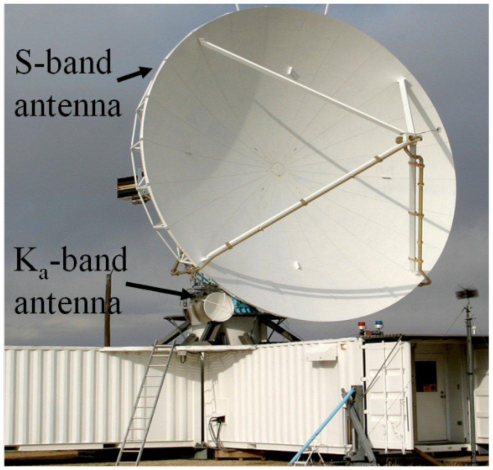
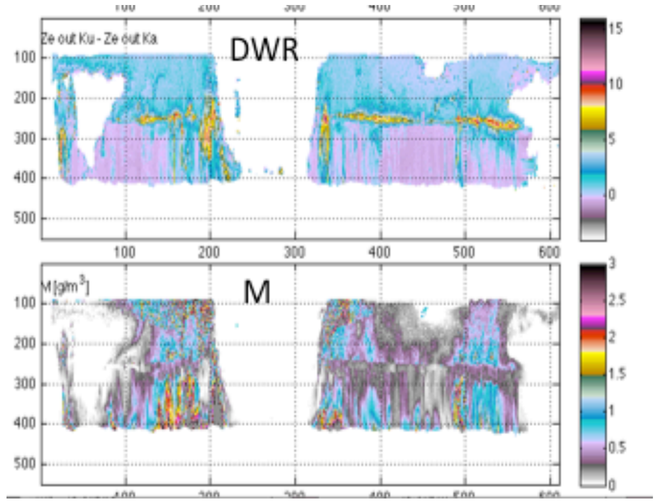
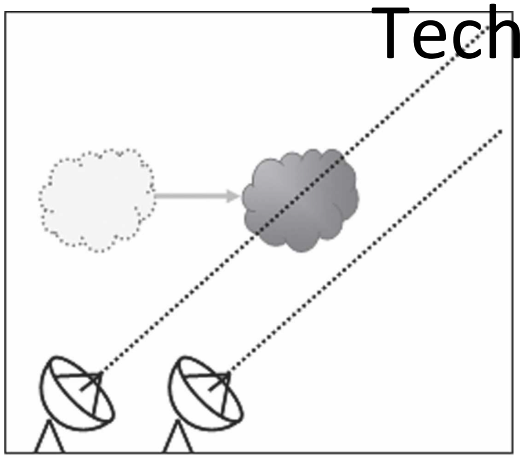




Multiple-Wavelength Radars: Assessment and Future Role?

Scott Ellis

NSF Community Workshop on Radar Technologies, November 27 2012



Radar Upgrades Always Provide More Useful Information

- Doppler
- Dual-pol
- Mobile
- Gap-filling
- Rapid scanning

What about multiple wavelength observations?

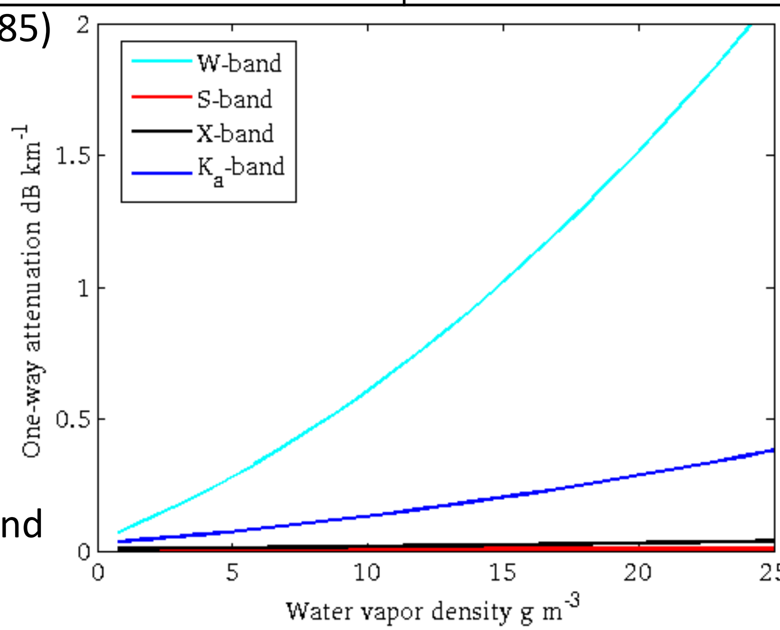
What Additional Measurements Do Multiple Wavelengths Add?

- Differential attenuation
  - Liquid
  - Ice
  - Gaseous
- Different Mie and Rayleigh scattering properties
- Differential Doppler velocity at vertical incident
- Differential Φ_{DP}
- Differential sensitivity to Bragg scatter

Liquid attenuation at sea level and 20° C

Frequency band (wavelength)	**1-way Attenuation dB km^{-1} $(g\ m^{-3})^{-1}$**
S-band (10 cm)	**0.005**
C-band (5 cm)	**0.015**
X-band (3 cm)	**0.058**
K_a-band (0.9 cm)	**0.70**
W-band (0.3 cm)	**4.09**

Liebe (1985)



Following Lhermitte (1987) and Liebe (1985)

What Additional Measurements Do Multiple Wavelengths Add?

- Differential attenuation
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  - Ice
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- Different Mie and Rayleigh scattering properties
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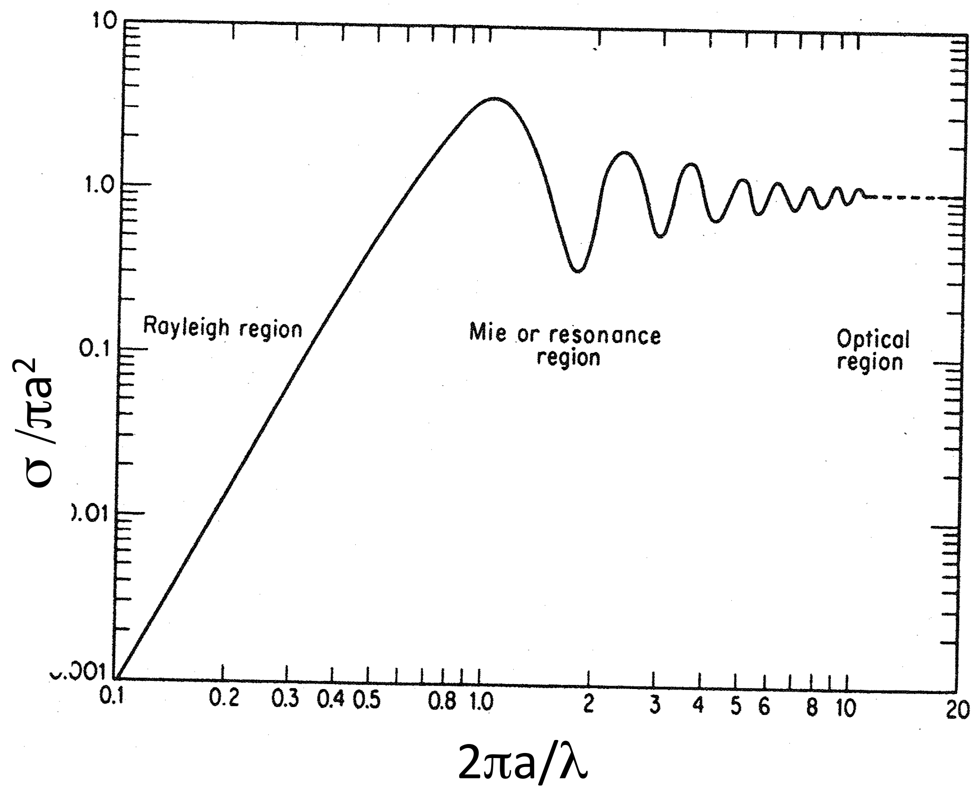


From Rinehart (2004)

What Additional Meteorological Information Results?

- Total mass content
  - Total mass = cloud + precip
  - Liquid Water Content (LWC)
  - Ice Water Content (IWC)
- Humidity
  - In cloud
  - In clear air
- Particle size distribution
- Separation of air motion and particle fall speed (vertical)

Scientific Motivation

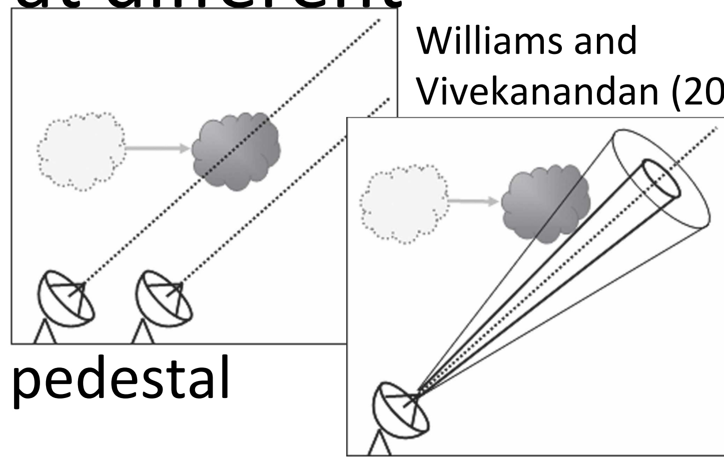
- LWC, IWC and particle size measurements have several applications
  - Cloud microphysics
    - Cloud properties
    - Precipitation development
  - Meso- and cloud scale numerical weather prediction
    - Validation
    - Data assimilation
  - Climate studies
    - Improved climate model parameterization of clouds
    - Improved radiation budget
  - Aviation safety
- Limited spatial coverage of in situ and/or radiometer LWC, IWC and particle size measurements

Scientific Motivation

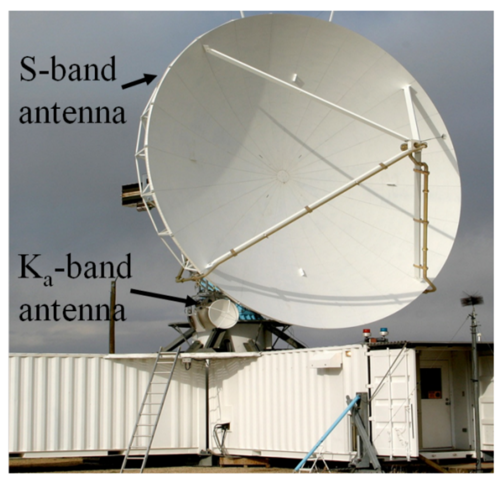
- Water vapor is an important variable for weather at many scales
  - Convection
    - Severe weather
    - Convective initiation
  - Hydrology in complex terrain
  - Tropical meteorology, e.g. the onset of the MJO
  - Numerical weather prediction and data assimilation
  - Quantitative precipitation estimation and forecasting

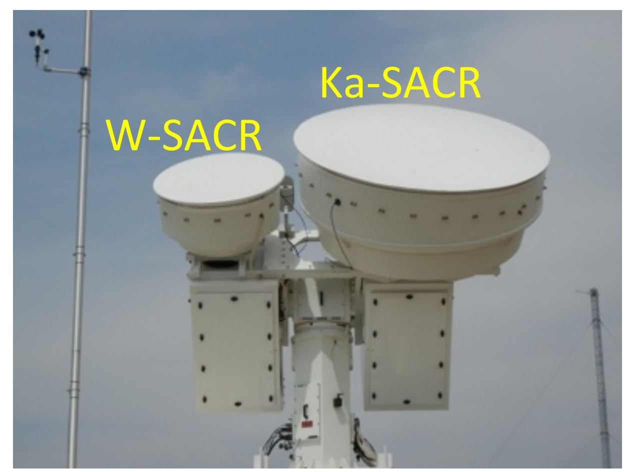
Technical Challenges of Multi-Wavelength Radar

- Requires two or more radars at different wavelengths
- Matched resolution volume
  - Beam width
    - Different sized antennas on one pedestal
  - Pointing angle
  - Range resolution



Williams and Vivekanandan (2007)



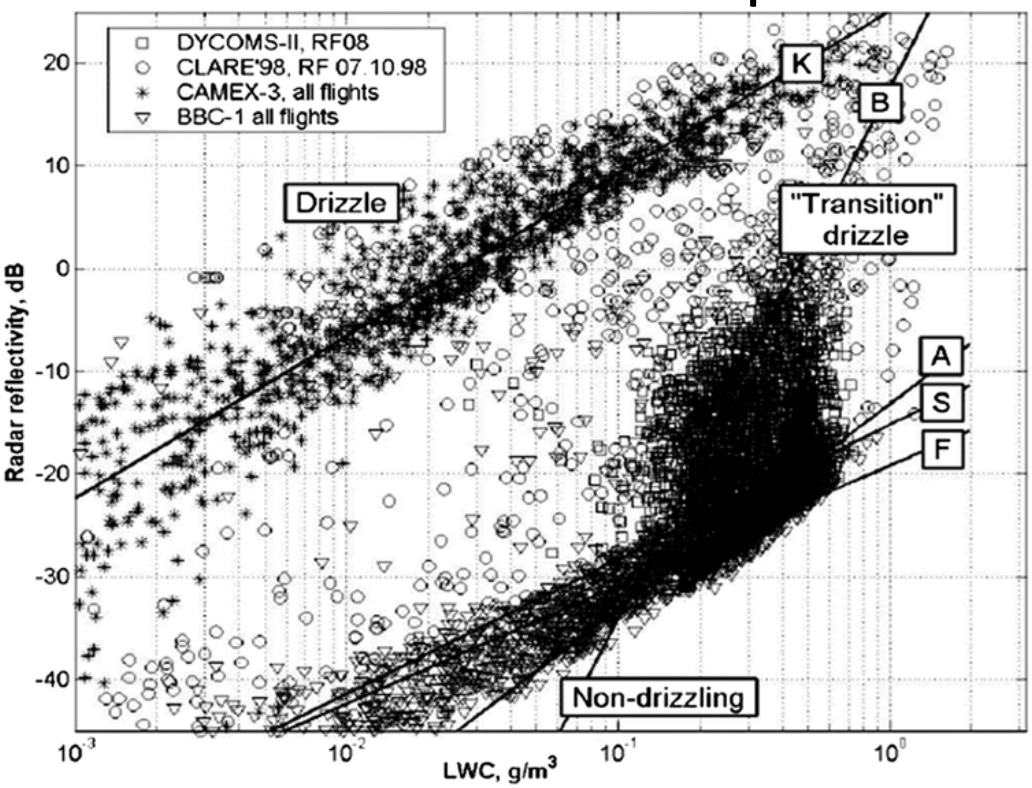


Outline

- **Attenuation-based techniques**
  - Liquid
  - Humidity
- Techniques based on scattering properties
  - Ice crystals
  - aggregates
- Applications using Bragg scattering and differential Φ_{DP}
- Discussion of future role of multi-wavelength radar

Why Use Liquid Attenuation?

- LWC estimates using radar reflectivity are difficult due to D^6 dependency
  - Large drizzle/rain drops dominate reflectivity
  - Small cloud drops can dominate LWC



Khain et al. (2008)

Photo by Bjorn Stevens

Why Use Liquid Attenuation?

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  - Small cloud drops can dominate LWC

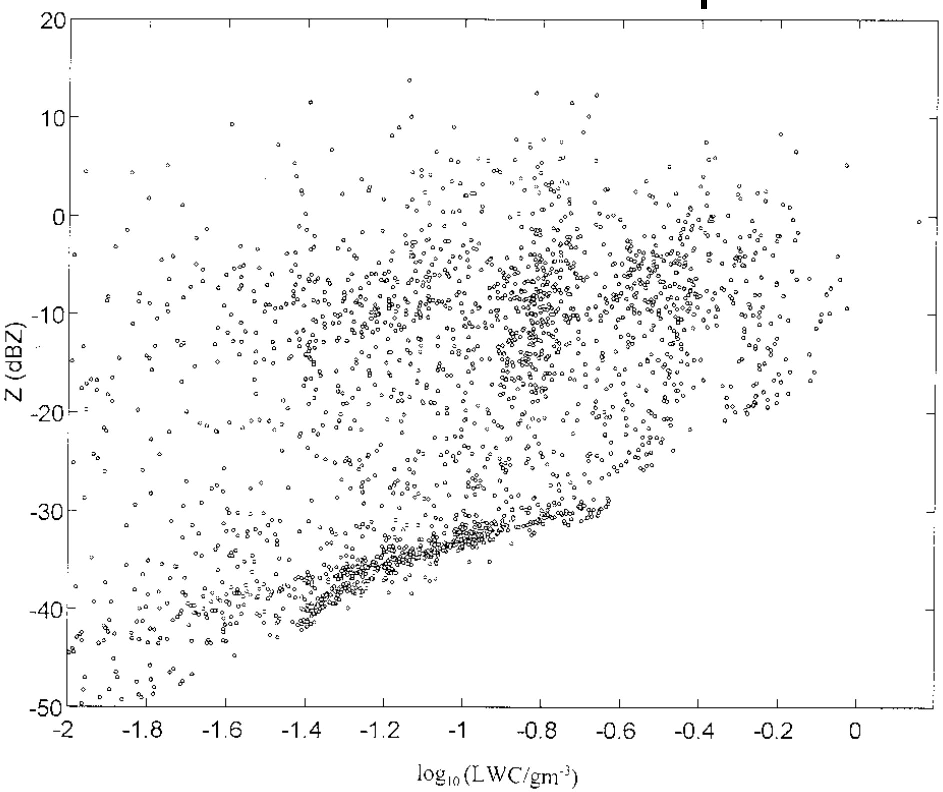
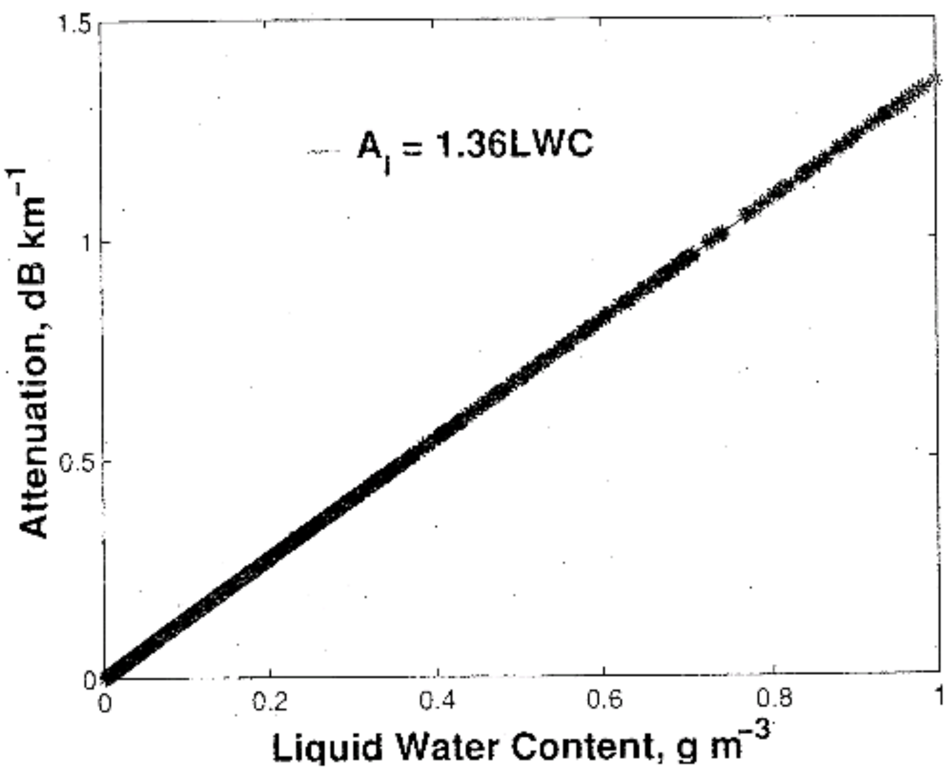


FIG. 1. Scattergram of *Z against LWC calculated from FSSP and* 2DC 10-s spectra made during 4000 km of cloud penetrations.

(Fox and Illingworth, 1997)

Why Use Liquid Attenuation?

- Vivekanandan et al. (1999) showed at K_a-band A_L = 1.36LWC (-10° C)
- Attenuation is directly related to LWC (no DSD!!)
- Differential attenuation in a cloud is independent of calibration



(b)

Liquid Attenuation a New Idea?

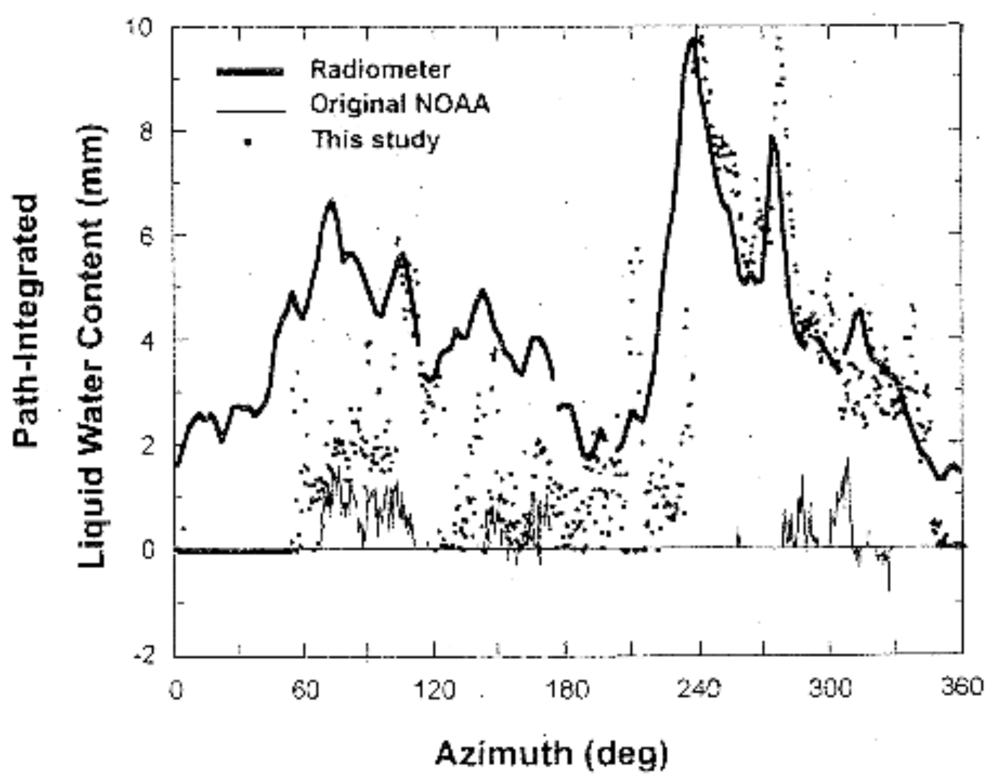
- Attenuation proposed to retrieve LWC by Atlas (1954)
  - Use two radars sampling similar paths, or
  - Use one radar and assume constant Z
- Atlas and Ulbrich 1977 also showed that attenuation at near 1 cm wavelength linearly related to rain rate

Technical Challenges Using Attenuation

- Measure Differential Wavelength Ratio (DWR, dB) by comparing coincident reflectivity (Z) values: DWR = $Z_2 – Z_1$
- Ambiguity between attenuation and Mie scattering effects – DWR impacted by
  - Liquid attenuation
  - Gaseous attenuation
  - Mie scattering
- SNR: differential attenuation (signal) versus measurement variance
  - Minimum path length is a function of dwell time, differential attenuation (Hogan et al., 2005; Williams and Vivekanandan, 2007)
- Attenuation dependency on temperature
- Presence of unwanted echoes
  - Biological
  - Bragg
  - Ground and sea clutter
- Hogan et al (2005) and Williams and Vivekanandan (2007) summarize sources of error and mitigation strategies

LWC Retrieval With X- and K_a-band

- Vivekanandan et al. (1999) Demonstrated LWC retrieval with NOAA X and K_a-band
  - 1.5° elevation angle
  - Mitigated Mie scattering using DWR threshold and assuming Rayleigh scattering at edge of cloud
  - Path length for attenuation estimation was 750 m
- Compared results to radiometer



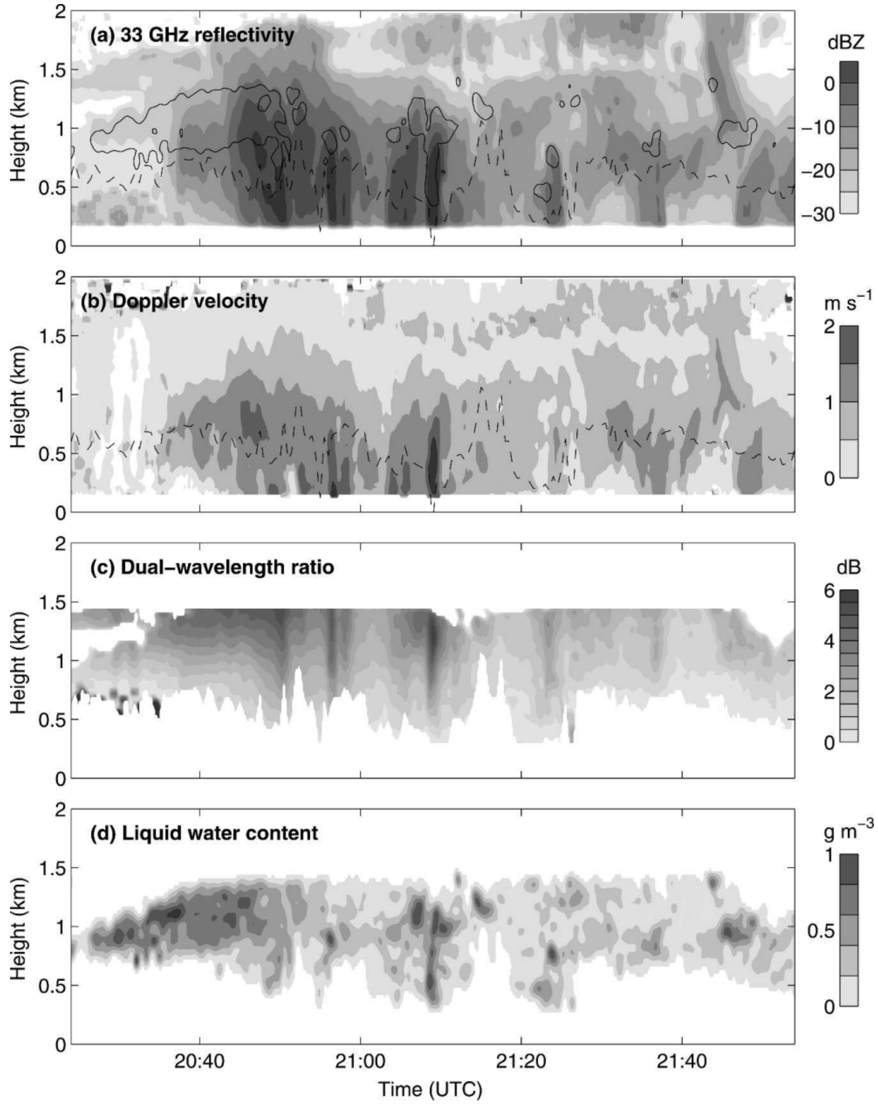
- Also showed MVD can be retrieved from LWC and Z

- MVD^3 = 2.16X10-4 Z/LWC

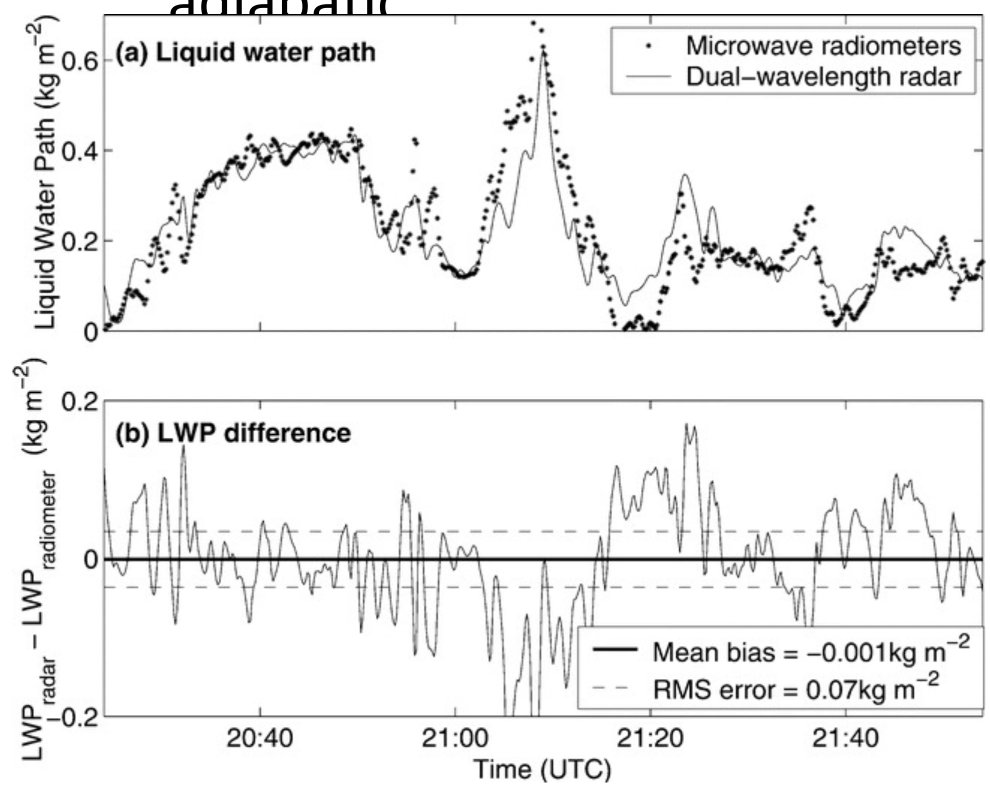
LWC From Vertically Pointing K_a- and W-band Radars

- Hogan et al (2005) estimated LWC in stratocumulus clouds with DOE ARM radars (OK)
- Detected Mie scattering by comparing radial velocity
- To achieve an LWC variance of 0.04 g m^{-3}
  - Minimum path was found to be 150 m (average 2 bins)
  - Dwell time of 1 minute

LWC From Vertically Pointing K_a- and W-band Radars



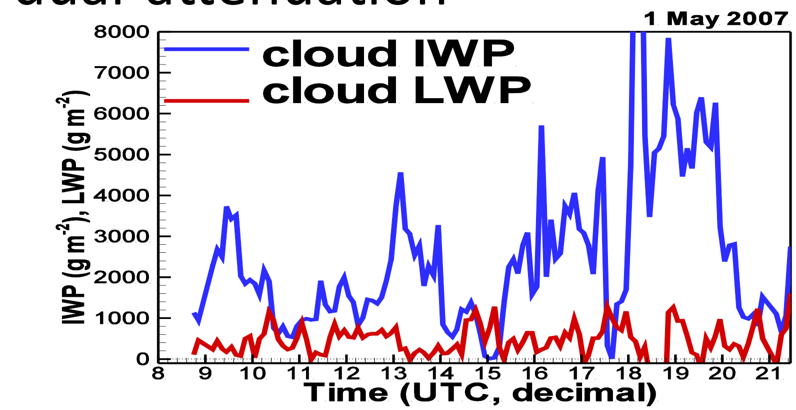
- Verification
  - Compared well to radiometer
  - LWC estimates nearly adiabatic

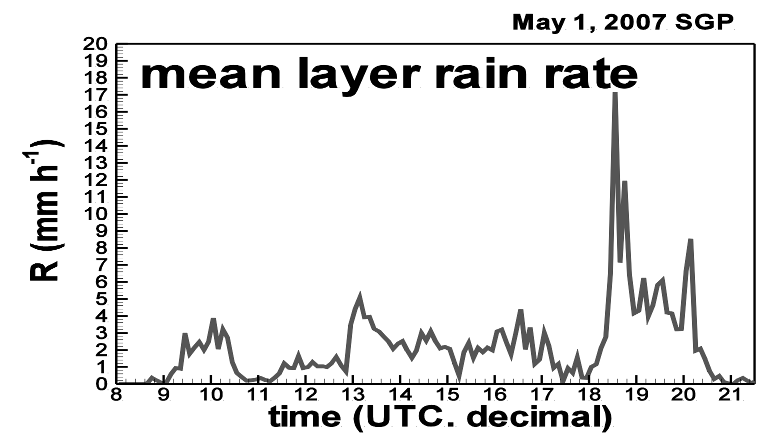


Estimates of Liquid, Ice and rainfall parameters in stratiform precipitation from Ka- and W-band ARM radar measurements

- Matrosov (2009) Retrieved IWP, LWP and rainfall
- Combined ARM radar with WSR-88D and disdrometer data

Retrievals: decoupling of cloud and rain water is based on K_a-W dual-attenuation

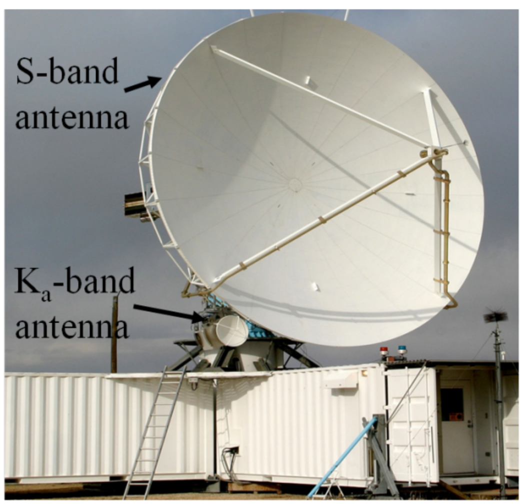




Courtesy Sergey Matrosov. doi: 10.1175/2009JAMC2106.1

LWC With Scanning S and K_a-band Radars

- Ellis and Vivekanandan (2011) used NSF/NCAR S-PolKa radar
- Detected Mie scattering using S-band polarimetric data
- Dwell time limited by scanning
- Minimum path length was 2 km (following Hogan et al, 2005)
- Estimate the range resolved attenuation (dB km^{-1}) following Tuttle and Rinehart (1983)
  - $A_L = Cz_s^p$ (z_s in units of $mm^6\ m^{-3}$)
- Estimated LWC and MVD following Vivekanandan et al (1999)



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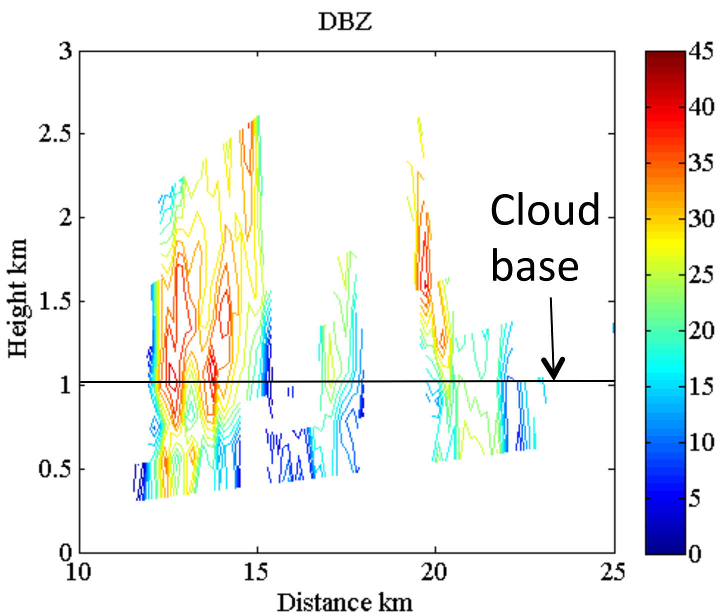
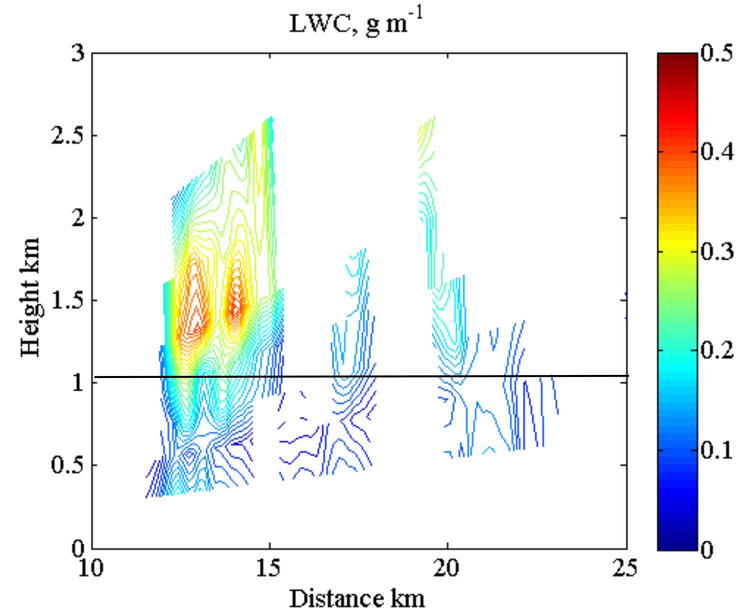
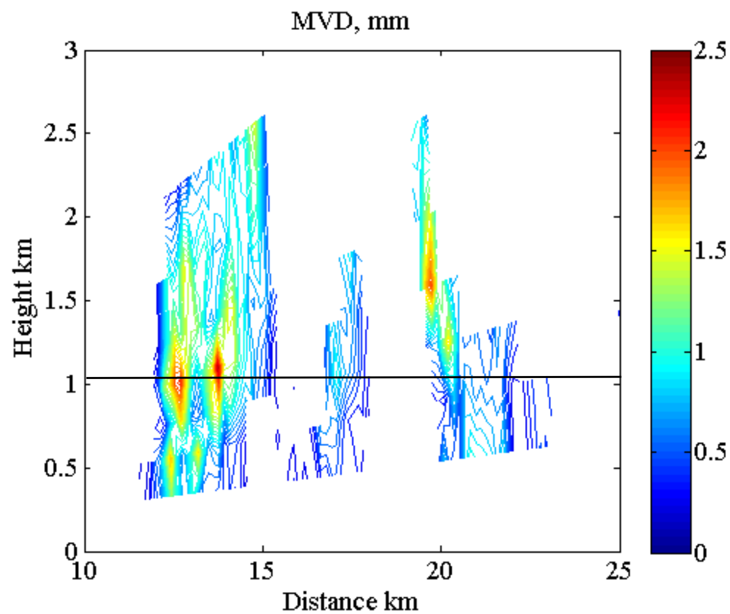
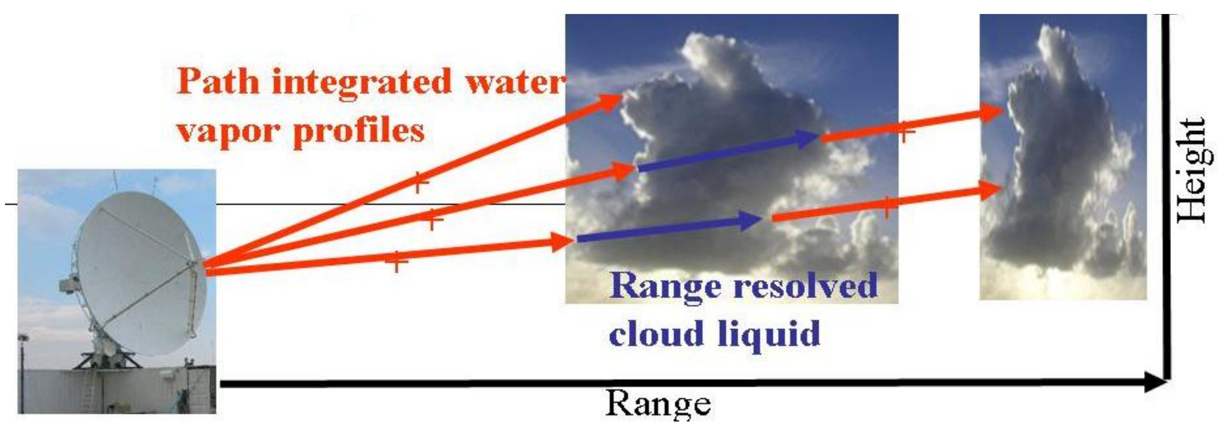


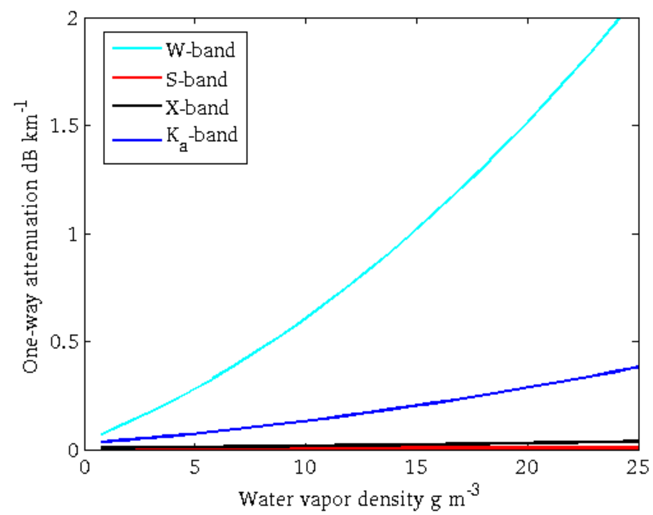




Humidity From S- and K_a-band

- Ellis and Vivekanandan (2010) demonstrated humidity profile estimates
- Estimate K_a-band gaseous attenuation by comparing S- and K_a-band reflectivity
- Min path length 15 km!
- Relate attenuation to humidity
- Complement spatial and temporal resolution of soundings when conditions allow





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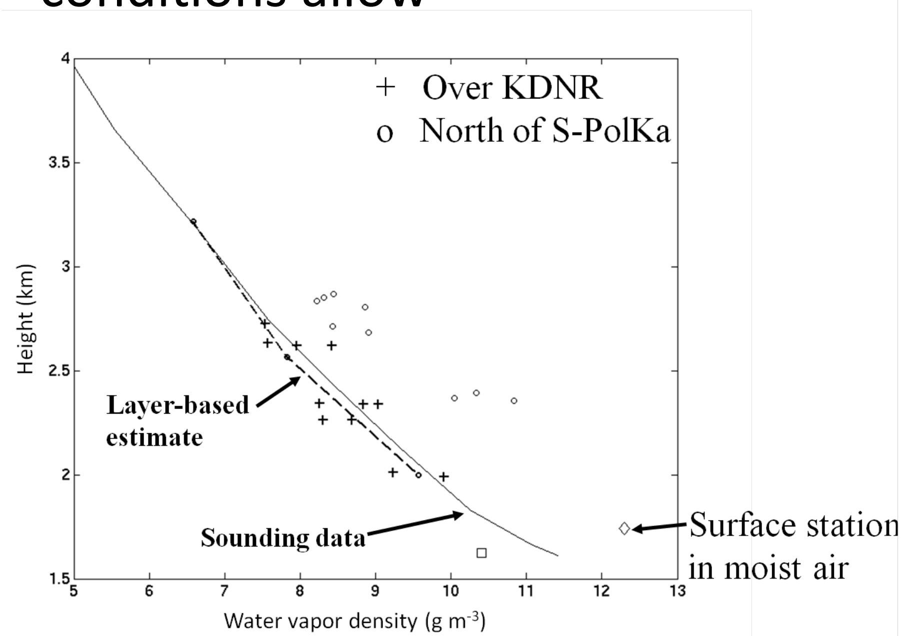
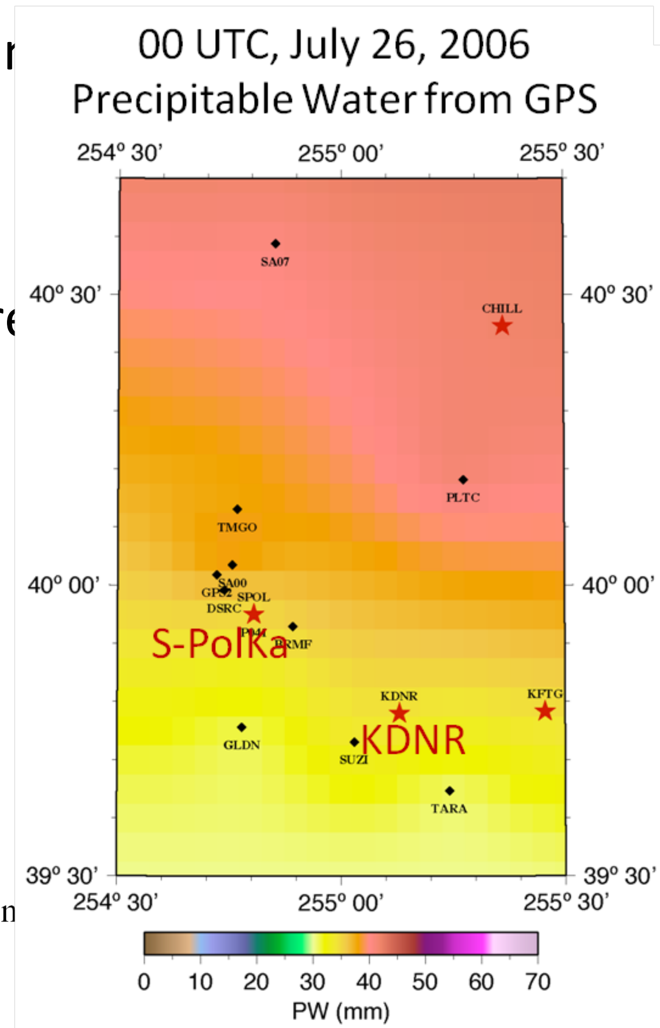
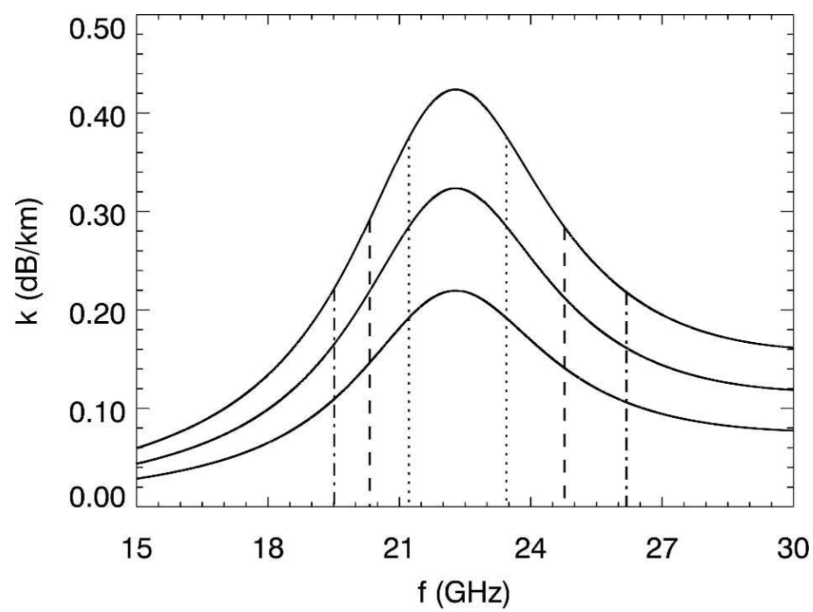




Courtesy of John Braun, NCAR

Humidity From Triple-Wavelength Radar

- Menighini et al (2005) proposed humidity retrieval from vertical pointing (airborne or spaceborne) radar
- Simulated retrievals and error
- Uses three wavelength measurements to account for 3 unknowns – attenuation by gas, liquid and Mie scattering
- Center wavelength ~ 22 GHz – on absorption line other two nearby on either side
- Similar conceptually to DIAL technique



Outline

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Using Scattering Properties

- For scatterers beyond the Rayleigh regime differences in Z at different wavelengths can be related to size
- Results in more accurate size estimates than with single frequency data
- Proposed by Atlas and Ludlam (1961) for hail detection using S- and X-band!
- First proposed for cirrus by Matrosov (1993)
  - Numerous scattering calculations

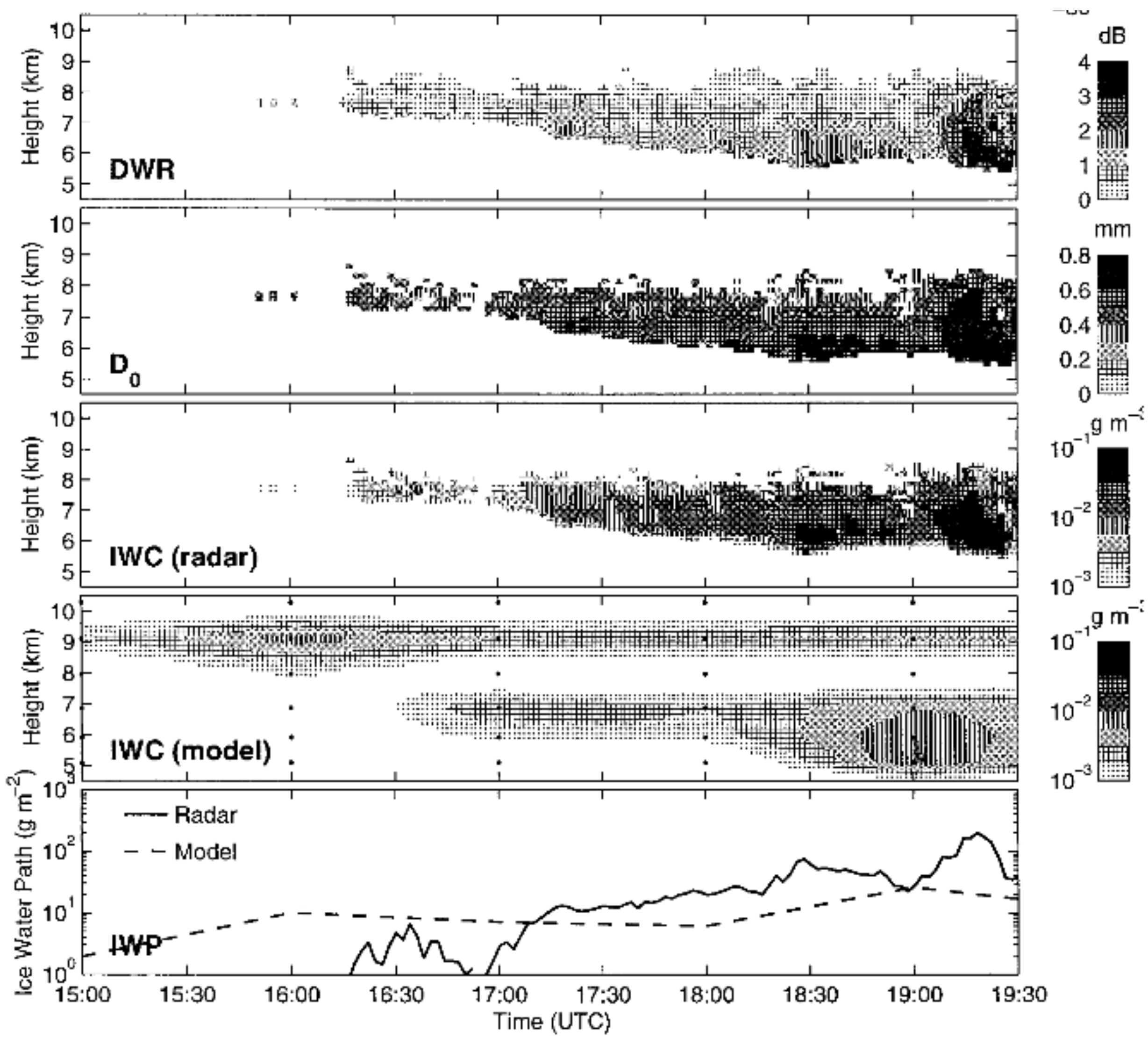
Technical Challenges Using Scattering Properties

- Ambiguity between Mie scattering effects and attenuation – DWR impacted by
  - Ice attenuation
  - Gaseous attenuation
  - Mie scattering
- Calibration
- Scattering calculations should be representative of study
- Unknown or variable density of ice and snow

Estimating Crystal Size and IWC Using Vertically Pointing K_a- and W-band

- Hogan et al (2000) demonstrated dual-wavelength ice retrieval in cirrus
- Use aircraft observations in scattering calculations to determine DWR relation to D_0
- Biggest error from density – similar to single wavelength
- In cirrus attenuation by ice was small
- Wavelengths shorter than W-band are impractical due to high gaseous attenuation

Estimating Crystal Size and IWC Using Vertically Pointing K_a- and W-band



Estimating Crystal Size Using Vertically Pointing K_a- and W-band

- Matrosov (2011) demonstrated ice size parameter estimates from both
  - DWR
  - Differential Doppler Velocity (DDV)
- DDV is immune to attenuation!

Estimating Crystal Size and IWC Using Vertically Pointing K_a- and W-band

Measurements

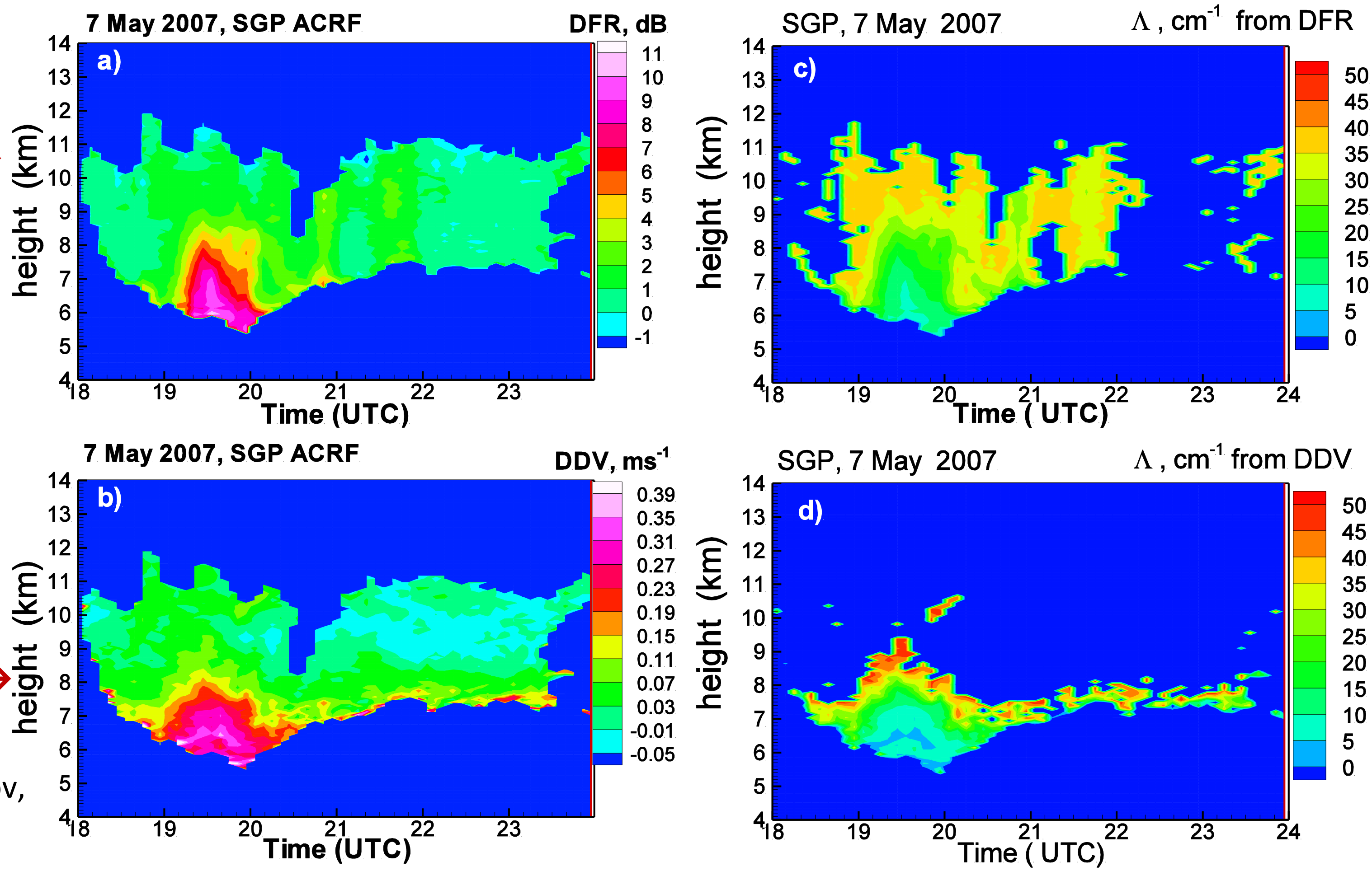
(DDV is immune to differential attenuation but noisier than DFR)

Retrievals of size parameter, Λ

(slope of the exponential size distribution), in cloud volumes with good SNR levels

DWR=$Z_e(K_a)$-$Z_e(W)$→

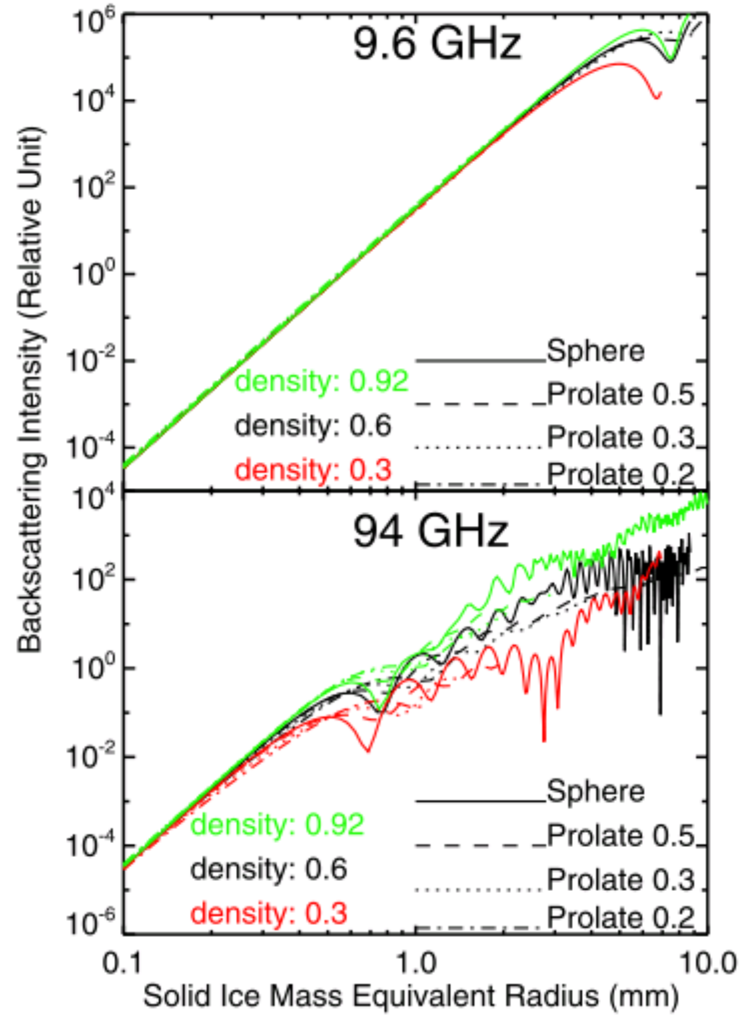
DDV=$V_D(K_a)$-$V_D(W)$→



Courtesy Sergey Matrosov, doi: 10.1029/2011JD015857

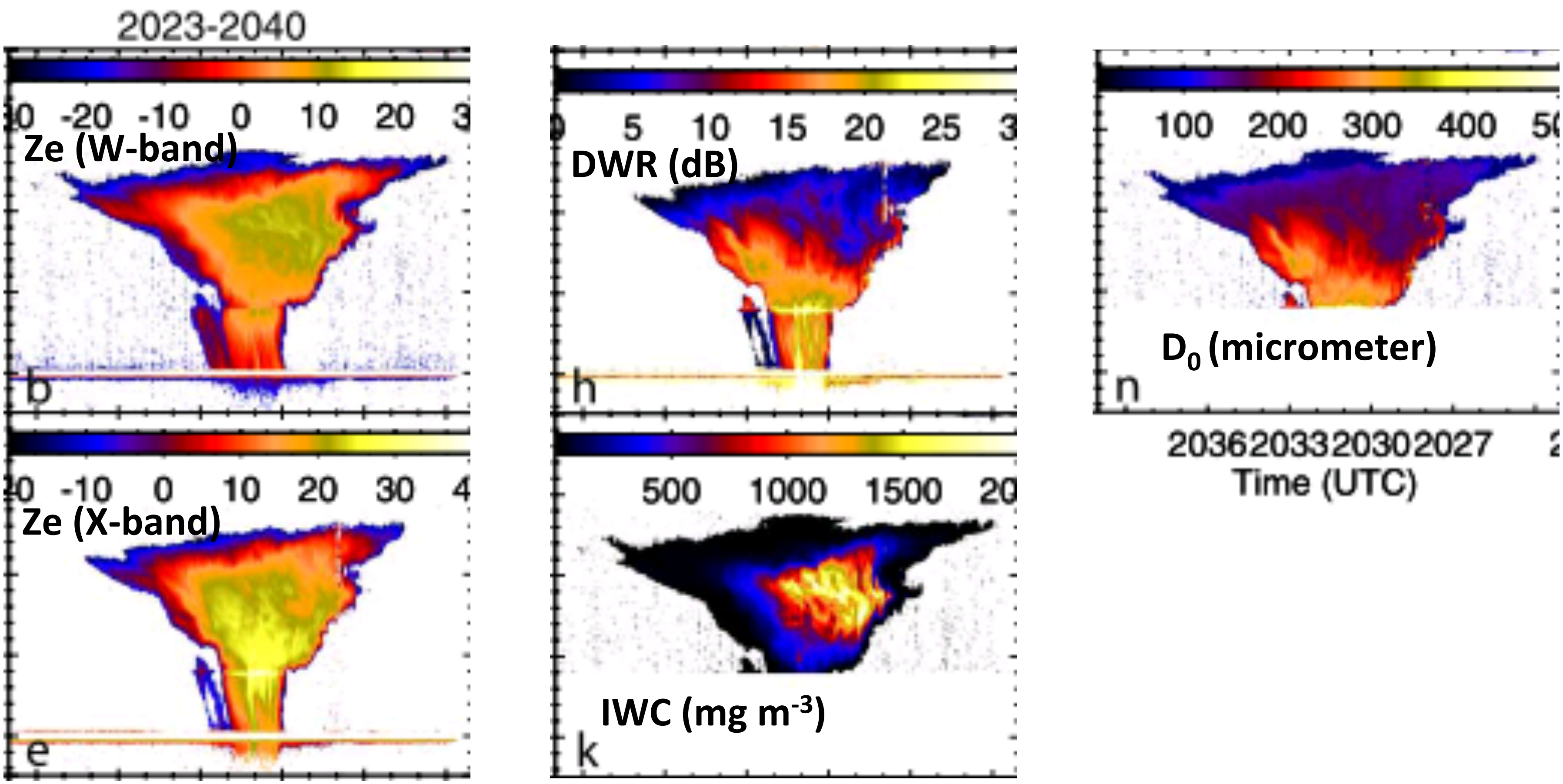
Ice Cloud Microphysical Retrievals With Airborne X-band and W-band

- Wang et al (2005) studied optically thick ice clouds
- Scattering calculations
  - Use CRYSTAL-FACE observations
  - Mass-length relationship is main factor
- Need to correct for W-band attenuation by IWC



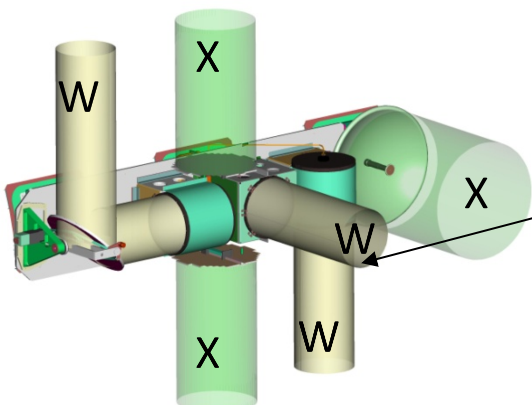
Wang et al (2005) Case Study

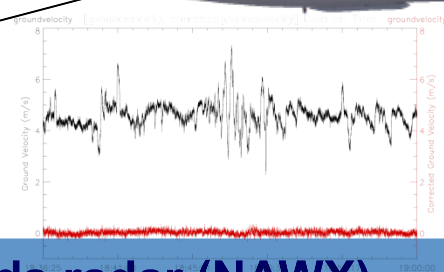
convective system observed on 29 July 2002
during CRYSTAL-FACE.



NRC Convair 580: C3VP Instrumentation / Data

Courtesy of Mengistu Wolde



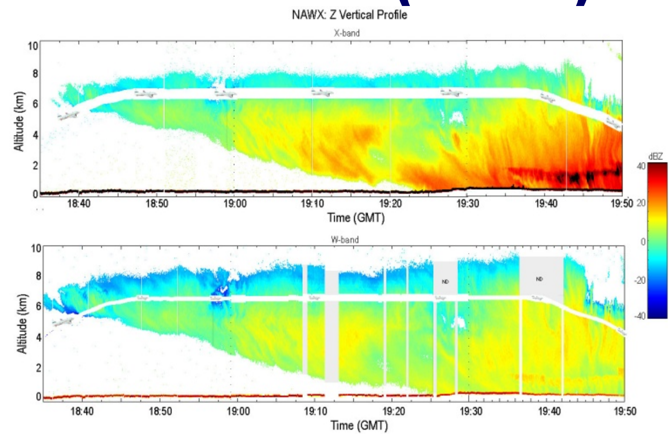


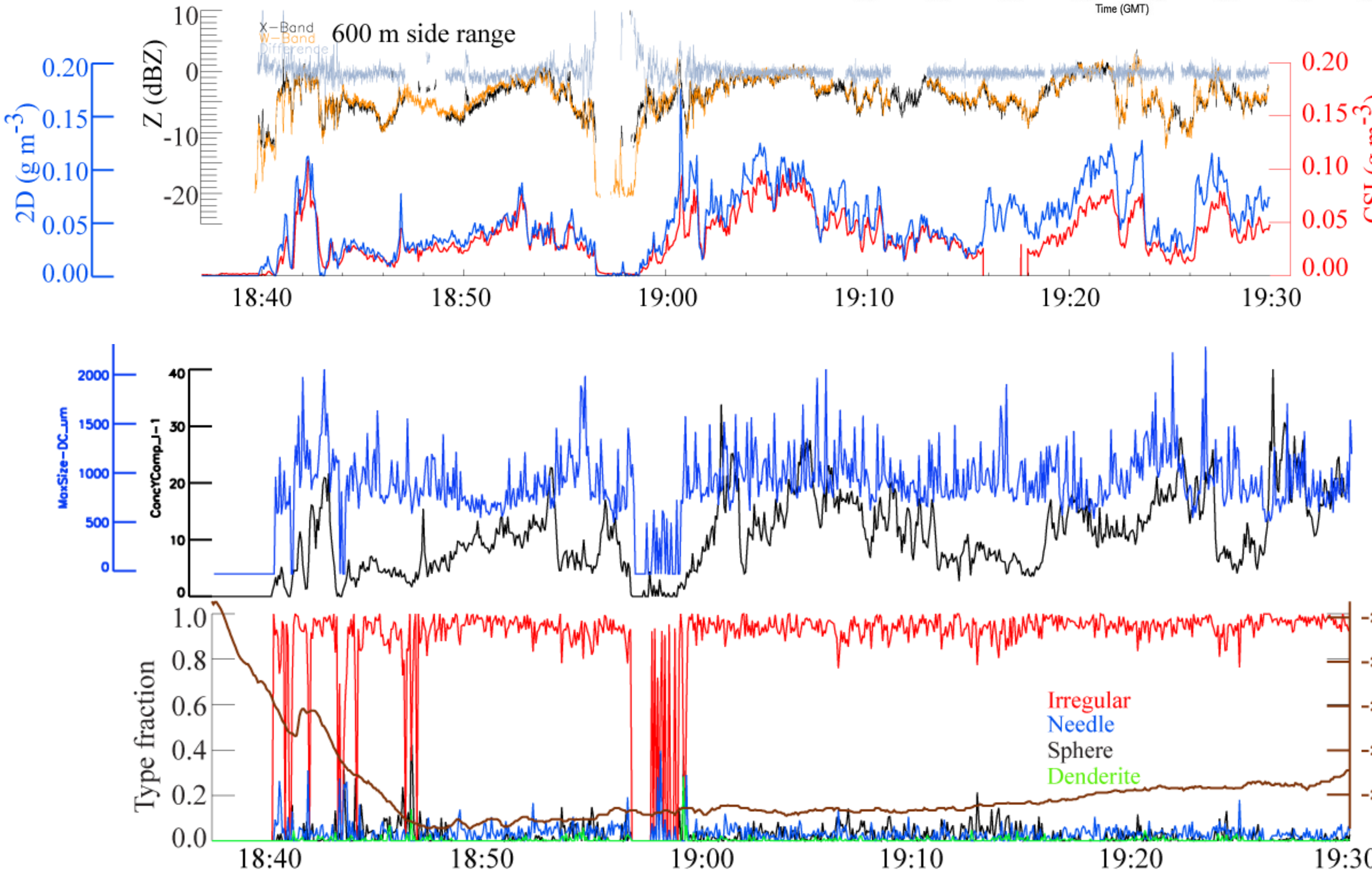
***N**RC **A**irborne **W** and **X**-bands radar (NAWX)* http://www.nawx.nrc.gc.ca	
Reflectivity - Z (dBZ)	±0.5 dB – relative cal
Dual-Frequency Ratio – DFR (dB)	Z_X - Z_W
Differential Reflectivity Factor - ZDR	$Z_{HH} – Z_{VV}$
Linear Depolarization Ratio (LDR)	$Z_{VH} – Z_{HH}$ < -30 dB isolation
Doppler Velocity (Vd) - vertical	A/C motion removed (±0.5-nadir; ±1.0 m/s -Aft

Arrays of in-situ sensors – aircraft, thermodynamic state sensors; cloud physics	
TWC	CSI; PMS 2D
Icing	RID
Type	Grouped into 4 categories Irregular, Sphere, Needle and Dendrite

Initial Climb (Snow)

Courtesy of Mengistu Wolde





DFR ~ 0 dB

IWC vs. NAWX

Size < 2 mm

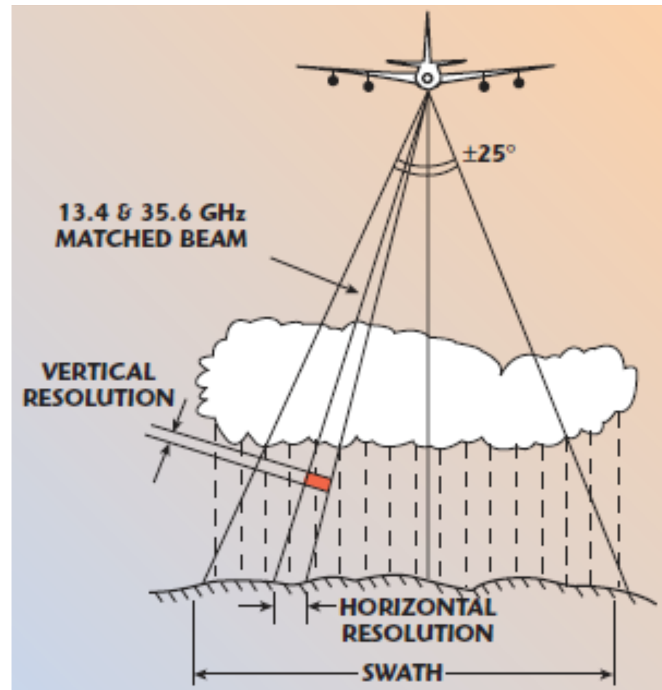
Max size vs. concentration

Irregular shape

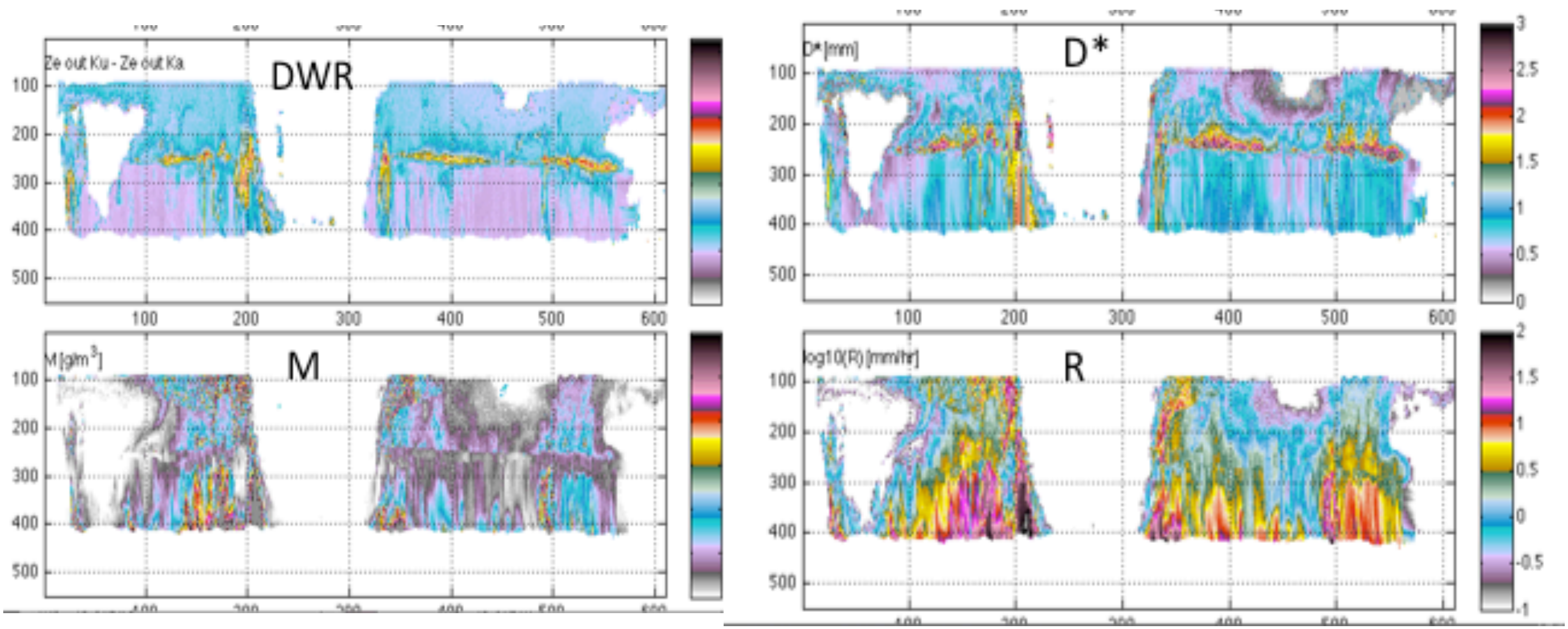
T -28 to -20C

Particle Type, Size and Mass Retrievals from Airborne Dual-Wavelength

- Durden et al (2012) use airborne K_u and K_a-band radars – APR-2
- Geometry and frequencies chosen to simulate GPM radar
- Uses both frequencies when available, Doppler, LDR
- Fully Bayesian approach performs multiple (up to ~100) retrievals by perturbing PIA, and a priori mean particle size assumptions. Deterministic classification is used as input, but fractional populations of liquid, snow, graupel, etc are refined based on Rasmussen and Heymsfield (1987).
- Final estimate is a weight average based on several performance measures.
- Proposing to add W-band for triple wavelength capability (e.g. Leinonen et al., 2012)



Durden et al (2012) Results: Tropical Cyclone



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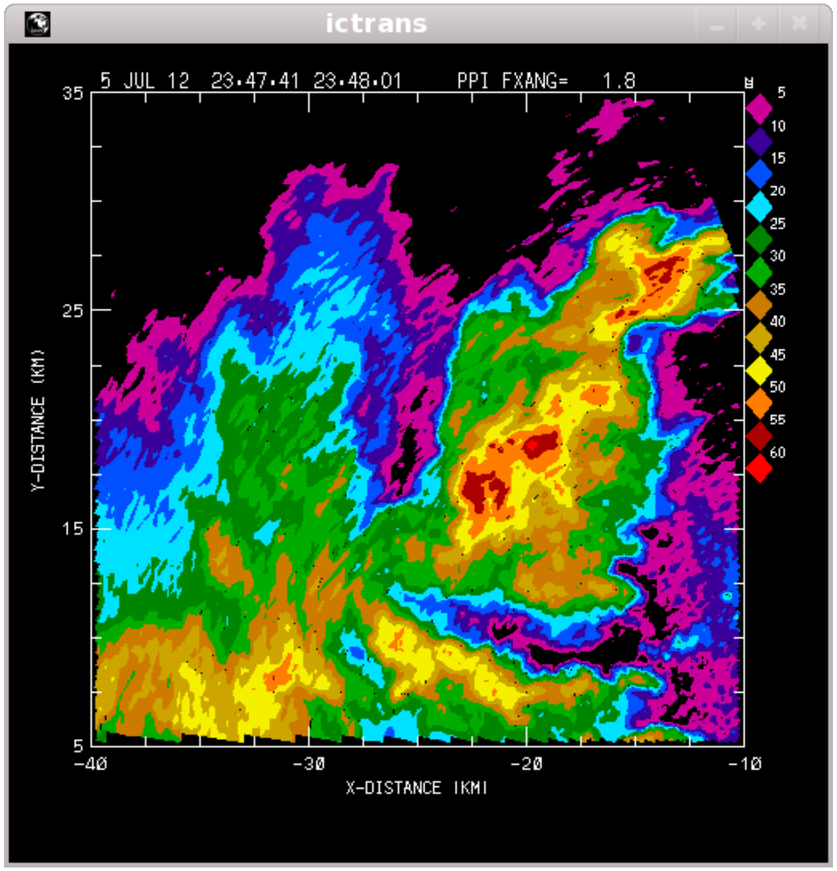
CSU-CHILL dual wavelength configuration

- Combined S and X-Band horn installed on 8.5m diameter dual-offset antenna.
- X-Band 3 dB beam width ~0.3 deg; beam axis coincident with S-band 1.0 deg beam

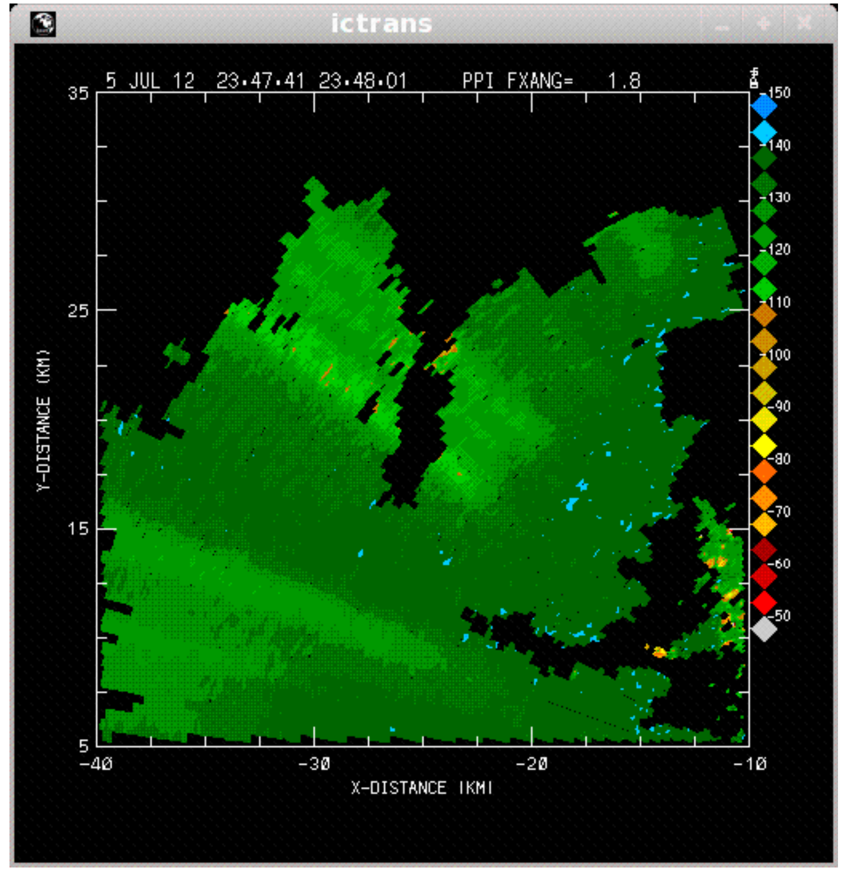
Courtesy Pat Kennedy

Two-minute interval time lapse interval thunderstorm observations

•S-Band differential propagation phase (ϕdp) magnitude peaks at ~20º



S-Band dBZ

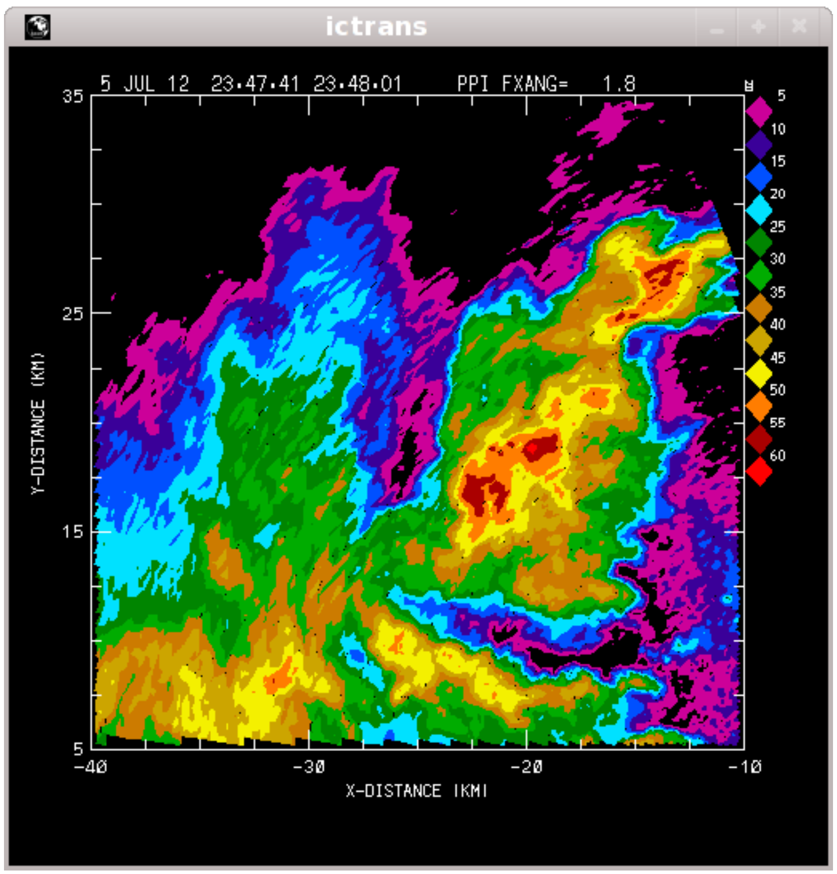


S-Band ϕdp

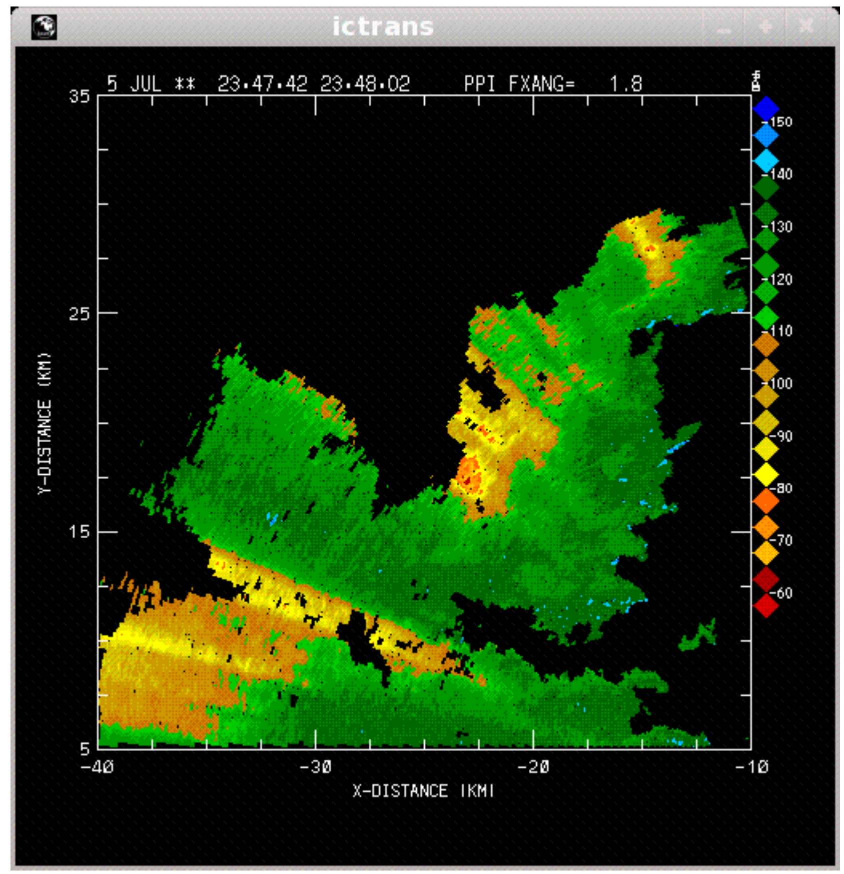
Courtesy Pat Kennedy

X-Band ϕdp (right) for same time lapse period

- Phase shift magnitudes ~3X larger at X-Band vs. S-Band
- Greater ϕdp sensitivity extends phase observations to lighter rain, ice regimes, etc.
- More accurate rain rate estimates in weaker echoes
- Differences in X/S-Band ϕdp and Mie scattering behavior can categorize hydrometeor sizes
- Combining S-band and X-band HID can improve results in weaker echoes



S-Band dBZ



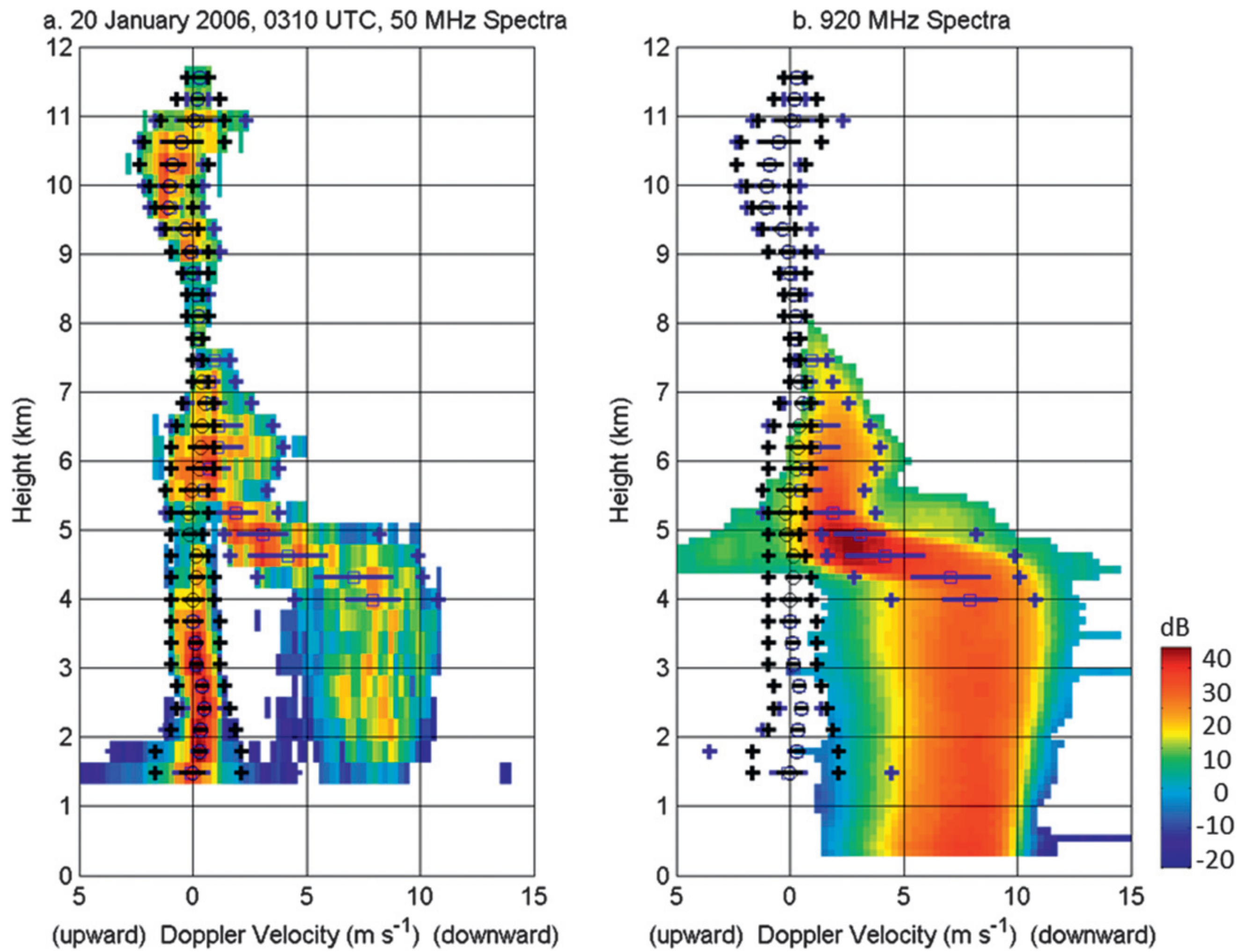
X-Band ϕdp

Courtesy Pat Kennedy

Estimation of Fallspeed and Vertical Air Motion with Dual-Wavelength Profiler

- Williams et al (2012) demonstrated technique using 920 and 50 MHz observations
- "Use the 920-MHz profiler to identify and filter the hydrometeor motion in the 50-MHz profiler Doppler velocity spectra before estimating the vertical air motion"
- Other wavelength pairs can be used

Estimation of Fallspeed and Vertical Air Motion with Dual-Wavelength Profiler



Discussion: Summary

- Multi-wavelength radars add complementary data and retrievals to existing radar technologies
  - Mass content (IWC and LWC)
  - Particle size
  - Humidity
- These data and retrievals are of high scientific value for a variety of atmospheric science disciplines
- Wavelength combinations can be optimized for type and scale of problem
- Research to date has demonstrated the value of multi-wavelength radar systems
- More multi-wavelength systems being planned

Discussion: Future Role in Research

- Retrieval Science
  - Verification and intercomparison
  - Combine with in-situ measurements to validate and improve scattering calculations
  - Tech transfer – move from research to routine
  - Combine with other radar measurements
    - Doppler
    - Dual-pol
    - Mobile
    - Rapid scan
    - Gap filling
  - Combine with different instruments
    - Lidar
    - Passive remote sensors
    - In-situ and Soundings

Discussion: Future Role in Research

- Atmospheric science
  - Microphysics studies – LWC, IWC, sizes, water vapor
    - Orographic
    - Warm rain
    - Stratocumulus
    - Convection
    - Tropical
  - Meso-scale modeling
    - Validation of IWC and LWC
    - Assimilation of IWC, LWC and humidity
  - Climate modeling
    - Validate cloud parameterization
    - Improve radiation budget

Discussion: Future Role in Operations

- Aviation safety – cold cloud hazards
  - High ice content clouds
  - Aircraft icing conditions
- Operational data
  - Humidity
  - Improved QPE
    - Rain
    - Snow

Discussion: Some Current and Planned Multi-Wavelength Radar Technologies

- NSF S-PolKa
  - S- and Ka-band
  - Dual-polarimetric
  - Transportable
  - Requestable facility
- CSU-CHILL
  - S- and X-band
  - Dual-polarimetric
  - Requestable facility

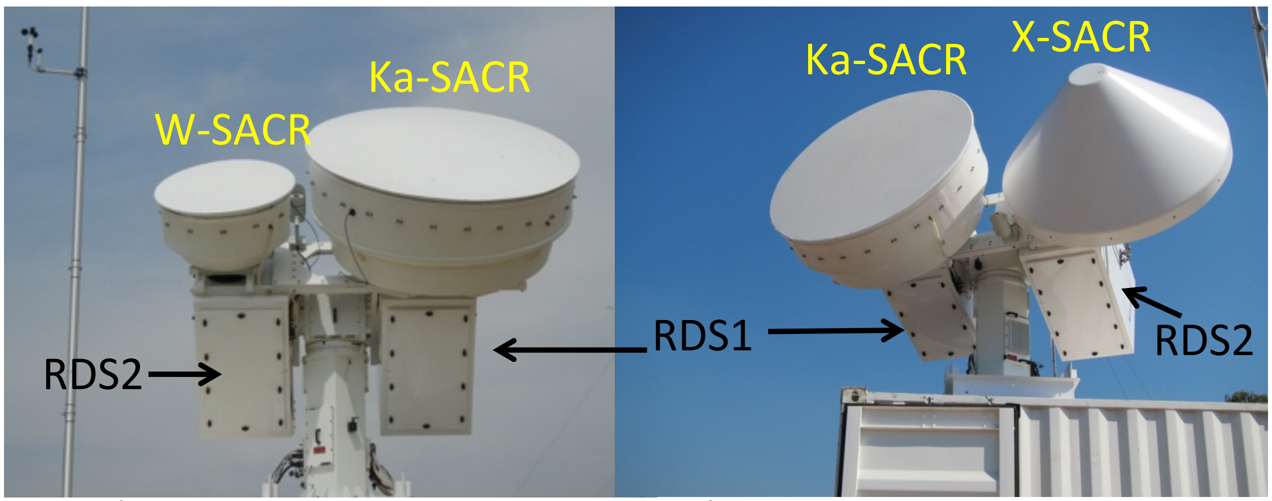
Discussion: Some Current and Planned Multi-Wavelength Radar Technologies

- ARM W- and K_a-band vertical pointing
- APR-2 at JPL
  - Ku and K_a-band (W-band in future)
- GPM
  - Ku and K_a-band

http://pmm.nasa.gov/

Discussion: Some Current and Planned Multi-Wavelength Radar Technologies

- ARM program has deployed two types of dual frequency radars
  - Ka/W-SACR
  - X/Ka-SACR
- Dual-polarization operations:
  - Transmit horizontal and receive horizontal and vertical polarization with Ka-band
  - Simultaneous transmit and receive with X-band cloud radar
- Capable and operates with frequency diversity pulse compression
- Dual frequency radars on same pedestal
- 24x7 operations
- Doppler spectra is stored for zenith pointing profiling mode



Ka/W-Scanning ARM cloud radar

1. Southern Great Plains, Oklahoma
2. Northern Slopes Alaska - Barrow
3. ARM Mobile Facility 1 - Cape Cod, MA
4. ARM Mobile Facility 3 – Oliktok, AK*
5. Azores – Graciosa Island*

X/Ka-Scanning ARM cloud radar

1. Tropical Western Pacific – Darwin, Australia
2. Tropical Western Pacific – Manus, PNG
3. ARM Mobile Facility 2 – Marine Deployment

Courtesy Nitin Bharadwaj

Discussion: Some Current and Planned Multi-Wavelength Radar Technologies

- Majurec et al (2012)
- Triple Wavelength Radar Developed by UMASS
- Three separate antennas mounted on pedestal
- Matched beams
- Mobile scanning radar

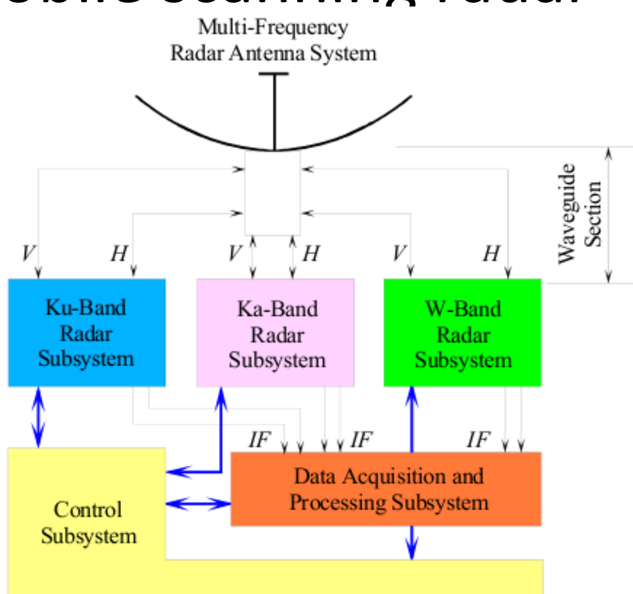


Figure 1. *AMFR block schematic.*

Parameter	Ku-band	Ka-band	W-band
Frequency (GHz)	13.4	35.6	94.92
Transmitted Polarization	Hybrid	Hybrid	Hybrid
Received Polarization	Hybrid	Hybrid	Hybrid
Peak Power (kW)	5	1.5	2
Pulse Compression Gain (dB)	19 max	19 max	19 max
Average Power (W)	250*	50*	35*
Antenna	1.8 m	0.91 m	0.35 m
Antenna Gain (dB)	48	48	48
Antenna Half Power Beamwidth	0.75 deg	0.7 deg	0.7 deg
Range Resolution (m)	30-120	30-120	30-120
Minimum Detectable dBZe (R=1km, 1sec avg, 150m)	-54	-57	-52.5
Minimum Detectable dBZe (R=10km, 1sec avg, 150m)	-47	-50	-47.0

* Limited by latching circulators average power

Table 1. *The AMFR'S Specifications*

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5 10 15 20 25
DWR
500 1000 1500
IWC
Thanks!
Questions and Comments?
Path integrated water vapor profiles
Range resolved cloud liquid
Height
Range

Proposed Area-Integrated Rainfall Estimate

- Atlas and Ulbrich (1977) proposed several attenuation based rain estimates.
  - 2-way methods involved a target of known cross-section
  - 1-way methods a separate receiver

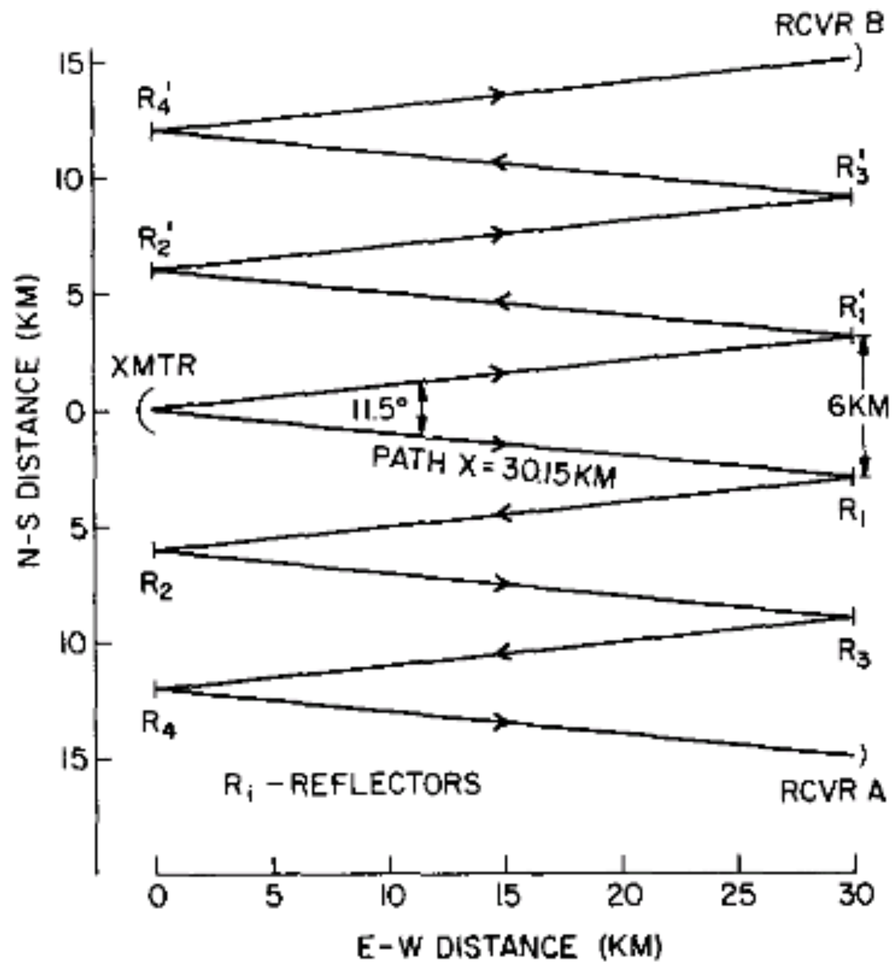
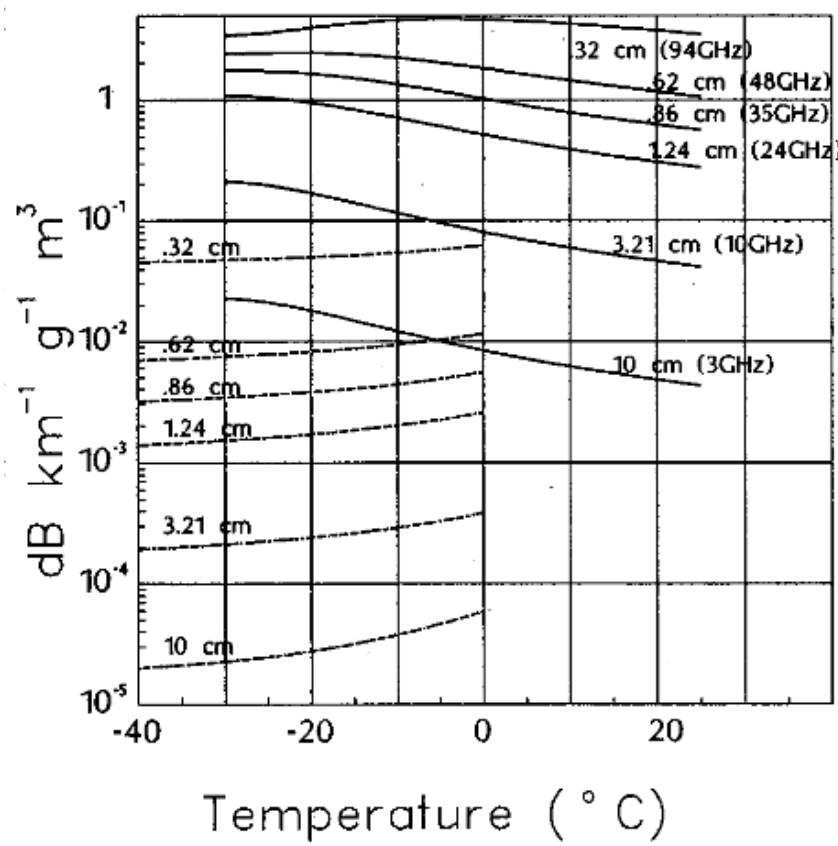


Fig. 4. Zig-zag method for area-integrated rainfall.

LWC in Mixed Phase

- Gosset and Sauvageot (1992) suggested to use dual-wavelength differential attenuation to deduce LWC in mixed phase clouds
- Then derive the ice water content from *Z using an empirical relationship.*
- Choice of wavelengths
  - Proposed X-band and K_a-band
    - Differential attenuation high enough
    - Extinction less of a problem than W-band

FIG. 1. Attenuation coefficient of clouds versus temperature for Rayleigh approximation. Solid curves represent attenuation by water clouds for several wavelengths. Dashed lines are attenuation by a cloud composed of a monodisperse population of ice spheres (diameter = 200 μm).



Snow Size Distribution With Ku, Ka and W-band Triple-Wavelength Radar

- Kneifel et al (2011) theoretically evaluated dual- and triple-wavelength radar techniques
- Utilized scattering calculations from wide variety of habits and aggregates
- Found that addition of W-band to Ku and Ka-band radar reduced the uncertainty in retrievals
  - Slope parameter
  - IWC
- Variable and unknown mass-size relationship still significantly impacts results
- Further challenges include particle orientation and mixtures of particle types