Optimal estimation retrievals of precipitation with active and passive measurements (using ARTS as a forward model)

S. Joseph Munchak
NASA GSFC

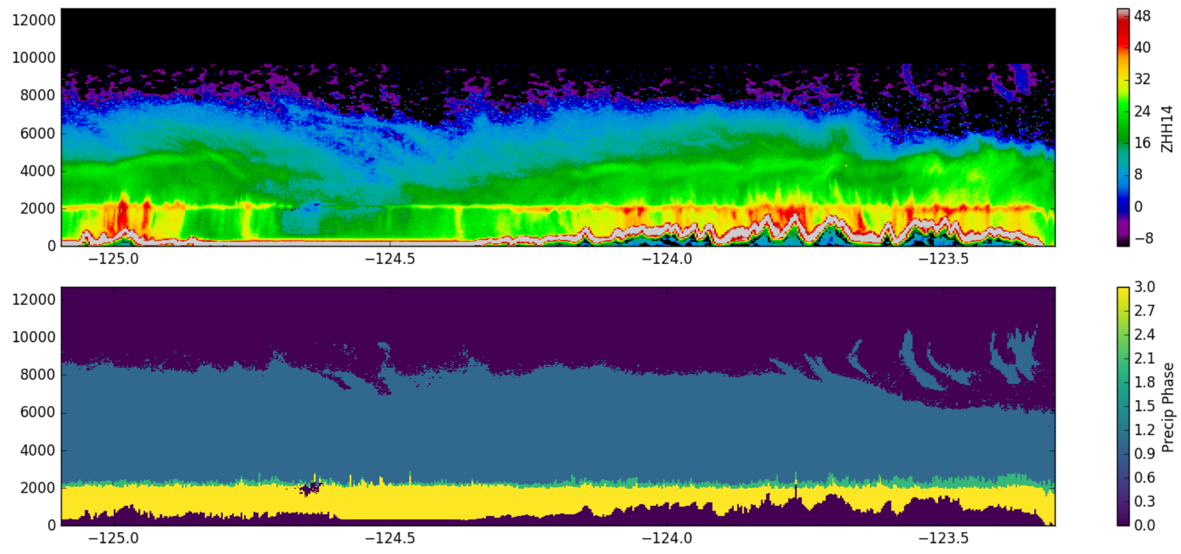
With contributions from: Ian S. Adams, Kwo-sen Kuo, Mircea Grecu, and Bill Olson

Outline

- Basic considerations, emerging ~~best~~ common practices for multi-frequency radar + radiometer precipitation retrievals
- Defining the retrieval parameter set
- Dimensionality and Solver options
- Examples
- ARTS Wish List

Basic considerations

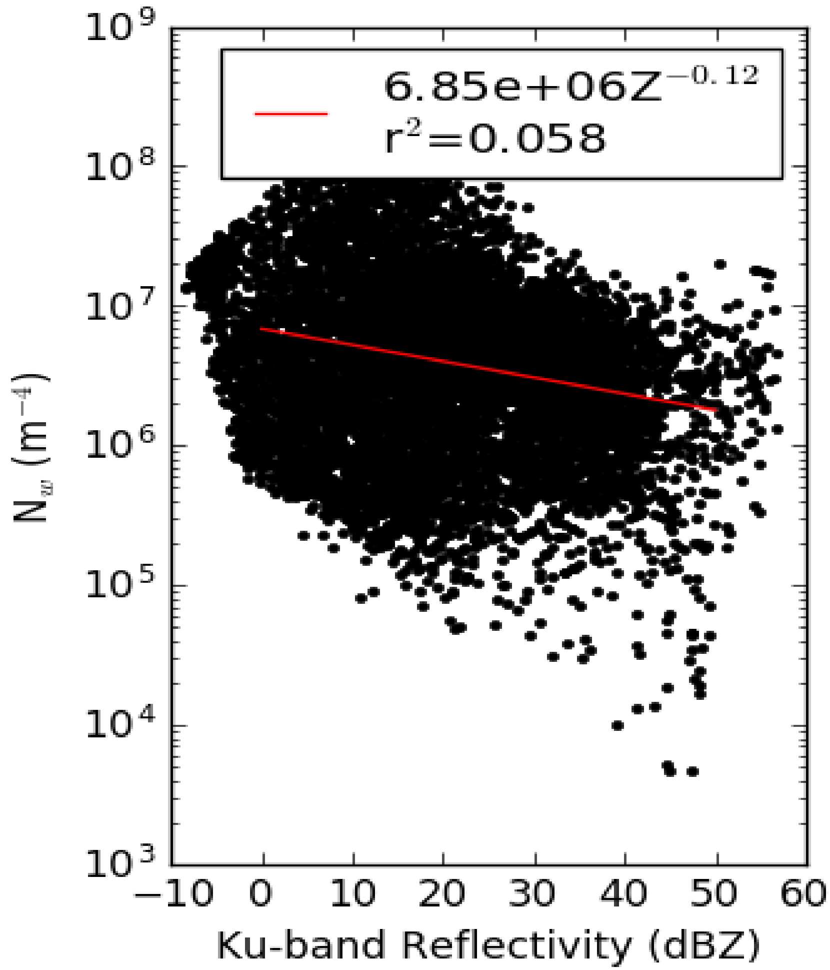
- Start with radar:
  - Map hydrometeor field (include phase)



  - Use Hitchfeld-Bordan to correct attenuation & convert Z to PSD parameters (prefer wavelength with minimal attenuation, MS)
- First-guess atmospheric (T, Qv, Qc) properties
  - Soundings, reanalysis, etc
- Surface Emissivity

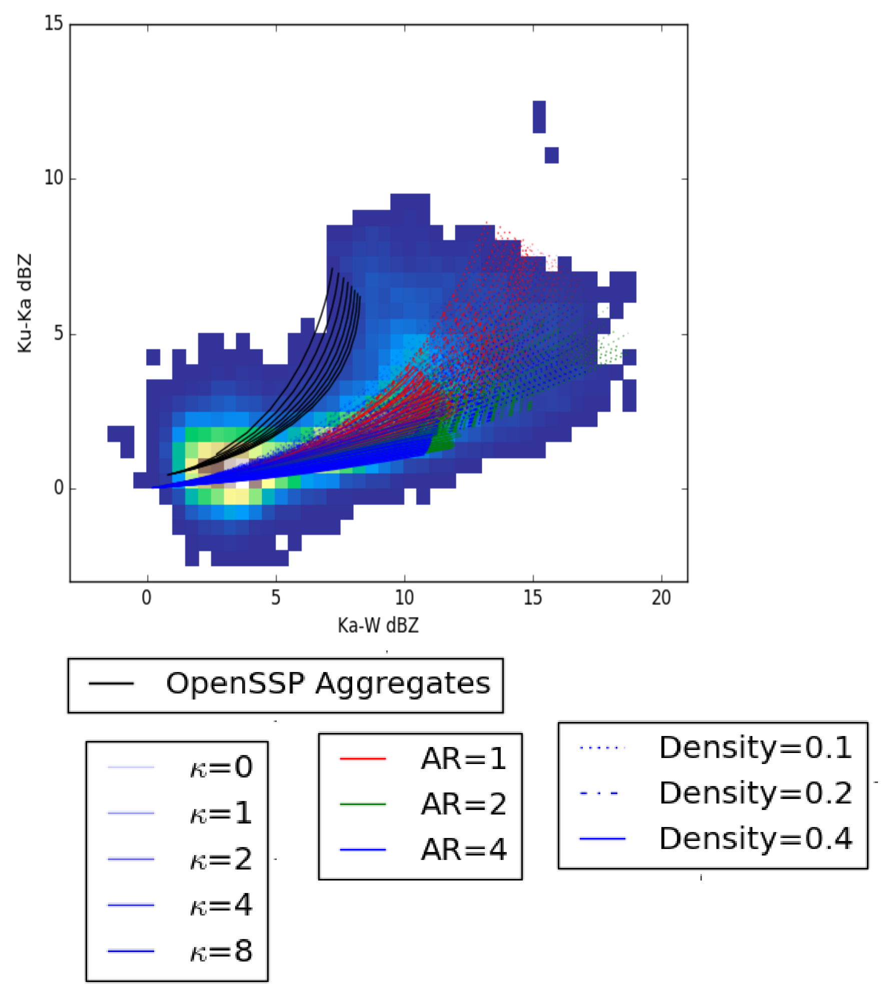
Hydrometeor "Retrievables": Liquid Phase

- PSD requires 2-3 parameters in rain
  - Concentration/Scaling parameter (N_0/N_w/W)
  - Characteristic Size (Λ/D_0/D_m/r_e)
  - Spread (μ/σ_m) – often assumed constant or f(D_m)
- Convenient to choose 1 parameter to be retrieved at high resolution (approaching radar res) and others on a lower-resolution grid. Low-res parameter(s) should be:
  - Not correlated with Z (N_w good choice)
  - Grid resolution should resolve decorrelation length of low-res parameter(s)



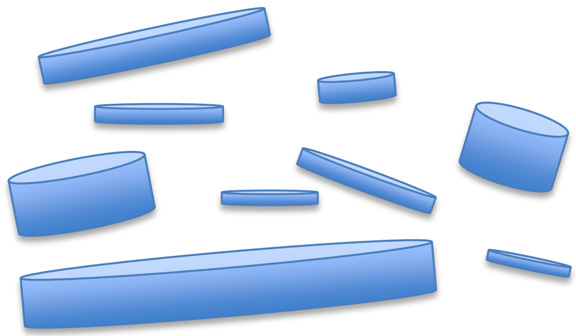
Hydrometeor "Retrievables": Ice Phase

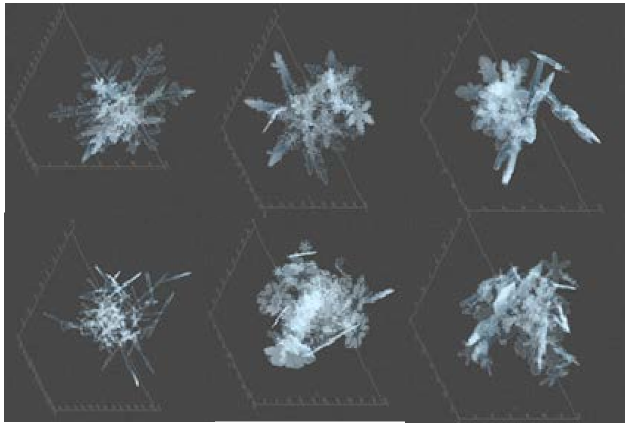
- Particle shape is important (aspect ratio, orientation distribution)
- Degree of riming (need scattering models)
- $N_w = f(T)$ (Field et al., 2005)
- Multiple species co-exist. Need compact representation.
- Heuristic:
  Define **Aggregate Fraction = $W_{agg}/(W_{agg}+W_{pristine})$** and add to $[N_w, \mu]$ in retrieval parameter set.



Scattering models

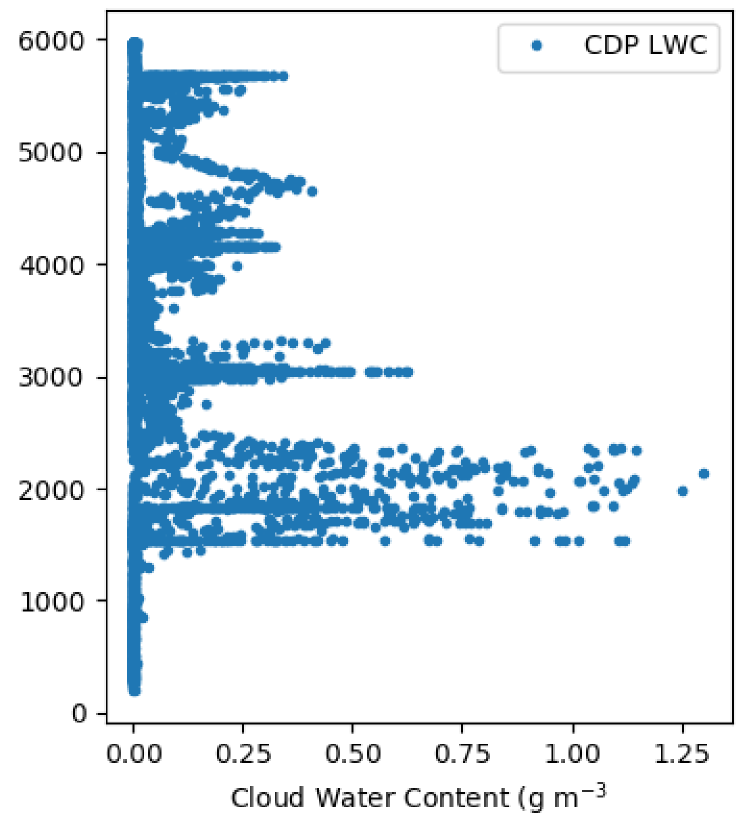
- Pristine: T-Matrix Cylinders
  - Shown to be a good approximation for plate-like particles by Adams and Bettenhausen (2012)
  - Convenient for testing sensitivity of observations to many geometric parameters
  - Using 4:1 aspect ratio, 0.4 g/cm^3 density, and κ=40 for convenience and reasonable simulation of GPM observations (see poster)
- Aggregates: OpenSSP database (Kuo et al., 2016)
  - Only randomly-oriented scattering properties currently available
  - Multiple size-density relationships can be constructed





Environment “Retrievables”

- Temperature, water vapor perturbations
  – How to represent? Coarse grid, EOFs
- Cloud Liquid Water
  – Often occurs in thin layers – poses difficulties for “traditional” OE (more later)
- Surface emissivity (wind)



Optimal Estimation

- Minimize a cost function:

$$J(X) = \left[(\mathbf{X} - \mathbf{X_a})^T \times \mathbf{S_a^{-1}} \times (\mathbf{X} - \mathbf{X_a}) \right] + \left[(\mathbf{Y} - f(\mathbf{X}))^T \times \mathbf{S_y^{-1}} \times (\mathbf{Y} - f(\mathbf{X})) \right]$$

- What is in x? What is in y?

X = [Grids of:
PSD parameters:
$\mathbf{D_m}/N_w$, $\boldsymbol{\mu}/\sigma_m$
Ice species/riming
T/Qv/Cloud Liquid
Surface emissivity]

Y = [Radar DFR (or non-primary freq Z), LDR, ZDR profiles
Radar PIA or dPIA
Radiometer Tbs]

- What is the forward model?
  - 1D Radar Pencil-beam (MCRadarSS)
  - 1D polarized RTM (RT4)
  - 3D multiple scattering radar (MCRadar)
  - 3D polarized RTM (MCGeneral)

Dimensionality: 1D vs. 3D Retrieval

1D Retrievals

- Observations (active and passive) should be along same line-of-sight & similar beamwidth
- Implicit assumptions: plane-parallel atmosphere and uniform beam-filling
- Can use nadir-only (curtain) observations
- Can use 1D RTM
- Computationally cheap

3D Retrievals

- Can use observations from many positions, lines-of-sight, and beam widths, as long as beam is contained within cloud box
- Require volume radar scan from at least 1 frequency
- Require 3D RTM
- Computationally expensive – need to optimize scene size

Solving Method

"Traditional" or Gauss-Newton OE (Rodgers 2000)

- Requires analytic or finite-difference Jacobian -> precludes use of MC RTMs

$\Delta\mathbf{X} = (\mathbf{K}^T\mathbf{S}_y^{-1}\mathbf{K}+\mathbf{S}_a^{-1})^{-1}(\mathbf{S}_a^{-1}(\mathbf{X}_a-\mathbf{X})+\mathbf{K}^T\mathbf{S}_y^{-1}(\mathbf{y}-\mathbf{F}))$

- Assumes Gaussian behavior of **X**
- Computational limiters:
  - Jacobian calculation (nvar x nobs)
  - Multiplication and inversion of nvar x nvar matrix: $O(N^3)$
  - Iteration of above

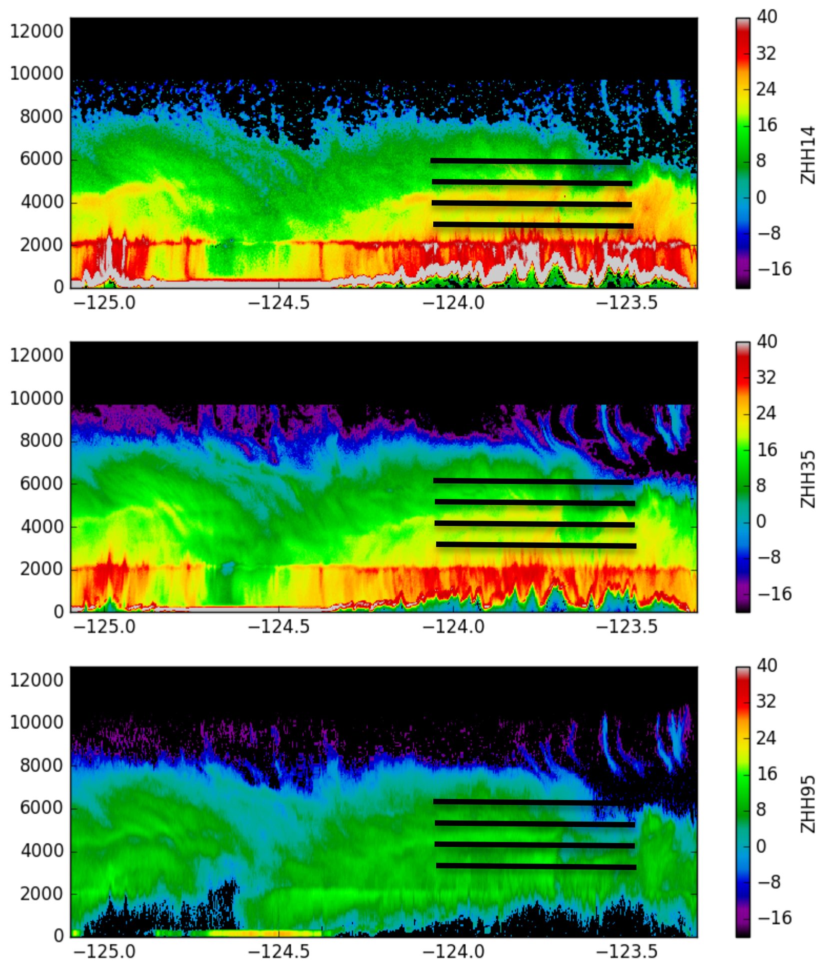
Ensemble Filter (Evensen 1994, 2003)

- Use sample covariance between **X** and **Y**=f(**X**) to guide adjustments:

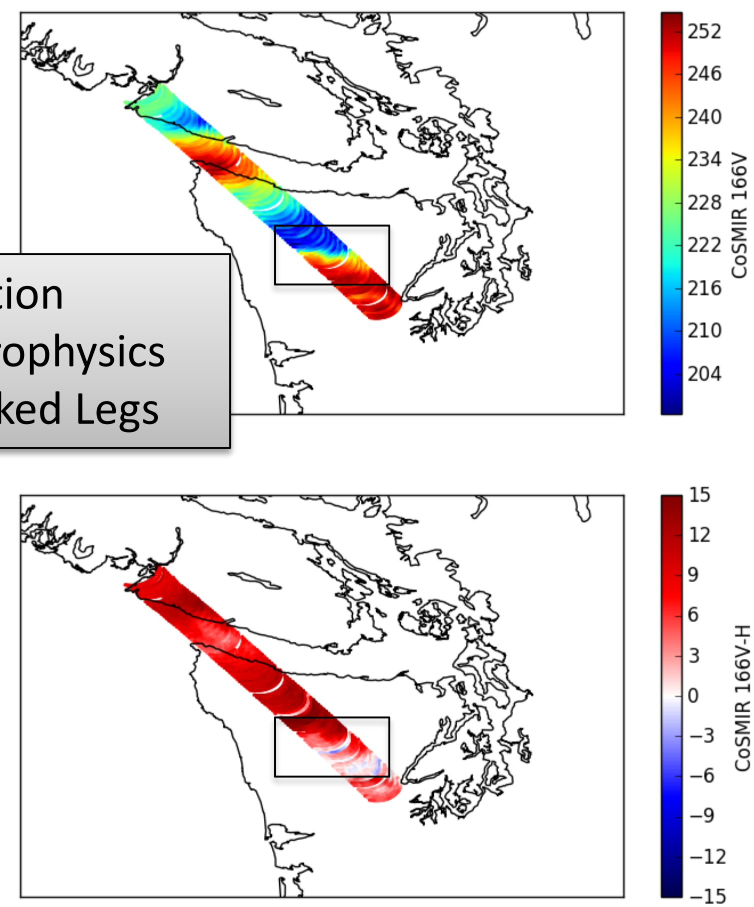
$$\overline{\mathbf{X}} = \overline{\mathbf{X}} + \mathbf{Cov}(\mathbf{X},\mathbf{Y})\left(\mathbf{Cov}(\mathbf{Y},\mathbf{Y})+\mathbf{R}\right)^{-1}(\mathbf{Y}_{\mathbf{obs}} - \overline{\mathbf{Y}})$$

- Can use MC RTMs at any precision
- Allows for non-Gaussian behavior e.g., multi-modal solution clusters
- Computational limiters:
  - Calculation of Cov(X,Y), Cov(Y,Y), and inverse
  - MC precision x N_{ens}

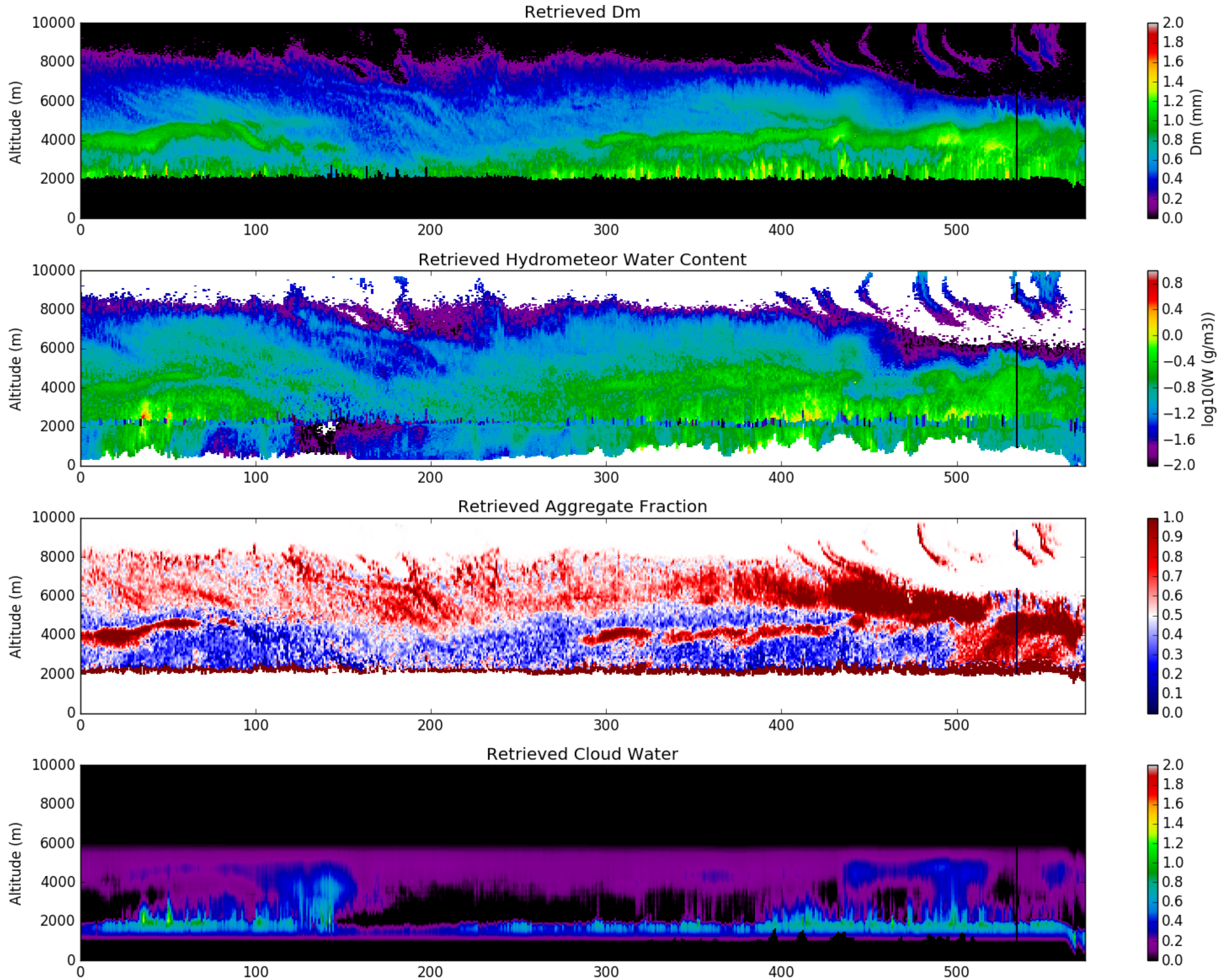
Case Study: OLYMPEX
3 December 2015



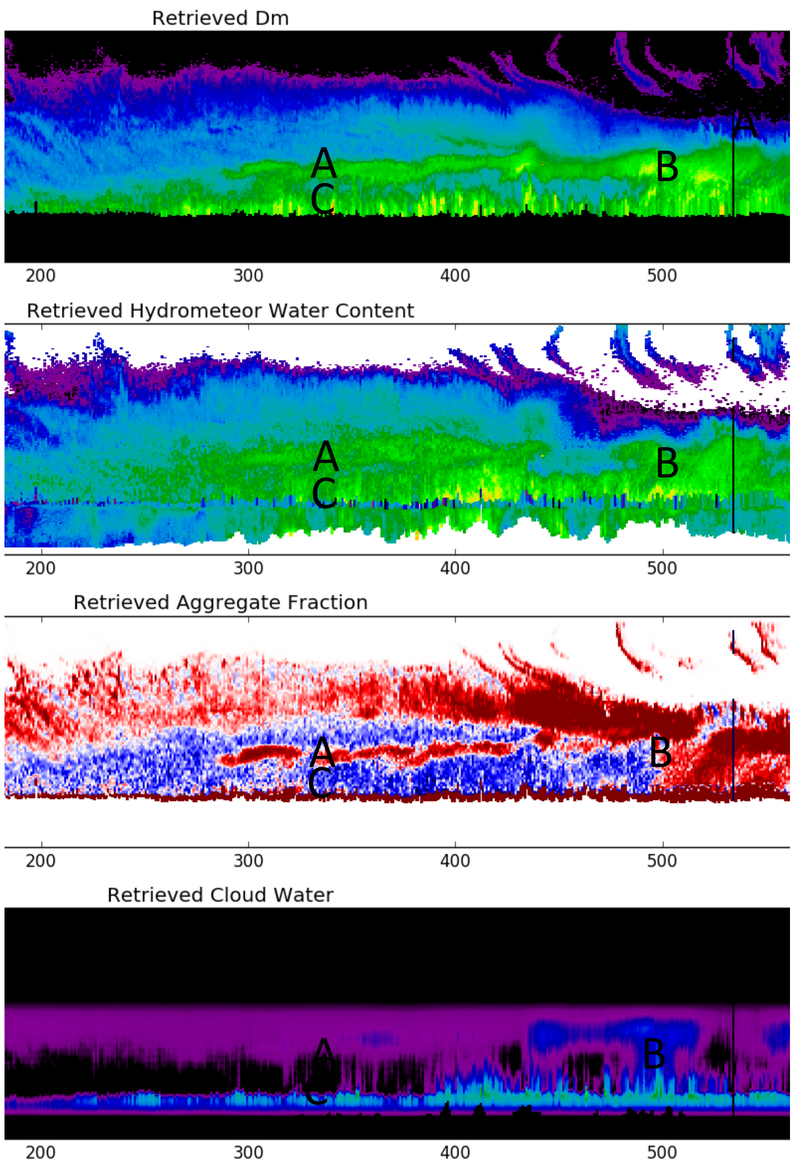
Citation
Microphysics
Stacked Legs



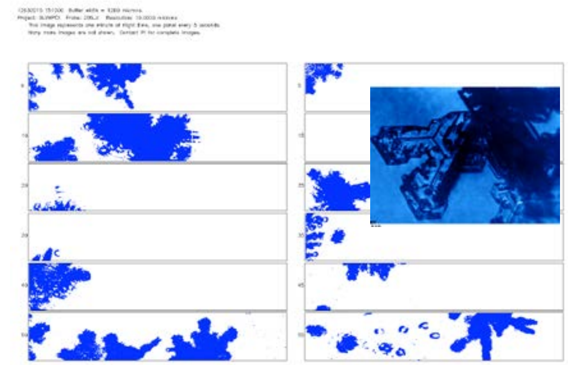
1D, Radar-only retrieval results



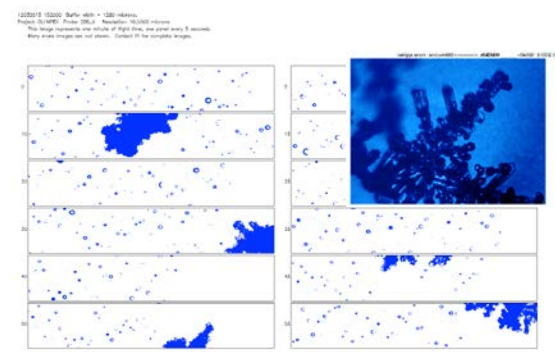
1D, Radar-only retrieval results



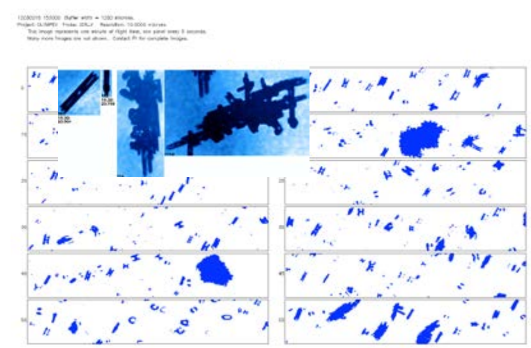
A



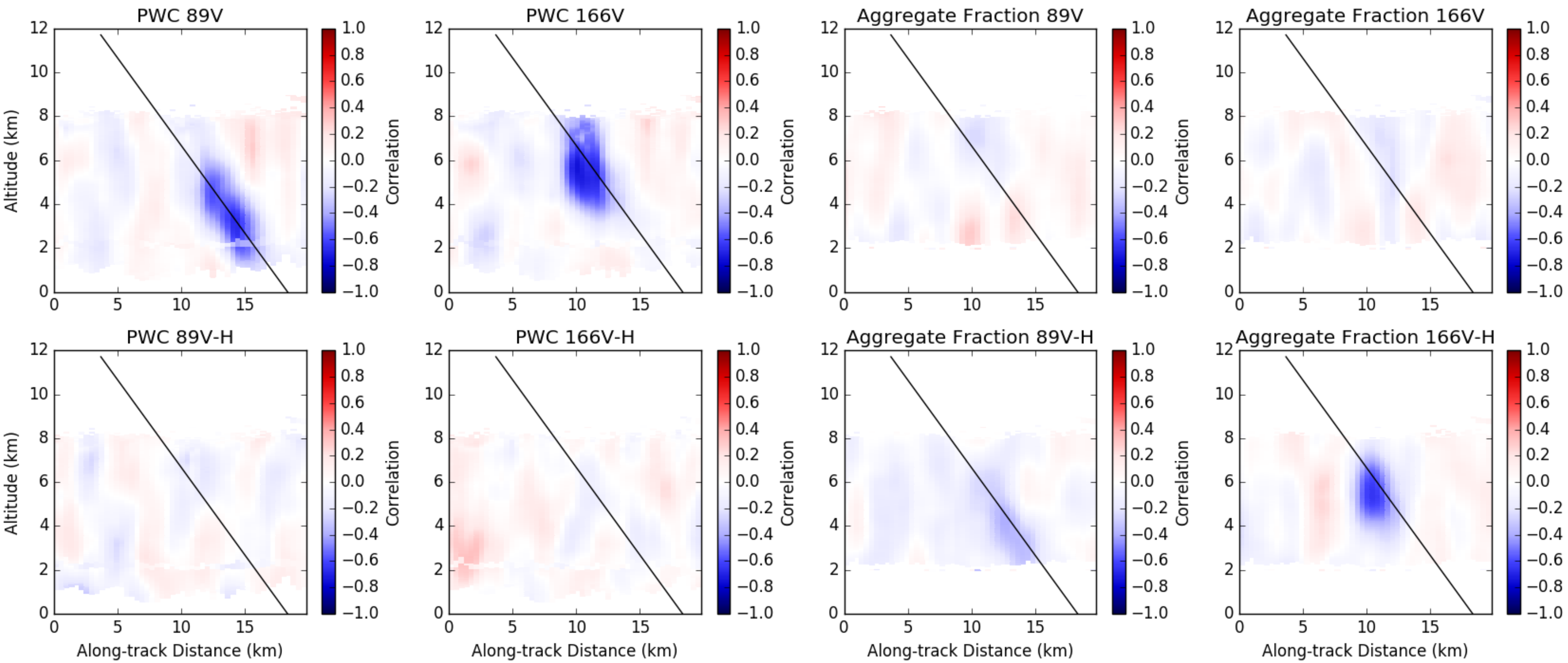
B



C



3D-ENS Covariances



My ARTS wish list:

- Particle Scattering
  - Efficient way to handle melting particles
  - More ice scattering models (oriented pristine habits, rimed pristine & aggregates)
- RT4 features:
  - (Fast) Analytic Jacobians
  - Interpolation of 1D profiles from 3D atmosphere along LOS
- MCGeneral:
  - Desired uncertainty in Q (not just I)
- OE & Ensemble solvers for radar-based precipitation retrievals:
  - Hitchfeld-Bordan uses ARTS scattering and absorption models, but run in Julia – could be implemented in ARTS (need to reconcile native radar grid w/ ARTS)
  - Currently using Python/Julia & calling ARTS as forward model
  - Direct implementation in ARTS would reduce overhead, but need to define inputs/variables in flexible way – is this possible for all applications?