PROGRESS IN POLARIMETRIC SNOW MEASUREMENTS

Alexander Ryzhkov and Petar Bukovcic

NEXRAD TAC meeting. 29 April 2019

Summary of Z(S) relations for dry snow listed in the literature and utilized by the WSR-88D network in the USA

Source	Z(S) relation for dry snow
Gunn and Marshall (1958)	$Z = 448\ S^{2}$
Sekhon and Srivastava (1970)	$Z = 399\ S^{2.21}$
Ohtake and Hemni (1970)	$Z = (90 – 739)\ S^{(1.5 – 1.7)}$
Puhakka (1975)	$Z = 235\ S^{2}$
Koistinen et al. (2003)	$Z = 400\ S^{2}$
Matrosov et al. (2009)	$Z = (100 – 130)\ S^{(1.3 – 1.55)}$
Huang et al. (2010)	$Z = (106 – 305)\ S^{(1.11 – 1.92)}$
Saltikoff et al. (2010)	$Z = 100\ S^{2}$
Szyrmer and Zawadzki (2010)	$Z = 494\ S^{1.44}$
Wolfe and Snider (2012)	$Z = 110\ S^{2}$
Huang et al. (2015)	$Z = (130 – 209)\ S^{(1.44 – 1.81)}$
Von Lerber et al. (2017)	$Z = (53 – 782)\ S^{(1.19\ - 1.61)}$
WSR-88D, Northeast	$Z = 120\ S^{2}$
WSR-88D, Great Lakes	$Z = 180\ S^{2}$
WSR-88D, North Plains / Upper Midwest	$Z = 180\ S^{2}$
WSR-88D, High Plains	$Z = 130\ S^{2}$
WSR-88D, Inter-mountain West	$Z = 40\ S^{2}$
WSR-88D, Sierra Nevada	$Z = 222\ S^{2}$

- The variability of the multiplier in the power-law relations is an order of magnitude!
- Very little progress has been made in radar measurements of snow during last decades

Basic formulas

Ice water content

$$IWC = \frac{\pi}{6}\int \rho_s(D)D^3N(D)dD \propto M_2$$

Snow rate

$$S = 6\,10^{-4}\pi\int_0^{D_{max}} \frac{\rho_s(D)}{\rho_w}D^3V_t^{(s)}(D)N(D)dD \propto M_{2+\gamma}$$

Radar reflectivity

$$Z = \frac{|K_i|^2}{|K_w|^2}\int_0^{D_{max}} \frac{\rho_s^2(D)}{\rho_i^2}D^6N(D)dD \propto M_4$$

$$M_n = \int D^n N(D)dD$$

$$S \propto f_{rim}^{0.12}N_{0s}^{0.35}Z^{0.62}$$

The multiplier in the S(Z) relation changes more than an order of magnitude because N_{0s} varies 4 orders of magnitude

Snow size distribution

$$N(D) = N_{0s}\exp(-\Lambda_s D)$$

Snow density

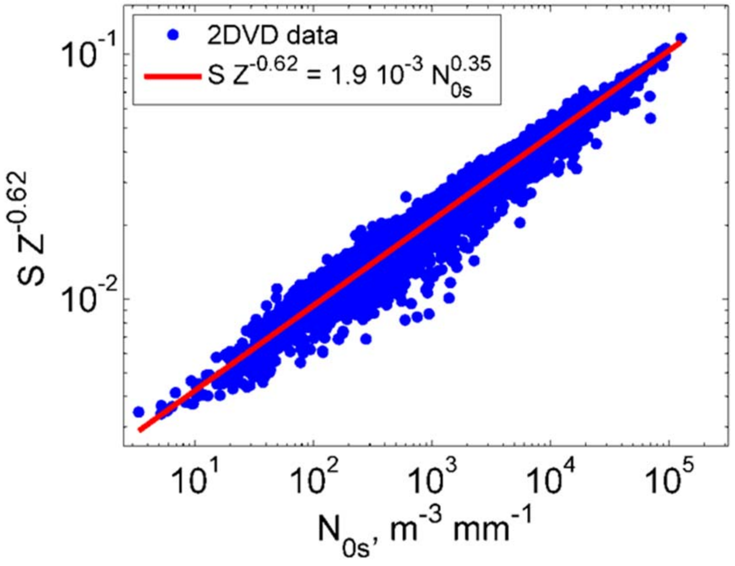
$$\rho_s(D) = \alpha_u f_{rim} D^{-1}$$

f_{rim} is the degree of riming

Snow fall velocity

$$V_t^{(s)} \propto D^{\gamma}$$

Analysis of snow disdrometer data



Polarimetric algorithms for snow estimation

Specific differential phase

$$K_{\mathrm{DP}} = \frac{0.27\pi}{\lambda\rho_i^2}\left(\frac{\varepsilon_{\mathrm{i}}-1}{\varepsilon_{\mathrm{i}}+2}\right)^2 F_{shape}F_{orinet}\int \rho_s^2(D)D^3N(D)dD \square M_1$$

Z is proportional to the 4th moment of snow SD whereas K_{DP} is proportional to its 1st moment

$$IWC(K_{DP}) = 3.22K_{DP}$$

Vivekanandan et al. (1994)

$$IWC(K_{DP},Z) = 0.23\left(F_sF_o\right)^{-0.66}K_{DP}^{0.66}Z^{0.28}$$

Bukovcic et al. (2019)

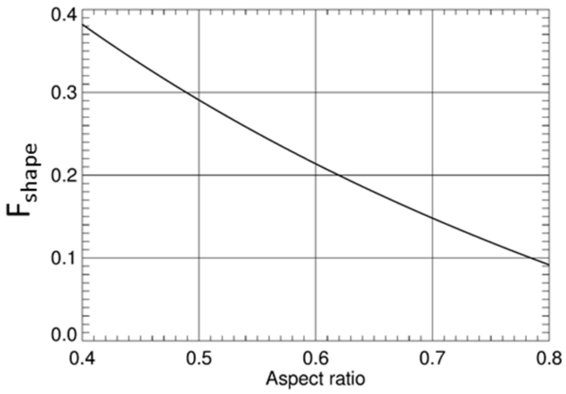
$$IWC(K_{DP},Z_{DR}) = 4.0\,10^{-3}\frac{K_{DP}\lambda}{1-Z_{dr}^{-1}}$$

Ryzhkov et al. (1998, 2018)

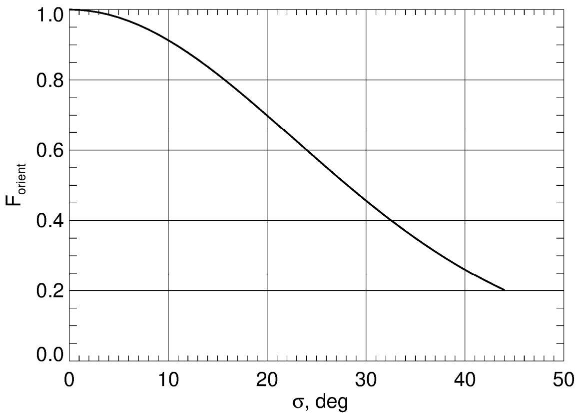
$$Z_{dr} = 10^{0.1Z_{DR}(dB)}$$

- All polarimetric relations are less sensitive to the SD variability than IWC(Z) or S(Z) relations
- The IWC(K_{DP}) and IWC(K_{DP},Z) estimates are prone to the variability of particle shape and orientation, whereas the IWC(K_{DP},Z_{dr}) estimate is not
- Airborne Convair-580 polarimetric and in situ measurements prove high efficiency of the IWC(K_{DP}) and particularly IWC(K_{DP},Z_{dr}) algorithms in ice clouds (Nguyen et al. 2017, 2019)

Shape factor



Orientation factor



Radar snow relations used in this study

$S(Z) = 0.088\, Z^{0.5}$ Eastern US

$S(Z) = 0.115\, Z^{0.5}$ Western US, mountain areas

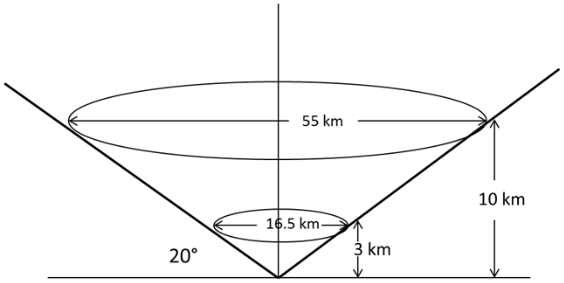
$$S(K_{DP}, Z) = 0.52\, f(\rho_a)(F_s F_o)^{-0.615} K_{DP}^{0.615} Z^{0.33}$$

$$S(K_{DP}, Z, Z_{DR}) = 3.05\, f(\rho_a) IWC(K_{DP}, Z_{DR}) D_m^{0.15} \qquad D_m = 2\left(\frac{Z_{dp}}{K_{DP}\lambda}\right)^{1/2} \qquad Z_{dp} = Z_h - Z_v$$

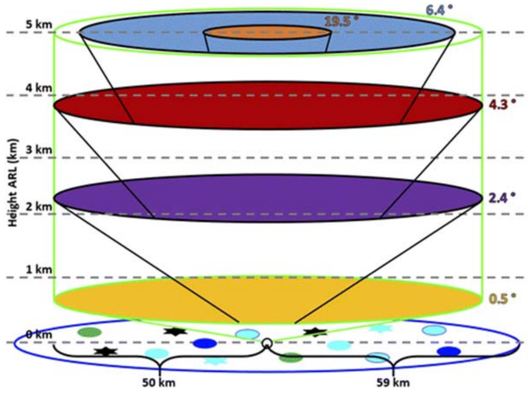
$f(\rho_a)$ is the fall velocity adjustment factor depending on air density ρ_a

- ***K_{DP} is low and noisy in snow at S band, therefore, additional spatial averaging is required to obtain robust estimates of K_{DP} (and Z_{DR})***
- ***Recently introduced radar products such as Quasi-Vertical Profiles (QVP), range-defined QVP (RD-QVP), and Column Vertical Profiles (CVP) imply aggressive spatial averaging and represent radar data in a height vs time format***

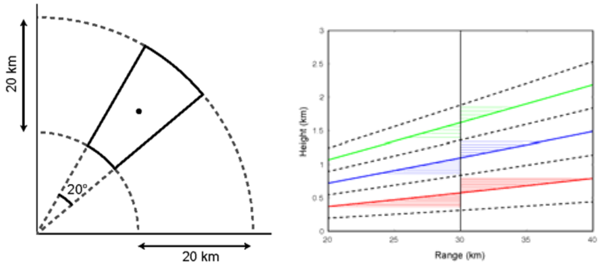
QVP



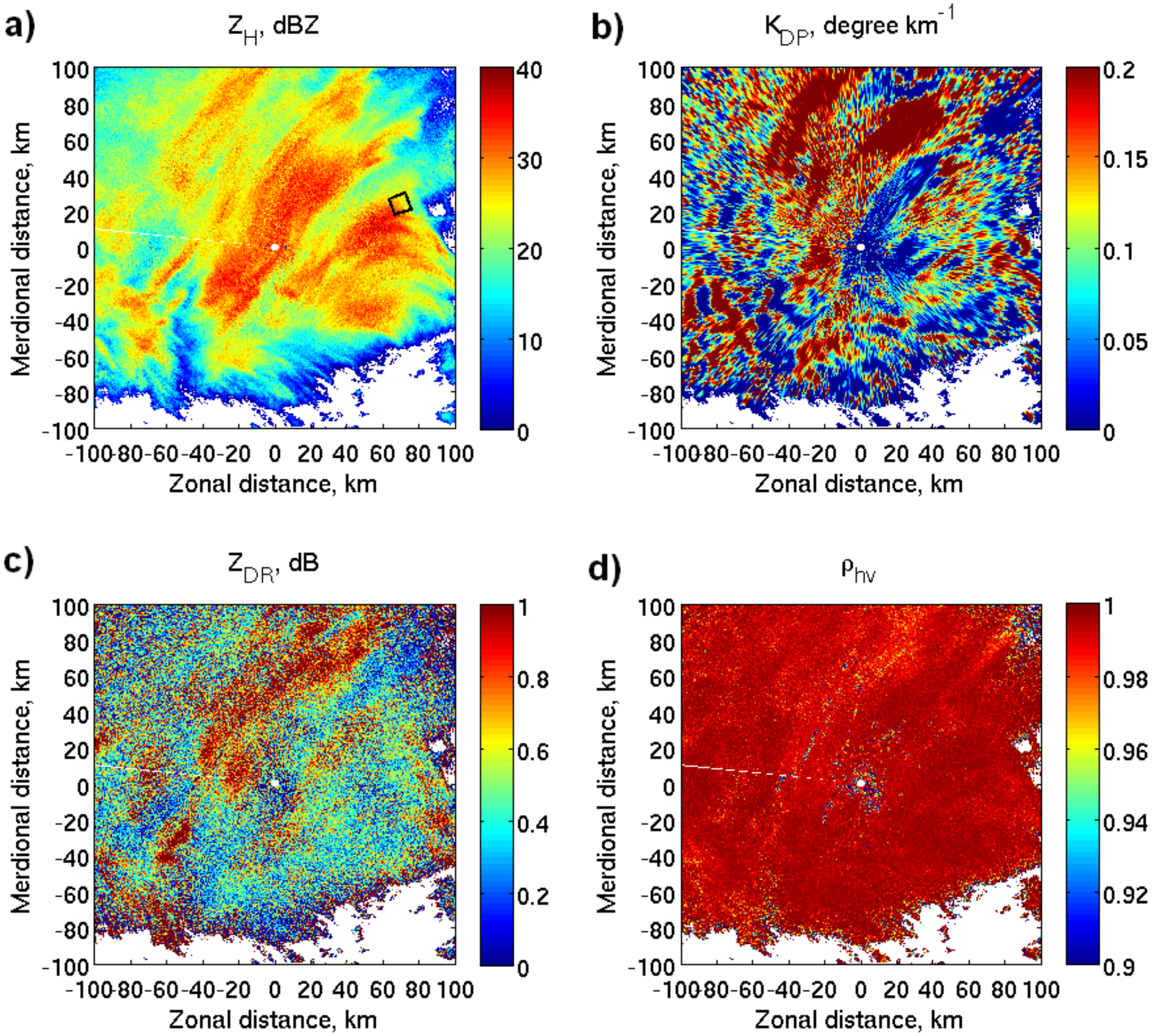
RD-QVP



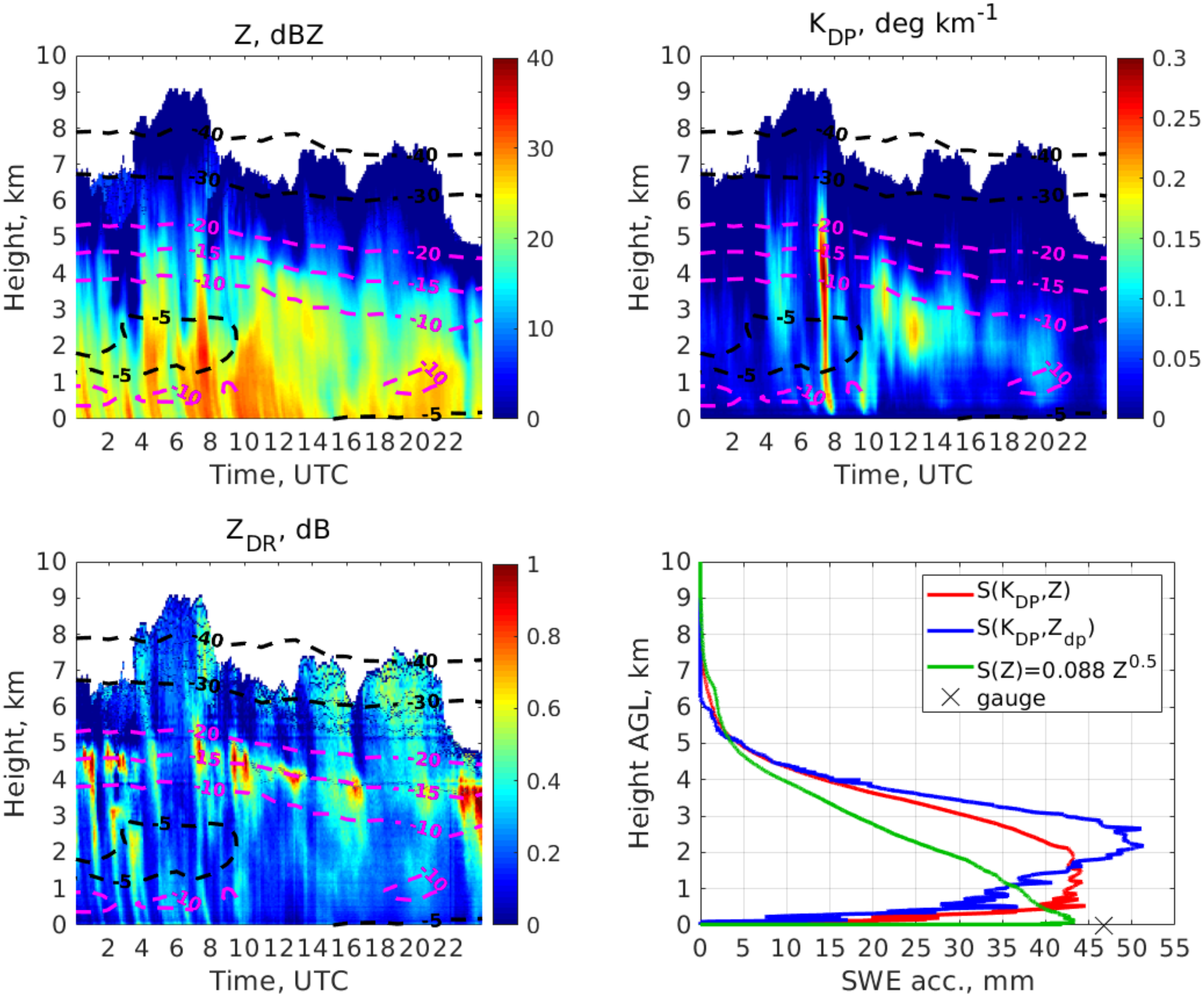
CVP



KLWX 1.45° PPI, Nor’easter, 2016-01-23

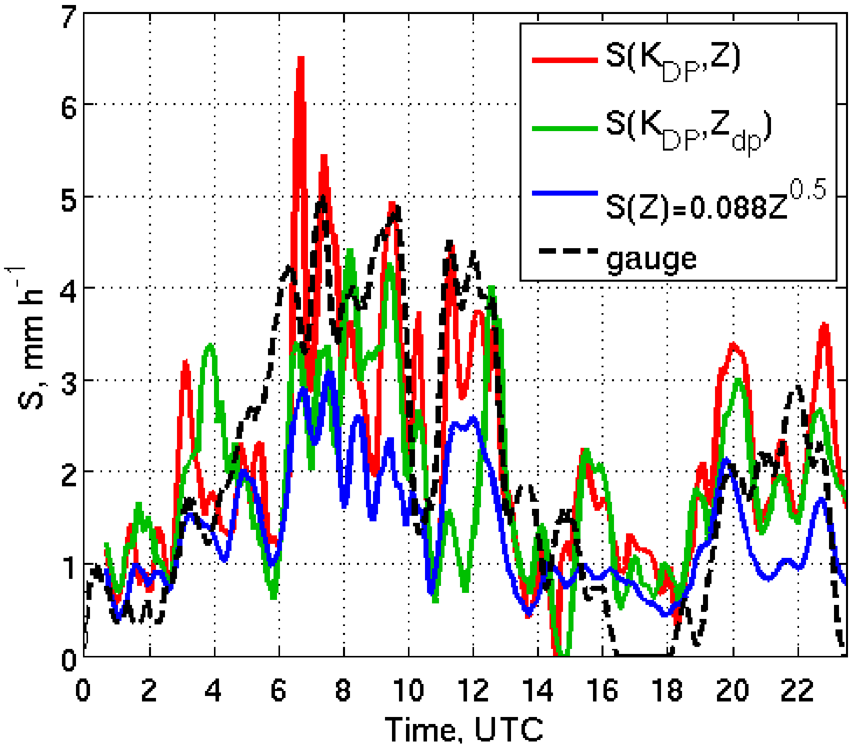


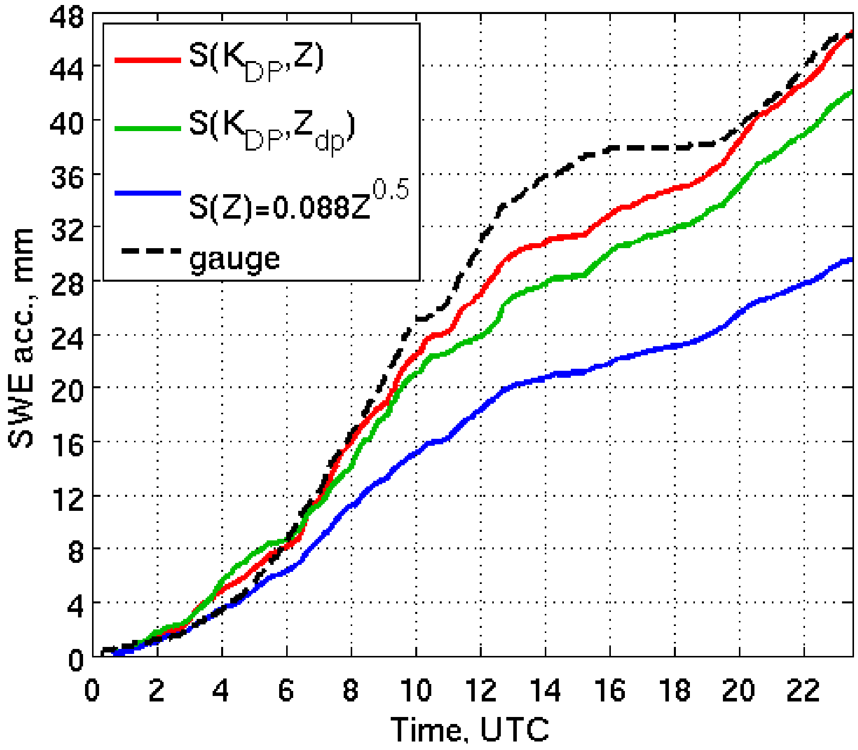
RD-QVP, KLWX, 2016-01-23



- S(Kdp, Z) – realistic profile, S(Kdp, Zdp) perform well in DGL, S(Z) – fortuitous estimate (ground)

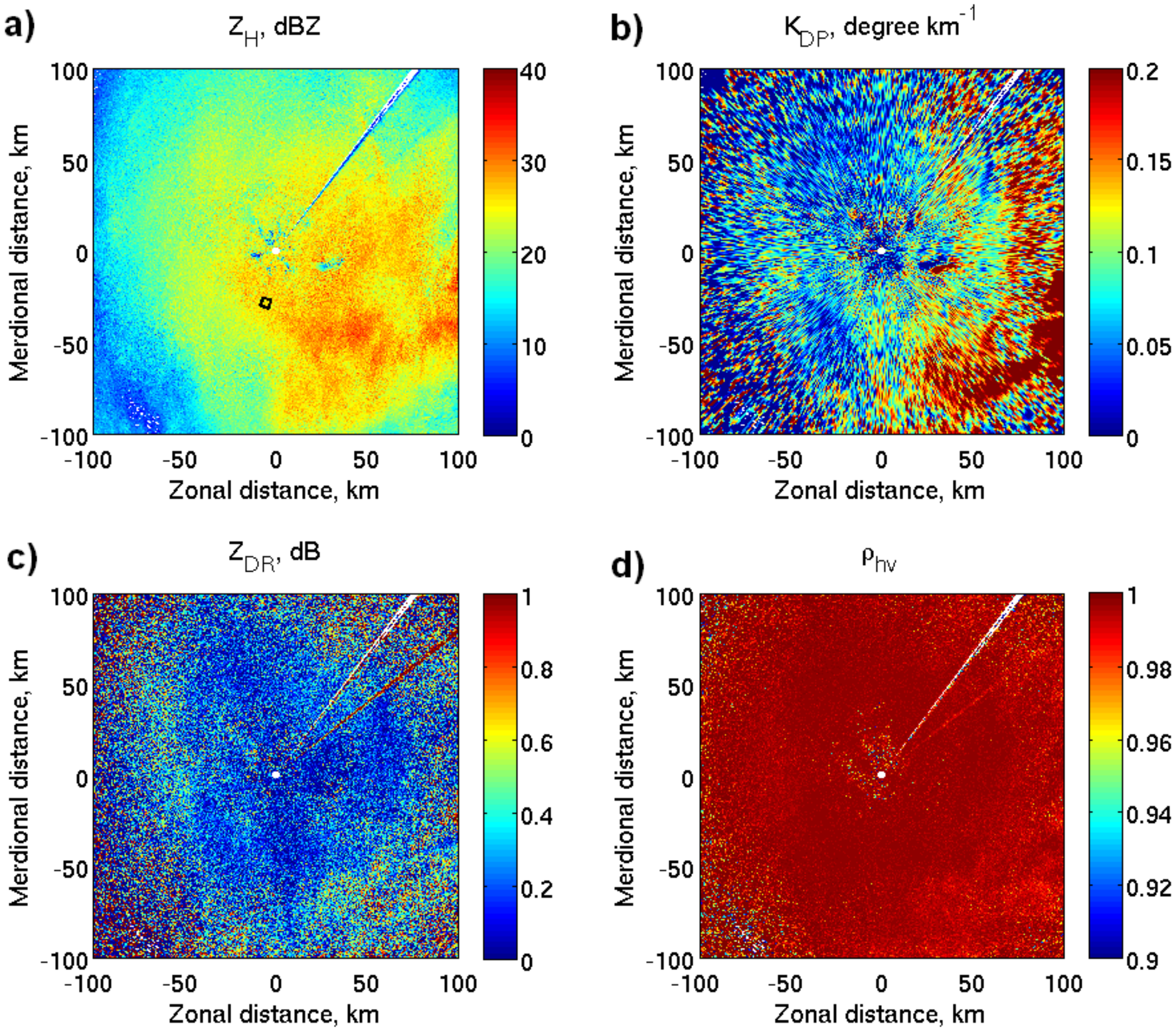
Snowfall rates and accumulations from 1.45° PPI, KLWX, 2016-01-23



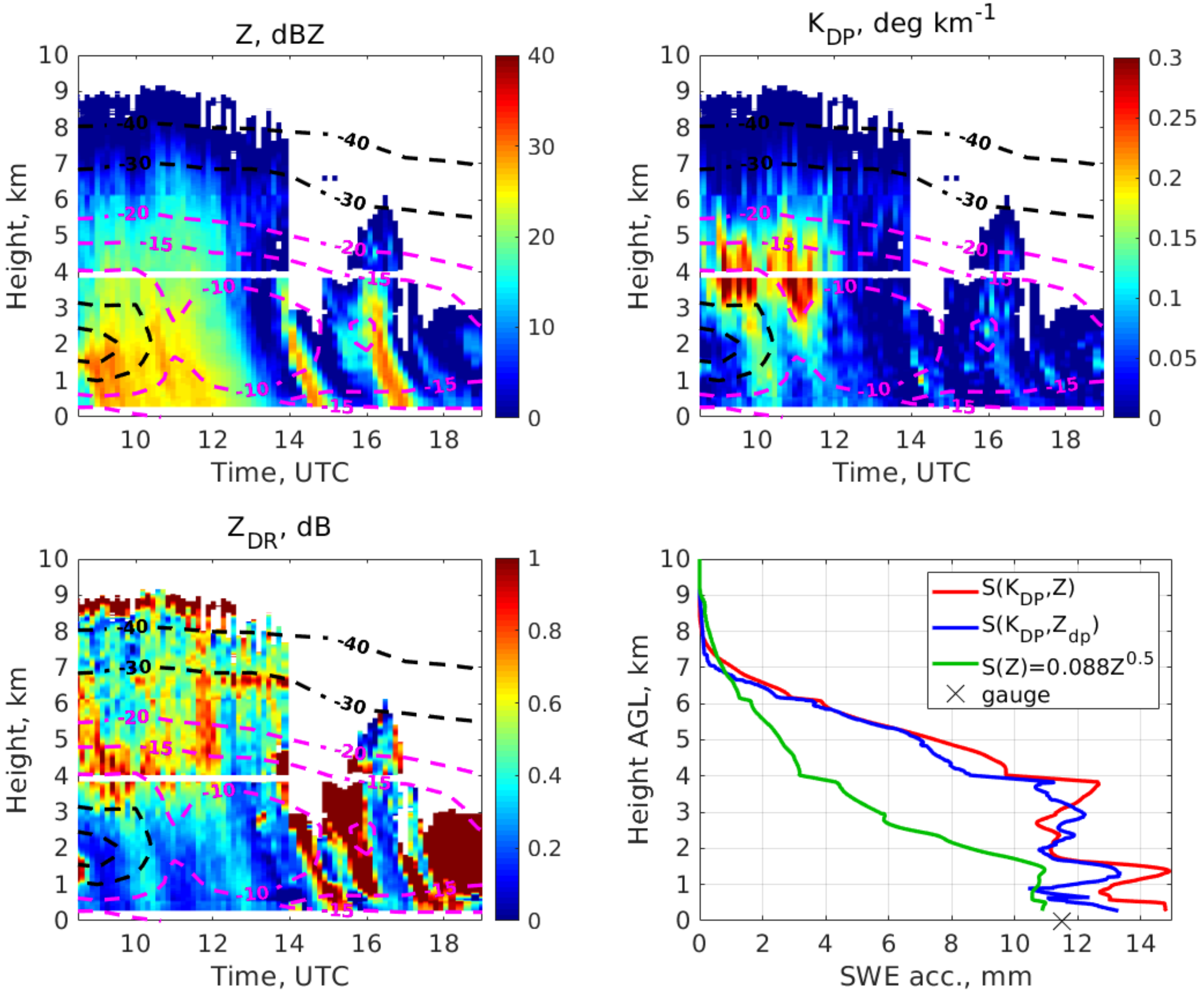


- S(Kdp, Z) – most realistic, very close to the gauge measurement; reproduces peaks in S
- S(Kdp, Zdp) – slightly underestimates S, close to the ground measurement
- S(Z) – moderately underestimates S, maximum < 3.1 mm/h

KOUN 1.45° PPI, 2011-02-01

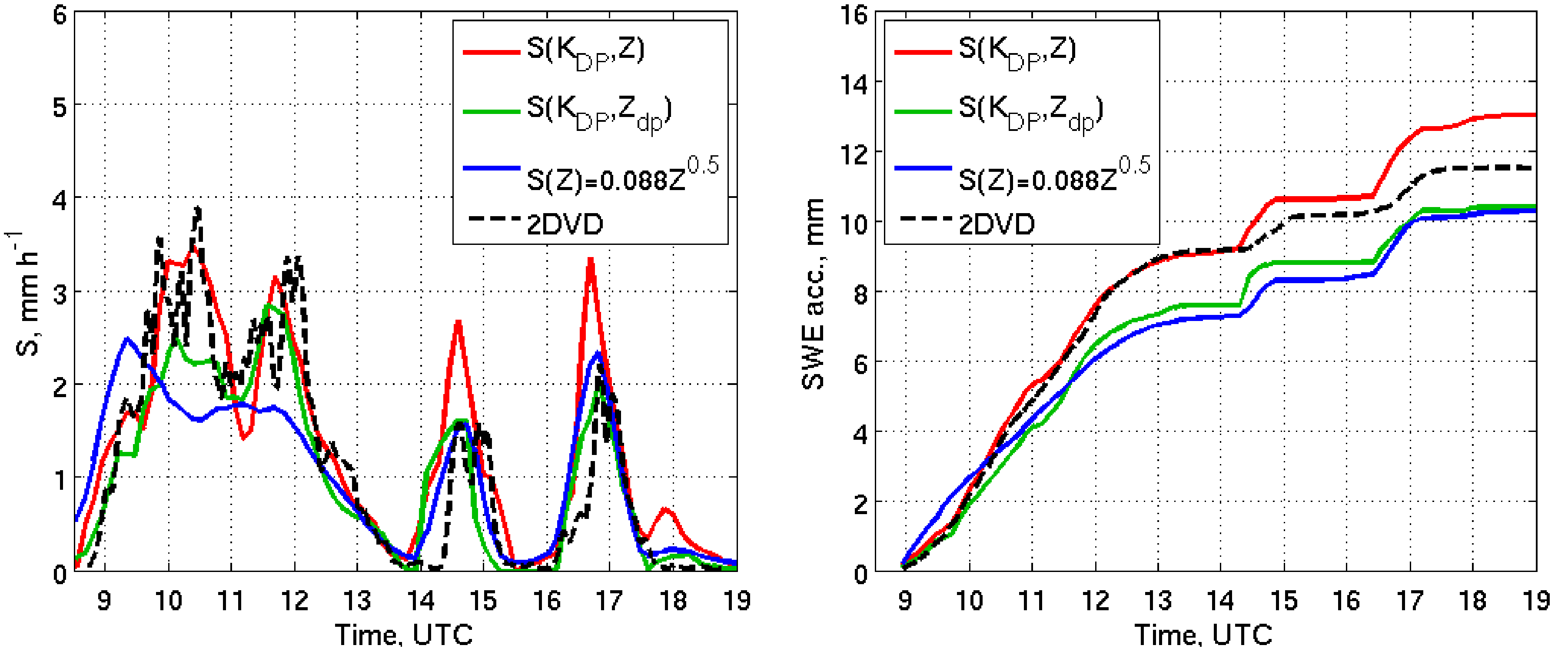


CVP, KOUN, 2011-02-01



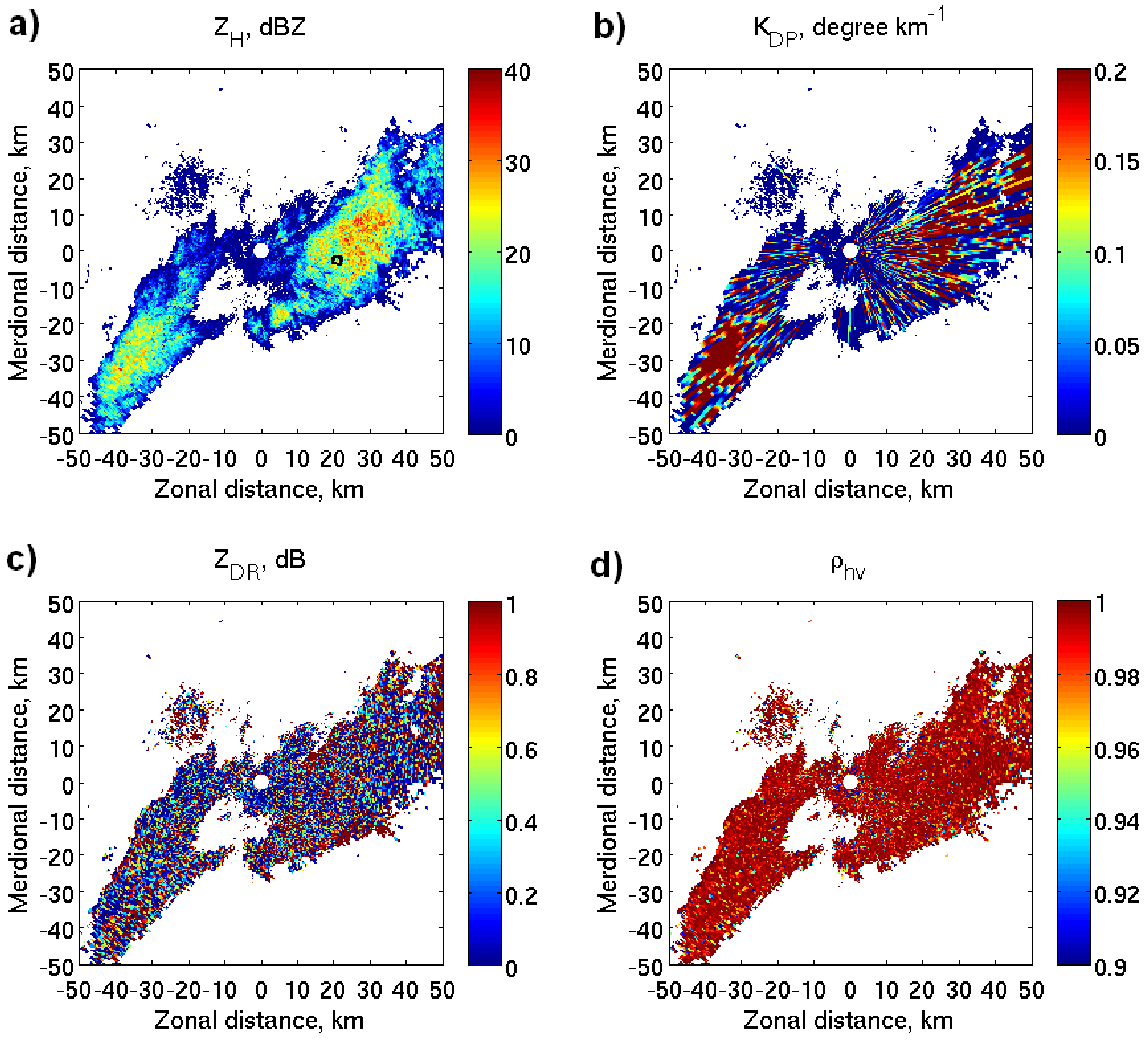
- S(Kdp, Zdp) and S(Kdp, Z) perform very well, S(Z) estimate has less realistic profile

Snowfall rates and accumulations from 1.45° PPI, KOUN, 2011-02-01

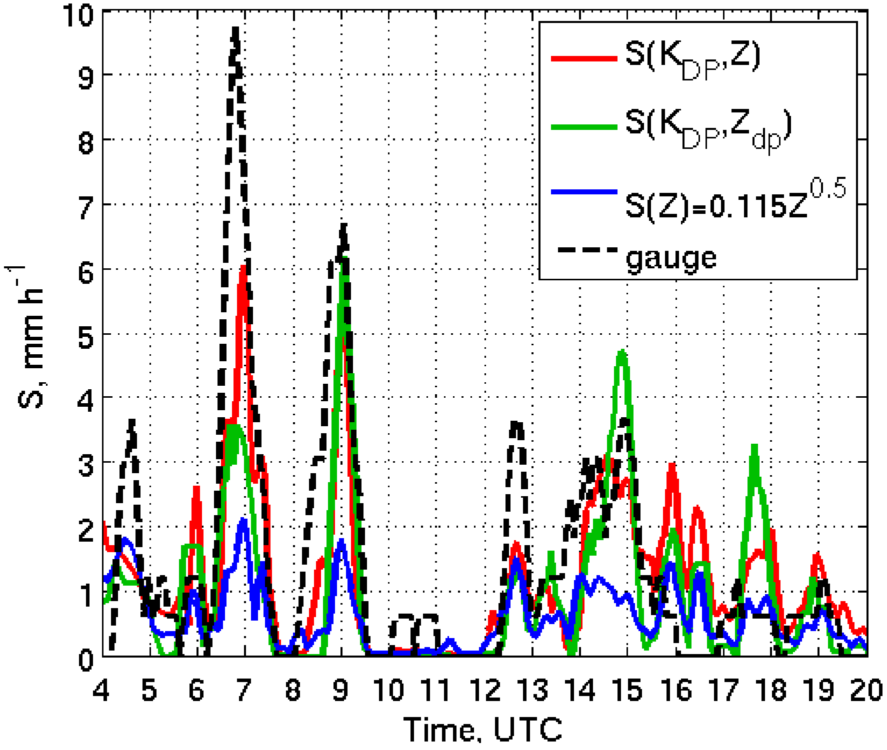


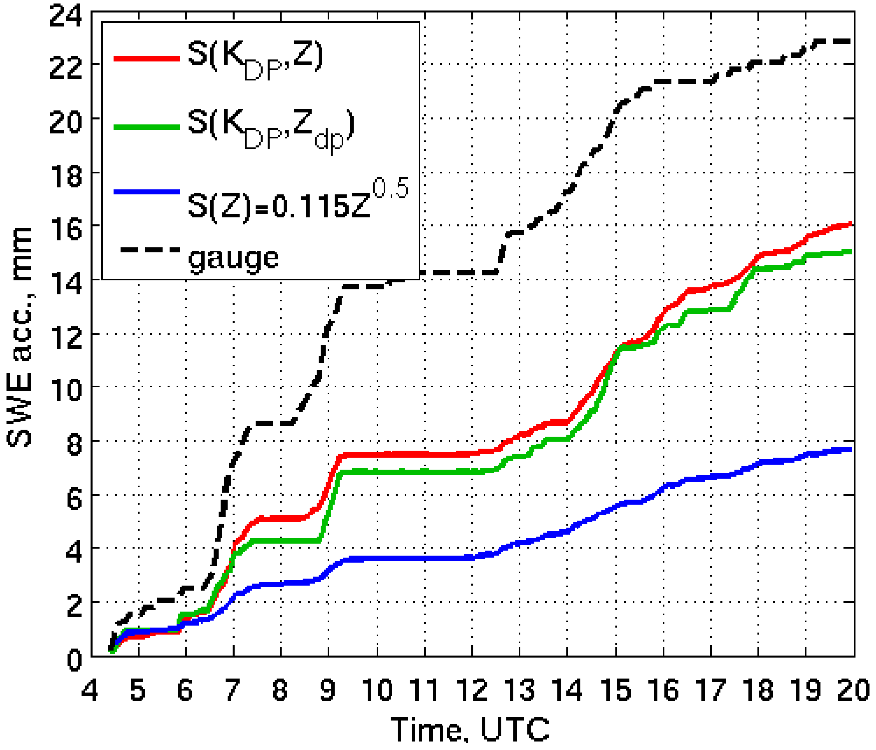
- S(Kdp, Z) – good agreement with the gauge in synoptic snow, overestimates in snow bands
- S(Kdp, Zdp) – slightly underestimates S in widespread snow, good performance in bands
- S(Z) – underestimates S in synoptic snow, good agreement in snow bands

KGJX 2.4° PPI, orographic, 2013-01-28



Snowfall rates and accumulations from 2.4° PPI, KGJX, 2013-01-28





- S(Kdp, Z) – moderately close to the gauge measurement; most realistic peaks in S
- S(Kdp, Zdp) – moderately close to the gauge measurement, slightly worse than S(Kdp, Z)
- S(Z) – heavily underestimates S, maximum < 2.1 mm/h

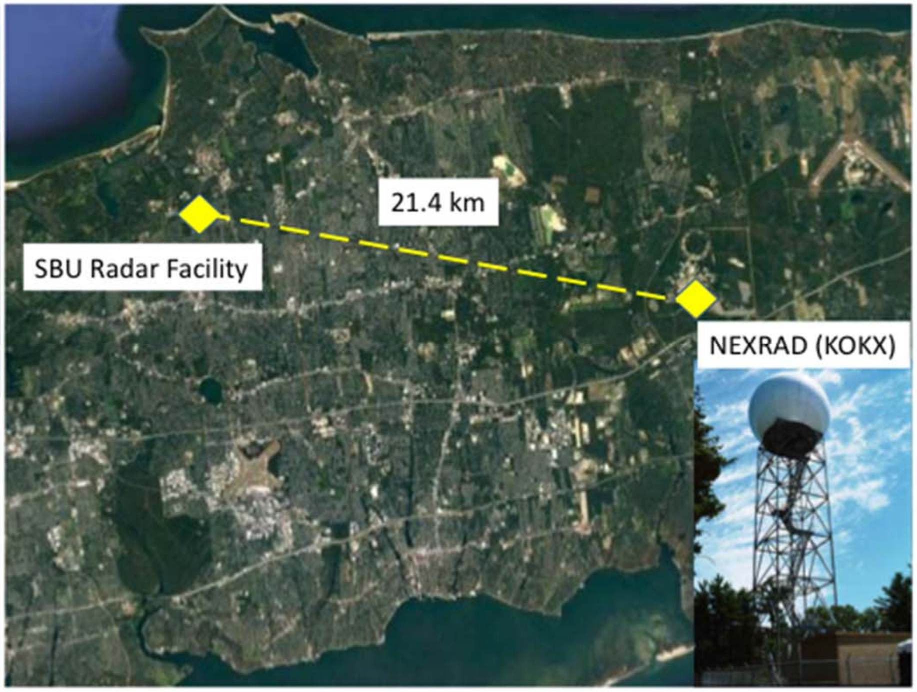
Instrumentation at the Kessler Farm

Dual-frequency polarimetric radar measurements with Ka-band and S-band radars

Courtesy of Pavlos Kollias and Mariko Oue

KASPR

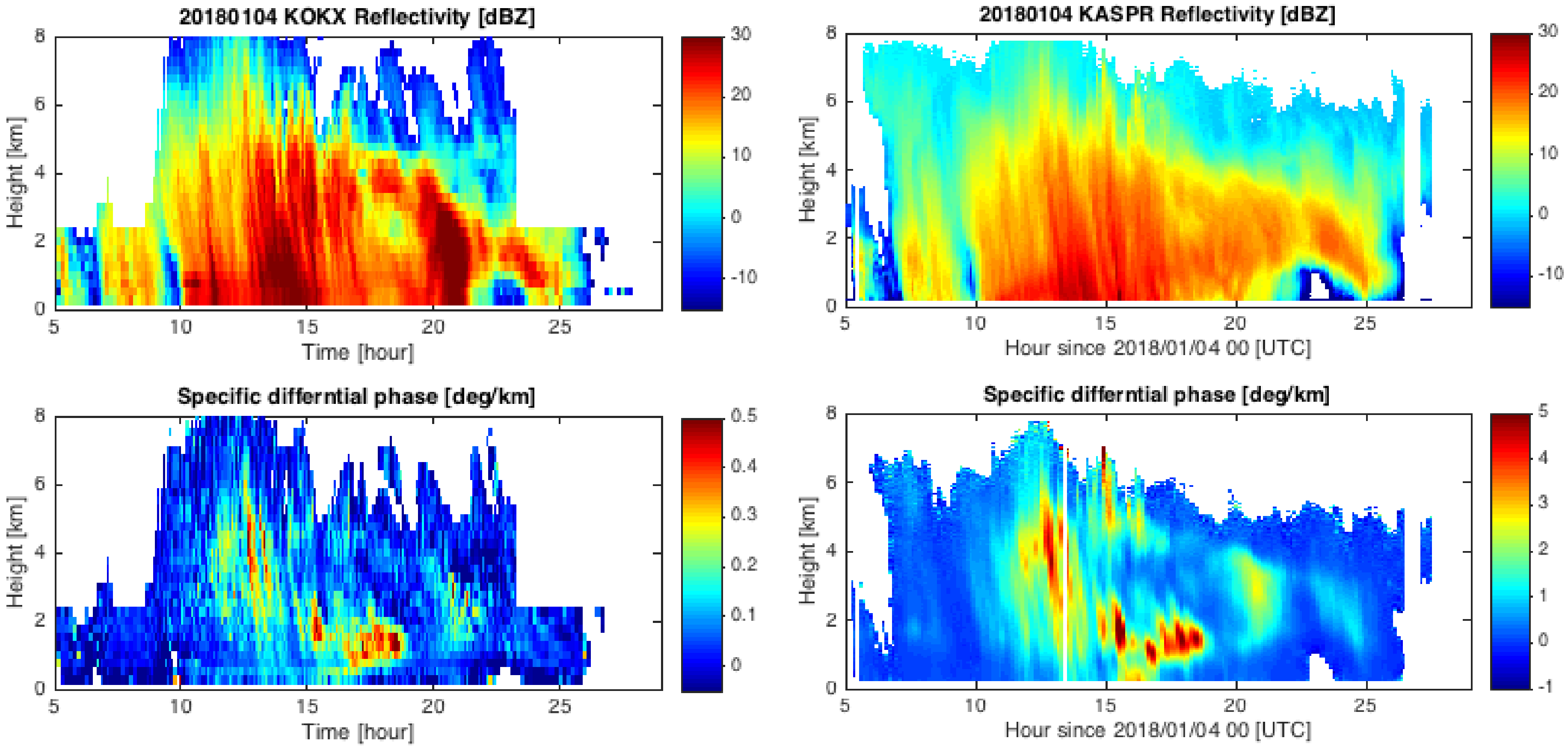
WSR-88D



SBU – Stony Brook University

KASPR – Ka-band scanning polarimetric radar

KOKX WSR-88D **KASPR**



KOKX and KASPR Kdps are almost perfectly matched

The difference between Z(Ka) and Z(S) are related to (1) resonance scattering, (2) attenuation, and (3) differences in sensitivities and sampling volumes

Conclusions

- Variability of the S(Z) relations is prohibitively large
- Polarimetric relations for snow estimation were tested for three heavy snowfall events and show good promise
- Aggressive spatial averaging is required to obtain robust estimates of polarimetric variables in snow at S band
- Further optimization and testing of the polarimetric algorithms for snow QPE will involve massive analysis of snowfall and stratiform rain events with low bright band and instrumented ground validation sites in the states of Oklahoma and New York