p_1(h_b,\tau)$ is the pdf of cloud base h_b and COD τ;
- $p_2(\tau)$ is the pdf of COD τ undetected by the 1064-nm channel;
- $p_3(r_{eff})$ is the pdf of effective radius r_{eff} for thin transparent clouds;
- $L(h_b,\tau,r_{eff};\Delta\psi)$ is the MC calculated range delay as a function of $\Delta\psi$.



Particle shape at South Pole Station

from Lawson et al., JAM 06

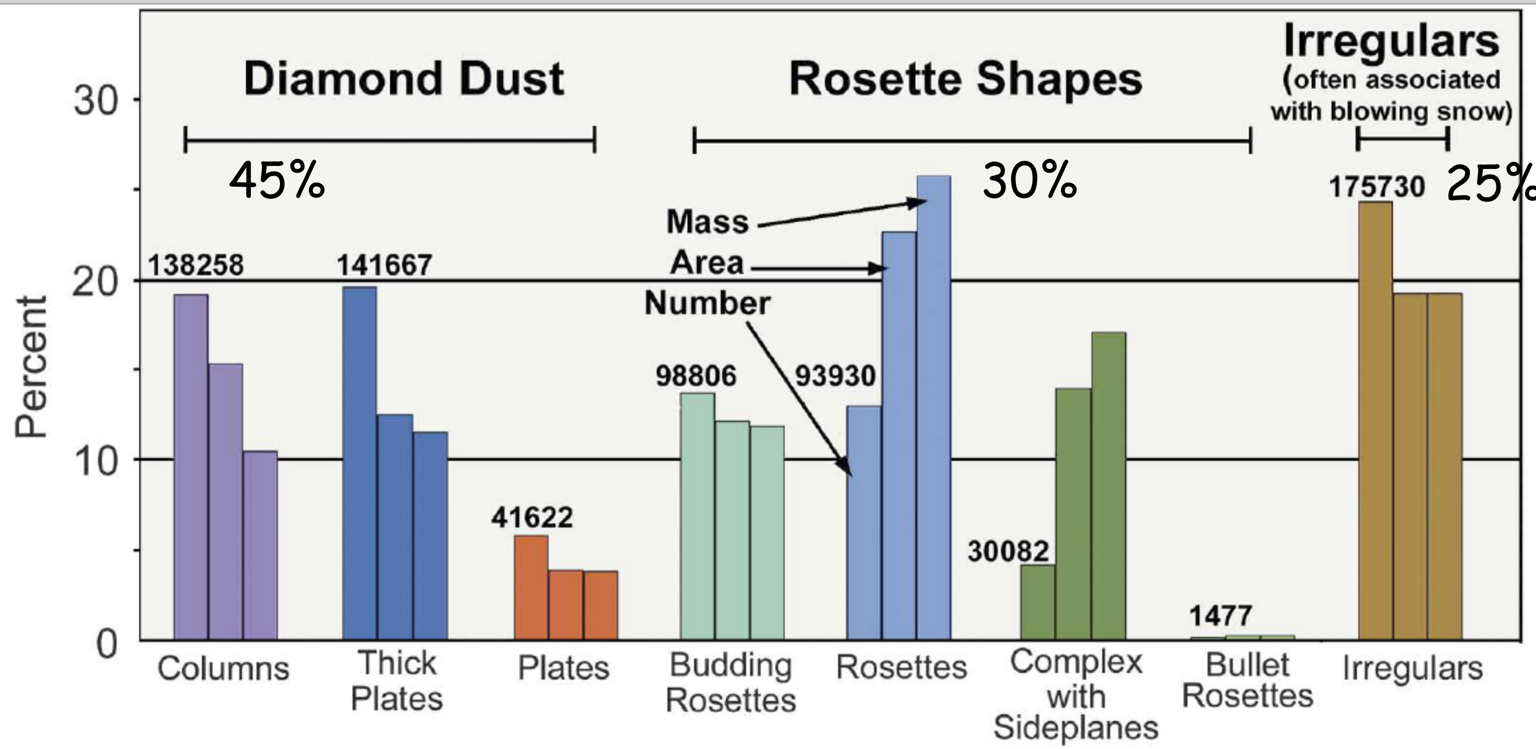


FIG. 5. Histogram of ice crystal habits observed at SPS during the period of 1–8 Feb 2001. The percentage weighted by concentration, area, and mass is shown for each habit category. Columns, thick plates/short columns, and plates are associated with diamond dust. Budding rosettes, rosettes, and complex with side planes are associates with rosette shapes. The total number of crystals of each habit is shown above its category. The total number of ice crystals categorized is 721 572.

Particle shape and size at South Pole Station

from Lawson et al., JAM 06

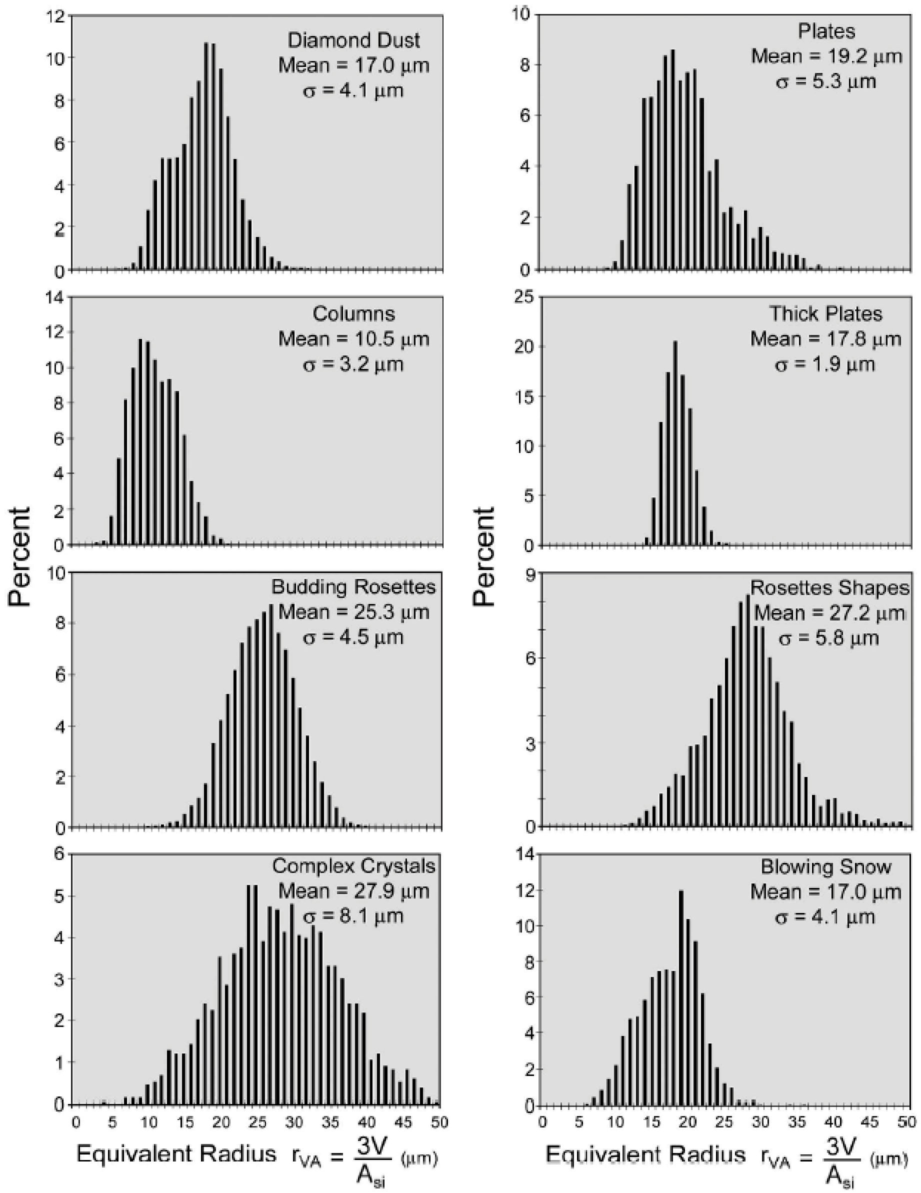


FIG. 11. Histograms showing size distributions of various ice crystal habits as a function of equivalent radius.

Particle size and shape for thin polar clouds

- *in-situ* measurements of droplet size distribution are rare in polar regions, esp. in Antarctica (there are some *ground-based* measurements, though).

- the differences between cirrus clouds in the tropics and in the polar regions are poorly understood;

- ice particle size strongly correlates with T; at least for tropical clouds, cold very thin clouds may have very small ice crystals;

- problems with small ice crystals (D < 50 μm): shattering of large particles overestimates concentration of small ice crystals;

- remote sensing retrievals have large uncertainties, esp. for very thin clouds;

- CALIPSO's Infrared Imaging Radiometer (IIR) retrieves R_{eff} but not yet available. Its accuracy over polar region clouds is unknown;

- Lidar/Radar/IR retrievals of particle size is, perhaps, the most promising;

Data

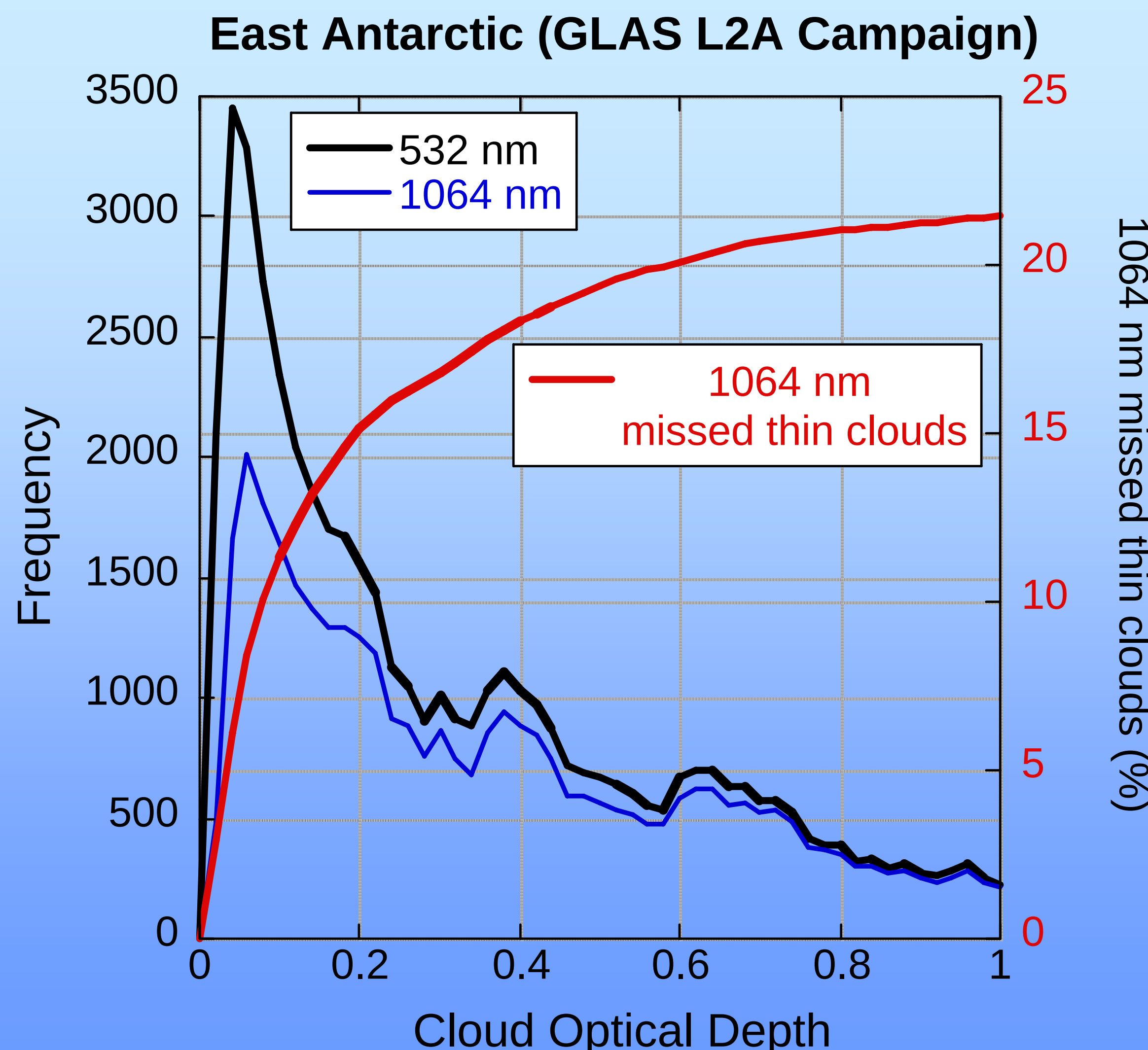
- ICESat
- MODIS
- CALIPSO

for Greenland, East and West Antarctica

GLAS: clouds missed by the 1064-nm channel

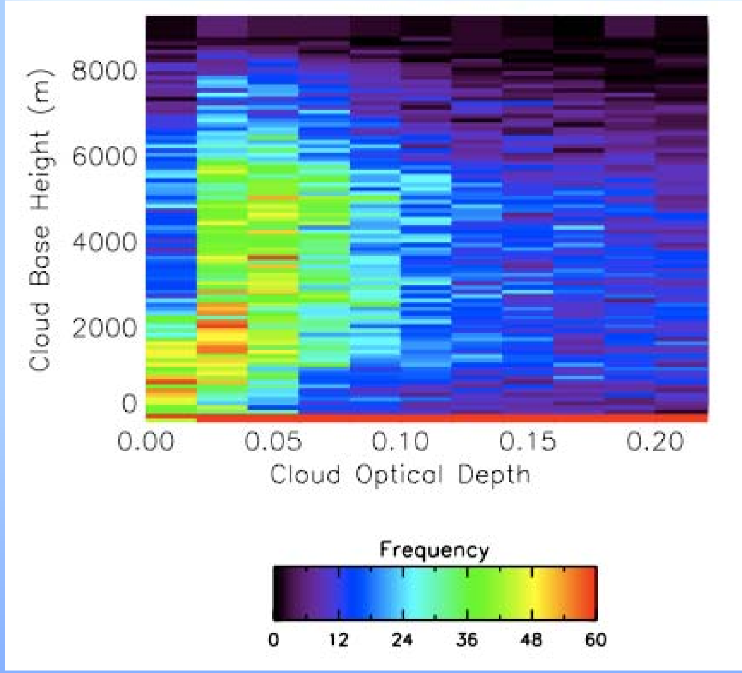
	CF(%)	Thin(%)	Missed(%)
EA:	34	56	22
WA:	59	55	11
GR:	60	42	31

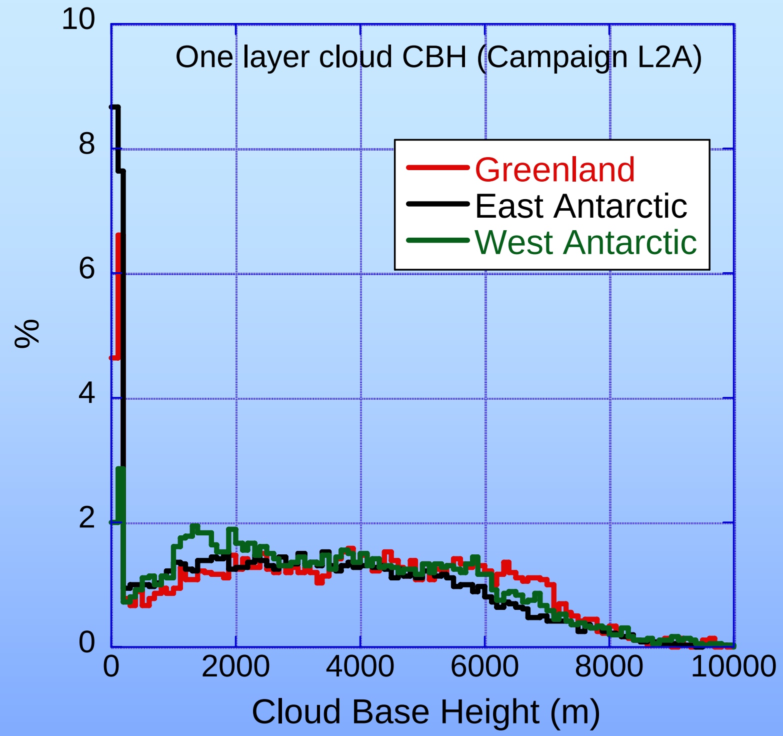
The relative frequency of COD retrieved from the 532-nm channel together with clouds detected by the 1064-nm channel. Red curve is the cumulative distribution function of thin transparent clouds missed by the 1064-nm channel.



GLAS data: CBH vs COD

Based on GLAS L2a campaign (Oct. 2003)





The pdf of CBH and COD for East Antarctica with COD < 0.2. 'Warm' colors mean high probability while 'cold' colors mean low.

The distribution of CBH for the one layer clouds COD < 0.2

GLAS data: CBH vs COD

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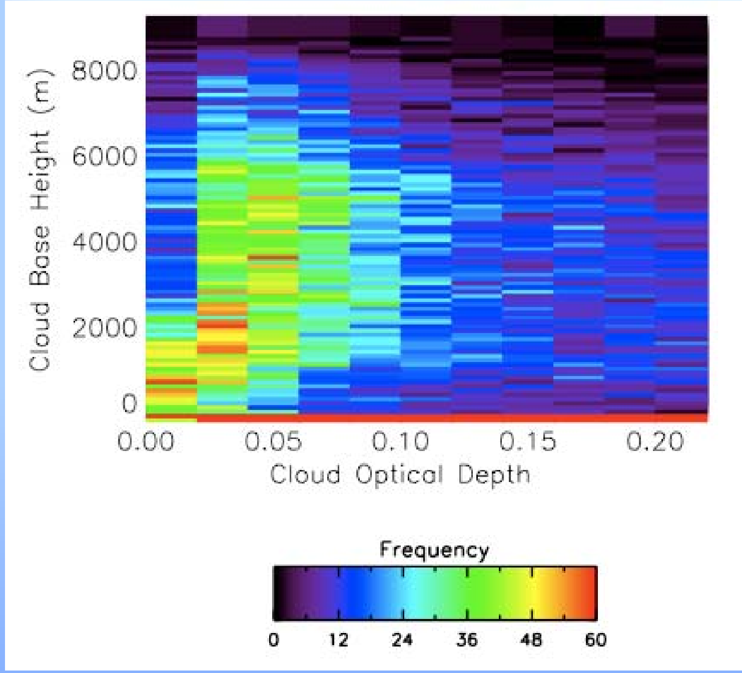
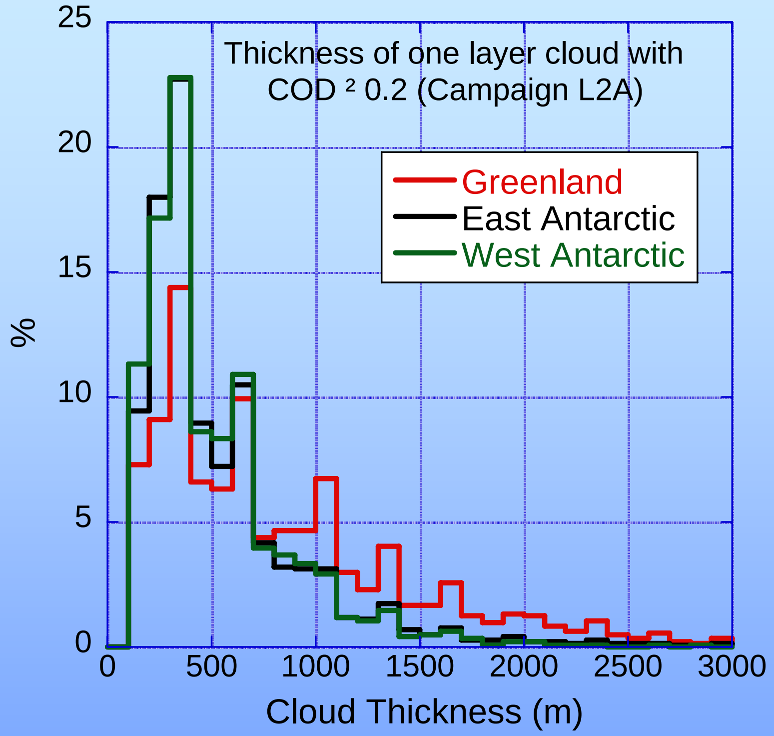


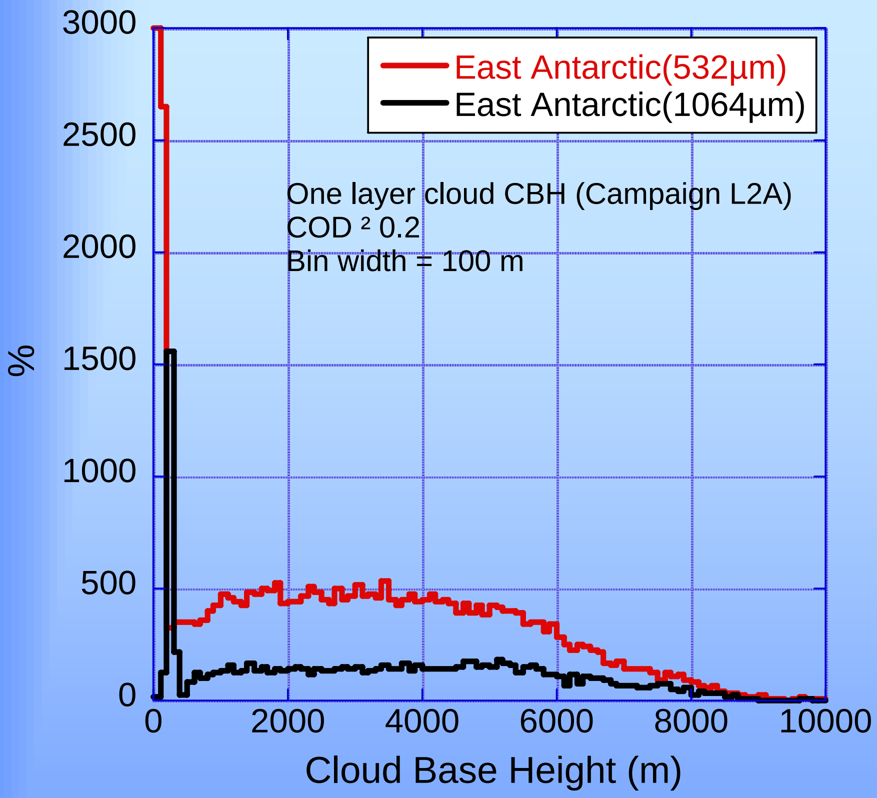


The pdf of CBH and COD for East Antarctica with COD < 0.2. 'Warm' colors mean high probability while 'cold' colors mean low.

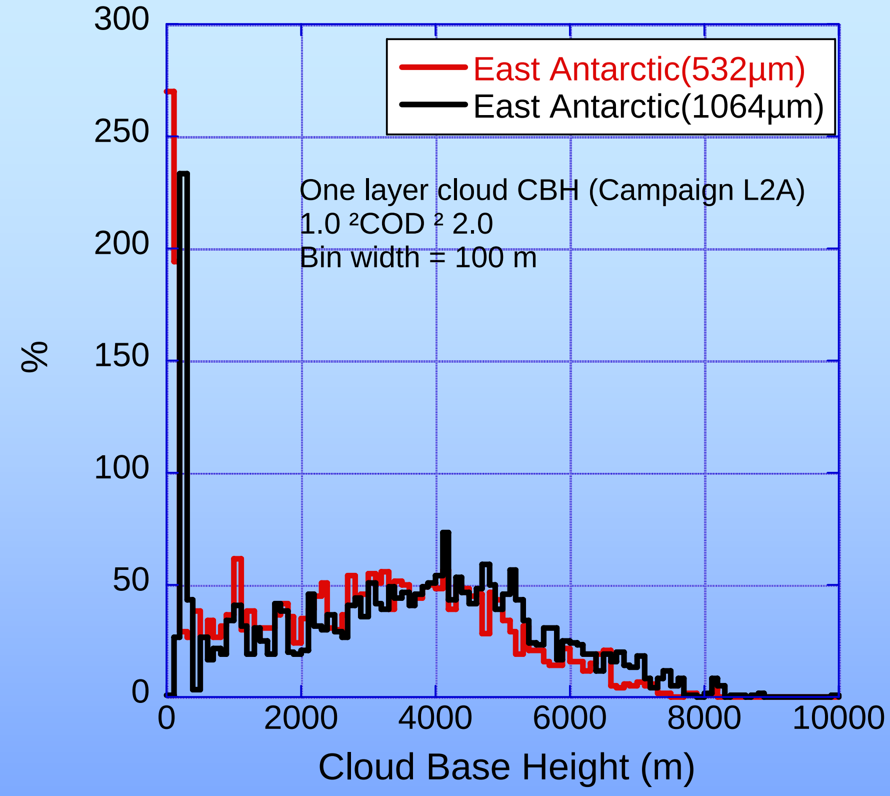
The distribution of cloud thickness for the one layer clouds COD < 0.2

GLAS data: CBH 532nm vs 1064nm

Based on GLAS L2a campaign (Oct. 2003)



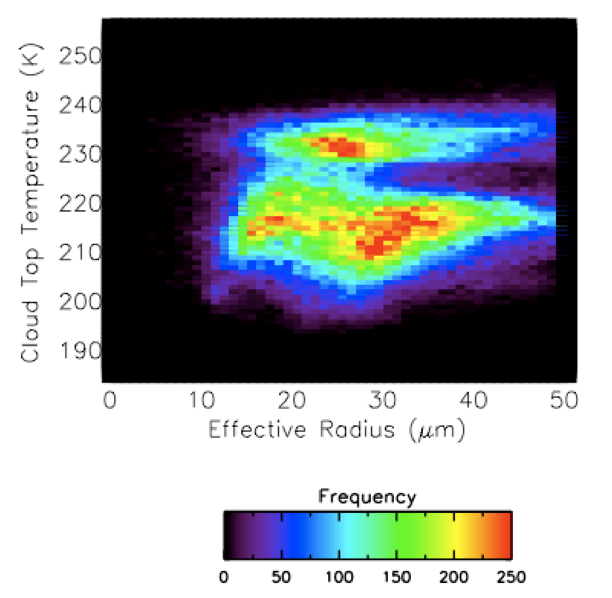
COD ≤ 0.2

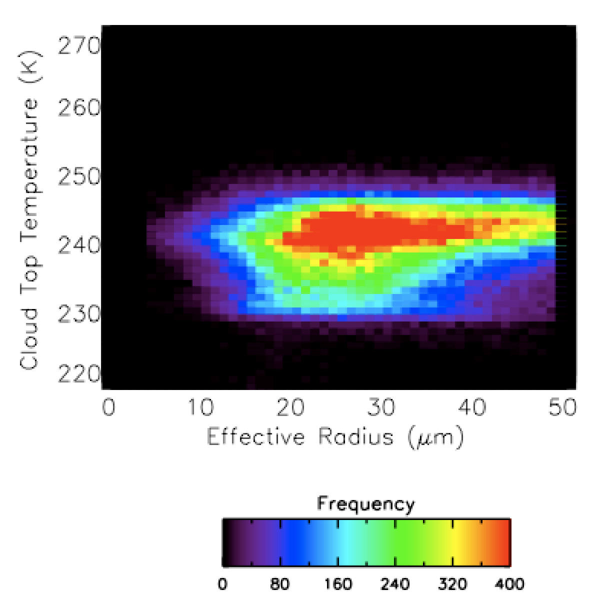


1 ≤ COD ≤ 2

MODIS data: R_{eff} vs CTT

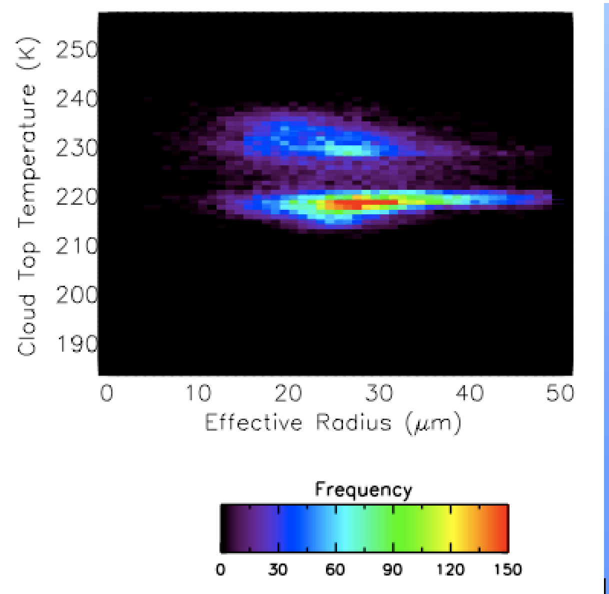
Fall





Winter

Spring

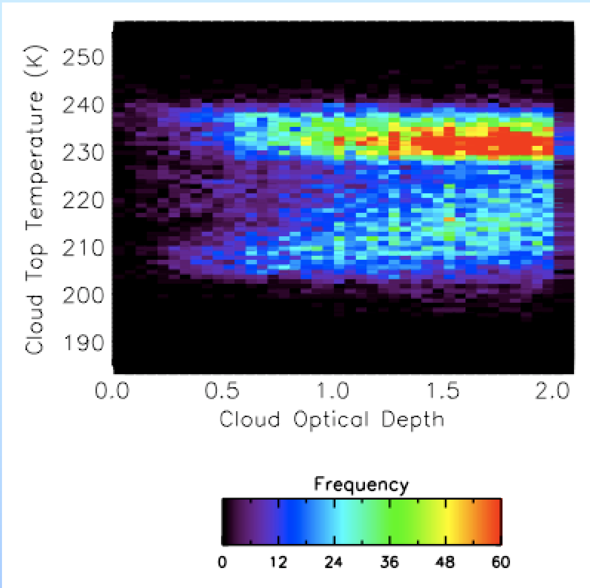


East Antarctica

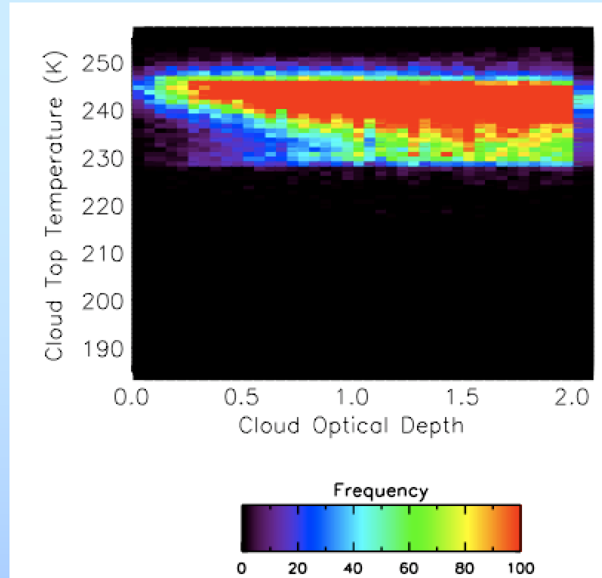
MODIS Aqua & Terra: Sep 2003 - Aug 2004

MODIS data: COD vs CTT

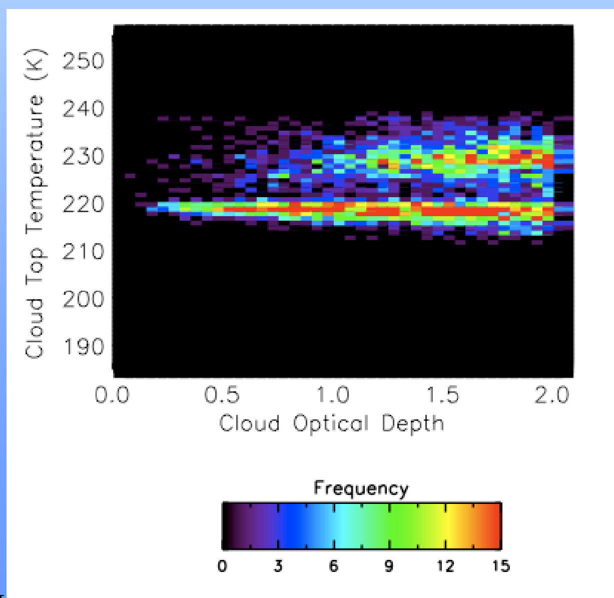
Fall



Winter



Spring



East Antarctica

MODIS Aqua & Terra: Sep 2003 - Aug 2004

Conclusions

- Properties of the forward-scattering phase function peak are the greatest unknown;

- Existing remote-sensing data on ice particle size have large uncertainties; not much ground-based measurements and rare in-situ observations;

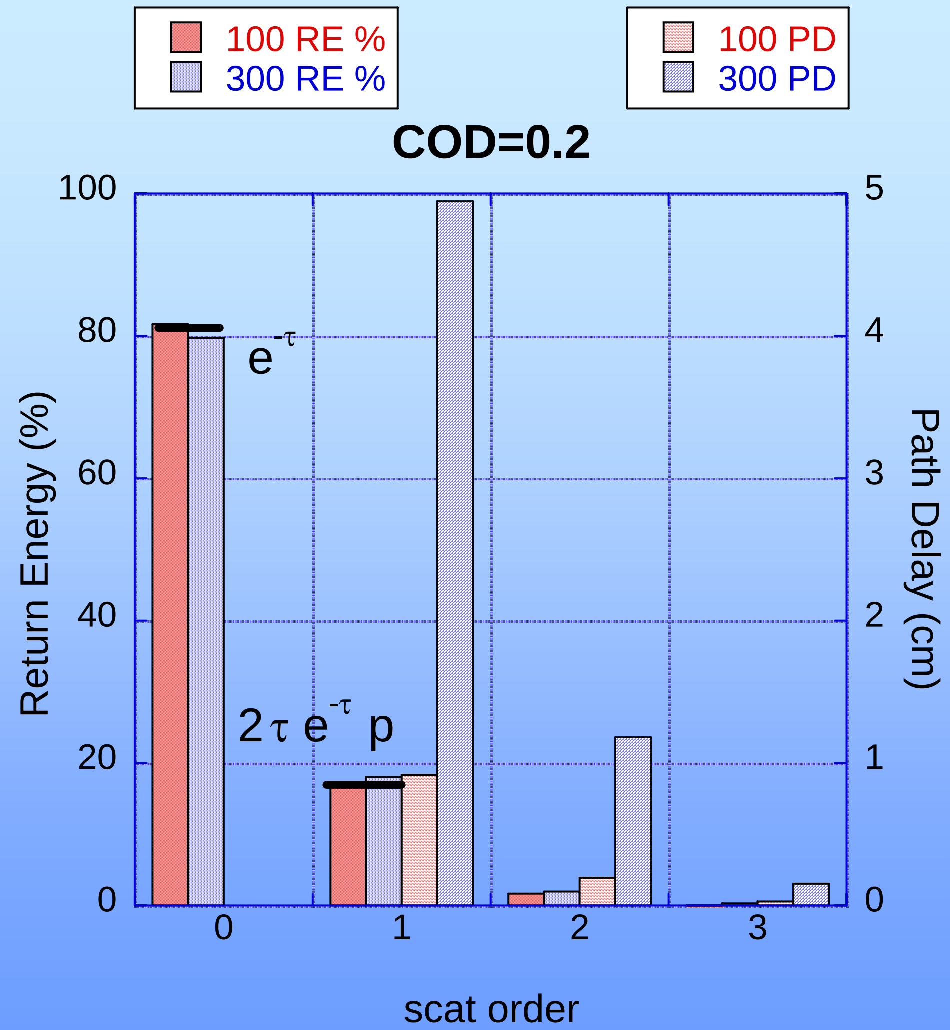
- Very preliminary calculations based on ICESat, CALIPSO and MODIS data estimate range delay as 5±2 cm for FOV=300 μrad and 0.7±0.5 cm for FOV=100 μrad;

- To reduce the uncertainties we suggest
  - to measure the forward scattering properties directly
  - to use two FOVs

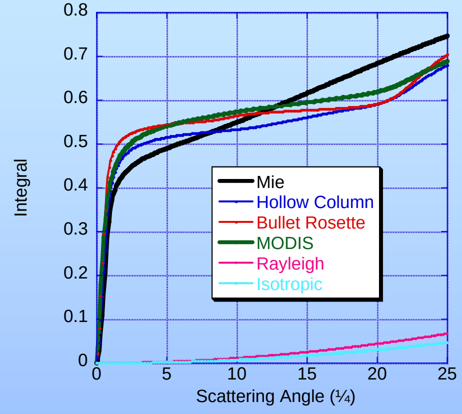
- The returned energy from one- and two-scatterings order photons can be well approximated by simple analytical expressions based on RT

Back-up slides

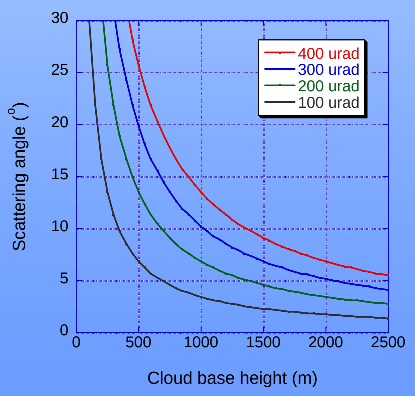
Scattering order: returned energy and path delay for two FOVs (100 & 300 μrad)



$$p(\theta) = \frac{1}{2}\int_0^{\theta} P(\theta')\sin\theta' d\theta'$$



Scattering Angle inside FOV



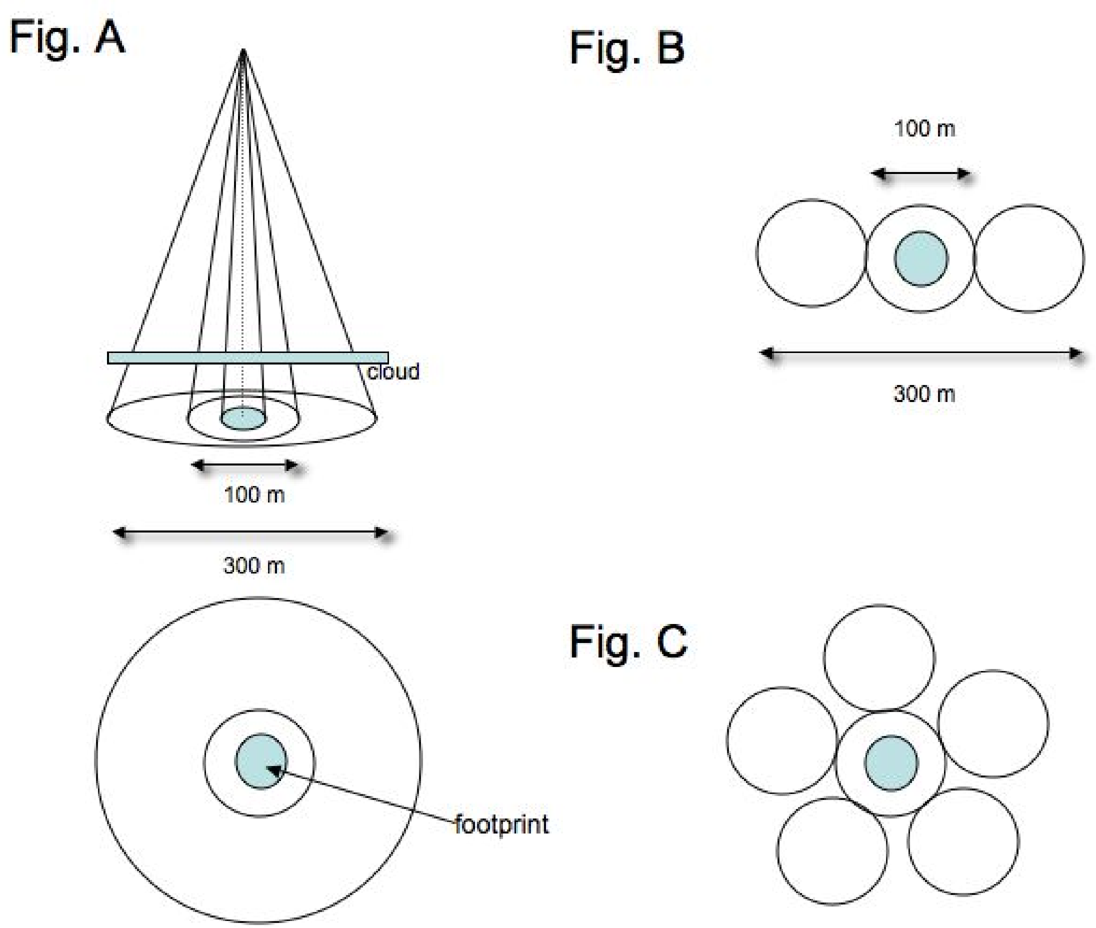
New suggestions

- Direct measurements of forward scattering properties
- Two-FOVs system

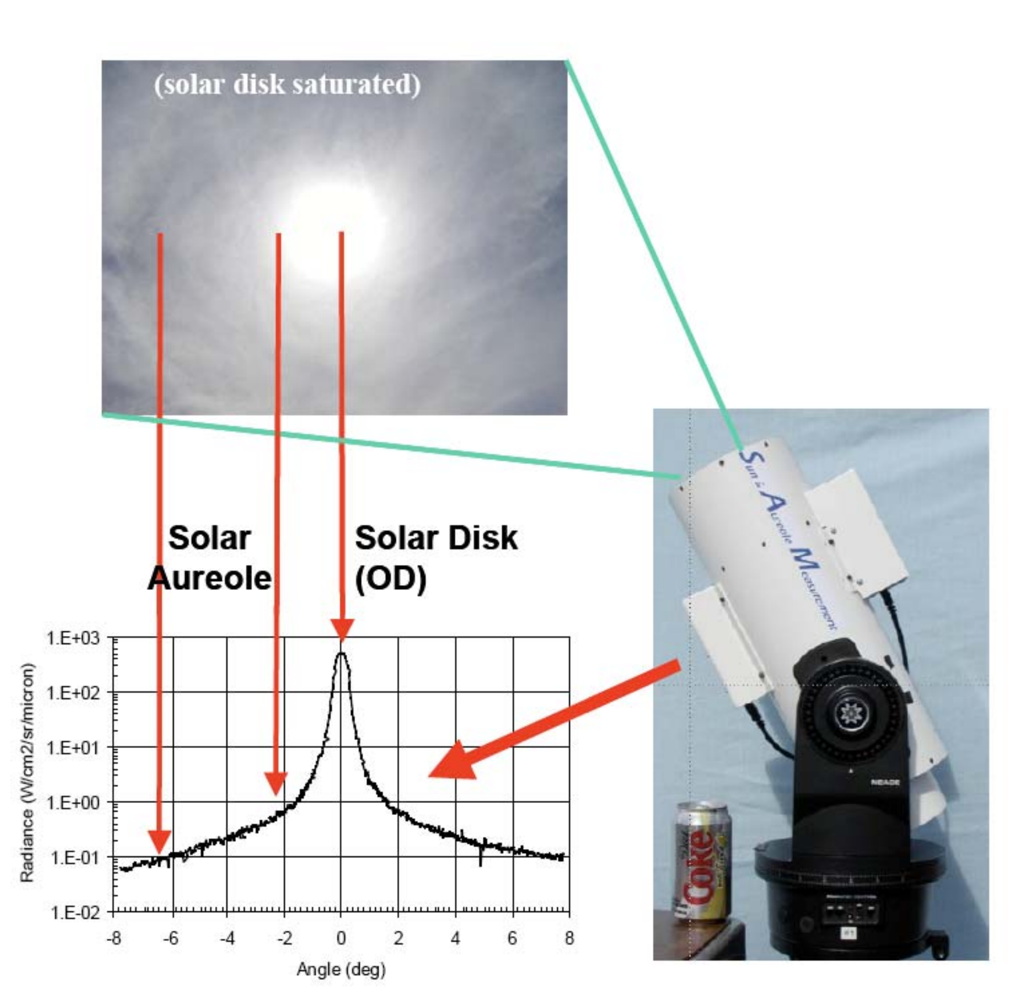
Dual FOV

(1) with 2FOVs we can solve the problem of undetected clouds **once and for all**.

(2) with 2FOVs we would be able to **correct altimetry data contaminated by clouds**.



Measuring the forward scattering properties: ground validation campaign?



SAM measures the radiance of the solar disk and surrounding aureole:

$$A(\theta) = \frac{1}{4\pi\mu_s^2} P(\theta)\tau F_{sun} e^{-\frac{\tau}{\mu_s}}$$

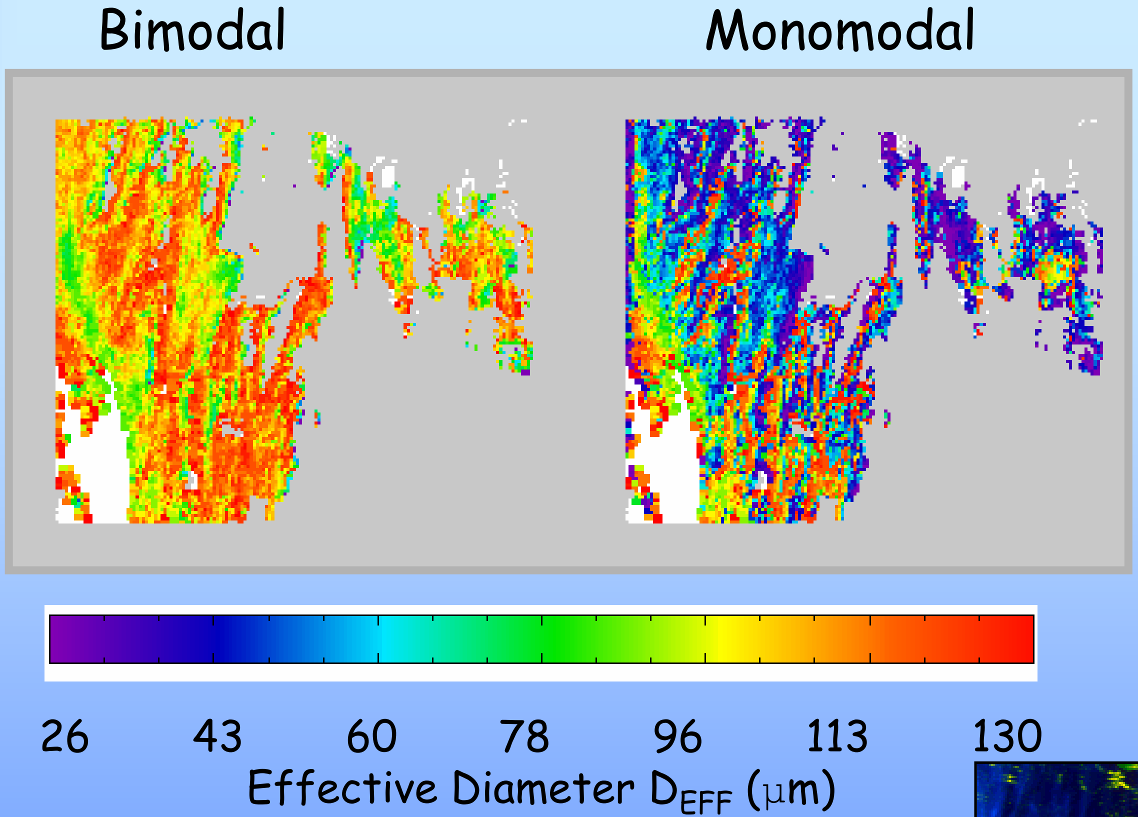
Retrieve thin cirrus scattering patterns P(θ) and compare with the existing models

Deployed at the roof of Bld. 33 at GSFC

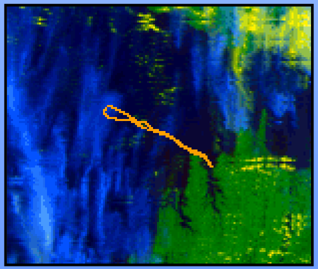
SAM - Sun and Aureole Measurement

Courtesy John DeVore, Visidyne Inc

Importance of particle shape: ice retrievals with different microphysical assumptions

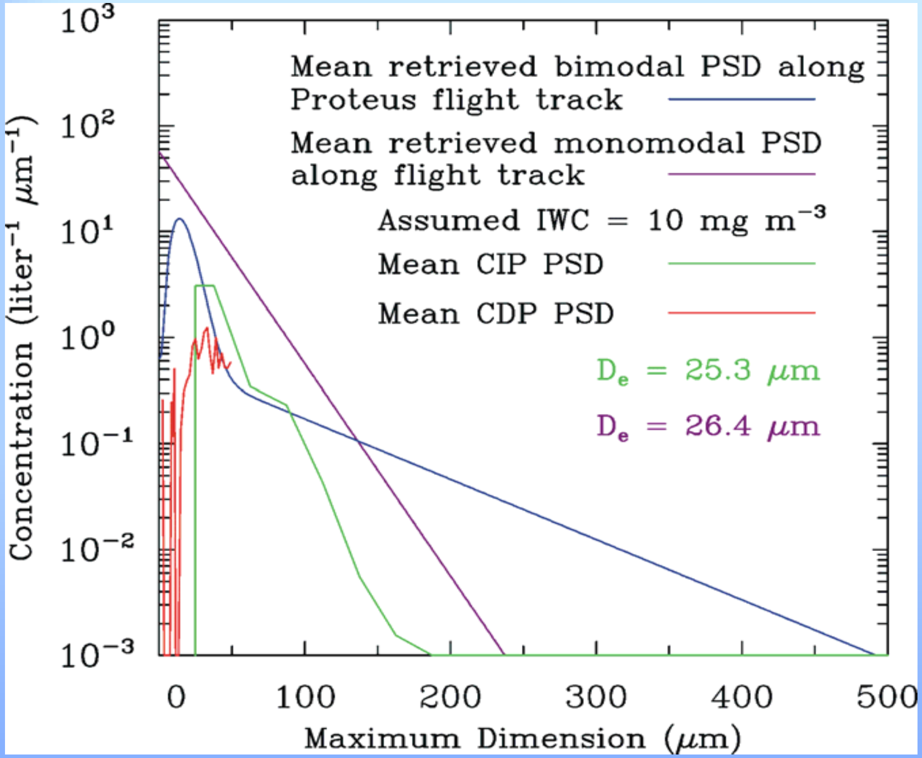


Courtesy of Dave Mitchell



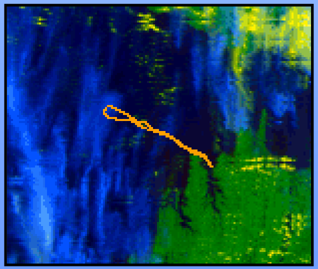
0.47 0.86 11.03-μm Composite

Particle shape is important but poorly known!



Comparing retrieved and measured PSD and D_e when sampling times and position coincide

TWP-ICE retrievals with different microphysical assumptions

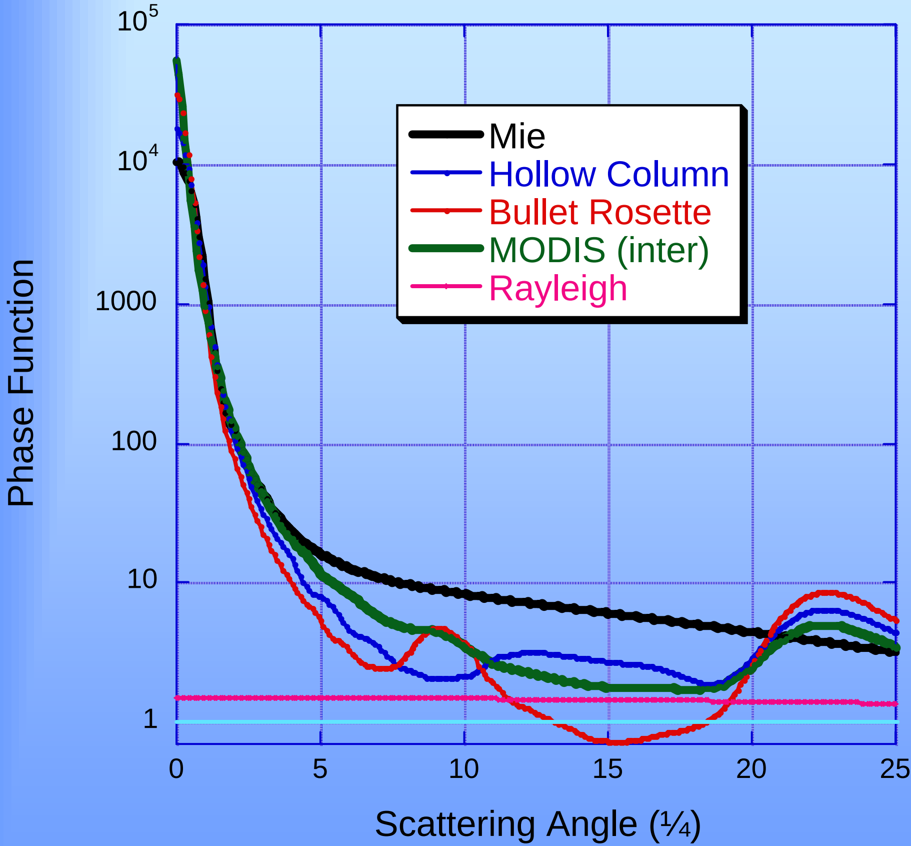


0.47 0.86 11.03-μm Composite

Courtesy of Dave Mitchell

Phase function and its cumulative

$$P(\theta)$$



$$p(\theta) = \frac{1}{2}\int_0^{\theta} P(\theta')\sin\theta' d\theta'$$