Advancing
cloud and precipitation observations from space
A radar perspective

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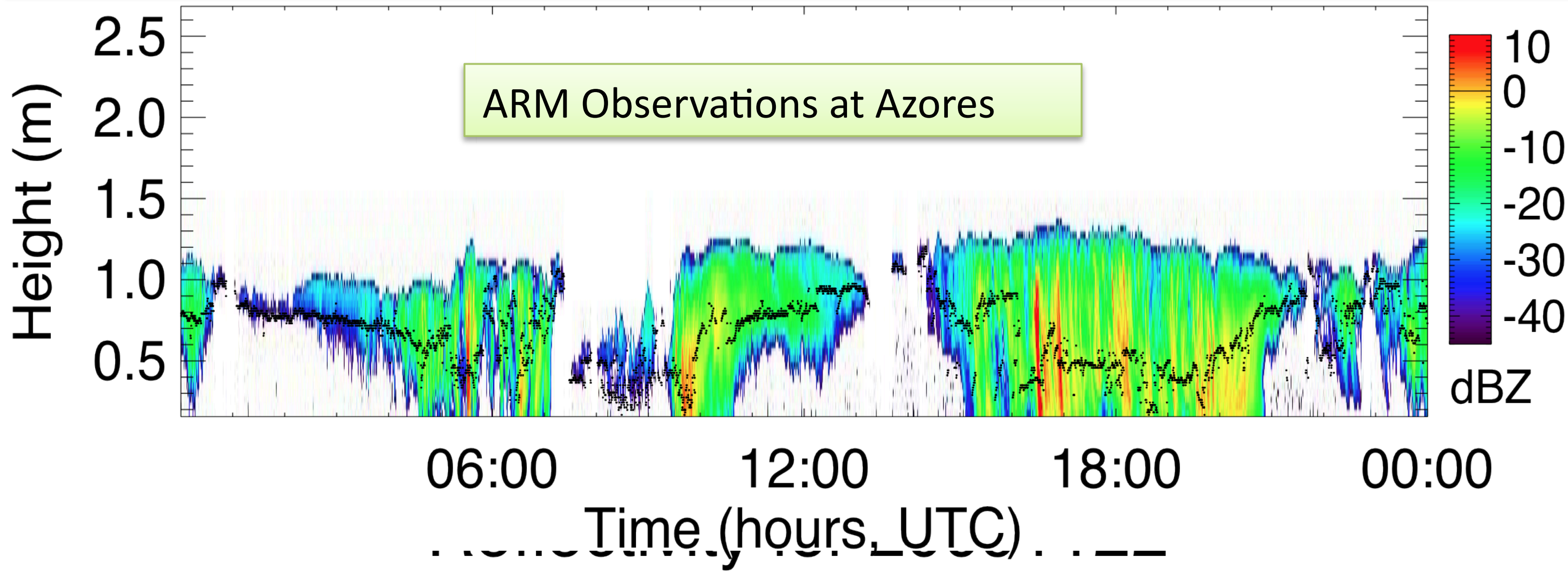
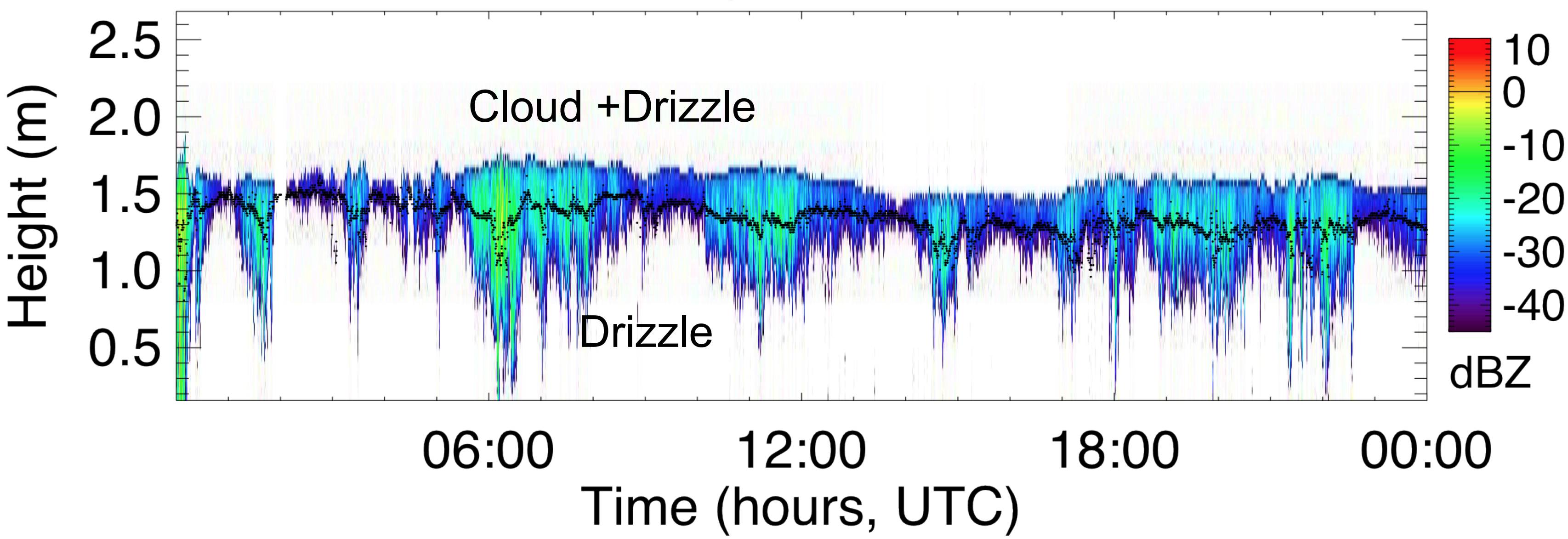
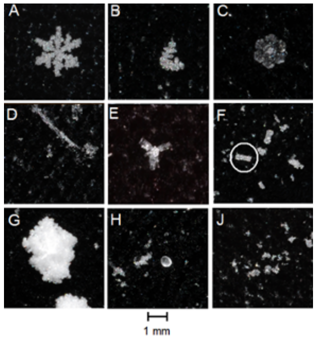
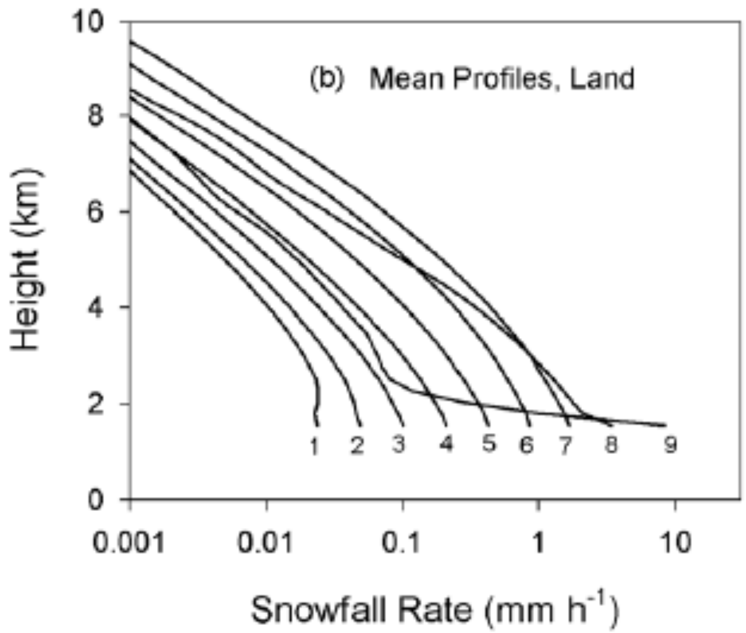
Primary target: Marine Boundary Layer Clouds



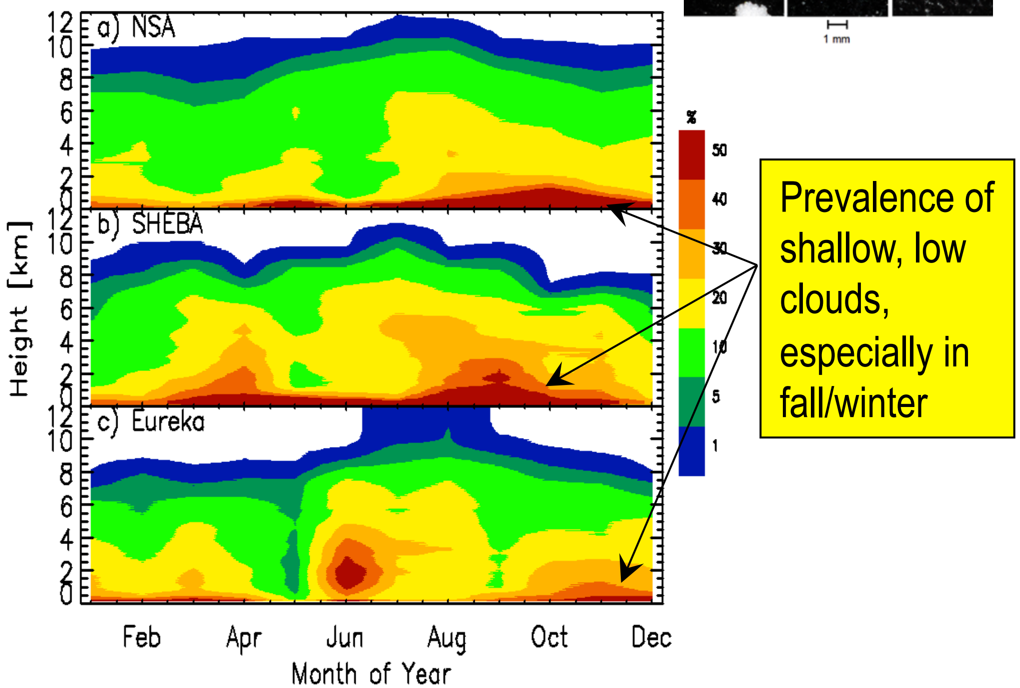


At higher latitudes, we have additional challenges related to cloud phase and shallow nature





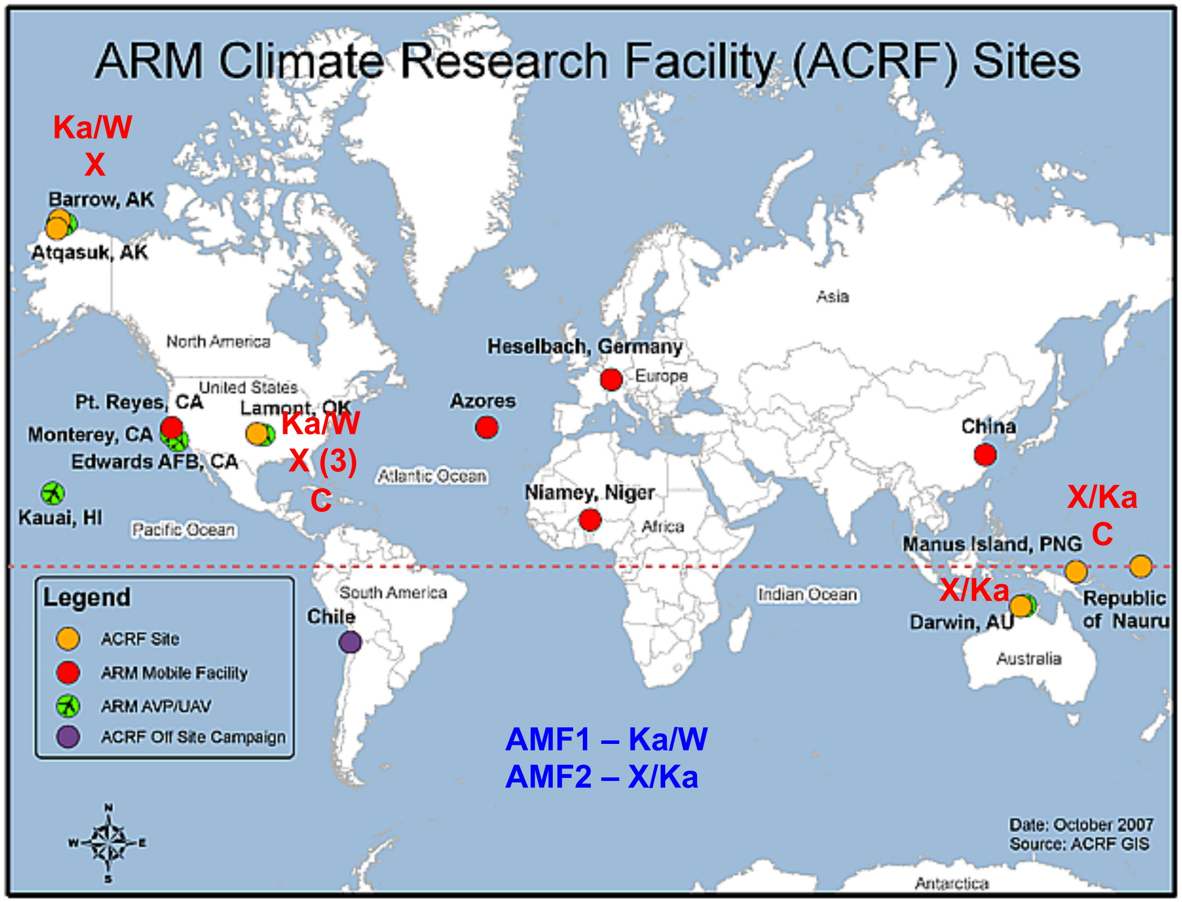
Deeper snow layers for heavier surface snowfall; BUT only the shallow snow events produce the heaviest surface snowfall



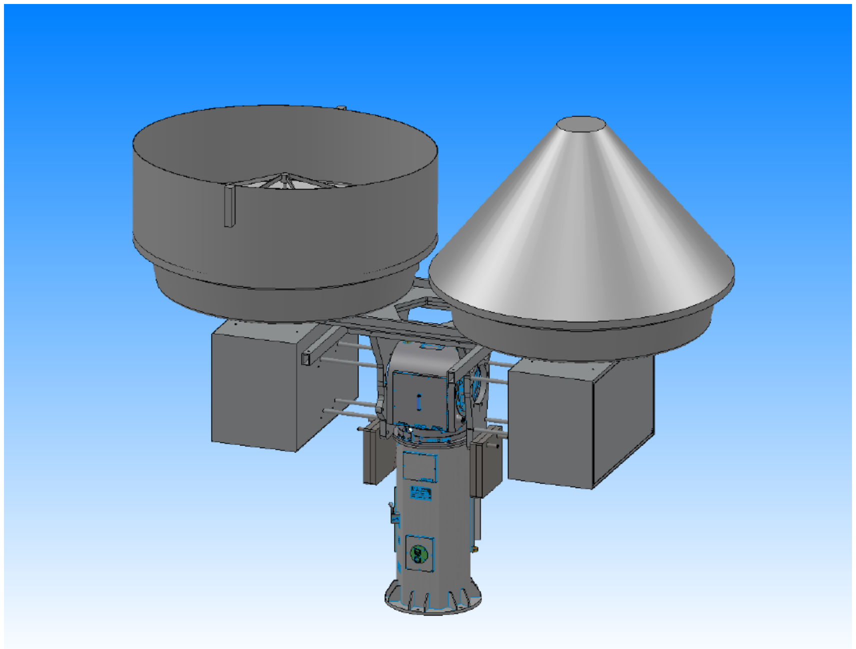
Contour frequency distribution of cloud from the North Slope of Alaska ARM site

Critical to have fine vertical resolution
(500 m CloudSat or EarthCARE unsatisfactory)

- ACRF received $60M under the 2009 American Recovery and Reinvestment Act.
- Approximately $30M will go to enhancing ACRF radar capabilities.
- Radars are slated to come on line in late 2010
- Will also upgrade 35 GHz MMCRs

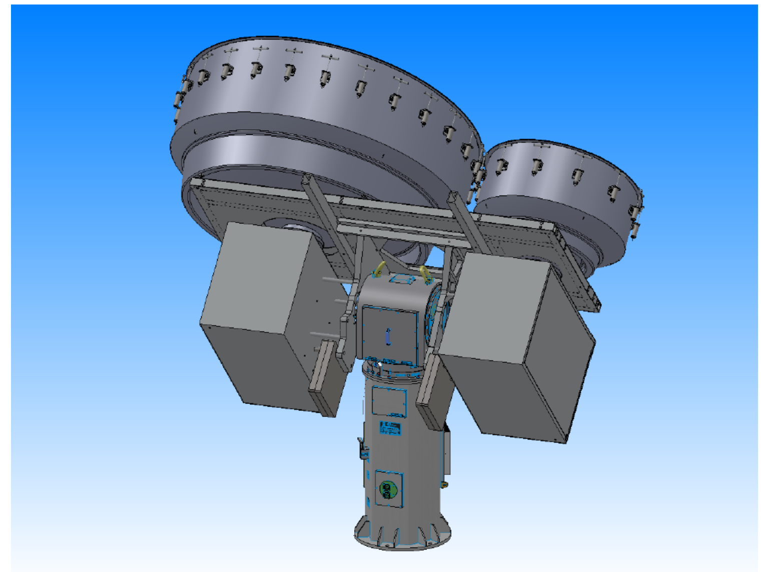


What are we doing from the ground up?
DOE/ARM: Ground-based sites



SACR (Ka/X; Darwin, Manus, AMF)

Traveling Wave Tube Amplifier
20.0 kW,
X-band Dual-polarization
1.84 m reflector, 1.40° 3-dB



SACR (Ka/W; SGP, NSA, AMF)

Extended Interaction Klystron Amplifier (EIKA)
1.7 kW, Transmit linear horizontal;
Dual-pol receiver – radiometer mode
1.82 m reflector (Ka-band, 0.33°)
0.91 m reflector (W-band, 0.29°)

Scanning Cloud ARM Radars

Three 35/94-GHz and three 35/9.4-GHz multi-parametric radars

Reflectivity (dBZ, DWR)

35-GHz: primary cloud sensing frequency (Location)

94-GHz: LWC, WV retrievals in clouds, velocity, size retrievals in rain

9.4-GHz: LWC in drizzle, 20-50 km mapping of drizzle/light rain

Doppler (Velocity, width)

Cloud/Drizzle turbulence and shear information

Horizontal Wind Profile (VAD)

Polarimetry (LDR/SLDR for 35/94-GHz, ZDR/Φ_{DP}/ρ_{HV})

Non-spherical particles ID

Radar data quality control (e.g., insects, attenuation-correction)

CloudSat

"Millimeter-wavelength radars bridge an observational gap in Earth's hydrological cycle by adequately detecting clouds and precipitation thus offering a unique and more holistic view of the water cycle in action"
Kollias et al., 2007 (BAMS)

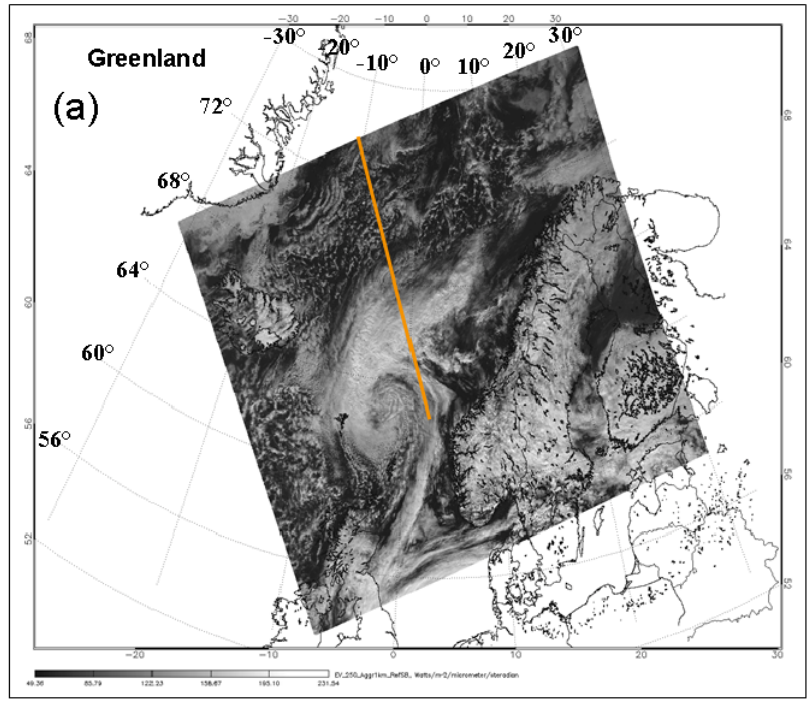
CloudSat

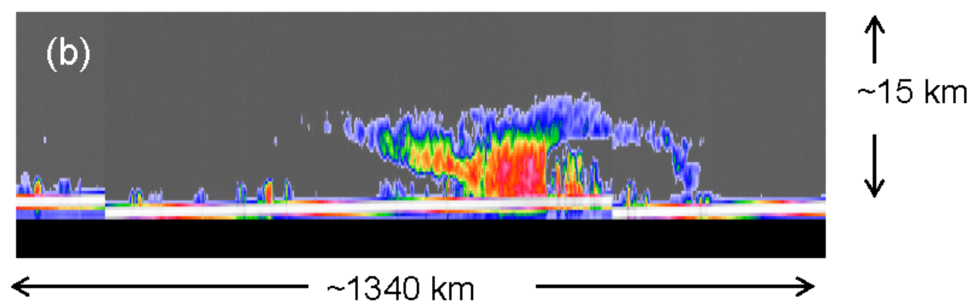
First spaceborne 94-GHz radar

CloudSat reached its forth anniversary in orbit on Monday, 28 April 2010. CloudSat completed its 22-month prime mission on 27 February, 2008 and is now in extended mission phase.

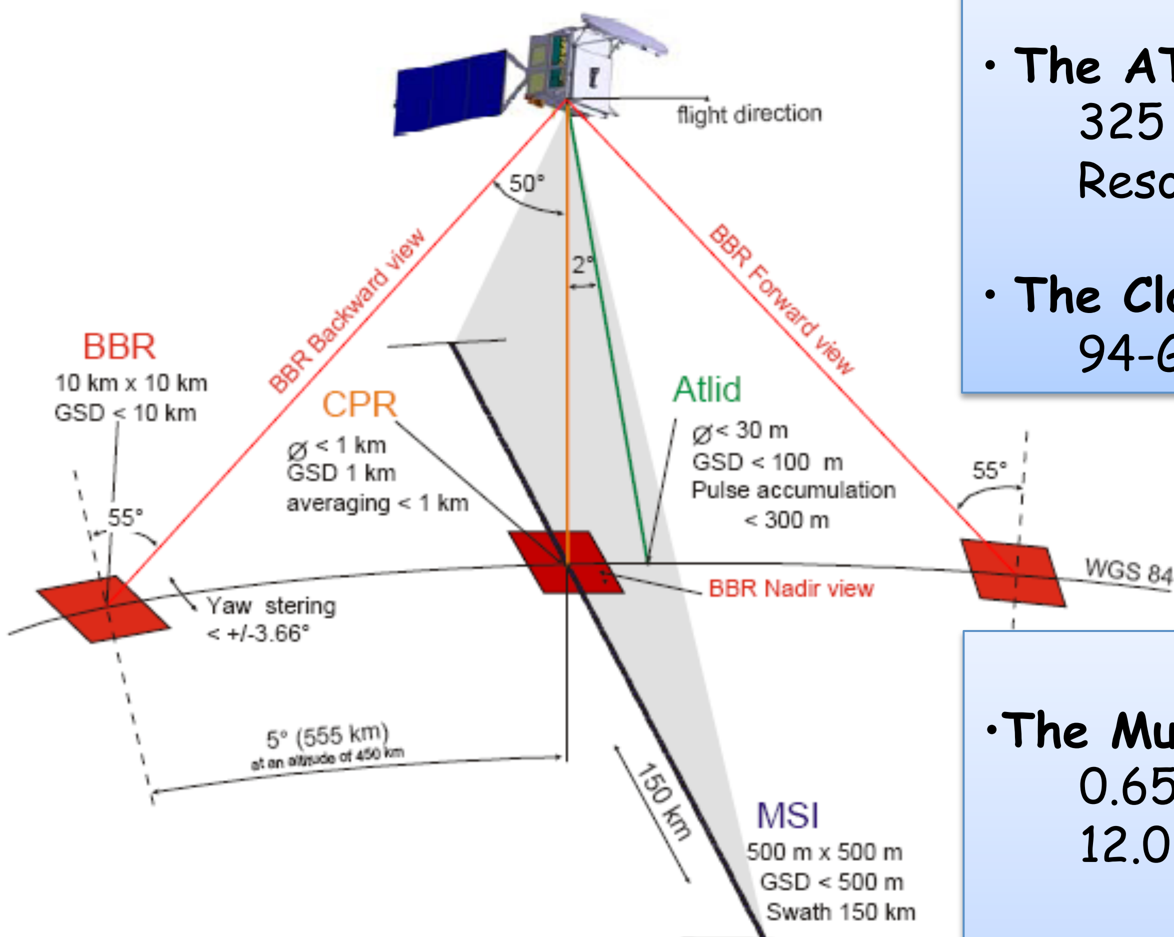
CloudSat: Sensitivity –30 to –31dBZ for 0.16s (1km) dwell

Works better than spec





EarthCARE – Earth Clouds, Aerosols and Radiation Explorer



Scheduled for 2013 launch

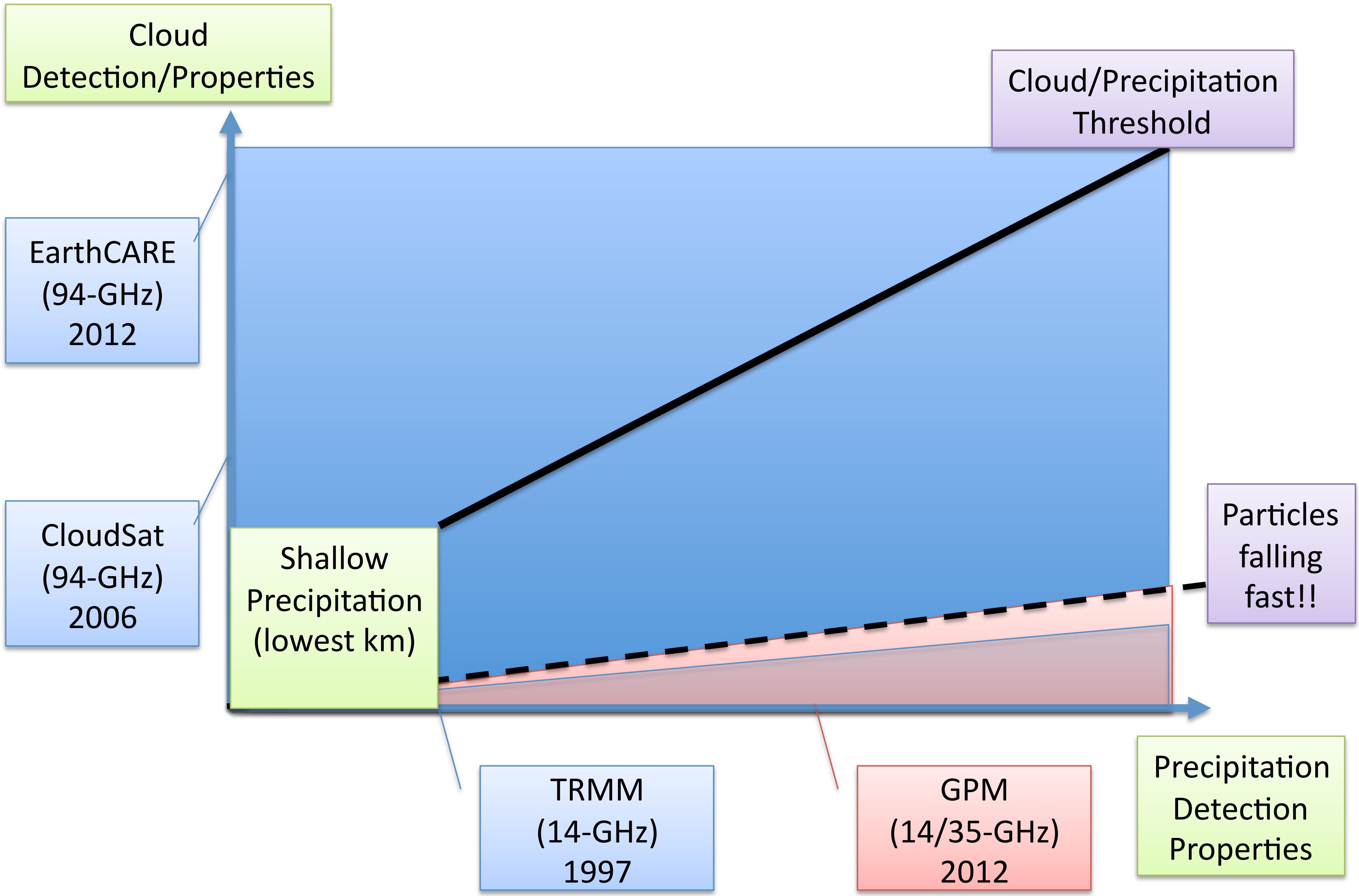
Active Payload

- **The ATmospheric LIDar (ATLID)**
  325 nm wavelength High Spectral Resolution Lidar (HSRL)
- **The Cloud Profiling Radar (CPR)**
  94-GHz Doppler radar

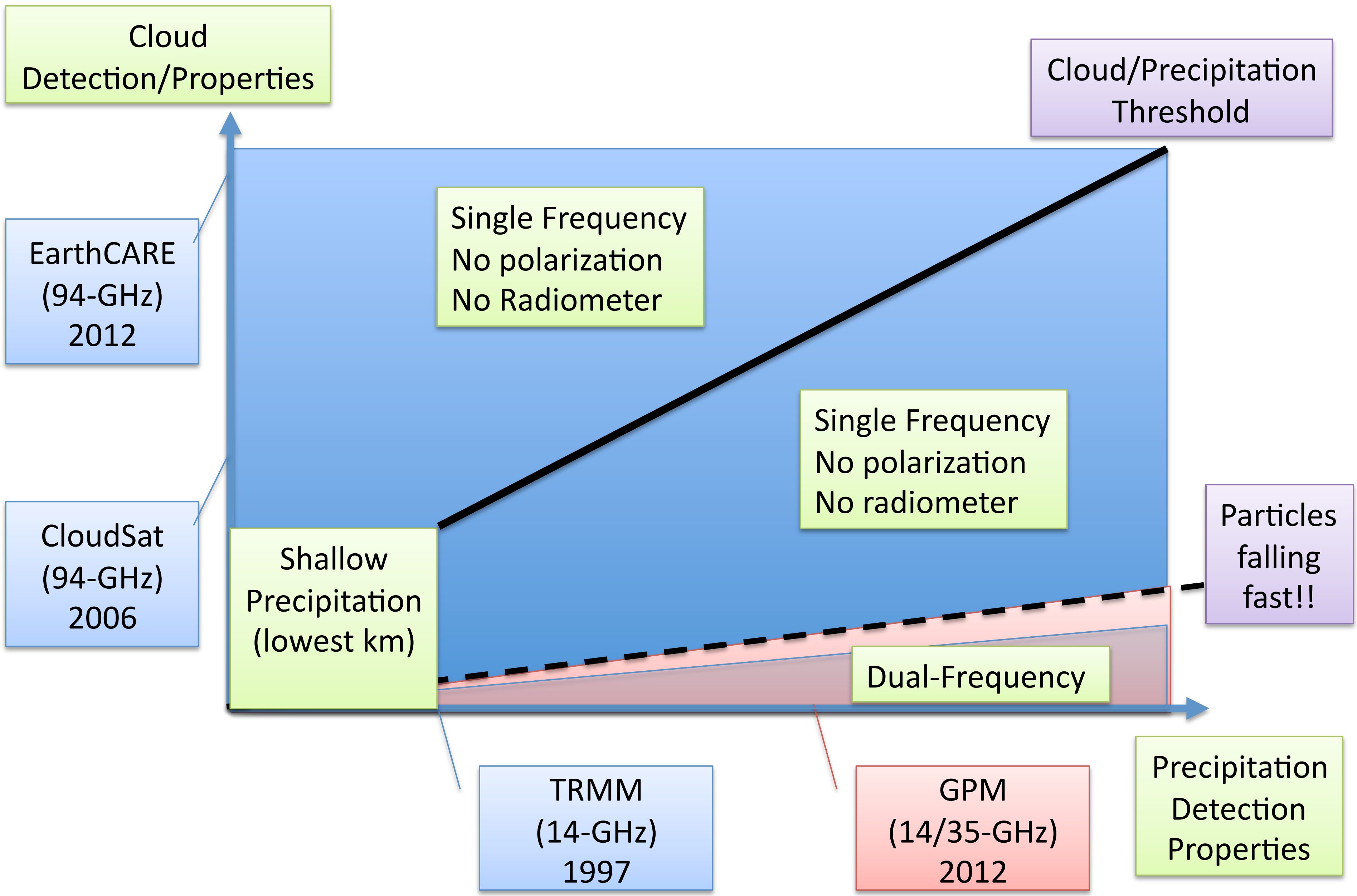
Passive payload

- **The Multi-Spectral Imager (MSI)**
  0.659, 0.865, 1.61, 2.2, 8.8, 10.8, 12.0
- **The Broad-Band Radiometer (BBR)**
  (SW 0.2–4 μm, LW, 4–50 μm)
  Forward/Backward 55°, Zenith

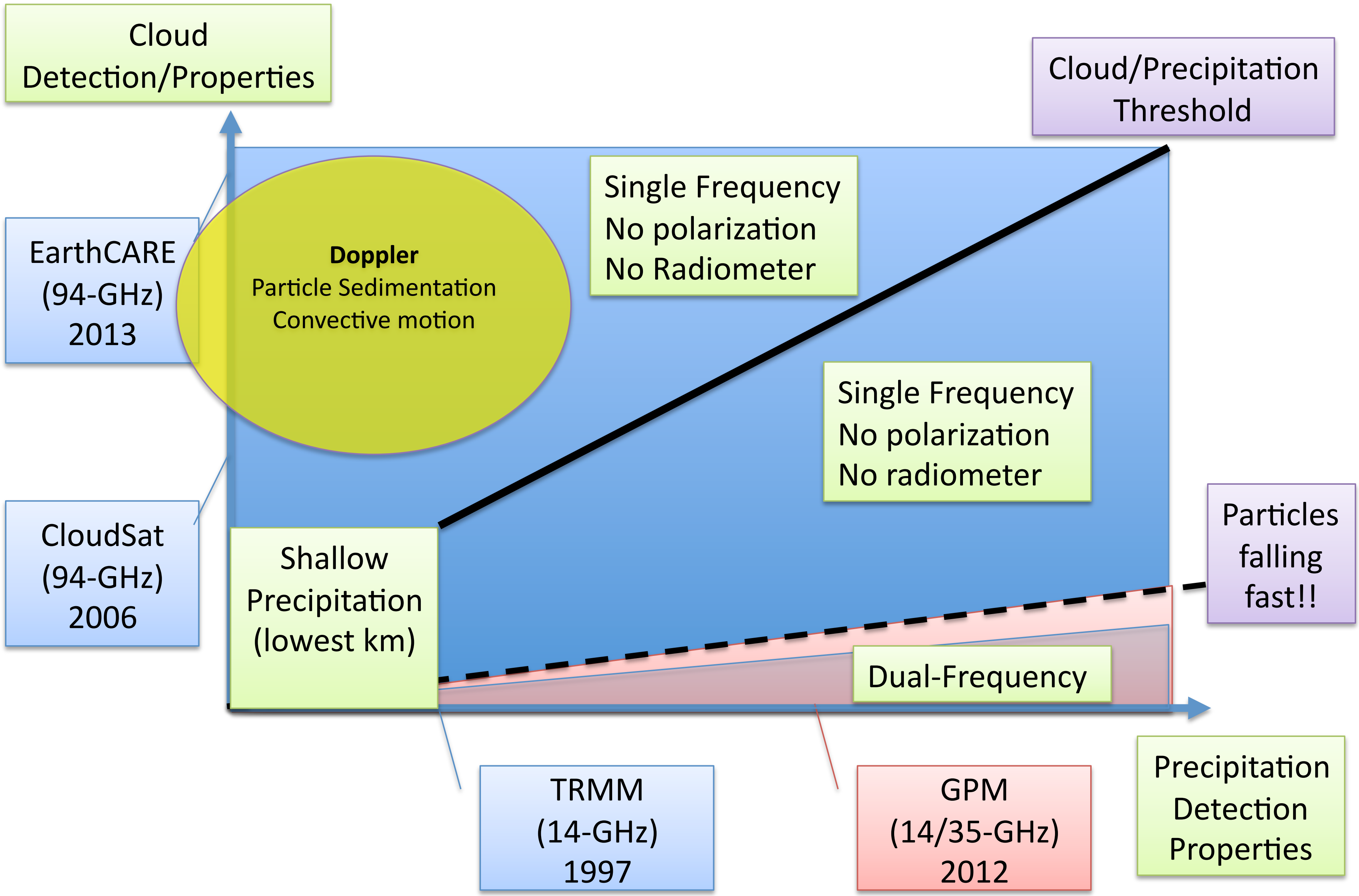
Have we reached an asymptote? Coverage



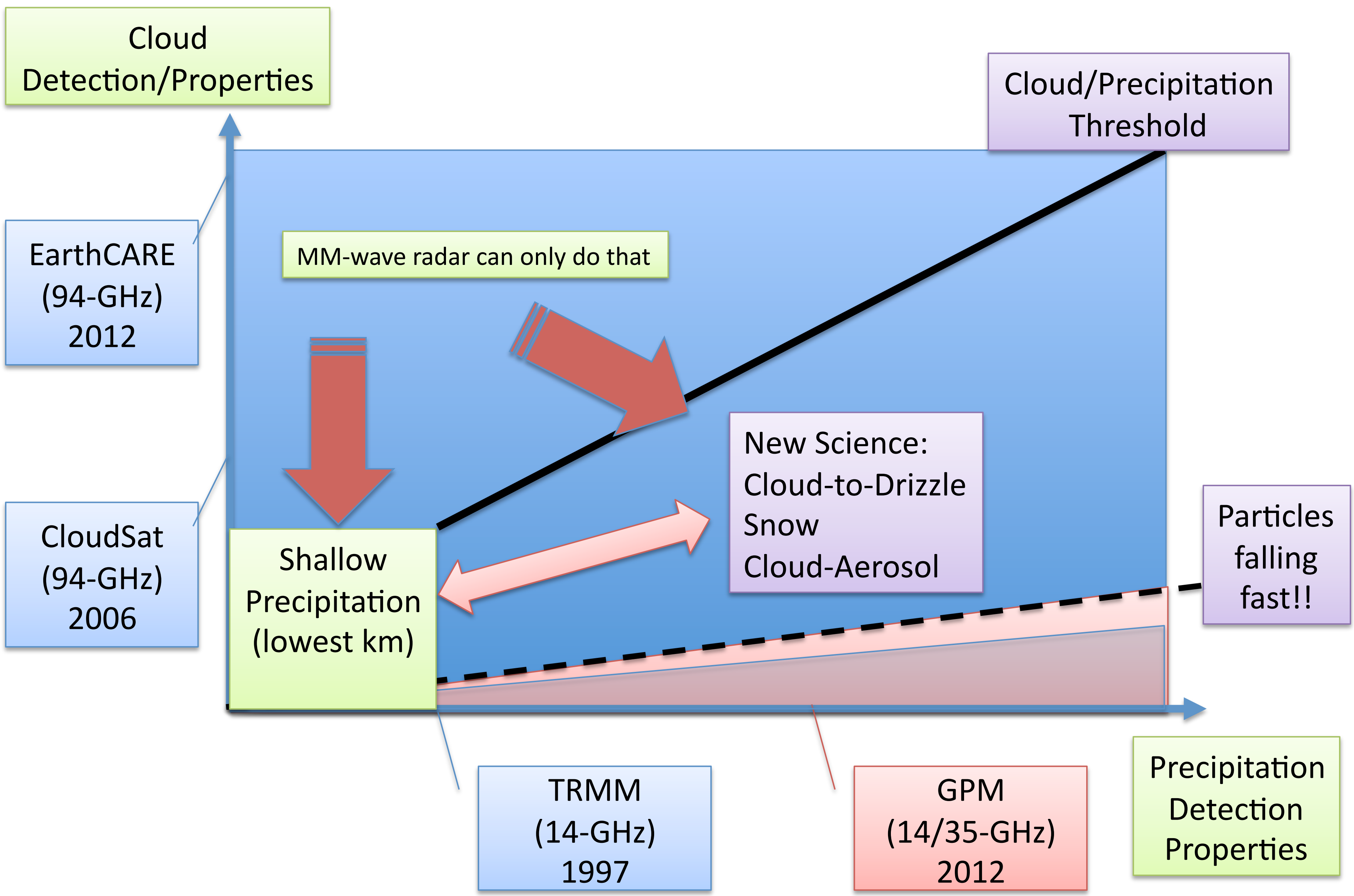
Have we reached an asymptote? Microphysics



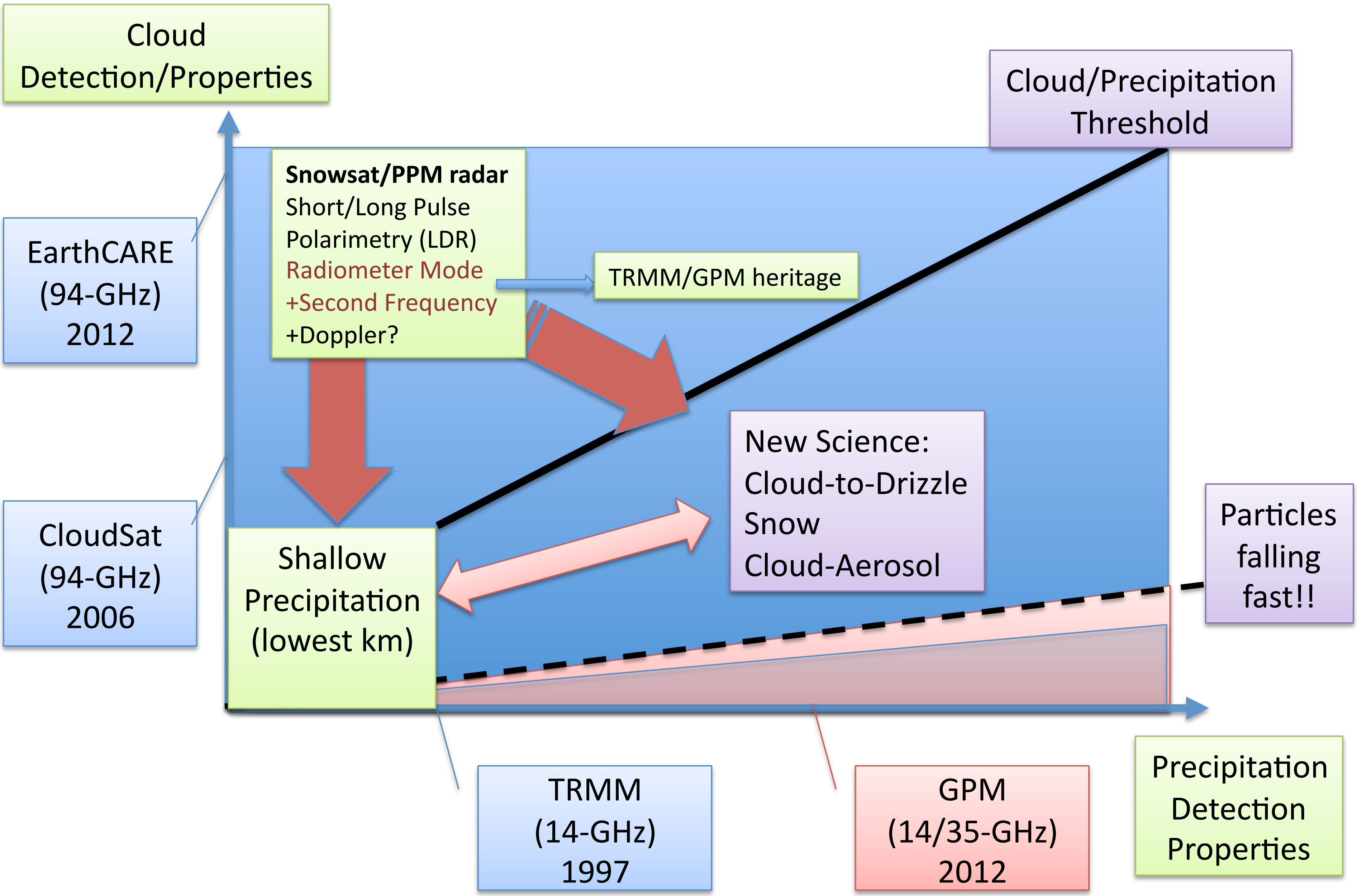
Have we reached an asymptote? Microphysics



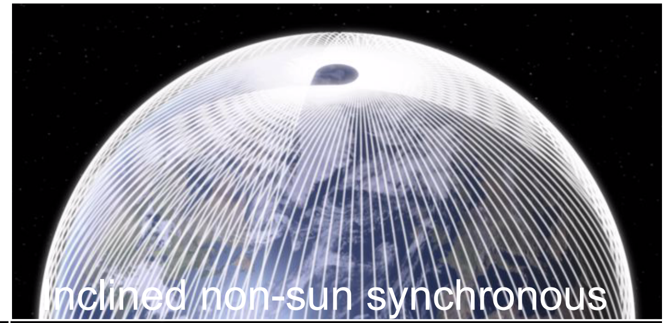
Have we reached an asymptote? New Science

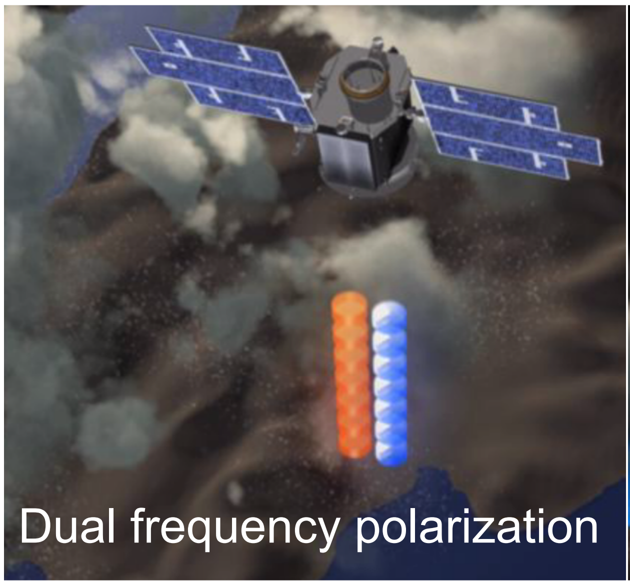


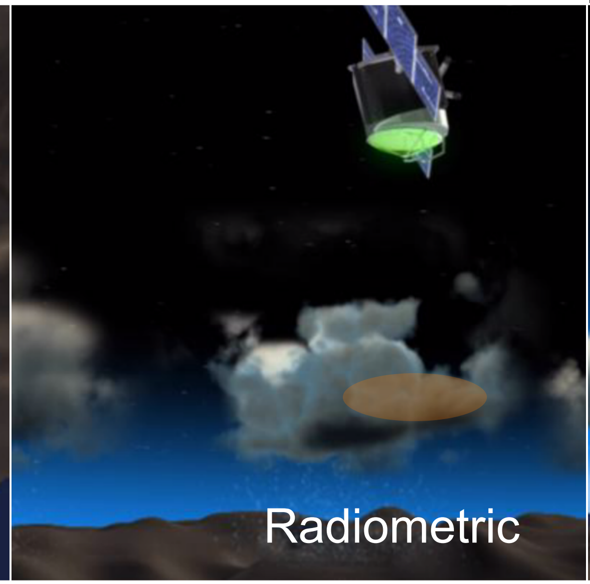
Have we reached an asymptote? Not yet!



The PPM Radar





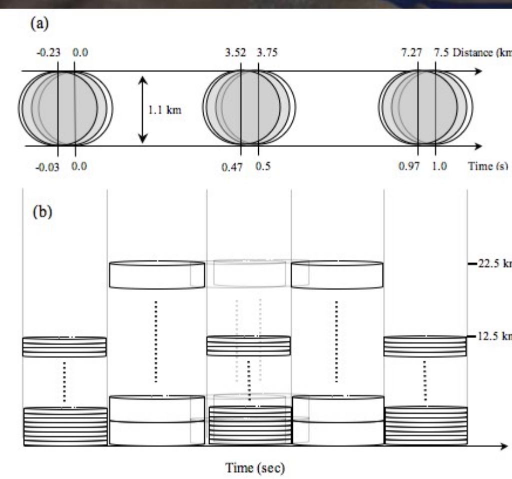


Dual Frequency (35 and 94 GHz), high sensitivity (-34BZ, -10dBZ), *high vertical resolution (<100m), near surface (<250m), polarization.*

Radiometric, Doppler and *cloud* modes

Non-sun synchronous *polar* orbit

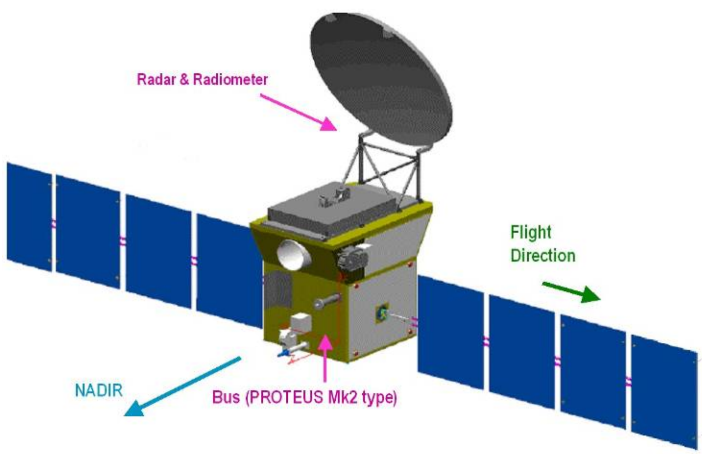
Made in Canada



High vertical and horizontal res

Freq-uency	Mode	Cross-Pol	Ground Footprint[1]	Radi-ometer Accuracy	Pulse Width	PRF	Sensitivity[2]	Range Res-olution	Lowest Resolved Altitude
94 GHz	Doppler Dual Polarization Radar	-23 dB	0.8 km	-	3.3 usec	6 kHz	-34 dBZ	500 m	500 m
		-23 dB	0.8 km	-	0.6 usec	6-14 kHz	-19 dBZ	100 m	<250 m
35 GHz	Doppler Radar	-23 dB	2.0 km	-	1.2 usec	6-14 kHz	-10 dBZ	200 m	<250 m
23.8 / 35 GHz	Passive Liquid Water Radiometer	-23 dB	3.0 km / 2.0 km	1 degK	-	-	-	-	-

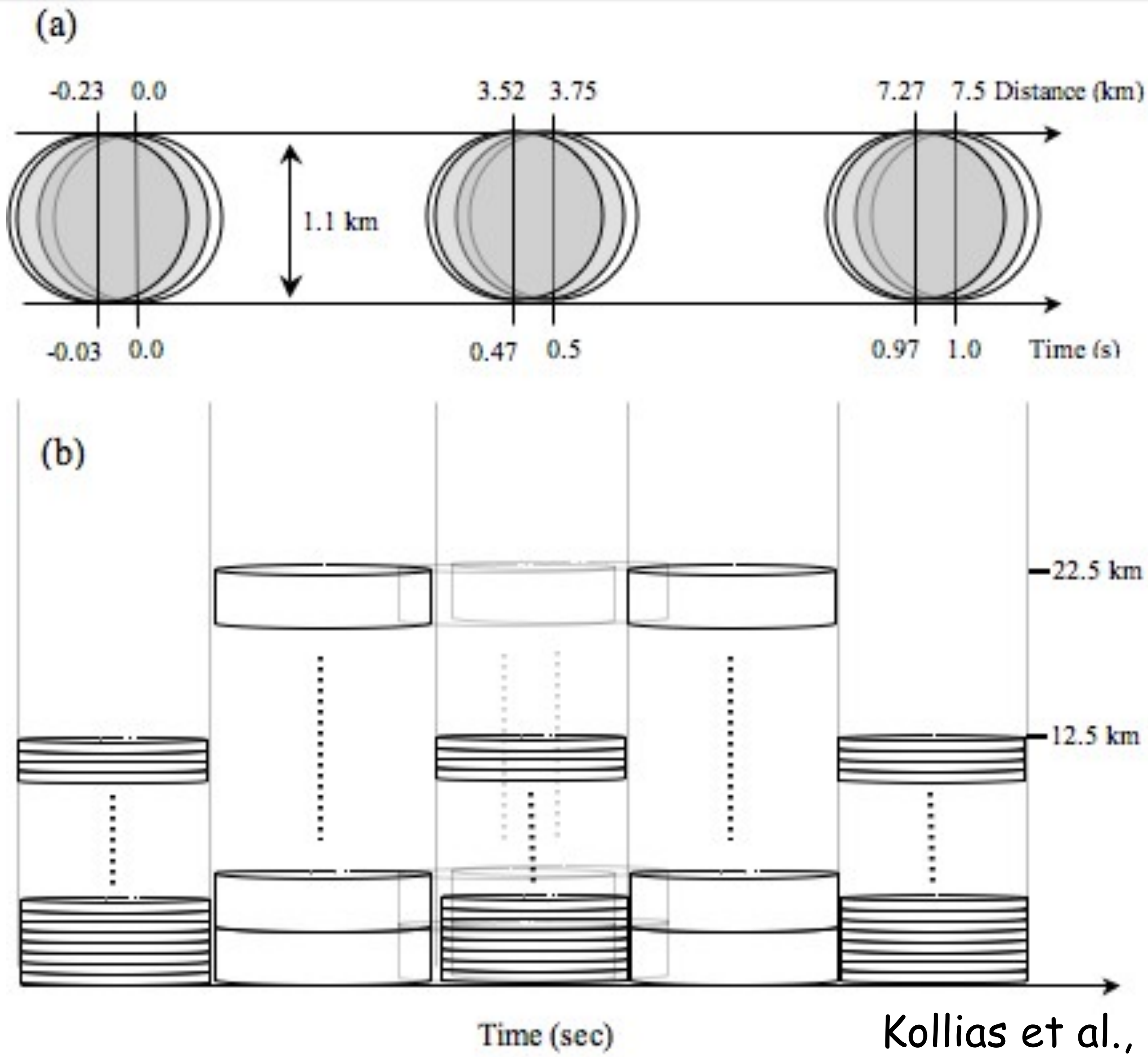
Note 1: From 400 km altitude, with 2.0 m antenna
Note 2: Sensitivity calculated for non-interleaved operation, 400km altitude, and integration over 7.5 km of ground track



Parameter
Reflectivity, Doppler Velocity, Spectral Width, Differential Reflectivity, correlation, Cross-pol reflectivity or depolarization ratio, other parameters for data quality (TBD)
Reflectivity, Doppler moments, other parameters for data quality (TBD)
Differential Wavelength Reflectivity (used with parameter above to derive, precipitation type, precipitation intensity mean particle size)
Brightness Temperature (used to derive water vapour, ice and liquid path)

Near-Simultaneous Retrieval of Cloud and Precipitation

Interleave Design (Frequency, PRF and Pulse Length Diversity)



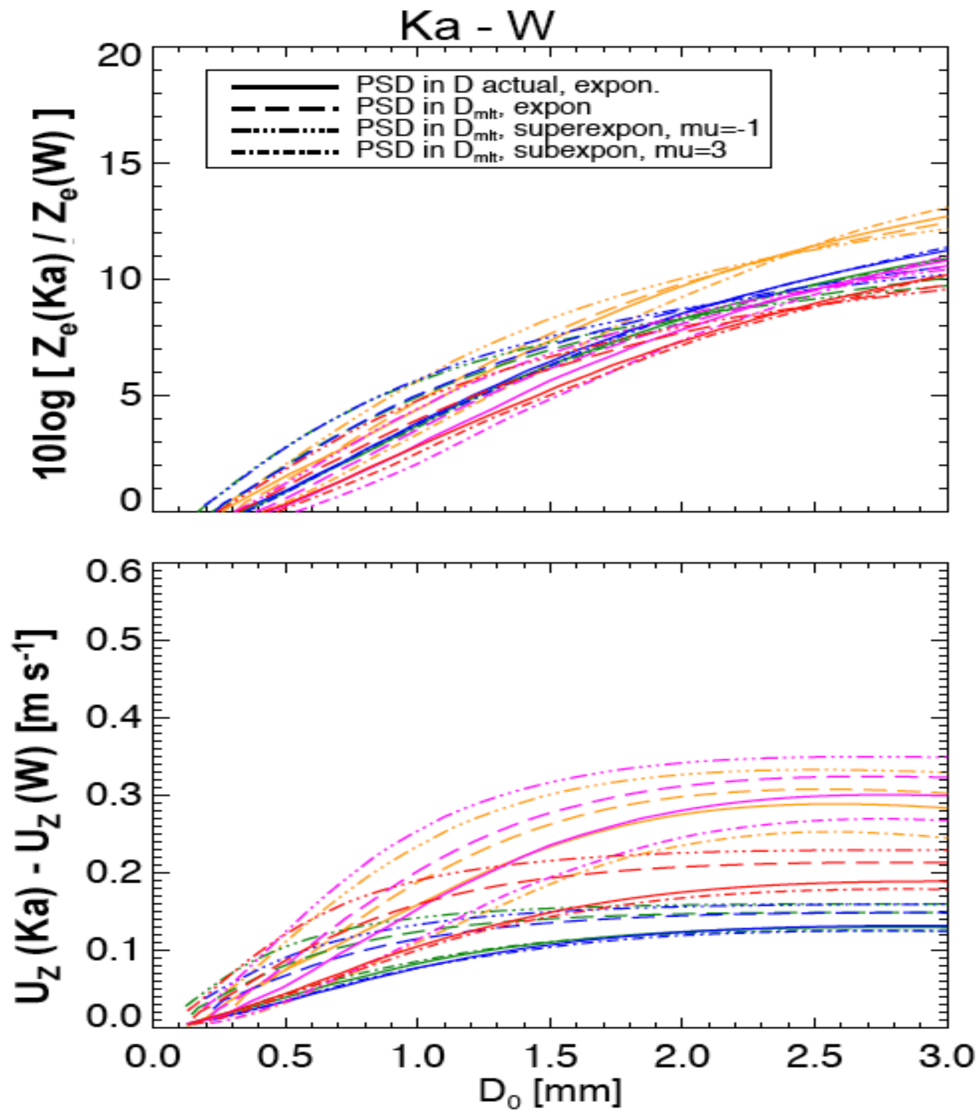
Kollias et al., 2007

Due to non-Rayleigh scattering, the radar reflectivity at 94-GHz reaches a near-asymptote (around 20 dBZ) that is insensitive to further increases in the snow amount/rate.

In addition, the use of a single frequency for snow measurements is subject to large uncertainties due to the errors associated with the assumption made about the particle density, size and shape of the particle size distribution.

In order to overcome these challenges, we propose the use of a second frequency (35-GHz). At 35-GHz, non-Rayleigh scattering is present but not strong enough to "saturate" the radar reflectivity. This will enable measurements at high snow rates.

Dual Frequency radar (35/94-GHz)



Dual Frequency

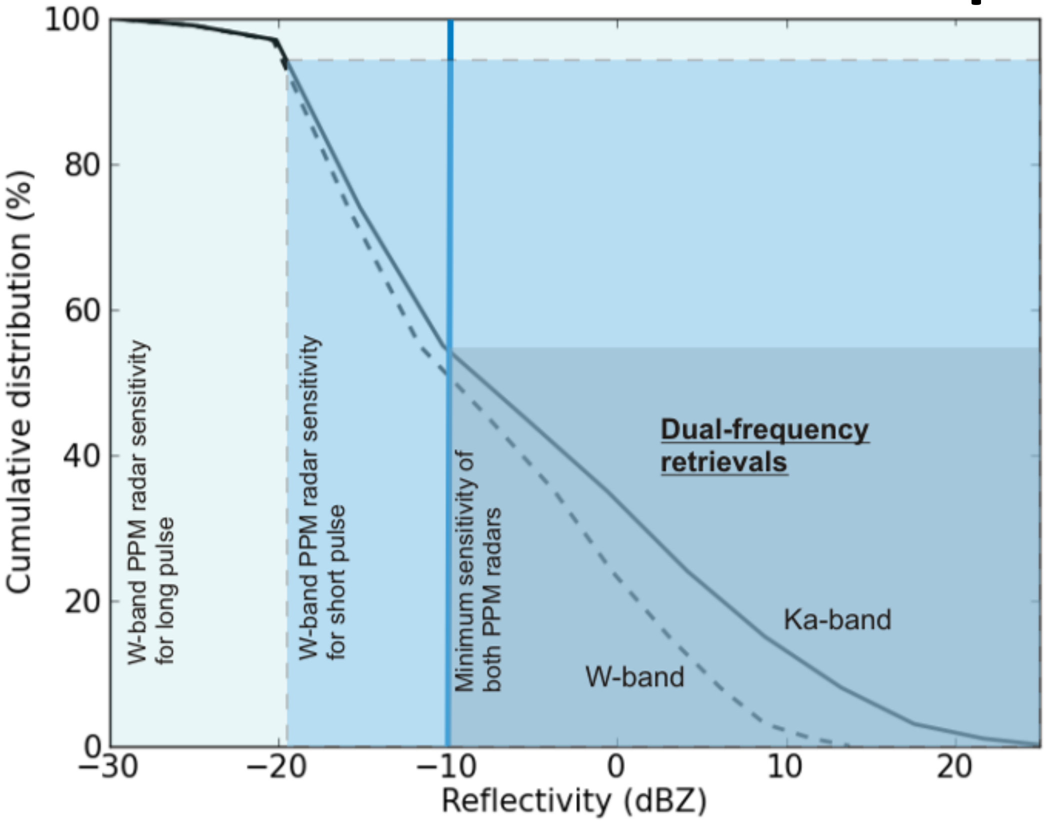


Figure 3.1: Cumulative distribution of Ka and W radar reflectivity of snow climatology in Finland. The measurements are converted from C-band weather radar observations (Leinonen et al., 2010). The blue line shows the minimum sensitivity requirement for PPM dual-frequency radars.

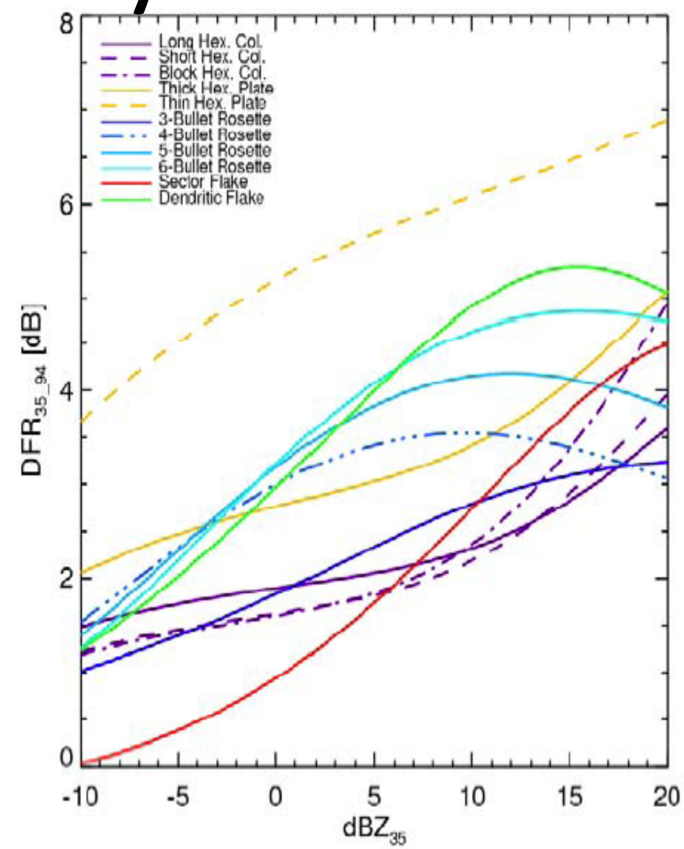


Figure 3.4: Simulated 35/94 GHz dual-frequency ratios as a function of 35 GHz reflectivity for various ice particle habits (Liu, 2008) using ice PSD parameterization (Field, et al., 2005). (Figure from Kulie and Bennartz, 2009)

Polarimetric Mode

A polarization mode for the spaceborne radar that provides co- and cross channel Doppler spectra and moments is proposed.

Requires:

Linearly/circularly polarized antenna for cross polarization measurements.

A second receiver channel for simultaneous reception of the cross-pol signal

Application:

Data Quality

Identifying the presence of non-spherical particles (e.g., ice crystals, snowflakes)

Melting layer detection.

Identification of multiple scattering events.

Wealth factor:

Existing and planned spaceborne millimeter-wavelength missions do not have this polarimetric capability.

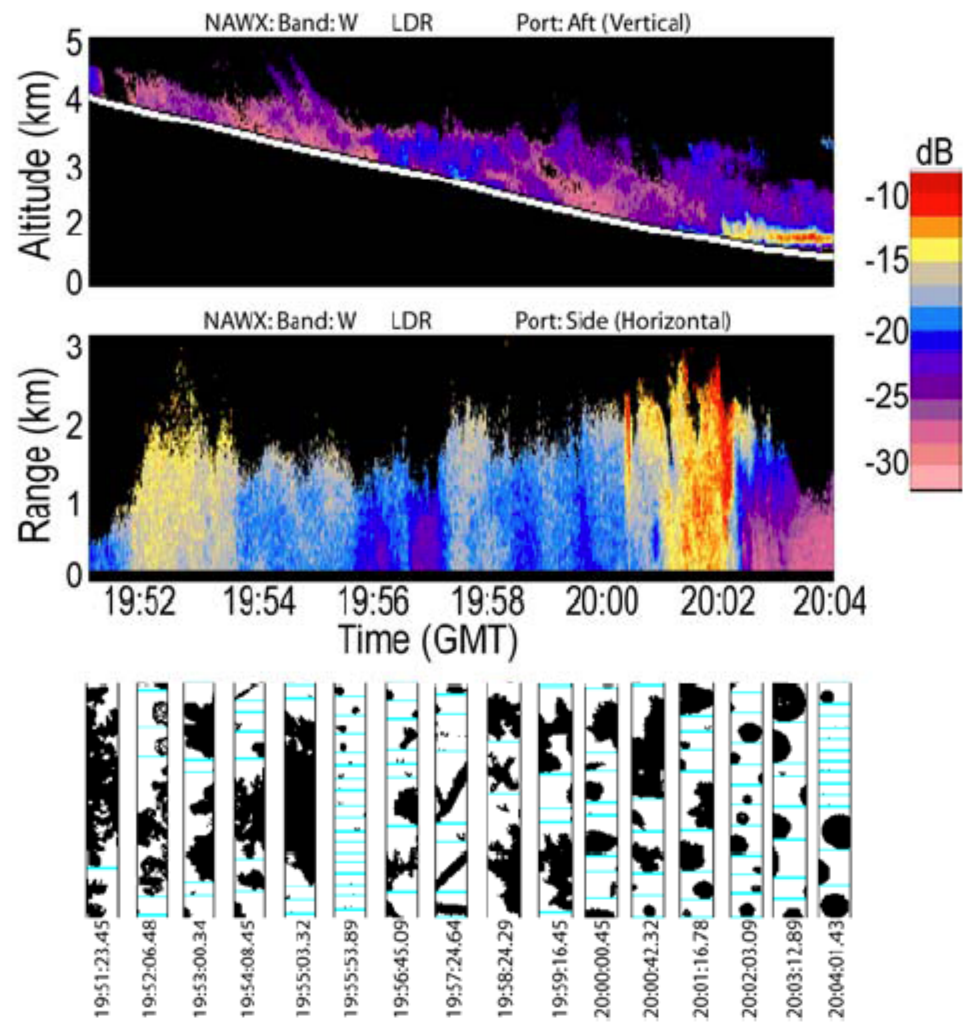


Figure 3.3: LDR measured by NAWX on Mar 01, 2007, as the aircraft descended from an altitude of 4 km to 1.5 km. Top: Vertical cross-section from upward point radar beam. The white line shows the aircraft altitude. Middle: LDR from the side-looking dual-pol antenna. Bottom: Sample of PMS 2D-C images corresponding to the aircraft altitude.

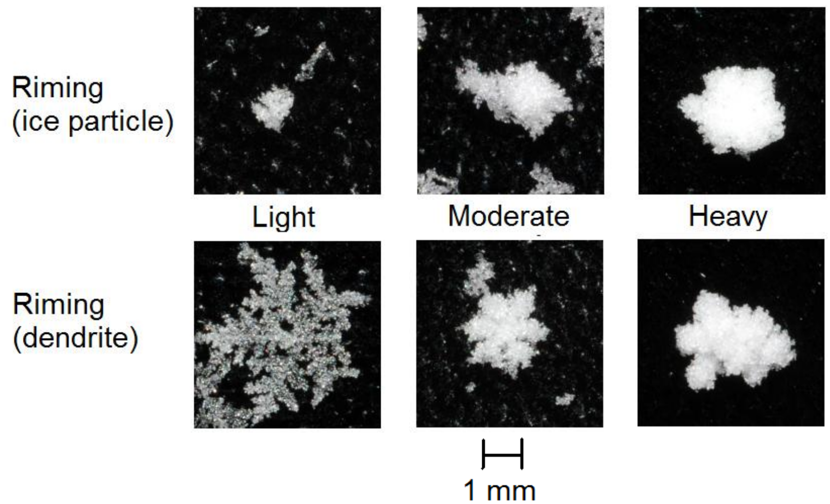
Radiometer Mode

Concept:
Microwave emissions from water vapor and liquid water amounts in the line-of-sight of the radar produce measurable increases in the radar receiver noise and can be used for the retrieval of the path-integrated water vapor and liquid water amounts.

Channels:
22-GHz (water-vapor absorption band),
35-GHz and 94-GHz (radar frequencies)

Application:
Measure the path-integrated water vapor and liqu water (riming).

Wealth factor:
The ability to combine a radiometer channel collocated with the radar can allow liquid water path to be estimated concurrently with the radar data.

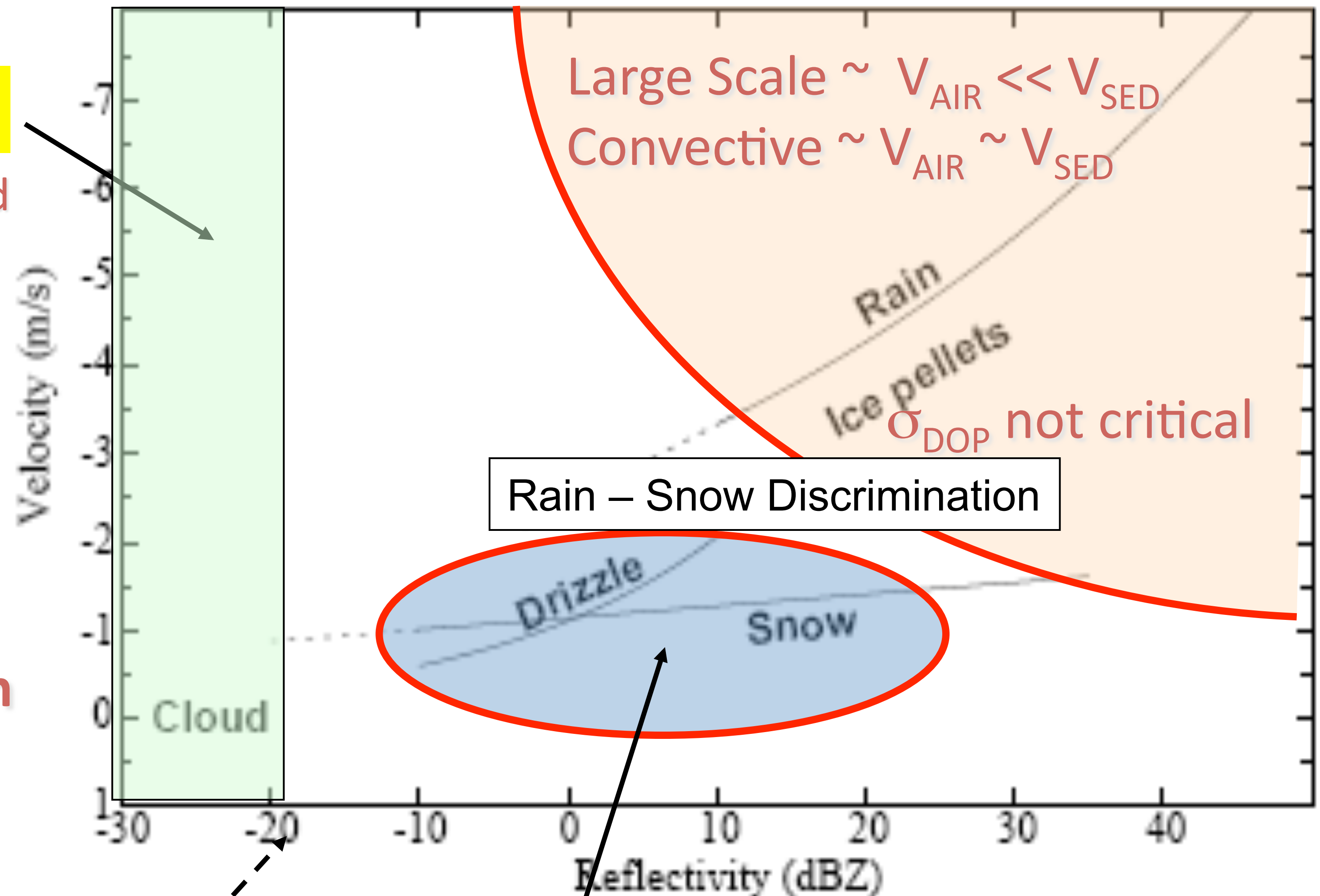


Liquid Water Detection
Mixed Phased

When Doppler matters?

$V_{AIR} >> V_{SED}$

TKE is undersampled
No size information



V_{DOP}: **Doppler**
V_{AIR}: **Air motion**
V_{SED}: **Sediment.**

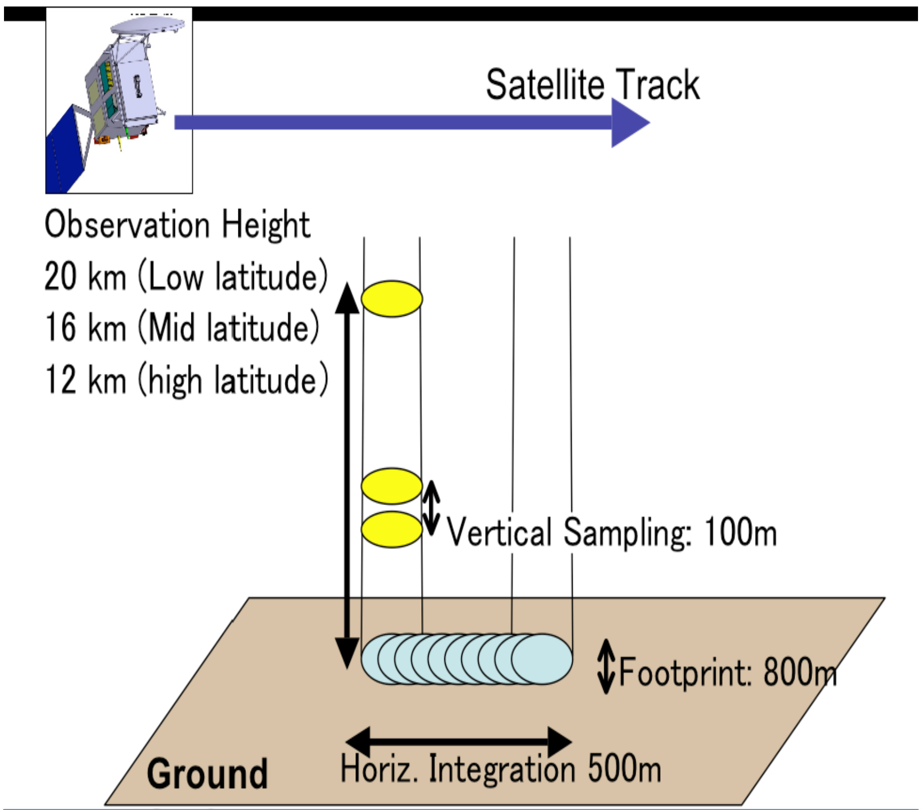
Benchmark
1 ms^{-1} uncertainty at -19 dBZ
with 10 km integration

σ_{DOP}
----------- Need to be small for μ-physical retrievals
V_{SED}

EarthCARE CPR – Cloud Profiling Radar

Radar Specifications

Frequency	94.050GHz
Peak power	1.5kW (EOL)
PRF	6100Hz to 7500Hz (during nominal observation)
Antenna diameter	2.5m
Beam width (Beam foot print)	0.095deg (800m)
Vertical resolution (Pulse width)	500m (3.3us)
Horizontal resolution	500m
Minimum sensitivity	-35dBZ (10km integration, uniform cloud)
Doppler measurement accuracy	1m/s (10km integration, -19dBZ clouds)



The accuracy of the Doppler measurements affects scientific applications (dynamics/μ-physics)

An Inconvenient Truth

Without polarization and/or frequency diversity options, the PRF selection must conform to the geometry of the troposphere and the cloud climatology

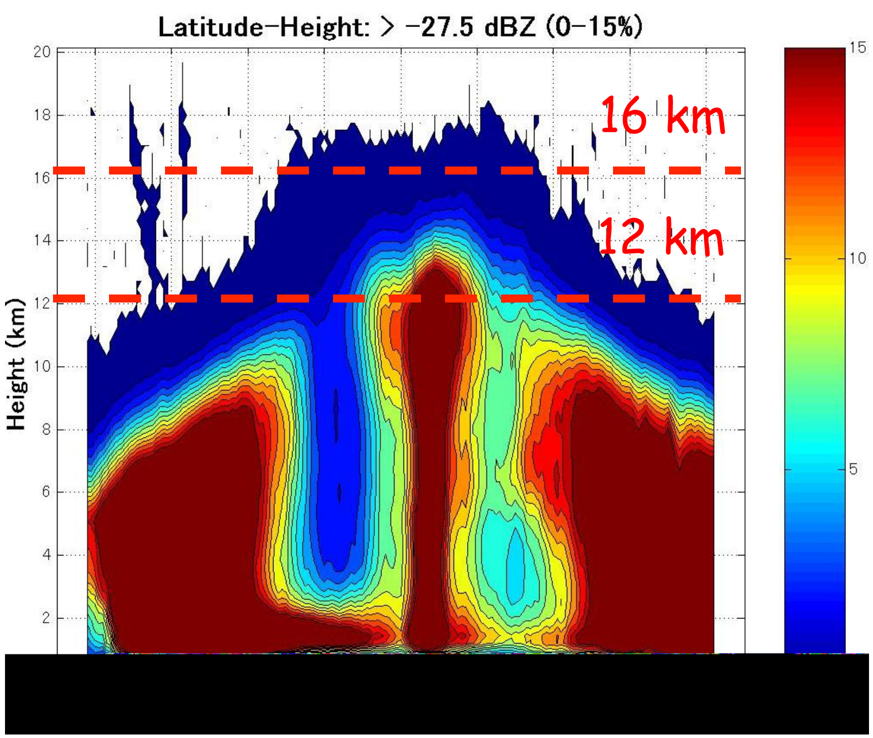
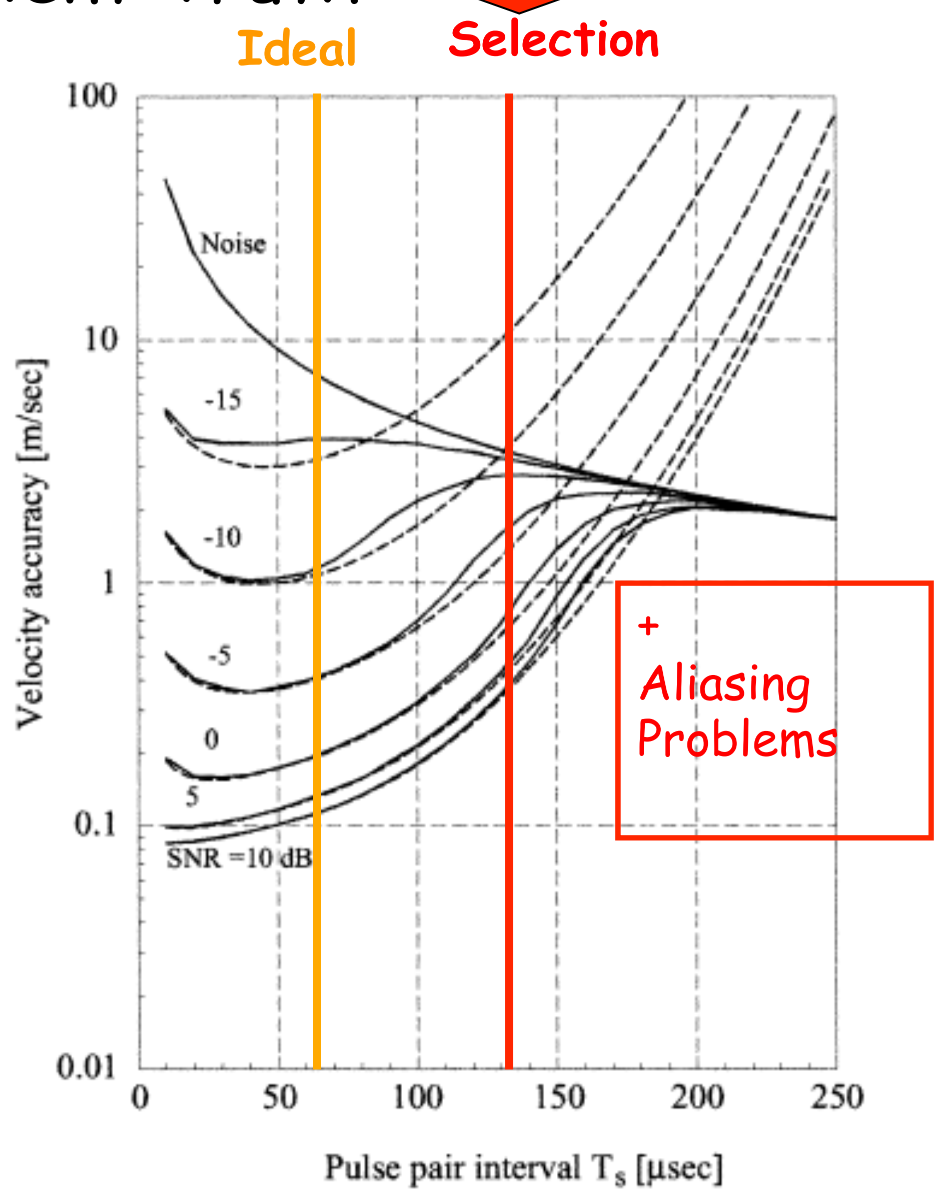


Figure from Y. Ohno (NICT)



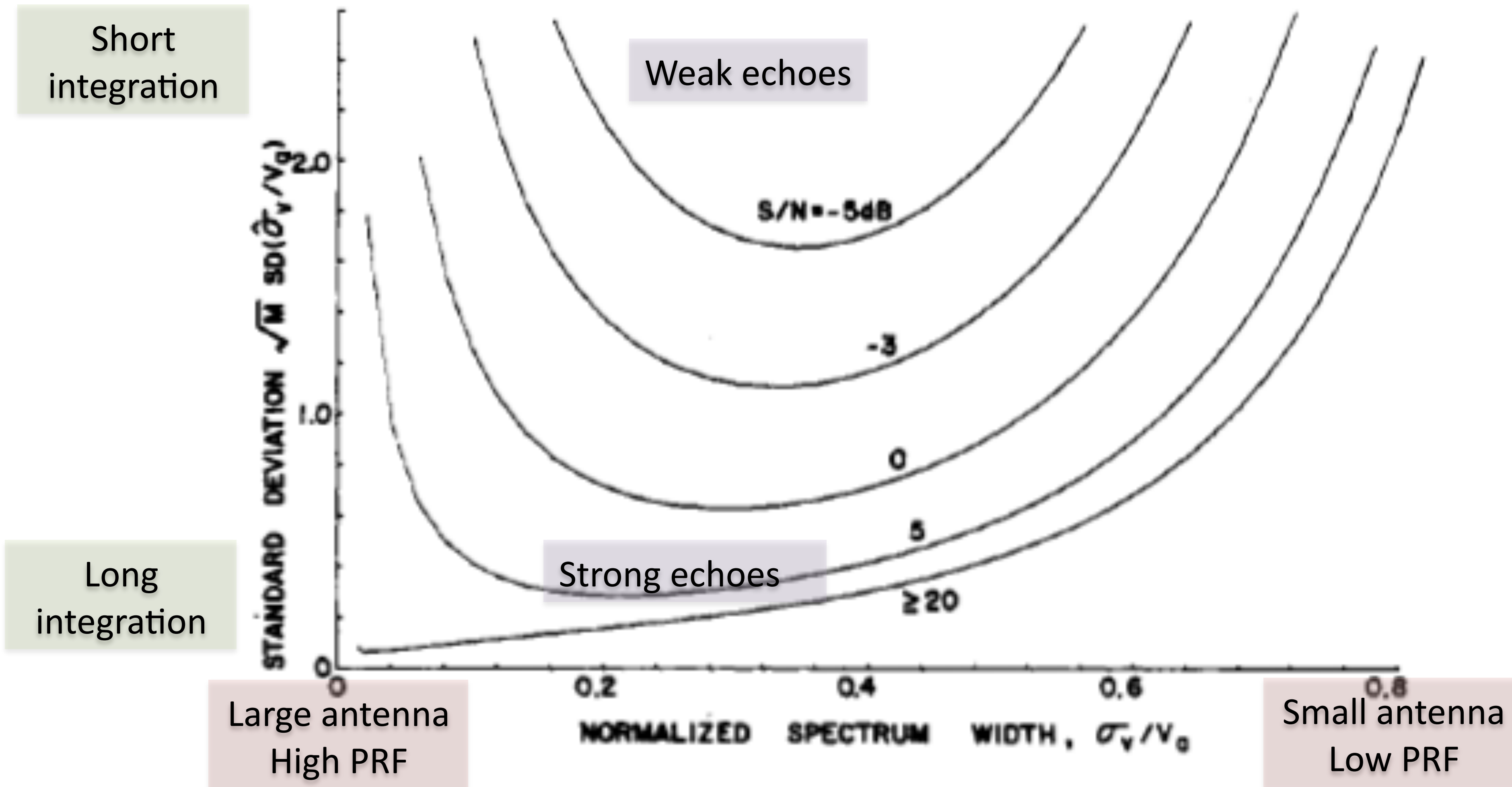
Kobayashi et al., 2003, JTech

Sources of errors and biases in the EarthCARE CPR Doppler velocity measurements

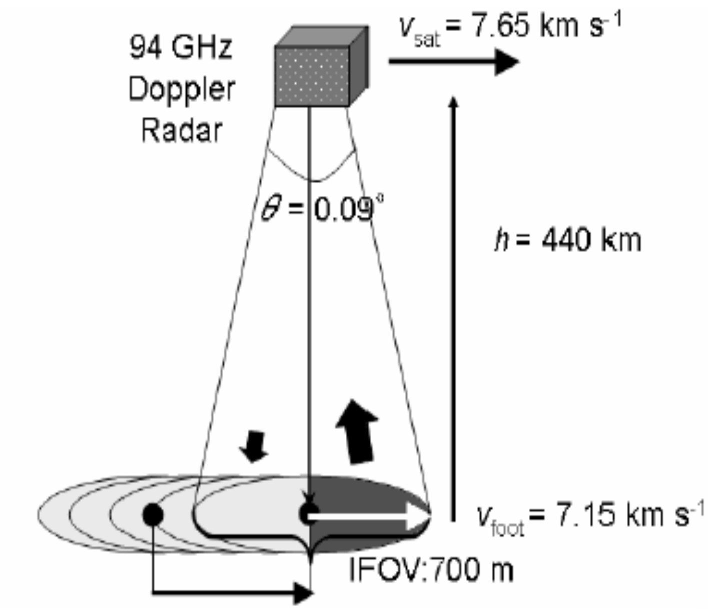
The Doppler spread due to the satellite motion is *given* by (Sloss and Atlas, 1968):

$$\sigma_{SatV} \approx 0.3 \cdot \theta_{3dB} V_{sat} \approx 3.7 \text{ ms}^{-1}$$

$V_{nyquist}$ ~ 5-6 ms^{-1}



Non-Uniform Beam Filling

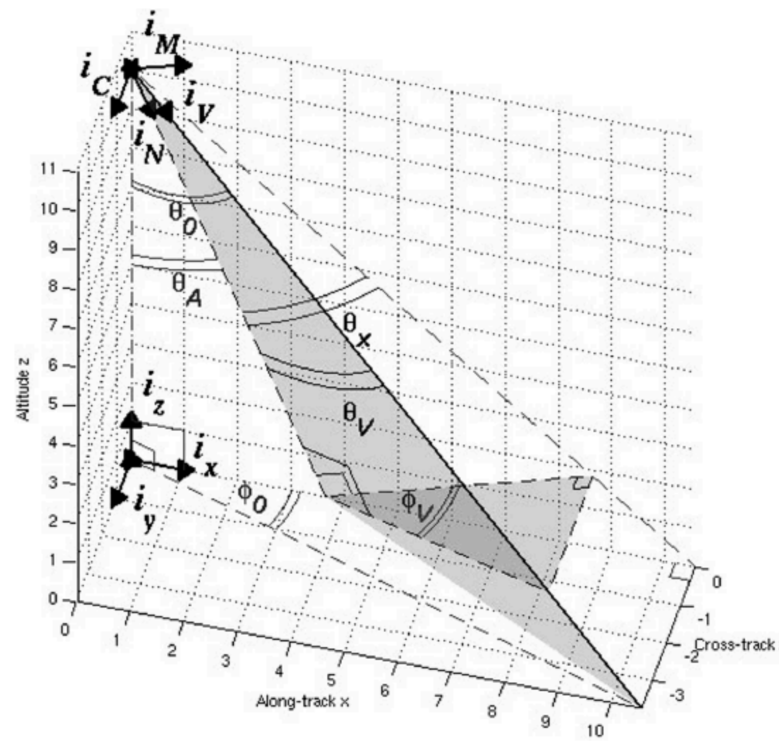


$$u_{rad} = -\left(v_{sat}/h_{sat}\right)x' + u_{z'}$$

Center of reflectivity mass

$$\bar{x}_z = \frac{\int_{-\infty}^{+\infty} Z_x(x)\cdot\, x dx}{\int_{-\infty}^{+\infty} Z_x(x) dx}$$

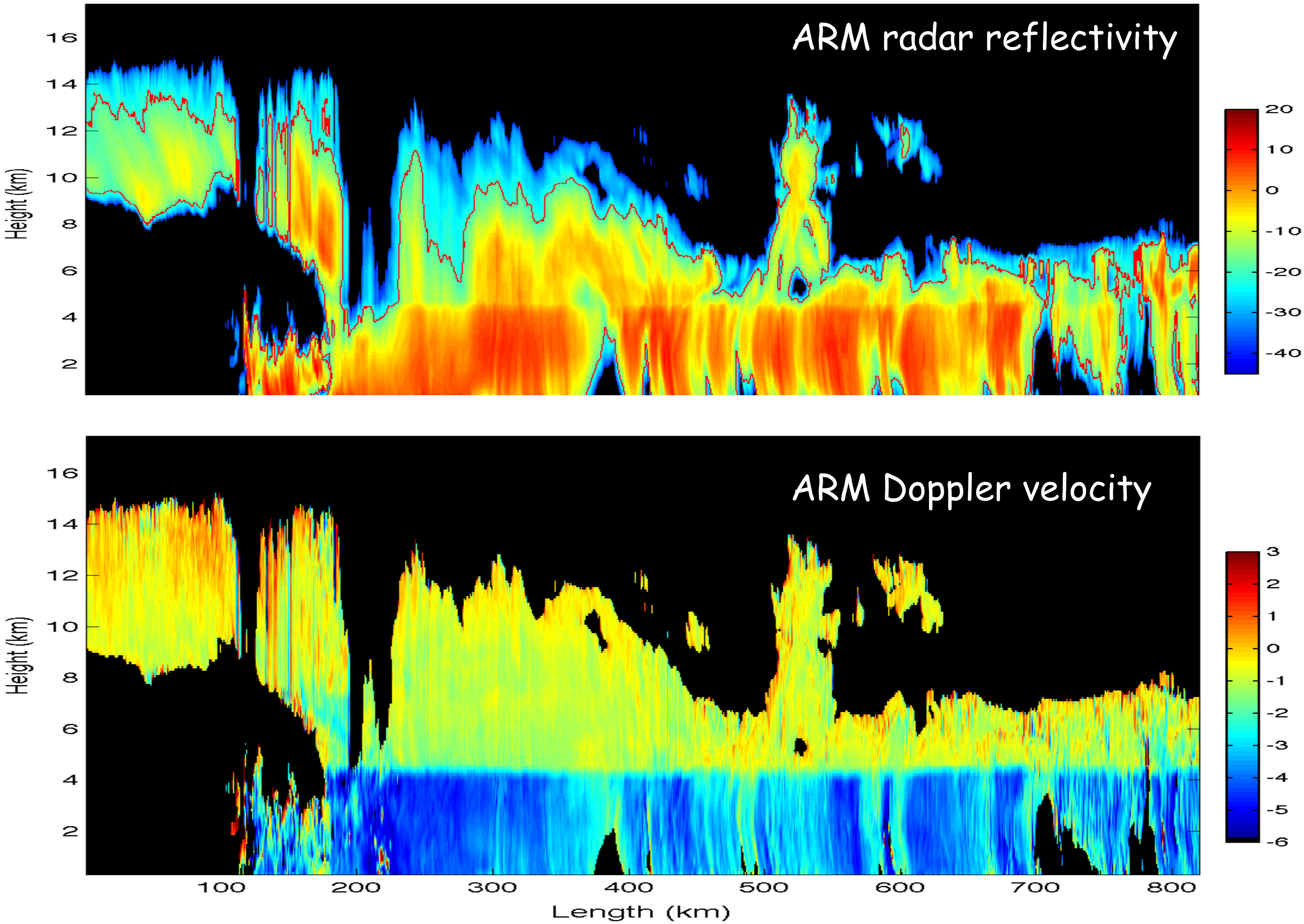
Antenna pointing uncertainty θ_α



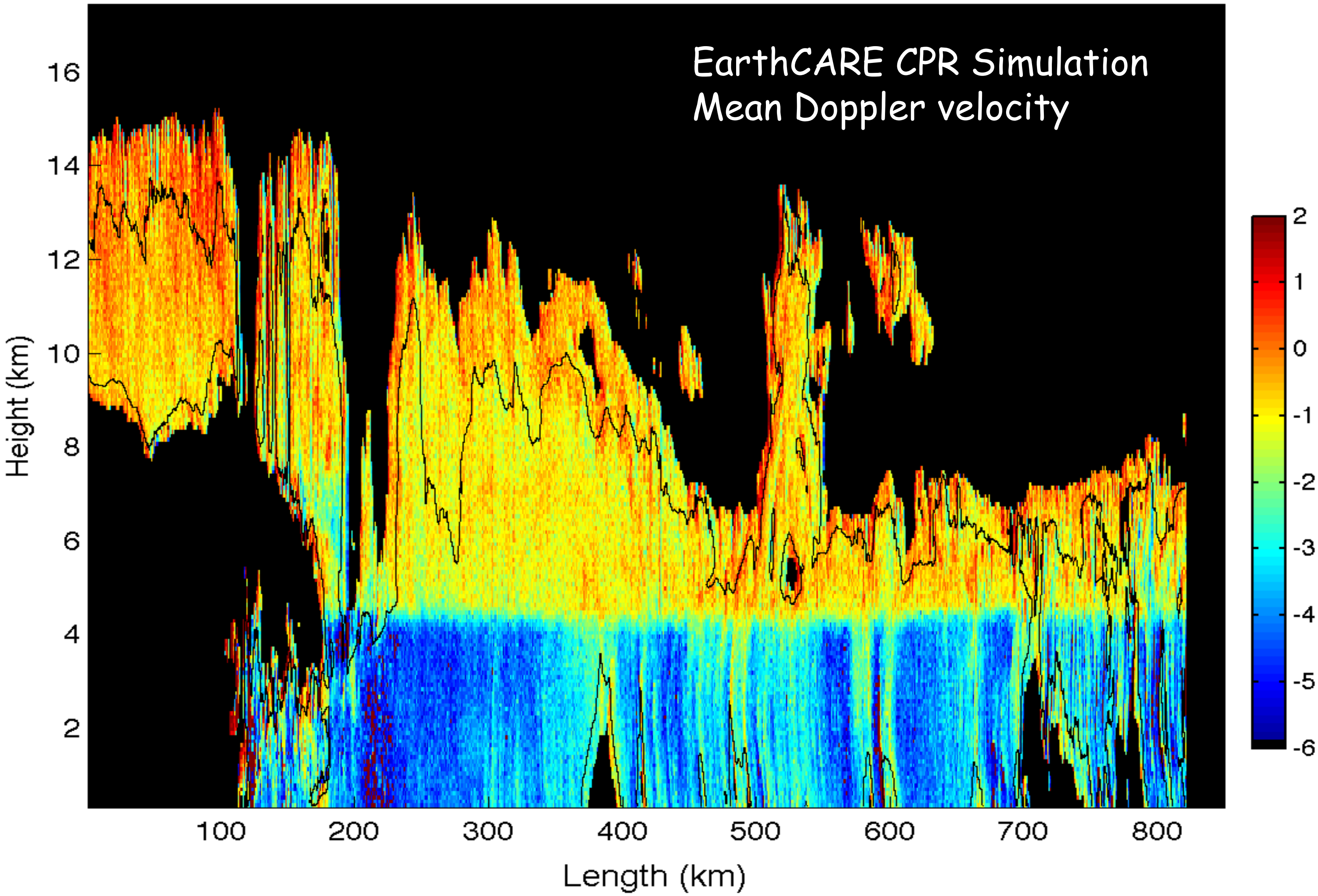
$$v_\alpha = -v_{sat}\theta_a$$

For EarthCARE: v_{sat} ~ 7 kms^{-1}.
For rms(θ_α) ~ 0.002 degrees,
rms(v_α) ~ 0.3 ms^{-1}

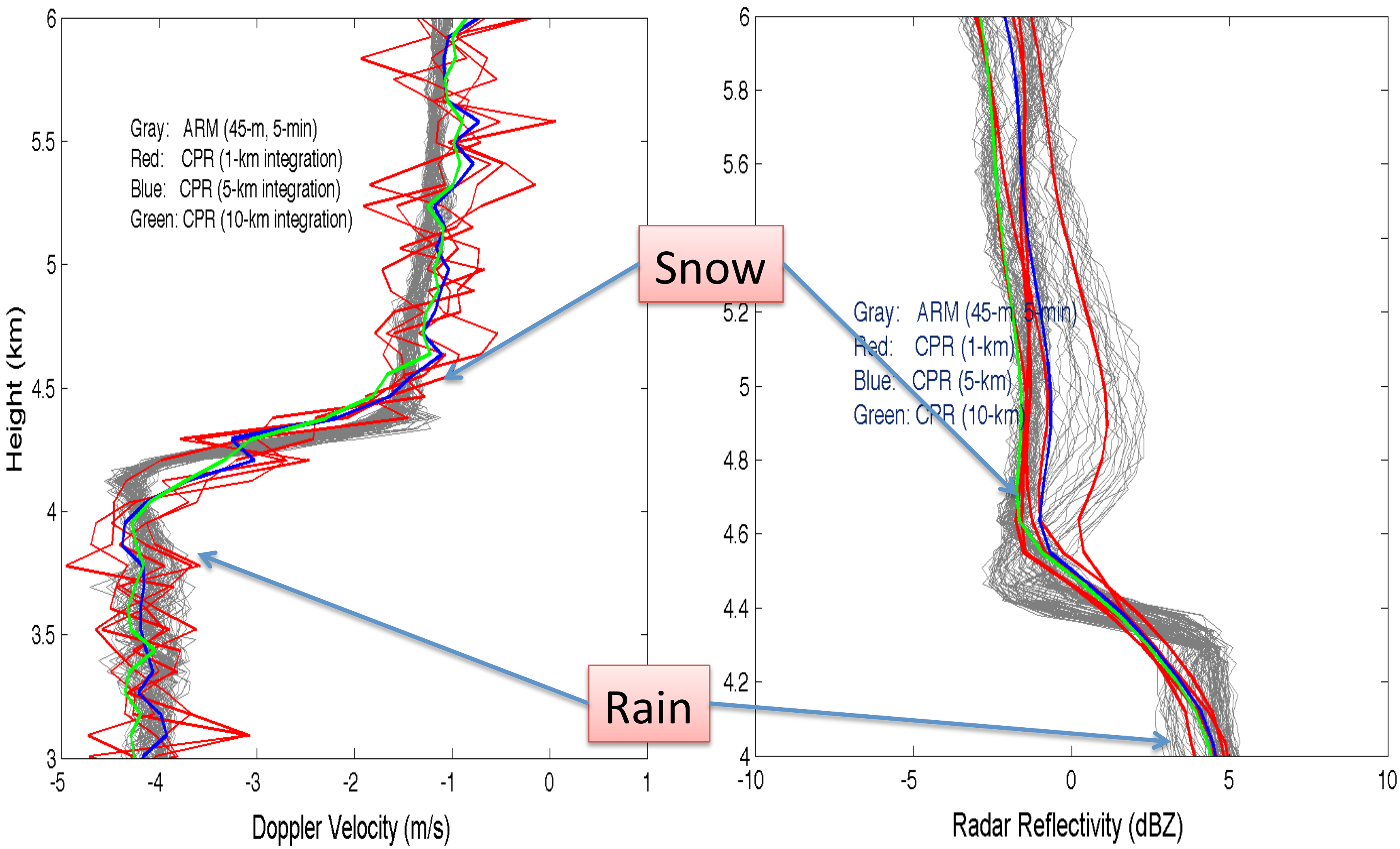
Large-scale precipitation (ARM/AMF-NIA)



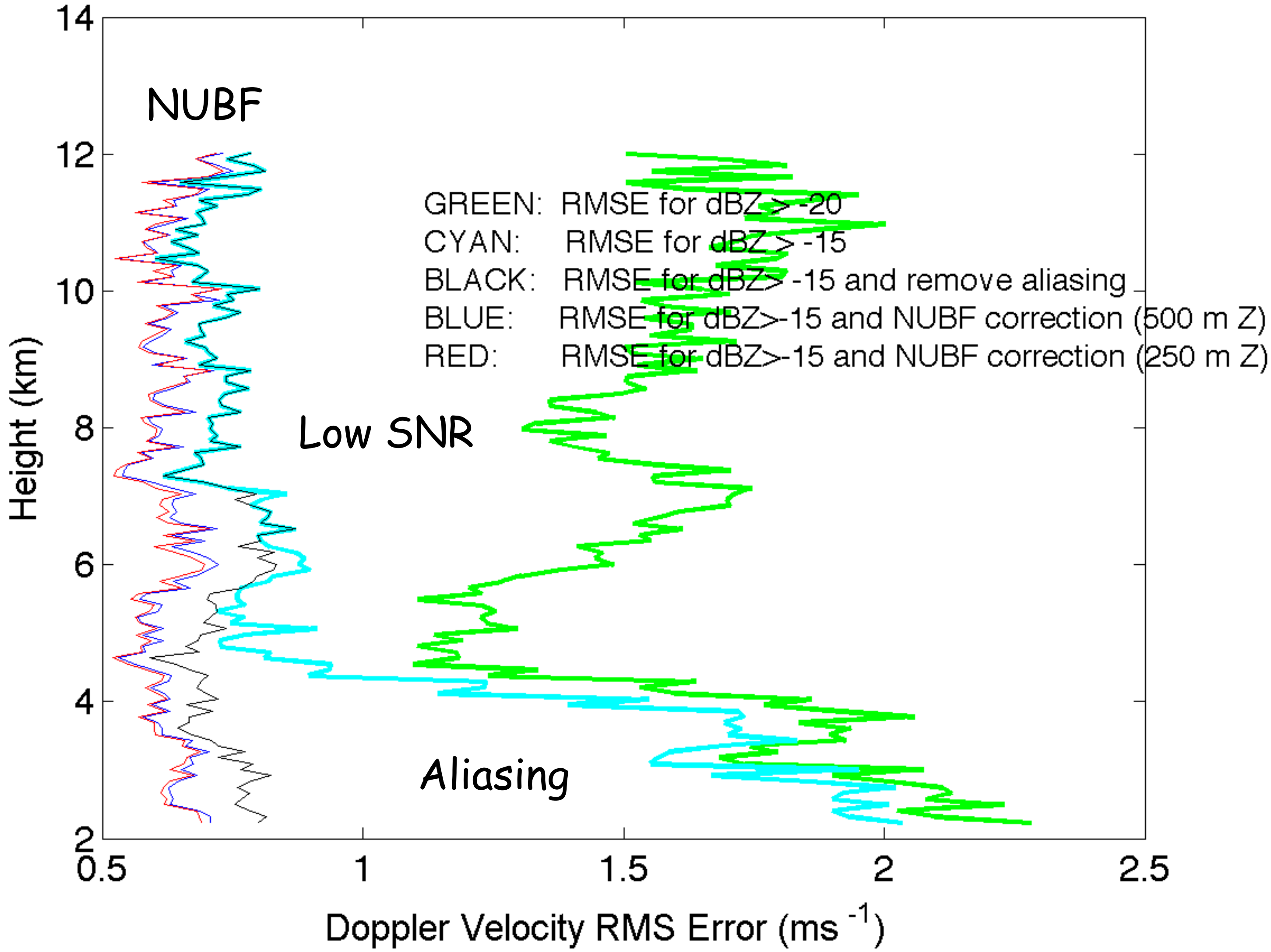
Large-scale precipitation (ARM/AMF-NIA) 1-km integration



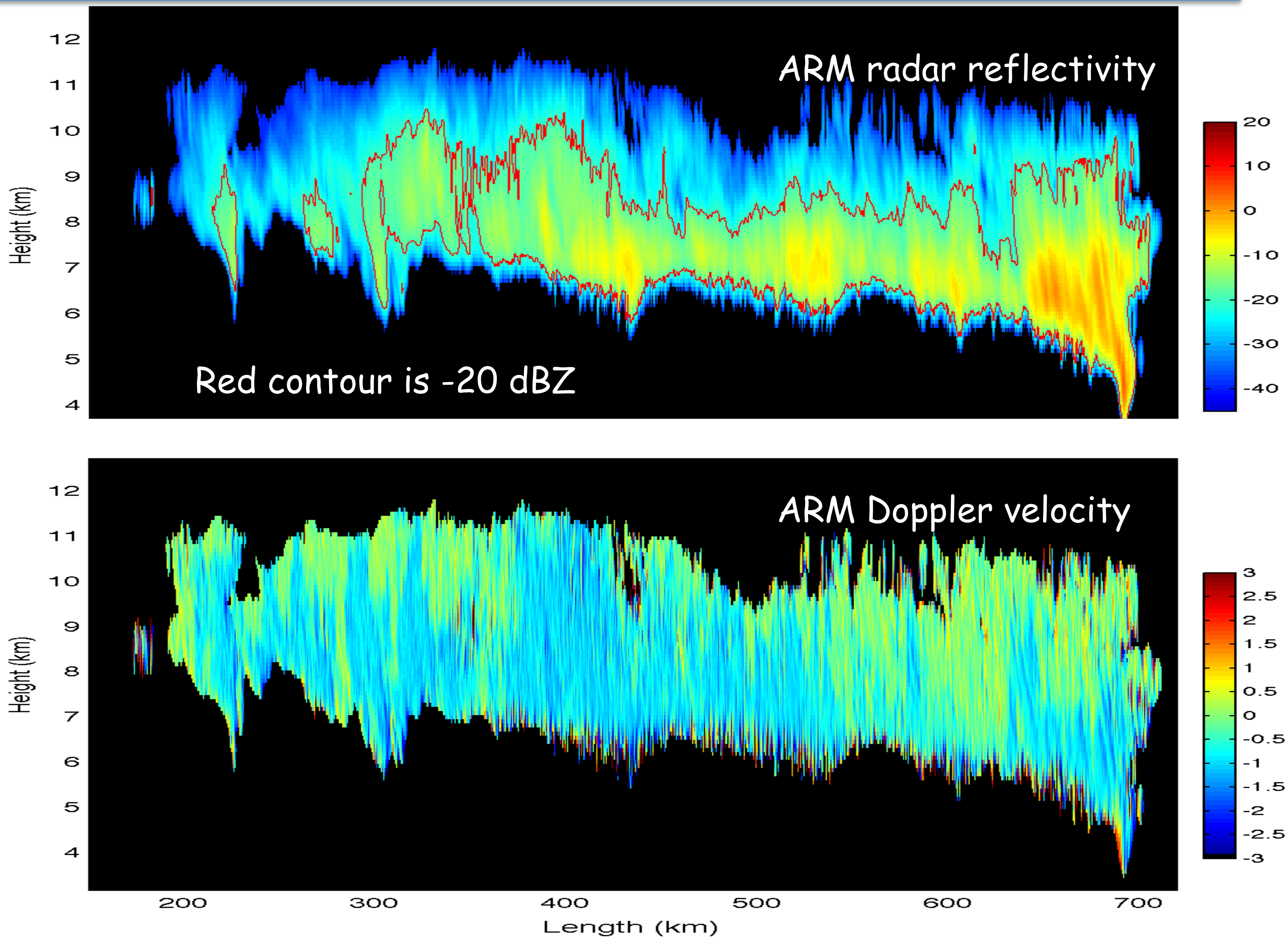
Melting Layer signature "stretching" >>> Need to account in precipitation retrievals
Doppler gradients sufficient to enable ML detection >>> Improve target classification



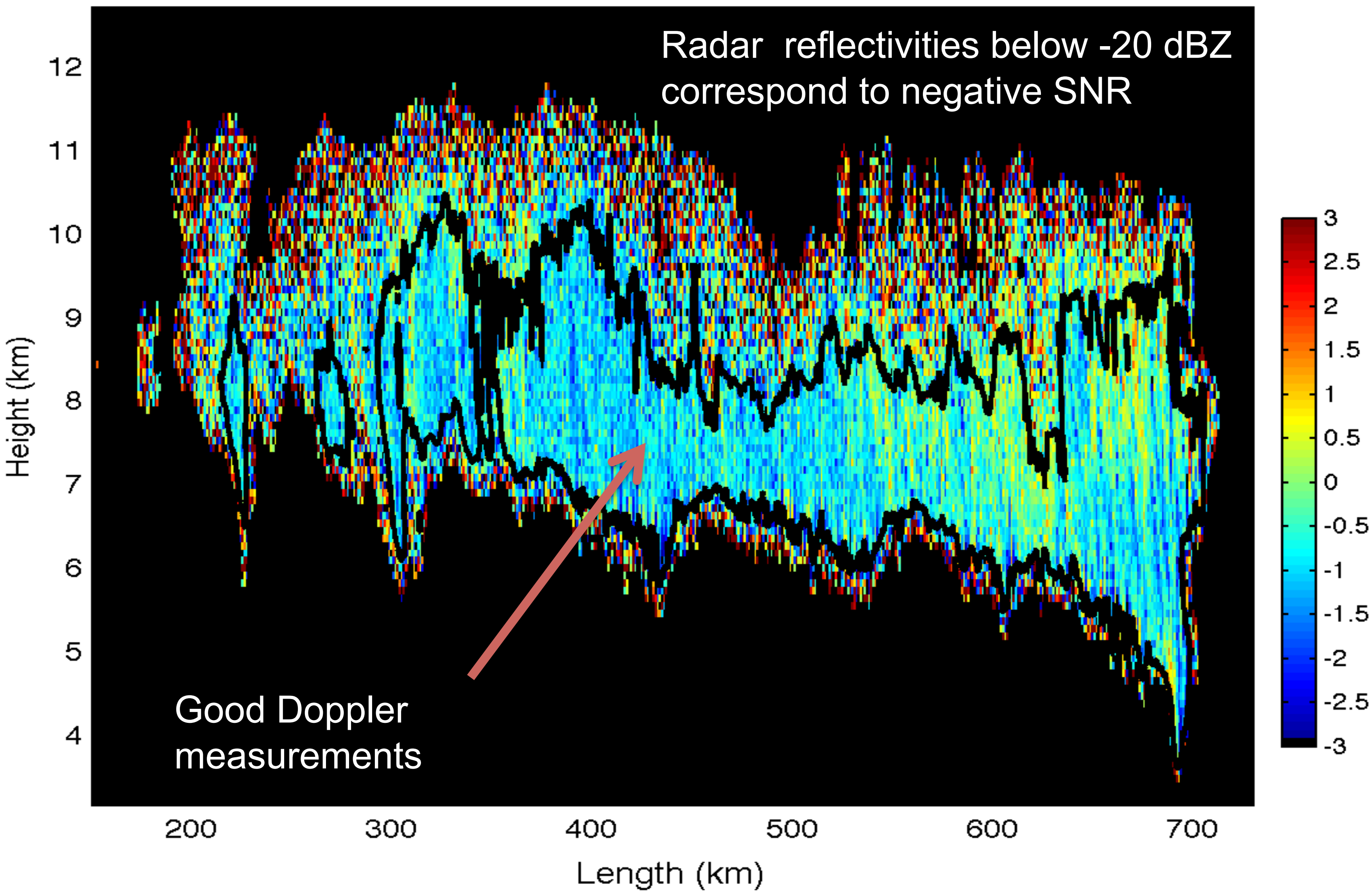
Large-scale precipitation (ARM/AMF-NIA)
Impact of SNR, Aliasing and NUBF on overall statistics



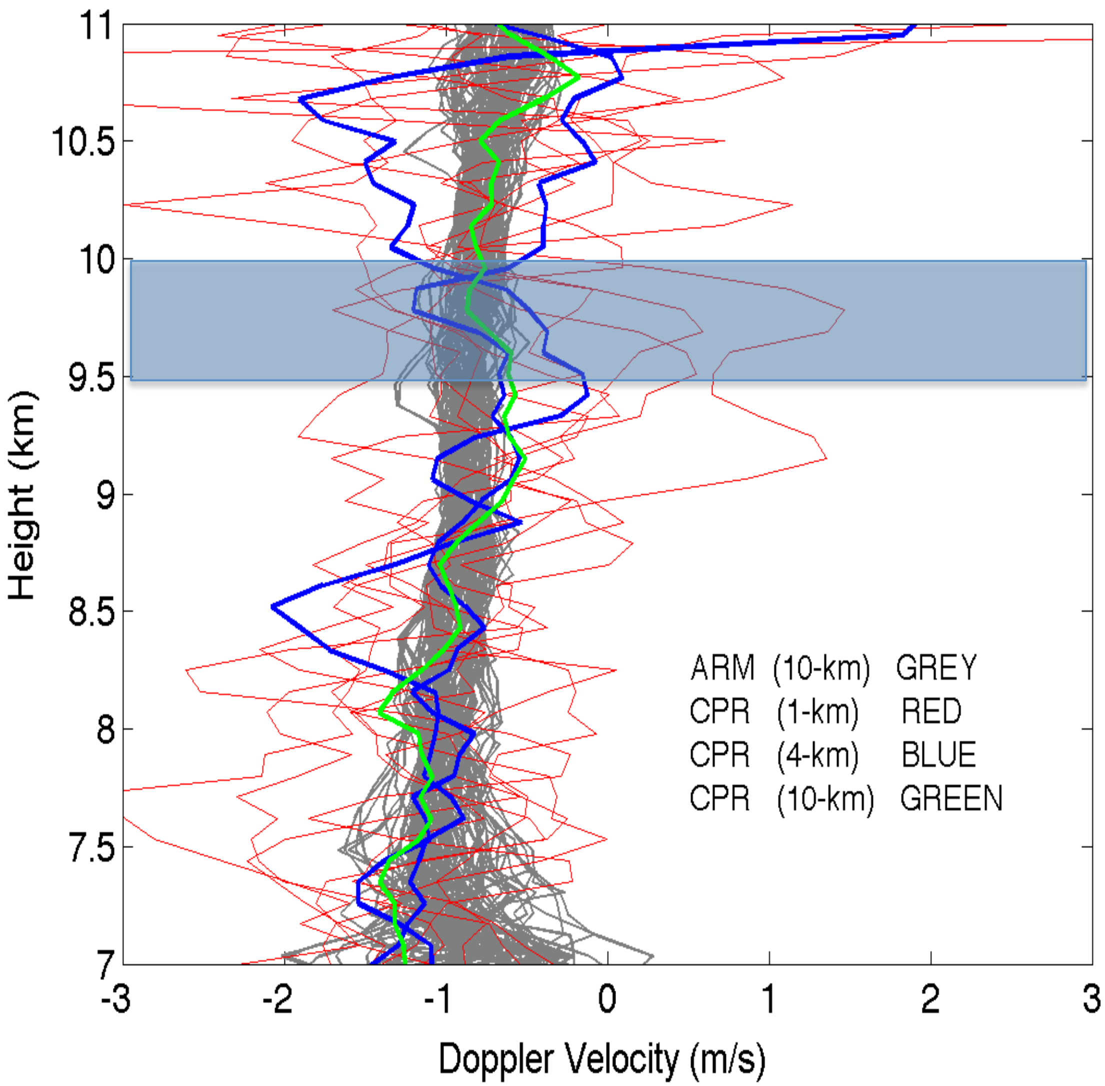
Deep cirrus (ARM/SGP)



Deep cirrus cloud (ARM/SGP) 1-km integration

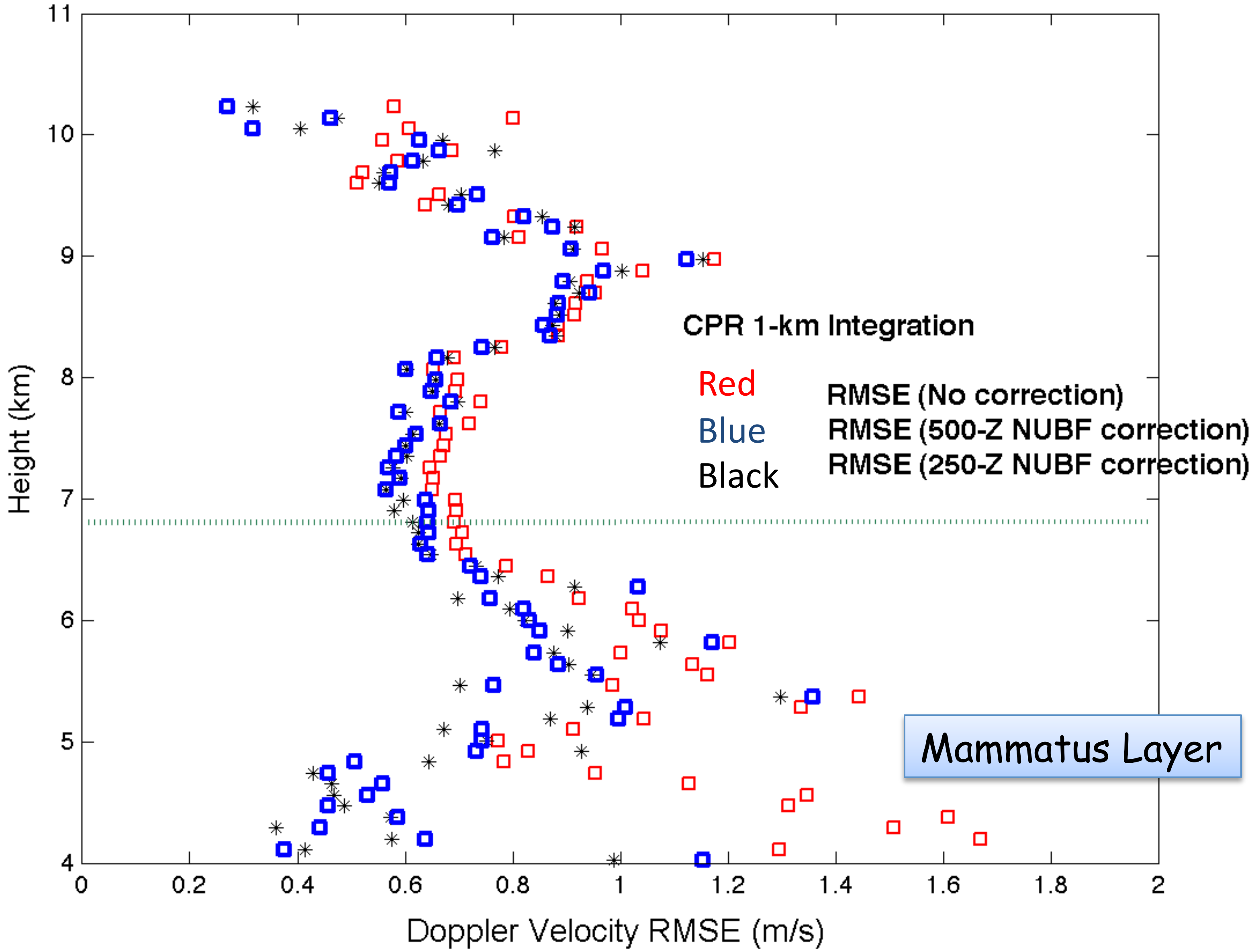


Velocity in cirrus

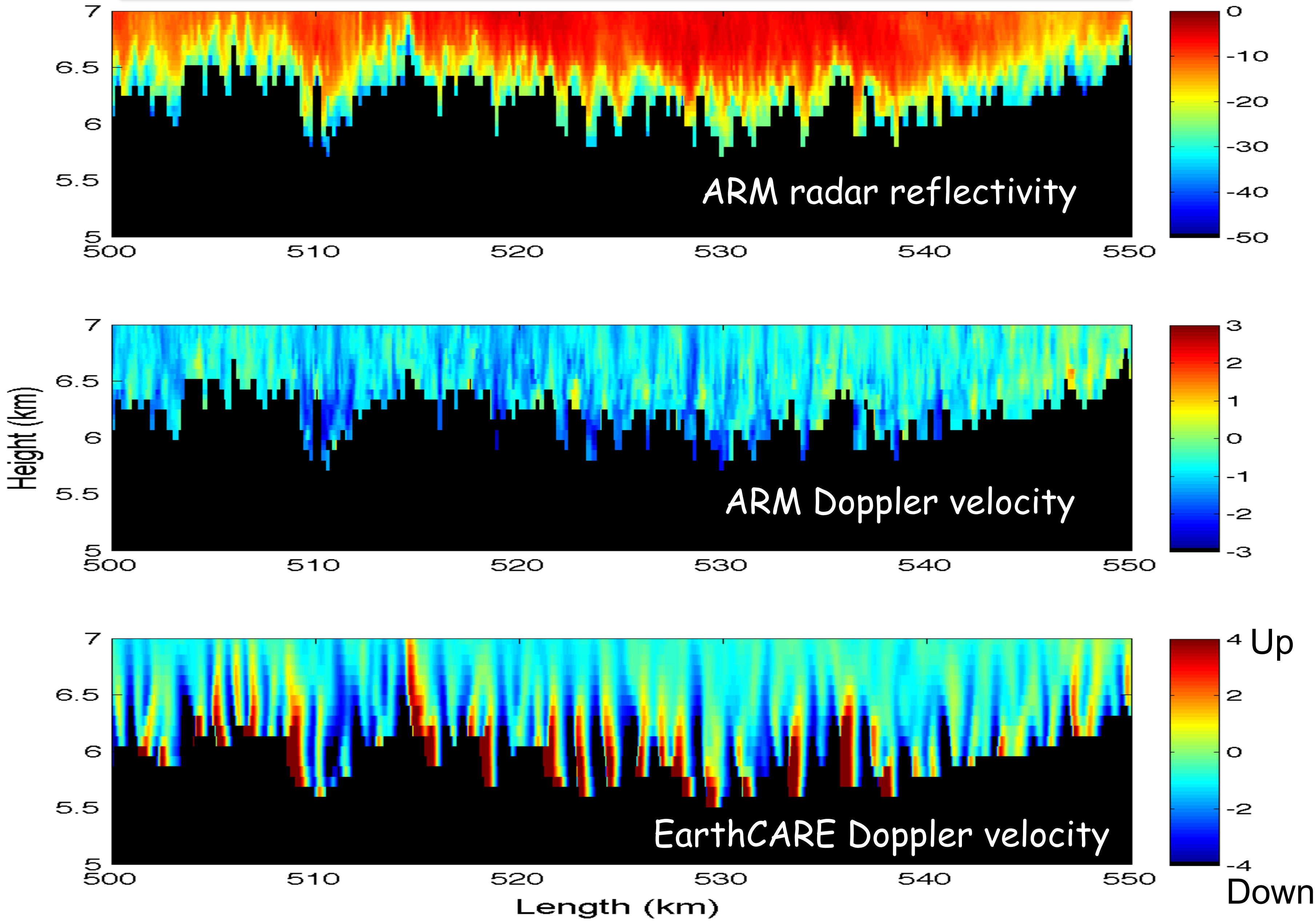


- 100-m range-sampling Doppler measurements are highly correlated:
  - For high SNR most of the signal fluctuation is due to scatterers relative positions.
- Along-range integration of Doppler velocity can help only if integration length exceeds significantly the 500-m.
  - Deconvolution in range of the Doppler estimates is not expected to provide much information
- Depends on reflectivity structure

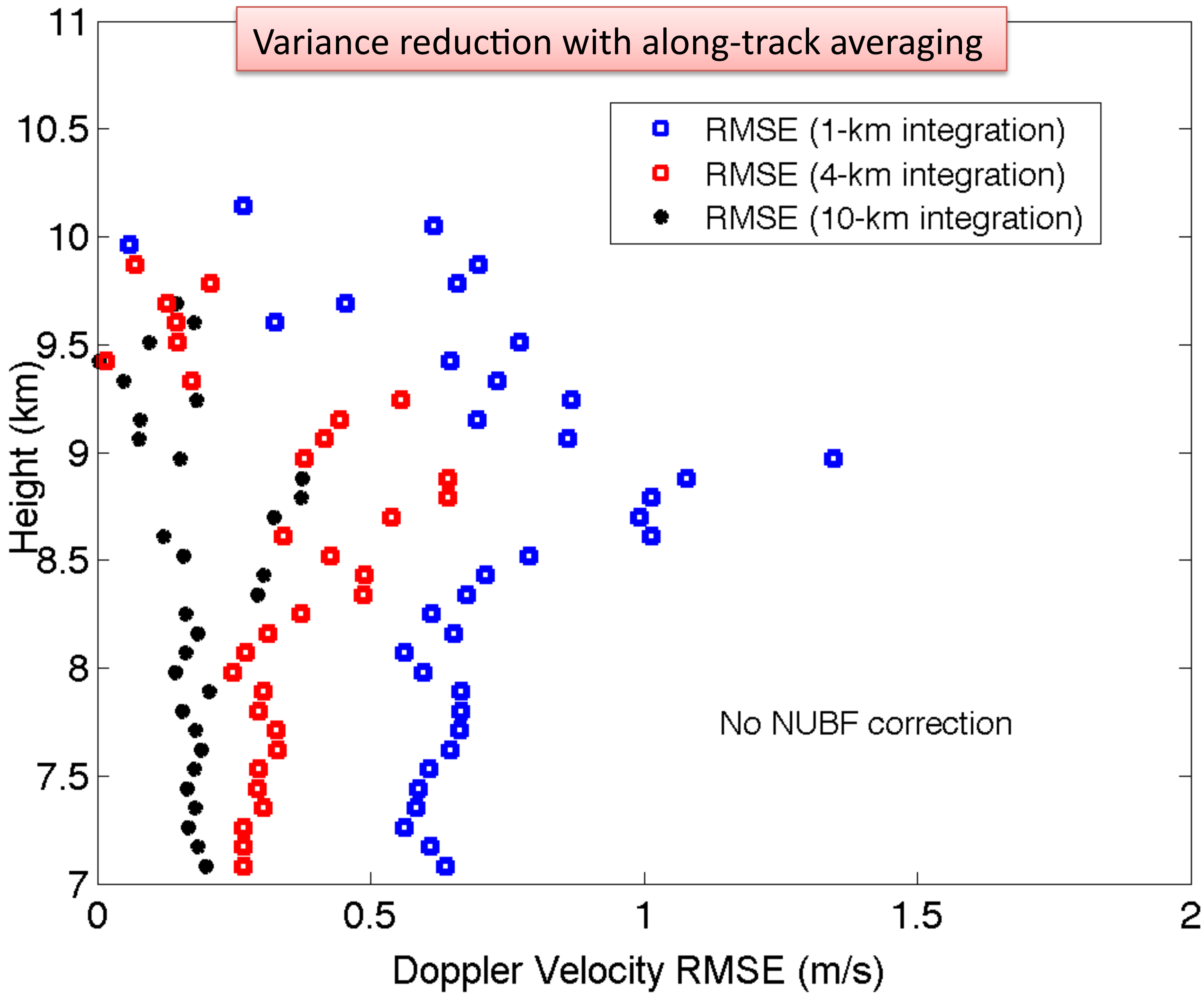
Deep cirrus cloud (ARM/SGP) Velocity RMS-Error



Example of NUBF



Deep cirrus cloud (ARM/SGP) Velocity RMS-Error



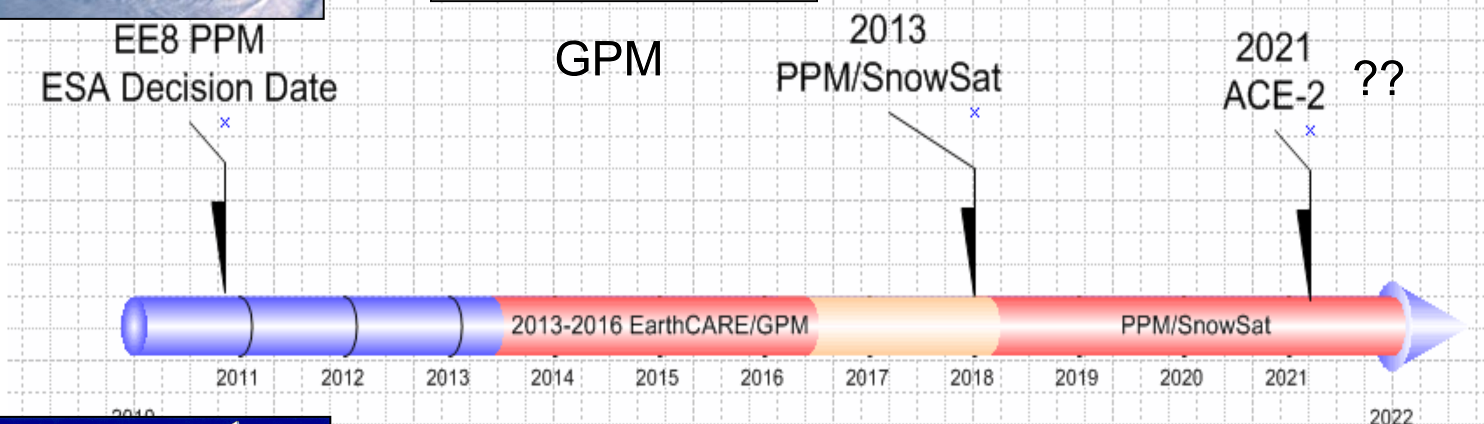
Preliminary assessment of Doppler performance on dynamical and microphysical retrievals

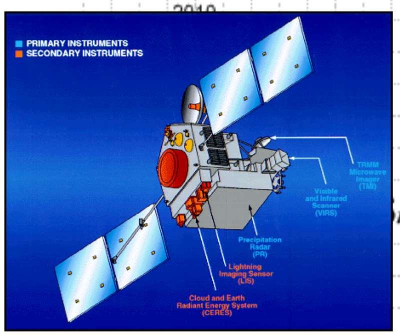
- Doppler “quality” indicator: $\sigma/|V_D|$

- **Convection**
  - NUBF and Multiple scattering are primary sources of uncertainty
  - NUBF correction is well established but we may be “integration challenged” – Need to flag observations for MS signatures
  - Pointing error would complicate matters.
- **Ice clouds**
  - $\sigma/|V_D|$~ marginally small at 3-10 km integration (depending on reflectivity structure) to use in ice clouds retrievals
  - Random pointing error (~40 μrad) could degrade the quality of the Doppler measurements.
- **Large-scale precipitation**
  - ML detection and Doppler magnitude at base and top of the ML can lead to improve R-retrievals
  - $\sigma/|V_D|$~ small enough at 3-5 km integration for use in quantitative retrievals of precipitation intensity and particle size
  - Random pointing is only a secondary problem.

Race to fill an anticipated gap in active spaceborne cloud observation

GPM





TRMM

–Cloud/precipitation measurement continuity post-CloudSat