Toward an Open-Source, Python-Powered, Multi-Doppler Radar Analysis Suite

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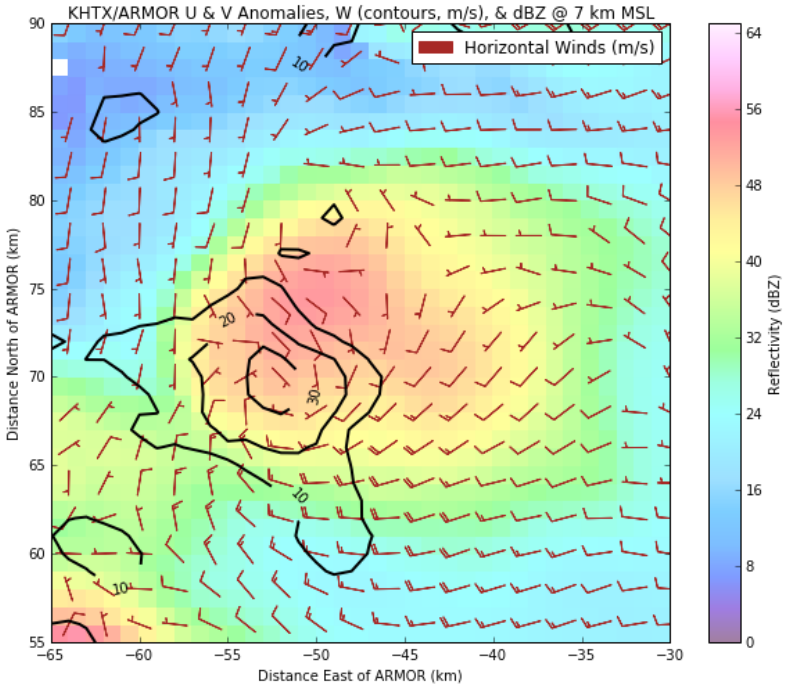
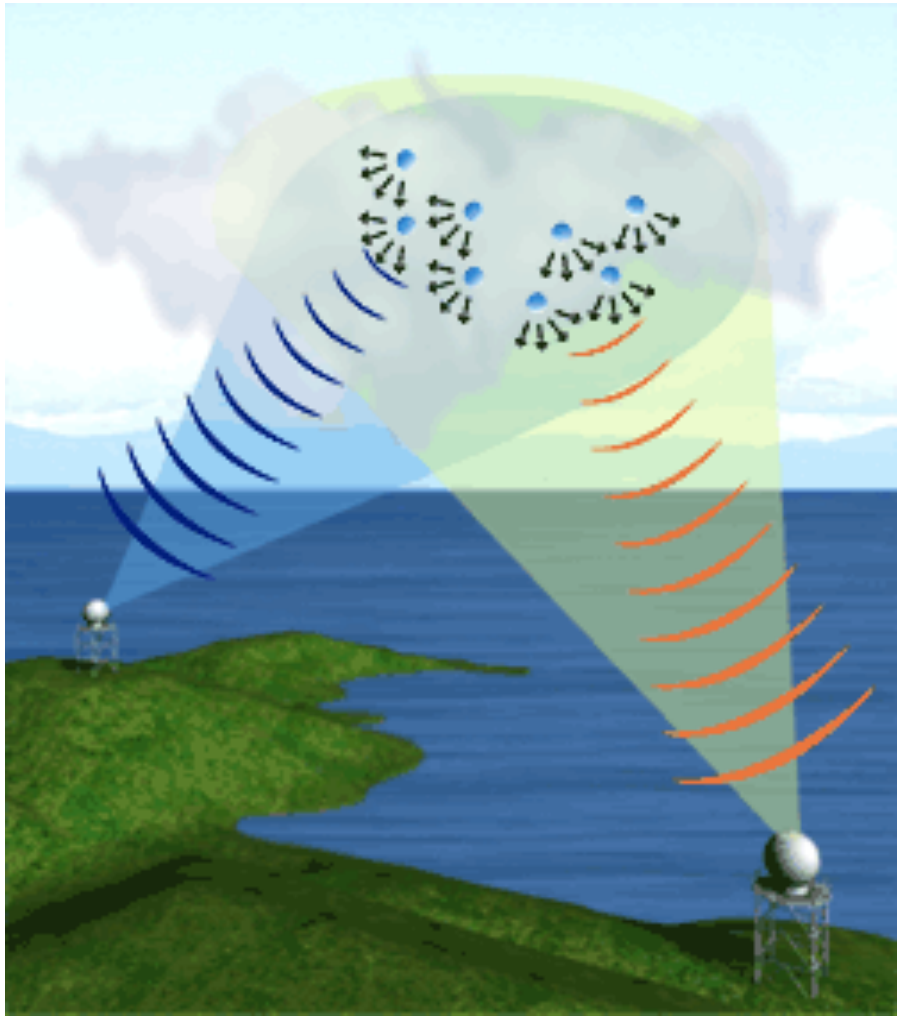


Multi-Doppler Radar Concept

- Measure radial Doppler velocities with more than one radar, spaced appropriately (typically ~10s km)
- Coordinated spatial and temporal scanning
- Subtract hydrometeor fallspeed, remap to obtain horizontal U and V wind components
- Integrate mass-continuity equation to recover vertical velocity W



NICT Okinawa

The Context

- NASA Weather program (under Tsengdar Lee) seeks to improve NASA severe weather observational and modeling capabilities - NASA STORM project, FY 2016
- Independent but parallel effort to VORTEX-Southeast
- Three Main Goals
    1. Expansion of North Alabama Lightning Mapping Array (NALMA)
    2. Advanced ensemble model severe weather forecasting
    3. Expand open-source tools for severe weather analysis

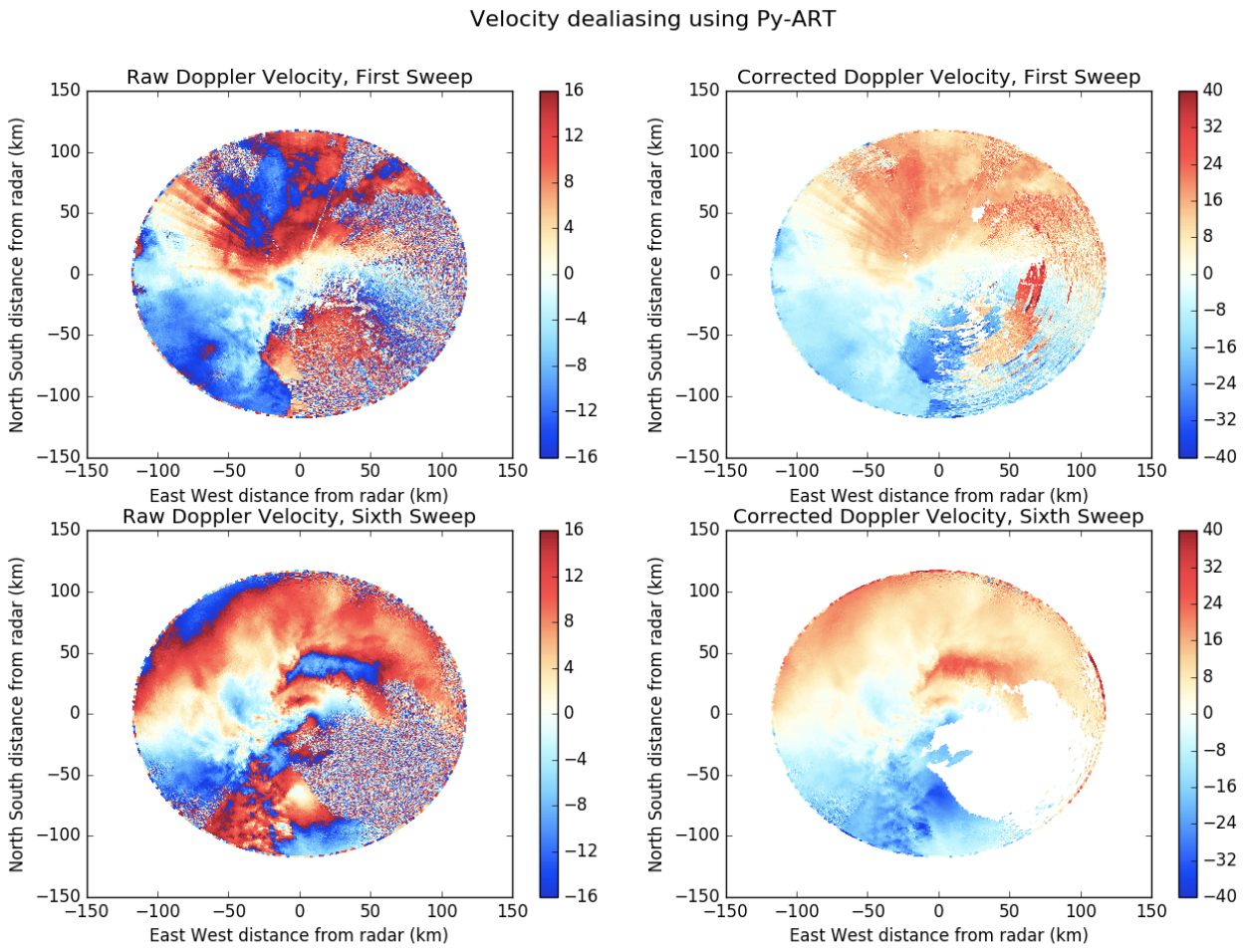
The Dream

Wouldn’t it be nice to have an open-source, Python-based toolkit for multi-Doppler wind syntheses?

- Three-dimensional winds from arbitrary radar networks
- Enable community-supported severe weather analyses
- Significantly lower barrier to entry for new users

Realizing the Dream, Part I - Python ARM Radar Toolkit (Py-ART)

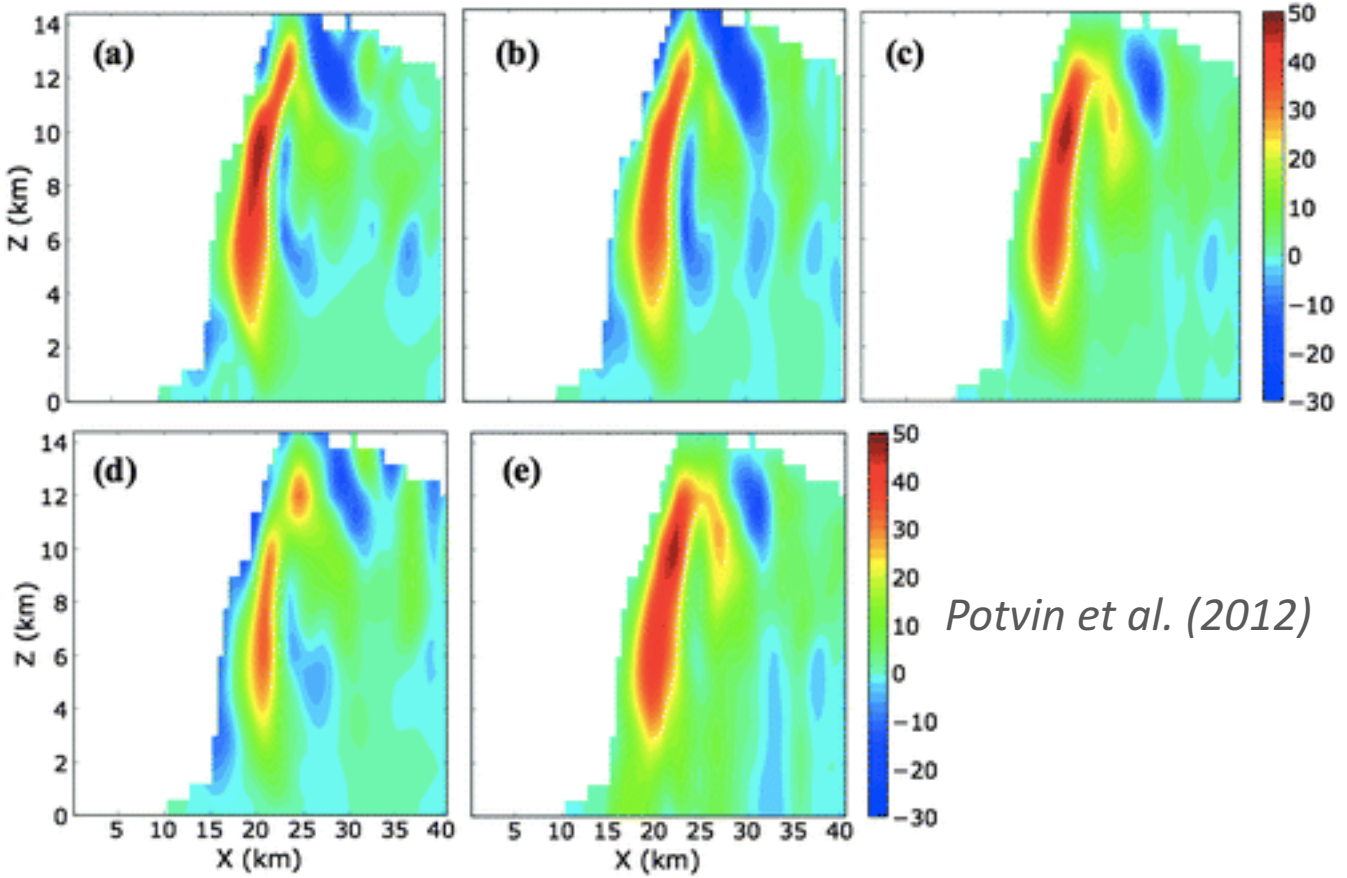
- Developed at Argonne National Lab
- Simplified File I/O
- Facilitates filtering via GateFilter object
- Automated Doppler velocity dealiasing
- Interpolating to a Cartesian grid
- Display of spherical and gridded data
- Advection correction under development



https://arm-doe.github.io/pyart/dev/auto_examples/index.html

Realizing the Dream, Part II - DDA C Application

- "Dual-Doppler Analysis" Developed at OU/CIMMS
- Based on 3D Variational Analysis (3DVAR)
- Mass conservation constraint becomes a tunable parameter
- Also tunable: Vorticity, Smoothness, Sounding weights



Potvin et al. (2012)

Total Cost Function $J = J_O + J_M + J_V + J_S,$

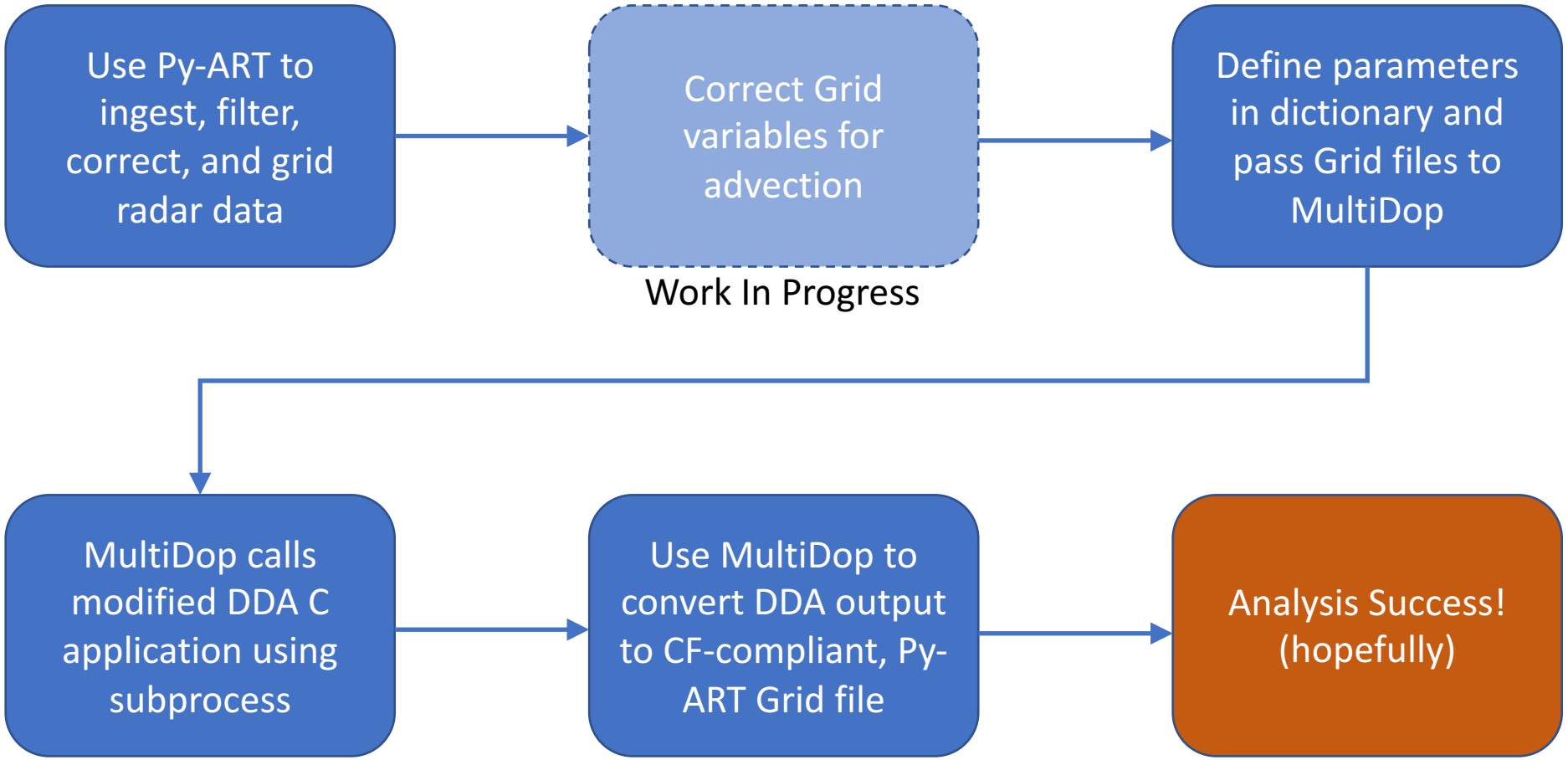
Obs Mass Cont. Vort. Smooth

The Culmination of the Dream - MultiDop

- Developed at NASA Marshall Space Flight Center
- Python wrapper for DDA C-based application
- Python classes to bridge Py-ART and DDA
- DDA updated to accept Py-ART grid format
- Python install script for compiling both C and Python components

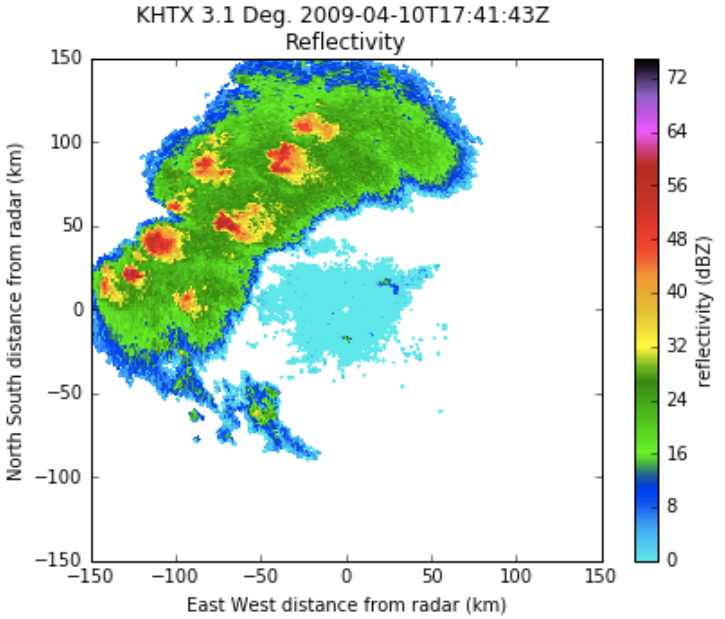
How Does It All Work, Then?

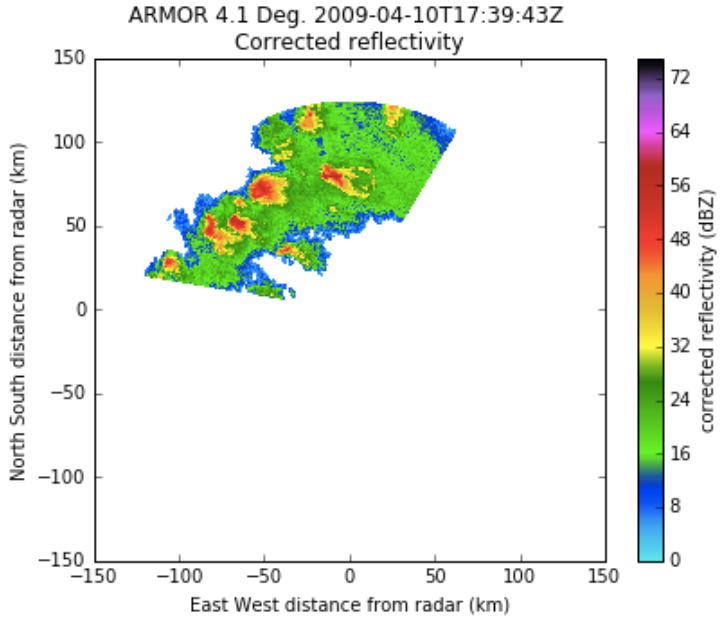
- MultiDop makes Py-ART and DDA work together
- A sample workflow is available as a Jupyter notebook

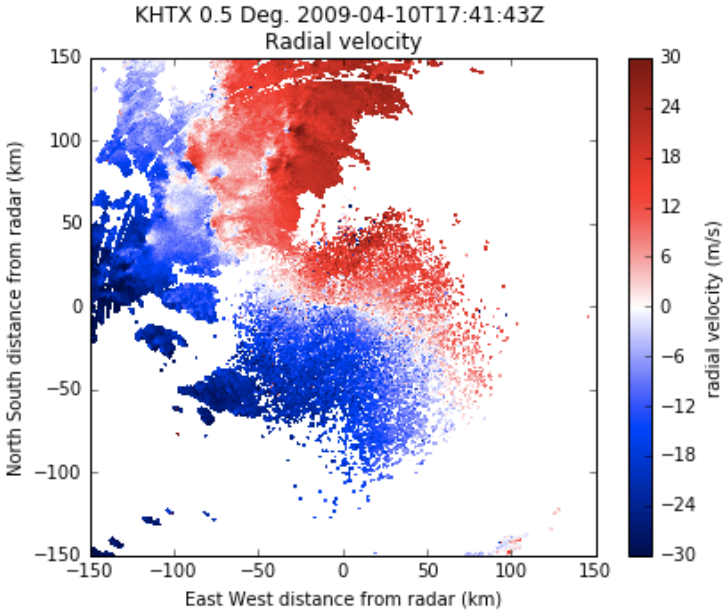


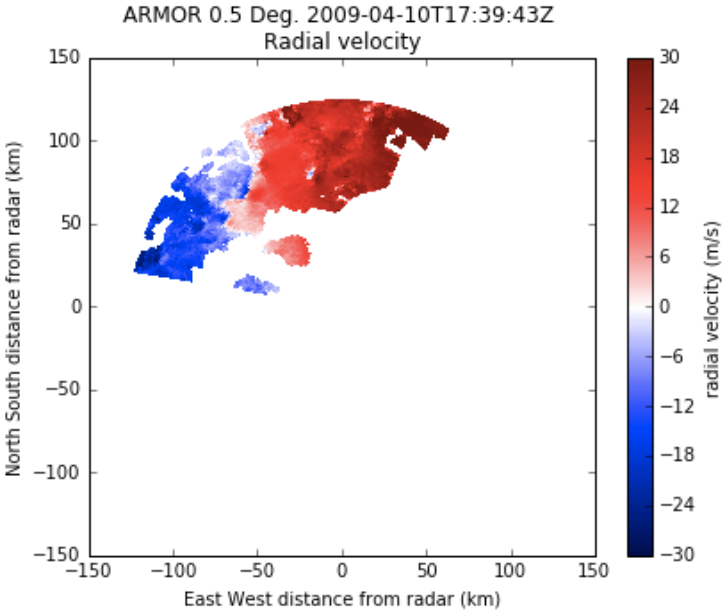
Py-ART Steps

- Use Py-ART to create Radar objects from volume files
- Use GateFilter or other editing on data if necessary
- Dealias velocity data if necessary
- Rename fields to match names among all volumes to be synthesized
- Create Py-ART Grid objects









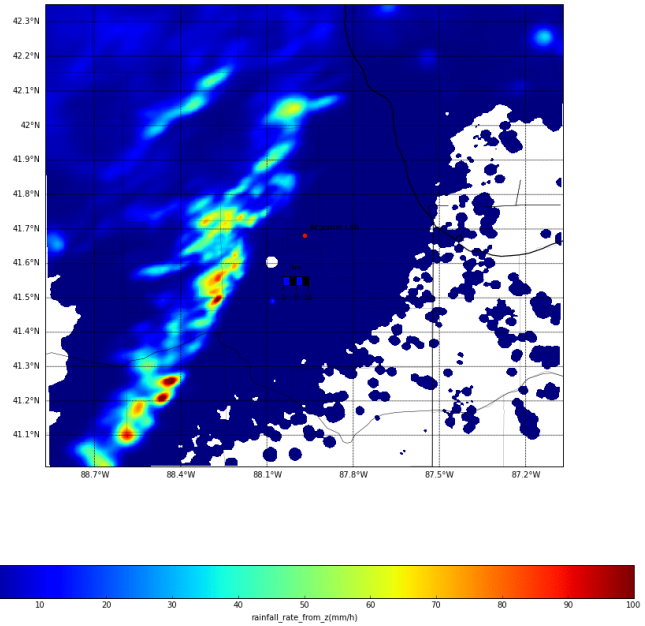
Py-ART Advection Correction

- For radars that are non-synchronized or we need to determine and correct for advection of radial velocity patterns.
- We have implemented a image shift detection technique to get X/Y advection between volumes using cross correlation (same as in image stabilization).
- We have implemented an image shifter using NDImage
- To Do: Combine forward and backward projected images, “Advective averaging”

$$R(t+\Delta t,z,y,x) = (1-\frac{t+\Delta t-t_1}{t_2-t_1})R_{t1}(t_1,z,y+v\Delta t,x+u\Delta t) + \frac{t+\Delta t-t_1}{t_2-t_1}R_{t2}(t_2,z,y-v\Delta t,x-u\Delta t)$$

$$\boldsymbol{G}_{t1} = \mathcal{F}\{R_{t1}\}, \boldsymbol{G}_{t2} = \mathcal{F}\{R_{t2}\}$$
$$C = \frac{\boldsymbol{G}_{t1} \circ \boldsymbol{G}_{t2}^*}{|\boldsymbol{G}_{t1} \circ \boldsymbol{G}_{t2}^*|}$$
$$r = \mathcal{F}^{-1}\{C\}$$
$$\Delta x, \Delta y = \text{argmax}\{r\}$$

where F is the Fourier transform, $*$ is the complex conjugate and $\circ$ represents element wise multiplication.



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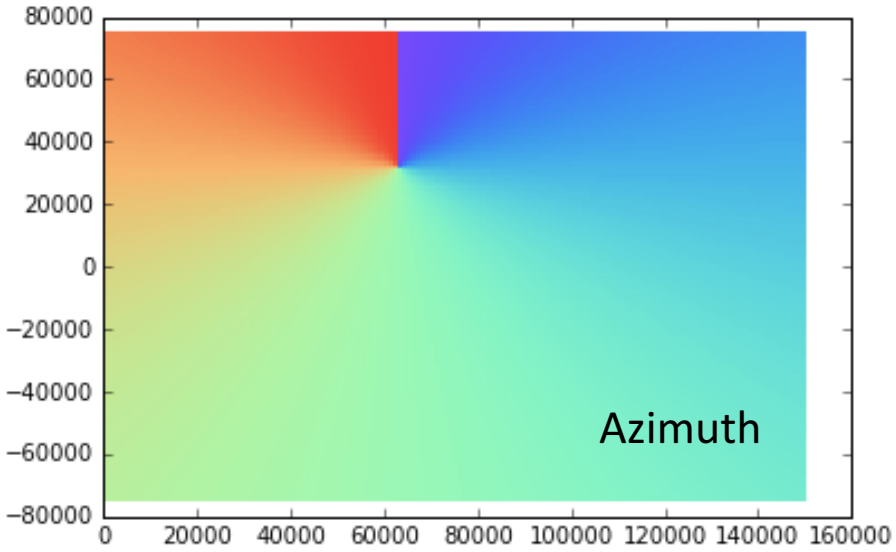
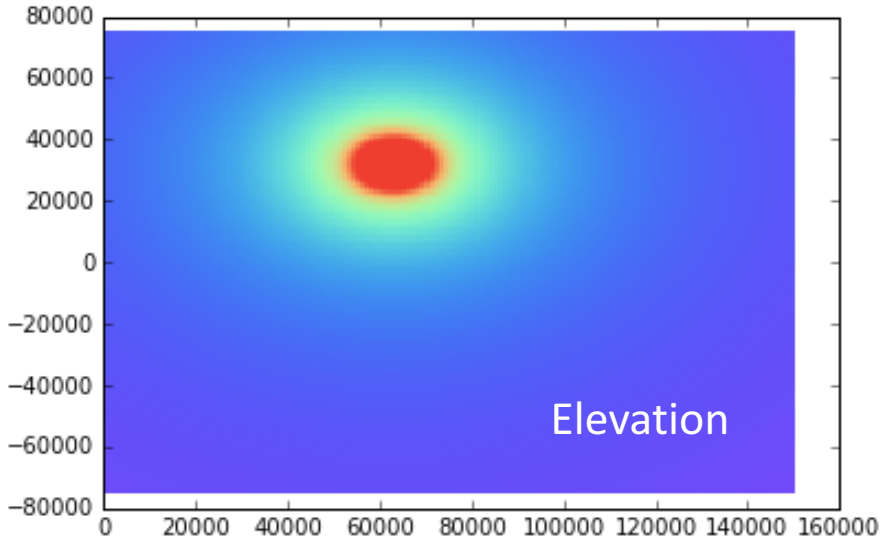
Other Special Py-ART Steps

- Azimuth and Elevation must be added as fields to the Py-ART Grid objects
- MultiDop has functions to do this automatically using Grid attributes

In [9]:
```
# The analysis engine requires azimuth and elevation to be part of the grid.
# This information is computed from the grid geometry.
g1 = multidop.angles.add_azimuth_as_field(g1)
g2 = multidop.angles.add_azimuth_as_field(g2)
g1 = multidop.angles.add_elevation_as_field(g1)
g2 = multidop.angles.add_elevation_as_field(g2)
```

In [10]:
```
# Save the input grids for later.
pyart.io.write_grid('khtx_supercell.nc', g1)
pyart.io.write_grid('armor_supercell.nc', g2)
```





Define Parameters Step

- Tunable and user-defined parameters are handled via a dictionary
- ParamFile and CalcParamFile objects use this dictionary to create input scripts used by the DDA application
- Default values are used to fill in what end user does not provide

```
localfile = tempfile.NamedTemporaryFile()
pd = {'dir': './',
      'x': [-100000.0, 1000.0, 151],
      'y': [0.0, 1000.0, 151],
      'z': [1000.0, 1000.0,  20],
      'grid': [g1.origin_longitude['data'][0], g1.origin_latitude['data'][0], 0.0],
      'files': ['khtx_supercell.nc',
                'armor_supercell.nc'],
      'radar_names': ['KHTX', 'ARMOR'],
      'refl': 'DT',  # Name of reflectivity field. Must be common between radars.
      'vt': 'VT',  # Name of velocity field. Must be common between radars.
      'bgfile': None,
      'writeout': localfile.name,
      'min_cba': 20.0,  # Minimum beam-crossing angle
      'calc_params': 'calc_example.dda',
      'anel': 1,
      'laplace': 0,
      'read_dataweights': 2,
      'max_dist': 10.0,
      'cutoff': 0.0,
      'UT': 0.0,
      'VT': 0.0,
      'output_error': 0,
      'weak_height': -1,
      'upper_bc': 1,
      'itmax_frprmn': [200, 10],
      'itmax_dbrent': 200,
      'C1b': 1.0,  # Data weighting factor
      'C2b': 10.0,  # Mass continuity weighting factor
      'C3b': 0,  # Vorticity weighting factor
      'C4b': 1.0,  # Horizontal smoothing factor
      'C5b': 0.0,  # Vertical smoothing factor
      'C8b': 0.0,  # Sounding factor
      'vary_weights': 0,
      'filter': ['none', '', ''],
      'cvg_opt_bg': [1, 1, 1],
      'cvg_sub_bg': [0, 0, 0],
      'cvg_opt_fil': [0, 1, 1],
      'cvg_sub_fil': [0, 0, 0],
      'cvg_bg': [0, 0, 0],
      'cvg_fil': [0, 0, 0],
      'sseq_trip': [1.0, 1.0, 0.0]
     }
pf = multidop.parameters.ParamFile(pd, 'example.dda')
pf = multidop.parameters.CalcParamFile(pd, 'calc_example.dda')
```

DDA Application Step

- MultiDop calls the DDA C application via the subprocess module
- Text output from the application is captured, but not displayed until after application completes
- Entire process usually takes a few minutes
- Future work – Refactor DDA into a library so that it can be accessed via ctypes for improved Python integration

```
# Unfortunately, text output from the analysis engine (DDA) will not display
# until after the program completes. Expect this step to take several minutes.
bt = time.time()
multidop.execute.do_analysis('example.dda')
print((time.time()-bt)/60.0, 'minutes to process')
```

```
DDA 0.8.2
./DDA: reading calculation parameters from calc_example.dda.
Changing working directory to ./
x: -100000.000000 to 50000.000000 in 150 steps of 1000.000000
y: 0.000000 to 150000.000000 in 150 steps of 1000.000000
z: 1000.000000 to 20000.000000 in 19 steps of 1000.000000
z_min=1000, cutoff=0
UT=0, VT=0
Anelastic mass cons
First-order smoothness constraint
Minimum beam crossing angle = 20 degrees
Py-ART grids for analyis and all radars must match to within (dx, dy, dz) < (10 10 10) meters.
Reading Py-ART filekhtx_supercell.nc
armor_supercell.nc

Radar positions:  (62656.4,31821.4) (0.123459,-0.013841)
Computing coverage: 155907 verification points out of 456020 total points.
radar0 249854 obs. radar1 163806 obs. 413660 total obs.
Analyzed obs = 413660. Mean Vr = 23.4908
C1b=1 C2b=10 C3b=0 C4b=1 C5b=0 C6b=0 C7b=1 C8b=0
C2a=10 C3a=0 C4a=1 C5a=0 C6a=0 C7a=1 C8a=0
Weighting all obs equally!
GradCheck: rchek = 1e+10. fx1 = 281865
GradCheck: gxnn = 2979.22
GradCheck: j = 1. fx2 = 9.246e+18. ffff = 3.104e+06
GradCheck: j = 2. fx2 = 9.246e+16. ffff = 3.104e+05
GradCheck: j = 3. fx2 = 9.246e+14. ffff = 3.104e+04
GradCheck: j = 4. fx2 = 9.249e+12. ffff = 3105
GradCheck: j = 5. fx2 = 9.276e+10. ffff = 311.4
GradCheck: j = 6. fx2 = 9.547e+08. ffff = 32.04
GradCheck: j = 7. fx2 = 1.251e+07. ffff = 4.104
GradCheck: j = 8. fx2 = 6.722e+05. ffff = 1.31
GradCheck: j = 9. fx2 = 3.126e+05. ffff = 1.031
GradCheck: j = 10. fx2 = 2.849e+05. ffff = 1.003
GradCheck: j = 11. fx2 = 2.822e+05. ffff = 1
GradCheck: j = 12. fx2 = 2.819e+05. ffff = 1
GradCheck: j = 13. fx2 = 2.819e+05. ffff = 1
GradCheck: j = 14. fx2 = 2.819e+05. ffff = 1
```

Last Step

- Nominal DDA output is not CF-compliant or Py-ART friendly
- MultiDop has function to convert output to Py-ART Grid file
- Option to mask winds outside Doppler lobes

```
# Baseline output is not CF or Py-ART compliant. This function fixes that.
# This is why we wrote the original output to a tempfile that can be safely removed.
# The final grid will have all wind solutions outside the coverage region masked.
fname = 'cf_compliant_grid.nc'
final_grid = multidop.grid_io.make_new_grid([g1, g2], localfile.name)
final_grid.write(fname)
localfile.close()
```

MultiDop Checkout

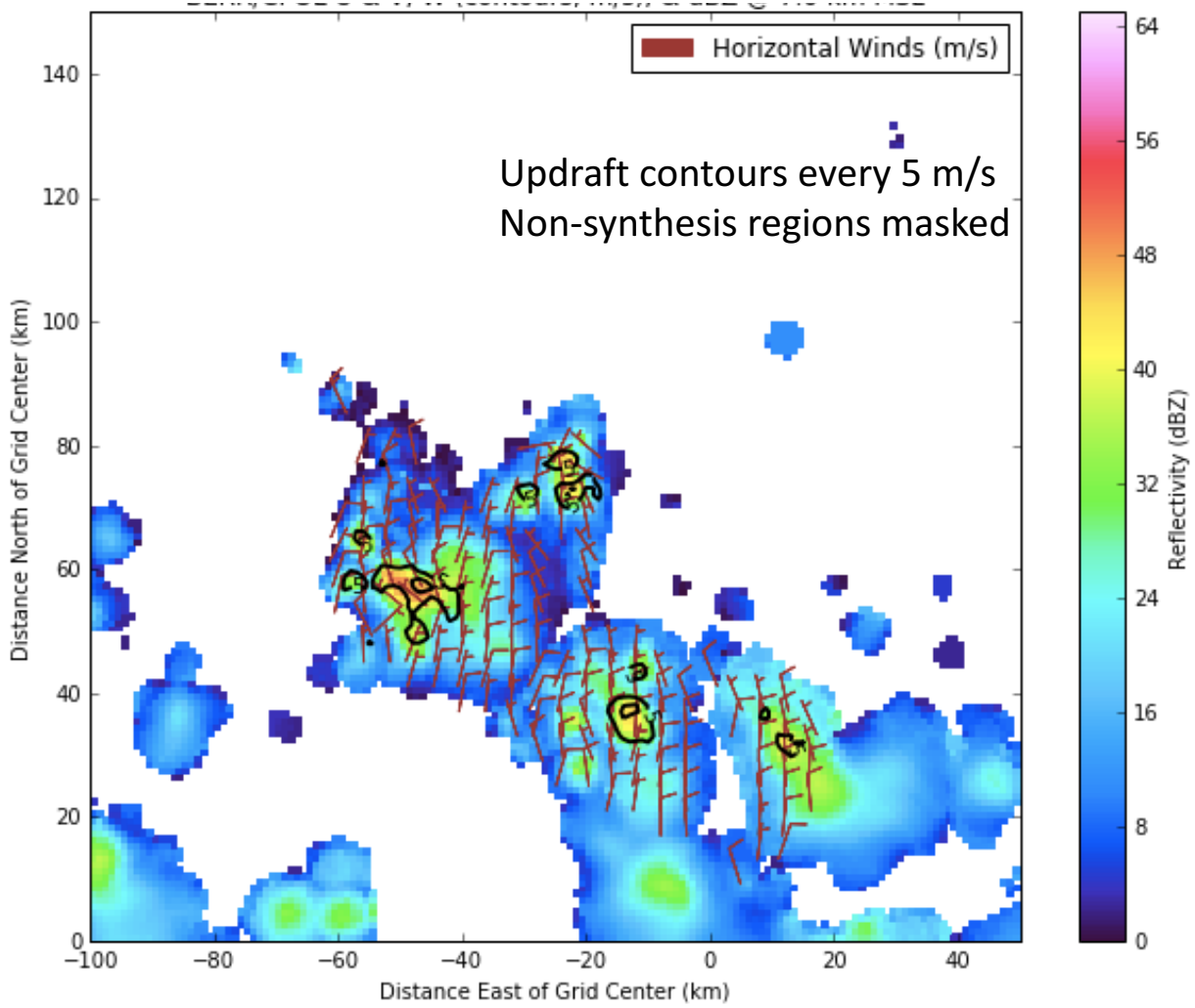
North Alabama convection

- Supercell
- Multicell
- QLCS

<u>Lessons Learned</u>

- CEDRIC/MultiDop updraft locations and magnitudes qualitatively match
- MultiDop tunable parameters can greatly modify results
- Pay special attention to horizontal and vertical smoothing

ARMOR and KHTX Radars



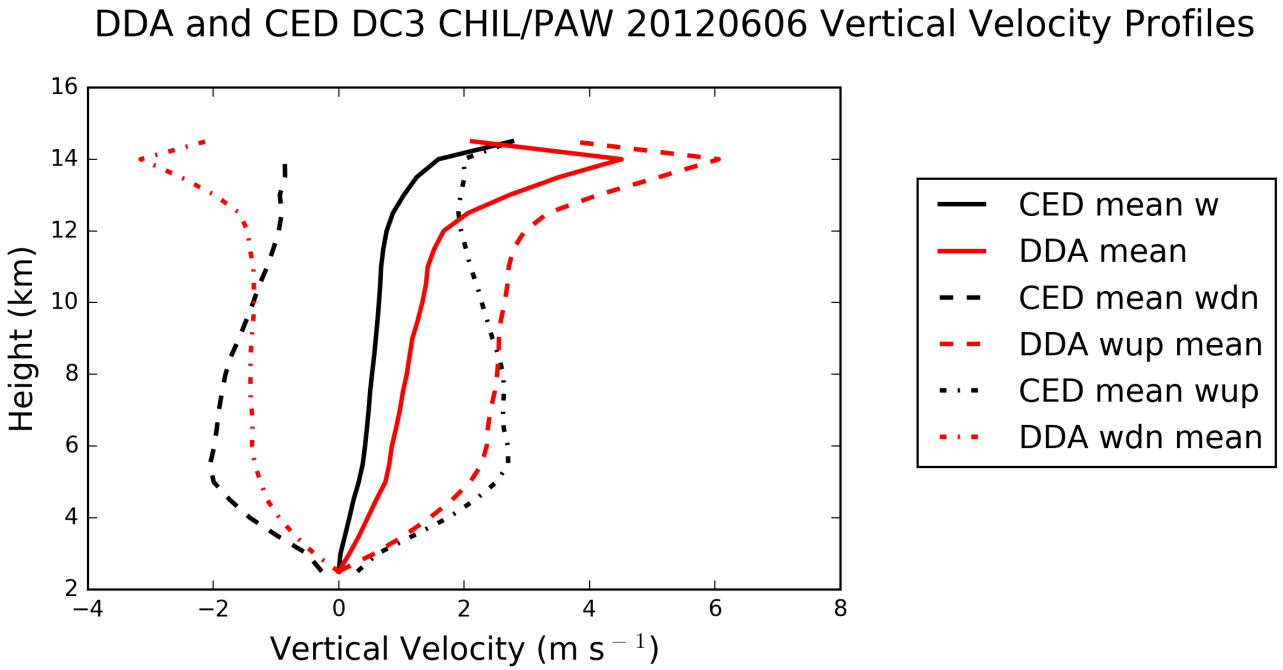
MultiDop Checkout (cont.)

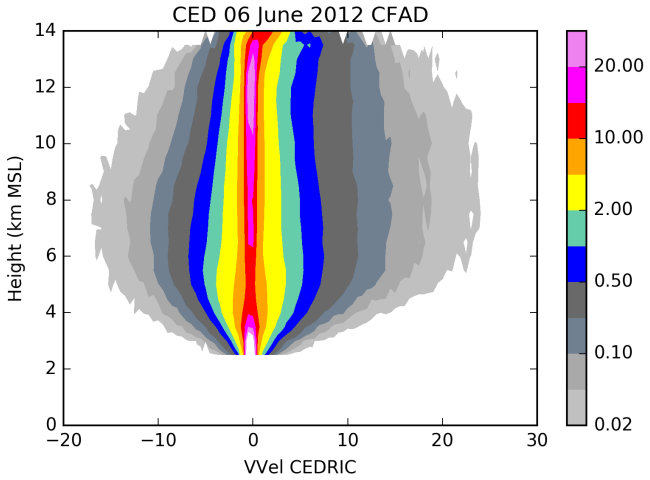
Northern Colorado DC3 Cases

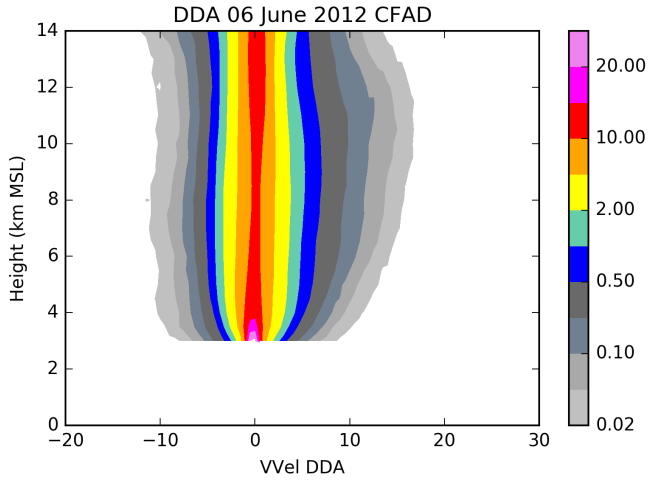
- CSU-CHILL and CSU-Pawnee
- Volumes from 5 & 6 June 2012
- Multicellular convection

<u>Lessons Learned</u>

- MultiDop w/in ~1 m/s of CEDRIC
- Good spatial correspondence
- MultiDop ~10x slower than CEDRIC, but many times easier to use!
- Pay special attention to Py-ART gridding







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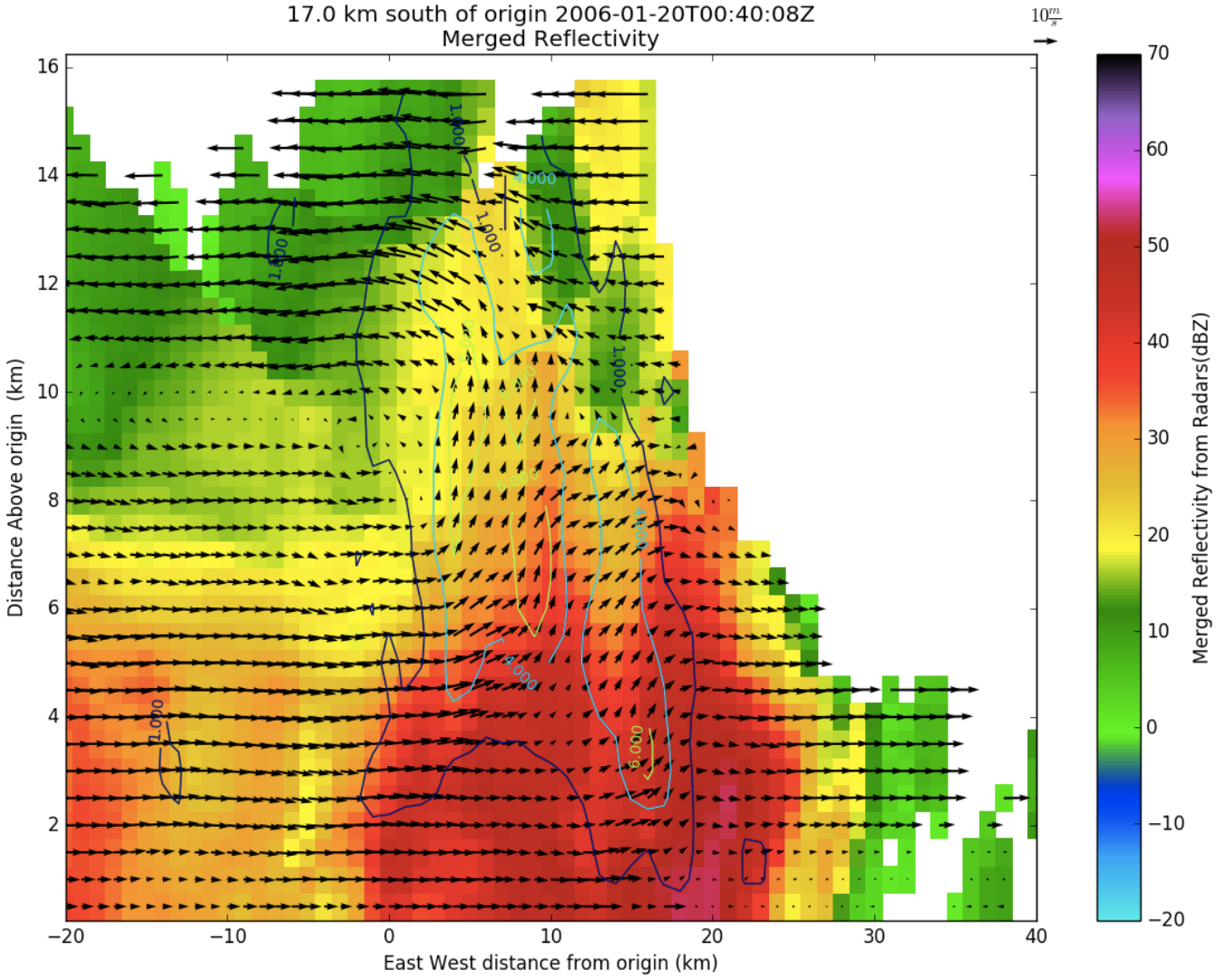
MultiDop Checkout (cont.)

Northern Australia Convection

- CPOL (Darwin) & Berrima S-band
- 19-22 January 2006, ~400 volumes
- Cluster: 1 instance MultiDop/core

<u>Lessons Learned</u>

- Needed strong mass continuity constraint (C2b = 1500) to suppress high-altitude noise in W
- Used Leise filter and strong horizontal smoothing to remove artifacts near edge of lobes
- Took advantage of 4/day soundings to help the retrieval



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MultiDop will become open source in Spring 2017
Contact timothy.j.lang@nasa.gov if you just can't wait!

If you use MultiDop, you **MUST** cite the following papers:

Shapiro, A., C. Potvin, and J. Gao, 2009: Use of a Vertical Vorticity Equation in Variational Dual-Doppler Wind Analysis. J. Atmos. Oceanic Technol., 26, 2089–2106, doi: 10.1175/2009JTECHA1256.1.

Potvin, C., A. Shapiro, and M. Xue, 2012: Impact of a Vertical Vorticity Constraint in Variational Dual-Doppler Wind Analysis: Tests with Real and Simulated Supercell Data. J. Atmos. Oceanic Technol., 29, 32–49, doi: 10.1175/JTECH-D-11-00019.1.

DualPol – Polarimetric radar hydrometeor ID, DSD, rainfall, etc.
SingleDop – 2D low-level wind retrievals from Doppler radar
PyBlock – Beam blockage correction for polarimetric radar
PyTDA – Turbulence retrievals from Doppler radar
MMM-Py – MRMS 3D radar reflectivity mosaic ingest and analysis
PyAMPR – Work with NASA AMPR airborne microwave radiometer data