Observations from D3R Radar from OLYMPEx and Wallops Island Deployment

V. Chandrasekar[1*], Haonan Chen[1], Mohit Kumar[1], Shashank Joshil[1], Manuel Vega[1,2],Walter Petersen[3], David Wolff[4] ,Mathew Schwaller[2]

[1] Colorado State University, Fort Collins, CO

[2] NASA Goddard Space Flight Center, Greenbelt, MD

[3] NASA Marshall Space Flight Center, Huntsville, AL

[4] NASA Wallops Flight Facility, Wallops Island, VA

*chandra@colostate.edu

Outline

- Deployment and Observation Summary of the NASA D3R during the OLYMPEx Field Campaign
- Attenuation Correction for D3R Observations
- Precipitation Classification and Quantification with D3R/Ku-band Observations
- D3R Observations from Wallops Island Deployment
- Recent Upgrade on D3R System
- Summary

NASA D3R Operation Summary

D3R Deployed in the Field

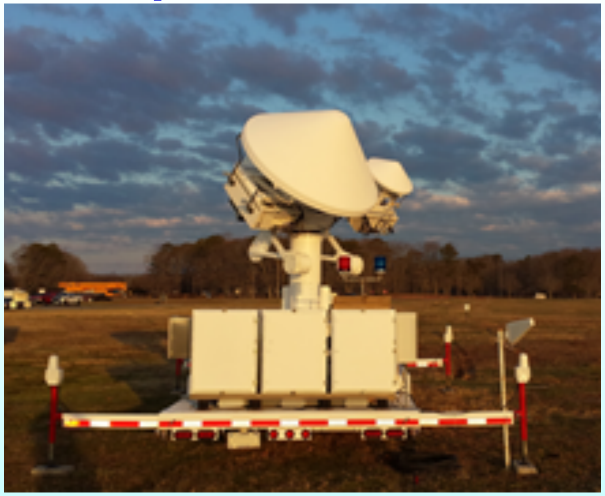
Greeley, CO

GCPEx, ON, Canada

IFloodS, IA

IPHEx, NC

Wallops Island, VA



OLYMPEx, WA

Development of the NASA D3R

Global Precipitation Measurement (GPM)

- an international satellite mission to provide next-generation observations of rain and snow worldwide every three hours.
- "Core Observatory" satellite was launched by NASA/JAXA on Feb 27, 2014.
- ground validation is an indispensable part of GPM mission

D3R

- GPM ground validation radar
- polarimetric solid state radar at Ku/Ka-band (same with GPM DPR)

Deployed in diverse geographical locations converging both winter and summer conditions over the past five years

Greeley, CO/GCPEx, ON, Canada/IFloodS, IA/IPHEx, NC/OLYMPEx, WA/Wallops Island, VA

D3R System Specifications

System	
Frequency	13.91 GHz±25 MHz, Ka: 35.56 GHz±25 MHz
Minimum detectable signal	Ku:−8dBZ,Ka:−3dBZ. Noise equivalent at 15 km and 150 m range resolution
Operational range resolution	150 m (nominal)
Minimum operational range	450 m
Maximum operational range	39.75 km
Angular coverage	0^o-360^oazimuth, -0.5^o-90^o elevation (full hemisphere)
Antenna	
Parabolic reflector diameter	Ku: 6 ft (72 in.), Ka: 28 in.
Gain	Ku: 45.6 dBi, Ka: 44.3 dBi
Half-power beam	Ku: 0.86^o, Ka: 0.90^o
Polarization	Dual linear simultaneous and alternate (H and V)
Maximum sidelobe level	~-25dB
Cross-polarization isolation	<-30dB (on axis)
Ka-Ku beam alignment	Within 0.1^o
Scan capability	$0^o - 24^o/s$ azimuth, $0^o - 12^o/s$ elevation
Scan types	PPI sector, RHI, surveillance, fixed, vertical pointing
Transmitter/Receiver	
Transmitter architecture	Solid state power amplifier modules
Peak power	Ku: 200W, Ka: 40 W per H and V channel
Duty cycle	30% maximum
Receiver noise figure	Ku: 4.8, Ka: 6.3
Receiver dynamic range	~90 dB
Clutter suppression	GMAP-TD

Measured Products:

- Reflectivity ($\boldsymbol{Z}$)
- Differential Reflectivity ($\boldsymbol{Z_{dr}}$)
- Differential Propagation Phase ($\boldsymbol{\varphi_{dp}}$)
- Co-polar Correlation Coefficient ($\boldsymbol{\rho_{co}}$)
- Linear Depolarization Ratio ($\boldsymbol{LDR}$)
- Cross-polar Correlation Coefficient ($\boldsymbol{\rho_{cx}}$)
- Radial Velocity ($\boldsymbol{V}$)
- Spectrum Width ($\boldsymbol{W}$)

Derived Products:

- Attenuation Corrected Reflectivity ($\boldsymbol{CZ}$)
- Attenuation Corrected Differential Reflectivity ($\boldsymbol{ZD}$)
- Specific Differential Phase ($\boldsymbol{K_{dp}}$)
- Rainfall Rate ($\boldsymbol{R}$)
- Drop Size Distribution ($\boldsymbol{D_o, N_w}$)
- Hydrometeor types ($\boldsymbol{HID}$)

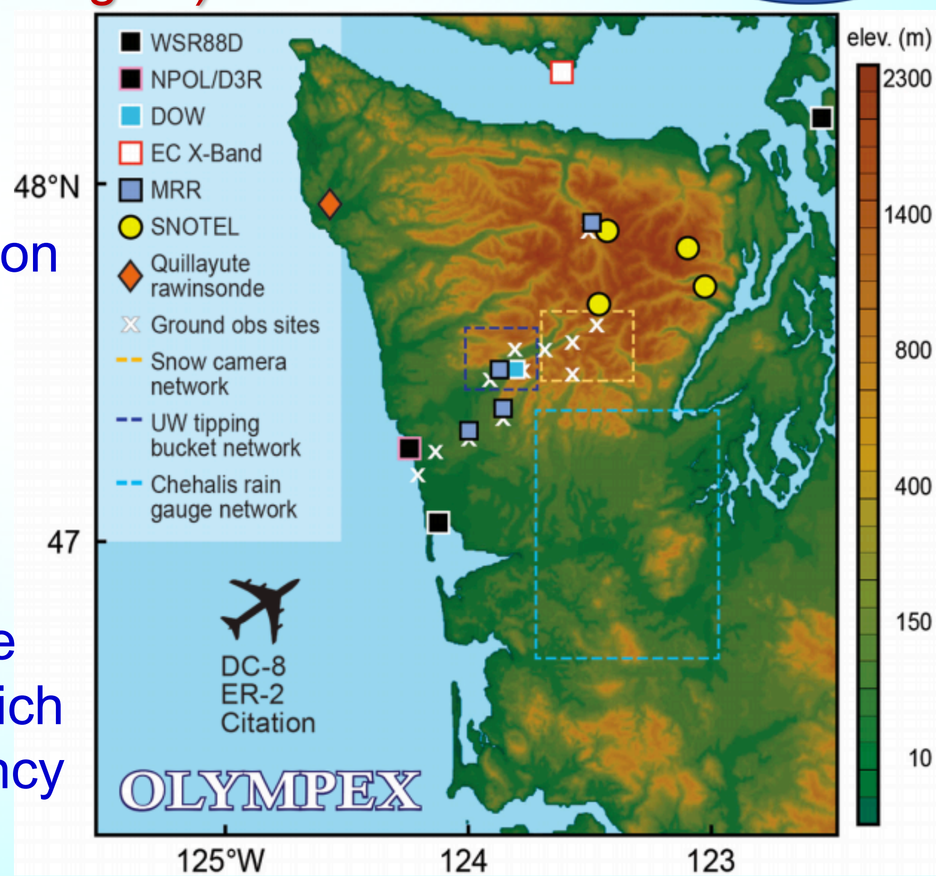
Observations from the NASA D3R during OLYMPEx

Recap: The OLYMPEx Mountain Experiment (OLYMPEx)

A NASA-led field campaign took place on the Olympic Peninsula of Washington State from November 2015 through February 2016 (coordinated by University of Washington).

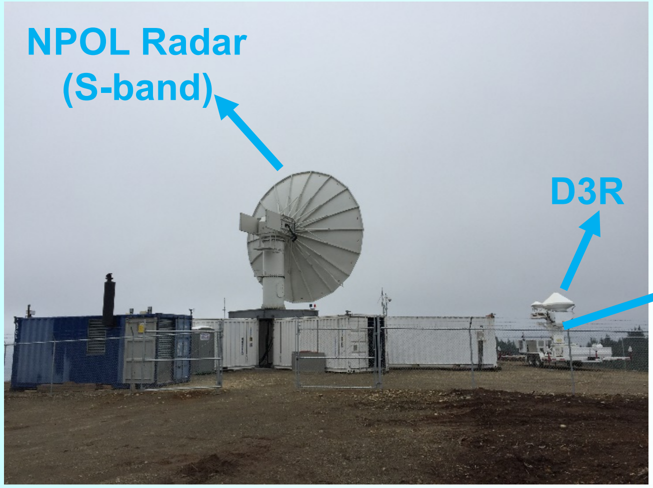
- to collect detailed atmospheric measurements that will be used to evaluate how well Global Precipitation Measurement (GPM) satellite measure rainfall and snowfall from space

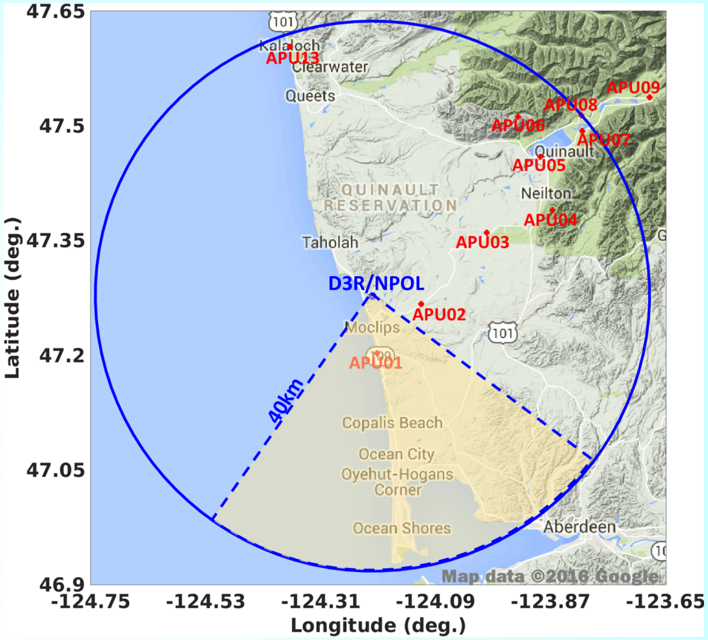
- OLYMPEX is particularly assessing satellite measurements made by the GPM mission Core Observatory which was equipped with the Dual-frequency Precipitation Radar (DPR) and the GPM Microwave Imager (GMI).

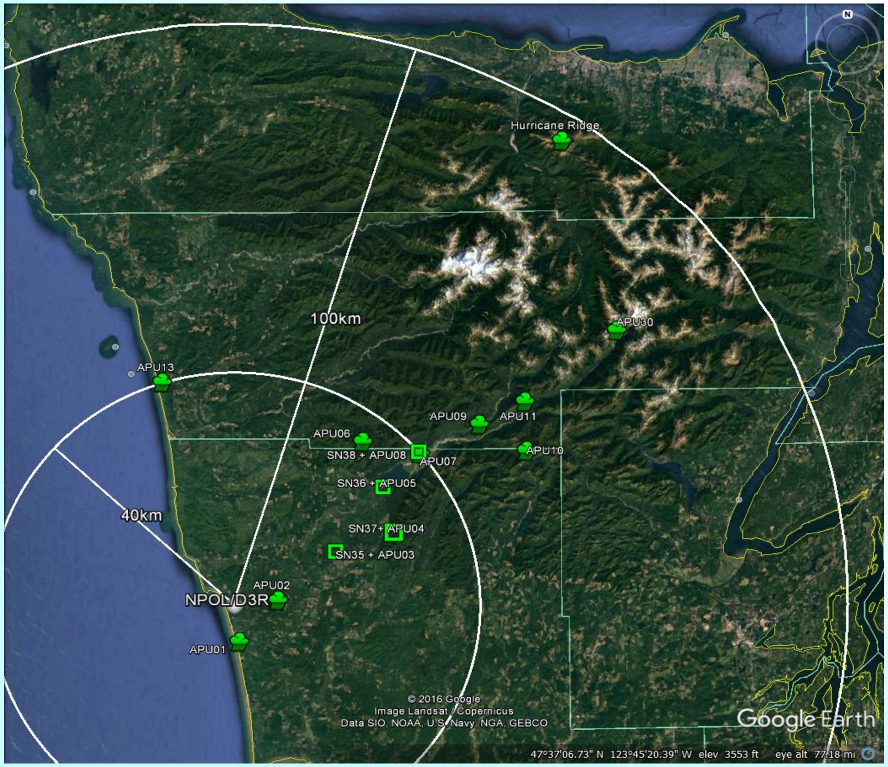


Map of ground instrumentation during OLYMPEX
(Credit: NASA)

Observations from the NASA D3R during OLYMPEx







- **D3R azimuth limits are set to 220-deg clockwise to 130-deg.**
- **The D3R operated without any incident during the campaign.**
- **Notable precipitation was observed on 38 of the 53 days' operation and over 180,000 individual scans were performed during the deployment.**

Observations from the NASA D3R during OLYMPEx

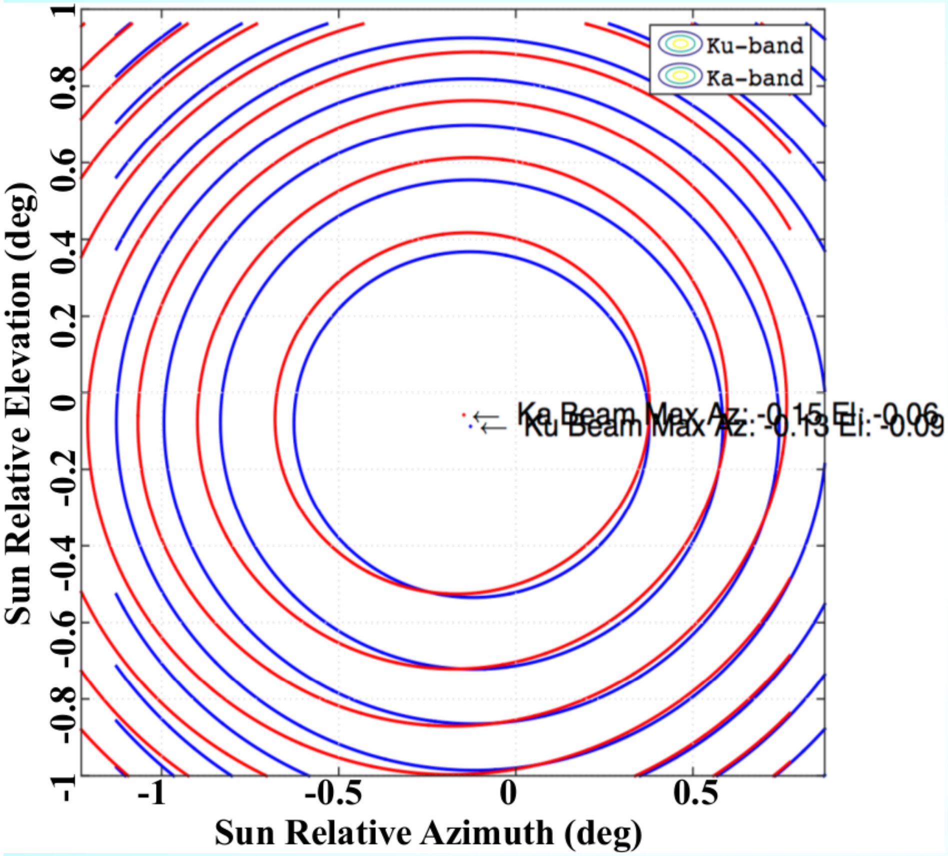
Date	Summary	Date	Summary
Nov. 8, 2015	Isolated rain	Dec. 7, 2015	Weak echoes and stratiform rain
Nov. 9, 2015	Weak echoes	Dec. 8, 2015	Scattered rain and weak echoes
Nov. 11, 2015	Stratiform rain, convective front with graupel	Dec. 9, 2015	Widespread stratiform rain
Nov. 12, 2015	Stratiform rain with low melting layer	Dec. 10, 2015	Shallow convection
Nov.13, 2015	Stratiform rain with embedded convection	Dec. 11, 2015	Convection and graupel at site. Stratiform rain
Nov. 14, 2015	Widespread stratiform rain	Dec. 12, 2015	Widespread stratiform with low melting layer. Isolated convection
Nov. 15, 2015	Stratiform rain with embedded convection. Graupel at radar	Dec. 13, 2015	Isolated convection
Nov. 16, 2015	Stratiform rain with embedded convection	Dec. 14, 2015	Weak echoes then clear
Nov. 17, 2015	Light stratiform rain	Dec. 15, 2015	Weak echoes and stratiform rain
Nov. 18, 2015	Shallow convection with graupel	Dec. 16, 2015	Light stratiform rain
Nov. 23, 2015	Light stratiform rain	Dec. 17, 2015	Stratiform rain and weak echoes
Nov. 24, 2015	Scattered light rain	Dec. 18, 2015	Light stratiform rain. Isolated convection
Nov. 30, 2015	Weak echoes and stratiform rain	Dec. 19, 2015	Stratiform rain with embedded convection
Dec. 1, 2015	Stratiform rain	Jan. 5, 2016	Light stratiform rain
Dec. 2, 2015	Stratiform rain and weak echoes	Jan. 6, 2016	Isolated rain and stratiform rain
Dec. 3, 2015	Weak echoes and stratiform rain with embedded convection	Jan. 7, 2016	Weak echoes
Dec. 4, 2015	Weak echoes	Jan. 11, 2016	Stratiform rain with embedded convection
Dec. 5, 2015	Shallow convection, widespread stratiform rain	Jan. 12, 2016	Light stratiform rain
Dec. 6, 2015	Widespread stratiform rain	Jan. 13, 2016	Widespread stratiform rain

Observations from the NASA D3R during OLYMPEx

D3R operating in alternate (ALT) mode: *about **310 hrs** during OLYMPEx*

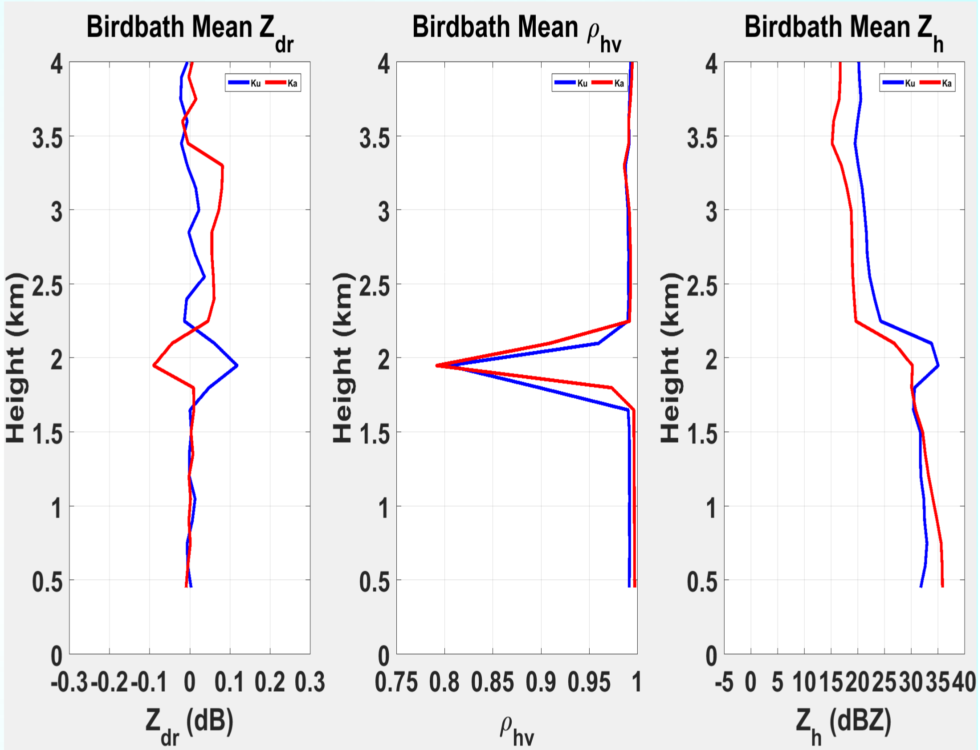
Date	Time	Duration	Date	Time	Duration
2015/11/08	0115-1739UTC 1945-2121UTC	17.85hrs	**2015/12/13**	173900-2400UTC	6.35hrs
2015/11/18	0600-2400UTC	18hrs	**2015/12/14**	0000-2400UTC	24hrs
2015/11/19	0000-2400UTC	24hrs	**2015/12/15**	0000-2400UTC	24hrs
2015/11/20	0000-2400UTC	24hrs	**2015/12/16**	0000-1625UTC	16.42hrs
2015/11/21	0000-2400UTC	24hrs	**2015/12/19**	0620-1948UTC	13.47hrs
2015/11/22	0000-2400UTC	24hrs	**2016/01/11**	0000-2223UTC	22.38hrs
2015/11/23	0000-1700UTC 1746-2110UTC	20.4hrs	**2016/01/12**	0000-2400UTC	24hrs
2015/11/30	2104-2400UTC	2.93hrs	**2016/01/13**	0000-1422UTC	14.37hrs
2015/12/01	0000-2400UTC	24hrs			
2015/12/02	0000-1456UTC	14.93hrs			
2015/12/10	2251-2400UTC	1.15hrs			
2015/12/11	0000-2400UTC	24hrs			
2015/12/12	0000-0108UTC	1.13hrs			

D3R System Calibration Check during OLYMPEx



Co-alignment verification of the D3R from solar observations at 19:27 UTC on November 04, 2015.

The solar observations from November 04, 2015 verify that the D3R's azimuth and elevation are co-aligned to within 0.06 degree in azimuth and 0.03 degrees in elevation.

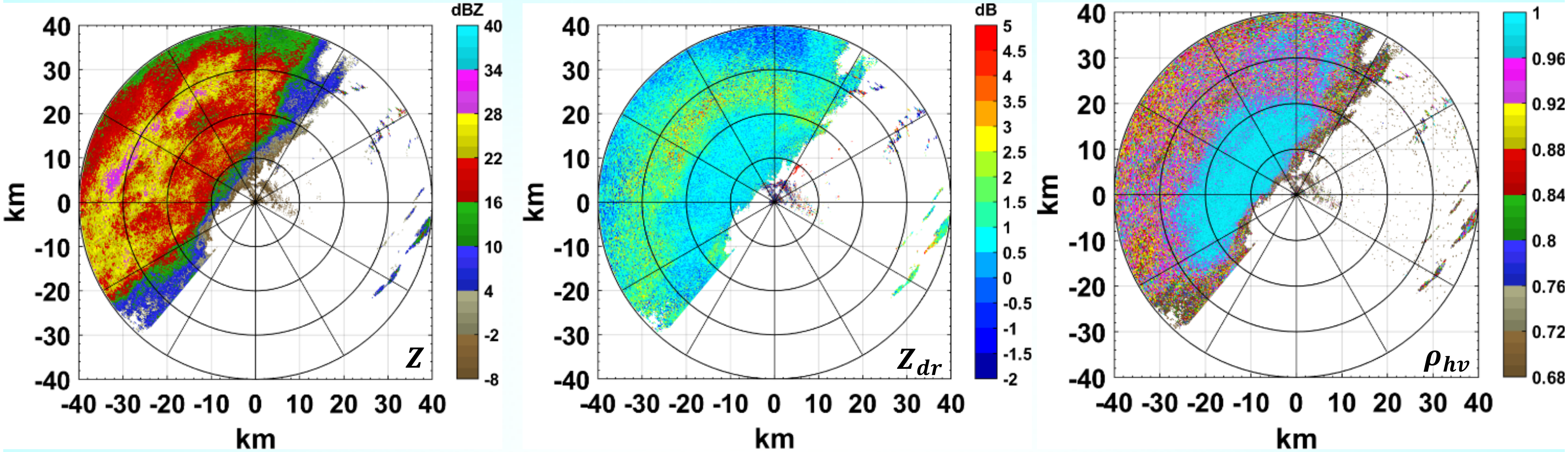


D3R observations from a birdbath scan at 21:17UTC, November 12, 2015.

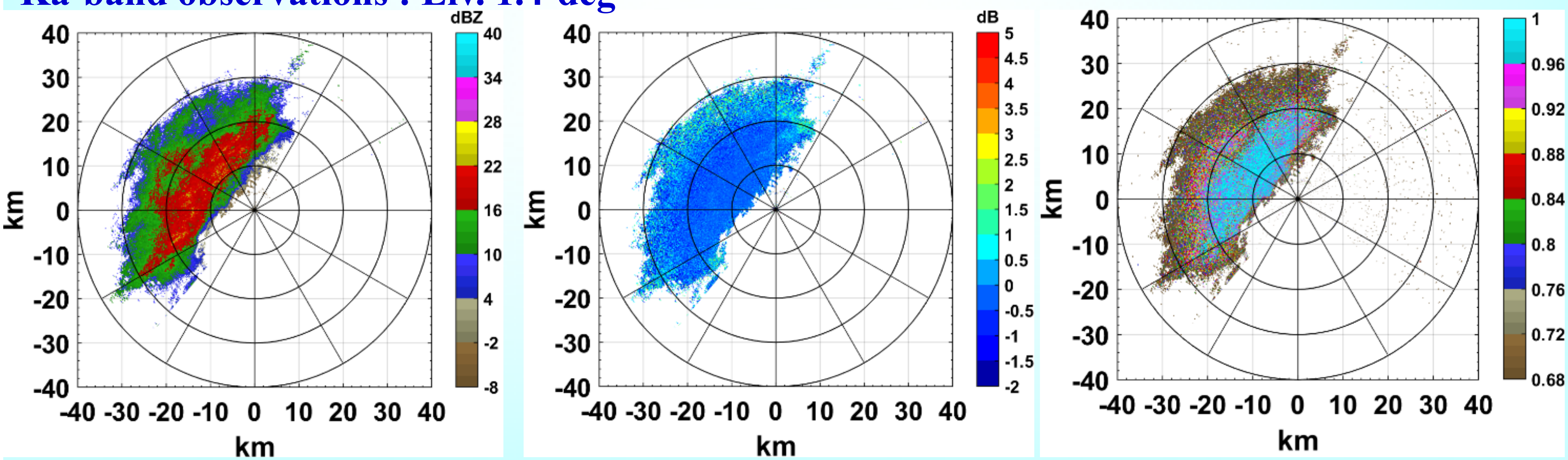
Sample PPI Observations from D3R during OLYMPEx

Ku-band observations: Elv. 1.4-deg

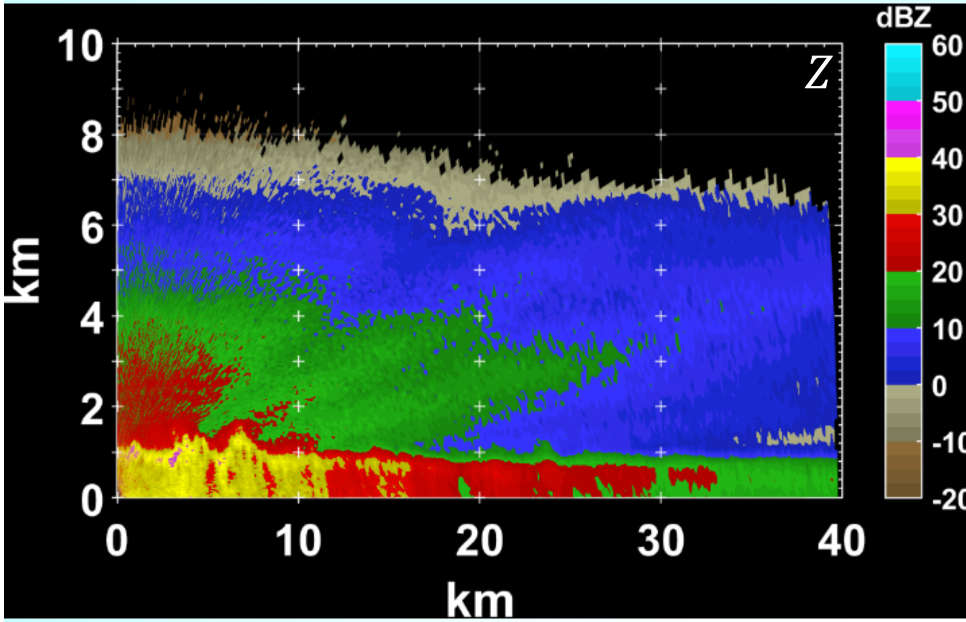
21:19 UTC, 23 November 2015

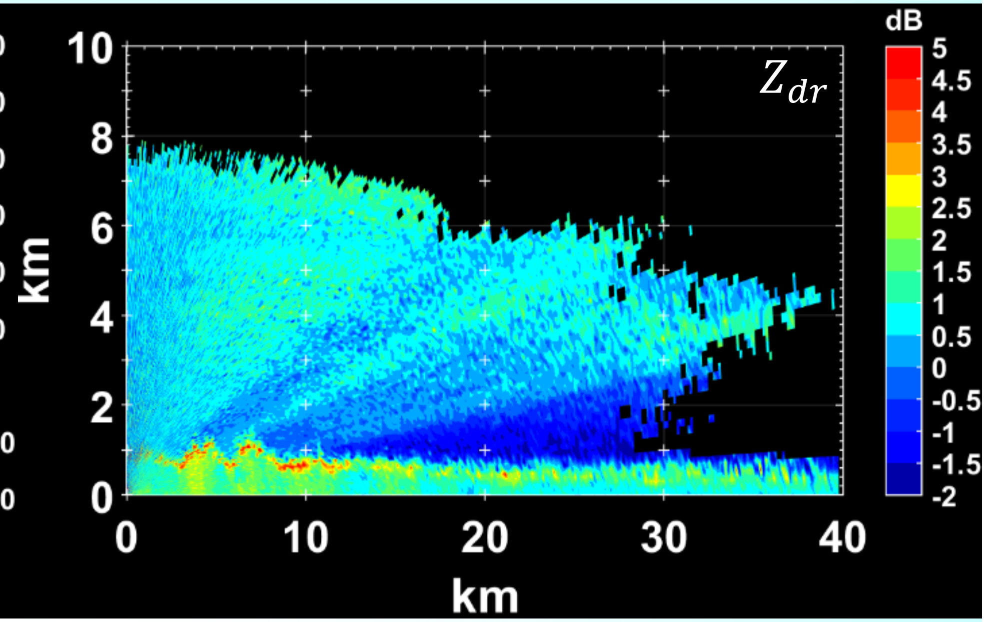


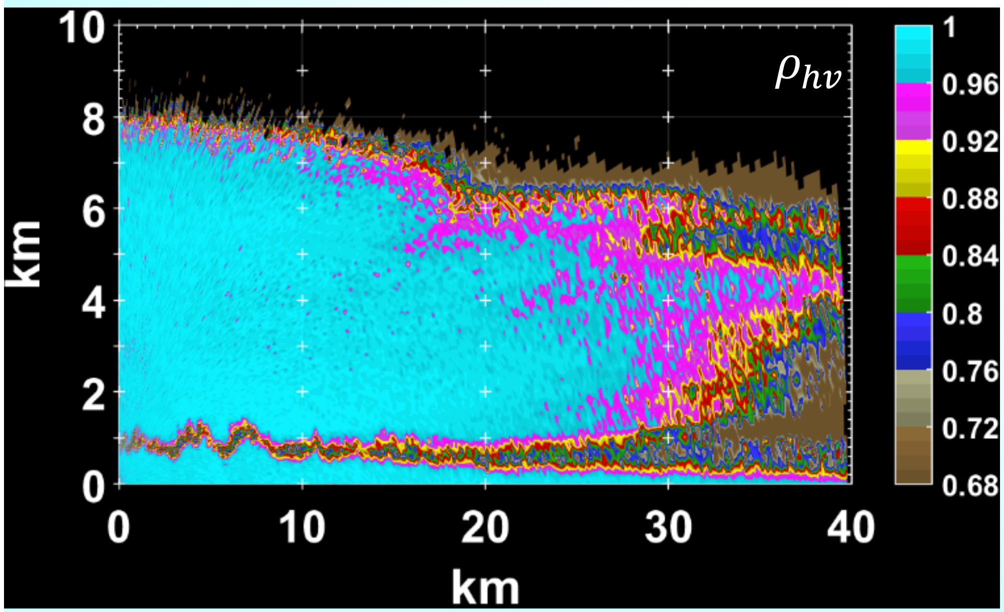
Ka-band observations : Elv. 1.4-deg



Sample RHI Observations from D3R during OLYMPEx





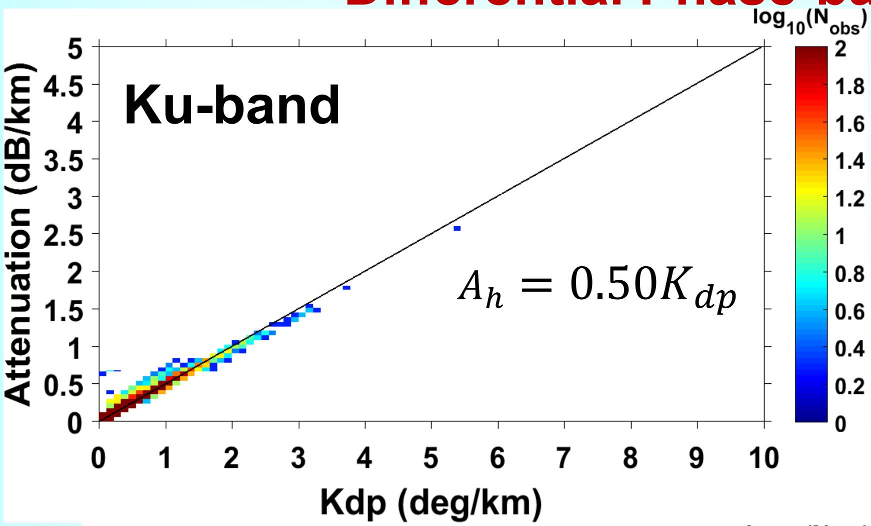


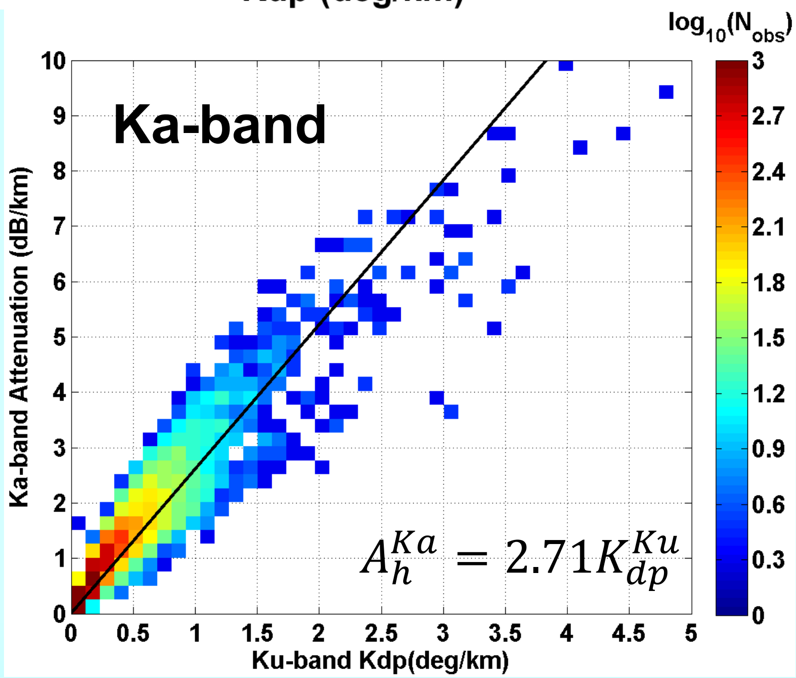
D3R Ku-band observations at 20:52 UTC on 16 November 2015 Azi. ~ 318-deg

stratiform with embedded convection

Attenuation Correction for D3R Observations

Differential Phase-based Attenuation Correction





$$PIA_h(r) = 2\int_0^r A_h(s)ds$$

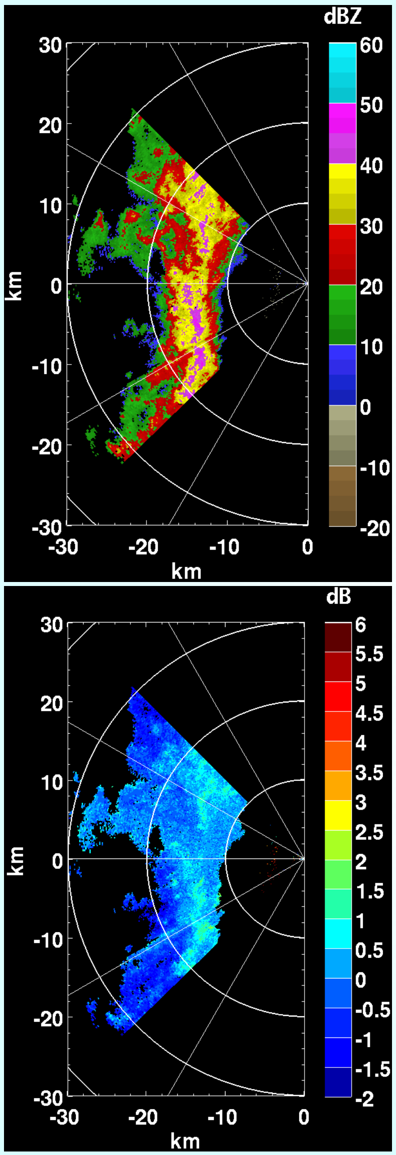
$$PIA_v(r) = 2\int_0^r A_v(s)ds$$

$$\hat{Z}_h = Z_h + PIA_h$$

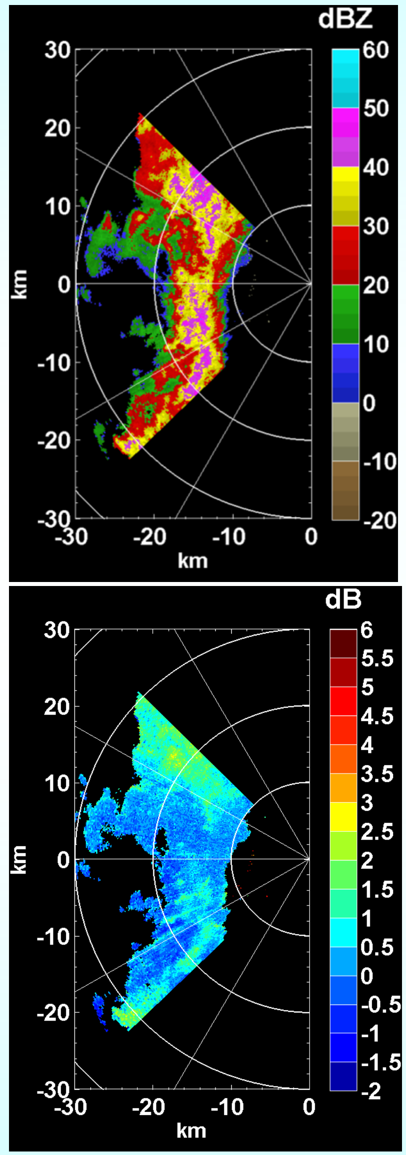
$$\hat{Z}_{dr} = Z_{dr} + PIA_h - PIA_v$$

Sample Observations and Attenuation Correction

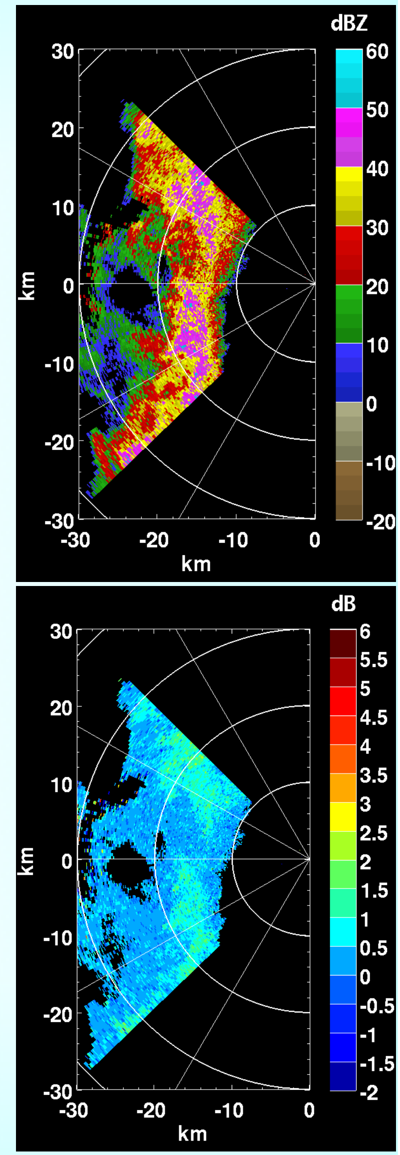
D3R Ku-band: before attenuation correction



D3R Ku-band: after attenuation correction

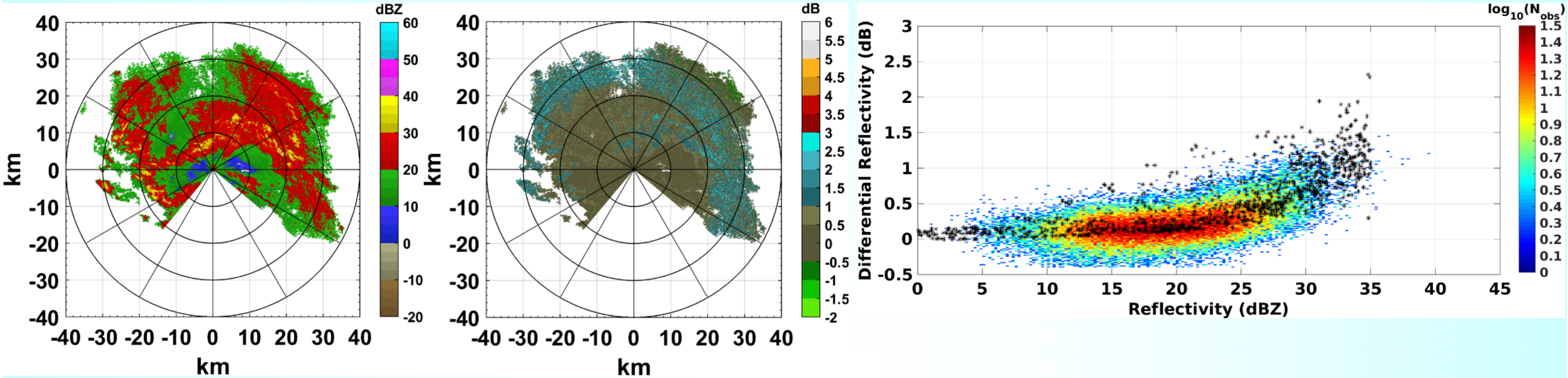


NPOL S-band Observations

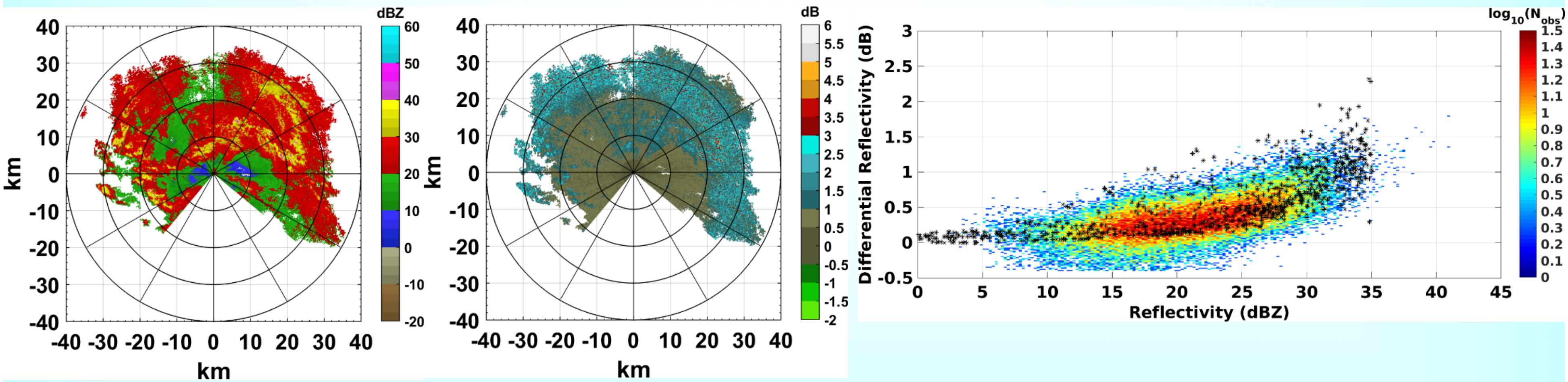


D3R Ku-band Measurements before and after attenuation correction: 18:32UTC, 2014-05-15.

Attenuation Correction for D3R Observations



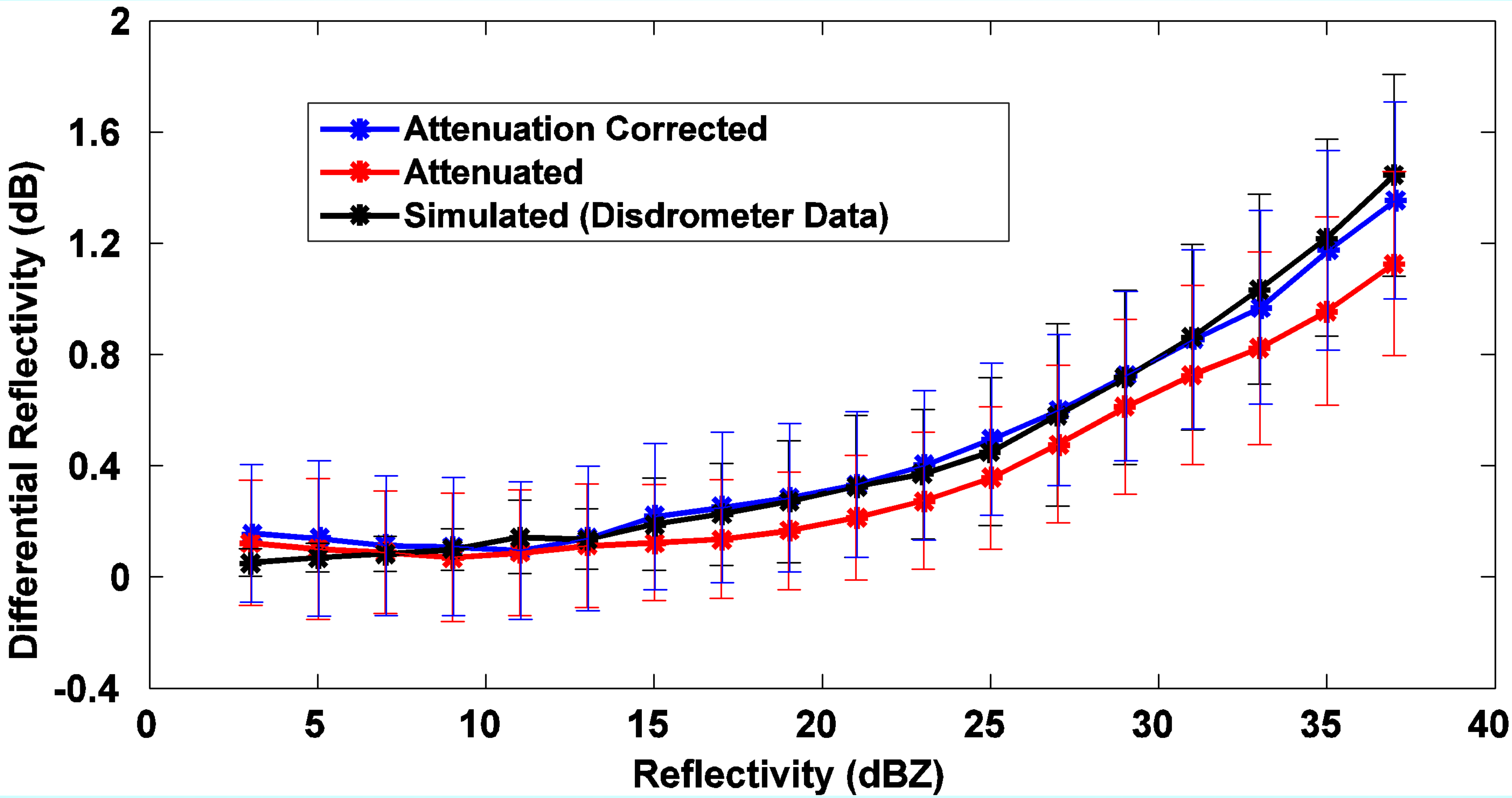
D3R Ku-band observations at 14:34UTC, November 12, 2015



Attenuation corrected observations at 14:34UTC, November 12, 2015

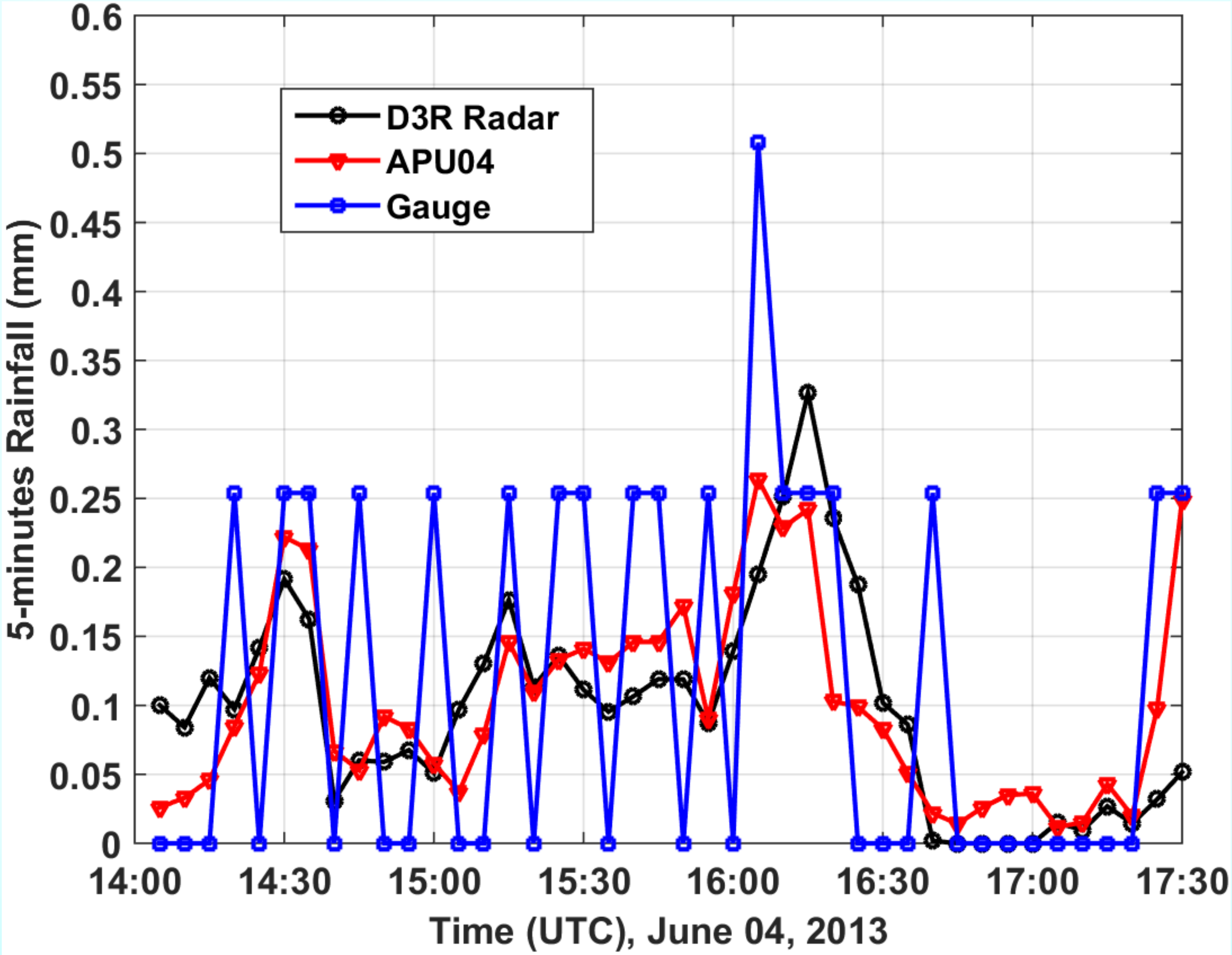
Attenuation Correction for D3R Observations

Qualitative Evaluation Using Simulated Observations with DSD Data
14:34UTC, 12 Nov. 2015



Rainfall Estimation with the NASA D3R

Rainfall Validation with *In-Situ* Measurement



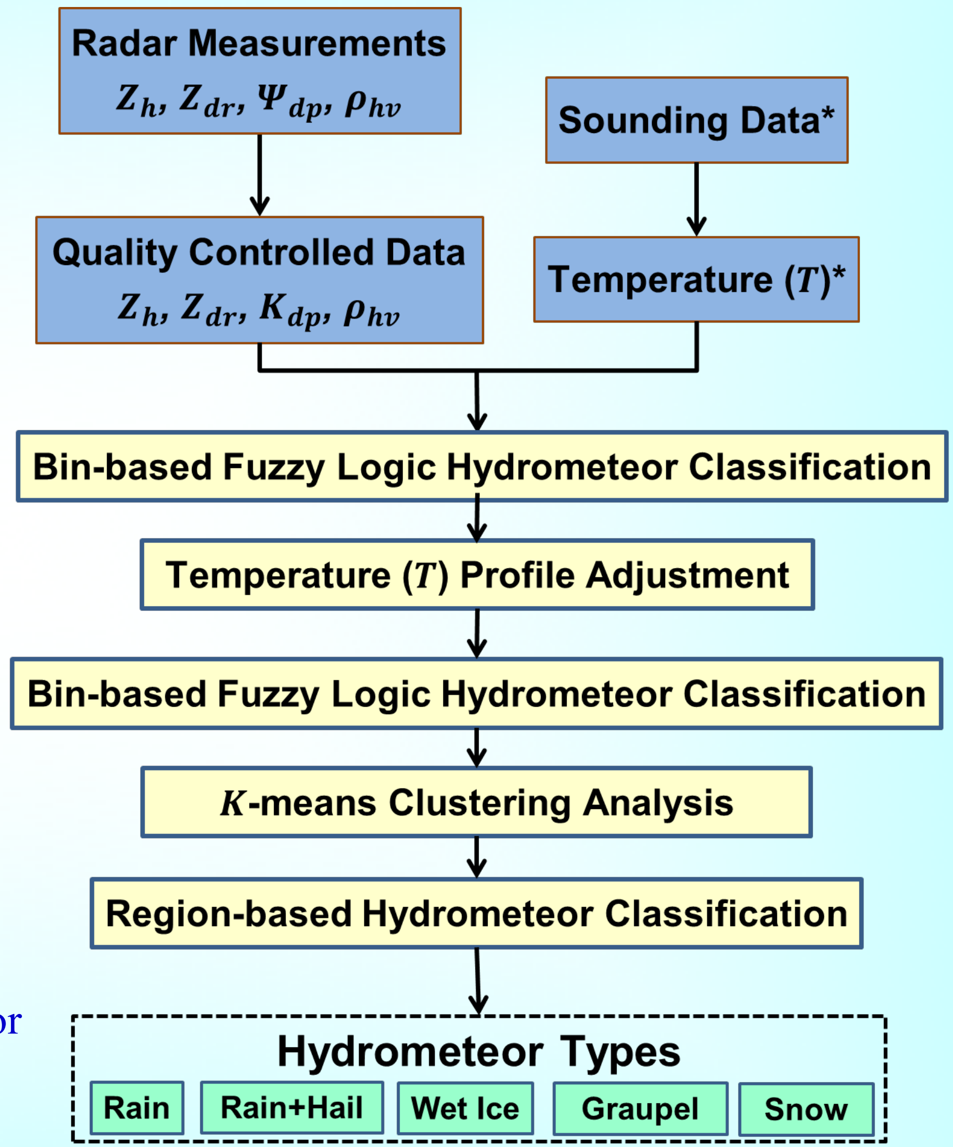
Precipitation Classification and Quantification with D3R

Traditional Hydrometeor classification

- The classification will be noisy if the input radar observations are noisy since the process is bin-based.
- the spatial coherence and self-aggregation of dual-polarization observables are not utilized.

New methodology implemented

Bechini, R., and V. Chandrasekar, 2015: A semi-supervised robust hydrometeor classification method for dual-polarization radar applications. *J. Atmos. Ocean. Technol.*, **32**, 22-47.

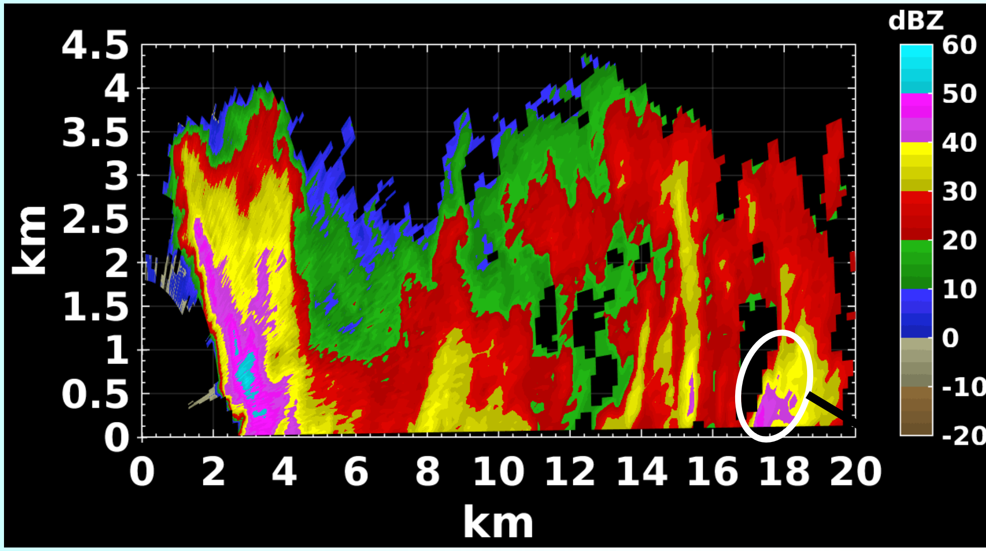


*Optional Input

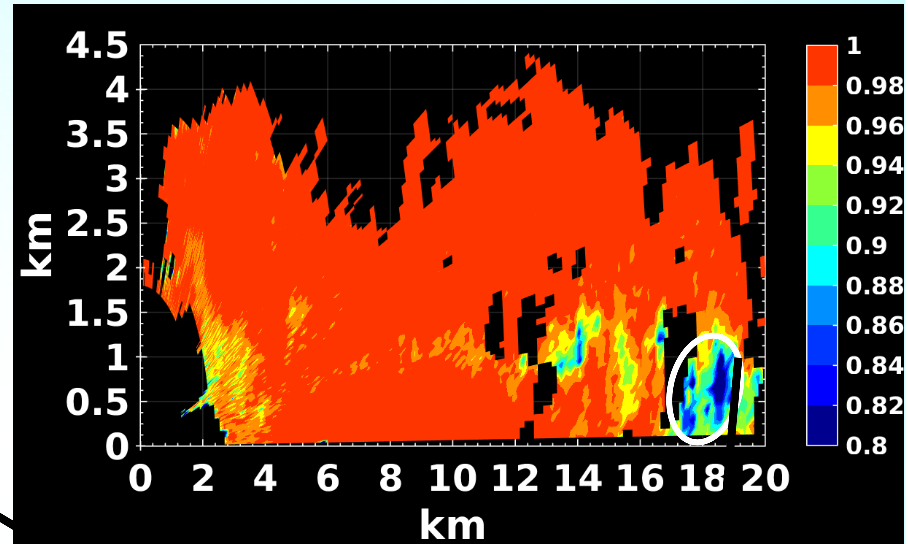
Precipitation Classification and Quantification with D3R

Convective Case: 02:59UTC, 05 Dec. 2015 (azi. = 52deg)

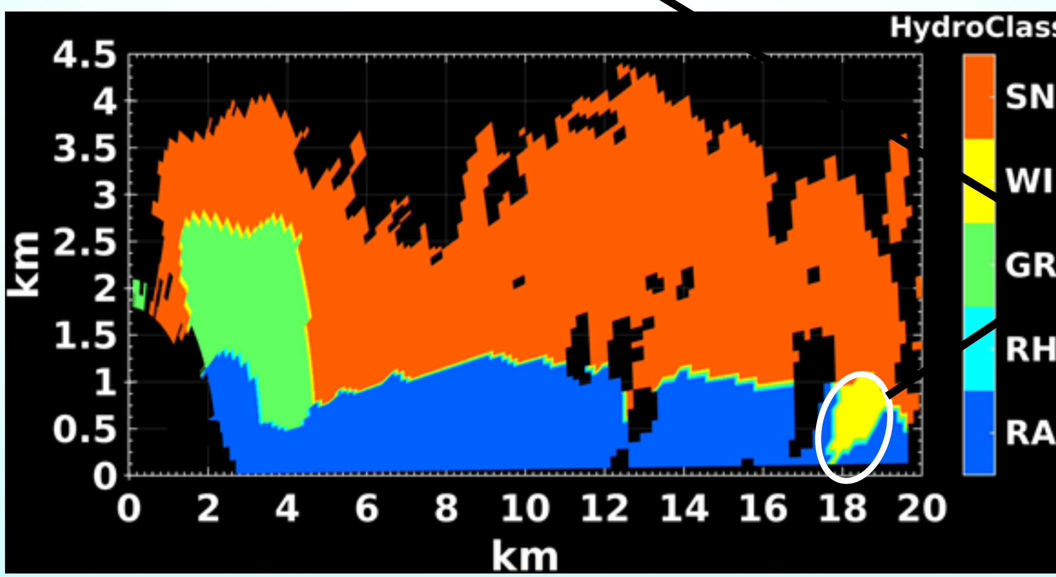
Reflectivity



Correlation Coefficient



Hydrometeor Types



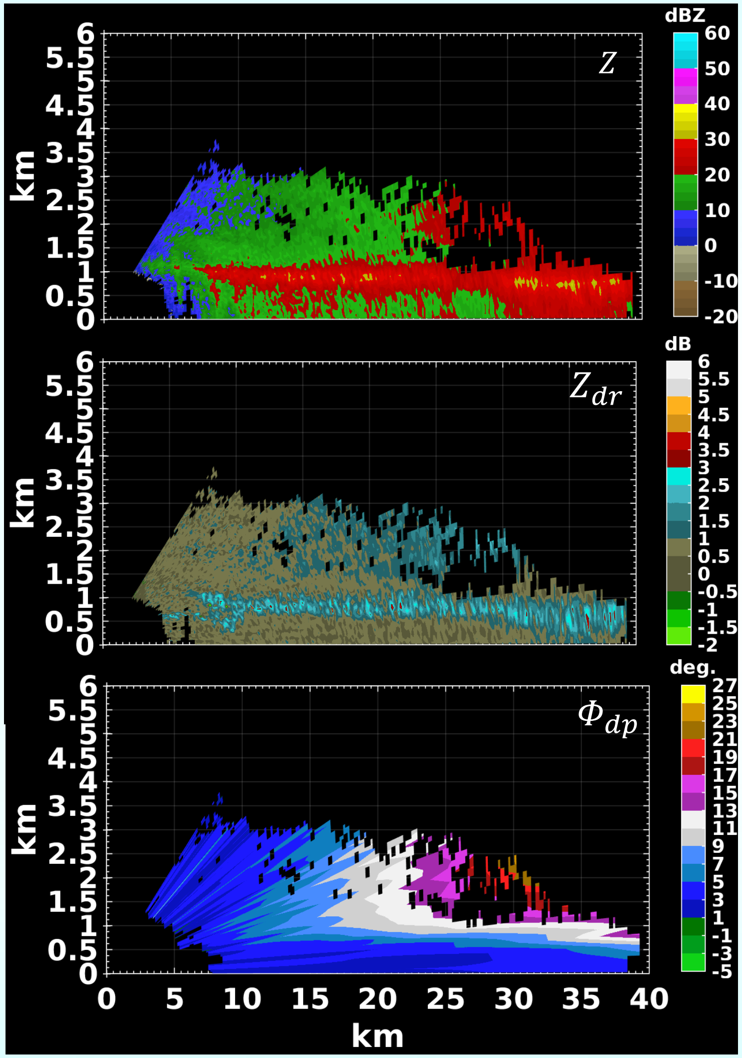
Mixed-phase precipitation near foothills

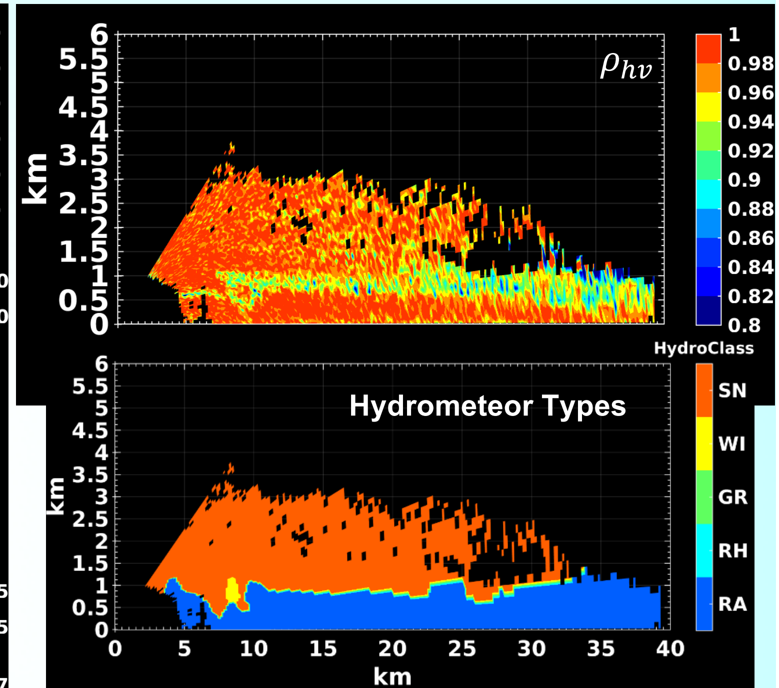
Precipitation Classification and Quantification with D3R

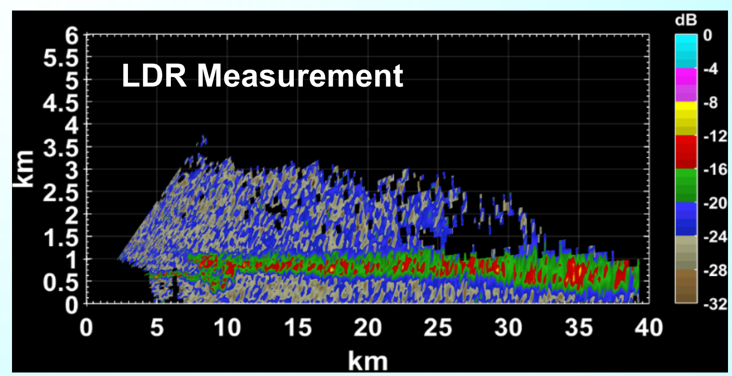
Stratiform Case: 21:25UTC, 23 Nov. 2015 (azi. = 263.9deg)

LDR Consistency

- a dual-polarization variable that can identify mixed-phase precipitation and solid hydrometeors
- of great interest for the microphysical investigation of hydrometeors in and above the melting layer where scattering from ice dominates





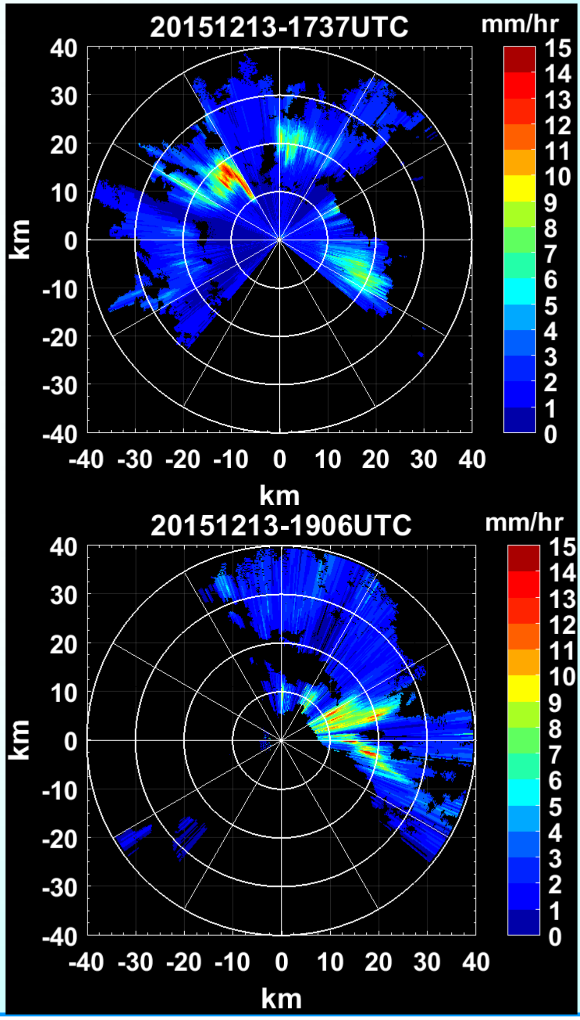


- OLYMPEx was the first field campaign where LDR has been produced by D3R. LDR was available when the radar was operating in the alternate transmit, simultaneous receive mode (ALT).

Precipitation Classification and Quantification with D3R

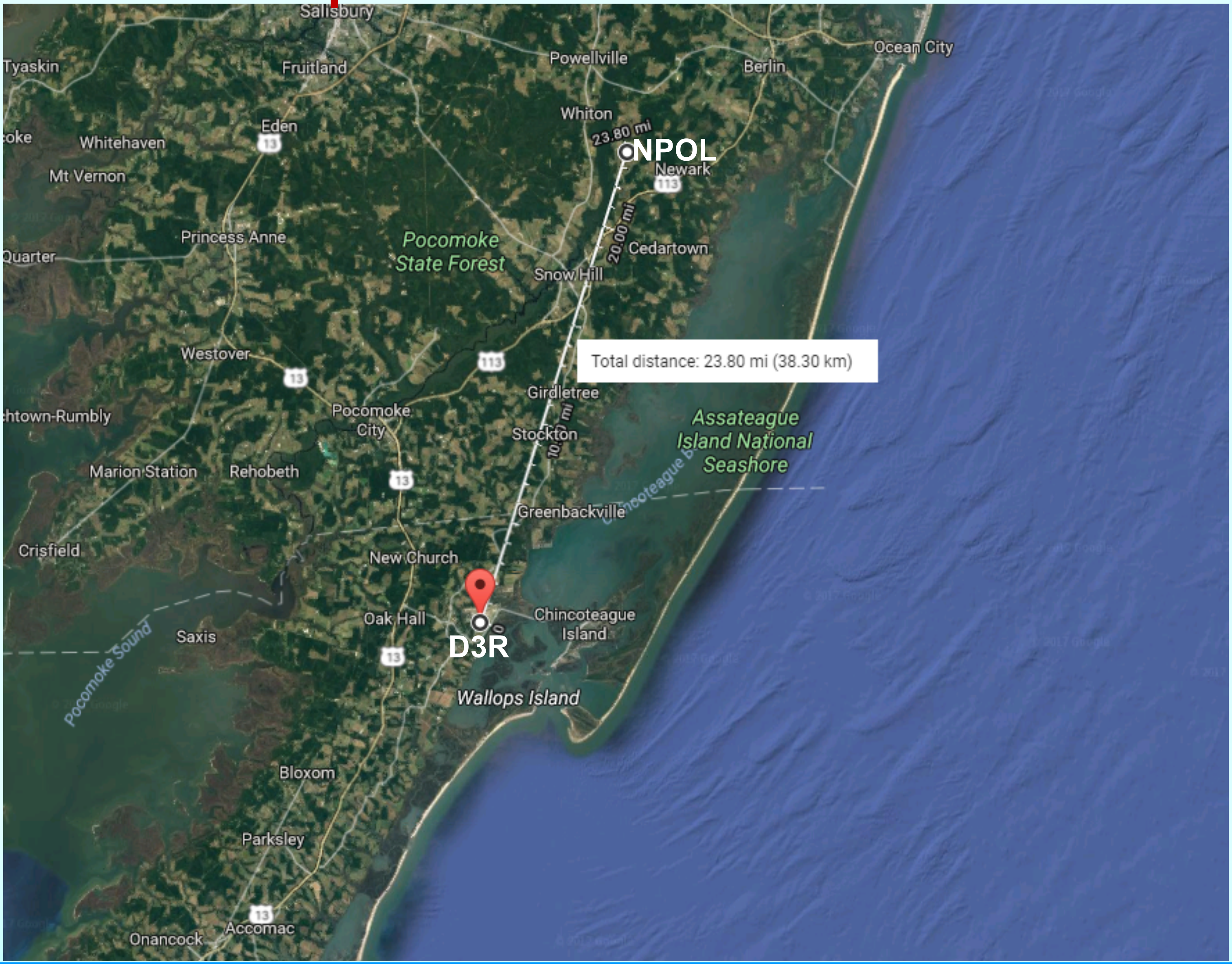
- the NASA D3R is a unique tool for validating instantaneous rainfall rate product from GPM, due to D3R's high resolution, especially in light rainfall cases
- A K_{dp}-based rainfall algorithm has been developed for D3R, using disdrometer data

Rain Rate, Elv.: 1.4-deg, 13 Dec. 2015



D3R Observations from Wallops Island Deployment

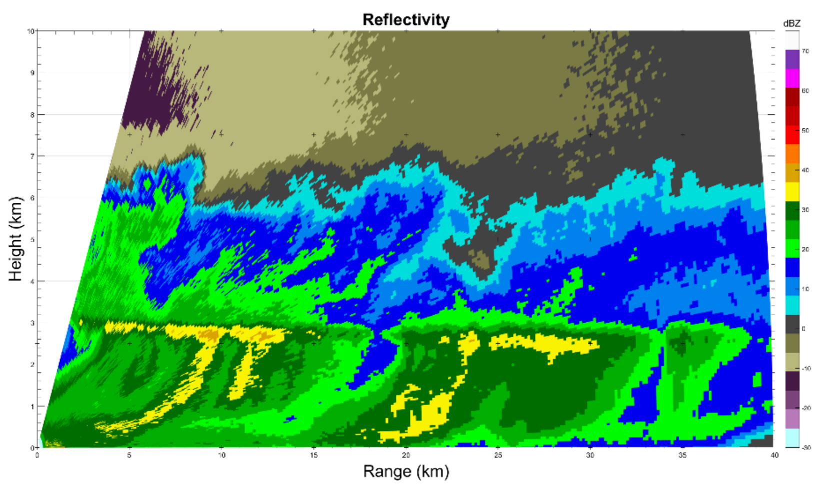
Deployment in Wallops Island



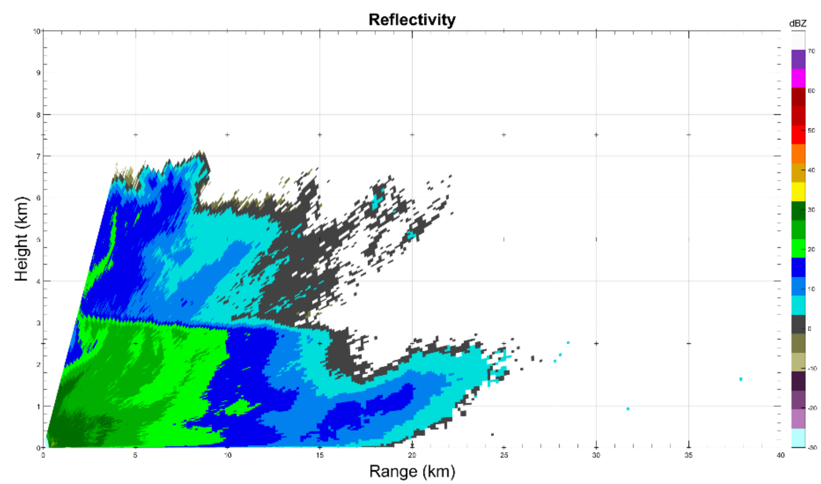
D3R Observations from Wallops Island Deployment

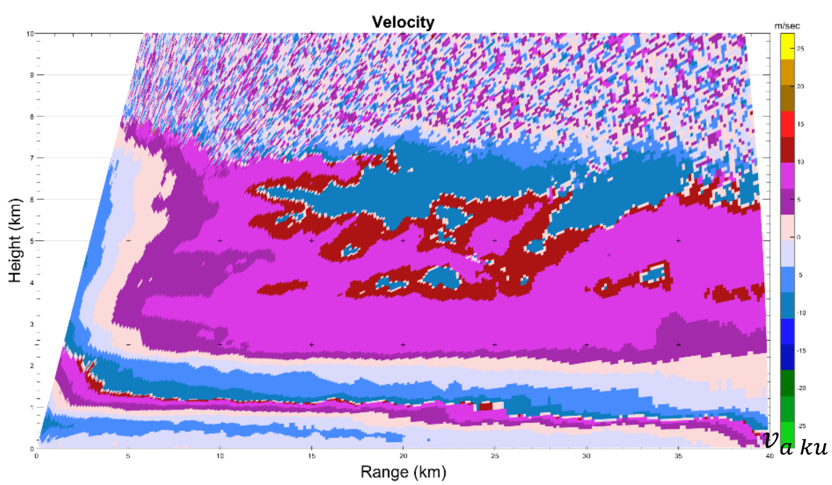
RHI Scan at 14:47UTC, 2016/04/02, Azi ~ 70.4-deg

Ku



Ka





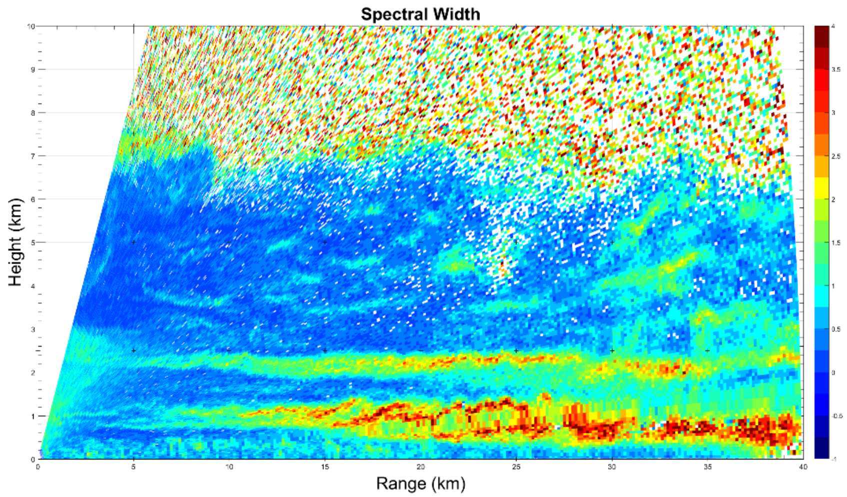
$v_{a\ ku} = 10.75\ m/s$

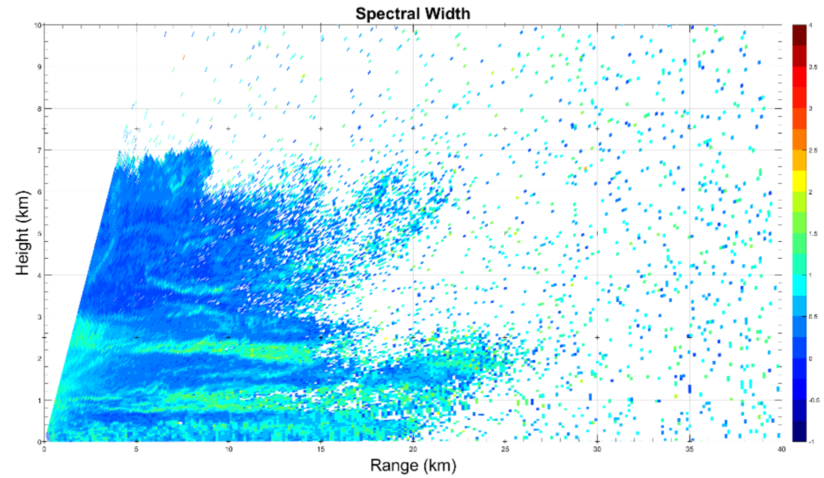
D3R Observations from Wallops Island Deployment

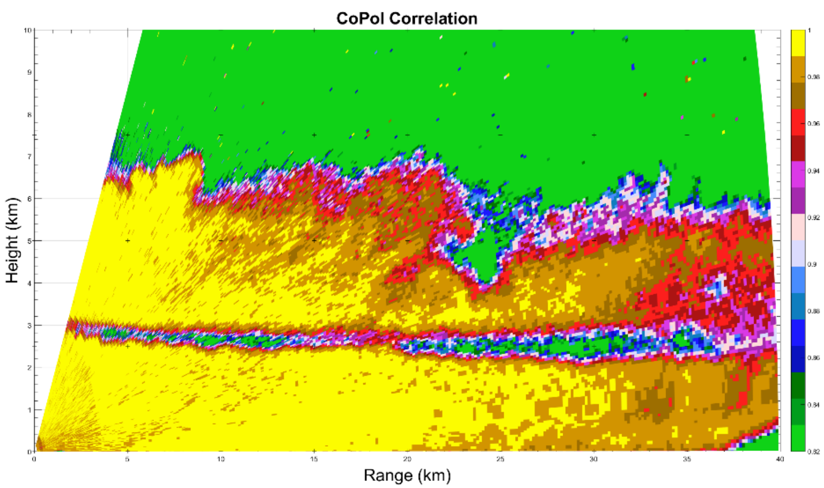
RHI Scan at 14:47UTC, 2016/04/02, Azi ~ 70.4-deg

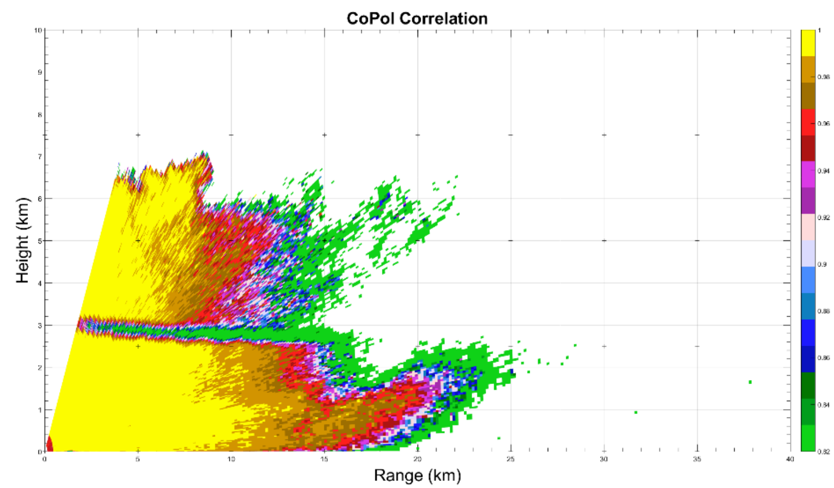
Ku

Ka

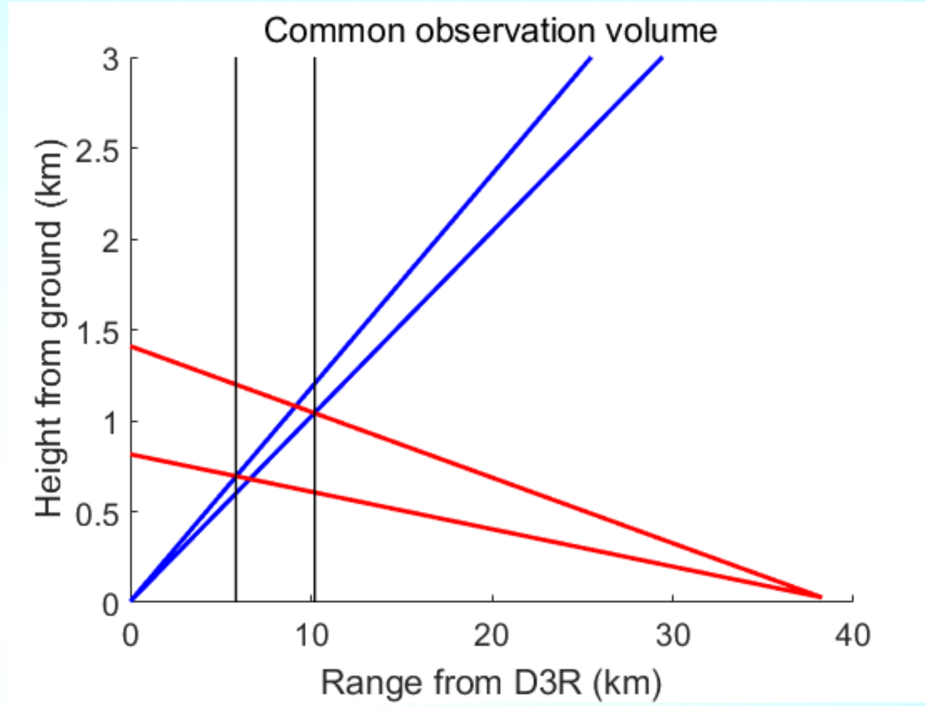








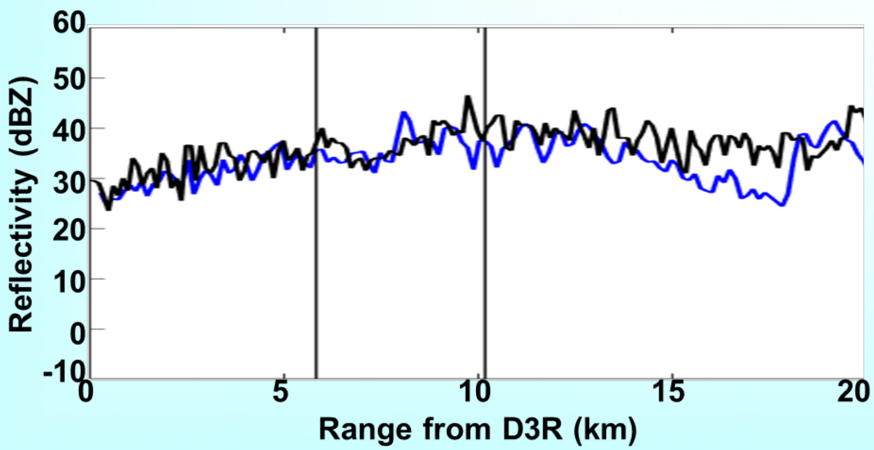
D3R Observations from Wallops Island Deployment



CASE: 07/29/2017 00:26 UTC

D3R: Azimuth:17.2° Elevation: 5.81° (blue)

NPOL: Azimuth:197.2° Elevation: 1.18°



Recent Upgrade on D3R System

Previous Design:

- Fixed design
  - 150m range bins, fixed frequencies, fixed filters
  - For the range resolution, sensitivity could be improved
  - The waveform is fixed by the digital receiver
- Existing hardware separates transmit waveform generation from receiver
- Existing FPGA at capacity

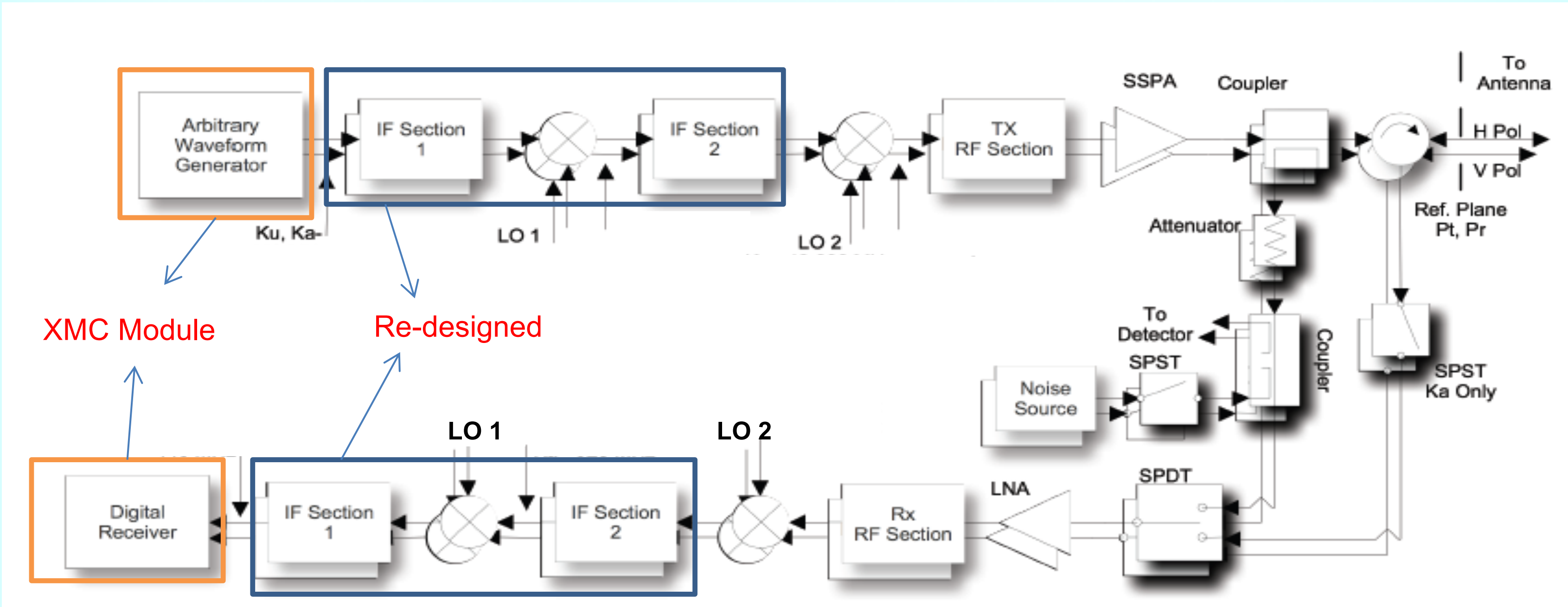
Recent Upgrade on D3R System

New Design Features

- **Coupled transmitter waveform generator and digital receiver**
  - Synchronous pulse-by-pulse changes of transmit waveform and receiver filters
  - Flexible sub-pulse frequency selection
  - New waveforms can be developed to meet science goals for sensitivity, range, velocity, etc.
- **Improved performance from new waveform and filter design enables**
  - Improve sensitivity through waveform design
  - 30 meter range gate size
- **Upgraded ability to use frequency, phase and time diversity, pulse to pulse**
  - Range overlay suppression can be enhanced
  - With more independent samples, increased accuracy of dual-pol measurements.
  - Better cross-pol isolation (more accurate Z_{dr} and ρ_{hv})
- **Common design with CSU CHILL S-band radar**
  - Enhancements to one design improves the other
  - More robust and thorough design qualification

Recent Upgrade on D3R System

Hardware Modifications



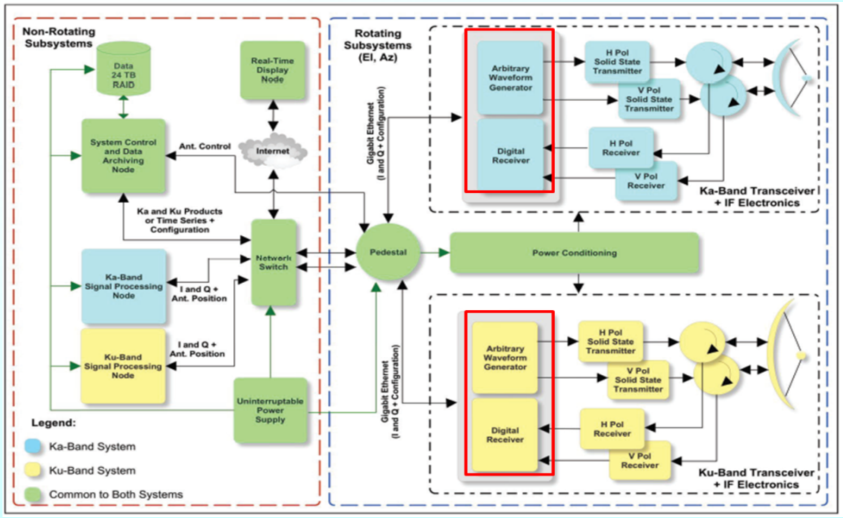
(Vega and Chandrasekar, 2014)

- Arbitrary waveform generator (H and V pol) and digital receiver (H and V pol) housed together in single XMC carrier board.
- Two of them used for Ku and Ka systems.
- IF Section 1 and 2 were redesigned with different IF and LO frequencies to accommodate operational frequency range of A/Ds and D/As.
- Reconfigurable firmware with high density FPGAs for programmable waveforms and filters.

Recent Upgrade on D3R System

Major Highlights

- The resolution of the radar can be enhanced up to 30m from the current resolution of 150m.
- The new design tightly couples the waveform generator, digital down-converter and pulse compressor design. Hence it can accomplish pulse by pulse change of waveform and filters, synchronously.
- New waveform set comprising of systematic and random phase codes, will reduce the second trip contamination and further enhance sensitivity by reducing contamination.
- Non uniform pulsing schemes can reduce the velocity and range ambiguities.
- The Red blocks highlight the changed sub-systems.



System Architecture Block Diagram
(Vega and Chandrasekar, 2014)

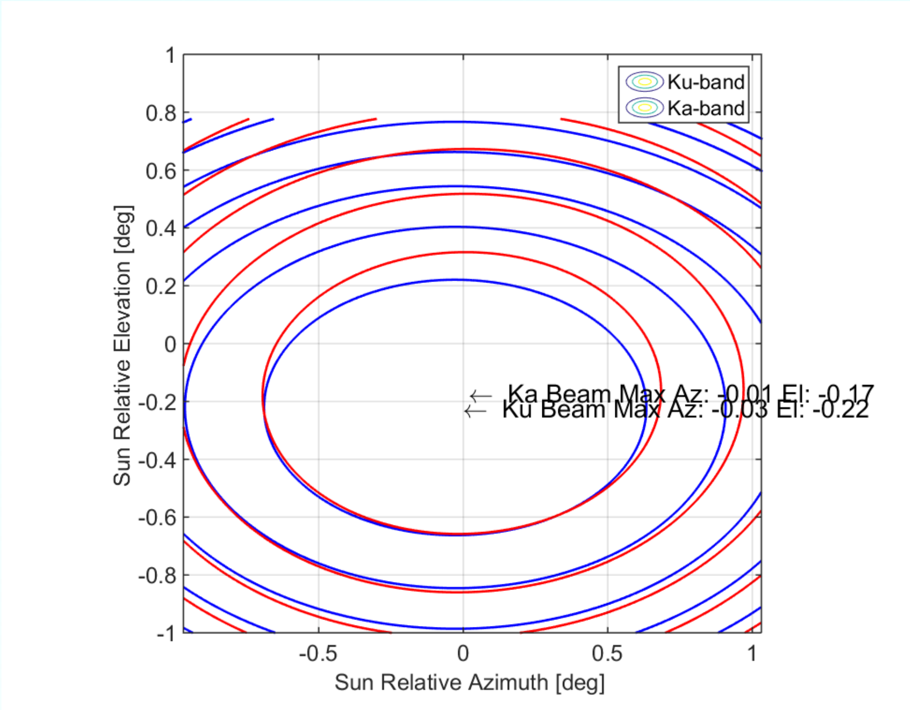
Recent Upgrade on D3R System

Software Controlled Radar

- With this upgrade, D3R becomes a truly **software defined precipitation radar system**.
- Adaptable and reconfigurable waveforms for application specific tasks (high resolution or enhanced sensitivity).
- All the controls will be brought out to GUI for configuration.
- Multiple staggered or block PRF modes to better resolve velocity and range.
- Phase codes for better retrieval of polarimetric variables in case of high power ratios from multi-trips and better velocity retrievals from the second trip echoes.
- Further enhancements possible retaining the current hardware configuration (by firmware changes).

Observations after Recent Upgrade

Solar Calibration on 09/05/2017



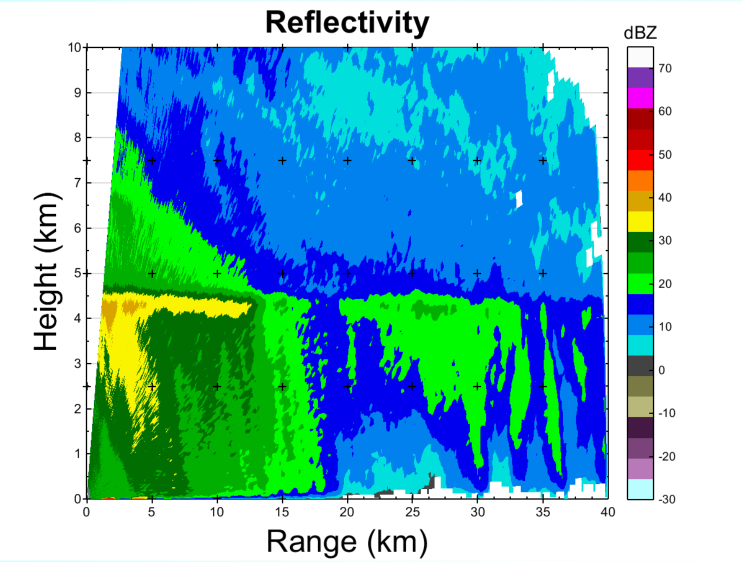
Azimuth and Elevation mean bias

Observations after Recent Upgrade

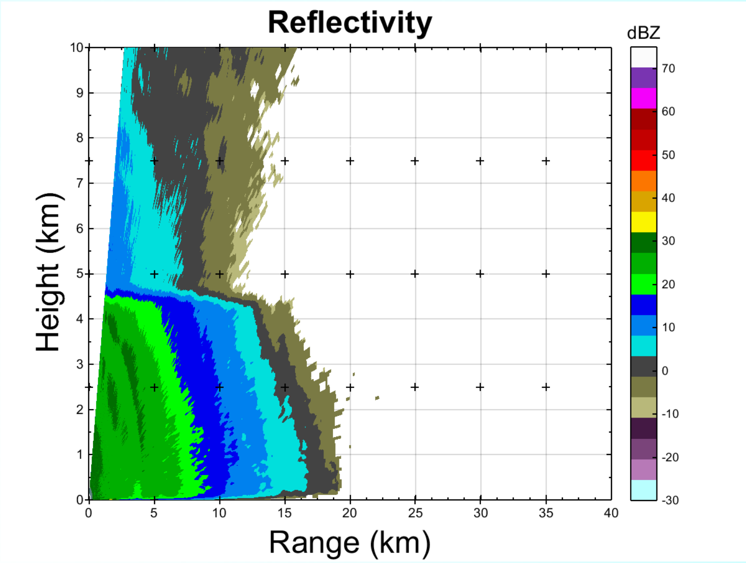
RHI Scan at 01:33UTC, 2017/07/15

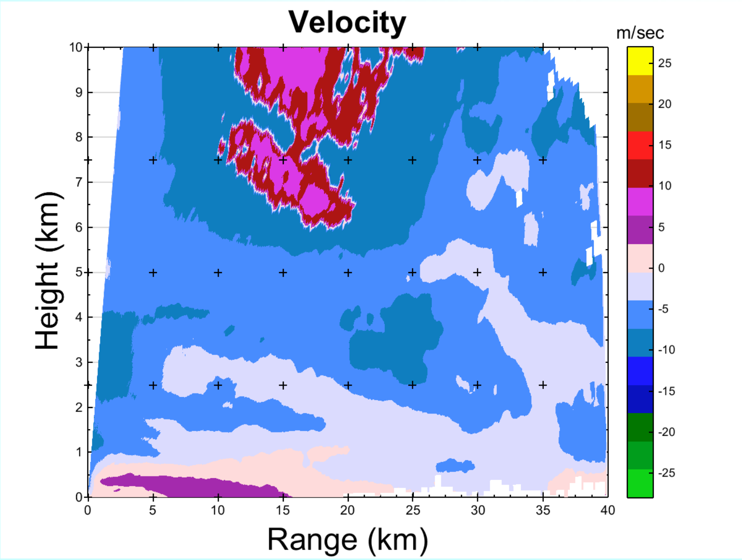
Az: 202.26 deg

Ku



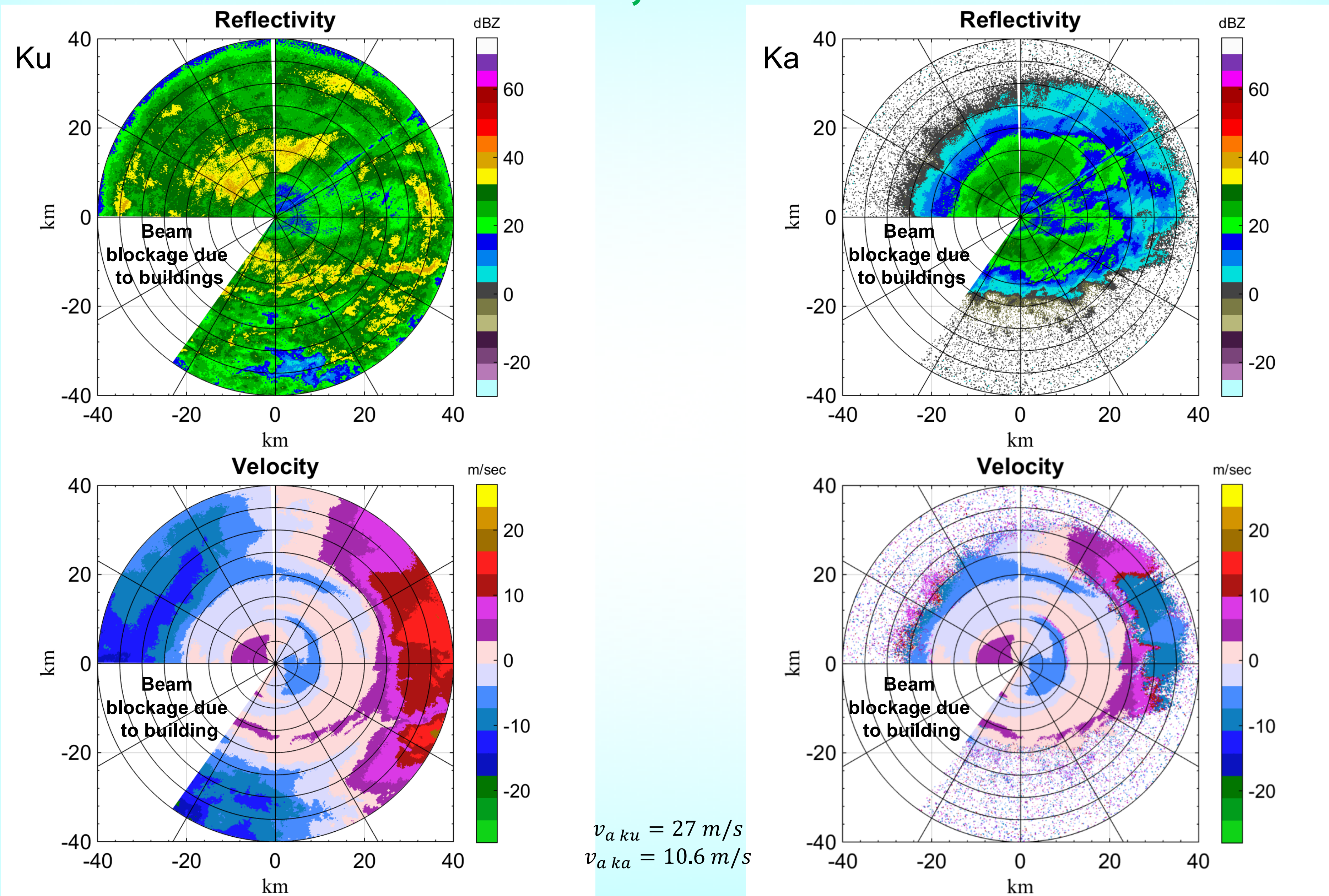
Ka





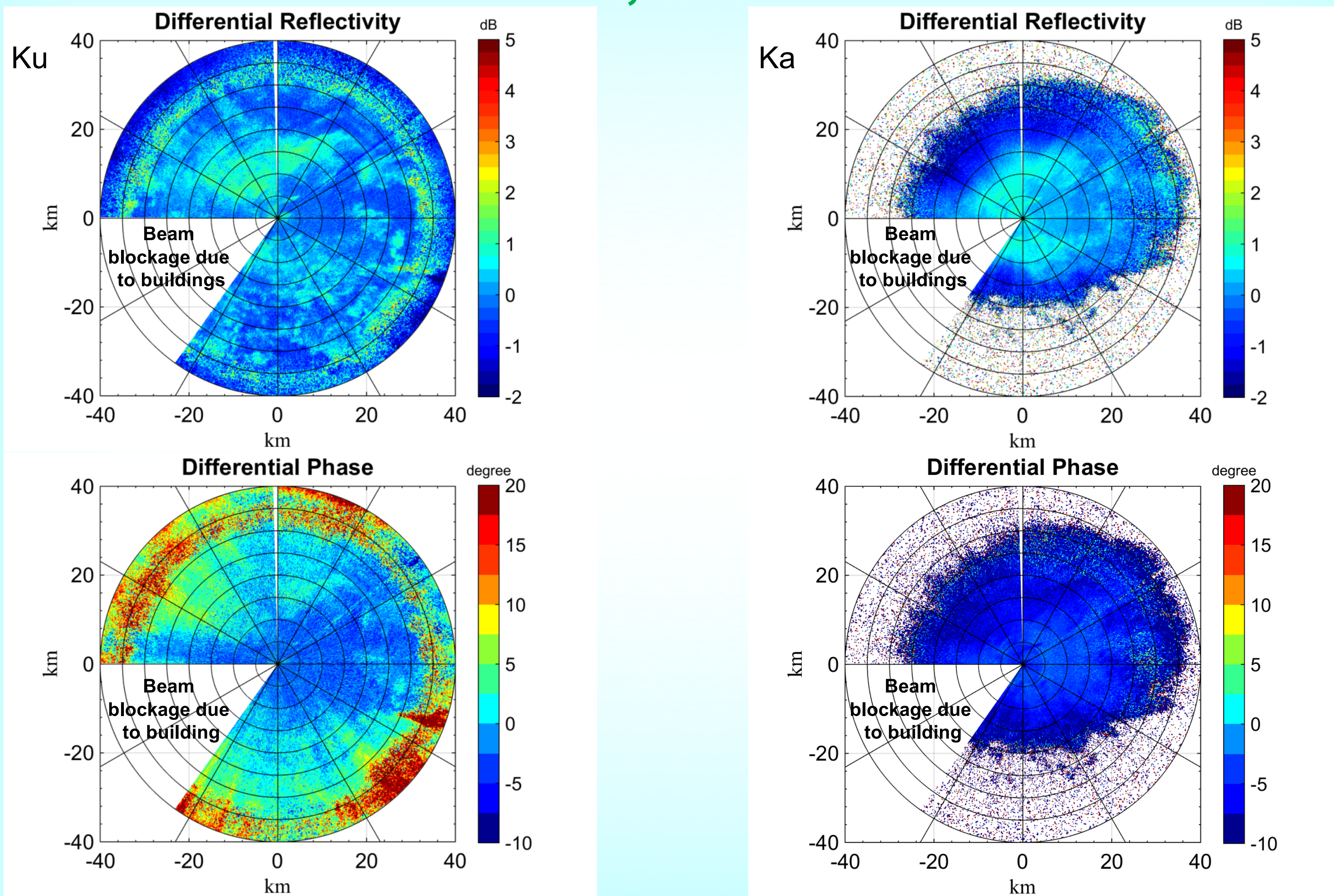
$v_{a\,ku} = 27\ m/s$

PPI Scan at 00:39UTC, 2017/09/02



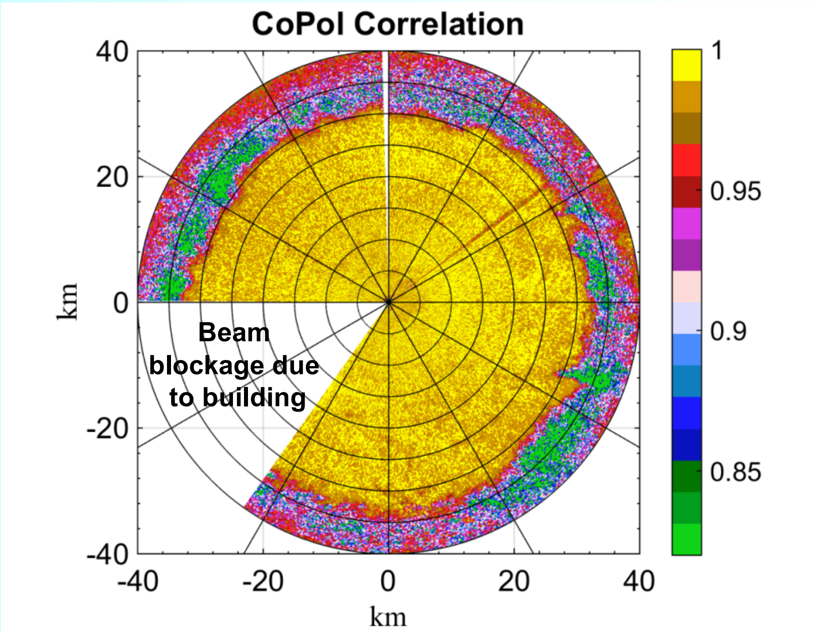
$v_{a\,ku} = 27\ m/s$
$v_{a\,ka} = 10.6\ m/s$

PPI Scan at 00:39UTC, 2017/09/02

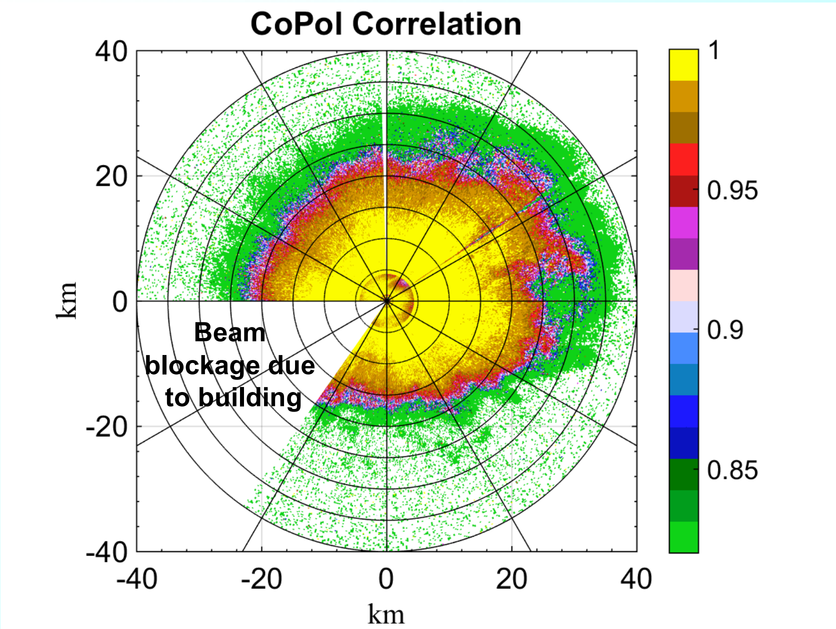


PPI Scan at 00:39UTC, 2017/09/02

Ku



Ka



Summary

- The NASA Ku/Ka-band D3R has been developed for GPM ground validation (GV). The ground-based D3R provides a dual-wavelength cross-validation platform for the space GPM DPR through detailed observations of precipitation microphysics.
- The D3R has been operating for over 5 years. It has participated in a number of GPM GV field campaigns: *Canada (GCPEx) – Iowa (IFloodS) – North Carolina (IPHEx) – Washington State (OLYMPEx) – Wallops Island (D3R base)*
- Meteorological observations from OLYMPEx and Wallops Island are presented.
- Accurate precipitation classification and estimation can be achieved by the D3R.
- A system update has been made to the D3R. The upgraded system is ready for next field deployment in South Korea, in support of the PyeongChang 2018 Olympics.

Thank you very much!
Questions?

This research is supported by the NASA GPM/PMM Ground Validation (GV) program.

Backup Slides

This research was primarily supported by the NASA GPM/PMM Ground Validation (GV) program.