Taranis: Advanced Precipitation and Cloud Products for ARM Radars

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CMDV

Mesoscale Convective Systems

Climate Model Development and Validation – Mesoscale Convective System

(CMDV-MCS) is a BER project headed by PNNL to develop and validate DOE's Accelerated Climate Model for Energy (ACME) model capability in simulating MCSs.

CMDV Mesoscale Convective Systems

Goal

To improve understanding of warm season continental convection and develop treatments of convection and microphysics capable of representing MCS features in large-scale models

More explicitly:

- Develop and evaluate cloud parameterizations using observations and LAM/LES.
- Evaluate developments using ACME with RR grid centered over the ARM SGP site.
- Use global observational data to evaluate ACME uniform-grid simulations.

PI: Jiwen Fan

CMDV-MCS

T1. Cloud macrophysics and dynamics (Mikhail Ovchinnikov)

T2. Cloud microphysics (Jiwen Fan)

T3. Q3D-MMF (David Randall)

T4. MMF aerosol and cloud microphysics (Jiwen Fan)

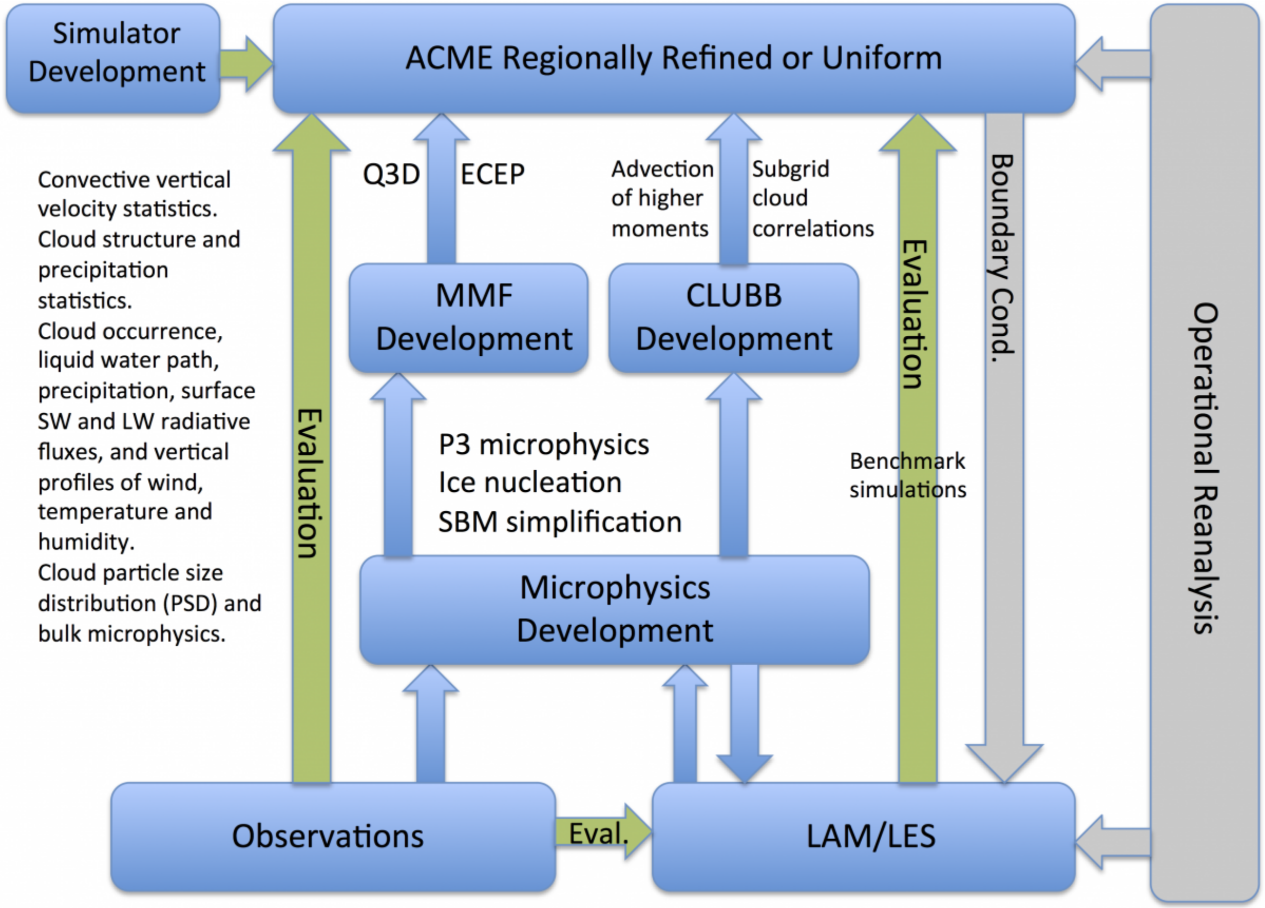
T5. Observations (Zhe Feng)

T6. LES/LAM (Bill Gustafson)

T7. Regional refinement (Erika Roesler)

T8. Evaluation (Jiwen Fan and Kai Zhang)

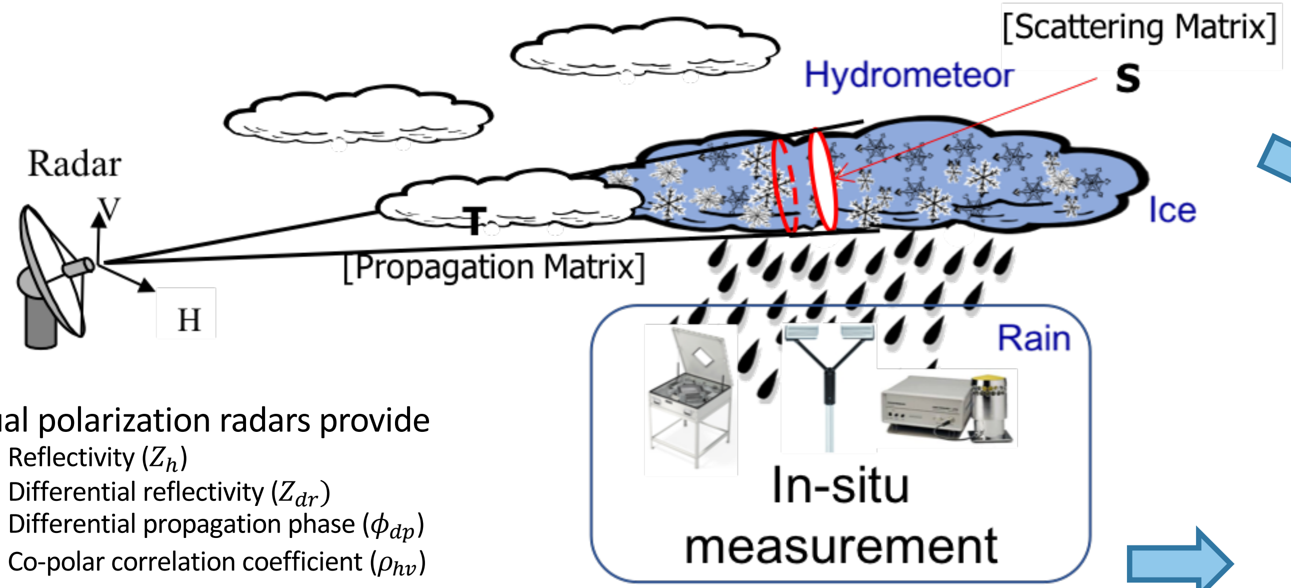
- CMDV had eight main task areas spread amongst the team.
- Regular integration between modelers and observationalists to ensure activities were synergistic.
- This talk will focus on one of the observation activities



Taranis

- A task area for CMDV was to develop a suite of products from ARM radars to support model evaluation that scaled to multiple campaigns.
- Initial focus on MC3E, with plans to support other campaigns.
- This talk examines this suite of products (**Taranis**) that includes corrections, gridding, and retrievals of geophysical quantities from cloud and precipitation radars.
- *Why some of these retrievals and corrections are necessary?*

Observations of Precipitation in CMDV



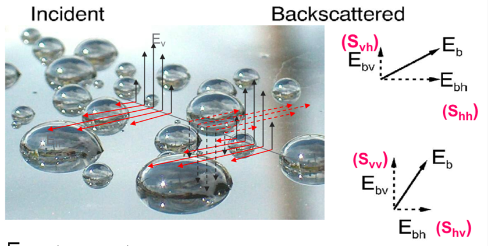
Dual polarization radars provide

- Reflectivity (Z_h)
- Differential reflectivity (Z_{dr})
- Differential propagation phase (ϕ_{dp})
- Co-polar correlation coefficient (ρ_{hv})

Derived products

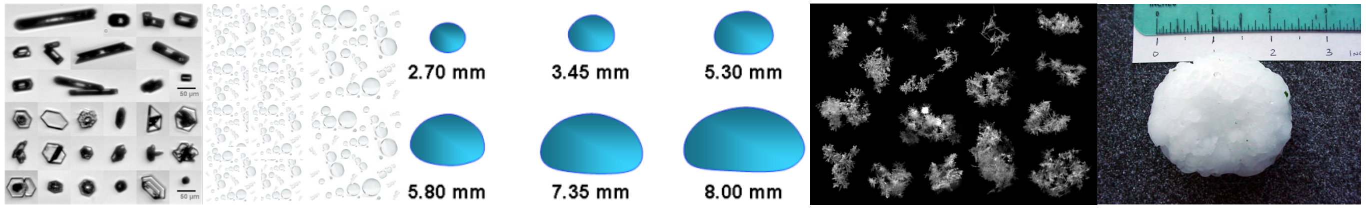
- Attenuation corrected Z_h
- Attenuation corrected Z_{dr}
- Specific differential phase (K_{dp})
- Co-polar correlation coefficient

Electric Fields



$$\Sigma = \begin{bmatrix} \langle |S_{hh}|^2 \rangle & \sqrt{2}\langle S_{hh} S_{vh}^* \rangle & \langle S_{hh} S_{vv}^* \rangle \\ \sqrt{2}\langle S_{vh} S_{hh}^* \rangle & 2\langle |S_{hv}|^2 \rangle & \sqrt{2}\langle S_{vh} S_{vv}^* \rangle \\ \langle S_{vv} S_{hh}^* \rangle & \sqrt{2}\langle S_{vv} S_{vh}^* \rangle & \langle |S_{vv}|^2 \rangle \end{bmatrix}$$

Elements depend on: size/l, shape, orientation, dielectric constant, elevation angle and their statistical distributions (mean, variance)

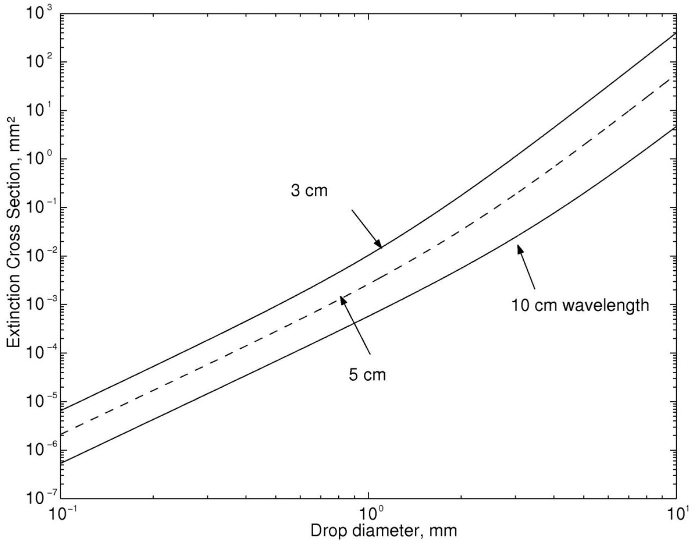


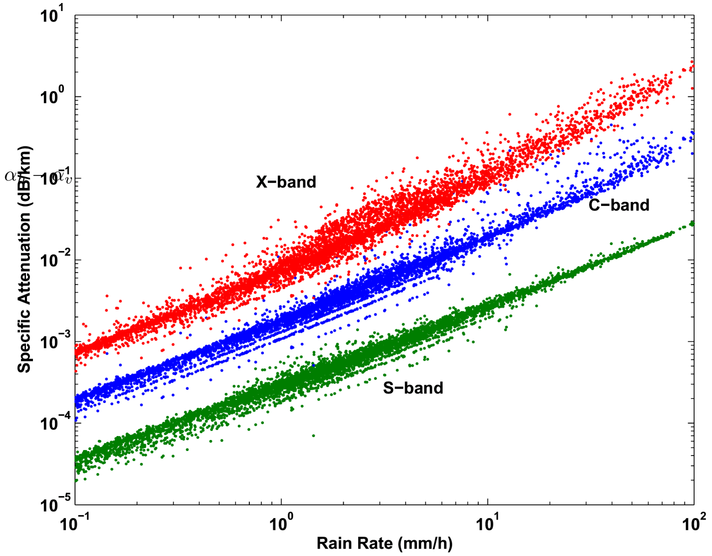
Radar Data: Attenuation

The hydrometeors in the propagation medium absorb a portion of the energy from the wave which cause the signal to attenuate. The attenuation levels are dependent on the DSD and the size of the hydrometeors relative to the wavelength. Attenuation is attributed to the extinction cross-section.

$\alpha_{dp} = \alpha_h - \alpha_v$

$$\alpha_{h,v} = 4.343\text{x}10^3 \int \sigma_{ext}^{h,v}(D)N(D)dD$$



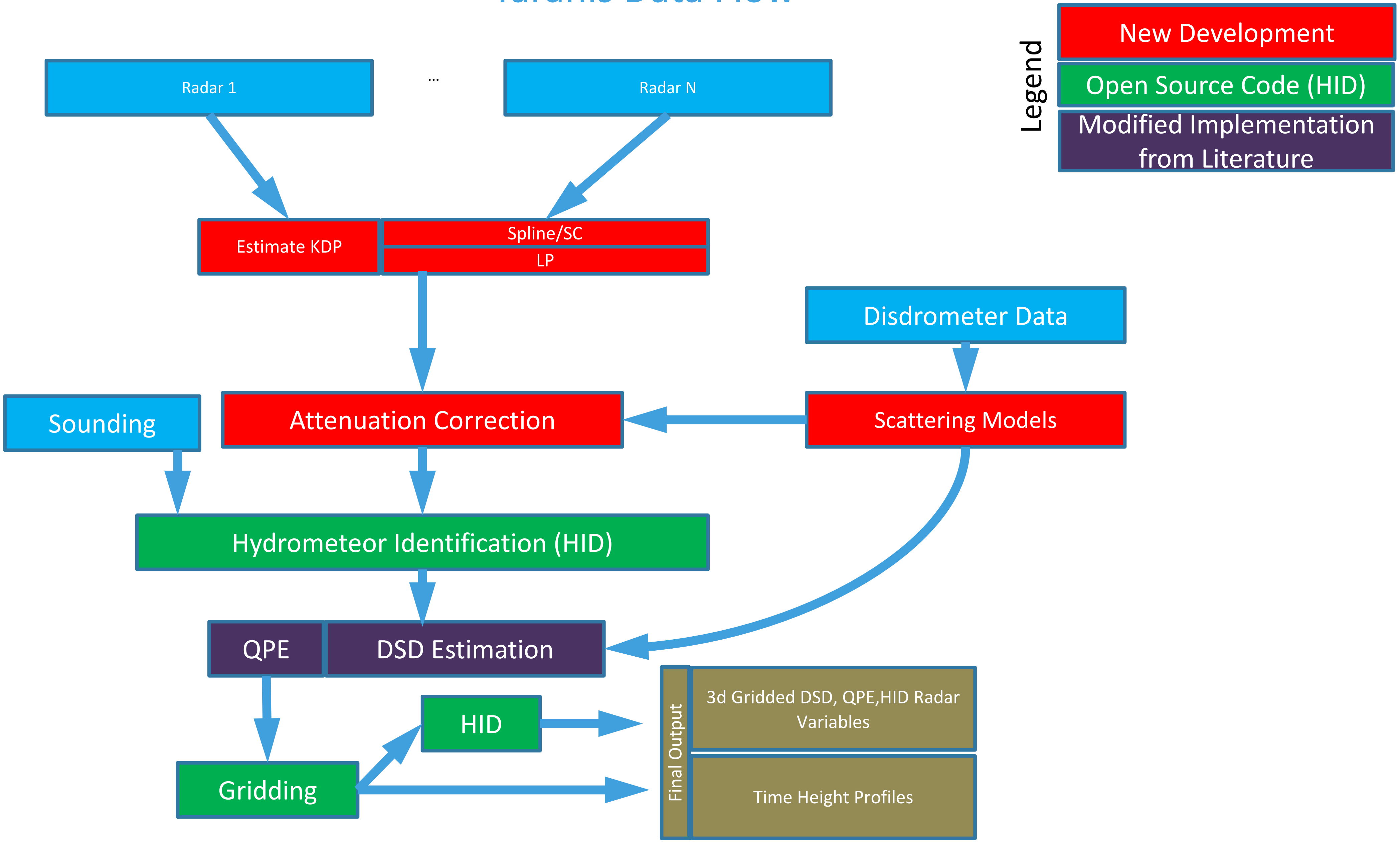


Shorter wavelength (higher frequency) radars suffer significant attenuation in rain. The observed data must be corrected for the bias induced by attenuation due to rainfall

Overview of Taranis

- Taranis is a new set of radar products that combines the best of open source implementations with some new algorithms.
- Taranis is a modular Python library that calculates geophysical quantities of interest using single or networks of radars.
- Intended to be used for model evaluation.
- Designed to be compatible with the various ARM frequency bands.
- This includes masking for QC, corrections of propagation effects, and retrievals of parameters of interest.
- Computationally expensive algorithms in C, everything driven by Python.

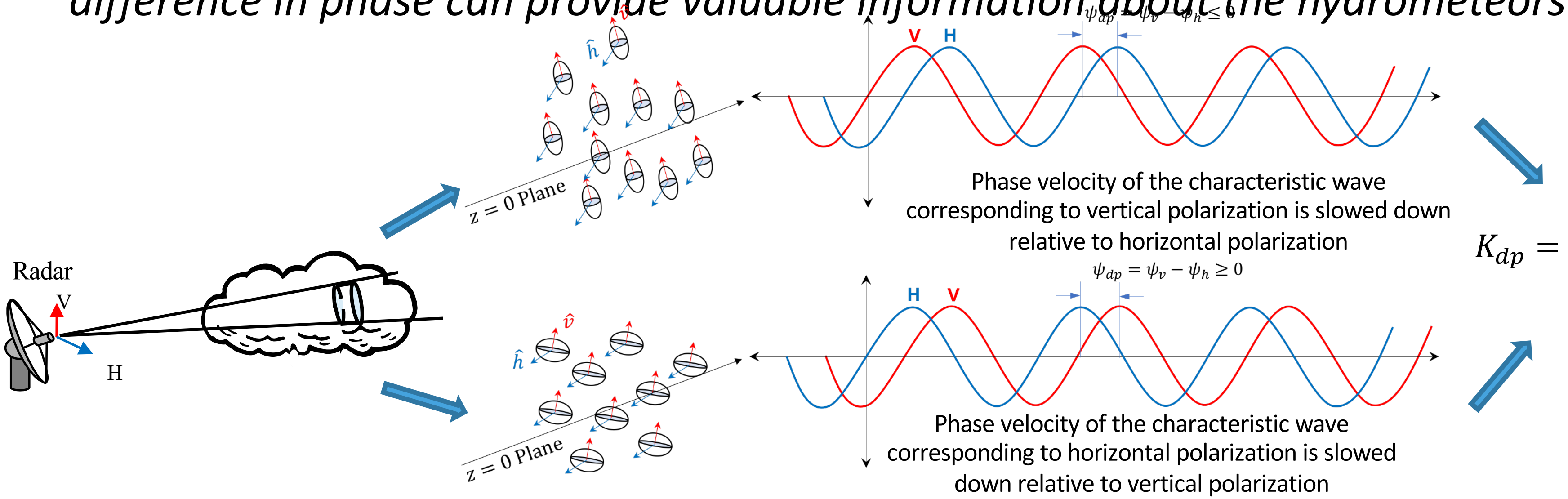
Taranis Data Flow



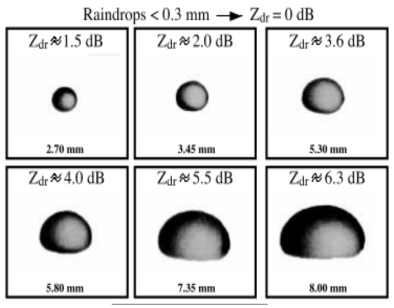
Radar Data Processing

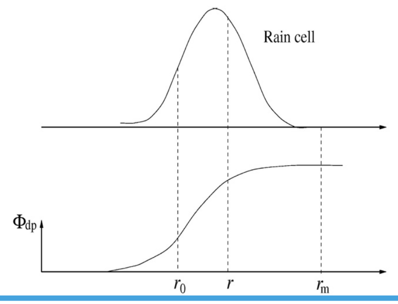
Radar Data Processing: Specific Differential Phase (K_{dp})

The specific differential phase (K_{dp}) is a wave propagation property determined the DSD, shape, and orientation of the particles. The phase velocity of the horizontally and vertically polarized wave differ as they propagate through hydrometeors. This difference in phase can provide valuable information about the hydrometeors.



$$K_{dp} = \frac{1}{2}\frac{d\psi_{dp}}{dr}$$





As the wave propagates through rain the phase difference accumulates. As a result differential propagation phase increases monotonically in range.

Challenges in K_{dp} Estimation

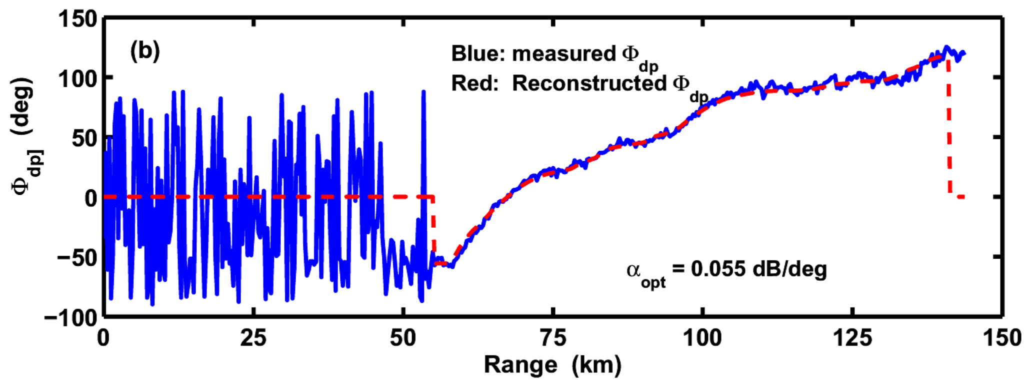
- KDP is not a measured quantity however. Instead we measure Ψ_{dp} where

$$\Psi_{dp}(r) = \Phi_{dp}(r) + \delta_{co}(r)$$

$$\Phi_{dp}(r) = \int_0^r K_{dp}(r)dr \cdot$$

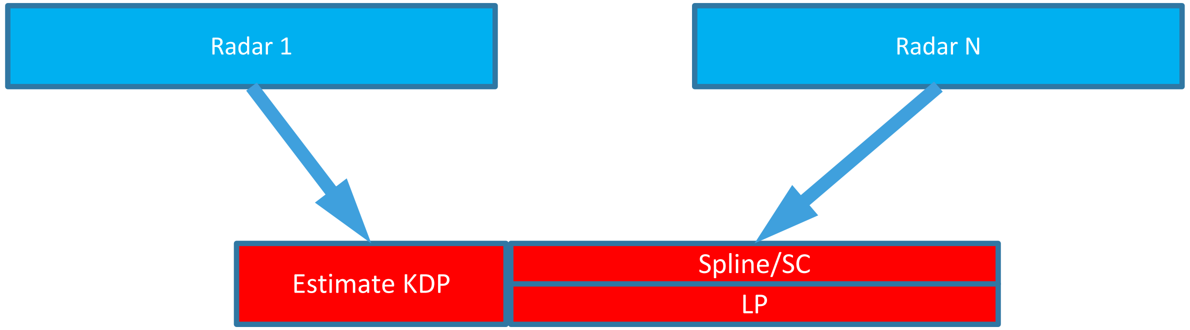
- K_{dp} is a useful quantity both for retrievals and for correcting for attenuation
- It is unaffected by attenuation and closely related to rain rate.

Challenge lies in estimating the slope of a noisy signal.



K_{dp} Estimation

- Taranis utilizes a new KDP estimation algorithm that combines the best of the spline approach from Yanting & Chandrasekar (2009) and the linear programming approach of Giangrande et. al. (2013).
- Additional self consistency and global constraints were added as well.
- Fast C-based multi-threaded implementation with Python interface.
- Hybrid retrieval reworks the constraints in LP to incorporate spline based processing.



Radar Data Processing: Specific Differential Phase (K_{dp})

- ψ_{dp} estimation is formulated as an optimization problem to minimize L_1

$$L_1 = \sum_{i=1}^{n} |x_i - b_i|$$

$\mathbf{b} = \{b_1, b_2, \ldots, b_n\}$ be the differential phase data

$\mathbf{x} = \{x_1, x_2, \ldots, x_n\}$ be the variables of the "fit"

- The above is formulated as a linear programming (LP) optimization problem

$$\min_{(\mathbf{z},\mathbf{x})} [\mathbf{0}^T \quad \mathbf{1}^T] \begin{bmatrix} \mathbf{z} \\ \mathbf{x} \end{bmatrix}$$

Such that:

$$\begin{bmatrix} -\mathbf{b} \\ \mathbf{b} \\ \mathbf{k}_{dp}^{l} \end{bmatrix} \leq \begin{bmatrix} \mathbf{I}_n & -\mathbf{I}_n \\ \mathbf{I}_n & \mathbf{I}_n \\ \mathbf{O}_{n-(m-1)/2,n} & \mathbf{M}_{n-(m-1)/2,n} \end{bmatrix} \begin{bmatrix} \mathbf{z} \\ \mathbf{x} \end{bmatrix} \leq \begin{bmatrix} -\mathbf{b} \\ \mathbf{b} \\ \mathbf{k}_{dp}^{u} \end{bmatrix}$$

and

$$\begin{bmatrix} \mathbf{z}_{lb} \\ \mathbf{x}_{lb} \end{bmatrix} \leq \begin{bmatrix} \mathbf{z} \\ \mathbf{x} \end{bmatrix} \leq \begin{bmatrix} \mathbf{z}_{ub} \\ \mathbf{x}_{ub} \end{bmatrix}$$

Where $\mathbf{M}_{n-(m-1)/2,n}$ is an derivative filter obtained from an m-point 2nd order Savitzky-Golay polynomial $C_{S-G}(i)$

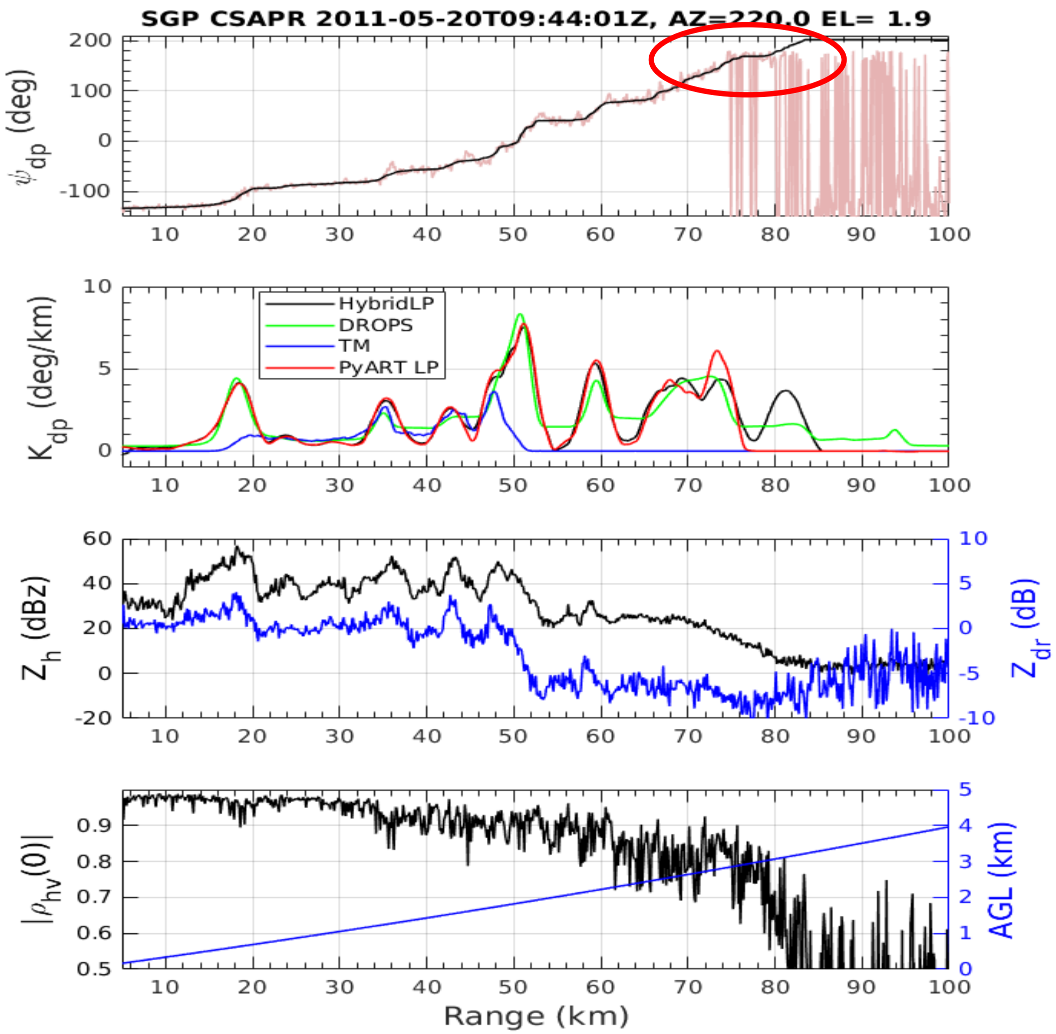
$$\mathbf{M}_{n-(m-1)/2,n} = \begin{pmatrix} C_{S-G}(1) & \cdots & C_{S-G}(m) & 0_{m+1} & 0_{m+2} & \cdots & 0_n \\ 0_1 & C_{S-G}(1) & \cdots & C_{S-G}(m) & 0_{m+2} & \cdots & 0_n \\ & \cdots & & & & \cdots & \\ 0_1 & \cdots & 0_{n-m-1} & C_{S-G}(1) & \cdots & C_{S-G}(m) & 0_n \\ 0_1 & \cdots & 0_{n-m-1} & 0_{n-m} & C_{S-G}(1) & \cdots & C_{S-G}(m) \end{pmatrix}$$

$$C_{S-G}(i) = \frac{6(2i - m - 1)}{m(m+1)(m-1)}, \quad i = 1, 2, \ldots, m$$

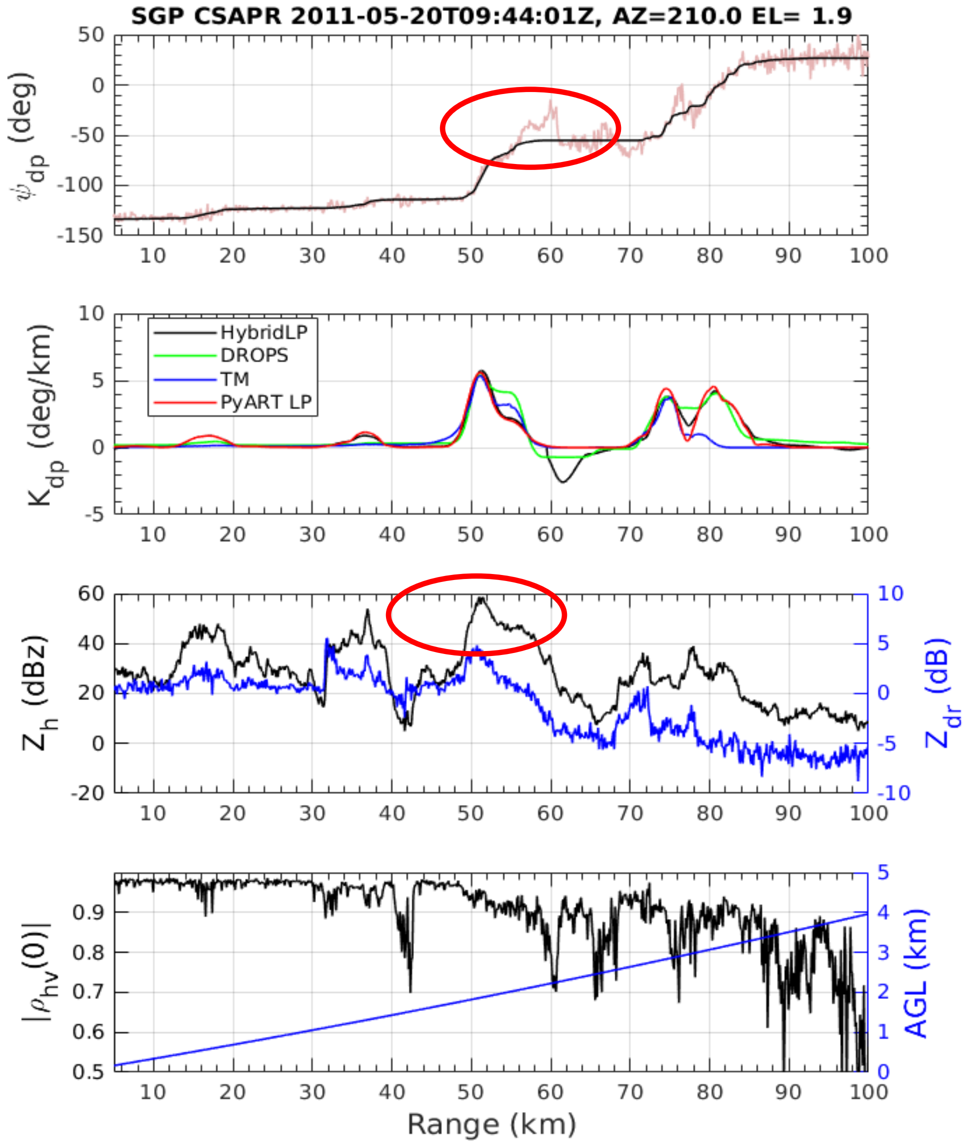
See Giangrande et. al. (2013)

Radar Data Processing: Specific Differential Phase (K_{dp})

Relative performance of KDP retrieval under different precipitation condition. The figures show KDP retrieval for a precipitating system with rain, heavy rain, heavy rain with large drops or hail. Attenuation correction has not been applied to reflectivity and differential reflectivity.



phase wrapped rain



heavy rain/hail with contamination from backscatter phase

Radar Data Processing: Attenuation correction

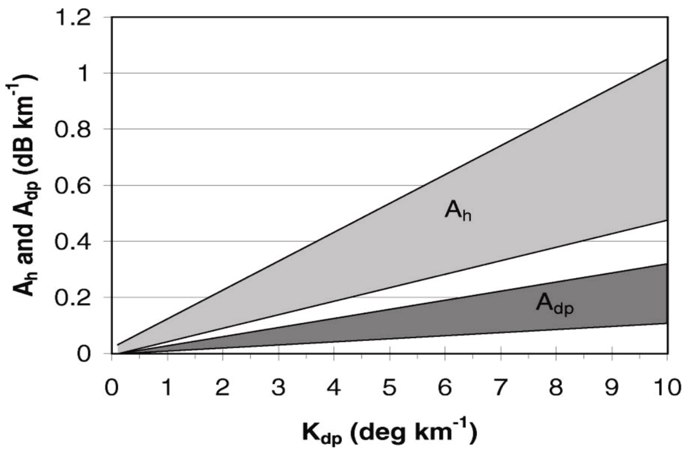
The two-way cumulative attenuation and differential phase (or K_{dp}) are related to each other and this relationship can be used to retrieve specific attenuation.

$$\alpha_{h,v} = 4.343\text{x}10^3 \int \sigma_{ext}^{h,v}(D)N(D)dD$$

$$\alpha_{dp} = \alpha_h - \alpha_v$$

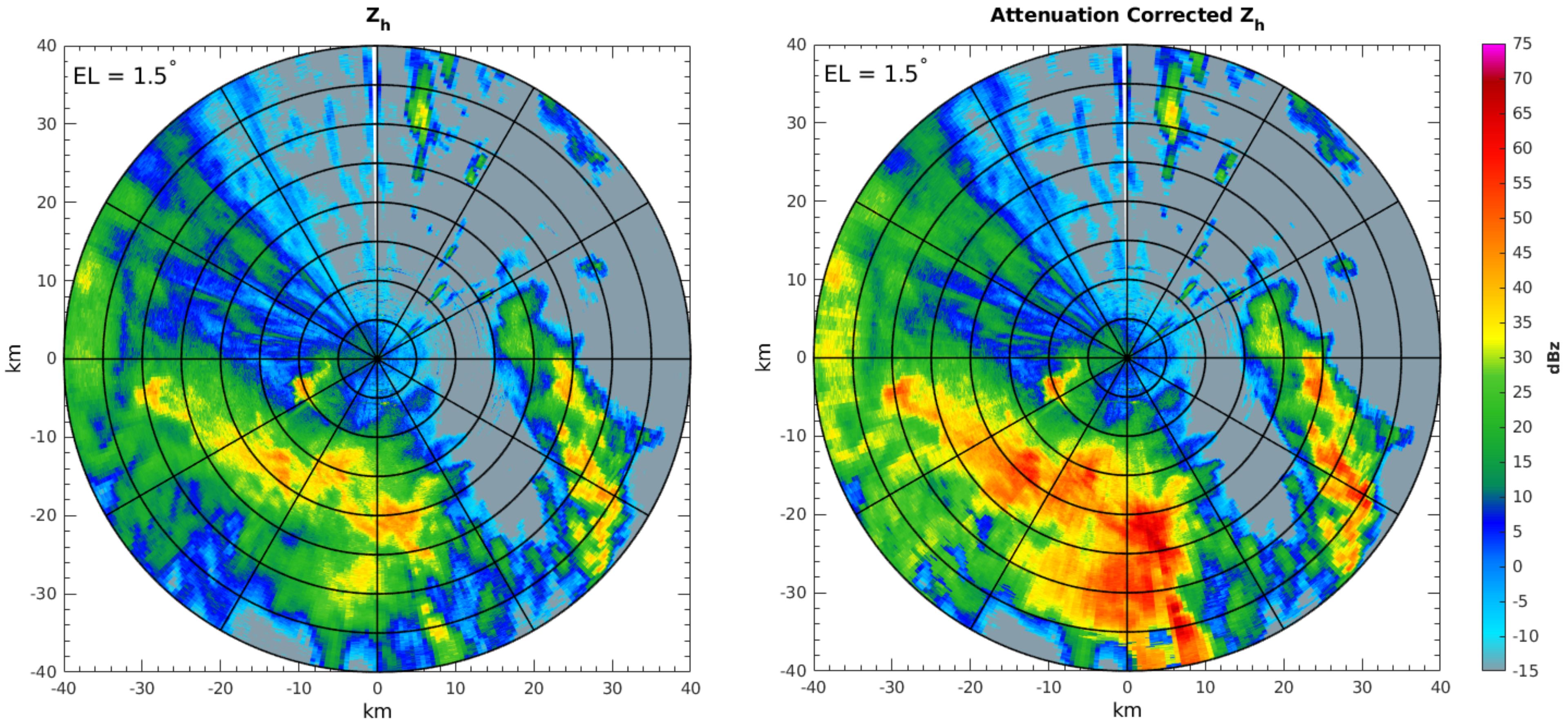
$$A_h = 2\int_{r_0}^{r} \alpha_h(s)ds$$

$$A_{dp} = 2\int_{r_0}^{r} \alpha_{dp}(s)ds.$$



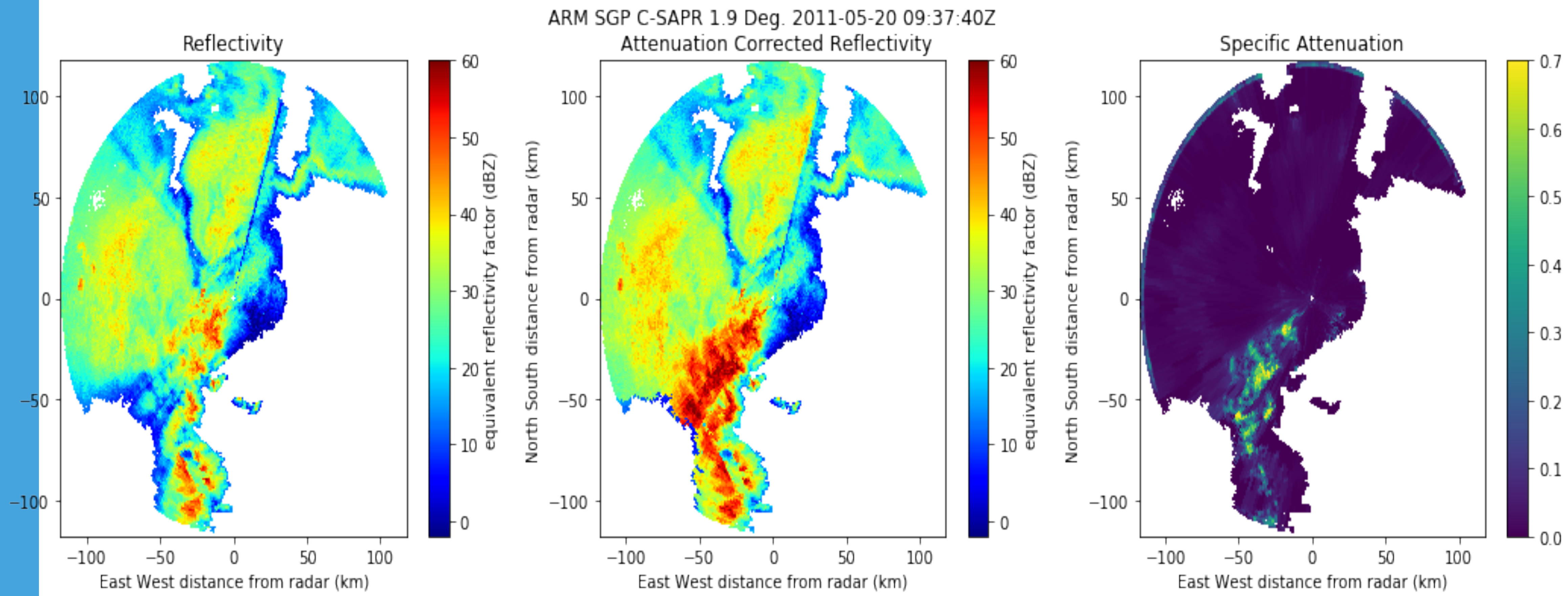
- Modification of the Lim & Chandrasekar (2016) attenuation correction algorithm.
- Utilizes a series of self-consistency relationships for different shape relationships and temperatures based on scattering models.
- Cost optimization over several candidate solutions.
- Can be tailored to individual sites, or used as-is.

X-SAPR I5



Attenuated Reflectivity

Attenuated Corrected Reflectivity



HybridLP gives better spatial detail in specific attenuation than other algorithms.

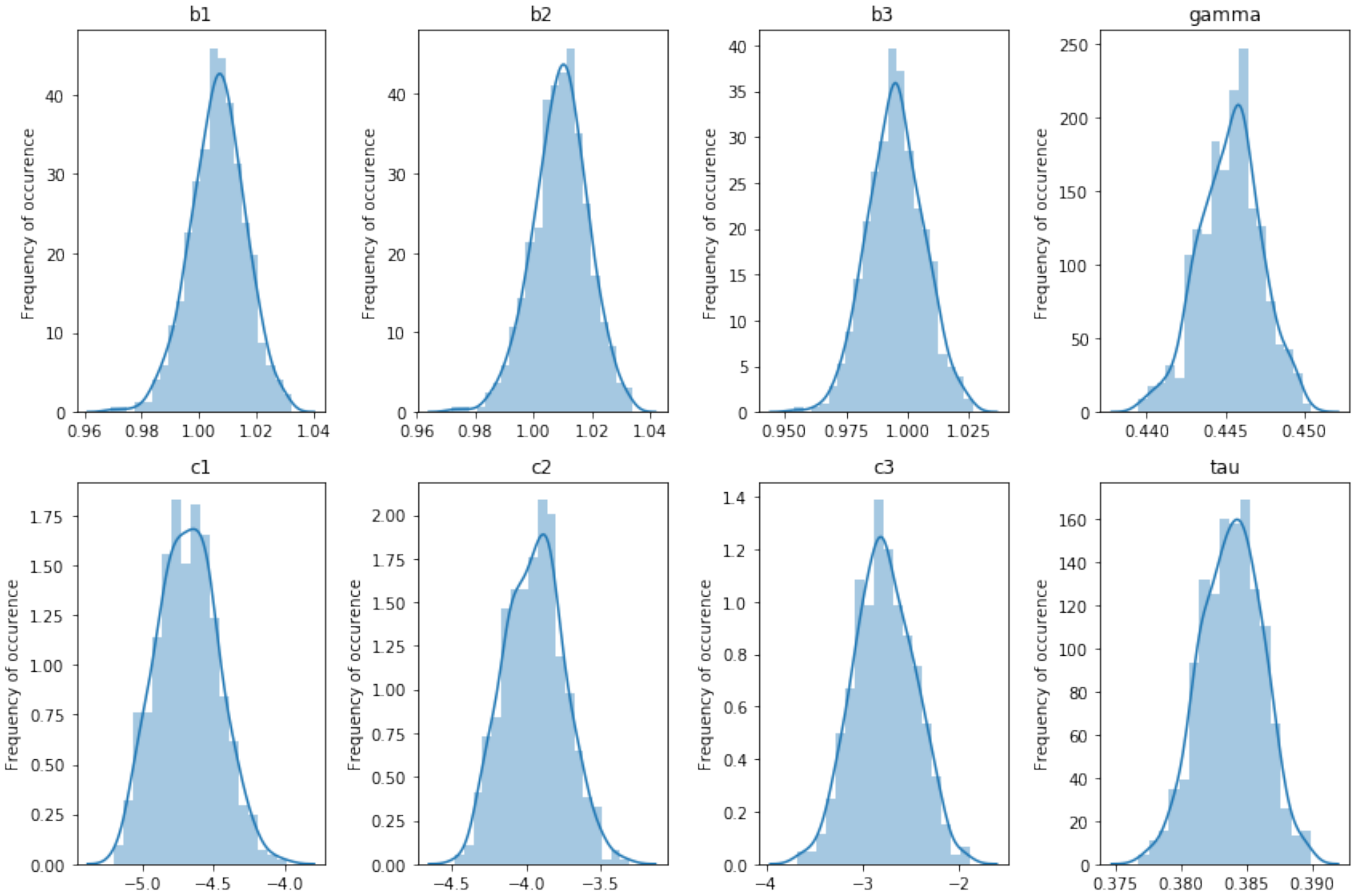
Self-Consistency Model

- The relations used in the attenuation correction algorithm come from scattering disdrometer data at the site and fitting the relevant relationships.
  - This is done at a range of temperatures (0-30 C)
  - And a range of drop shape models (Beard-Chuang, Thurai-Bringi, Andsager-Beard-Chuang, Pruppacher-Beard
  - For each relevant frequency.

$$\alpha_h = a_1 Z_h^{b_1} Z_{DR}^{c_1}$$
$$\alpha_v = a_2 Z_v^{b_2} Z_{DR}^{c_2}$$
$$\alpha_{dp} = a_3 Z_h^{b_3} Z_{DR}^{c_3}$$
$$K_{dp} = a_4 \frac{\alpha_h^{b_4+1}}{Z_h^{b_4}}$$
$$\delta_{co} = \frac{a_5 + c_5 Y^{b_4}}{b_5 + Y^{b_4}} \qquad \textbf{where} \qquad Y = \frac{K_{dp}}{\alpha_{dp}}$$
$$K_{dp} = a_6 Z_h^{b_6}$$

Self Consistency Model: Uncertainty Estimation

- We use ”bootstrap” to calculate uncertainties in self consistency coefficients.



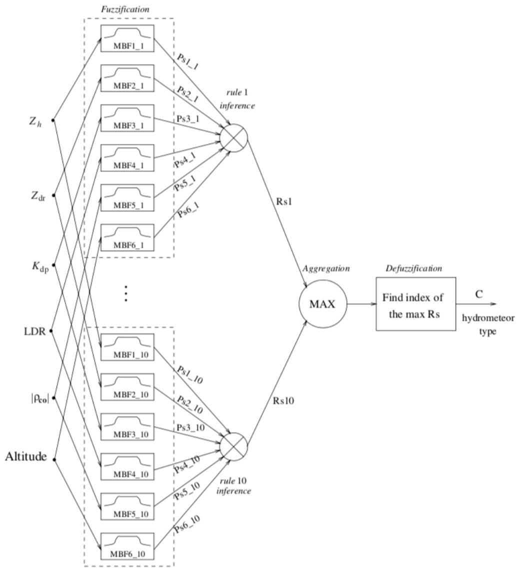
Geophysical Retrievals

Geophysical Retrievals – Hydrometeor Identification

- Hydrometeor identification (HID) is accomplished with the fairly standard neural-fuzzy network approach.
- Algorithm from Dolan et al[2].; implementation from open source CSU radar tools
- 10 class output

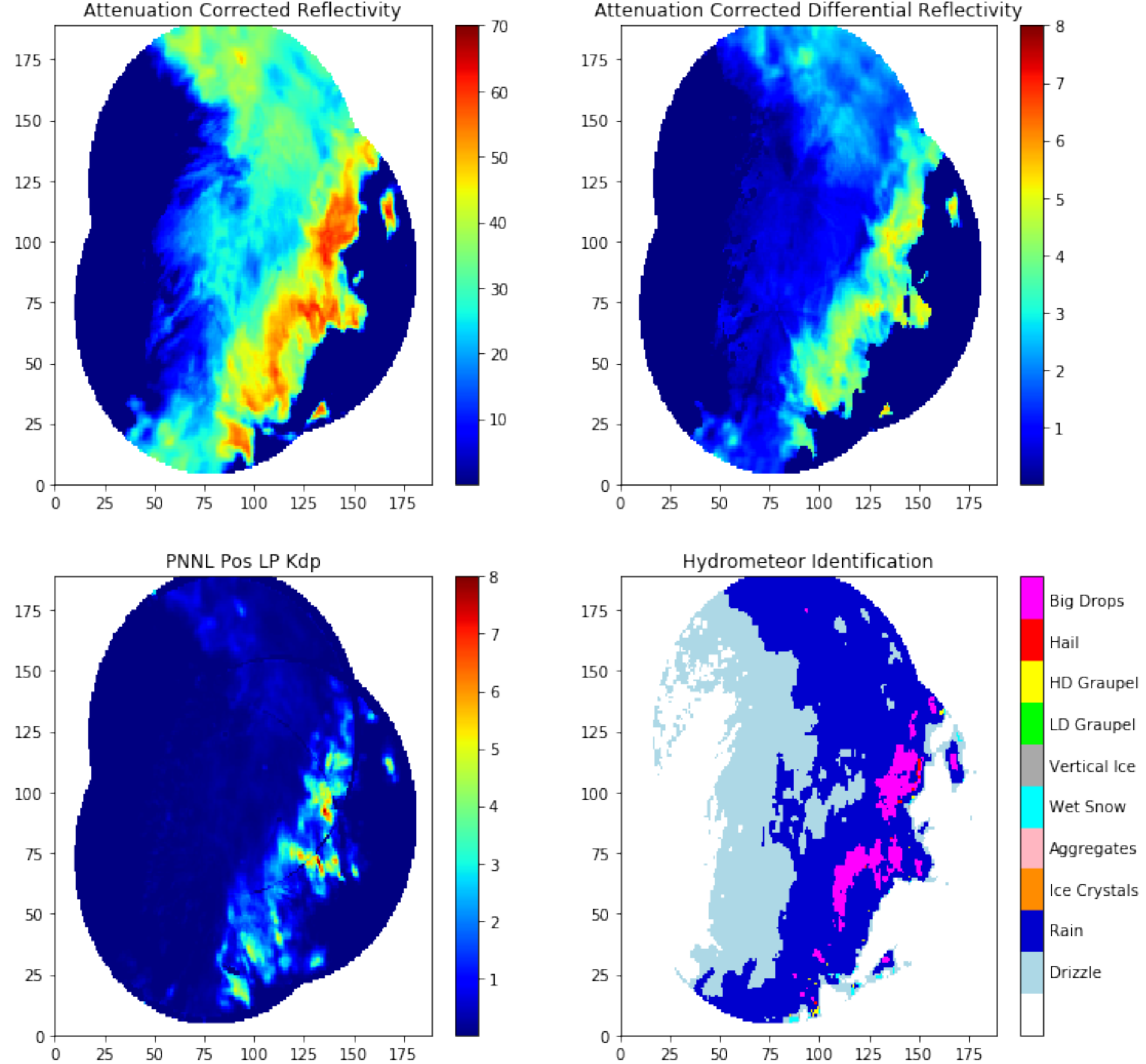
- HID Calculated once from each radar for use in QPE
  - Limit rain rate estimation to liquid
- Calculated again on gridded data at end.
  - Avoids gridding categorical variable

Tempe rature



[2]Dolan, B. and S.A. Rutledge, 2009: A Theory-Based Hydrometeor Identification Algorithm for X-Band Polarimetric Radars. *J. Atmos. Oceanic Technol.*

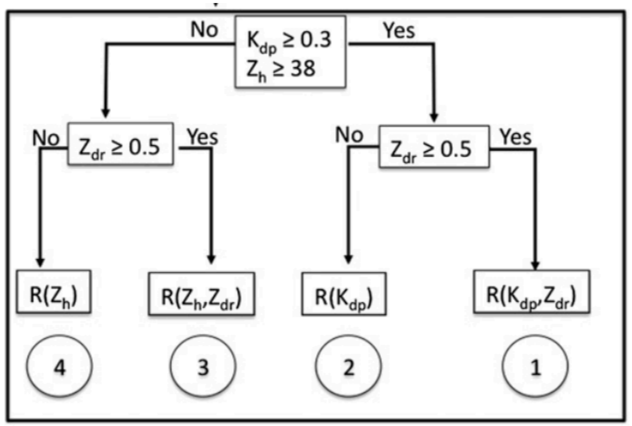
General block diagram for fuzzy logic system from Bringi and Chandrasekar


Attenuation Corrected Reflectivity
Attenuation Corrected Differential Reflectivity
PNNL Pos LP Kdp
Hydrometeor Identification
Big Drops
Hail
HD Graupel
LD Graupel
Vertical Ice
Wet Snow
Aggregates
Ice Crystals
Rain
Drizzle

Geophysical Retrievals - QPE

- Blended rain rate estimator
  - Utilizes HID to reject ice categories.
  - Multiple individual rain rate estimators combined
- Implemented as a decision tree.
  - Utilizes different rain rate relationships in different regimes.
  - Can be setup for multiple frequencies.
- Individual estimators are tuned using disdrometer data from campaign and T-Matrix scattering results.

- In liquid, $\mathbf{D_m}$, $\mathbf{N_w}$ estimated using power law estimator[2]

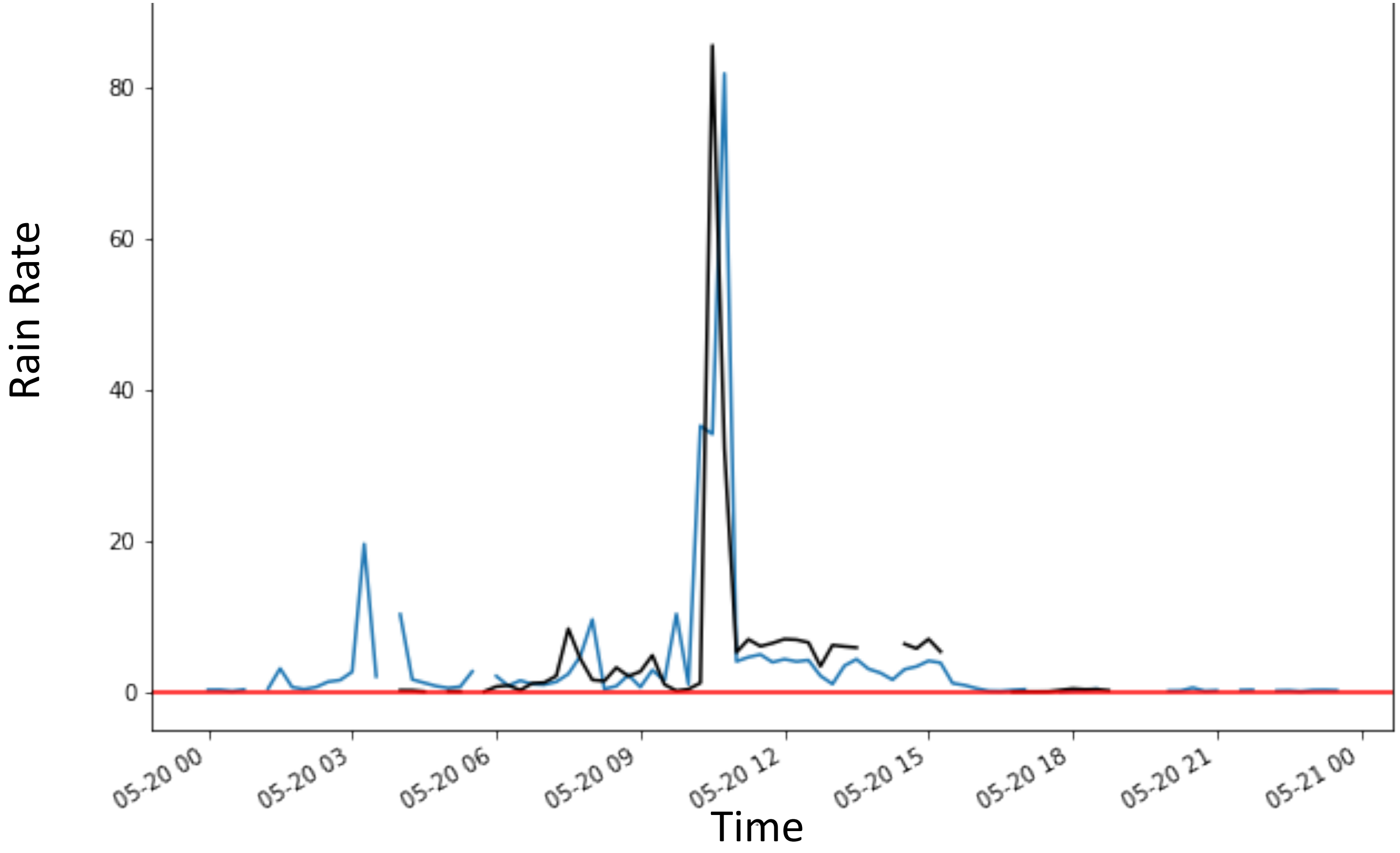


Decision tree for method choice[1]

[1]Cifelli, R., et. al., 2011: A New Dual-Polarization Radar Rainfall Algorithm: Application in Colorado Precipitation Events. *J. Atmos. Oceanic Technol.*
[2]Bringi, V. N., & Chandrasekar, V. (2001). *Polarimetric Doppler weather radar: principles and applications*. Cambridge university press.

QPE

- Validation is run against nearby gauges and disdrometers.
- For MC3E we used weighting bucket rain gauges as well as disdrometers from NASA and ARM and processed them with PyDSD to apply data filtering.

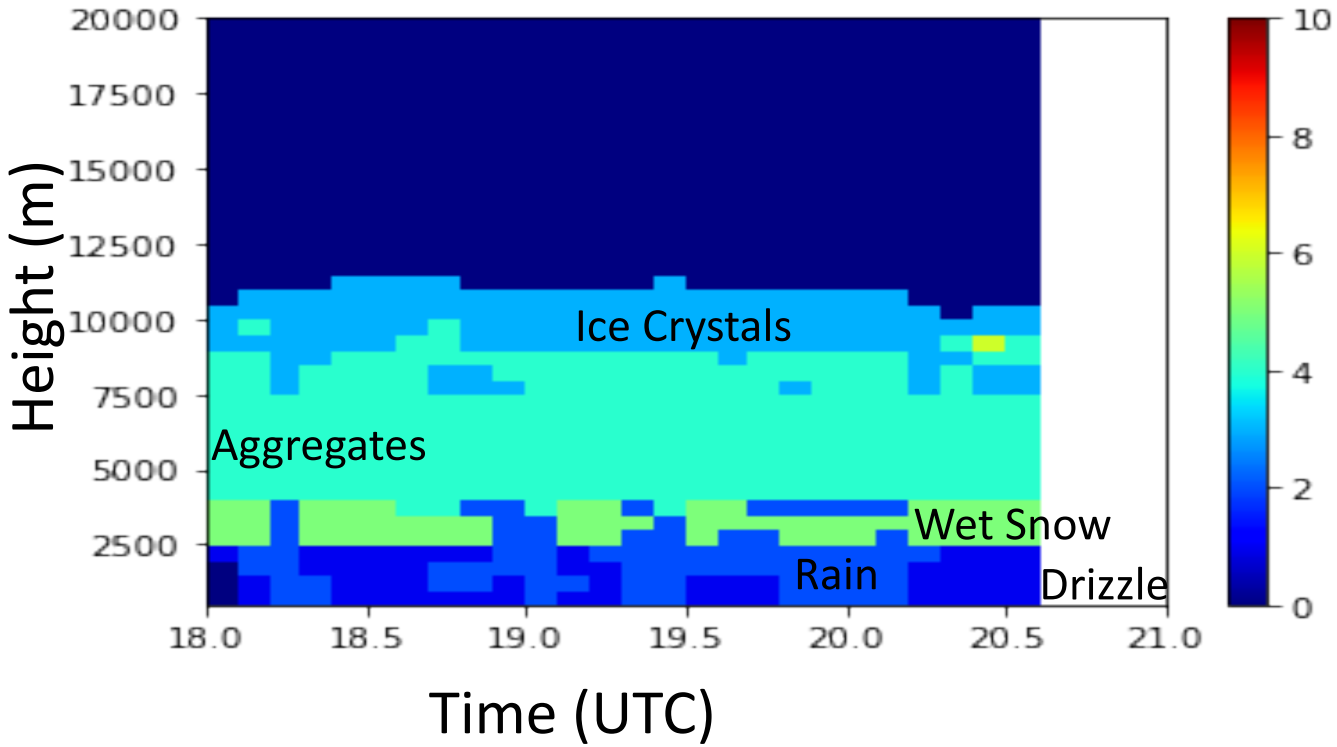


Radar network retrieved rain rate compared to weighing bucket over SGP on 5-20-2011

Gridding

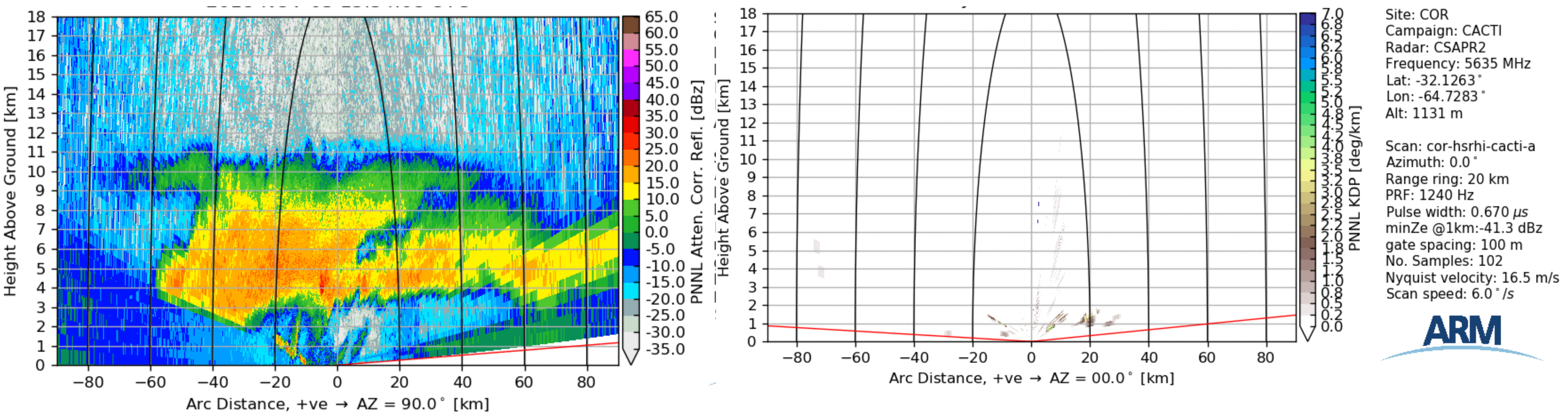
- After parameters are calculated, the data is gridded onto a 3D rectangular grid.
- After gridding, HID is run once more.
- Quantities are then released on both spherical radar coordinate grid, and a cartesian grid matched to several resolutions.

Time-Height Display of HID from Gridded PPIs.



Real-time operation during CACTI

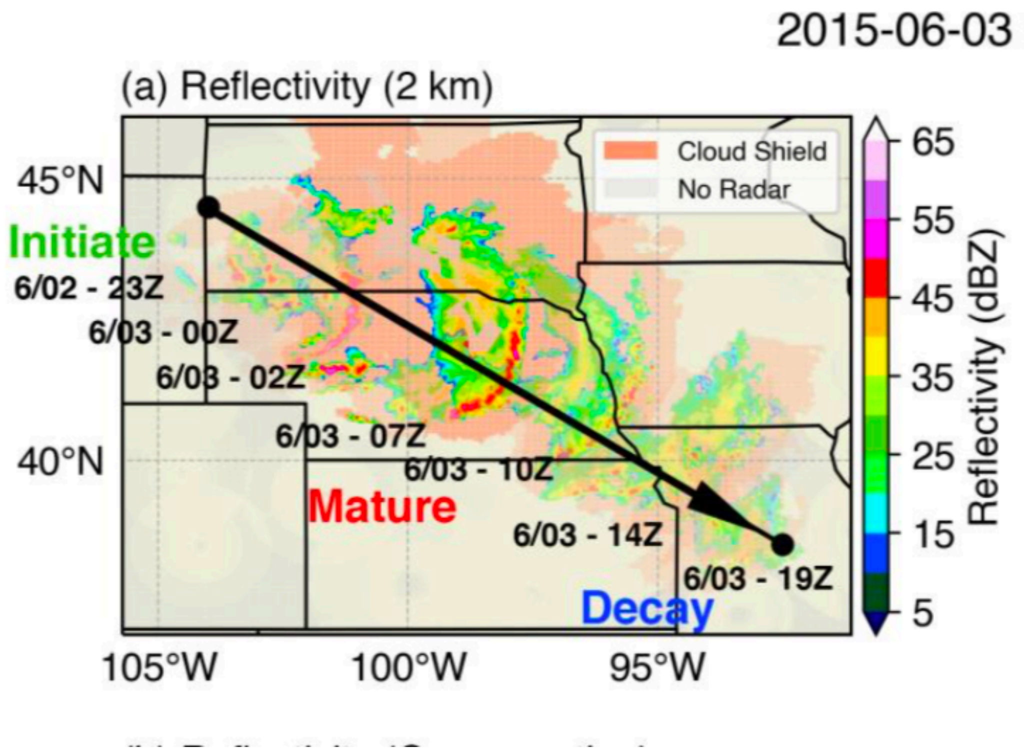
- Taranis was used to drive the CACTI quicklooks during the field campaign.
  - Provided attenuation correction, KDP estimation, and quality flags
- The suite was run on a single computer co-located with the CSAPR radar in real-time.



Future Work

- We would like to extend the results into the melting layer and ice regions.
  - Target arctic and high frequency radars.

- We are currently integrating the processing of Taranis cases into FLEXTRKR, a flexible object tracker for storms developed at PNNL that utilizes multiple instruments and platforms to track storm systems.



Conclusions

- We've introduced a set of products that is robust and works at multiple sites, frequencies, and networks.
- The algorithms are efficient, and run on multiple HPC clusters (STRATUS & NERSC)
- They have been used in model evaluation studies for CMDV.
- Algorithms have been validated against disdrometers, rain gauges, and NEXRAD, as well as being compared to aircraft observations.

- Datasets will be uploaded as PI datasets through ARM archive.
  - Several MC3E cases have been processed and distributed for evaluation.
  - MC3E datasets will be uploaded by end of August 2019
- Several cases from CACTI have been run as well and the rest of the campaign will be processed.
  - Additionally currently running XSAPR summer experiment from SGP.