Integrated Framework for Retrievals in a Networked Radar Environment and Error Characterization of Retrievals

V. Chandrasekar[1], Joseph C. Hardin[1], Haonan Chen[1], Michael P. Jensen[2]

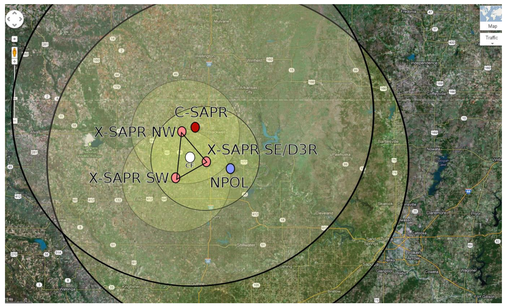
[1]Colorado State University, [2]Brookhaven National Laboratory

ABSTRACT

The Mid-Latitude Continental Convective Clouds Experiment (MC3E) (Jensen, et al. 2011), was a joint DOE Atmospheric Radiation Measurement (ARM) and NASA Global Precipitation Measurements (GPM) field campaign that took place from April - June 2011 in Central Oklahoma centered at the ARM Southern Great Plains site. The experiment was a collaborative effort between the U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Climate Research Facility and the National Aeronautics and Space Administration (NASA) Global Precipitation Measurement (GPM) mission Ground Validation (GV) program. The field campaign involved a large suite of observing infrastructure currently available in the central United States, combined with an extensive sounding array, remote sensing and in situ aircraft observations, NASA GPM ground validation remote sensors, and new ARM instrumentation. This paper presents a comprehensive integrated retrieval methodology to obtain microphysical retrieval such as the drop size distribution for the complete MC3E network, for the ARM multi frequency radar systems.

Mid-Latitude Continental Convective Clouds Experiment

The Mid-latitude Continental Convective Clouds Experiment was a multi-agency field campaign in northern Oklahoma during Summer 2011 with an emphasis on studying convective cloud activity at multiple scales. The campaign included multiple radars with overlapping fields of views as well as several other instruments. Shown in Fig. 1 is the layout of some of the primary instruments. In this coverage field are also several disdrometers that give us measurements of the drop shape distributions at ground level.



• Fig. 1: Radar Layout at MC3E

Radar Measurements: Governing Equations

The matrix $\boldsymbol{F^w}$ in our Bayesian formulation utilizes the relationship between Drop Size Distribution and the radar observed parameters at a given frequency, and encodes the relationship. At a frequency of index $\boldsymbol{w}$ the relationship between drop size distribution and radar observed parameters of interest can be characterized as,

Reflectivity: $Z_{hm}(r) = 10\log_{10}(Z_{hi}) - 2\int_0^r A_h(r)dr$

Differential Reflectivity: $Z_{dr}(r) = 10\log_{10}\left(\frac{Z_{hi}}{Z_{vi}}\right) - 2\int_0^r A_{dr}(r)dr$

The path integrated attenuation is given by,

$$A_h(r) = 8.68\lambda\int_D \mathrm{Im}[f_{hh}(D)]N(D,r)dD$$

$$A_{dr}(r) = 8.68\lambda\int_D \mathrm{Im}[f_{hh}(D) - f_{vv}(D)]N(D,r)dD$$

Attenuation at C band and above can be very significant. At X-band and above, attenuation regularly causes complete extinction of the signals.

Specific Differential Propagation Phase

The third parameter we will utilize is the specific differential propagation phase. This parameter is the most frequency dependent and scales linearly with wavelength.

$$K_{dp}(r) = \frac{180\lambda}{\pi}\int_D \mathrm{Re}[f_{hh}(D) - f_{vv}(D)]N(D,r)dD$$

Drop Size Distributions

The underlying field we are interested in is the drop size distribution. If this distribution is known, the intrinsic radar measurements can be calculated. The drop size distribution can be represented by the Gamma Model

$$N(D) = N_w f(\mu)\left(\frac{D}{D_0}\right)^{\mu}\exp\left(-(3.67+\mu)\frac{D}{D_0}\right)$$

$$f(\mu) = \frac{6}{(3.67)^4}\frac{(3.67+\mu)^{\mu+4}}{\Gamma(\mu+4)}$$

N_w ~ Intercept Parameter of Equivalent Exponential Distribution
D_0 ~ Median Drop Diameter
μ ~ Shape Parameter

Bayesian Framework

This retrieval algorithm builds on the work by Yoshikawa et al. which proposed a single frequency single radar solution. The first stage calculates the optimal DSD's for each individual radar. The second stage combines the multiple remote sensing instruments into an optimal network retrieval. We follow the method by Yoshikawa et al. and set up a Bayesian likelihood framework for each radar individually, given as:

$$P\left(\mathbf{y}^{(m)}\middle|\mathbf{x}^{(m)}\right) = N\left(\mathbf{y}^{(m)}\middle|\boldsymbol{F^w}\left(\mathbf{x}^{(m)}\right), \Sigma_{\mathrm{y}^{(m)}}\right)$$

where the m^{th}ray DSD profile is given as

$$\mathbf{x}^{(m)} = \left[N'_w{}^{(m,1)} \quad \cdots \quad N'_w{}^{(m,N)} \quad D'_0{}^{(m,1)} \quad \cdots \quad D'_0{}^{(m,N)} \quad \mu'\right]^T$$

And the m^{th}measured ray variables are given as

$$\mathbf{y}^{(m)} = \left[Z_{Hm}{}^{(m,1)} \quad \cdots \quad Z_{Hm}{}^{(m,N)} \quad Z_{DRm}{}^{(m,1)} \quad \cdots \quad Z_{DRm}{}^{(m,N)} \quad \Phi_{DPm}{}^{(m,1)} \quad \cdots \quad \Phi_{DPm}{}^{(m,N)}\right]^T$$

while $\boldsymbol{\Sigma}_y$ is the covariance matrix of the radar measurements that is known, and $\boldsymbol{F^w}$ encodes the relationship between the DSD parameters and the radar measured variables at frequency $\boldsymbol{w}$.

We then solve for the posterior distribution as,

$$P(\mathbf{x}|\mathbf{y}) \approx N\left(\mathbf{x}\middle|\tilde{\mathbf{x}}, \tilde{\Sigma}\right) * P_{ni}(\tilde{\mathbf{x}})$$

where P_{ni} represents a non-informative prior for the current ray.

The transformation of the covariance matrix $\boldsymbol{\Sigma}_y$ to the covariance matrix of the intrinsic field $\boldsymbol{\Sigma}_x$ takes the form

- $\tilde{\boldsymbol{\Sigma}}_x = \left(\boldsymbol{F^{w'}}^T\boldsymbol{\Sigma}_y\boldsymbol{F^{w'}}\right)$
- $\boldsymbol{F^{w'}} = \frac{\partial \boldsymbol{F^w}(x)}{\partial x}\Big|_{x=\tilde{x}}$

By maximizing this distribution we get not only the optimal underlying field, we also get the likelihood of any other set of measurements allowing a more comprehensive error analysis on the returned parameters. In addition this framework allows us to incorporate different radar frequencies, as well as entirely new instruments in a relatively straightforward manner.

Network Formulation

Each radar is in a polar coordinate system. We can use the operator $\mathbf{T}$ to transform this to a Cartesian coordinate system giving us:

$$P(\mathbf{x}_C|\mathbf{y}) = N\left(\mathbf{x}_C\middle|\mathbf{x}_C^{(\mathrm{w})}, \Sigma_C^{(\mathrm{w})}\right)$$

where $\mathbf{x}_C^{(\mathrm{w})} = \mathbf{T}\tilde{\mathbf{x}}_R$, and $\Sigma_C^{(\mathrm{w})} = \mathbf{T} * \tilde{\Sigma}_R * \mathbf{T}^T$.

A common choice of $\mathbf{T}$ operator is the nearest neighbor interpolation. While this step introduces errors related to gridding, it is necessary to integrate multiple radars to have them on a common coordinate system.

If we have a single frequency we can combine the distributions from each radar at each point in the Cartesian space by maximizing

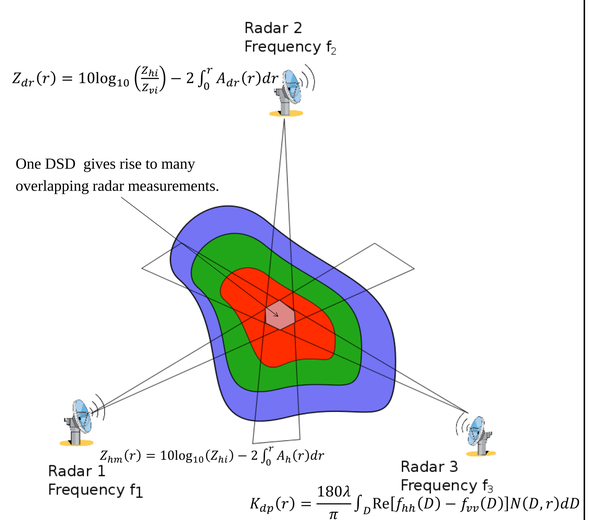
$$p(\boldsymbol{x_C}|\boldsymbol{y}^1, \ldots \boldsymbol{y}^L) \equiv N(\boldsymbol{x_C}|\,\tilde{\boldsymbol{x}}_C, \boldsymbol{\Sigma}_C) = \Pi_{l=1}^{L} p(\boldsymbol{x_C}|\boldsymbol{y}^l)$$

for each of the L radars.

If we have multiple frequencies, we maximize

$$p(\boldsymbol{x_C}|\boldsymbol{y}^1, \ldots \boldsymbol{y}^L) \equiv N(\boldsymbol{x_C}|\,\tilde{\boldsymbol{x}}_C, \boldsymbol{\Sigma}_C)$$

Over the entire set of L radars. We incorporate the different frequencies both by the choice of the matrix $\boldsymbol{F^w}$, as well as in the covariance matrices in this step.



Error Characterization

A critical and important step for error characterization is to have a formulation where all the errors can be accounted for. The sources of error can generally be divided into the following three categories:

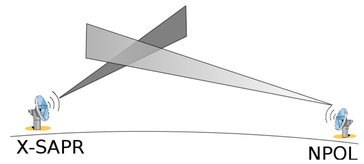
Instrument Errors	Observational Errors	Retrieval Errors
• Inaccuracies of Instrumental Precision (random error) • System Biases	• Attenuation • Beam Mismatch • Time Mismatch	• Prior Assumption • Transition Matrix • Network Integration • Physical Assumption on Hydrometeors

Hardware Errors

- Calibration errors represent a significant source of systematic bias in the retrieval process.
- Ideal calibration error: 1dBZ (Zh), 0.2 dB (Zdr)
- In actuality these can reach 3-5dBZ (Zh) and 0.7dB (Zdr)
- This level of error can create 40%+ error in the rainfall retrieval.
- This is mitigated by
  - the choice of initial solution
  - Incorporation of Phase Based Measurements
  - PreProcessing

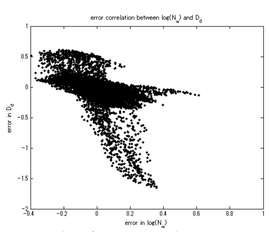
Observation Errors

- Beam Mismatch
  - We are not measuring the same volume cells, so the measurements between two radar volumes is not 1-1.
- Time Mismatch
  - We are not guaranteed to see range cells at the exact same time between different radars.
- Attenuation



Algorithm Errors

Drop size distribution retrieval algorithm, and radar parameter estimation error, etc.



Example of error correlation structure.

Retrieval Error

Retrieval error is a culmination of all the errors in the system. Quantification of the errors for the retrievals is a goal of this research.

Acknowledgement

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