Emerging Technologies: Spaceborne W-band Radars

CloudSat, EarthCARE, and ACE

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Overview

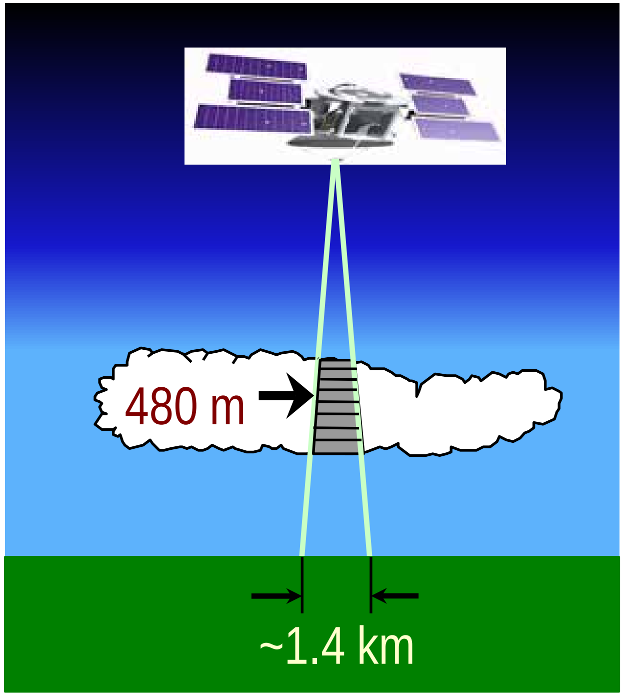
- Introduction to Spaceborne W-band Radar
  - What is CloudSat?
  - Comparison to Other Platforms
  - Standard Data Products
- Algorithm Considerations
- Retrieval Methodology
- Measuring Snowfall
- Data Products and Limitations

CloudSat

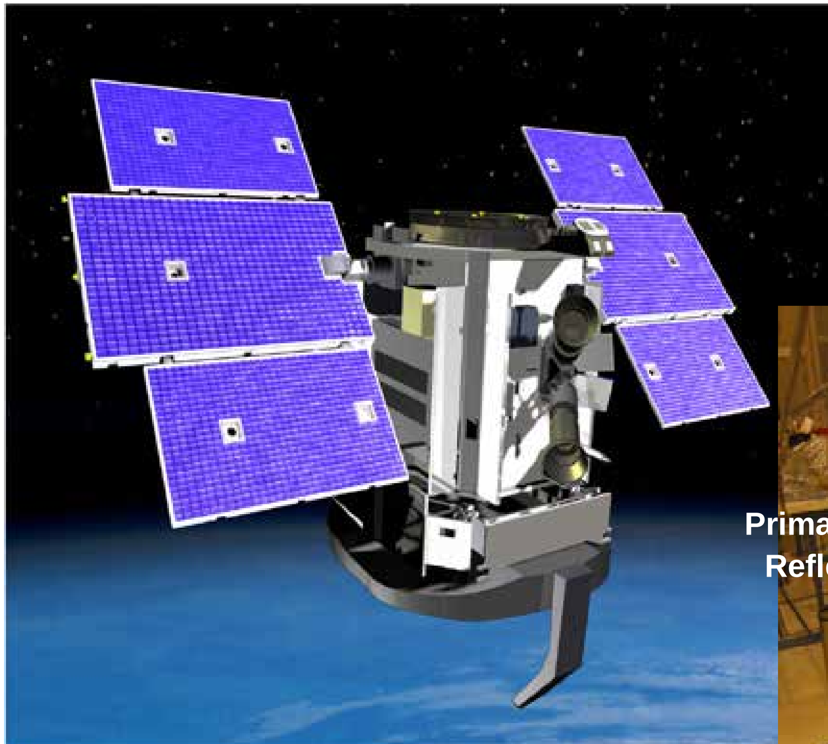
Objective: To provide, from space, the first global survey of cloud profiles and cloud physical properties, with seasonal and geographical variations needed to evaluate the way clouds are parameterized in global models, thereby contributing to weather predictions, climate and the cloud-climate feedback problem.

The Cloud Profiling Radar

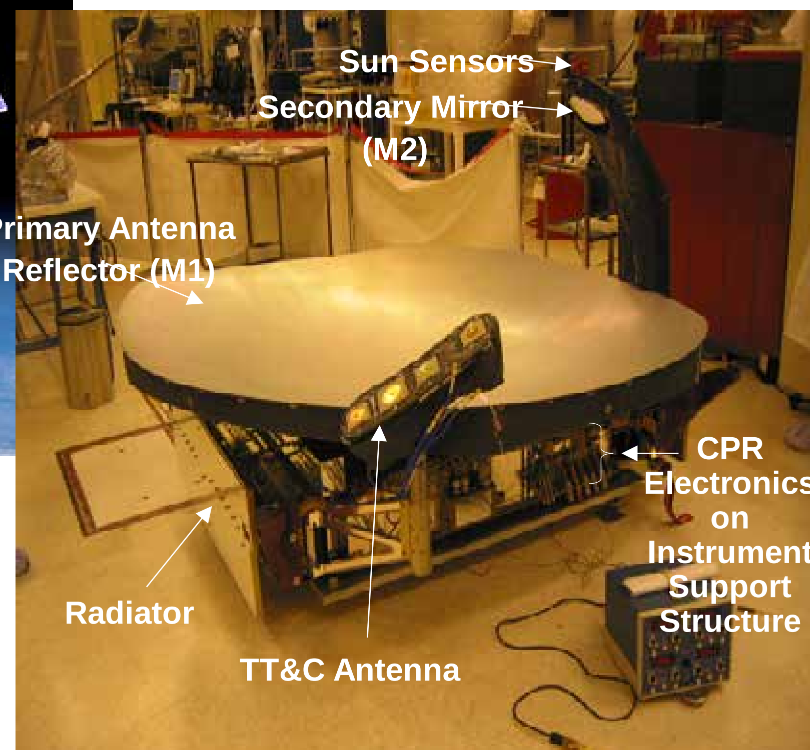
- Nadir pointing, W-band (94 GHz) radar
- 3.3ms pulse è 480 m (oversampled to 240 m)
- 1.4x2.5 km horizontal res.
- Sensitivity: -30 dBZ
- Dynamic Range: 80 dB
- Antenna: 1.85 m; 322 W



CloudSat



Cloud Profiling Radar

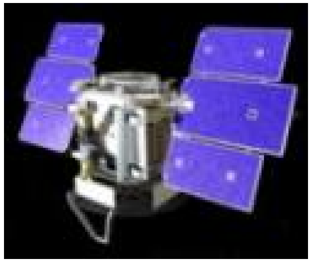


Comparison of Radar Characteristics

	WSR-88D	TRMM PR	CloudSat
Frequency	2.8 GHz	13.8 GHz	94 GHz
Wavelength	10.8 cm	2.2 cm	3.2 mm
Antenna	9 m	2.25 m	1.85 m
Beamwidth	0.9°	0.71°	0.108°
Resolution	~1 km	4.5 km	1.5 km
Coverage	2°	±36°	±82°
Sampling	~15 min.	~2 days	Only partial coverage every 16 days

Size Comparison

CloudSat



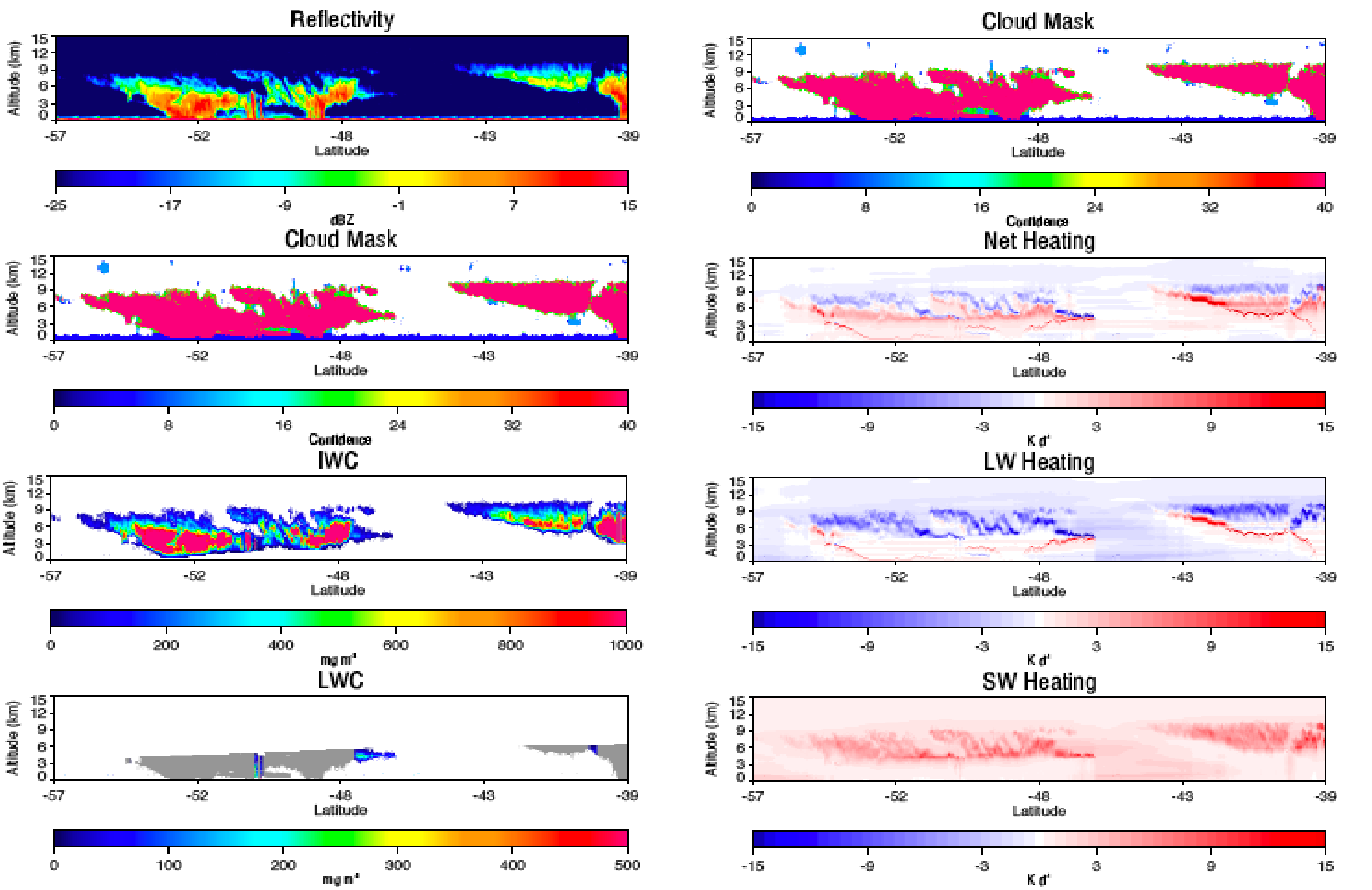
TRMM PR

2 m

CloudSat Data Products

Product	Resolution	Accuracy	Description
Cloud Mask	500 m	N/A	Cloud geometric distribution
Cloud Classification	N/A	N/A	Cloud type identification
Cloud IWC	500 m	30-50 %	Vertical profile of cloud IWC
Cloud LWC	500 m	30-50 %	Vertical profile of cloud LWC
Fluxes	500 m	10 Wm^{-2}	Broadband radiative fluxes
Heating Rates	500 m	1 K d^{-1}	Broadband heating rates

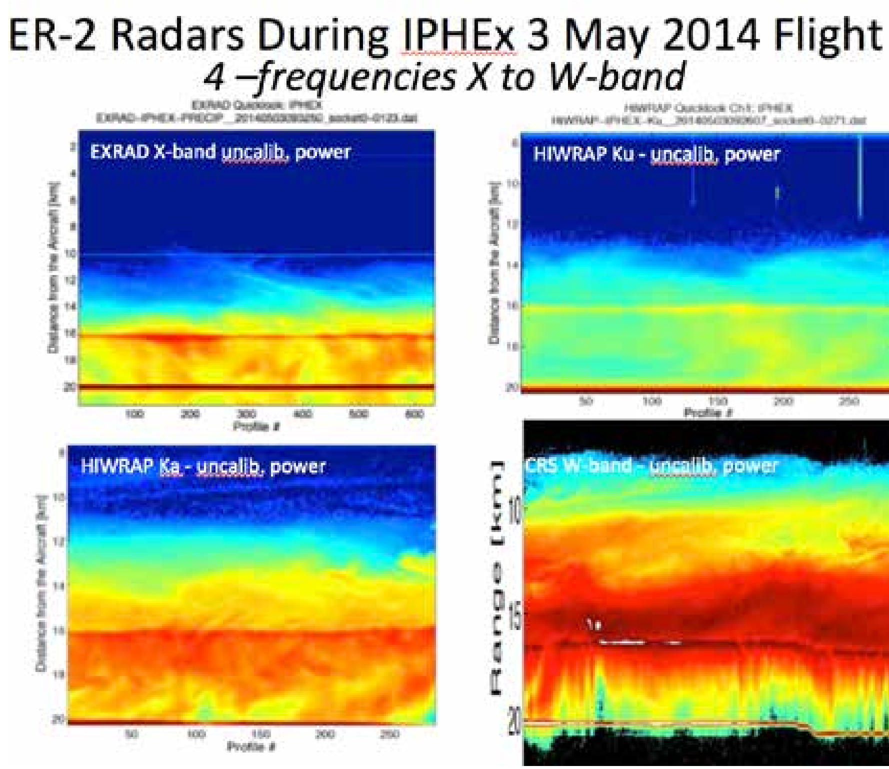
Example

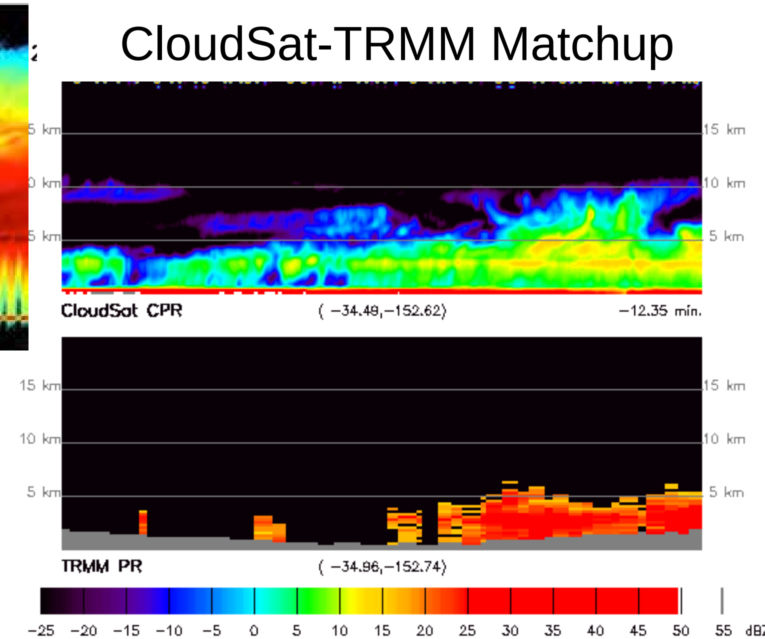

Reflectivity
Altitude (km)
Latitude
dBZ
Cloud Mask
Confidence
Net Heating
K d'
Cloud Mask
Confidence
LW Heating
K d'
IWC
mg m³
SW Heating
K d'
LWC
mg m³

Can *rainfall* be measured with a *cloud* radar?

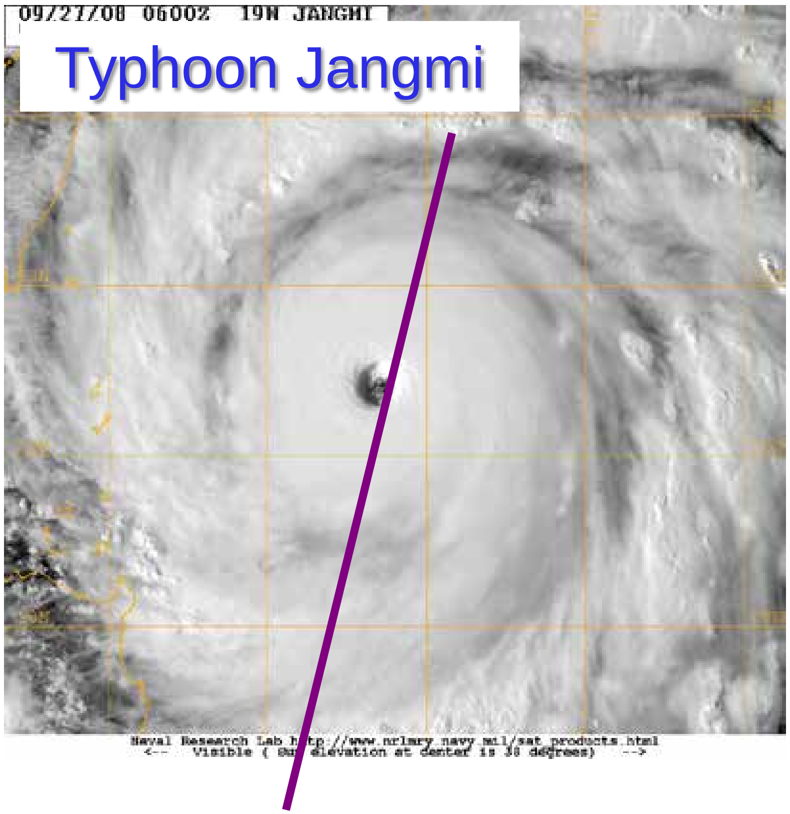
… and if so, how do we estimate its intensity?

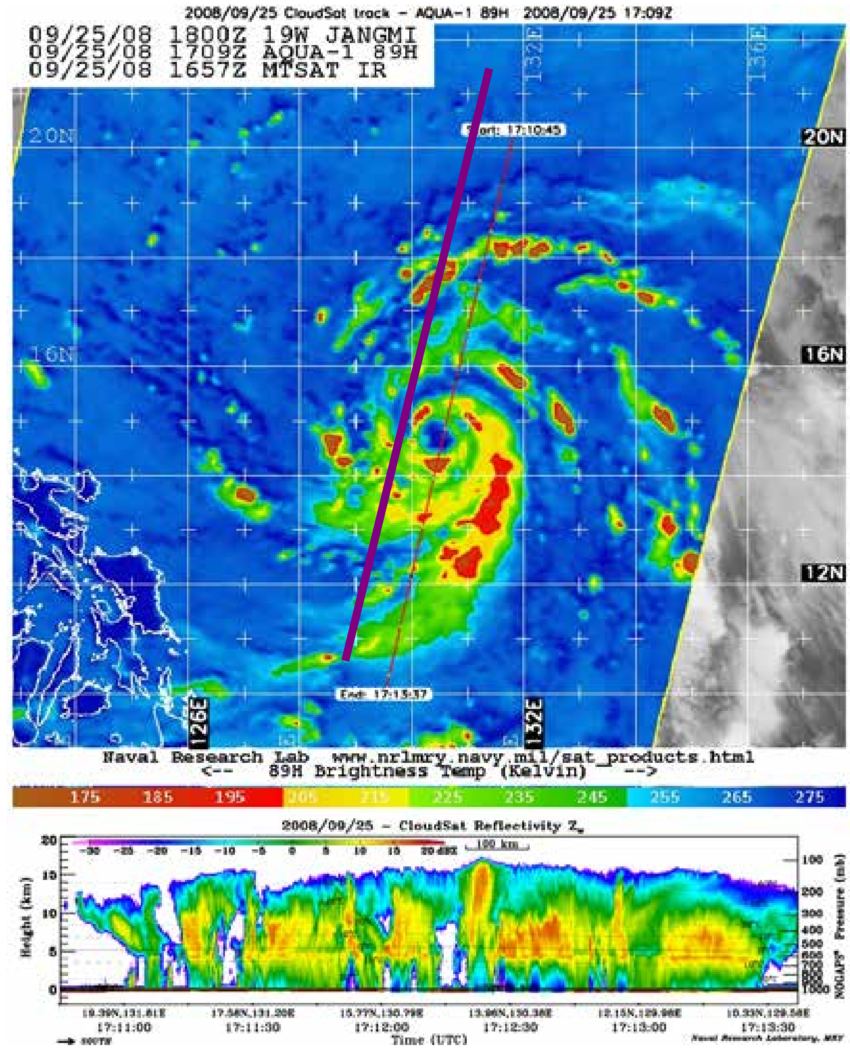
Cloud Radar Sensitivity to Rain





Tropical Cyclone Overpass





Advantages

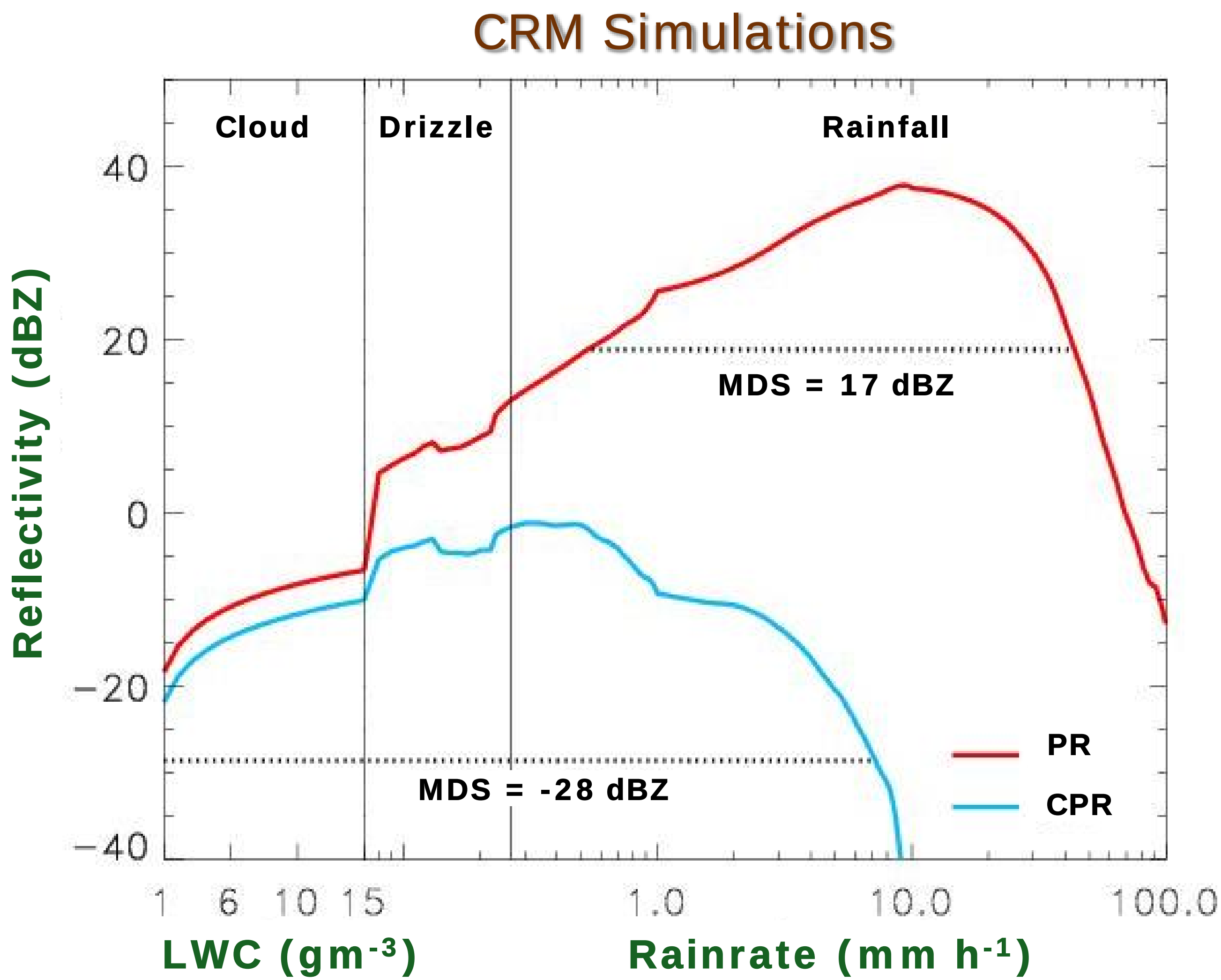
- Advantages relative to ground-based radars:
  - Spatial coverage
  - Access to remote/challenging regions (eg. oceans, jungles, deserts, ice sheets, mountains, etc.)
  - No beam-blockage or significant range effects
  - Uniform global calibration
- Advantages relative to conventional space-borne sensors:
  - Higher spatial resolution
  - Very high sensitivity
  - More direct measurement of microphysical parameters and less sensitive to underlying surface than passive microwave

Disadvantages

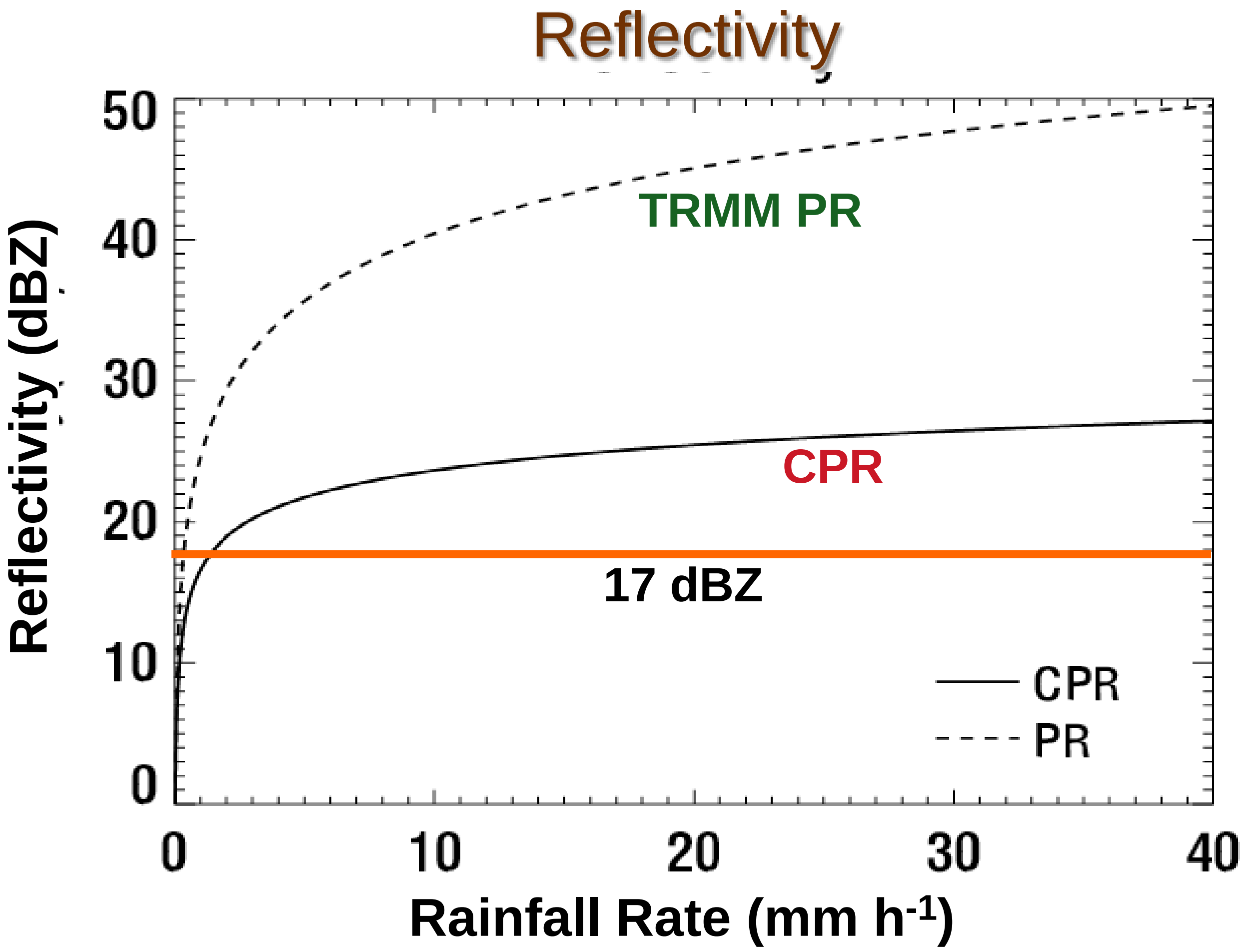
- Single frequency and, unlike ground radars, no Doppler and no polarization is currently available
- Limited sampling
  - Crude temporal sampling due to polar orbit
  - Narrow swath due to rapid movement of satellite and SNR requirements
- Strong attenuation in rainfall

Physical Differences and their Implications for Rainfall Estimation

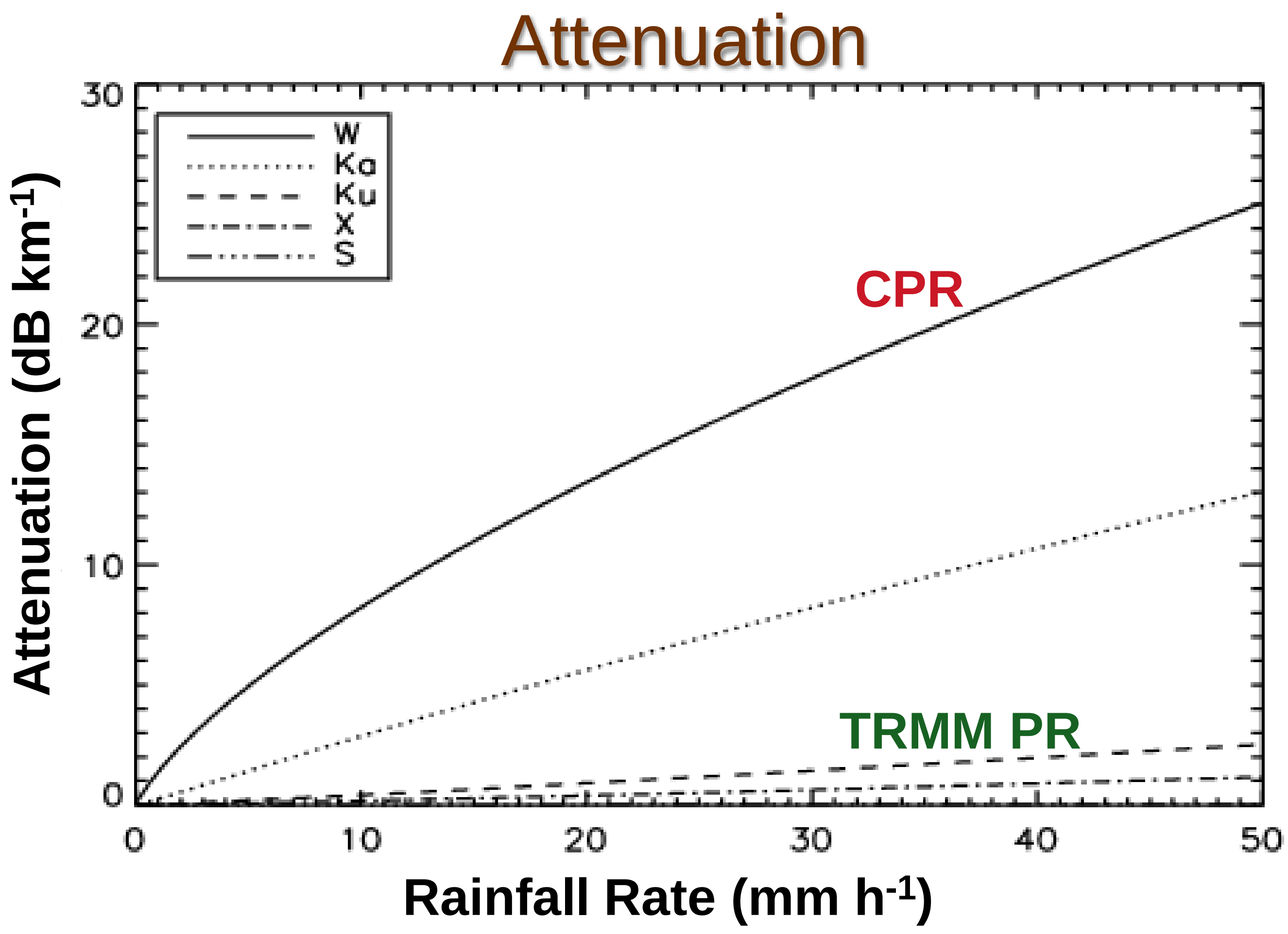
Sensitivity



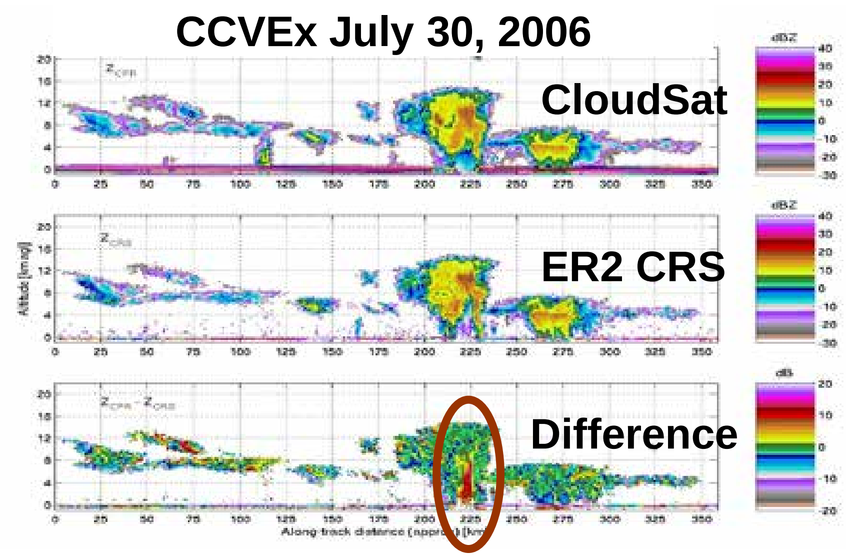
Reflectivity

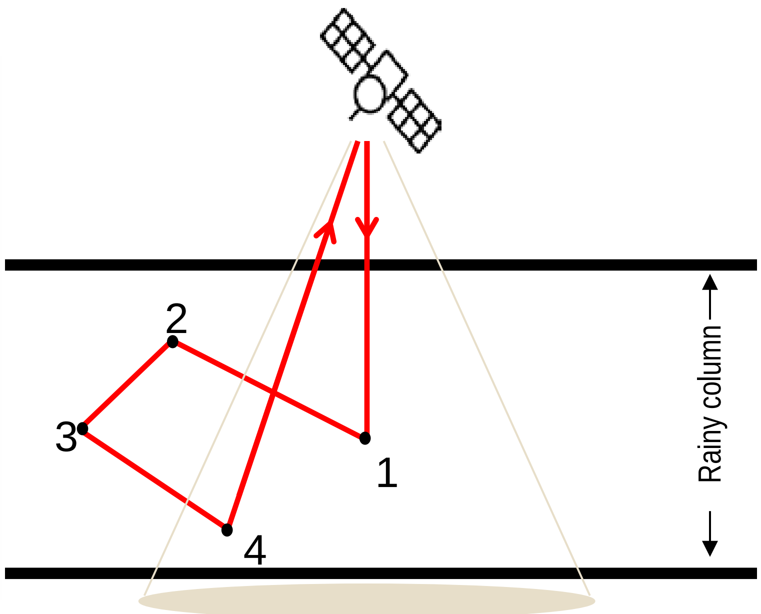


Attenuation



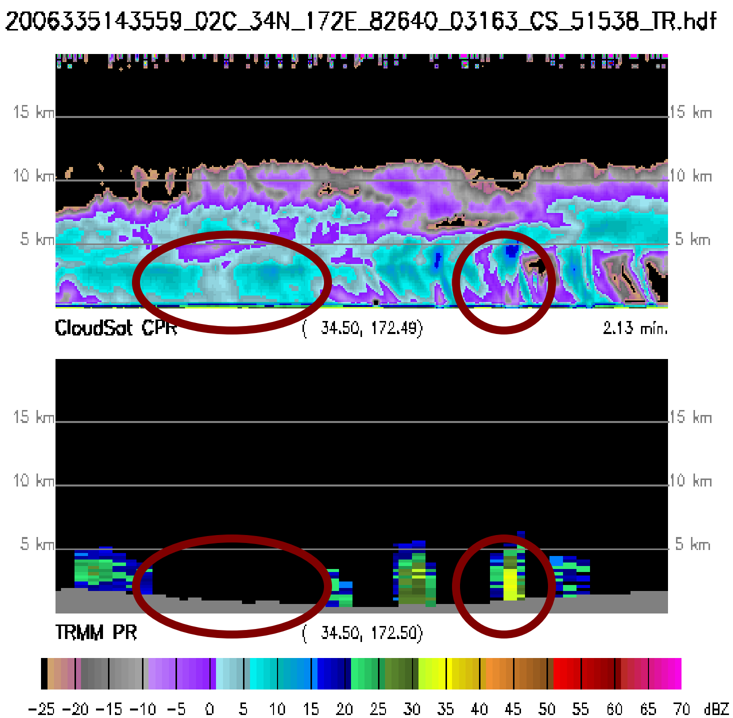
Multiple Scattering

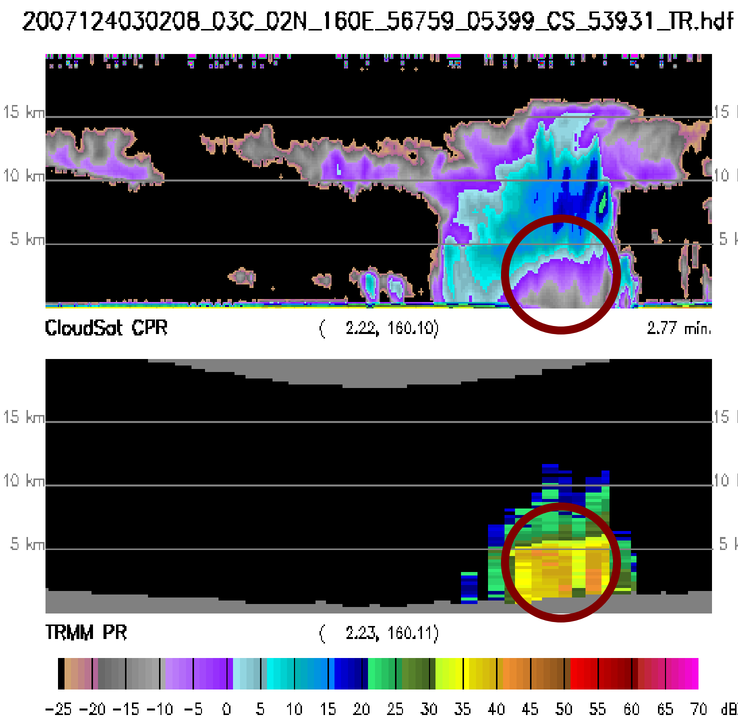




- At W-band, multiple scattering is significant over 3 mm h^{-1}
- High orders of scattering (>3) frequently contribute more than backscatter itself to radar reflectivity

TRMM-PR Comparisons

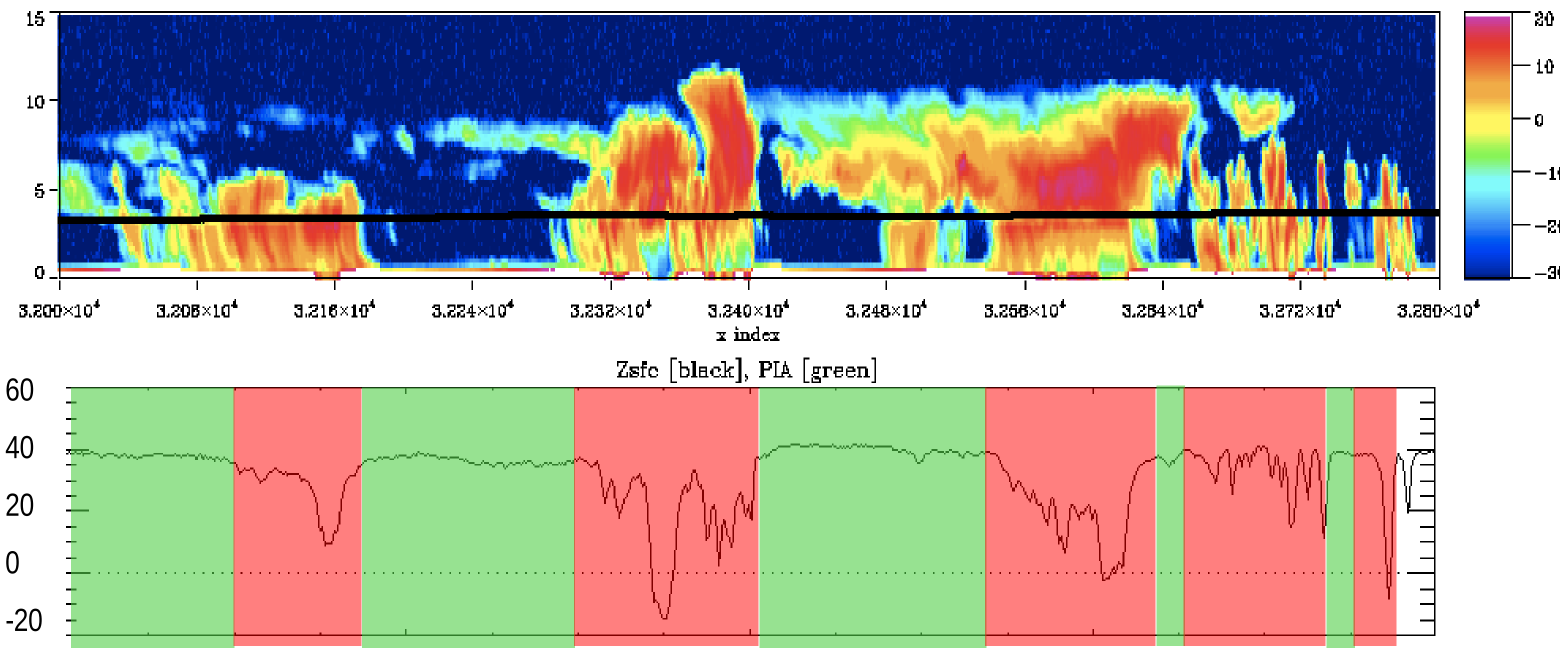




Courtesy: K.-S. Kuo, H. Carty, and E. Smith

Detecting Rainfall with Cloud Radar

The key is attenuation! An expected clear-sky return can be estimates from SST and wind speed. Departures from this value provide a **very sensitive** indicator of rainfall.

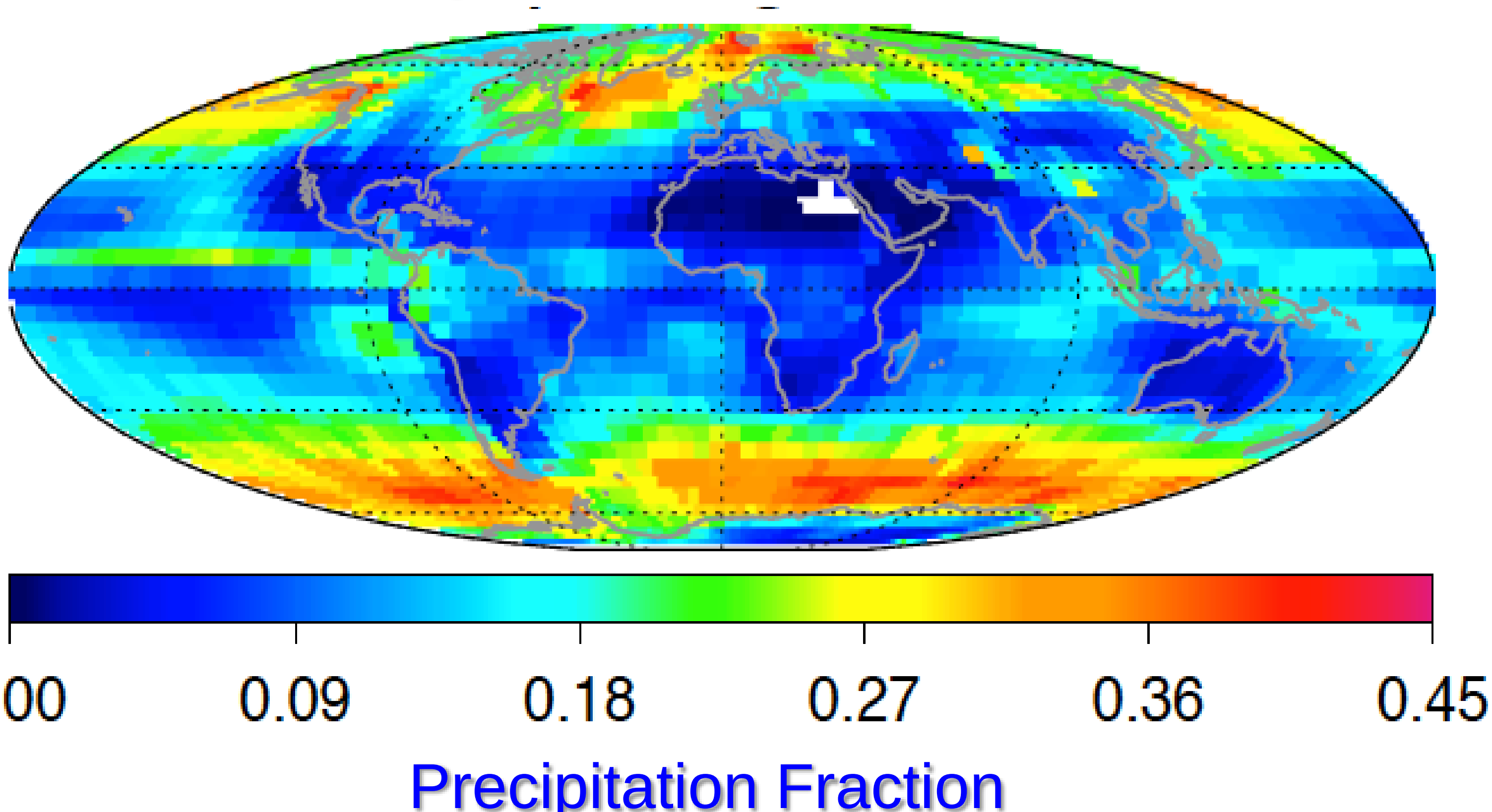


Signal significantly attenuated è precipitation

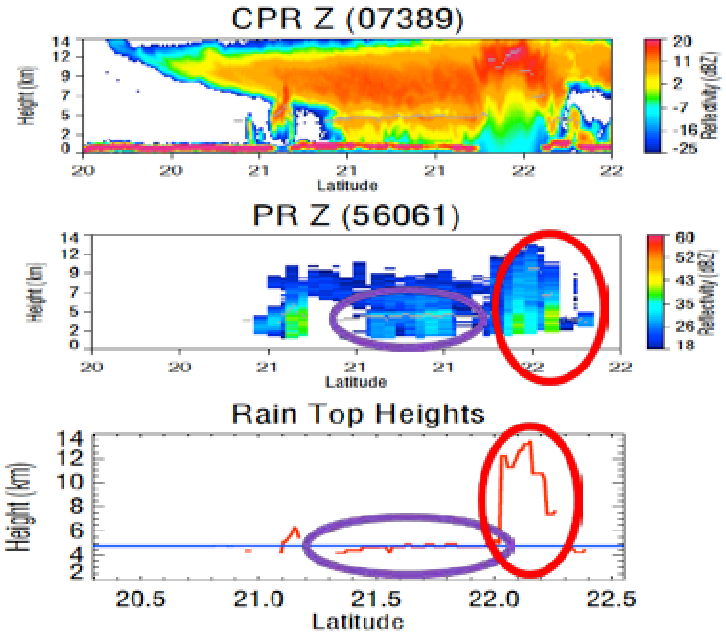
Areas where the surface reflectivity is near the background value - unlikely to contain rain

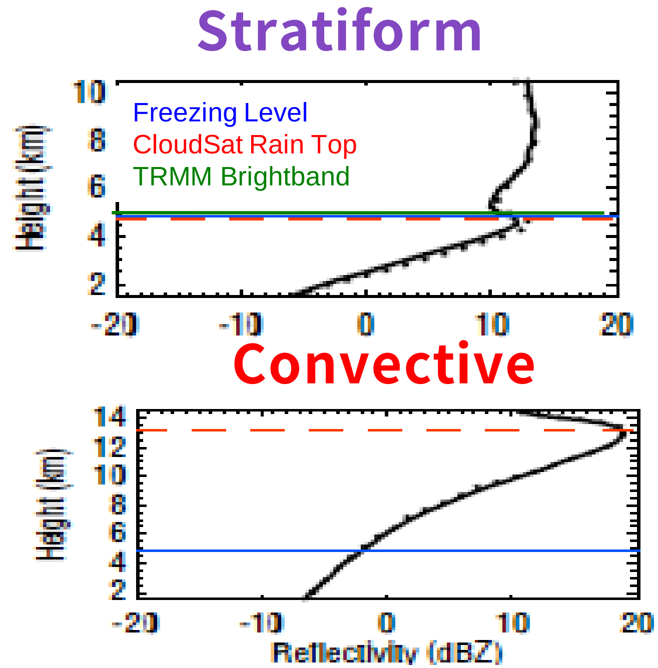
Annual-Mean Distribution

August 2006-April 2011



Identifying Convection





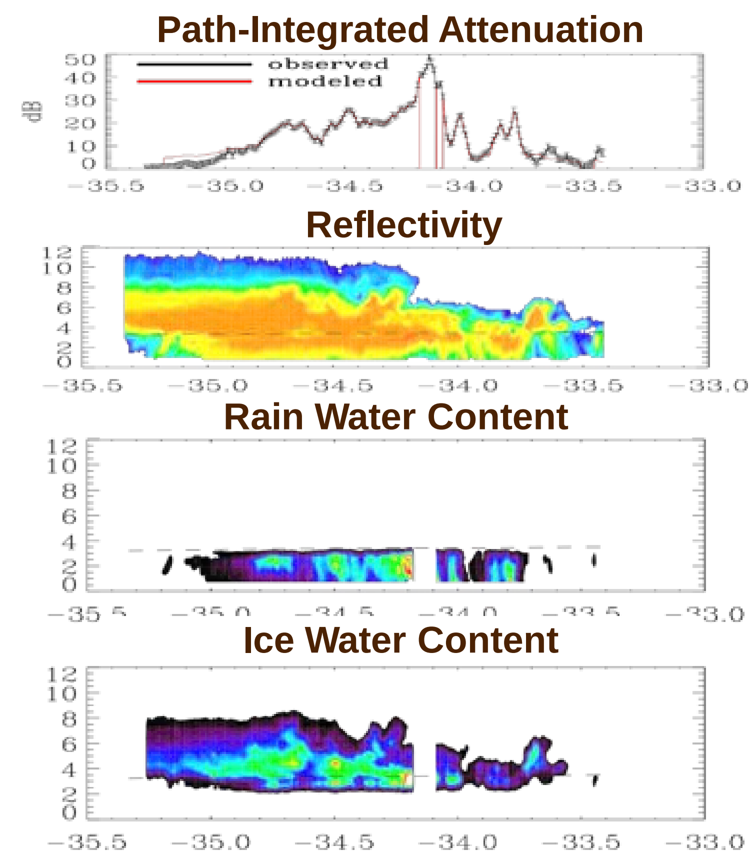
- Since convection lofts liquid water to higher altitudes than surrounding areas, the height at which reflectivity structures show marked attenuation can be used to distinguish convective and stratiform rainfall.
- In convection, the rain top height is typically above the freezing level.
- In stratiform regions the rain top is located at or just below the freezing level.

Rainfall Intensity Retrieval

HIGHLIGHTS

- Variational Retrieval (Error Predicted)
- Z-profile + Attenuation Constraint
- Evaporation Model
- Attenuation Model
- Multiple-scattering Correction
- Drizzle Size Distribution

EXAMPLE



Lebsock and L'Ecuyer, *J. Geophys. Res.*, 2011

Algorithm Strengths and Weaknesses

- Strengths:
  - Probabilistic retrieval framework explicitly accounts for uncertainties in unknown parameters and provides Q.C. and error diagnostics
  - Cloud radar offers higher spatial resolution than other sensors that directly measure precipitation
  - Sensitivity to continuum of clouds, drizzle, rainfall, and snowfall facilitates studying transition regions

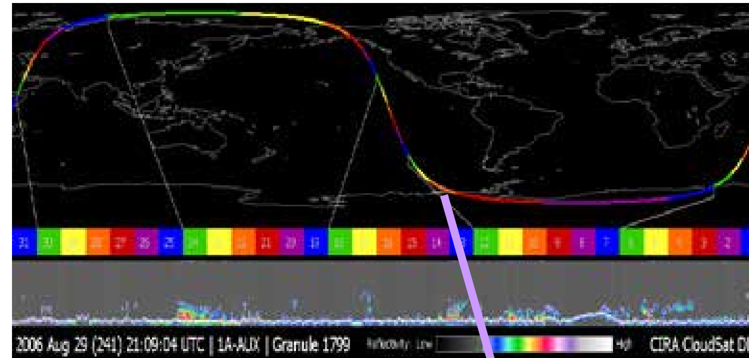
- Weaknesses:
  - Strong attenuation at 94 GHz can lead to retrieval instability
  - Single-frequency method limits information regarding the dielectric properties of the melting layer and restricts drop size distribution assumptions
  - Cloud radars typically do not scan (to improve sensitivity) and so they only provide a 2D slice of the real world

If *rainfall* can be measured, how about falling *snow*?

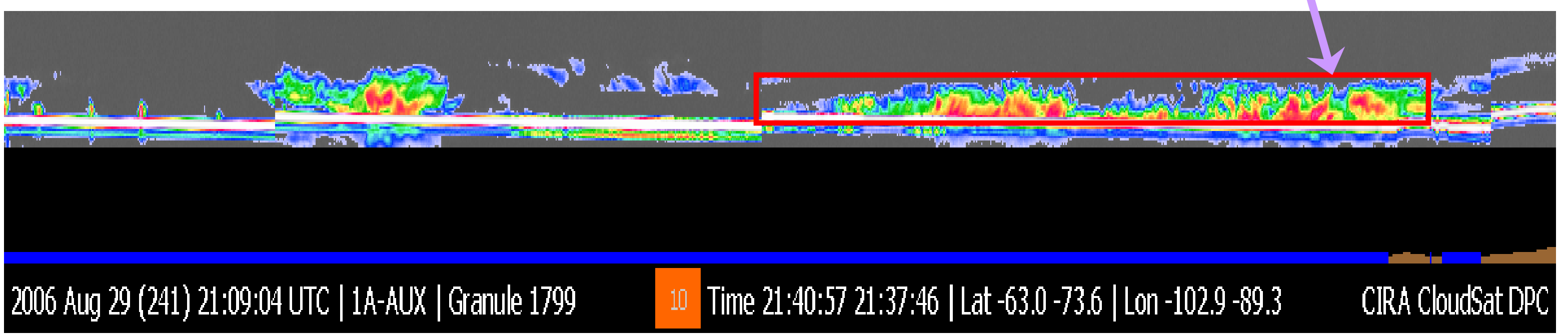
… and how do we address the added complications of snow particle shape?

Observing Falling Snow with CloudSat

Strengths of CloudSat:



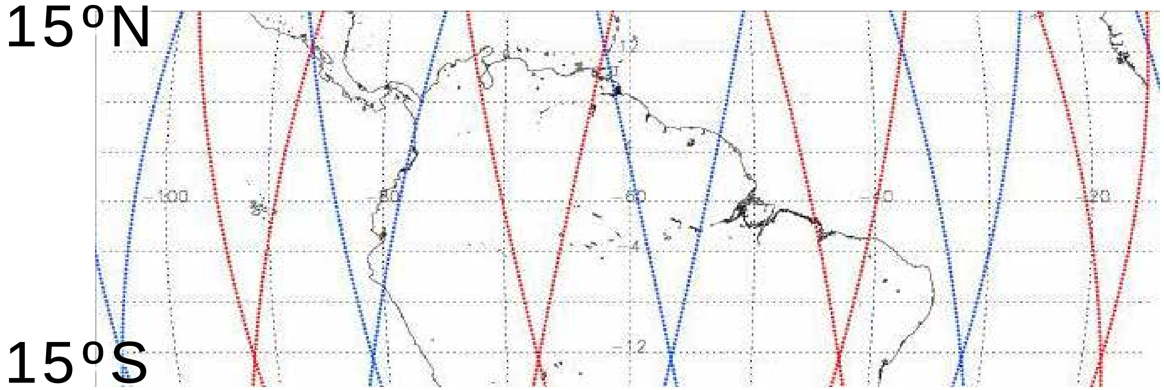
- Active sensor
- Excellent sensitivity
- Near-global coverage
- Coincident measurements from other A-Train sensors

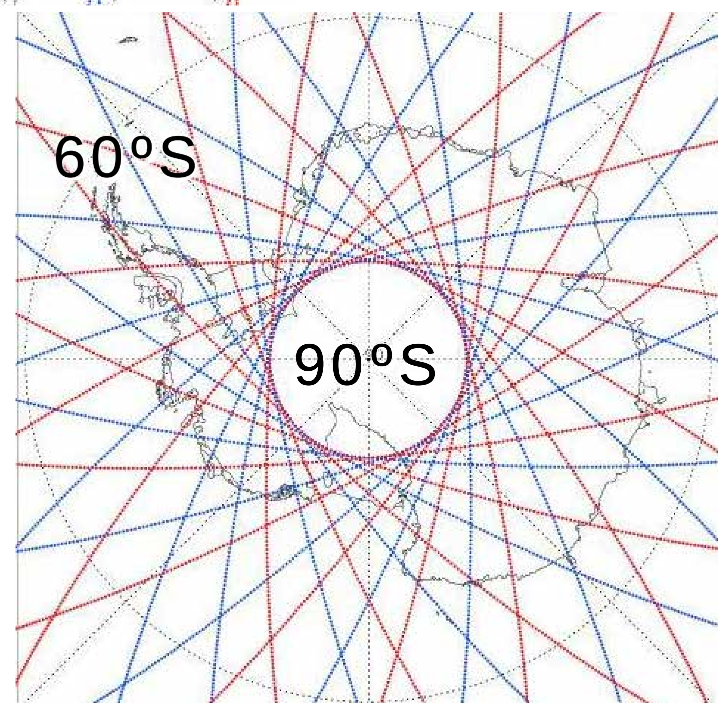


Challenges:

- Complex relationship between reflectivity and snowfall rate/IWC
- Rain/snow discrimination
- Sampling
- Ground Clutter

Sampling Considerations





- The region poleward of 60° is sampled ~4 times more frequently than an equal area region at the equator!
- A 1x2 ° box at 70 ° is sampled 7,000 times per year.

Snowfall Intensity Retrieval

HIGHLIGHTS

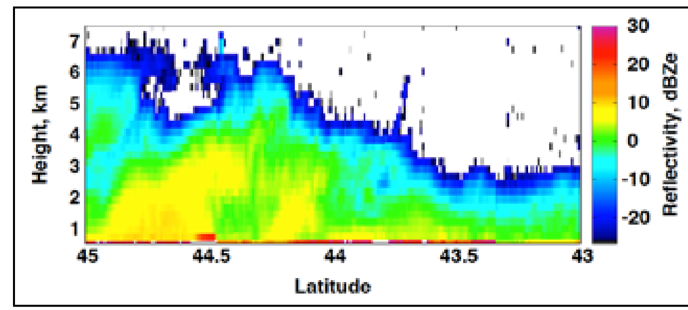
- Variational Approach
  - Allows inclusion of prior information
  - Predicts uncertainties
- Retrieve intercept and slope of exponential particle size distribution

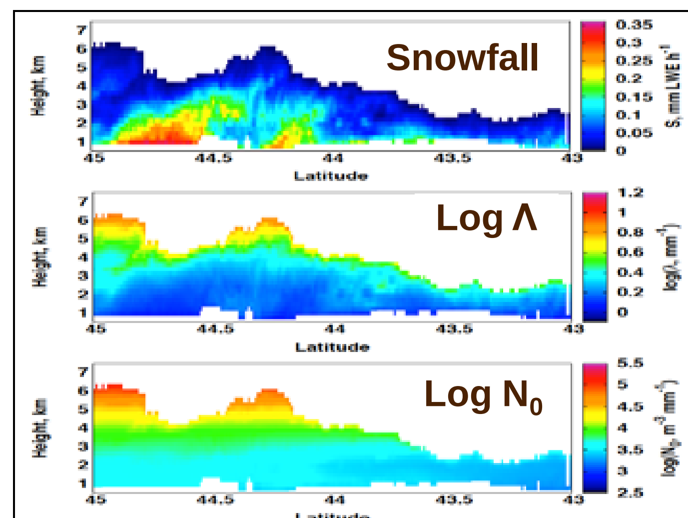
$$N(D) = N_0 e^{-\Lambda D}$$

- Scattering properties, PSD, and density based on field observations

EXAMPLE

Reflectivity

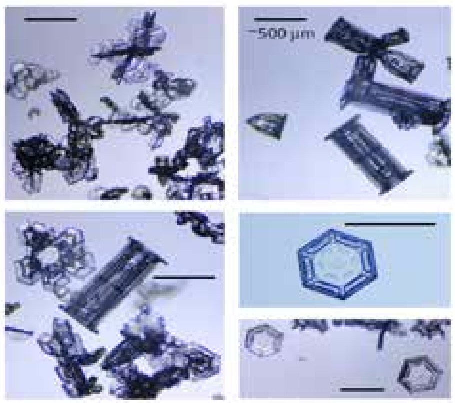




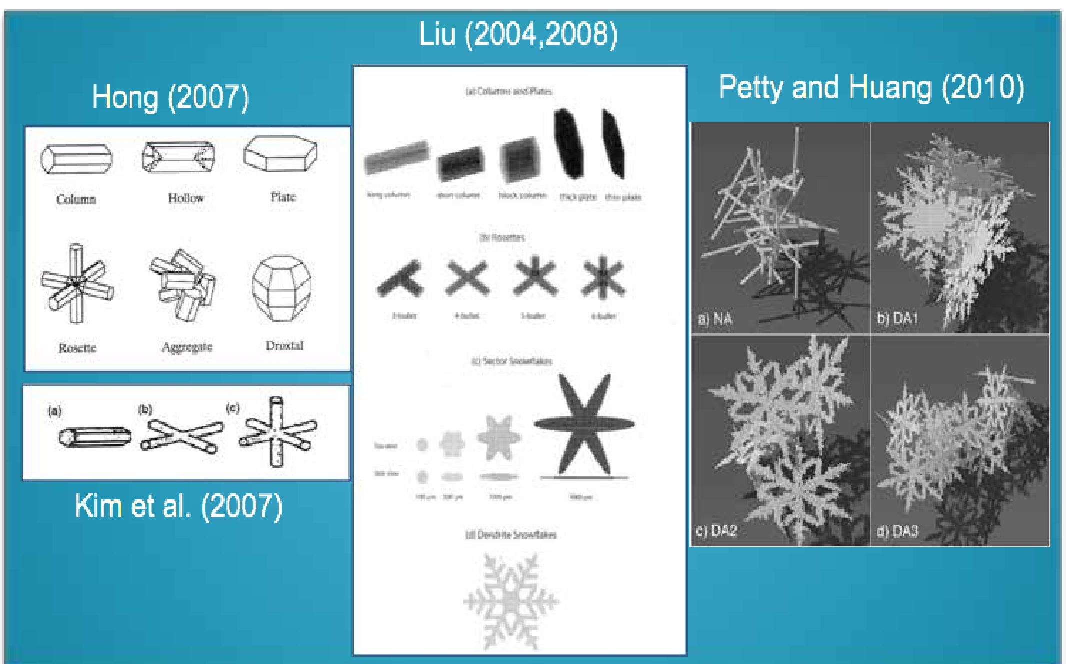
Wood et al., *J. Geophys. Res.*, in review

Complications

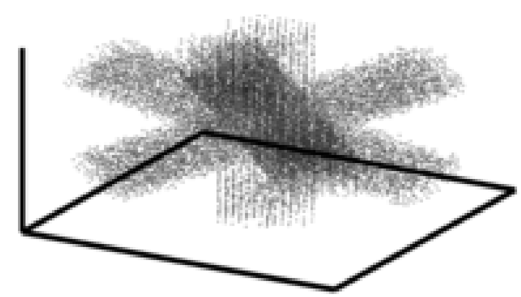
Particle Shape and Size



Photos from Summit Observatory, Greenland Shupe et al. (2012)

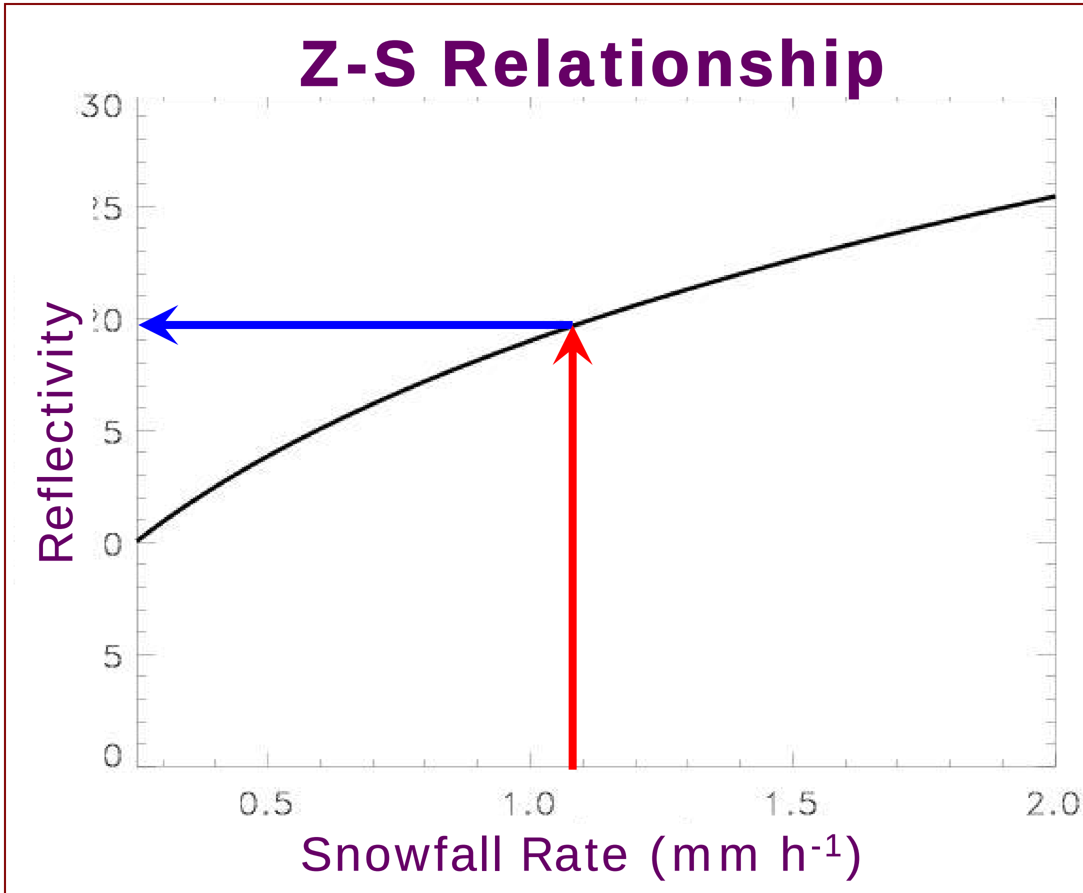


- Non-spherical scattering effects are included in retrieval
- Mass and projected area relationships are constrained using in situ measurements



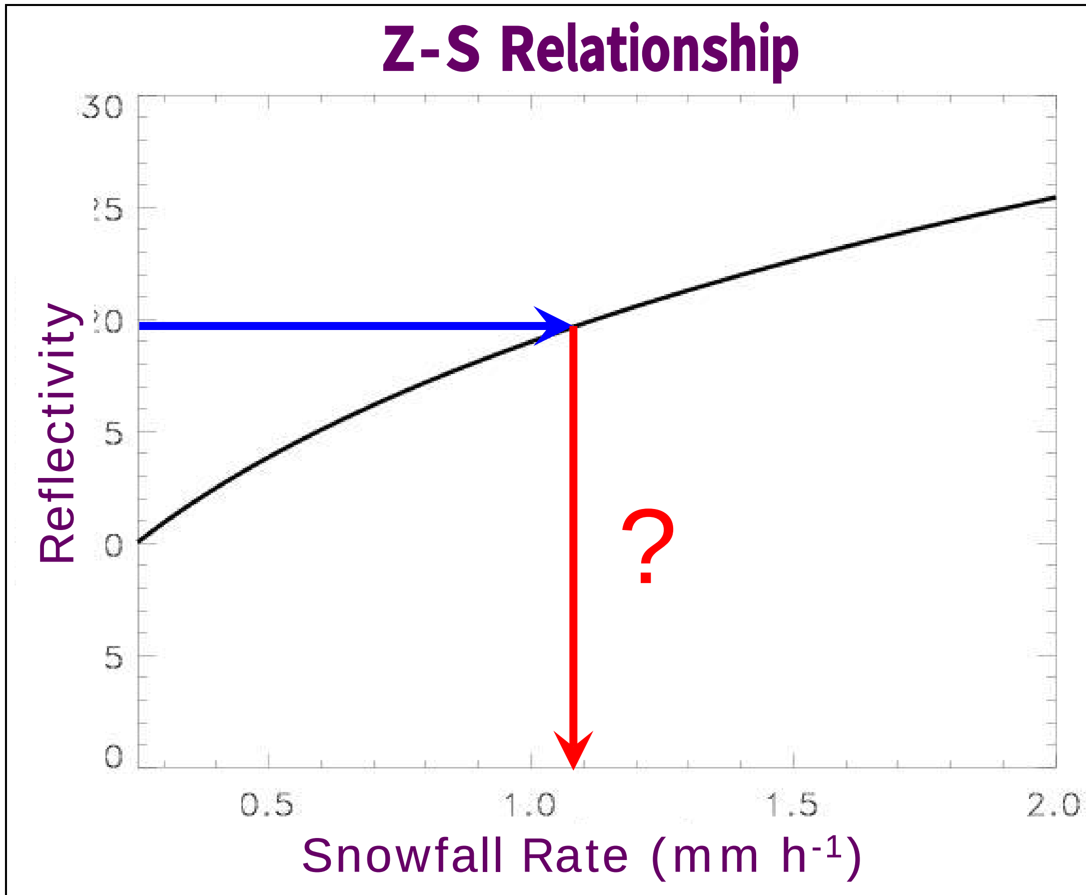
- These assumptions remain the largest source of uncertainty in CloudSat snowfall estimates

Forward Model Relates Z to S



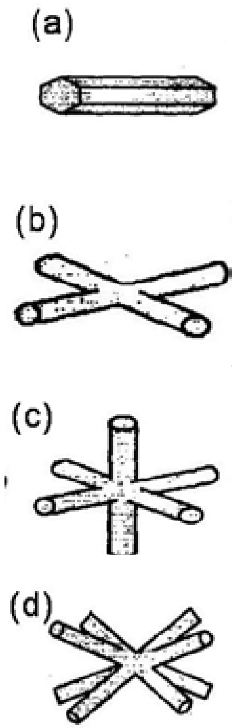
Given knowledge of snow crystal size distribution, shape, and fall speed, calculate Z and S.

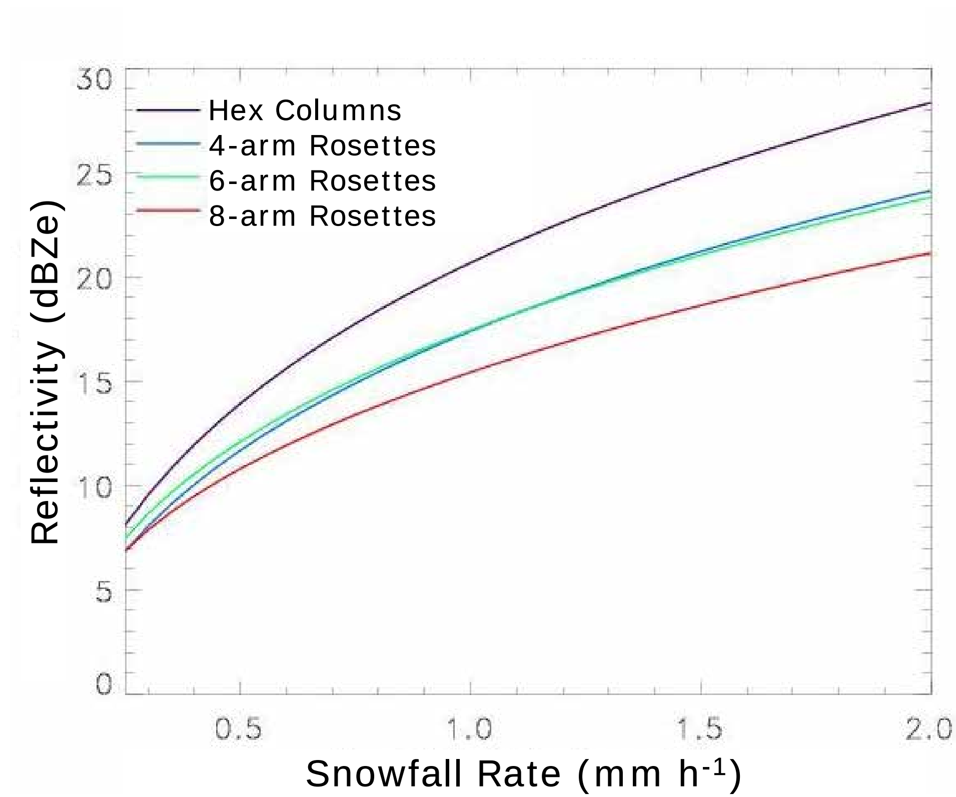
Inverse Problem



Given a reflectivity estimate snowfall rate S.

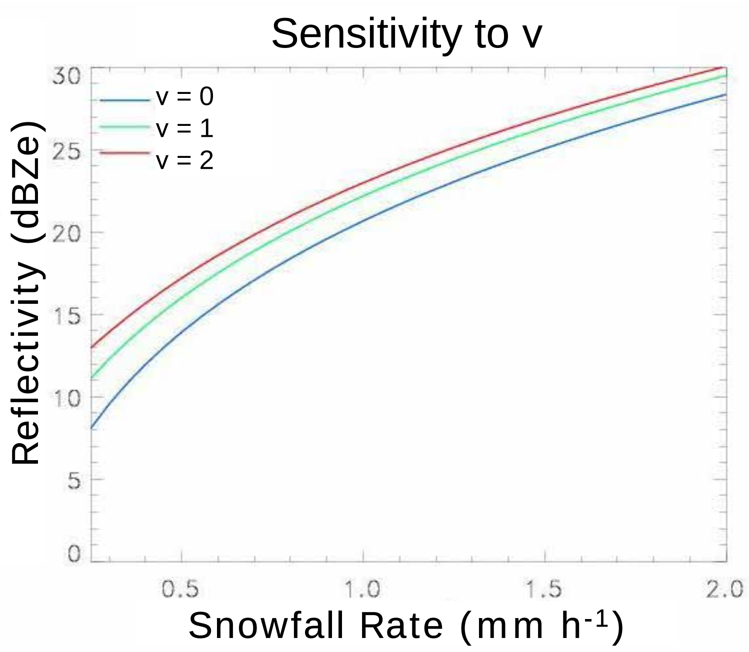
Impacts of Crystal Shape (2-7 dBZ)

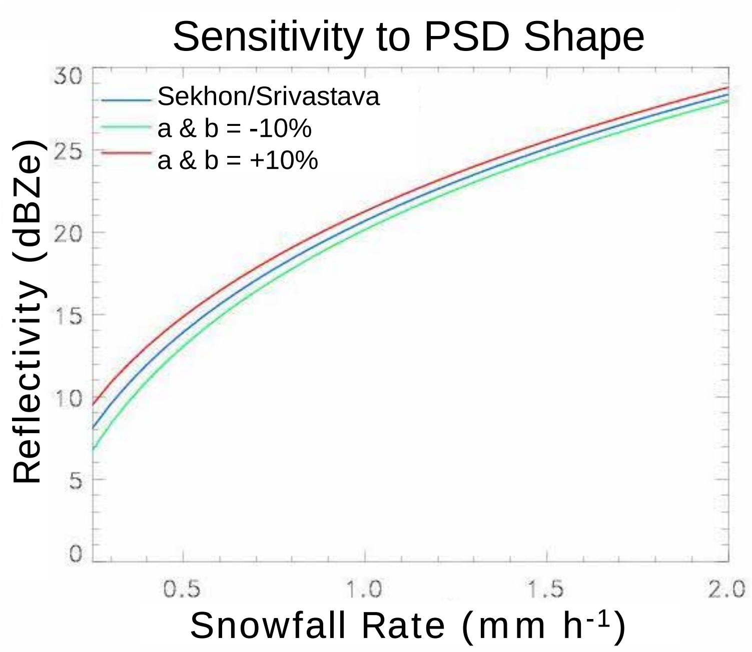




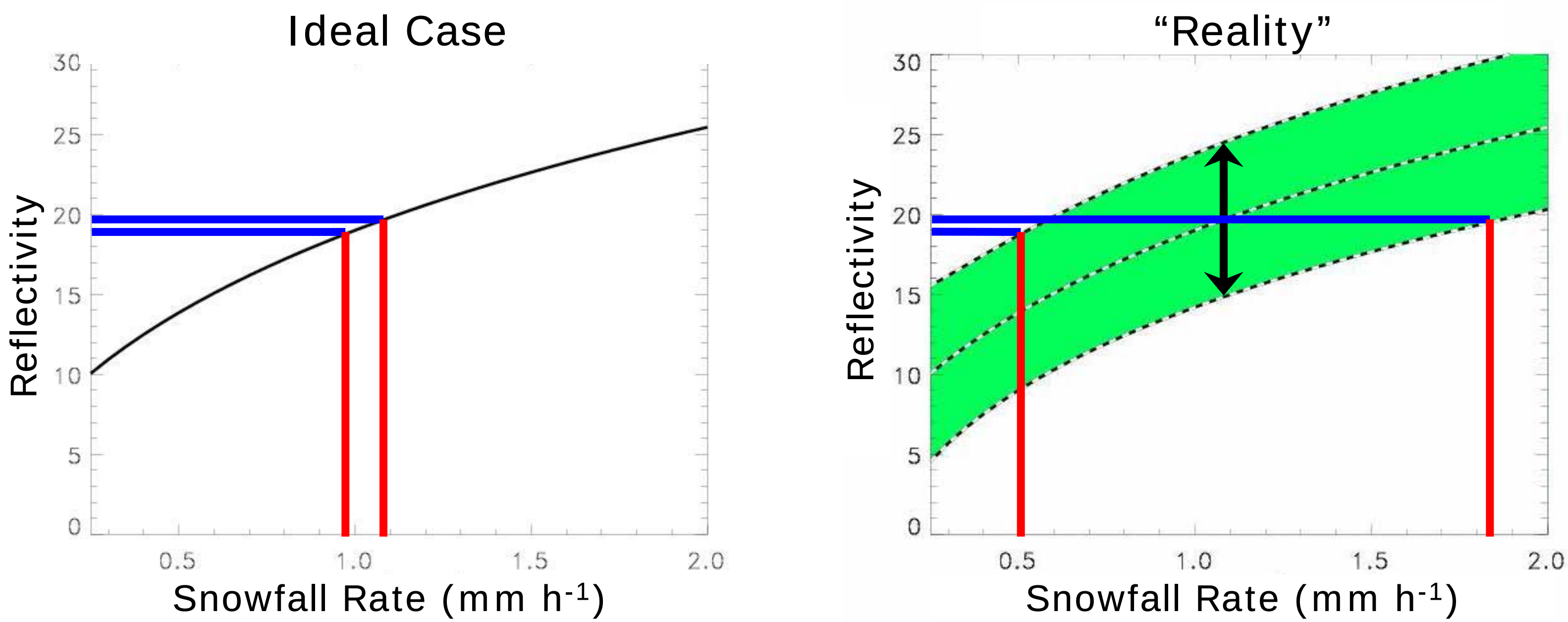
Impacts of Particle Size (3-6 dBZ)

$$N(D) = N_0 D^{\nu} e^{-\Lambda D} \qquad N_0 = aS^b \quad \Lambda = \alpha S^{\beta} \quad \nu = 0$$



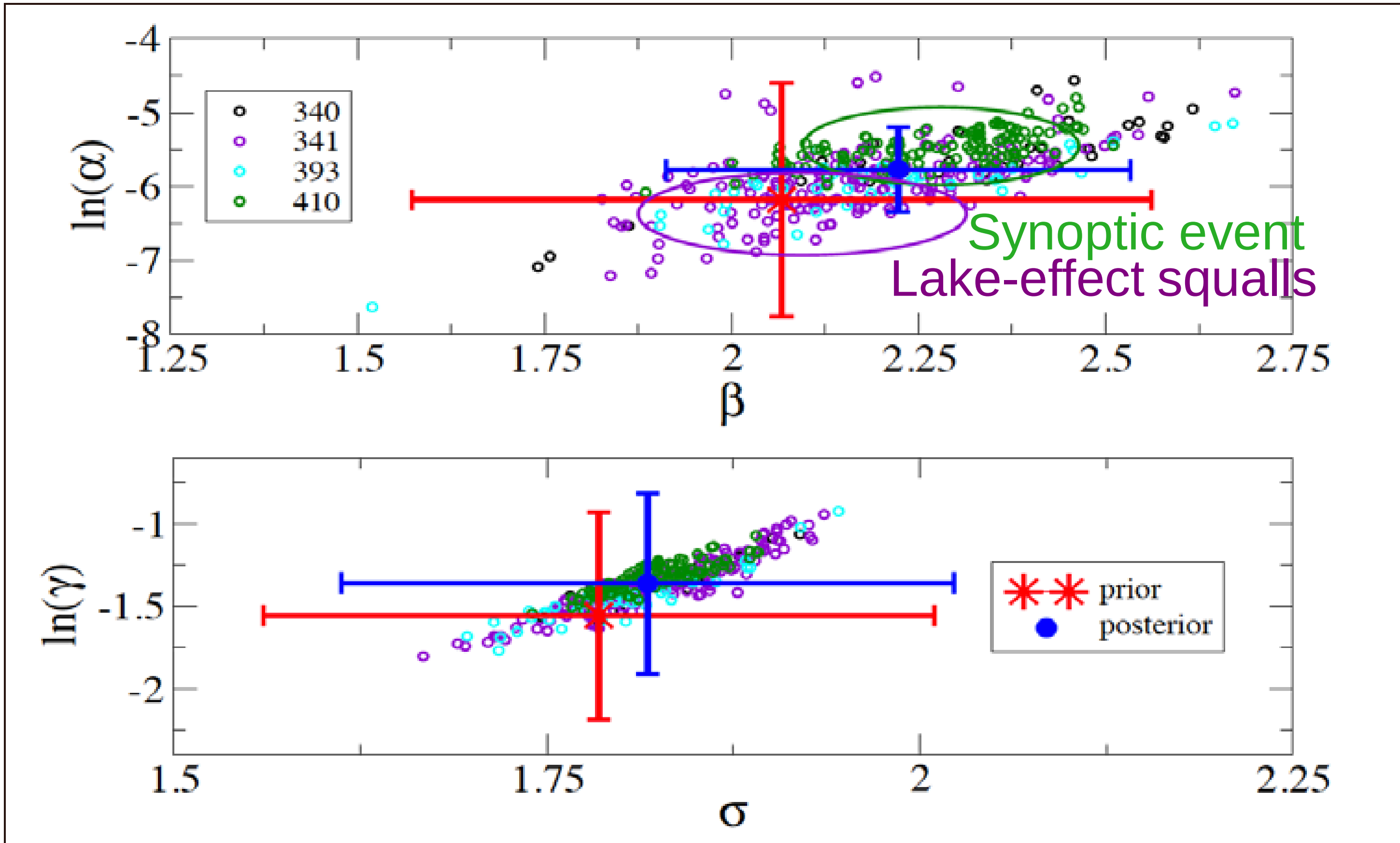


Implications for Retrievals



- In an ideal world with a perfect forward model, a 1 dB measurement error lead snowfall errors of less than 10 %
- In reality, however, uncertainties in the influence parameters (PSD and snow crystal shape) spread the range of allowable solutions causing uncertainty in the retrieval.

One Solution: Field Observations



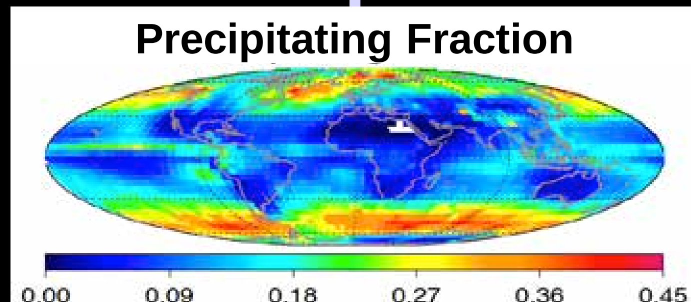
Values of mass and projected area-dimension parameters (α, β, γ, σ) derived from field obs. are used to constrain scattering models.

$m(D) = \alpha D^{\beta}$

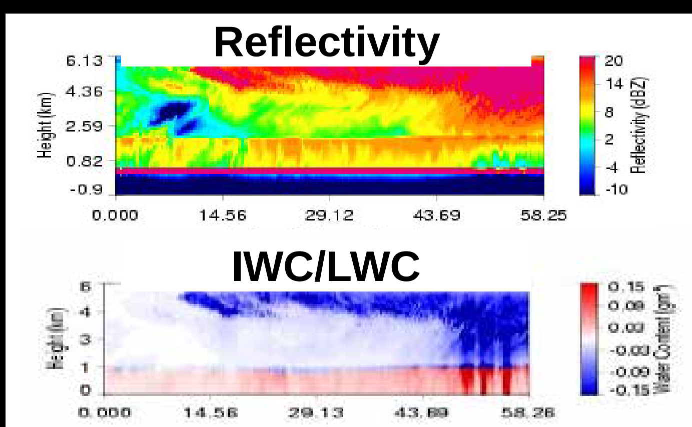
$A_p(D) = \gamma D^{\sigma}$

CloudSat's Precipitation Datasets

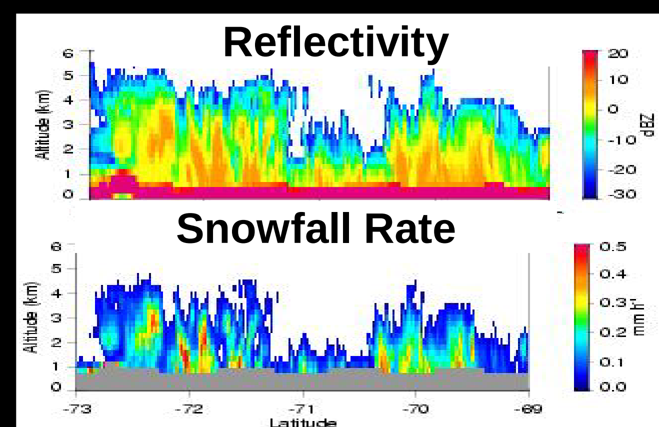
2C-PRECIP-COLUMN



2C-RAIN-PROFILE



2C-SNOW-PROFILE



Summary

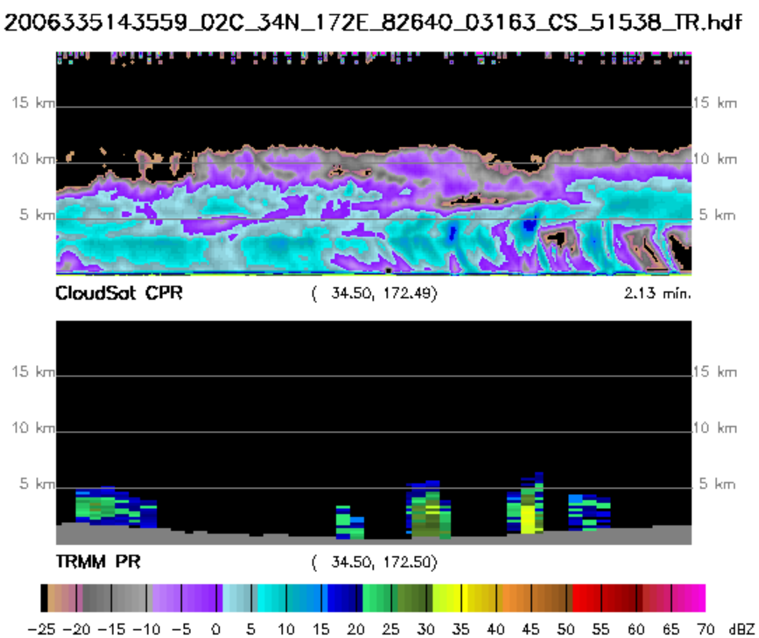
- Despite their challenges, space-borne cloud radars offer a valuable source of vertically-resolved measurements of light rainfall and snowfall.
- The combination of reflectivity and attenuation allows almost all precipitating hydrometeors to be detected.
- Attenuation is the central measurement behind rainfall intensity retrievals from space-borne cloud radars.
- Cloud radars provide the best sensitivity to falling snow among current sensors but particle size and shape can lead to large uncertainties.
- Similar characteristics will apply to the next generation W-band radars: EarthCARE and ACE but these radars will add a new dimension: the ability to directly measure vertical motion.

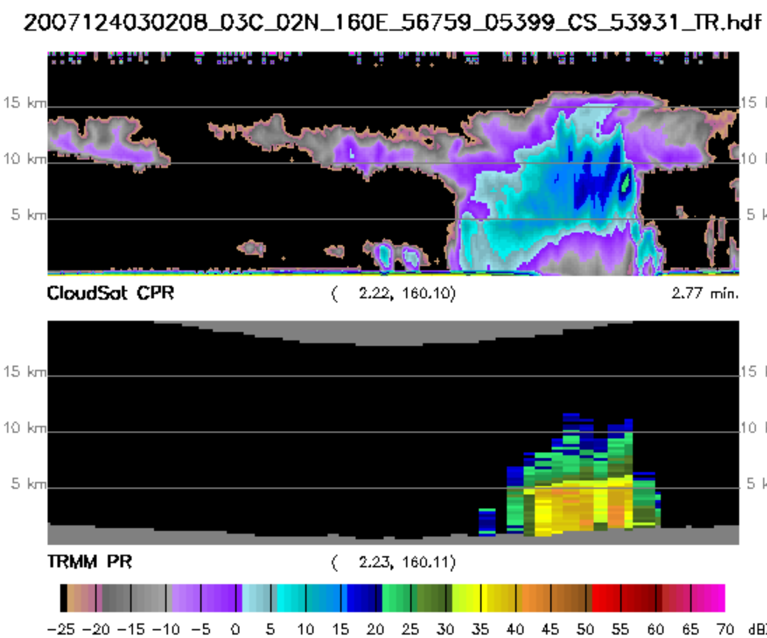
Extras

EarthCARE

- The combined ESA/JAXA EarthCARE mission will carry the next generation CPR with a higher vertical resolution (100 m), better sensitivity (-35 dBZ), and crude Doppler capability (~1 m s^{-1} resolution).
- EarthCARE resembles the A-Train on one satellite.

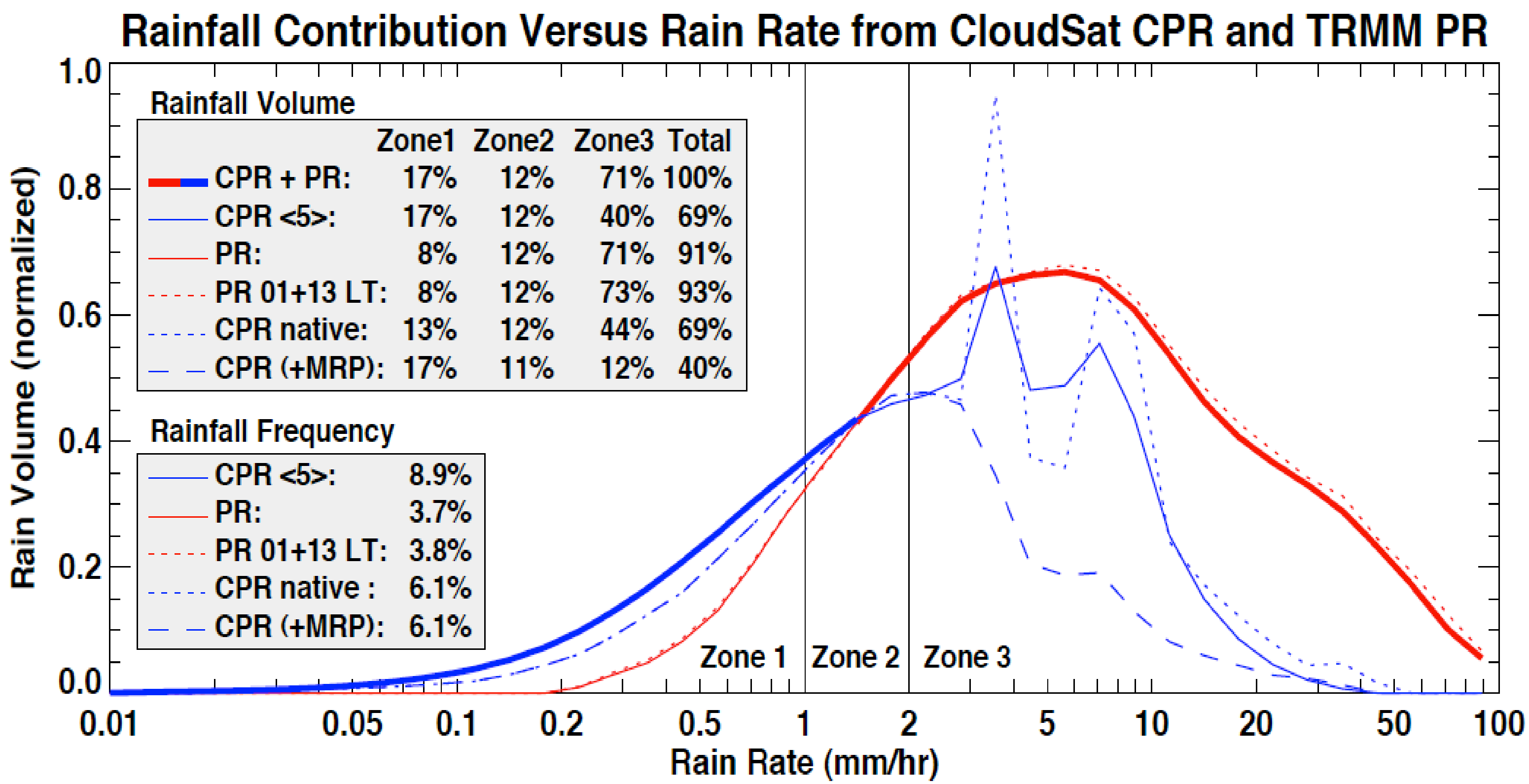
TRMM/CloudSat Synergy





Courtesy: K.-S. Kuo, H. Carty, and E. Smith

Toward a Global Rainfall PDF



- R < 1 mm h^{-1}: CPR accumulation is 0.47 mm/d, PR's is 0.19
- R > 5 mm h^{-1}: CPR accumulation is 1.35 mm/d, PR's is 1.86

Global Cloud Vertical Distributions