Investigating Raindrop Evaporation, Breakup, and Coalescence in Stratiform Rain

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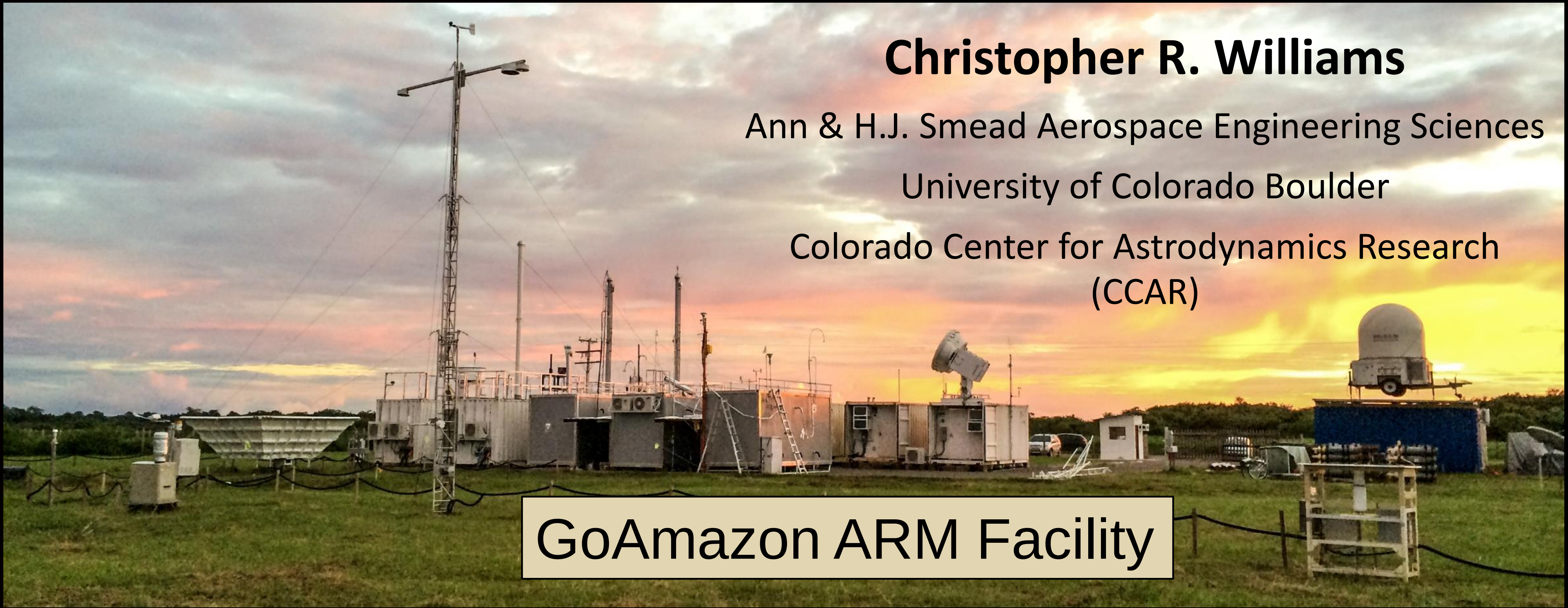
Colorado Center for Astrodynamics Research (CCAR)



University of Colorado Boulder

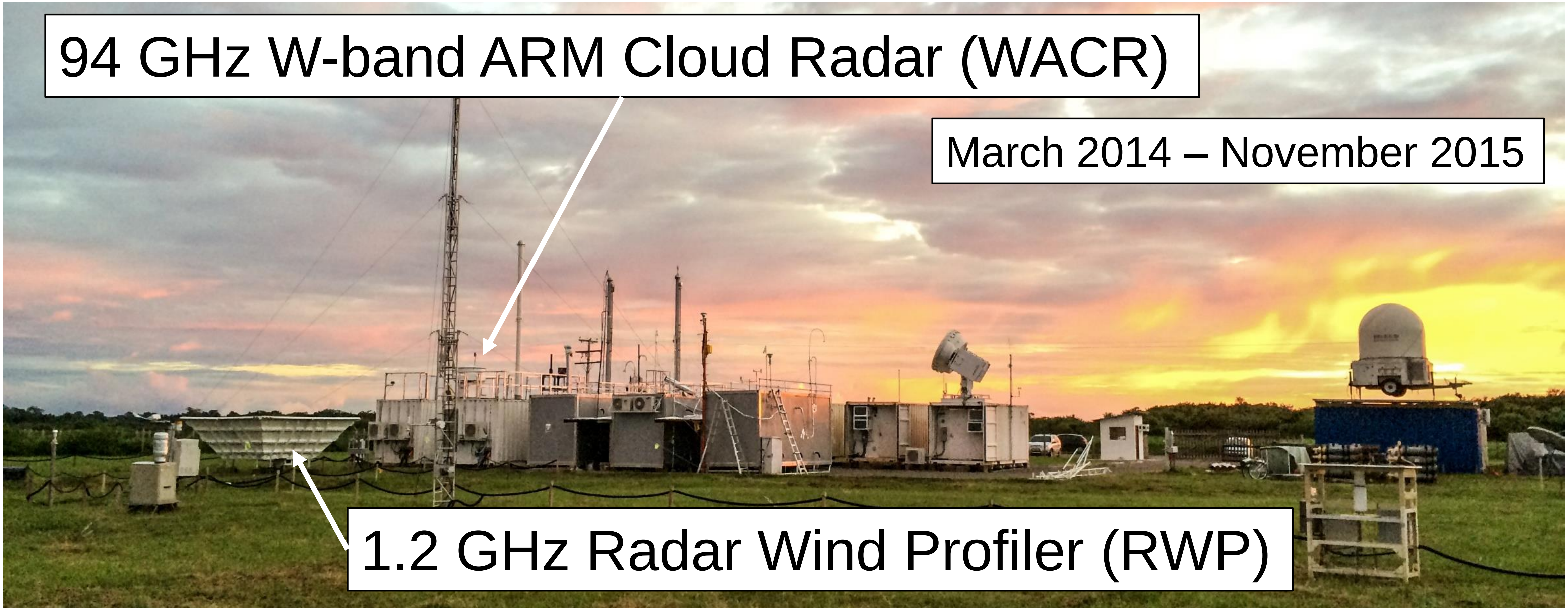
Support for this work:
DOE Atmospheric Science Research (ASR)
NASA Global Precipitation Measurement (GPM)

CCAR

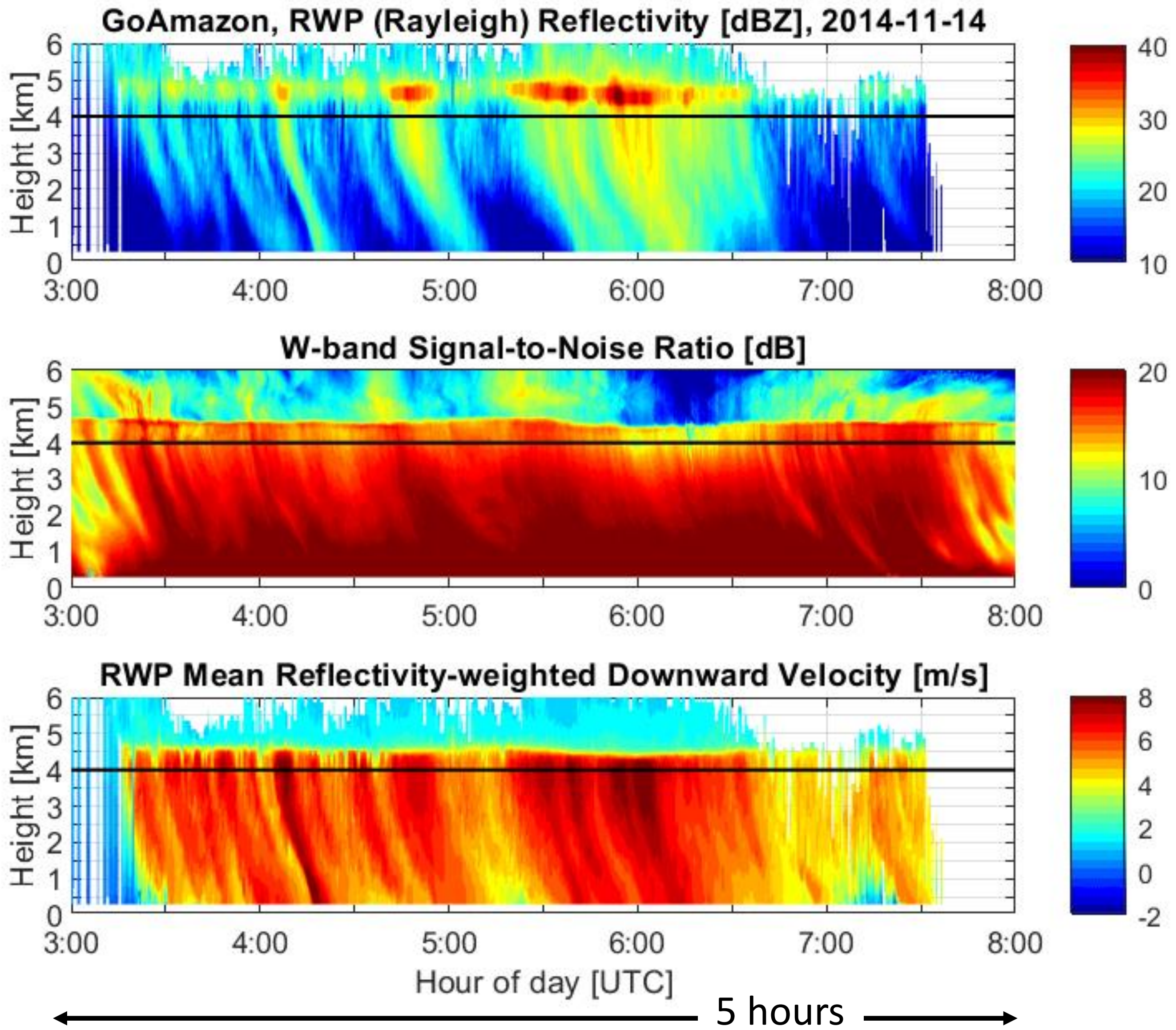
Presentation Outline

1. Vertically Pointing Radar (VPR) Observations
   - Green Ocean Amazon (GOAmazon) Field Campaign
   - Radar wind Profiler (RWP) at 1.2 GHz
   - mm-Wave Cloud Radar (W-band) at 94 GHz
2. Retrieve Raindrop Size Distribution
   - Exploit Rayleigh & “non-Rayleigh” scattering from raindrops
   - Convert DSD parameter N_w to N_t (to be more physical)
3. Vertical Decomposition Diagrams
   - Liquid Water Content ($q^{dB}, N_t^{dB}, D_q^{dB}$)
   - ‘Fingerprints’ - evaporation & breakup/coalescence
4. Next Steps

GoAmazon Field Site: Manous, Brazil



Vertical Structure of an Event: 14-Nov-2014



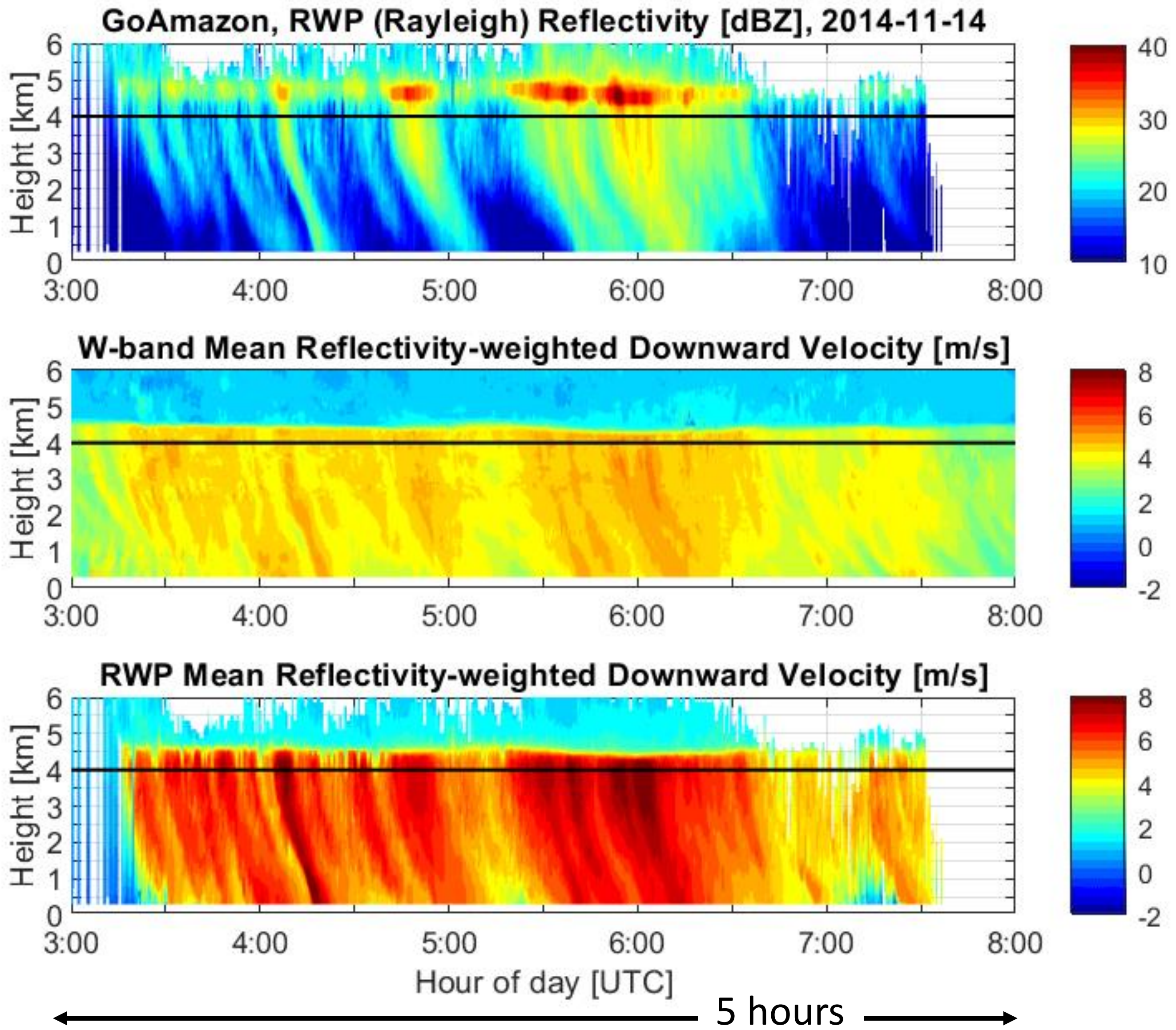
Match W-band profiles every 2 sec

1.2 GHz
Reflectivity [dBZ]
Dwell: 2 second
Repeat vertical beam every 12 seconds
Beamwidth ~9°

94 GHz
Signal/Noise [dB]
Dwell: 2 second
Repeat: every 2 seconds
Beamwidth ~0.1°

1.2 GHz
Mean Reflectivity Downward Velocity [m/s]
(Positive values are downward)

Vertical Structure of an Event: 14-Nov-2014



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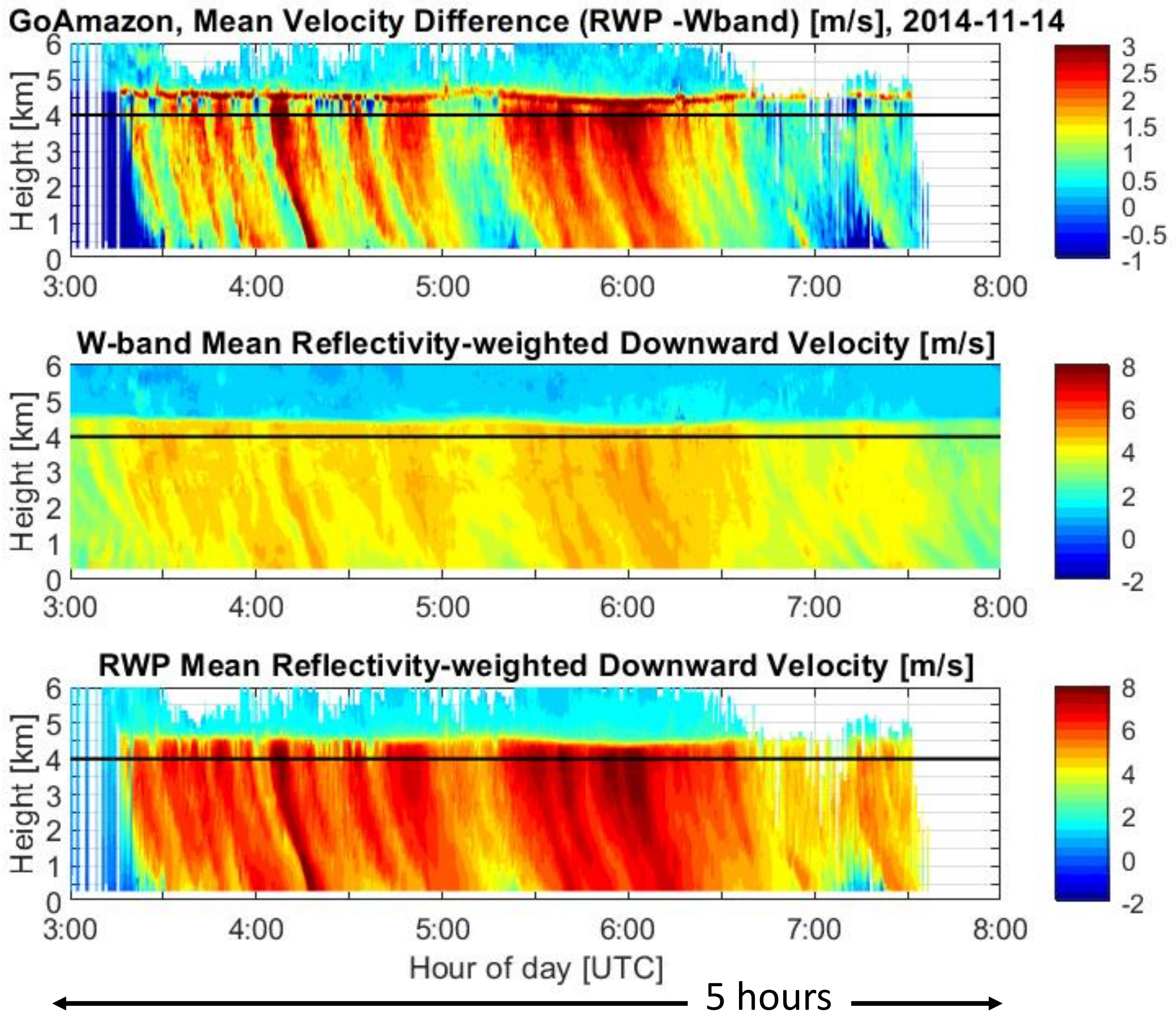

Downward Velocity Difference (DVD)
(RWP – W-band) [m/s]

94 GHz
Mean Reflectivity Downward Velocity [m/s]
(Positive values are downward)

1.2 GHz
Mean Reflectivity Downward Velocity [m/s]
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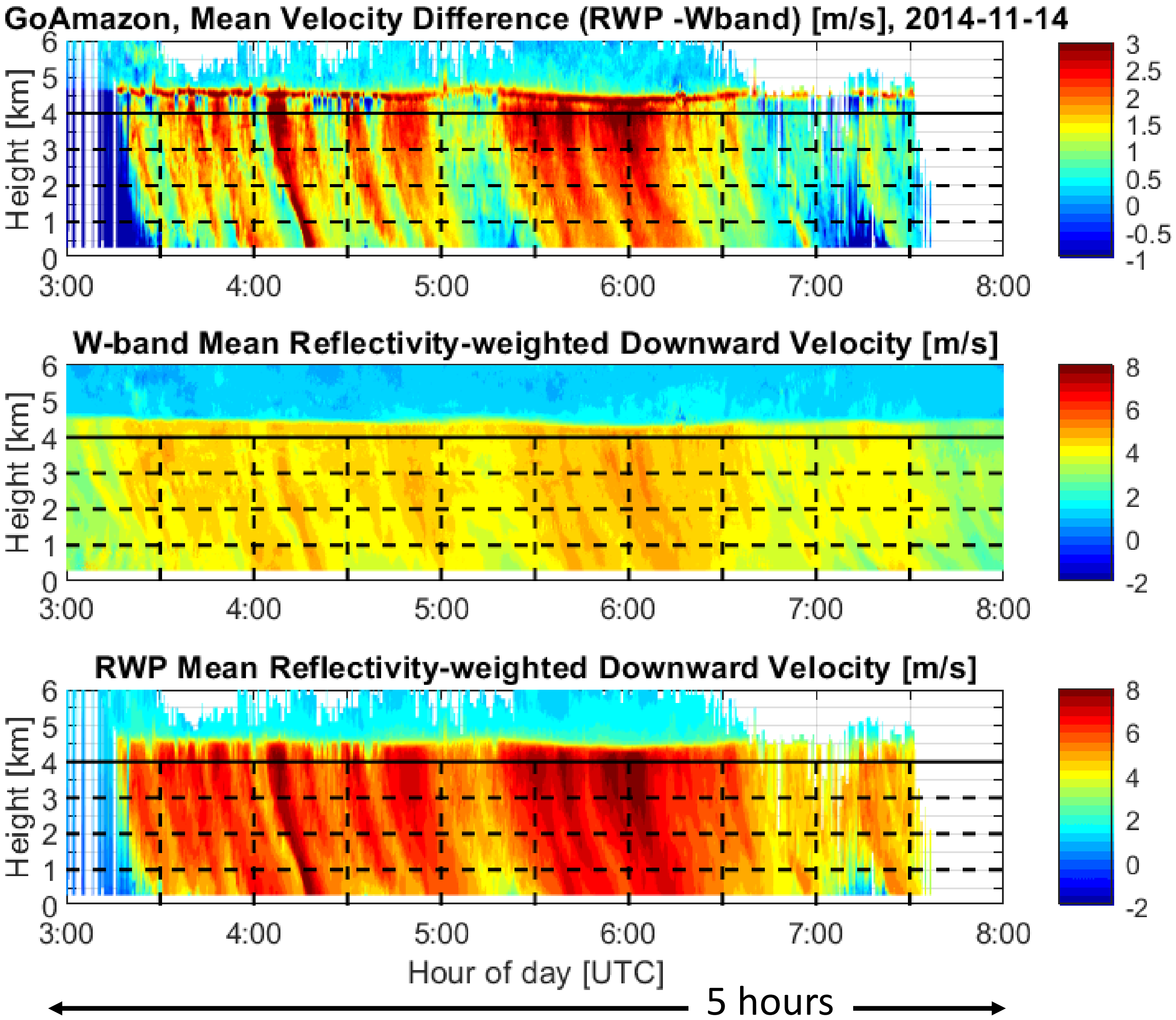
Vertical Structure of an Event: 14-Nov-2014



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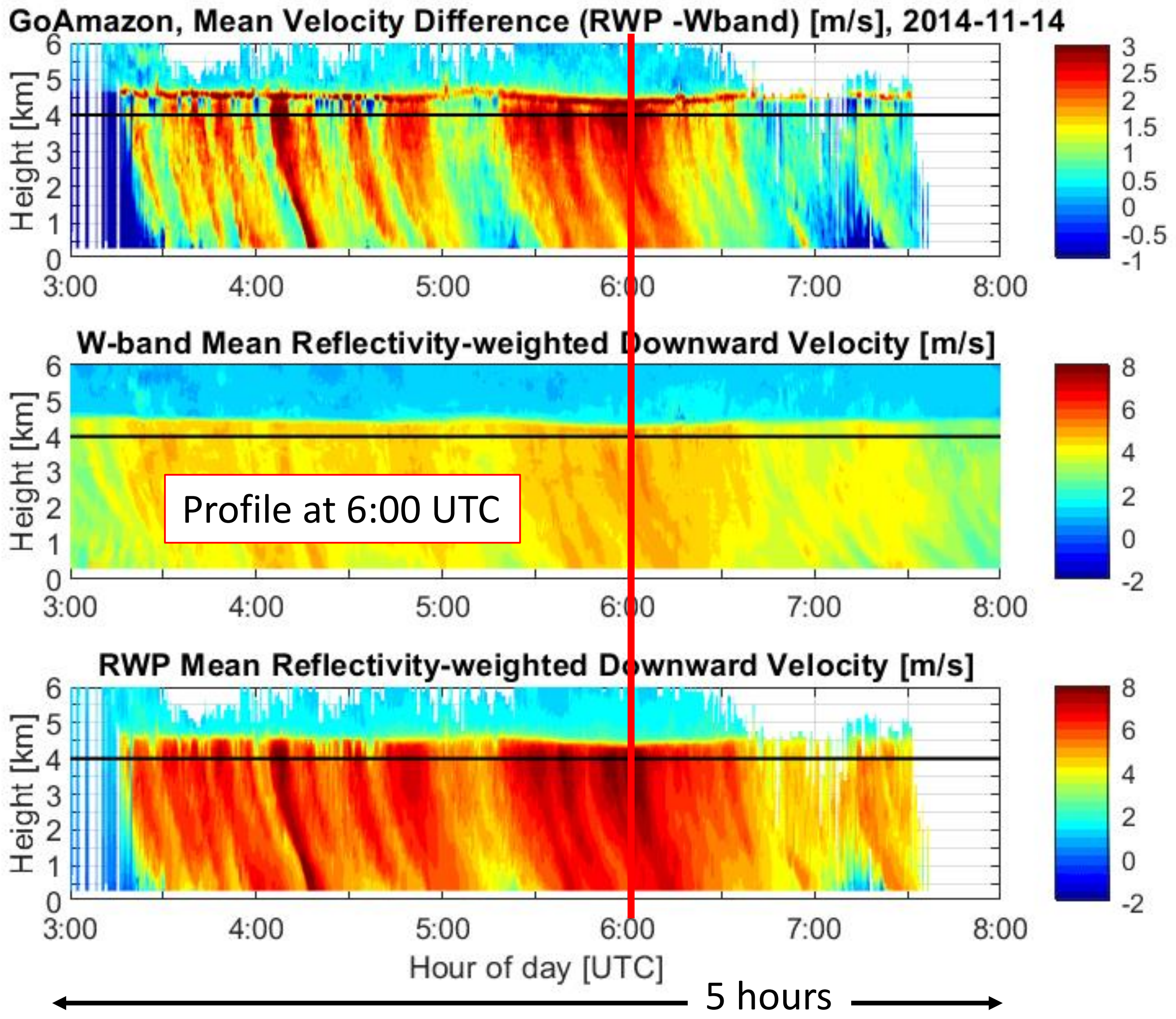

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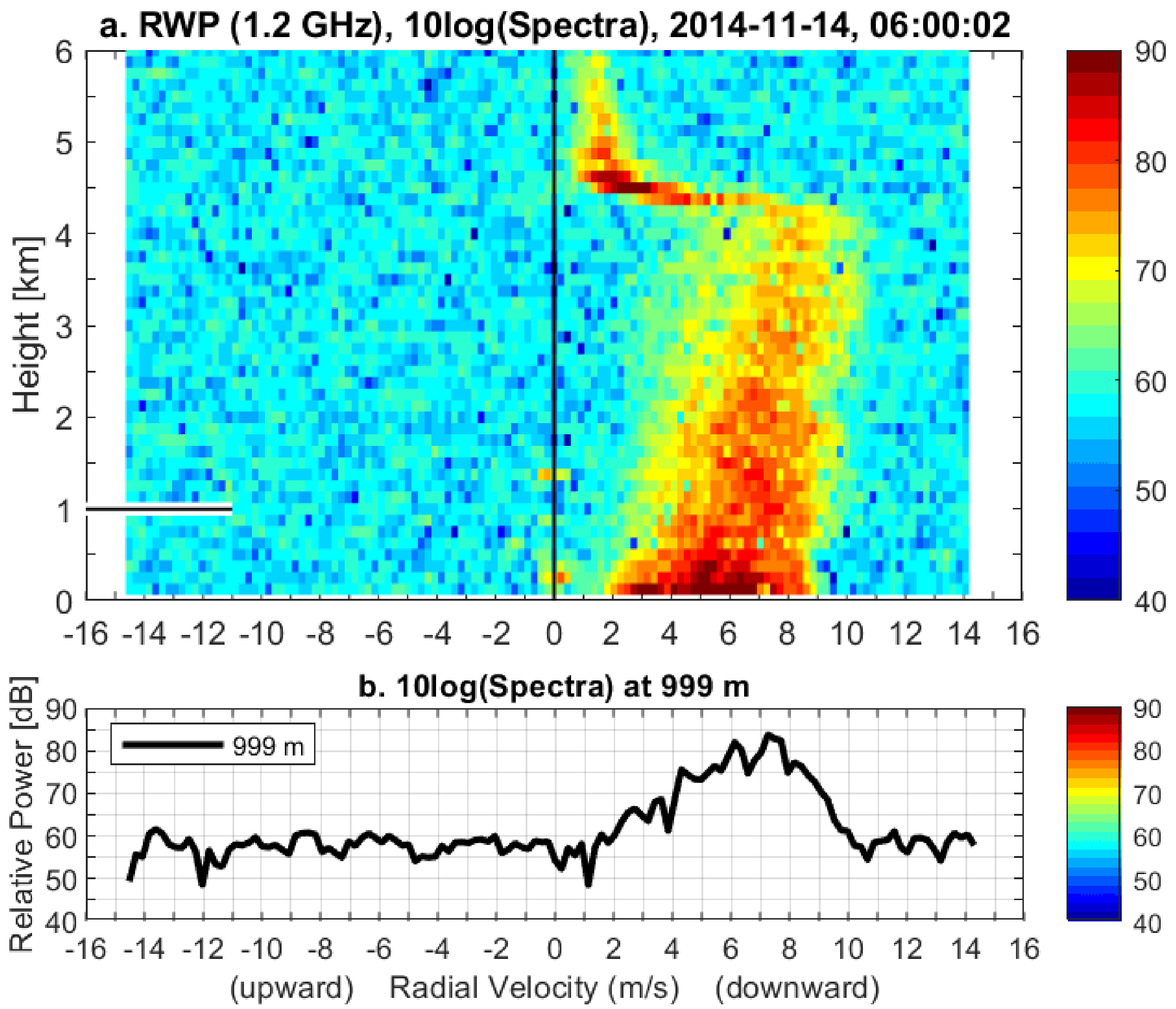
RWP (1.2 GHz) Spectra Profile at 6:00:02 UTC



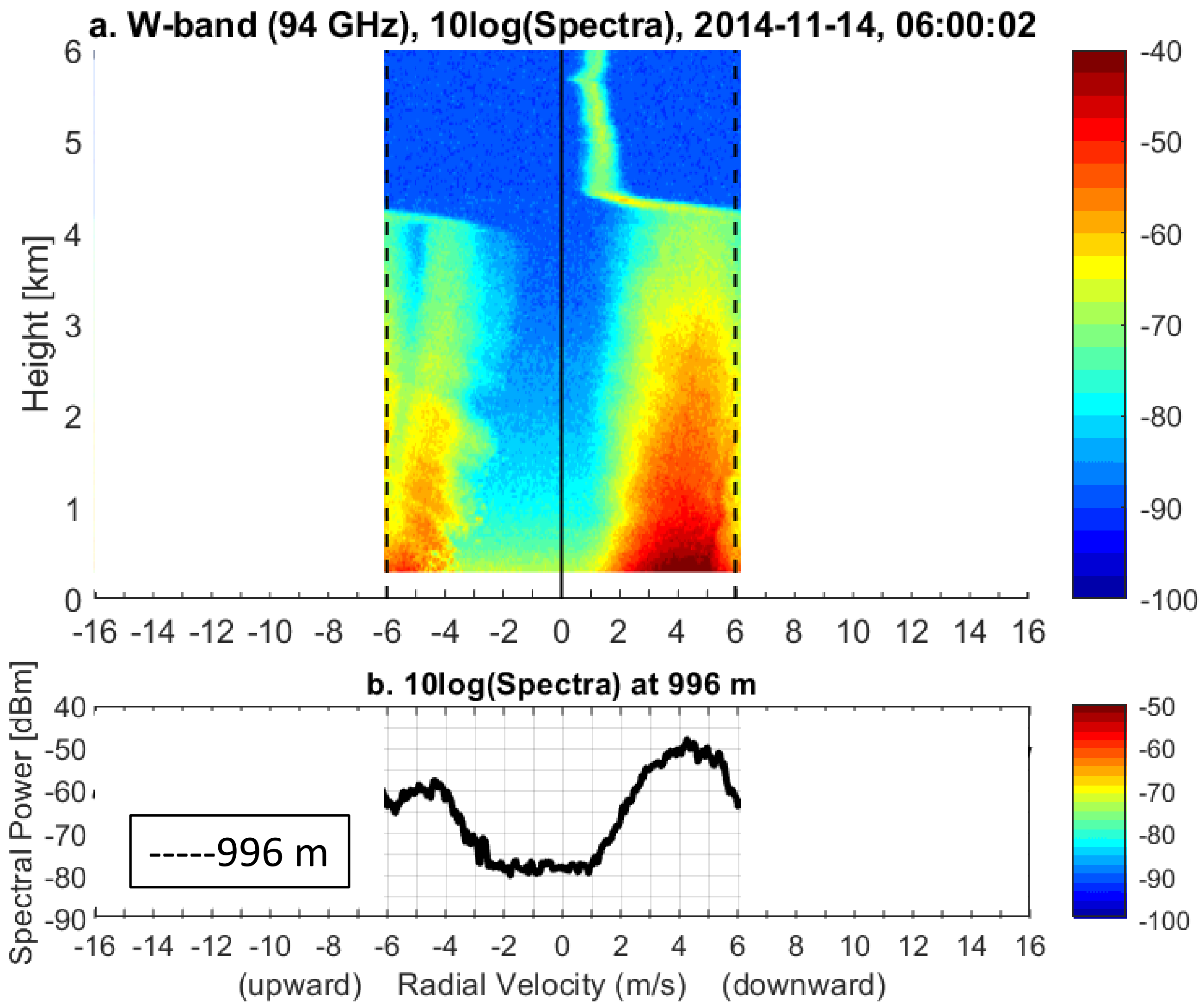
Reflectivity spectral density

Units are: 10*log([Intensity/(m/s))
Intensity is relative power before calibration

Nyquist velocity 14 m/s

Spectrum at 1 km
(Positive velocities are downward)

W-band (94 GHz) Spectra Profile at 6:00:02 UTC



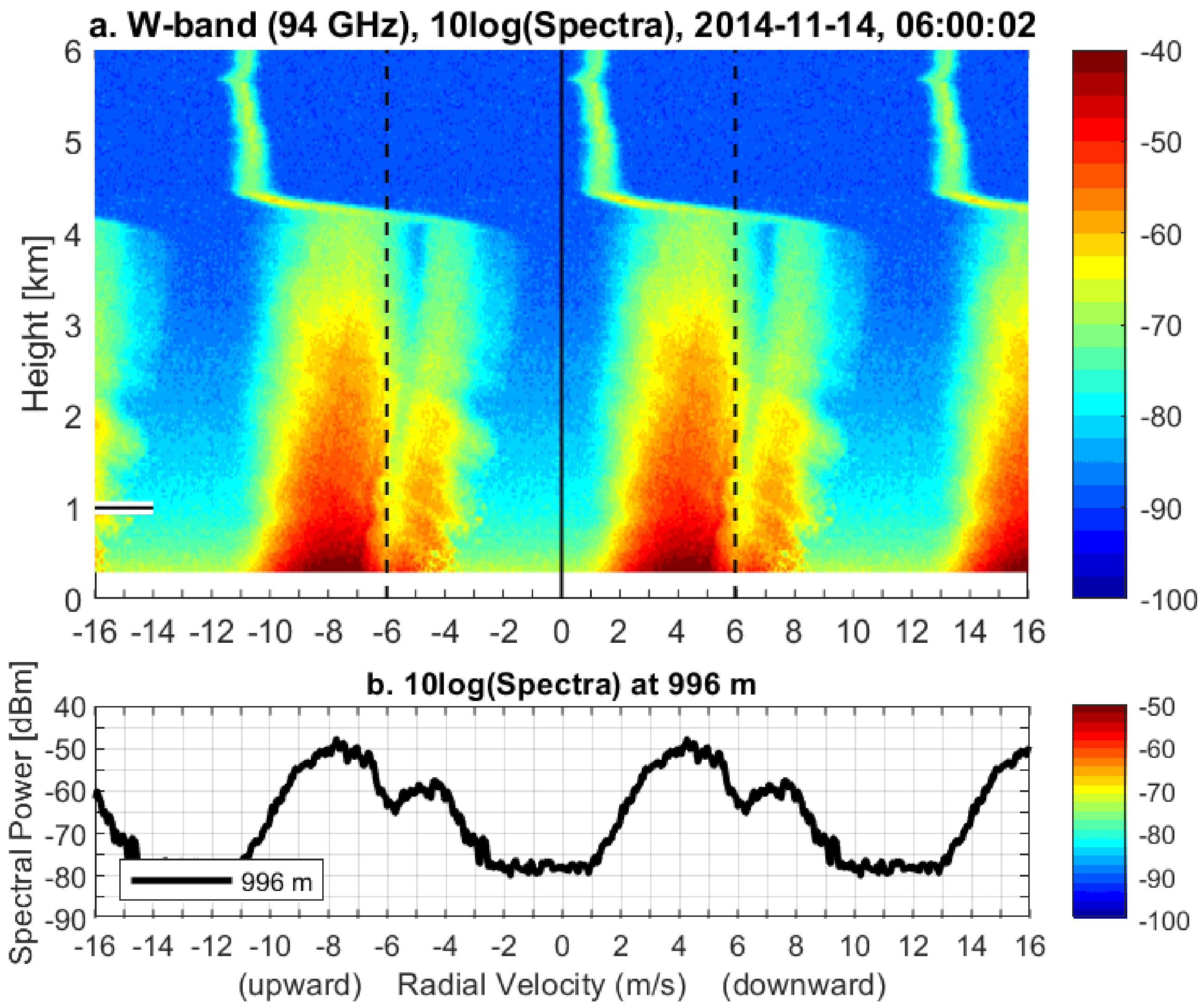
Reflectivity spectral density

Units are: 10*log([Intensity/(m/s))
Intensity is received power after applying an engineering calibration

Nyquist velocity 6 m/s

Spectrum at 1 km
(Positive velocities are downward)

W-band (94 GHz) Spectra Profile at 6:00:02 UTC



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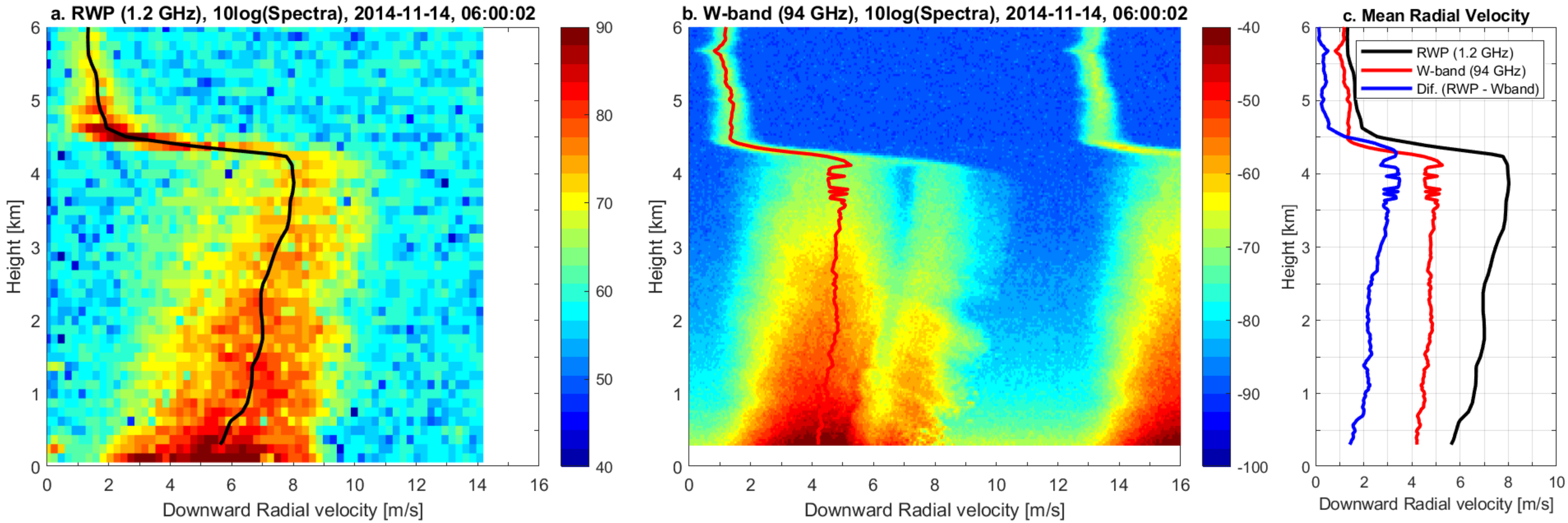

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DSD & Vertical Air Motion Retrieval Framework

Desire to Estimate four (4) Unknowns:

3 DSD Parameters: N_w, D_m, μ

1 Dynamic parameter: air motion, ω

Observations:

Measured Quantity	1.2 GHz Radar	94 GHz Radar
Spectra	Not Good for fitting (too noisy)	Good for fitting
Reflectivity	Good (calibrated with surface disdrometer)	Not Good (need to correct for path attenuation)
Mean Velocity	Good	Good
Spectrum Width	Not Good (DSD breadth and turbulence)	Good (but dependent on SNR)

Retrieval Steps:

1. Measure velocity difference: $\Delta v = v_{RWP} - v_{Wband}$
2. Fit 94 GHz spectra with Δv constraint. Yeilds: D_m, μ, and air motion ω
3. Use Z_{RWP} with D_m and μ to estimate N_w

How are Doppler velocity spectra produced?

- Reflectivity factor of raindrop, with diameter D:

$$z(D) = \frac{\lambda^4}{\pi^5 |K_w|^2} \underline{N(D)} \; \underline{\sigma_b^\lambda(D)} \; \underline{\Delta D} \quad [\text{mm}^6\ \text{m}^{-3}]$$

$\underline{N(D)}$ – Raindrop number concentration

Number of raindrops, per diameter, per cubic meter, which is expressed as: [# mm^{-1} m^{-3}]

Also know as: rain<u>d</u>rop <u>s</u>ize <u>d</u>istribution (DSD)

$\underline{\sigma_b^\lambda(D)}$ – Radar backscattered cross-section (RCS)

Cross-sectional area [mm^2] dependent on wavelength λ

$\underline{\Delta D}$ – Diameter interval [mm]

$\sigma_b^\lambda(D)$ – Radar backscattering cross-section

- Rayleigh scattering

  $\sigma_b^\lambda(D) \sim D^6$: Radar wavelength is large relative to raindrop diameter
  - 1.2 GHz: all raindrops
  - 94 GHz: raindrops smaller than 1 mm diameter
- Mie Scattering ("non-Rayleigh" scattering)

  $\sigma_b^\lambda(D) < D^6$: Radar wavelength is similar to raindrop diameter

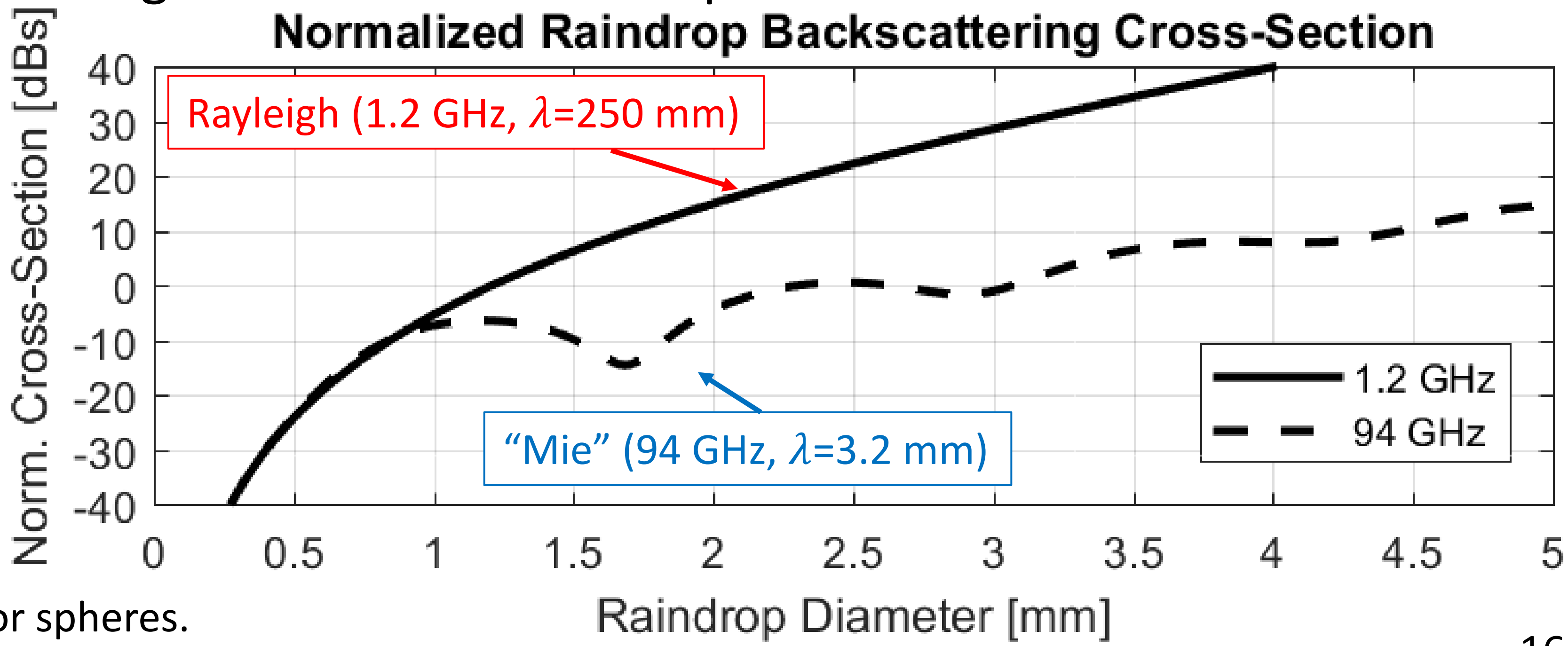
Normalization:

$$\sigma_{b,norm}^\lambda(D) = \left[\frac{\lambda^4}{\pi^5 |K_w|^2}\right] \sigma_b^\lambda(D)$$

Units:

$\sigma_b^\lambda(D)$ - [mm^2]

$\sigma_{b,norm}^\lambda(D)$ - [mm^6]



Note: "Mie" calculations are only valid for spheres.
"Non-Rayleigh" indicates deviations from Rayleigh assumption.

Define DSD Parameters

- Assume
  - Gamma distribution
  - Full integrals: no small & large drop truncation
  - Parameters: N_w, D_m, μ

$N_w = N_0^*$ (Testud et al. 2001)

$$N(D) = N_w f(D; D_m, \mu) =$$

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$$N(D) = N_w f(D; D_m, \mu) = N_w \left(\frac{6}{4^4} \frac{(\mu+4)^{\mu+4}}{\Gamma(\mu+4)} \right) \left(\frac{D}{D_m} \right)^{\mu} \exp\left(-(\mu+4) \left(\frac{D}{D_m} \right) \right)$$

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$$N_w = \frac{4^4}{\pi \rho_w} \left(\frac{q}{D_m^4} \right)$$

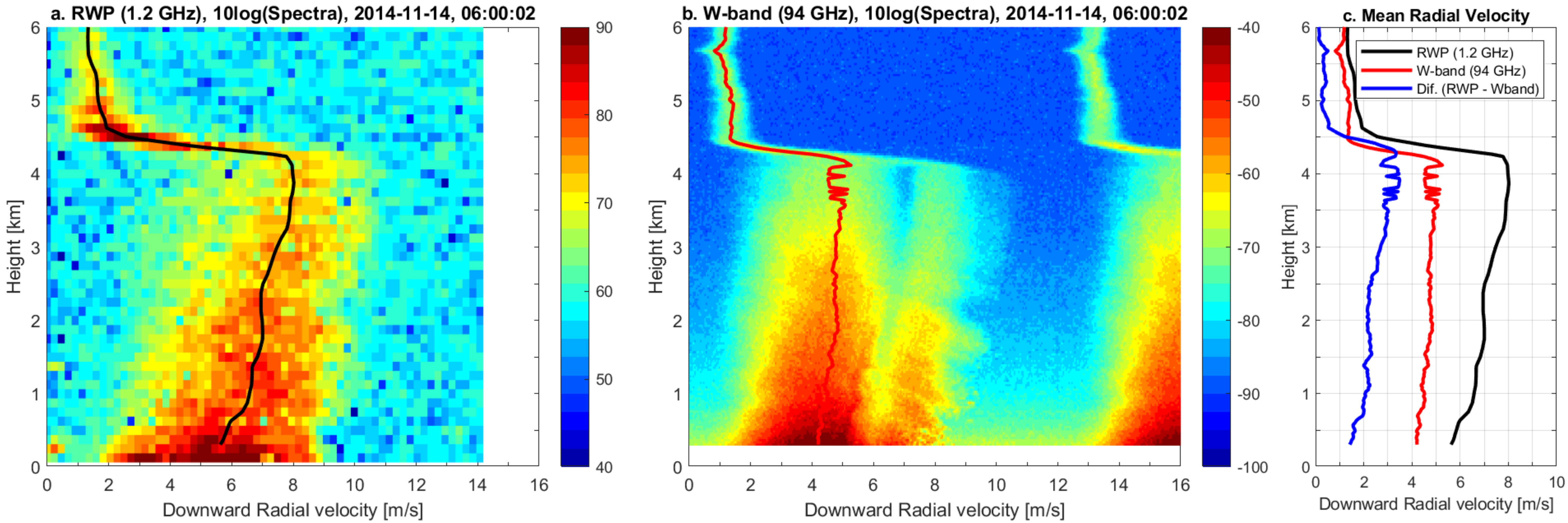
$$q = \frac{\pi \rho_w}{6x10^3} \int_0^\infty N(D) D^3 dD = \frac{\pi \rho_w}{6x10^3} M_3$$

Liquid water content (g m^{-3})

$$D_m = \frac{\int_0^\infty N(D) D^4 dD}{\int_0^\infty N(D) D^3 dD} = \frac{M_4}{M_3}$$

Definition of N_w: Intercept parameter (N_0 – # of drops with zero diameter) of an exponential distribution with the same liquid water content q and mean diameter D_m (Testud et al. 2001).

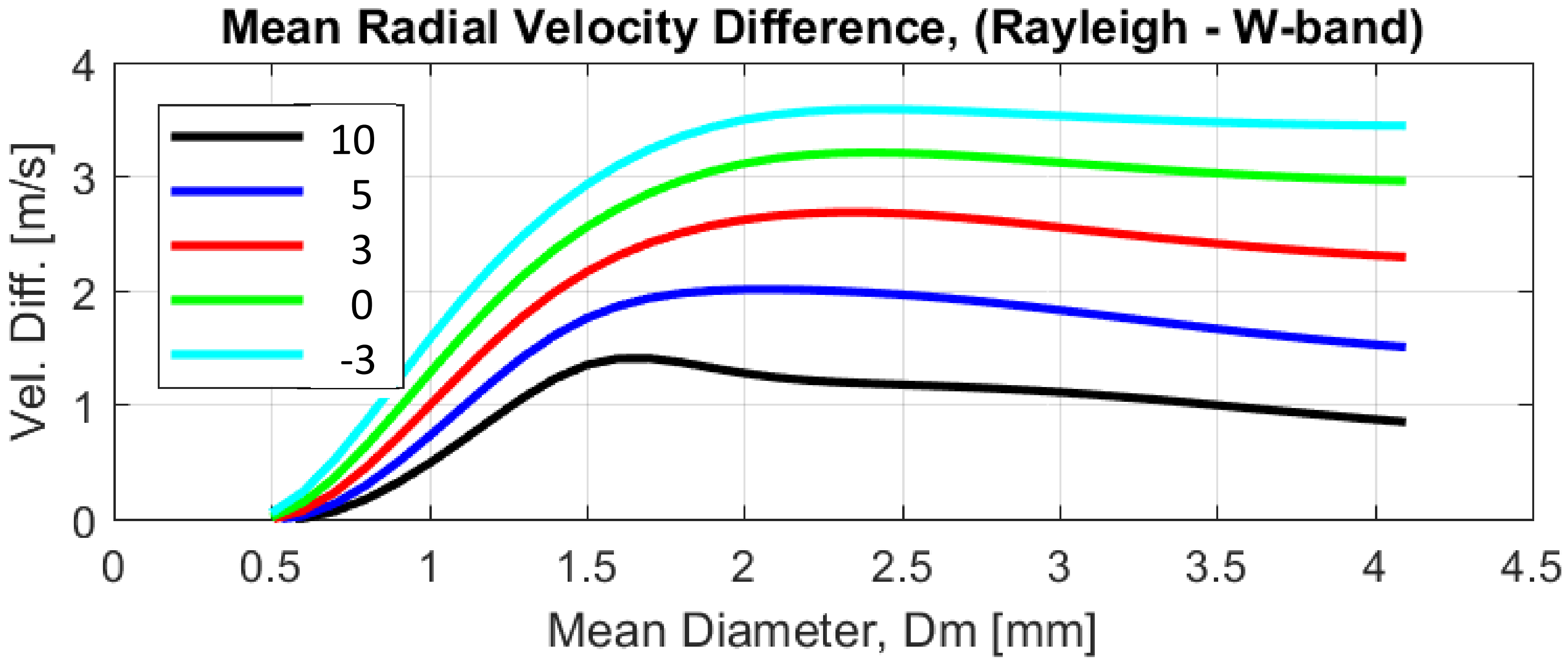
RWP (1.2 GHz) & W-band (94 GHz) Spectra Profile at 6:00:02 UTC



Expected Mean Downward Velocity Difference (DVD)

The mean radial velocity for both RWP and W-band are a function of D_m and μ.

Plot shows simulated downward radial velocity difference (DVD) as a function of D_m for a constant value of μ.



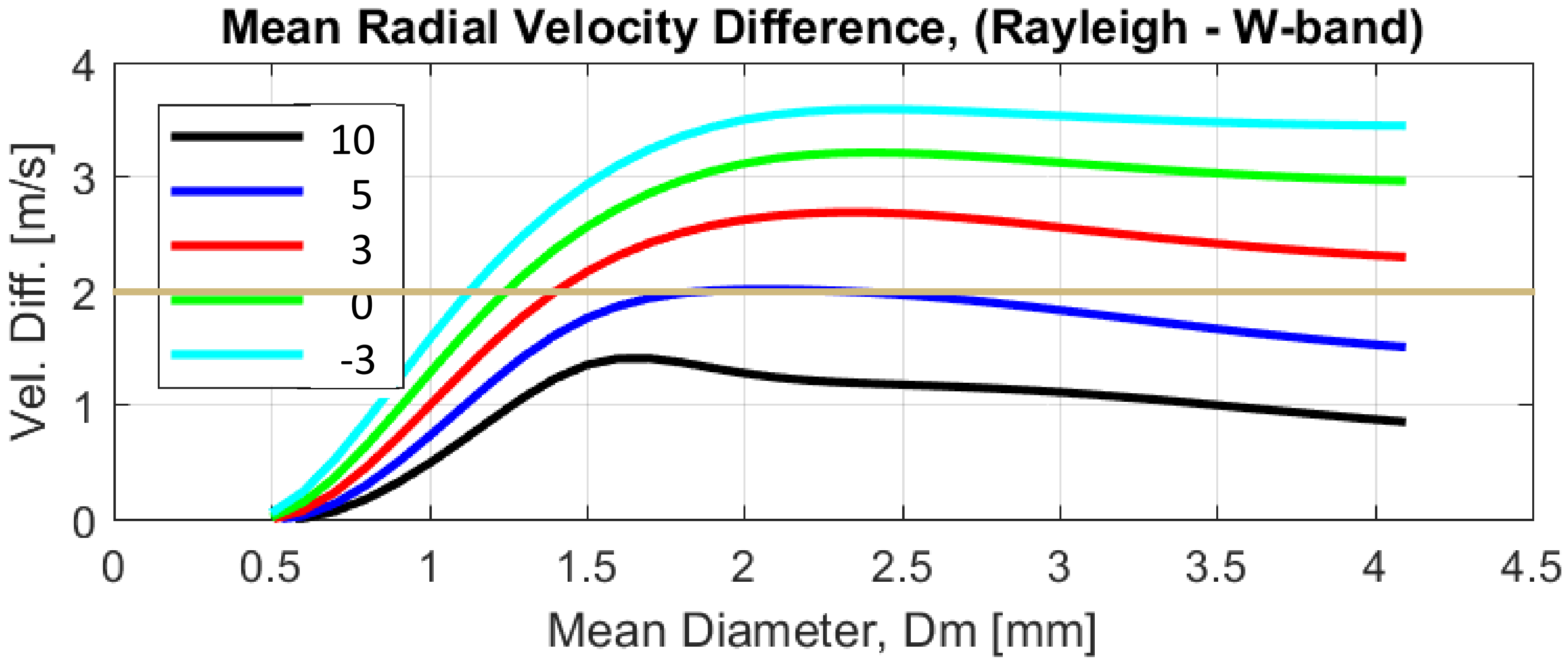
For a measured DVD, there is a family of (D_m,μ) possible solutions.

Expected Mean Downward Velocity Difference (DVD)

The mean radial velocity for both RWP and W-band are a function of D_m and μ.

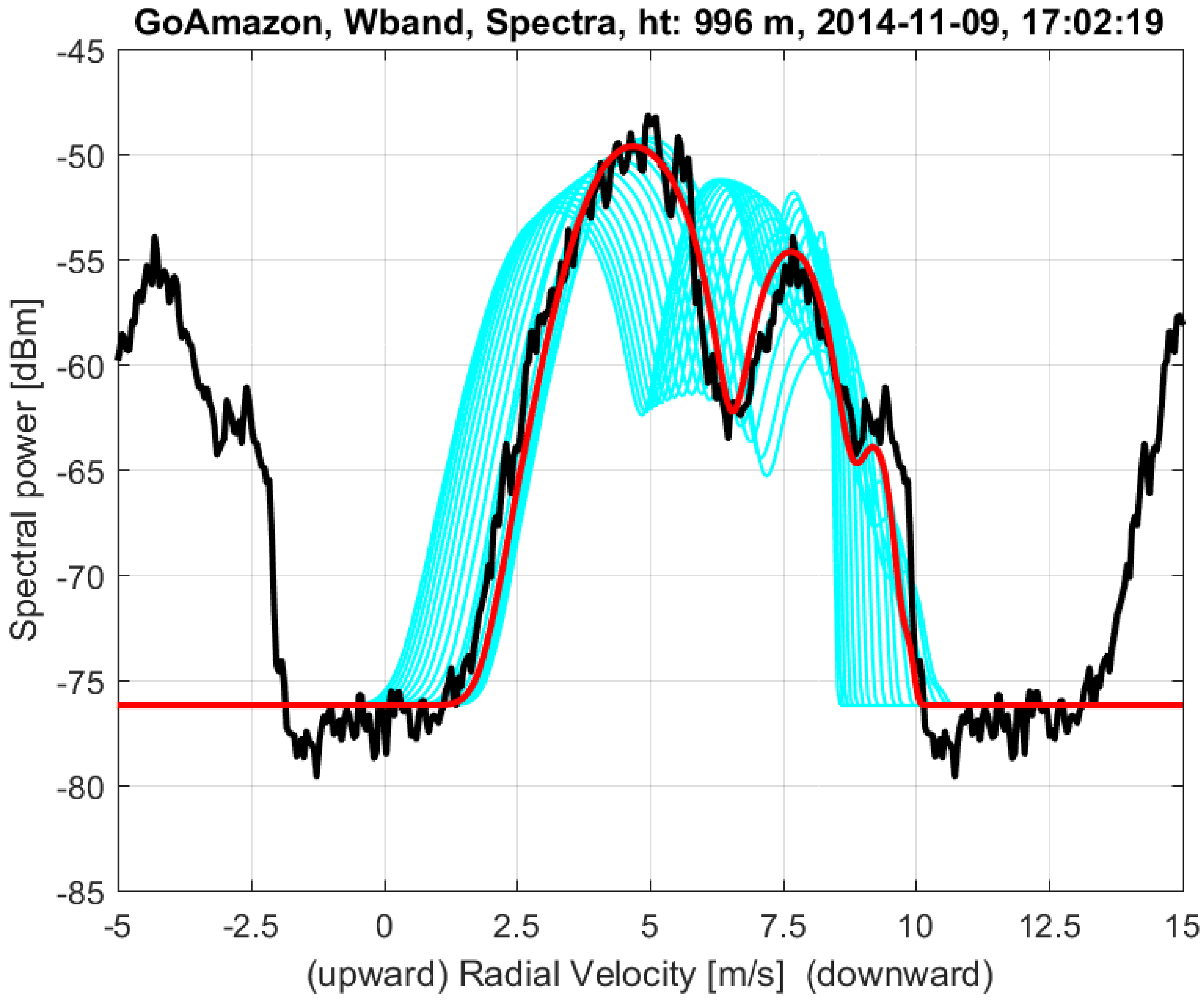
Plot shows simulated downward radial velocity difference (DVD) as a function of D_m for a constant value of μ.

For a given value of observed DVD (example $DVD = 2\, m/s$)



For a measured DVD, there is a family of (D_m, μ) possible solutions.

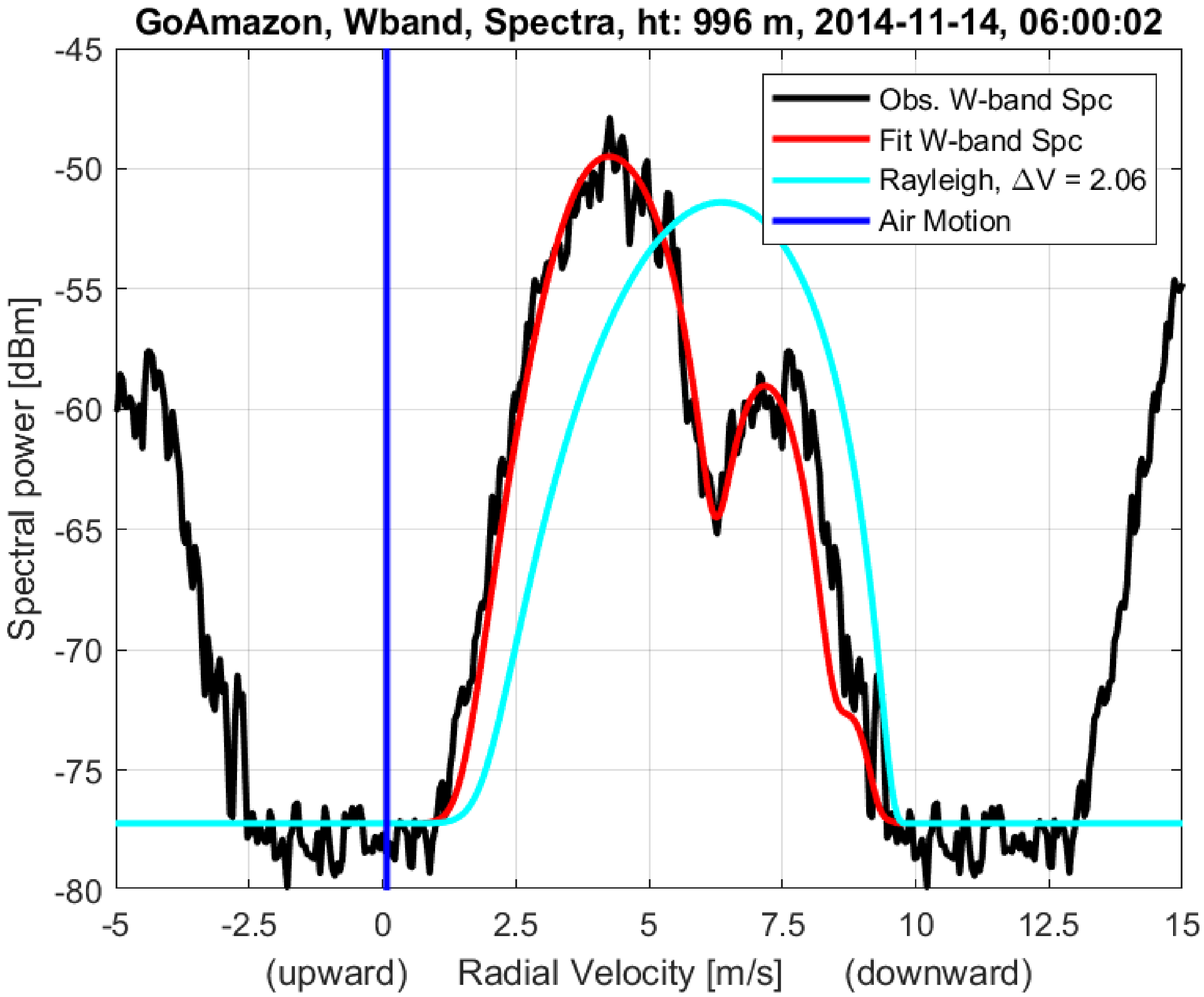
Find Best Solution by Fitting to W-band Spectra



Blue lines are all possible (D_m, μ) solutions from observed DVD.

Red line is "best" fit by minimizing a cost function.

Find Best Solution by Fitting to W-band Spectra



Black line is observed W-band spectra

Red line is "best" fit by relative to observed W-band spectrum.

Blue line is RWP (Rayleigh) spectrum using "best" fit (D_m, μ) paramters.

Dark Blue line is estimated vertical air motion.

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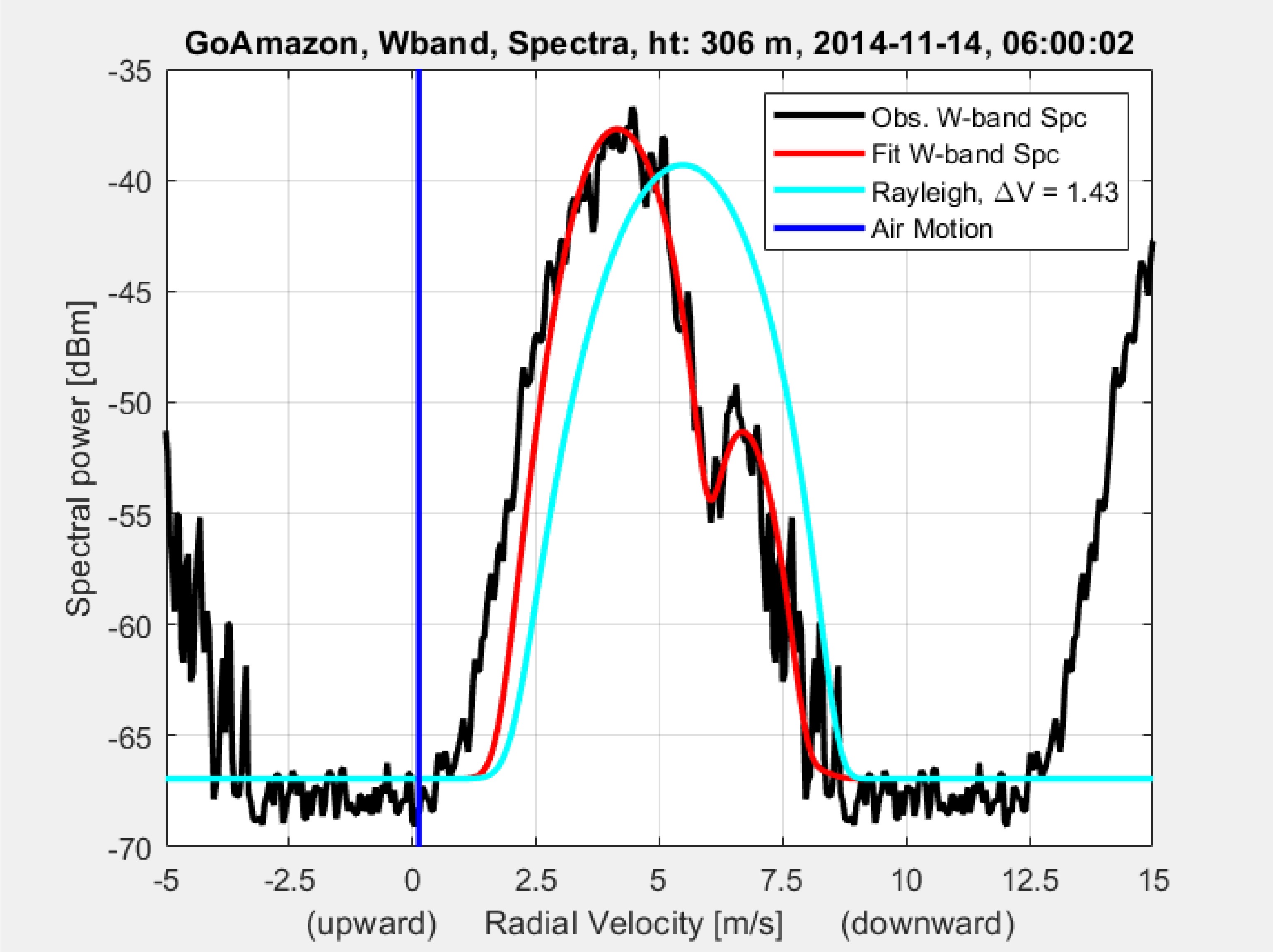

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Step 3. Estimate N_w

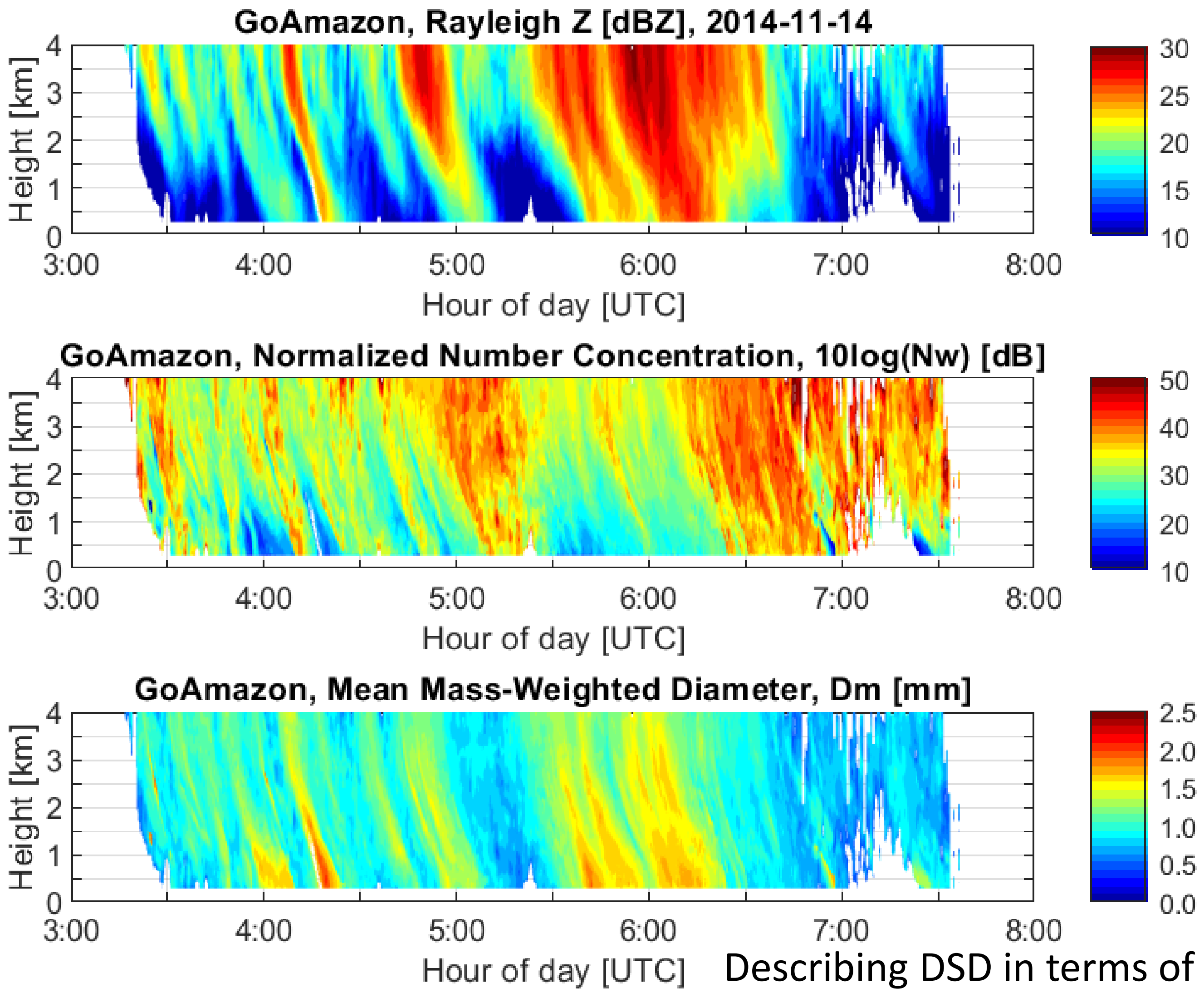
Estimate N_w using:

- RWP measured reflectivity Z and
- retrieved D_m and μ parameters

$$z = \int \frac{\lambda^4}{\pi^5 |K_w|^2} N(D) \;\; \sigma_b^\lambda(D) \;\; \Delta D$$

$$z = N_w \int \frac{\lambda^4}{\pi^5 |K_w|^2} f(D; D_m, \mu) \;\; \sigma_b^\lambda(D) \;\; \Delta D$$

Reflectivity, N_w^{dB} & D_m



Reflectivity [dBZ]

Normalized Number Concentration

$N_w^{dB} = 10\log(N_w)$ [dB]

Retrieved Mass-Weighted Mean Diameter, Dm [mm]

Describing DSD in terms of N_w^{dB} and D_m may be good for radar retrievals, but not good for interpreting physical processes.

Converting N_w into N_t

- Normalized number concentration N_w:
  - Good for estimating DSD parameters
  - Good for comparing shape of DSDs
  - Not a ‘physical’ quantity
- Total number concentration N_t:
  - Total number of raindrops per cubic meter [# m^{-3}]
  - Physical quantity
  - Map N_w to N_t:

$$N_t = N_w \frac{6}{4^4} \frac{(4+\mu)^3}{(\mu+3)(\mu+2)(\mu+1)} D_m$$

$$N(D) = N_t g(D; D_m, \mu) =$$

From Tapiador et al. (2014), *J. Hydrometeor.*

N_w versus N_t

- Normalized number concentration N_w:
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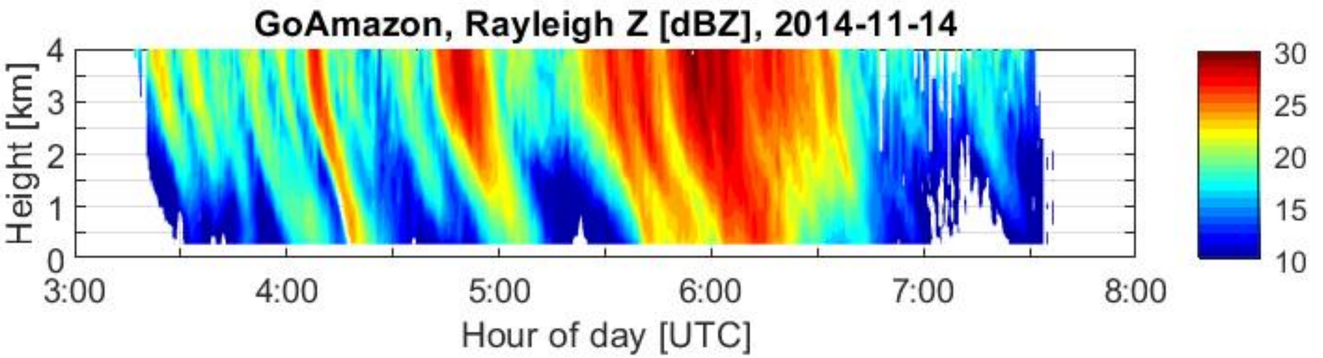
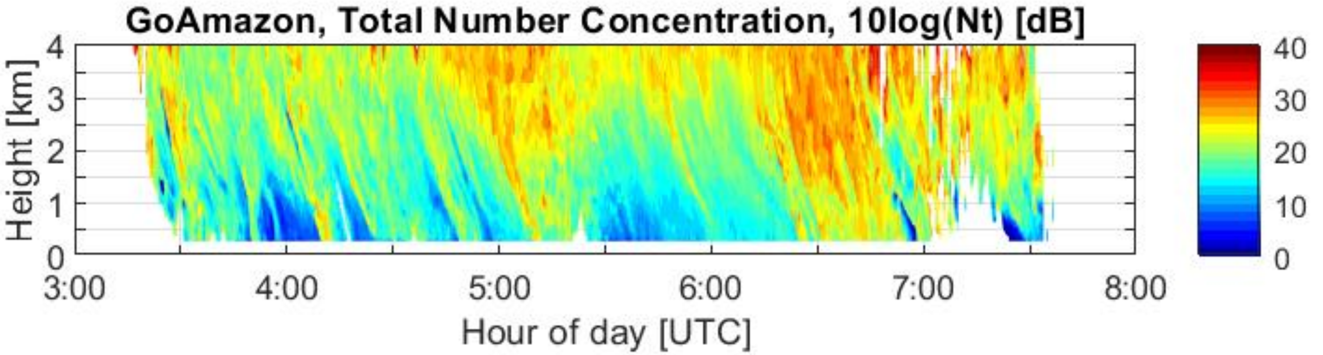
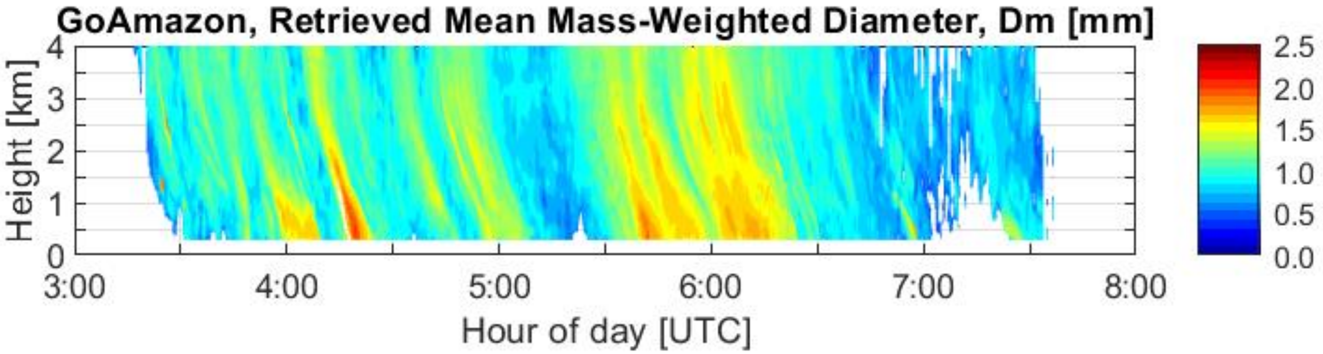
Reflectivity, N_t^{dB} & D_m



Reflectivity [dBZ]



Total Number Concentration
$N_t^{dB} = 10\log(N_t)$ [dB]



Retrieved Mass-Weighted Mean Diameter, Dm [mm]

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LWC Decomposition using N_t

- Number concentration: scaled PDF

$$N(D) = N_t g(D; D_m, \mu)$$

LWC Decomposition using N_t

- Number concentration: scaled PDF

$$N(D) = N_t g(D; D_m, \mu)$$

- Liquid Water Content (LWC) [g m^{-3}]:

$$q = N_t \frac{\pi}{6} \rho_w \sum_{D_i = D_{\min}}^{D_{\max}} g\left(D_i; D_m, \mu\right) D_i^3 \Delta D$$

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- LWC in logarithmic units [dB]: $q^{dB} = 10\log(q)$

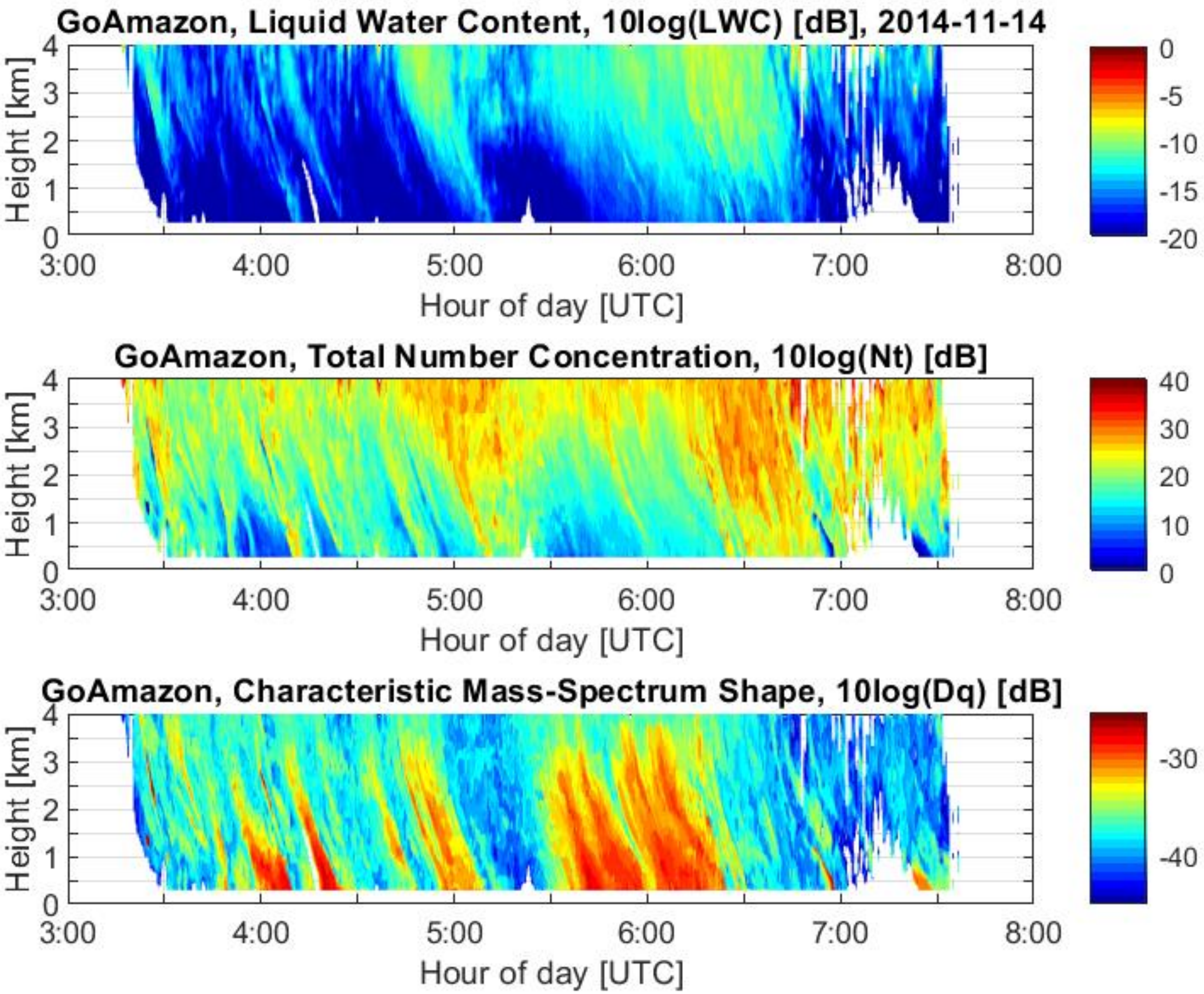
$$q^{dB} = \underbrace{10\log(N_t)}_{} + \underbrace{10\log\left(\frac{\pi}{6} \rho_w \sum_{D_i = D_{\min}}^{D_{\max}} f(D_i; D_m, \mu) D_i^3 \Delta D\right)}_{}$$

$$q^{dB} = N_t^{dB} + D_q^{dB}(D_m, \mu)$$

1 dB = 26% change   2 dB = 58% change   3 dB = factor of 2 change

Williams (2016) JTECH

q^{dB}, N_t^{dB} & D_q^{dB}



Liquid Water Content

$$q^{dB} = 10\log(LWC) \quad \text{[dB]}$$

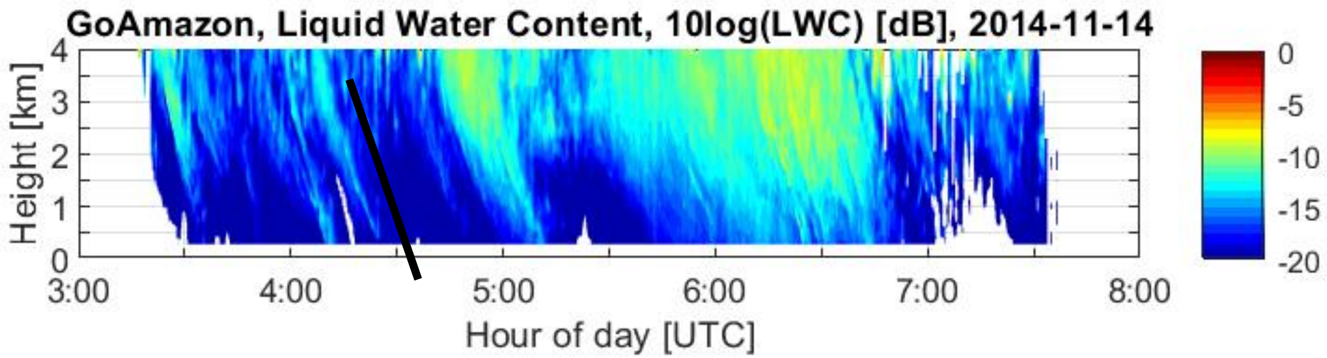
Total Number Concentration

$$N_t^{dB} = 10\log(N_t) \quad \text{[dB]}$$

Characteristic Mass-Spectrum Shape

$$D_q^{dB} = 10\log(D_q) \quad \text{[dB]}$$

q^{dB}, N_t^{dB} & D_q^{dB}



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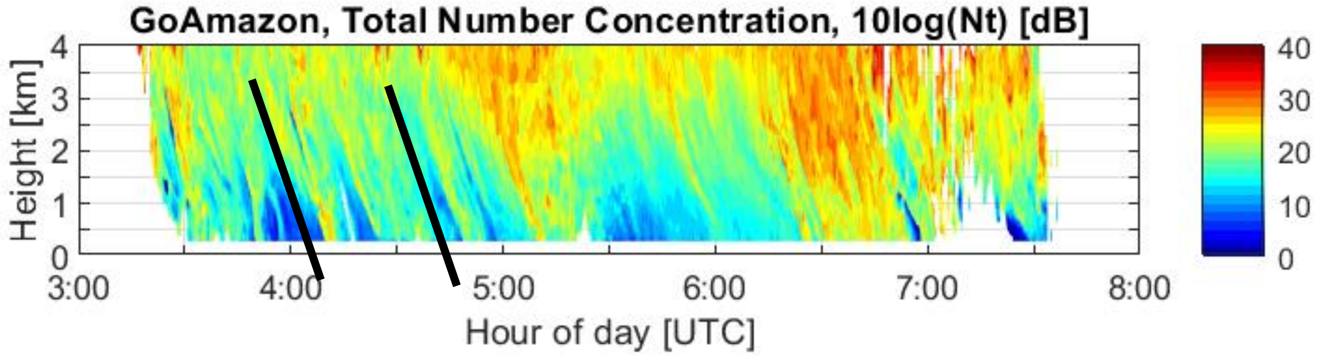

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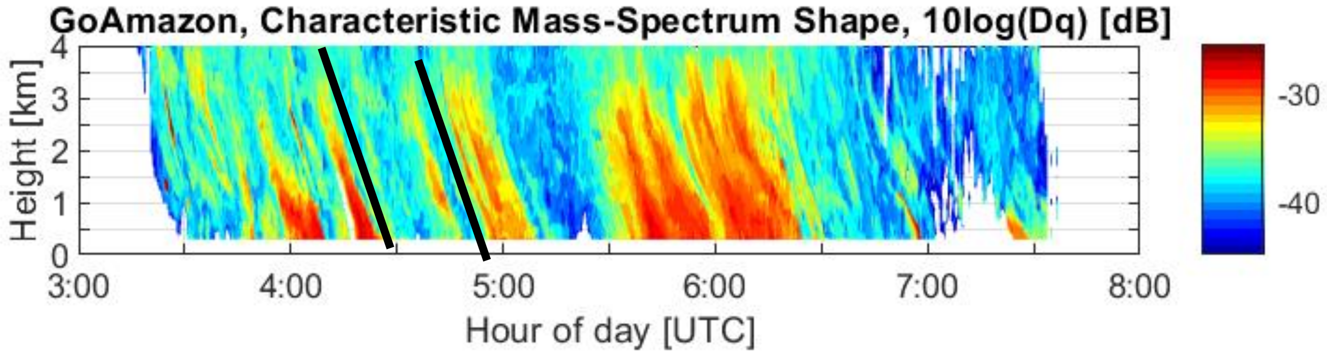
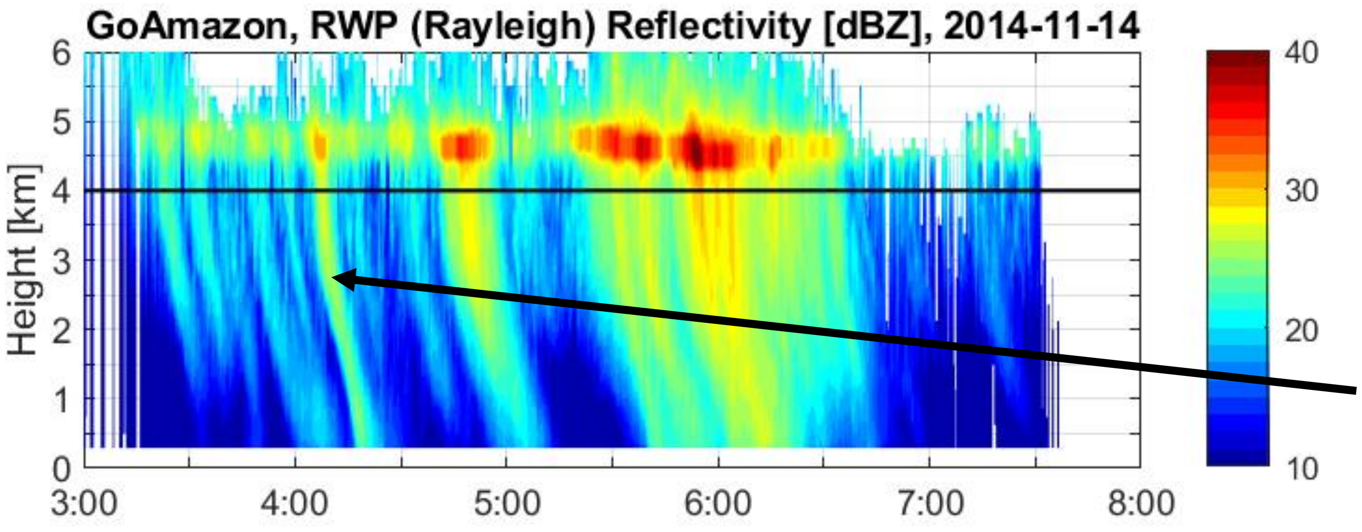


Characteristic Mass-Spectrum Shape

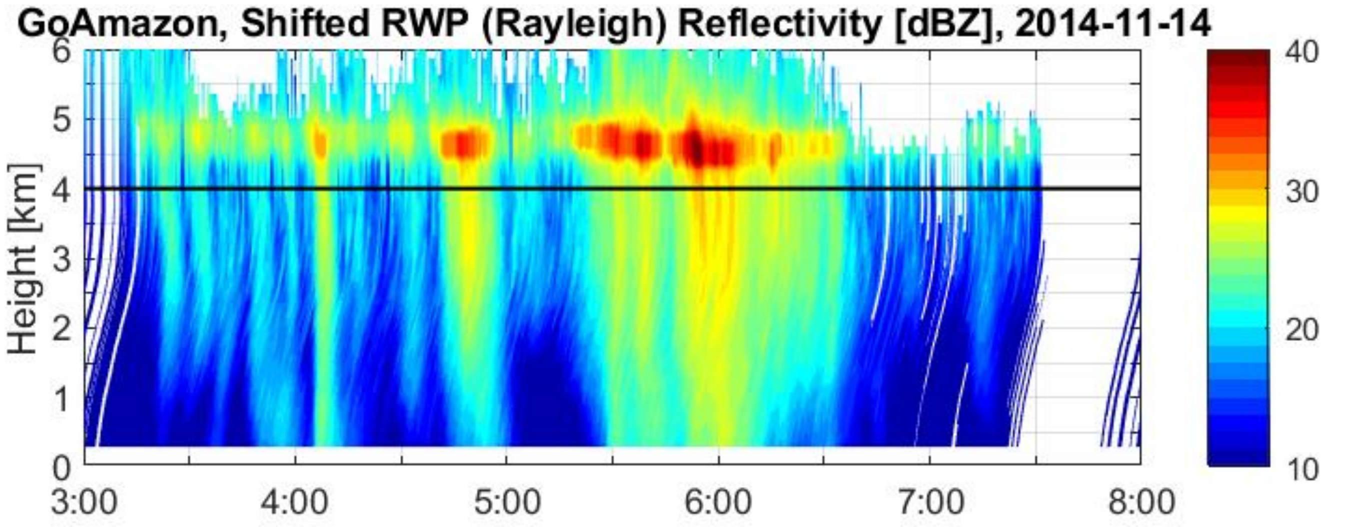
$D_q^{dB} = 10\log(D_q)$ [dB]

Fall Streak Advection Correction



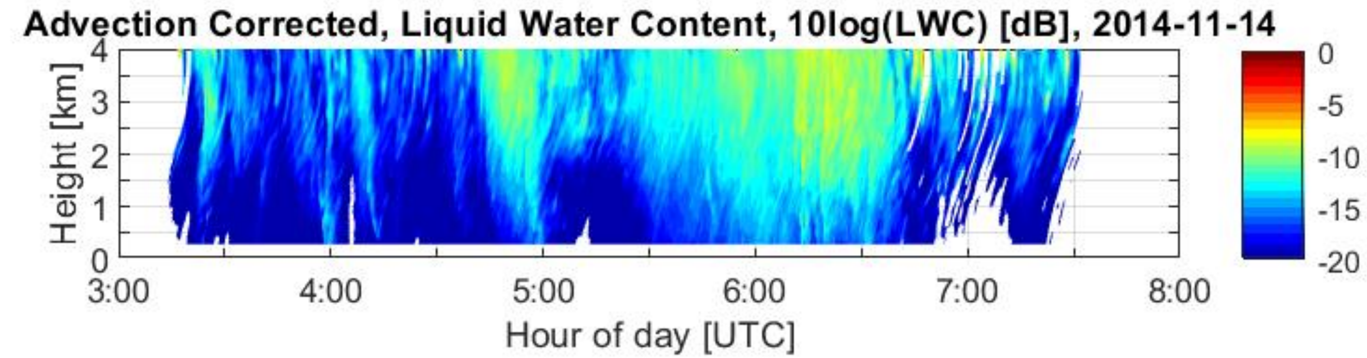
1.2 GHz Reflectivity
Before Fall Streak Correction

Reference Streak:
Ht: 4 to 0.3 km
Time: 4:07 UTC



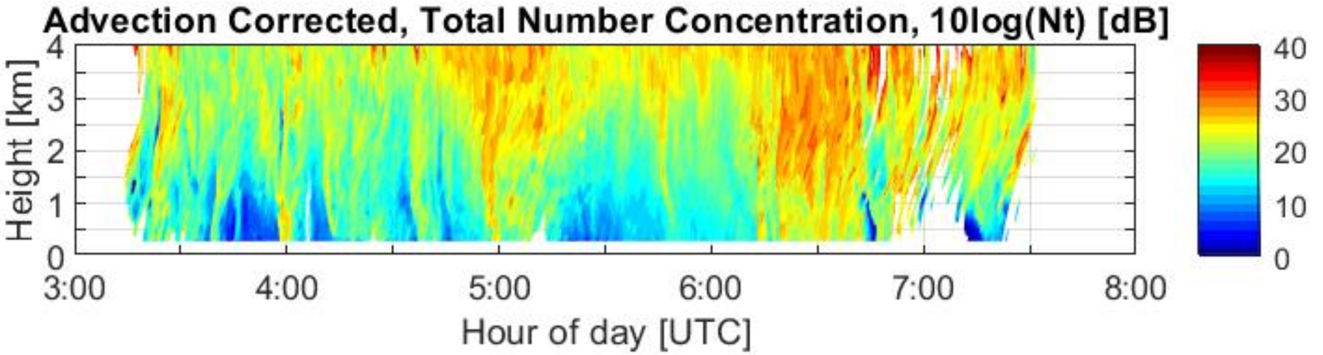
1.2 GHz Reflectivity
After Fall Streak Correction

Advection Corrected: q^{dB}, N_t^{dB} & D_q^{dB}



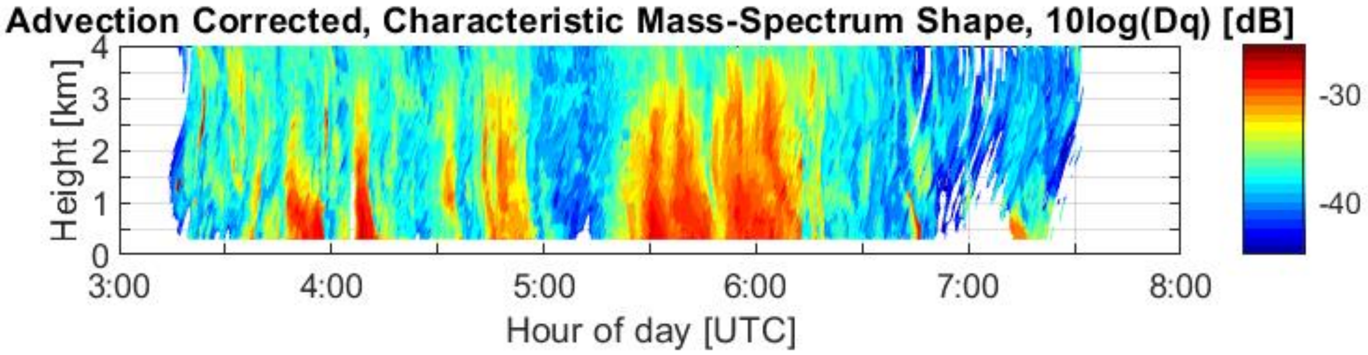
Liquid Water Content

$q^{dB} = 10\log(LWC)$ [dB]



Total Number Concentration

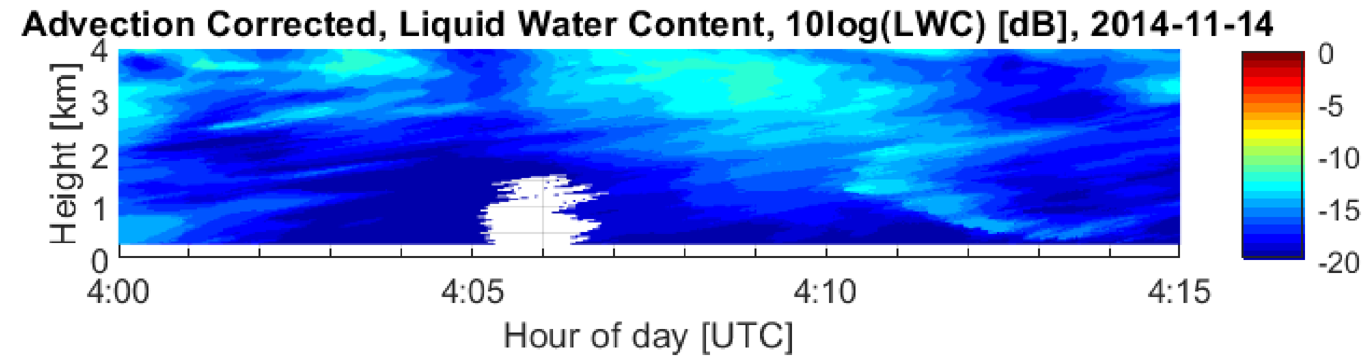
$N_t^{dB} = 10\log(N_t)$ [dB]



Characteristic Mass-Spectrum Shape

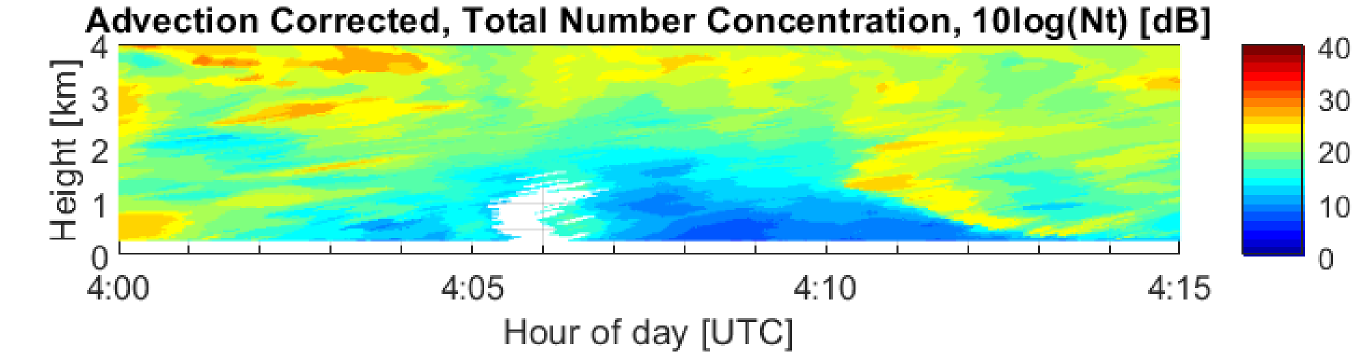
$D_q^{dB} = 10\log(D_q)$ [dB]

Advection Corrected: q^{dB}, N_t^{dB} & D_q^{dB}



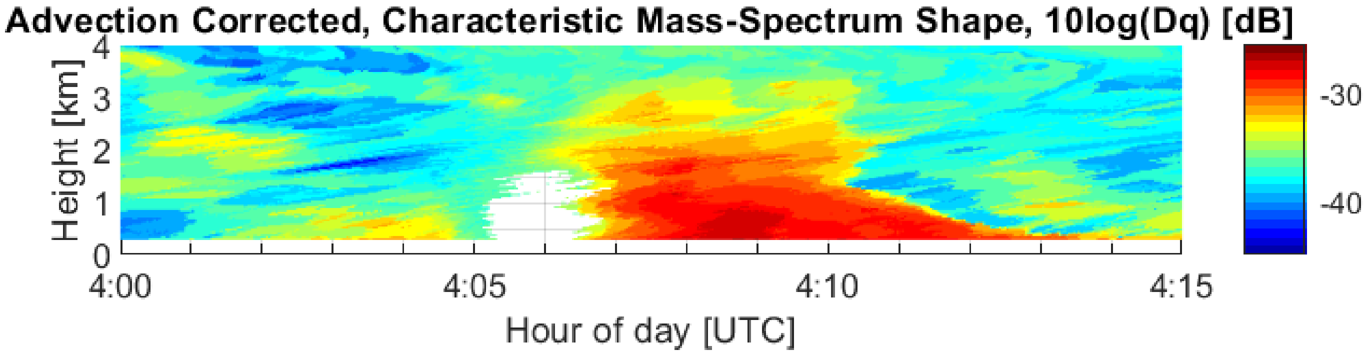
Liquid Water Content

$q^{dB} = 10\log(LWC)$ [dB]



Total Number Concentration

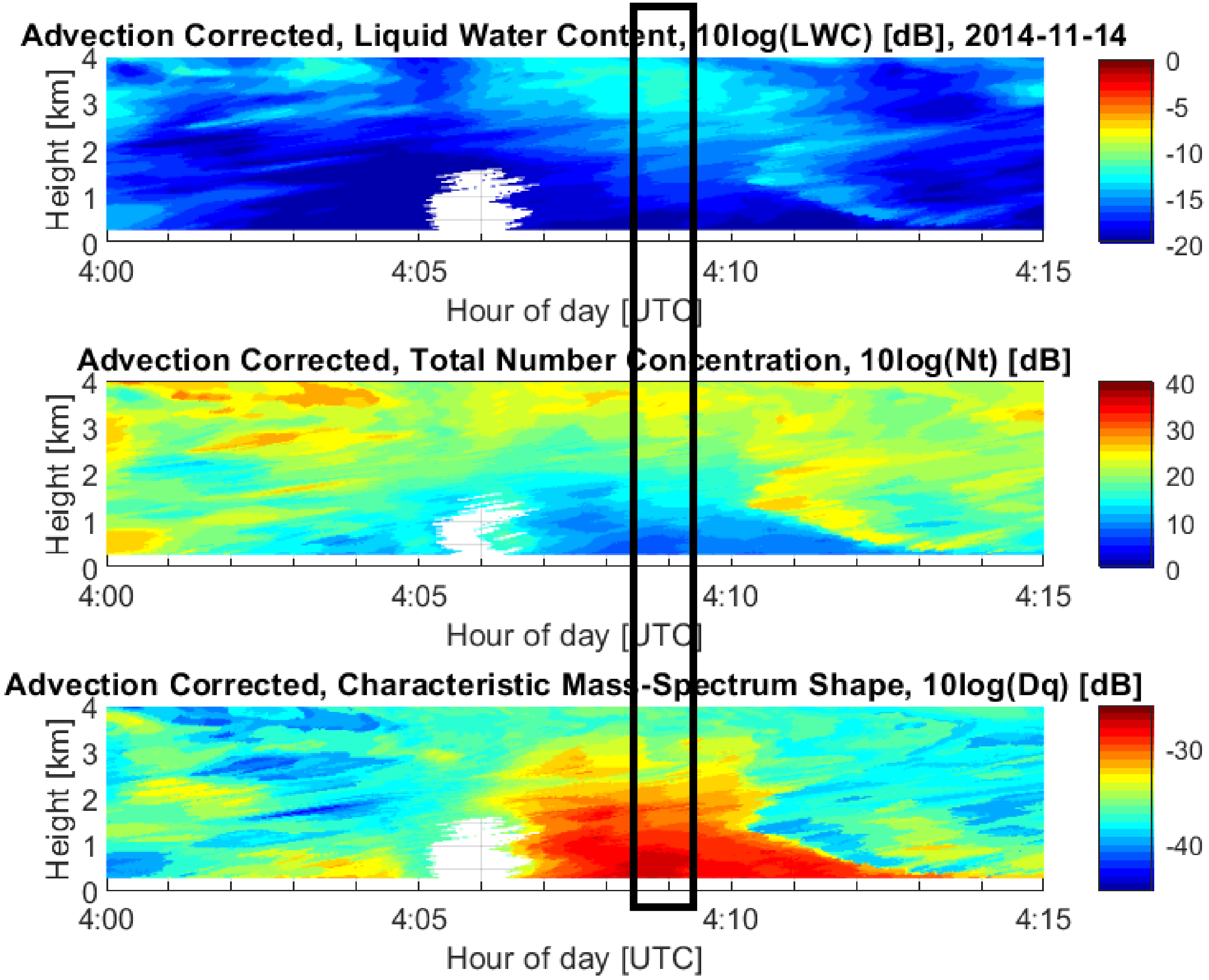
$N_t^{dB} = 10\log(N_t)$ [dB]



Characteristic Mass-Spectrum Shape

$D_q^{dB} = 10\log(D_q)$ [dB]

Advection Corrected: q^{dB}, N_t^{dB} & D_q^{dB}



Liquid Water Content

$q^{dB} = 10\log(LWC)$ [dB]

Total Number Concentration

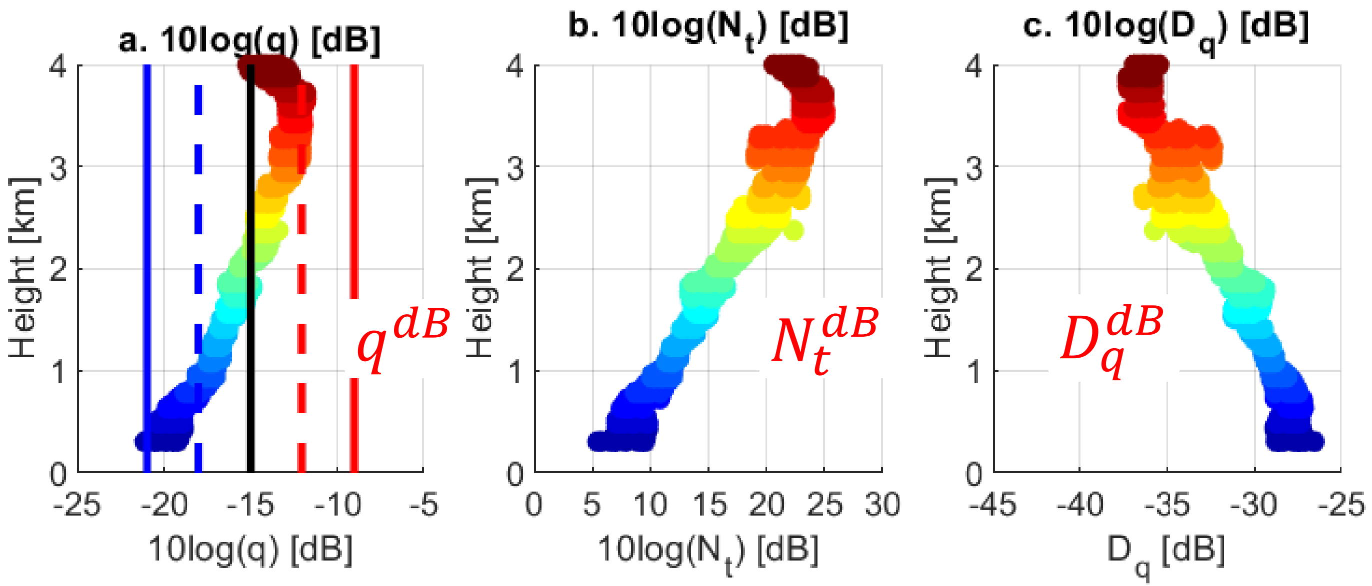
$N_t^{dB} = 10\log(N_t)$ [dB]

Characteristic Mass-Spectrum Shape

$D_q^{dB} = 10\log(D_q)$ [dB]

LWC Decomposition Diagram

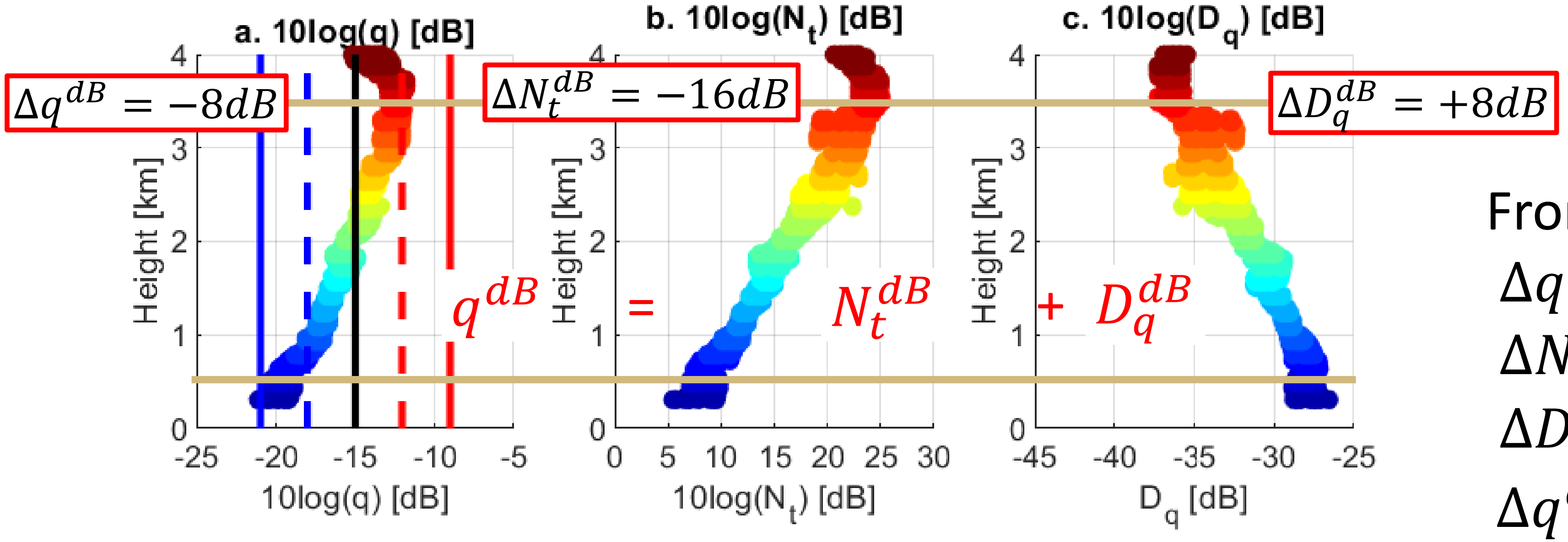
30 Profiles at 04:09 UTC
(each 2 sec dwell)



+3 dB is a doubling
−3 dB is a halving

LWC Decomposition Diagram

30 Profiles at 04:09 UTC
(each 2 sec dwell)



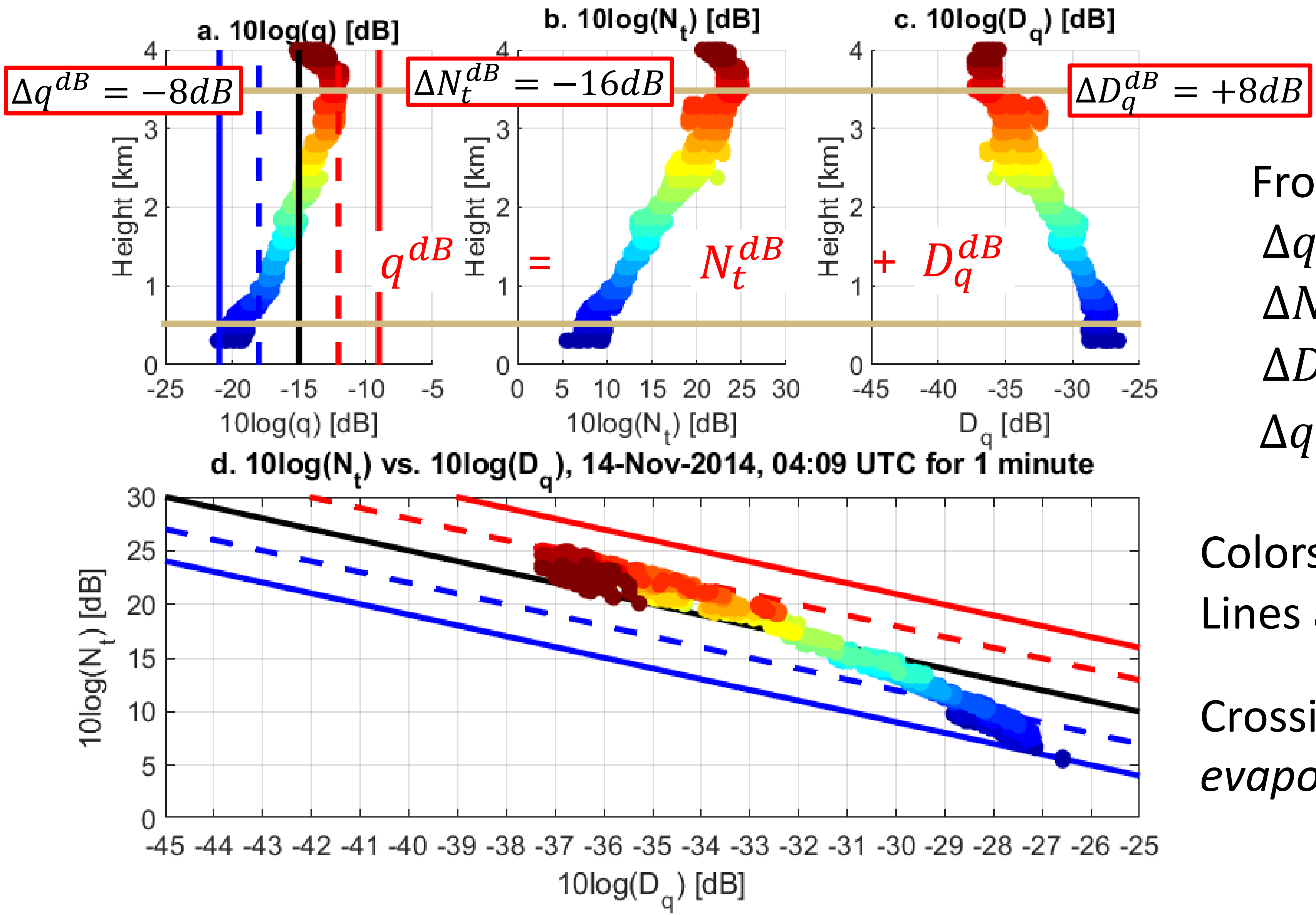
+3 dB is a doubling
−3 dB is a halving

From 3.5 to 0.5 km:

$$\Delta q^{dB} = -8dB$$
$$\Delta N_t^{dB} = -16dB$$
$$\Delta D_q^{dB} = +8dB$$
$$\Delta q^{dB} = \Delta N_t^{dB} + \Delta D_q^{dB}$$

LWC Decomposition Diagram

30 Profiles at 04:09 UTC
(each 2 sec dwell)



+3 dB is a doubling
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$\Delta q^{dB} = -8dB$

$\Delta N_t^{dB} = -16dB$

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$\Delta q^{dB} = \Delta N_t^{dB} + \Delta D_q^{dB}$

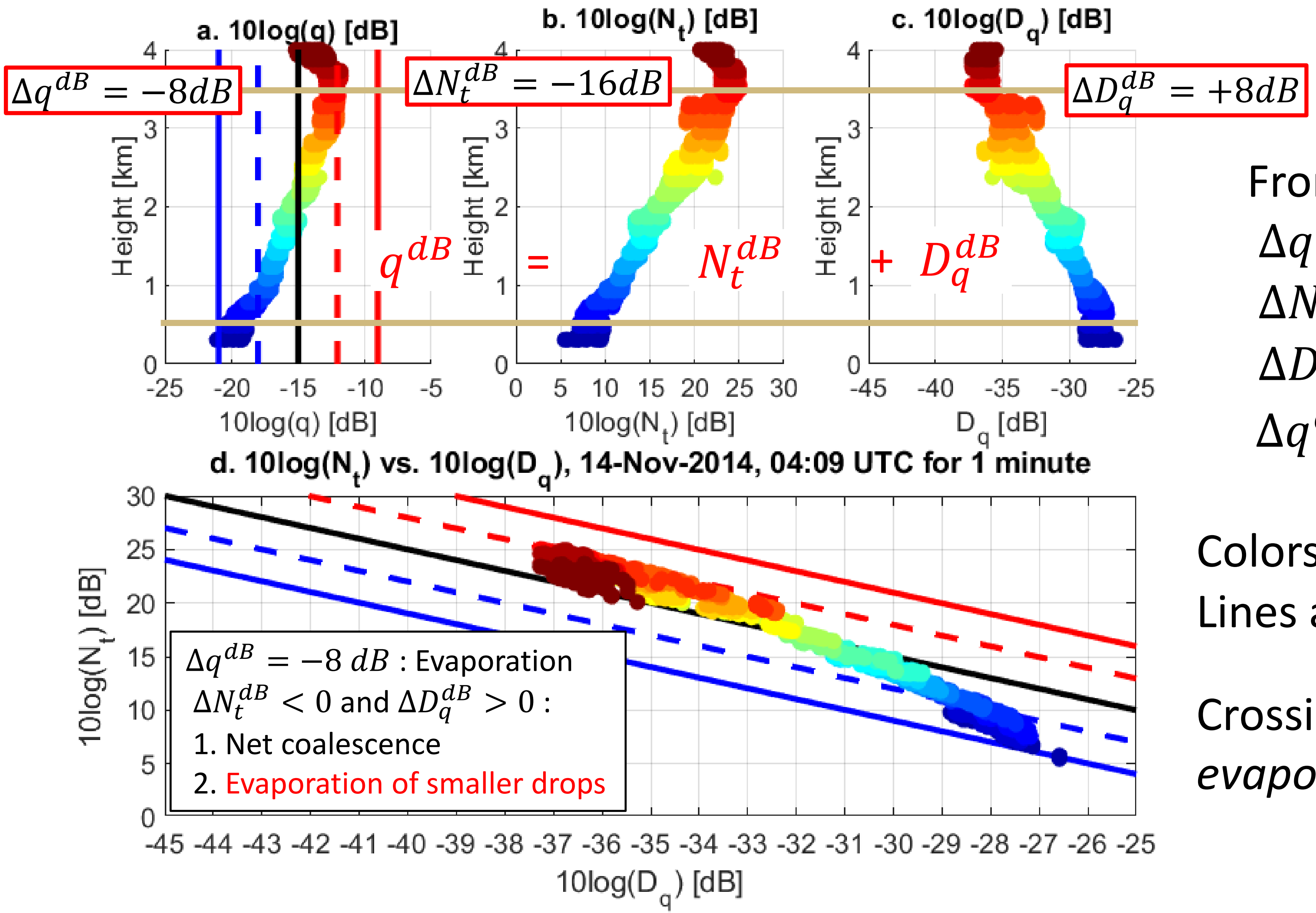
Colors represent height

Lines are constant q^{dB}

Crossing of lines indicates *evaporation* or *accretion*

LWC Decomposition Diagram

30 Profiles at 04:09 UTC (each 2 sec dwell)



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Colors represent height

Lines are constant q^{dB}

Crossing of lines indicates *evaporation* or *accretion*

Next Steps

- Apply retrievals to full GoAmazon data set (18 Months)
- Relationships between Δq^{dB}, ΔN_t^{dB} & ΔD_q^{dB}
  - Verify that decrease in N_t^{dB} and increase in D_q^{dB} is evaporation of small drops
  - Place retrievals and vertical structure into meteorological context
- Decomposition diagrams can be applied to model output
  - Use decomposition diagram to compare 1-, 2-moment and bin-microphysics schemes

- References
  - Vertical Decomposition Diagrams

    Williams, C.R., JTECH, 2016, doi: 10.1175/JTECH-D-15-0208.1
  - DSD retrievals using Doppler velocity difference

    Williams, C.R., R.M. Beauchamp, and V. Chandrasekar, IEEE TGRS, 2016, doi: 10.1109/TGRS.2016.2580526

Backup Slides

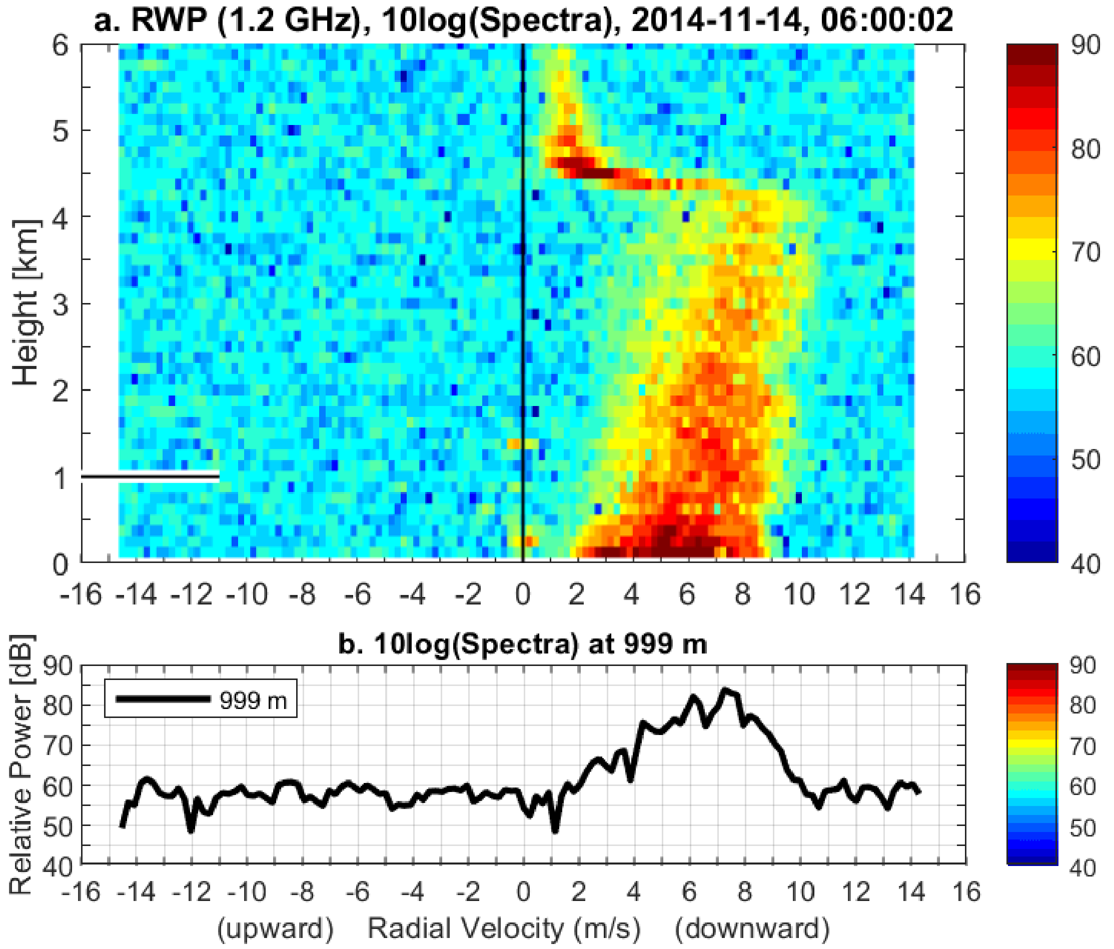
Science Objective

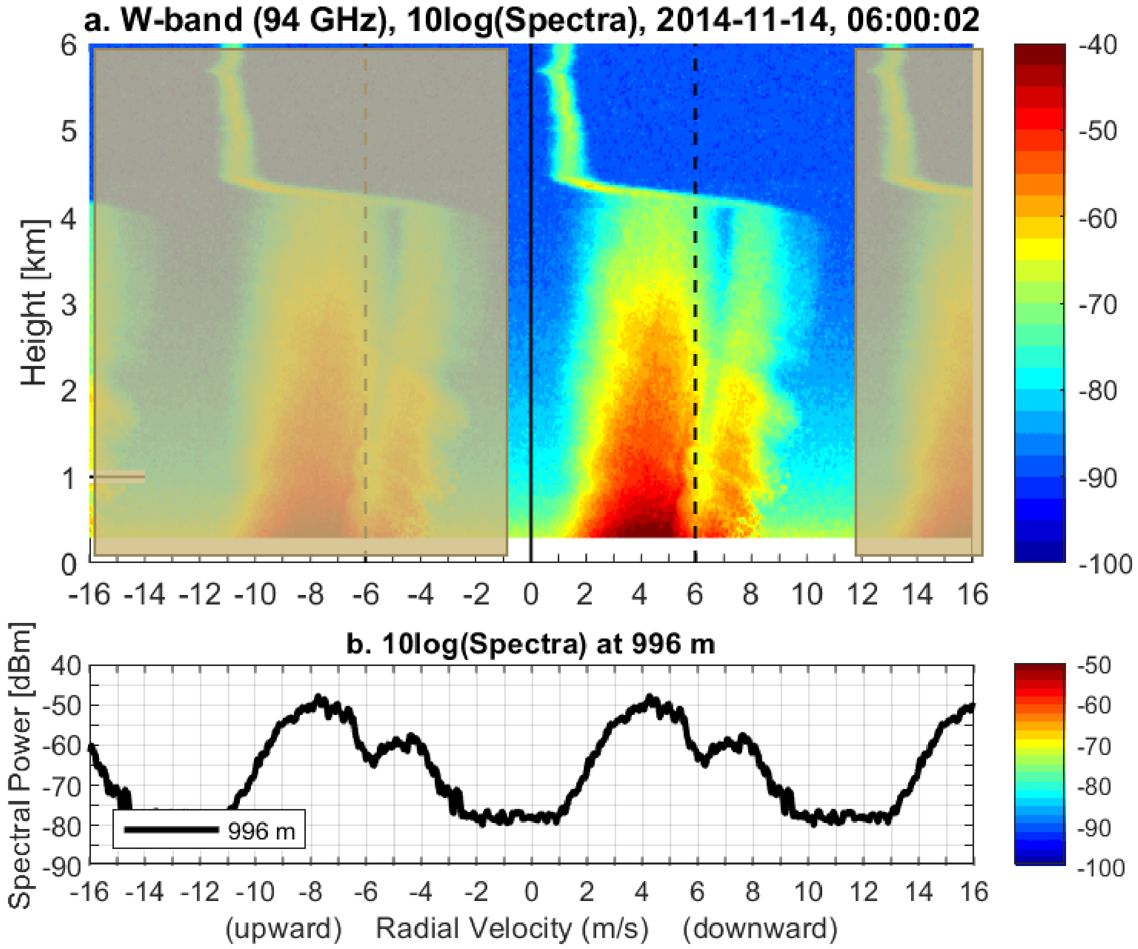
Improve microphysical processes in numerical models

- Improve microphysical representations
  - 1-moment scheme
    - Numerically fast
    - Not very accurate
  - 2-moment schemes
    - Better representation of nature
    - May get the right answer for the wrong reason
  - Bin microphysics scheme
    - Best representation of nature
    - But really expensive (numerically)
- Processes act upon the falling raindrops
  - *Evaporation & accretion (mass decrease or increase)*
  - *Breakup & coalescence processes (mass redistributed)*

How can we use radar observations to improve model parameterizations?

RWP (1.2 GHz) & W-band (94 GHz) Spectra Profile at 6:00:02 UTC

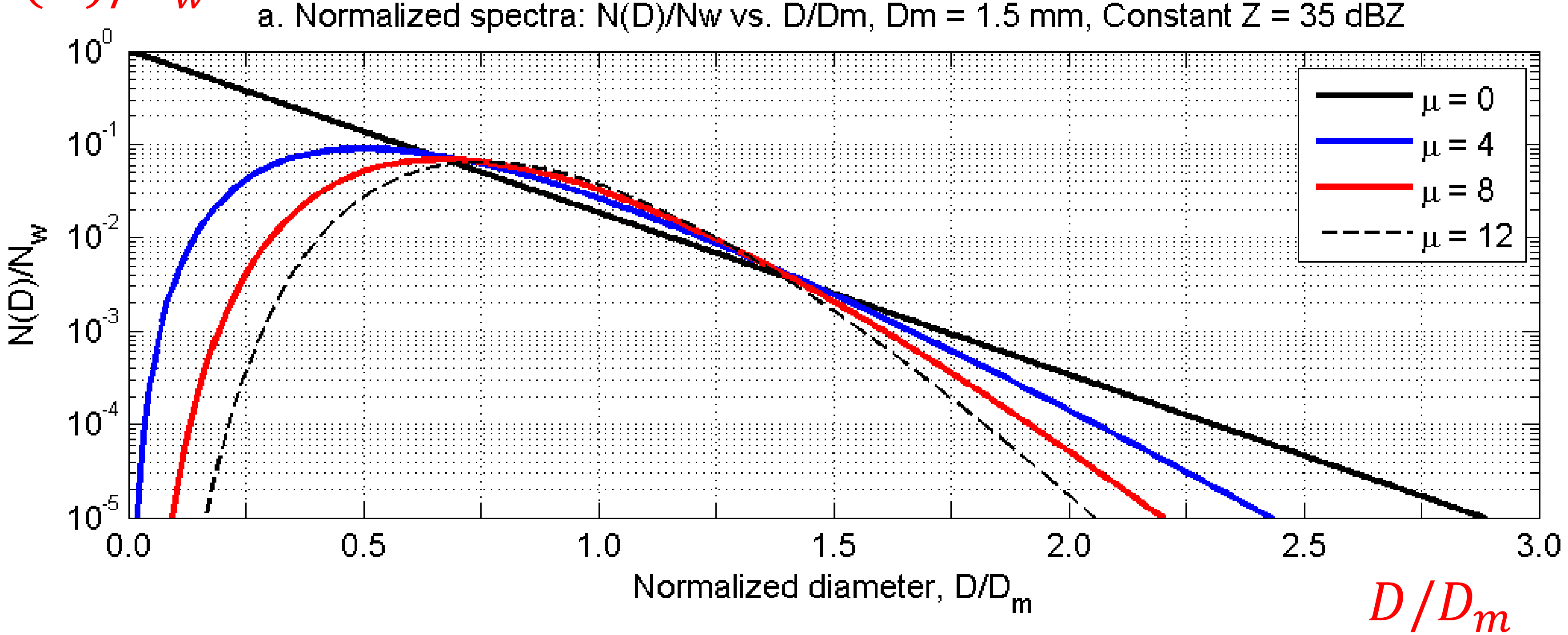




Normalized DSDs

$N_w = N_0^*$ (Testud et al. 2001)

$N(D)/N_w$



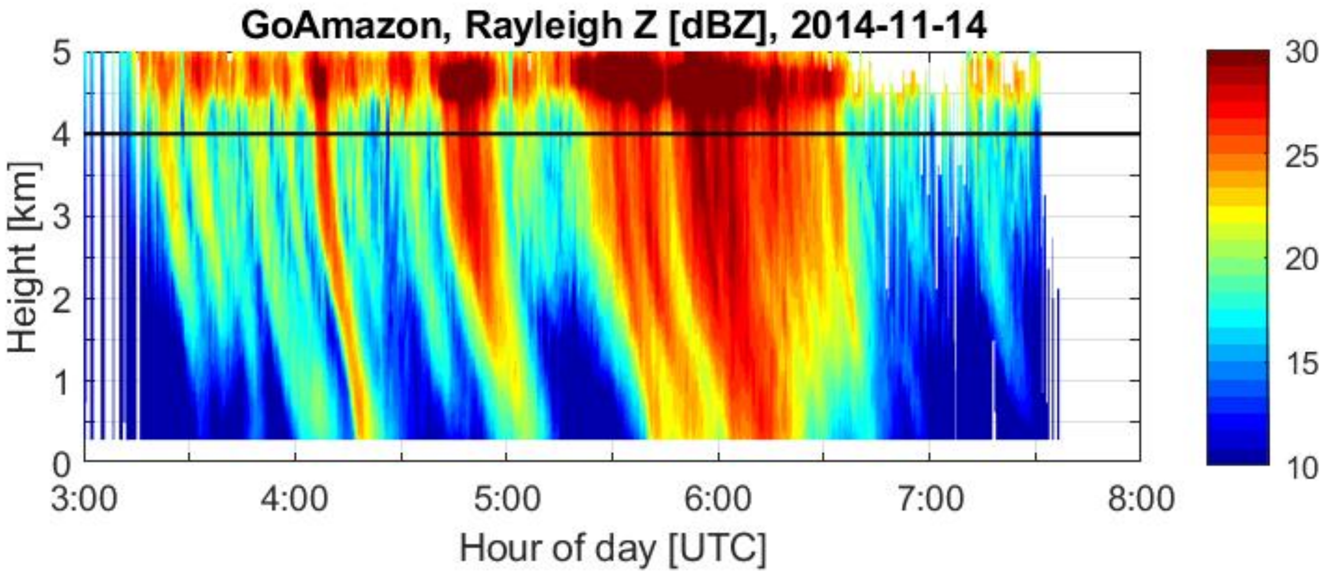
D/D_m

Constant Z = 35 dBZ
Constant D_m = 1.5 mm

μ	LWC	N_w
0	0.26	4200
4	0.35	5600
8	0.39	6250
12	0.41	6600

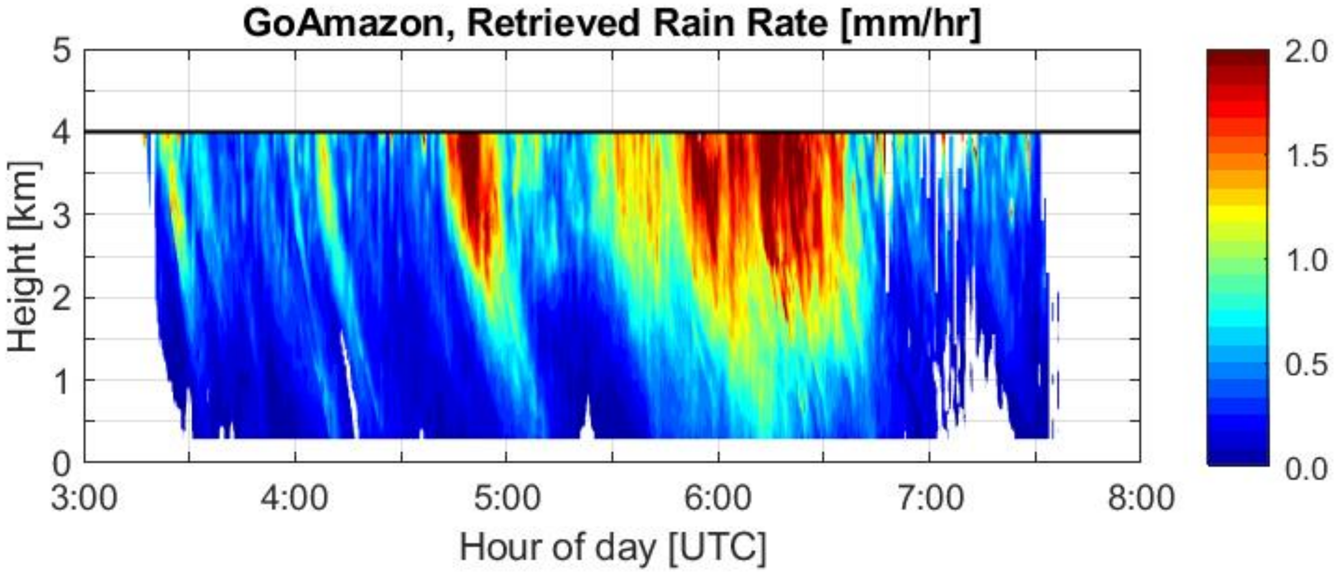
Shape of distribution determined by D_m and μ

Observed Reflectivity & Retrieved Rain Rate



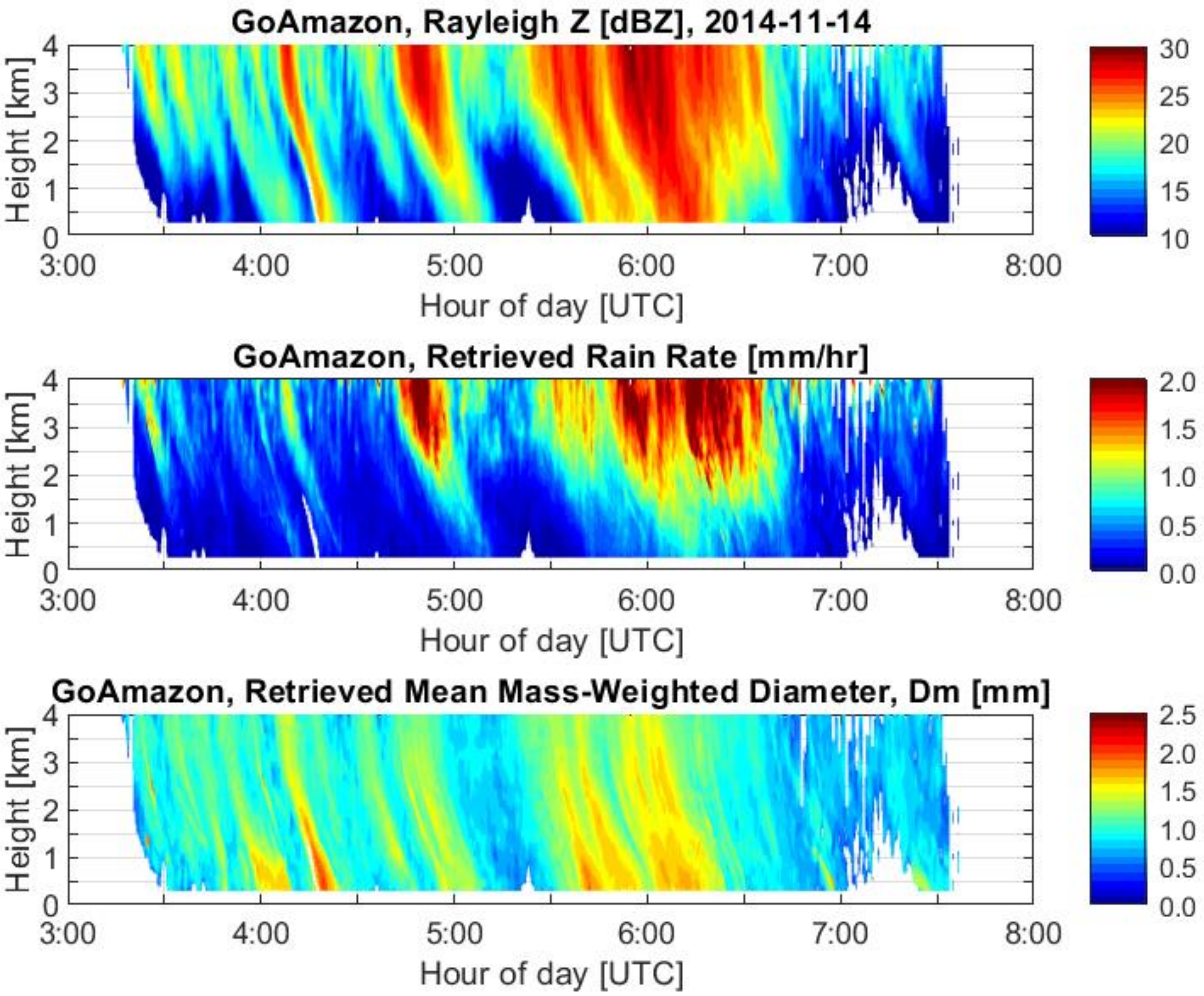
1.2 GHz
Reflectivity [dBZ]

Retrievals are below brightband (4 km).



Retrieved Rain Rate [mm/hr]
Dwell: 2 second
Repeat: every 2 seconds

Reflectivity, Retrieved Rain Rate & Dm



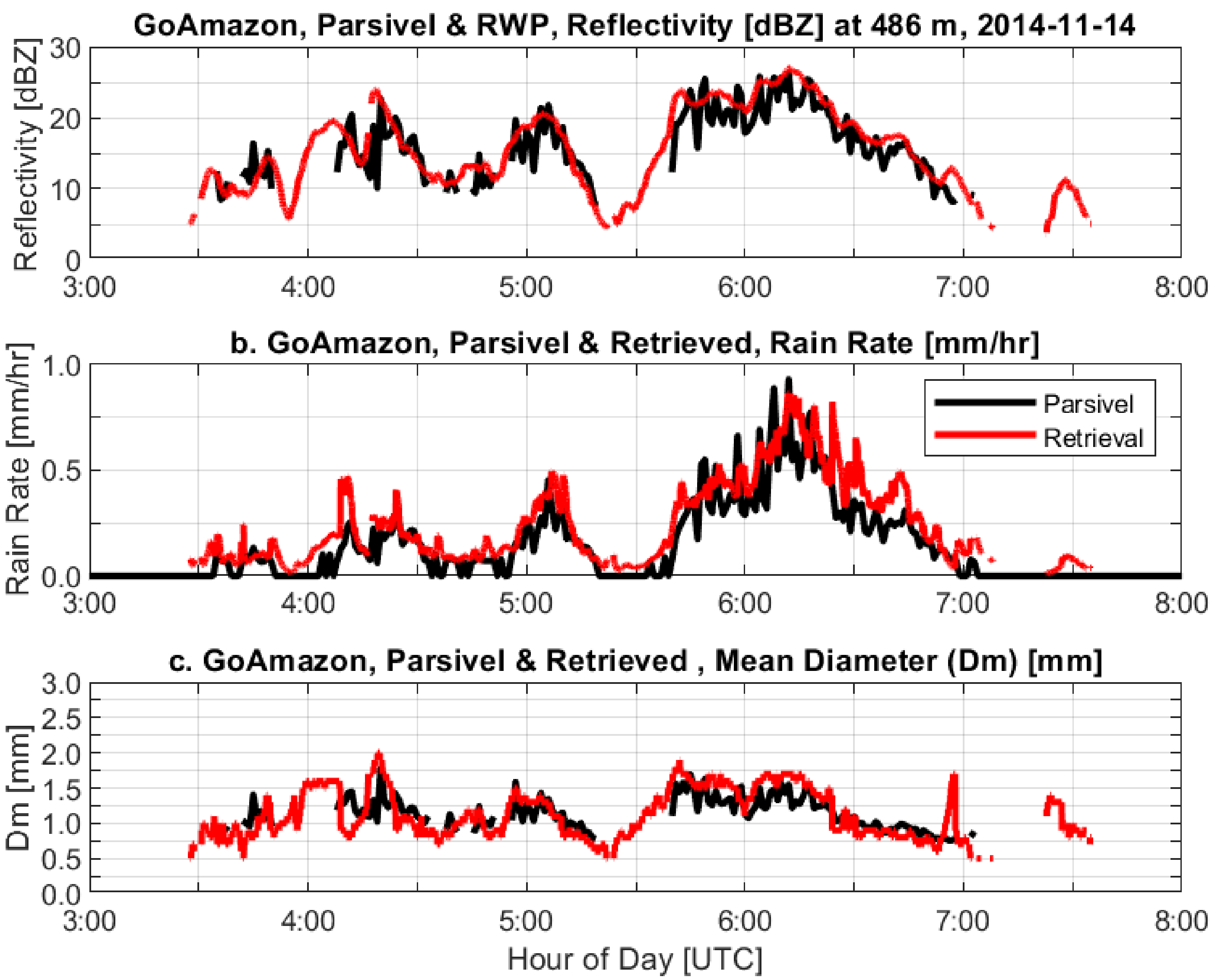
1.2 GHz
Reflectivity [dBZ]

Retrieved Rain Rate [mm/hr]

Retrieved Mass-Weighted Mean Diameter, Dm [mm]

Retrievals are below brightband (4 km).

Retrievals vs. Surface Parsivel Disdrometer



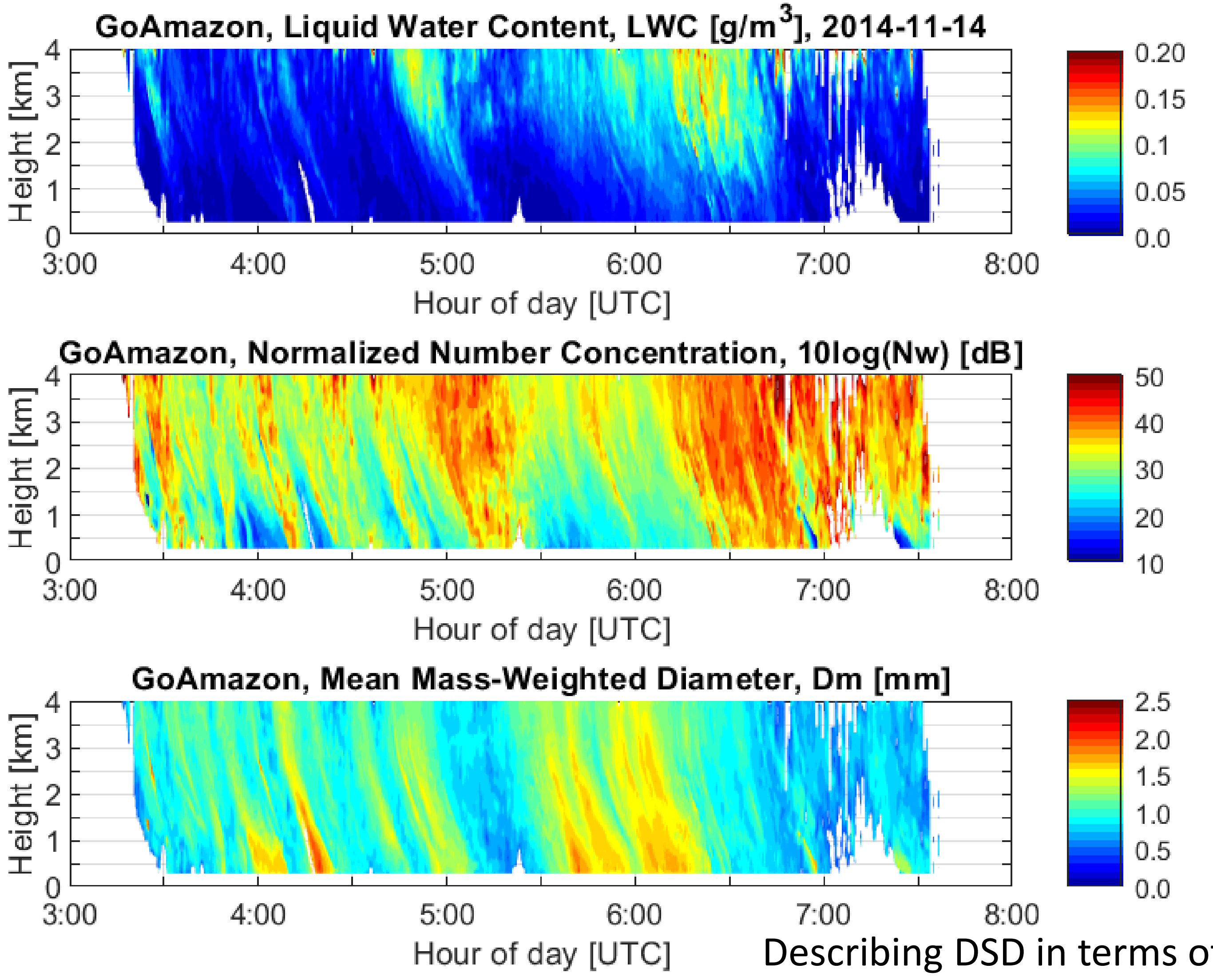
Parsivel disdrometer vs. Retrieval
(surface) (500 m)

1.2 GHz
Reflectivity [dBZ]

Retrieved Rain Rate [mm/hr]

Retrieved Mass-Weighted Mean Diameter, Dm [mm]

Liquid Water Content, N_w^{dB} & D_m



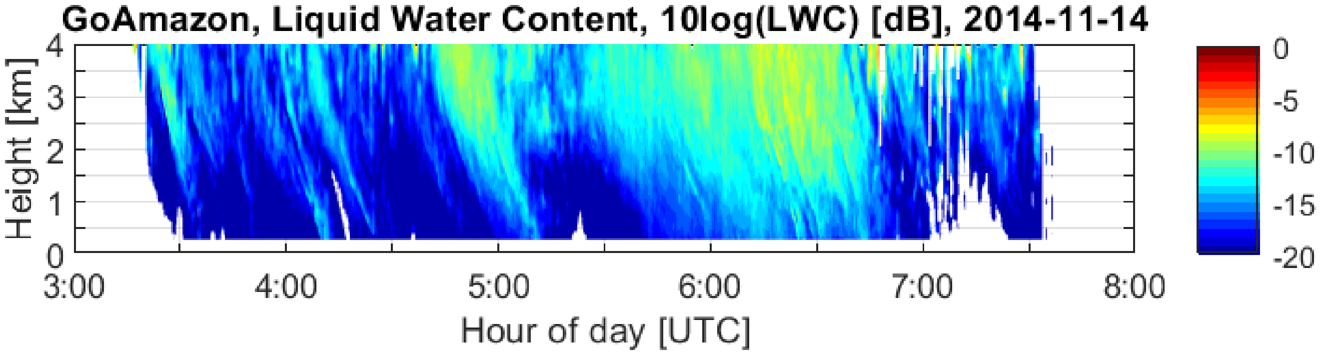
Liquid Water Content, LWC [g/m^3]

Normalized Number Concentration
$N_w^{dB} = 10\log(N_w)$ [dB]

Retrieved Mass-Weighted Mean Diameter, Dm [mm]

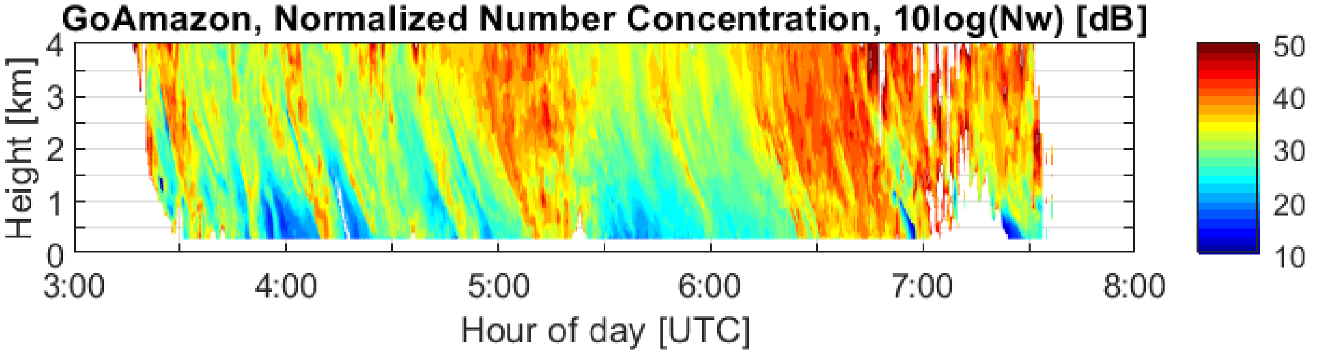
Describing DSD in terms of N_w^{dB} and D_m may be good for radar retrievals, but not good for interpreting physical processes.

q^{dB}, N_w^{dB} & D_m



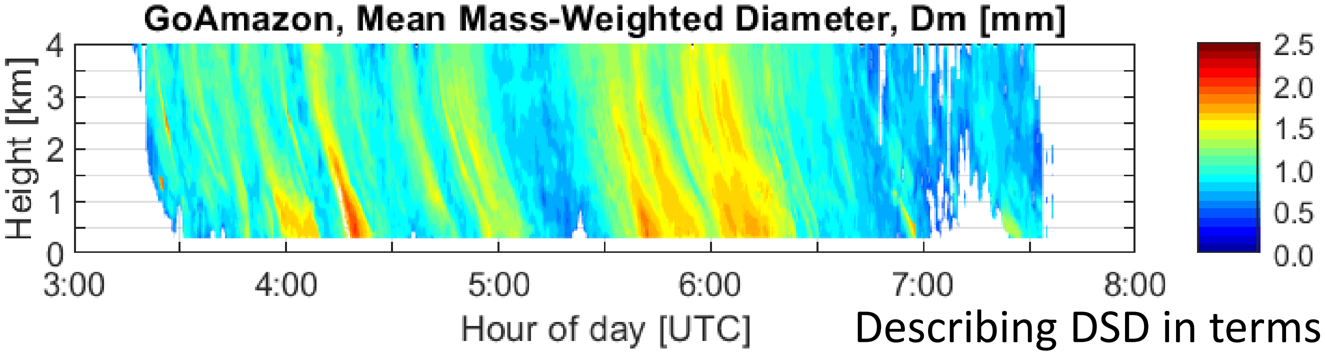
Liquid Water Content

$q^{dB} = 10\log(LWC)$ [dB]



Normalized Number Concentration

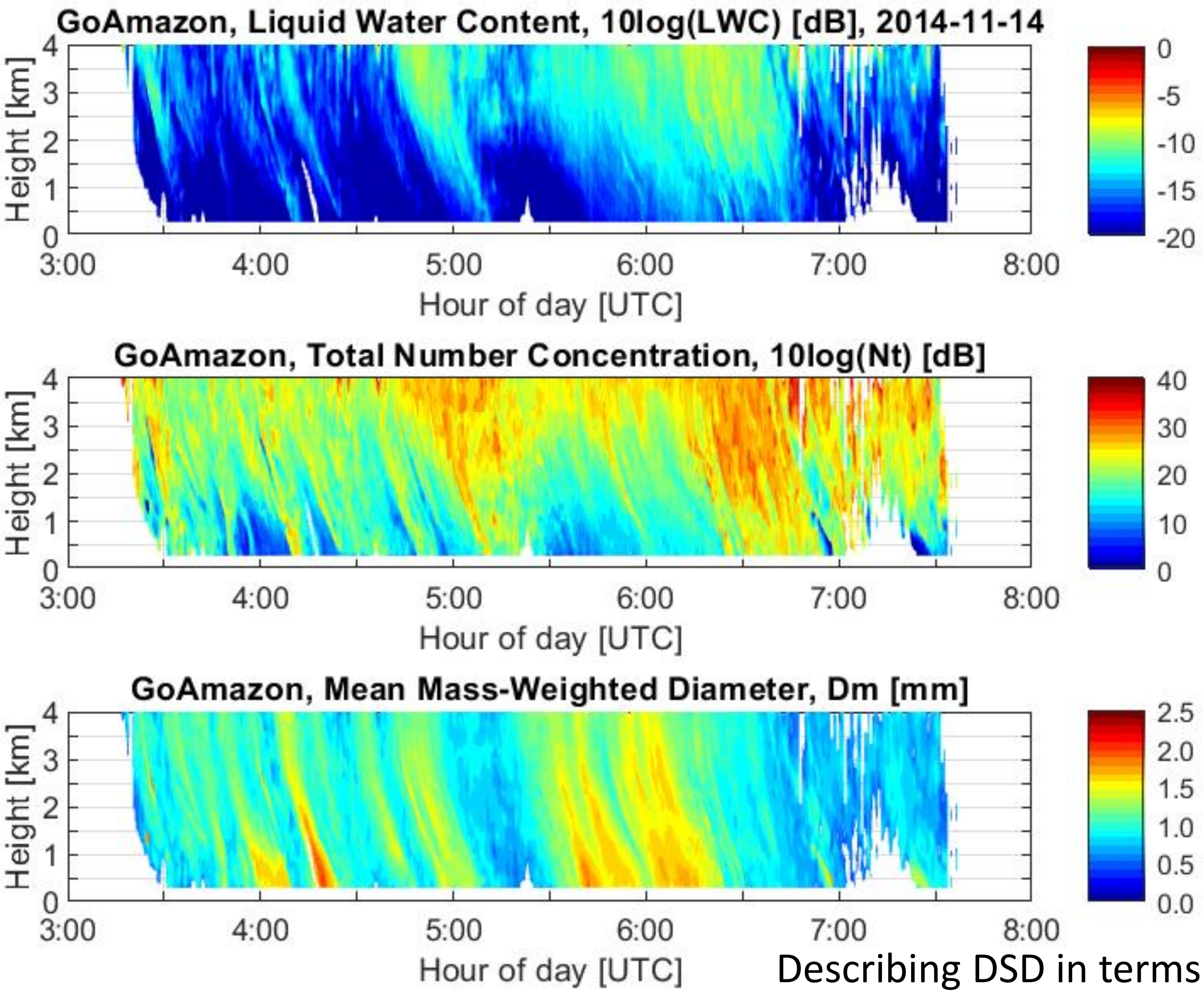
$N_w^{dB} = 10\log(N_w)$ [dB]



Retrieved Mass-Weighted Mean Diameter, Dm [mm]

Describing DSD in terms of N_w^{dB} and D_m may be good for radar retrievals, but not good for interpreting physical processes.

q^{dB}, N_t^{dB} & D_m



Liquid Water Content

$q^{dB} = 10\log(LWC)$ [dB]

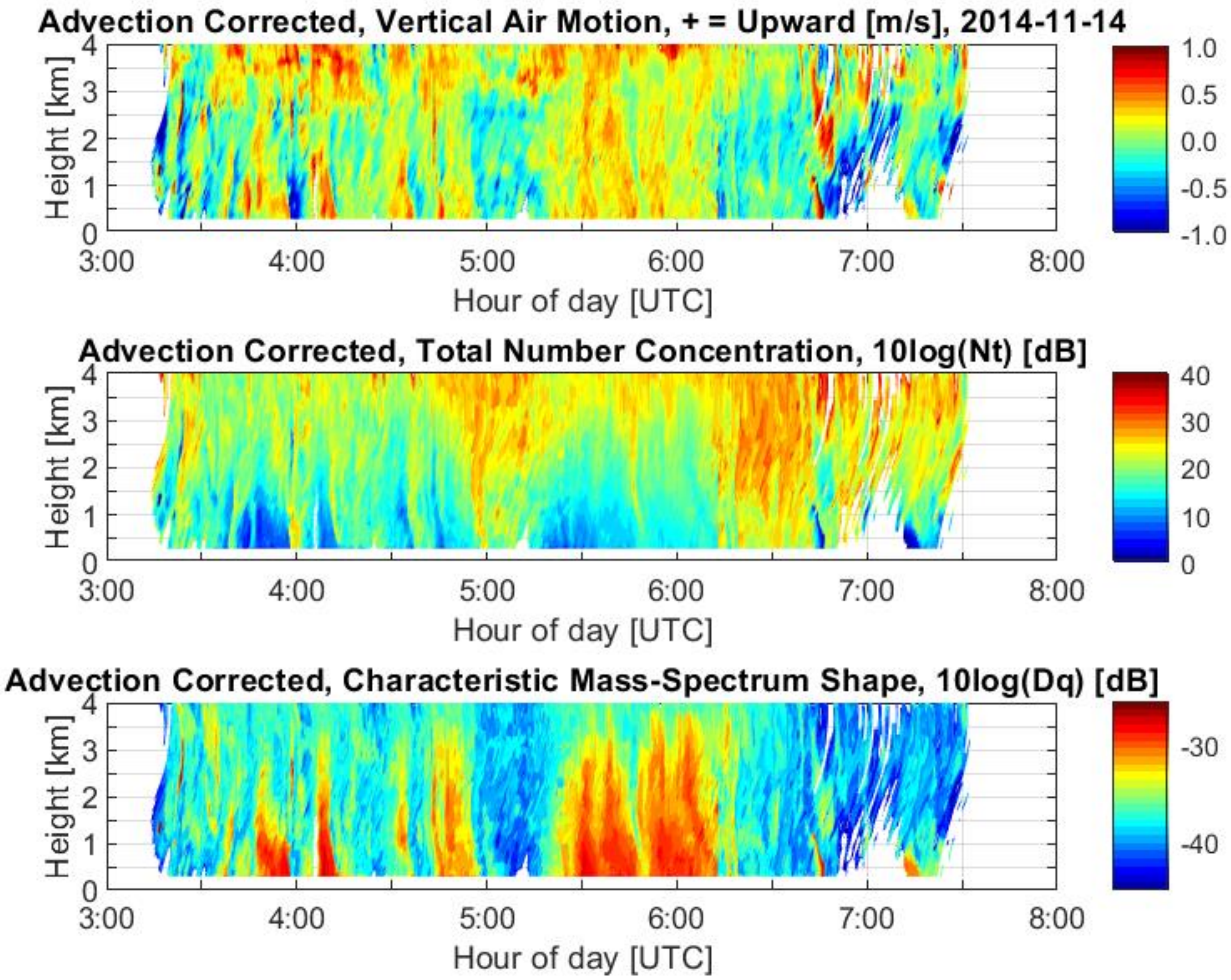
Total Number Concentration

$N_t^{dB} = 10\log(N_t)$ [dB]

Retrieved Mass-Weighted Mean Diameter, Dm [mm]

Describing DSD in terms of N_w^{dB} and D_m may be good for radar retrievals, but not good for interpreting physical processes.

Advection Corrected: q^{dB}, N_t^{dB} & D_q^{dB}



Vertical Air motion

Positive values = Upward motion [m/s]

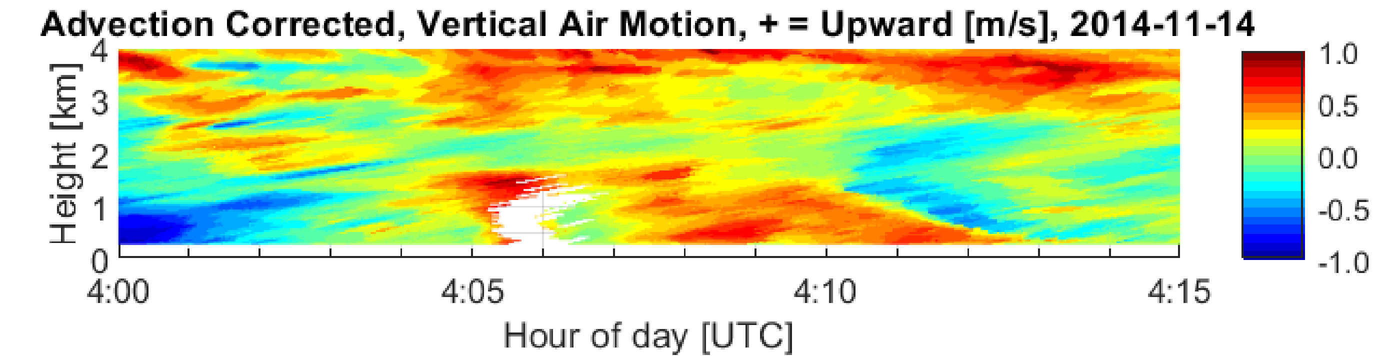
Total Number Concentration

$N_t^{dB} = 10\log(N_t)$ [dB]

Characteristic Mass-Spectrum Shape

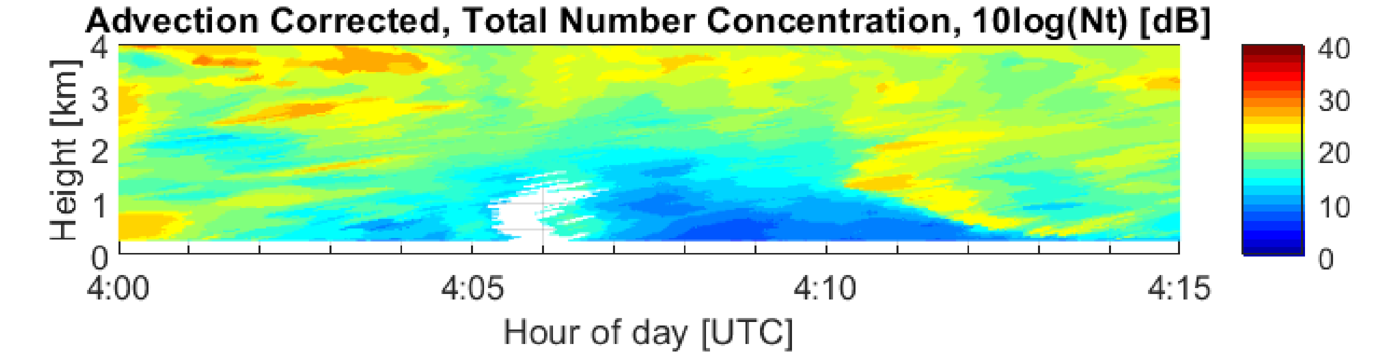
$D_q^{dB} = 10\log(D_q)$ [dB]

Advection Corrected: q^{dB}, N_t^{dB} & D_q^{dB}



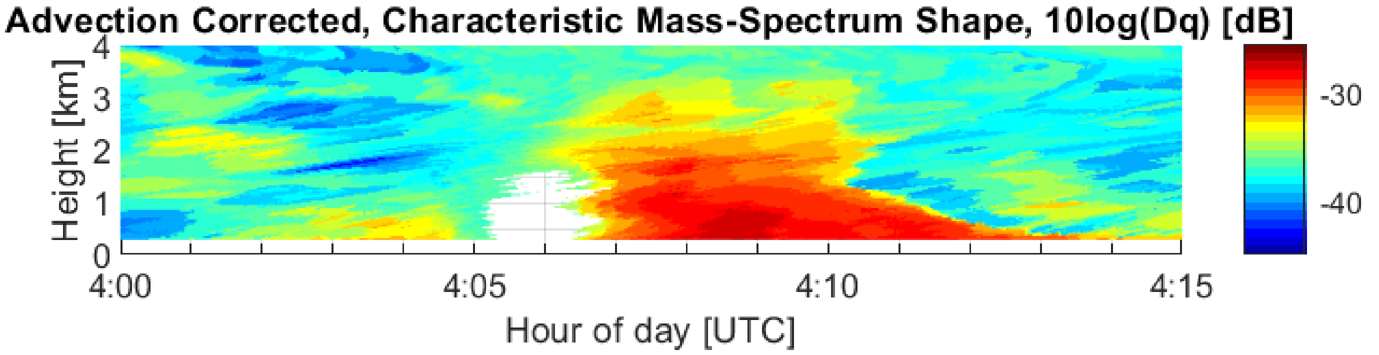
Vertical Air motion

Positive values = Upward motion [m/s]



Total Number Concentration

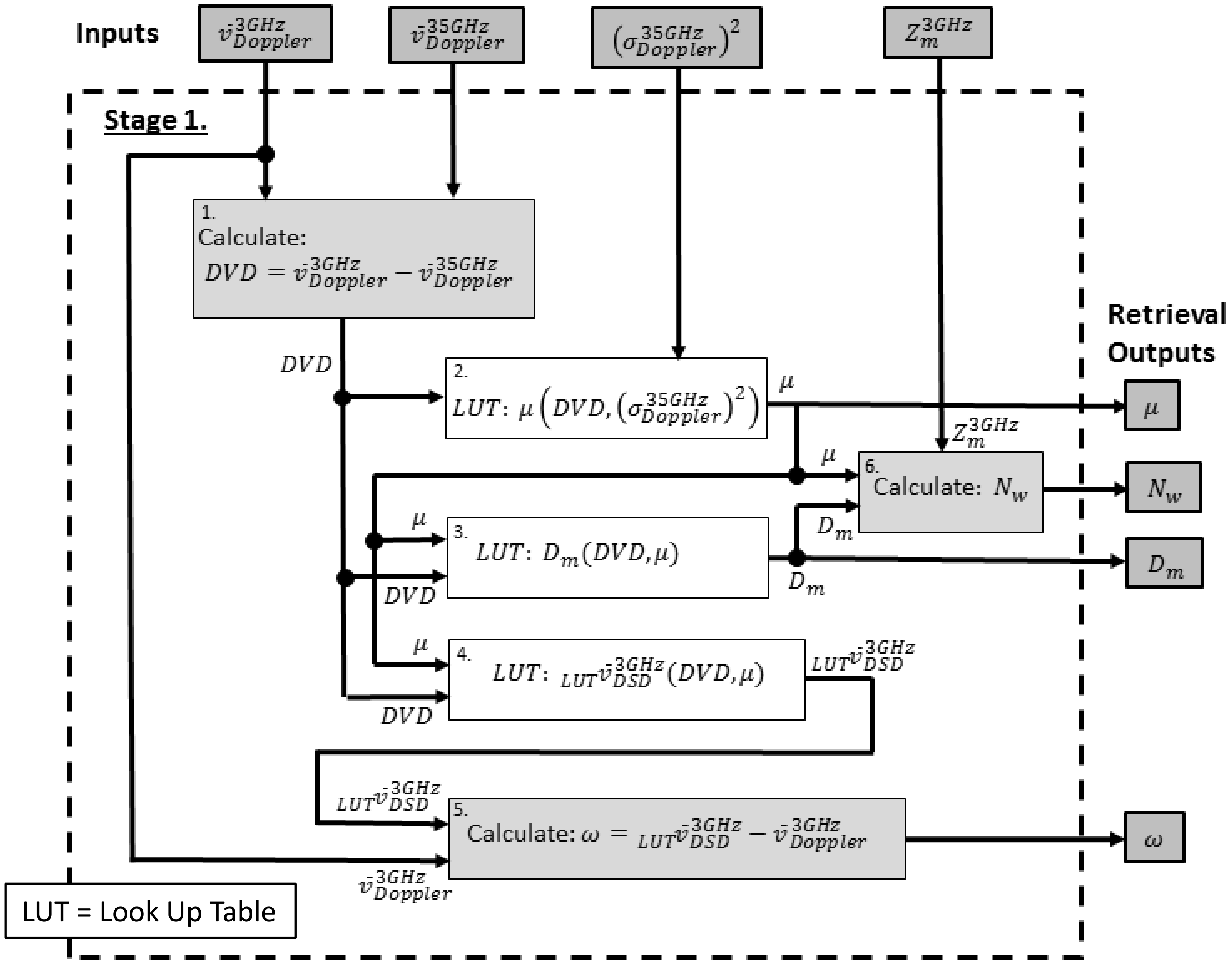
$N_t^{dB} = 10\log(N_t)$ [dB]



Characteristic Mass-Spectrum Shape

$D_q^{dB} = 10\log(D_q)$ [dB]

Retrieval Flow Diagram



See Williams et al. (2016) IEEE TGRS for details of 3/35 GHz retrieval method

Retrieval Frame Work

Desire to Estimate four (4) Unknowns:

3 DSD Parameters: N_w, D_m, μ

1 dynamic parameters: Vertical air motion, ω

Moment Method

Use moments from 0.915 and 35 GHz radar

- 0.915 GHz Reflectivity
- 0.915 GHz mean Downward velocity
- 35 GHz mean Downward velocity
- 35GHz spectrum variance

See Williams et al. (2016) IEEE TGRS for details.

This Work

Use three moments and the 94 GHz spectra:

- 1.2 GHz Reflectivity
- 1.2 GHz mean Downward velocity
- 94 GHz mean Downward velocity
- 94 GHz velocity spectrum