NCAR Turbulence Detection Algorithm

John K. Williams, NCAR/RAP

NEXRAD Technical Advisory Committee Meeting

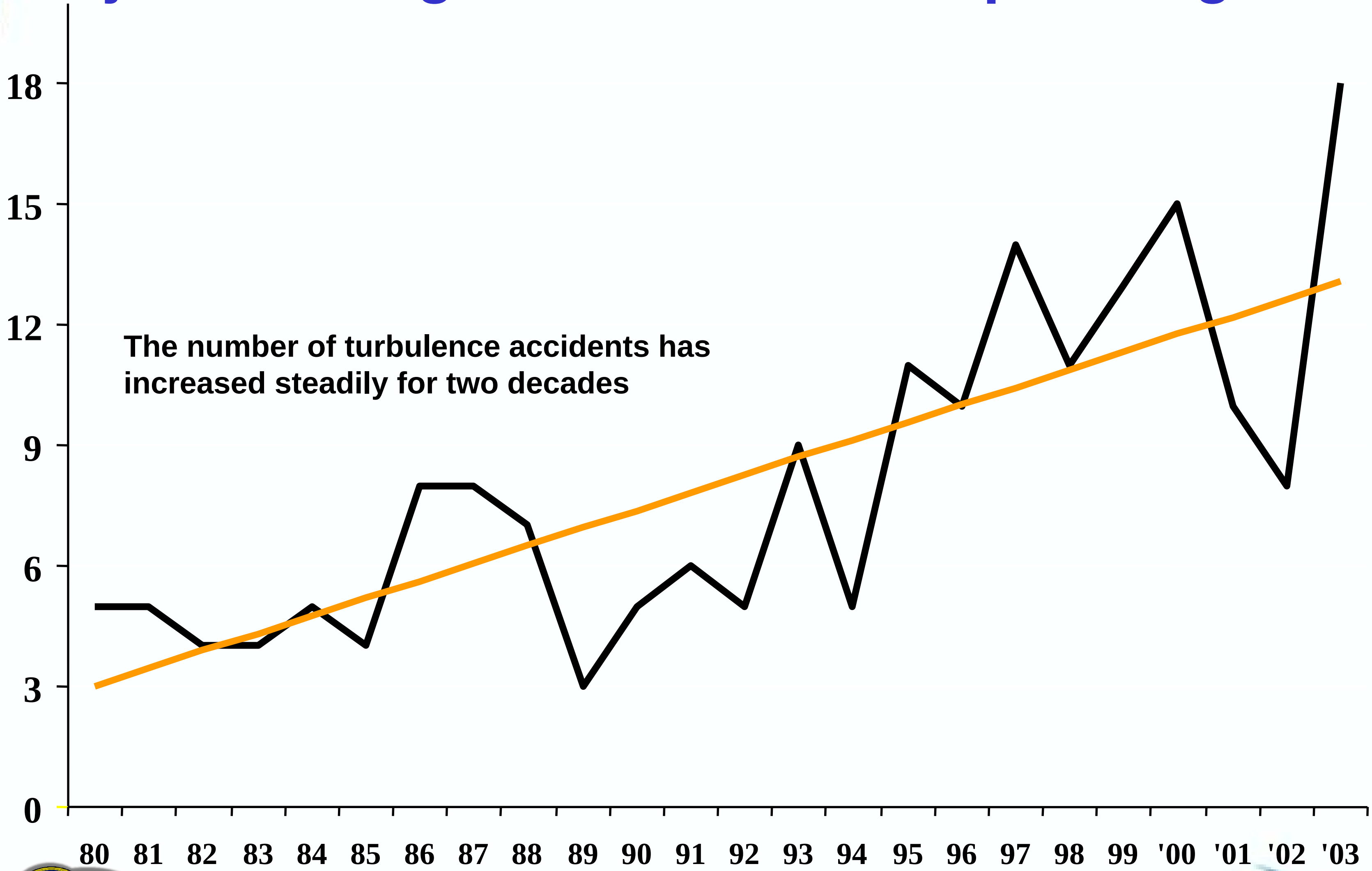
Indianapolis, IN

October 21-22, 2004

Outline

- Motivation and goals
- NCAR Turbulence Detection Algorithm (NTDA) description
- Accident case studies
- Verification using field program data
- Operational demonstration plans
- Proposed implementation schedule
- Potential impact of proposed OpenRDA changes
- Future needs

Turbulence is the leading cause of nonfatal injuries to flight attendants and passengers

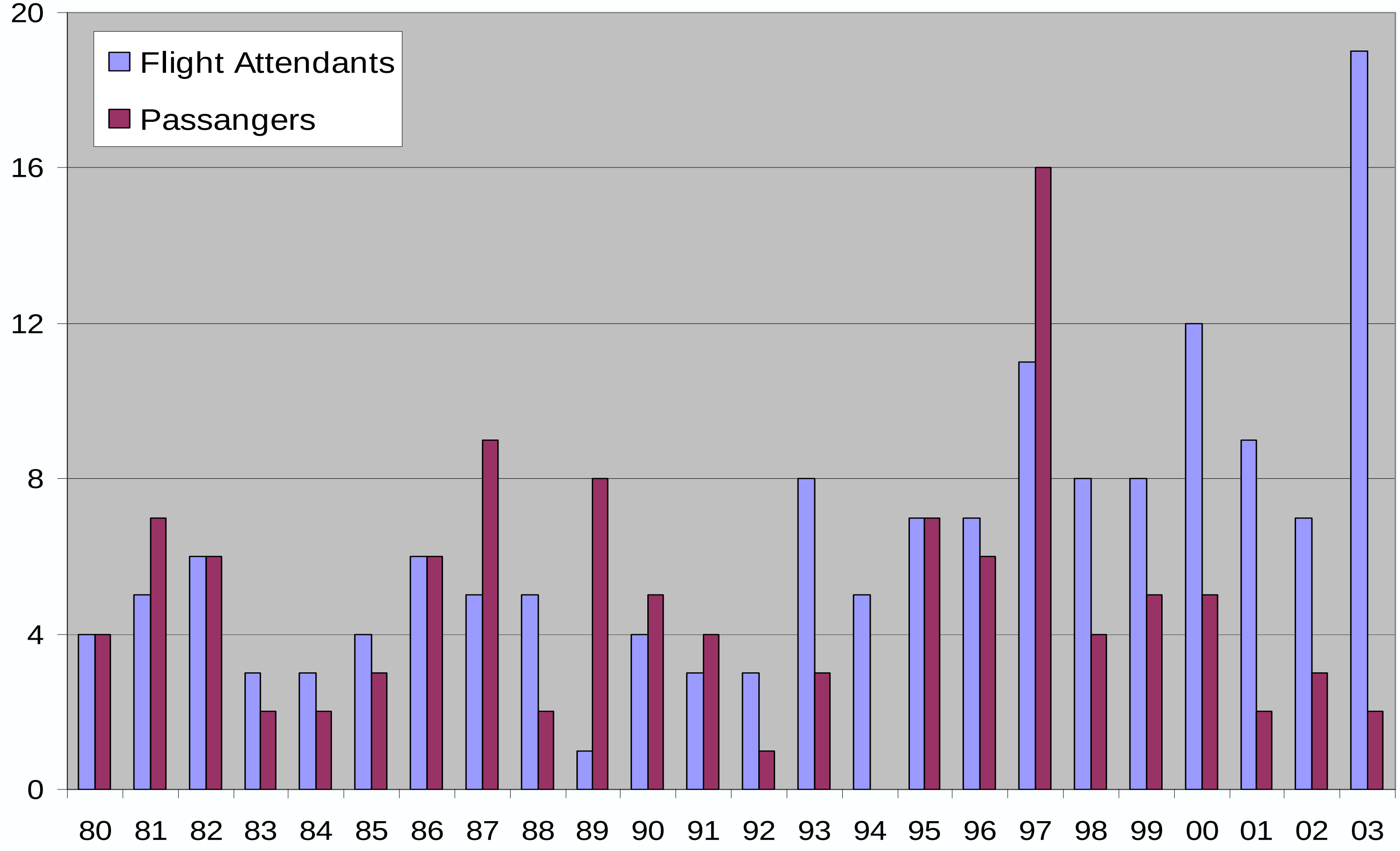


Turbulence Accidents, 1980-2003, Part 121 Operators (as defined today)

AWRP

NCAR

Flight Attendants and Passengers Seriously or Fatally Injured: 1980-2003



Source: Analysis of data from National Aviation Safety Data Analysis Center (NASDAC), Office of System Safety, Federal Aviation Administration, NTSB Weather Related Accident Study. (https://www.nasdac.faa.gov/aviation_studies/weather_study).

Turbulence accident costs

- "It has been estimated that turbulence-related costs to the airline community amount to over $100 million per year." *Source: NASA Langley Research Center (http://tpaws.larc.nasa.gov/overview.htm)*
  - Injuries (compensation and missed work)
  - Damage to aircraft
  - Disruptions when aircraft are out-of-service for inspections and repairs
- For commercial (Part 121/129), air taxi (Part 135), and general aviation (GA, Part 91) between 1983-1997, turbulence contributed to 664 accidents leading to 609 fatalities (mostly GA), 239 serious and 584 minor injuries, for an estimated annual societal cost of $134 million. *Source: H. Eichenbaum, 2000: "Historical overview of turbulence accidents", MCR Federal, Inc, report TR-7100/023-1.*
- "On an annual basis, Part 121 carriers experience…567.8 turbulence related injury events that result in 687.4 minor flight attendant injuries, 38.4 serious flight attendant injuries, 119.5 minor passenger injuries, and 17.1 serious passenger injuries" with a cost to airlines of between $30 and $60 million. *Source: P. Kauffmann and A. Sousa-Poza, 2001: "Market Assessment of Forward-Looking Turbulence Sensing Systems", NASA report CR—2001-210905.*

AWRP

NCAR

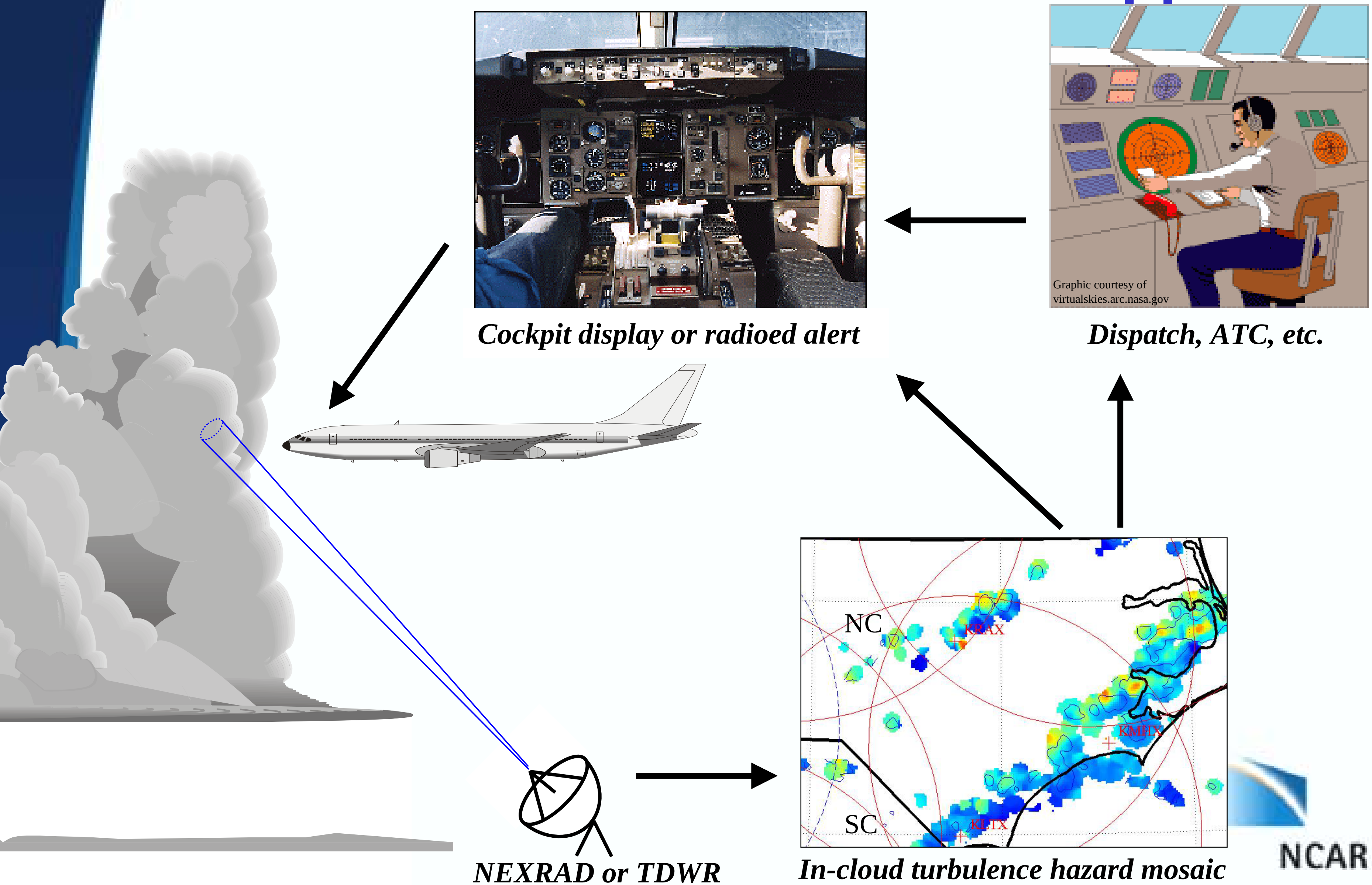
Why turbulence detection?

- > 60% of turbulence encounters are convectively induced, and many occur in low-reflectivity regions
- Convective turbulence can be highly localized, dynamic, and difficult to forecast accurately
- Remote sensing could effectively augment PIREPs, in-situ sensors and forecasts for tactical decision support
- NEXRAD and TDWR radars provide good temporal and spatial coverage of the CONUS
- Recent improvements in dissemination enables access to real-time NEXRAD data

AWRP

NCAR

Goal: Real-time turbulence hazard detection for tactical decision support



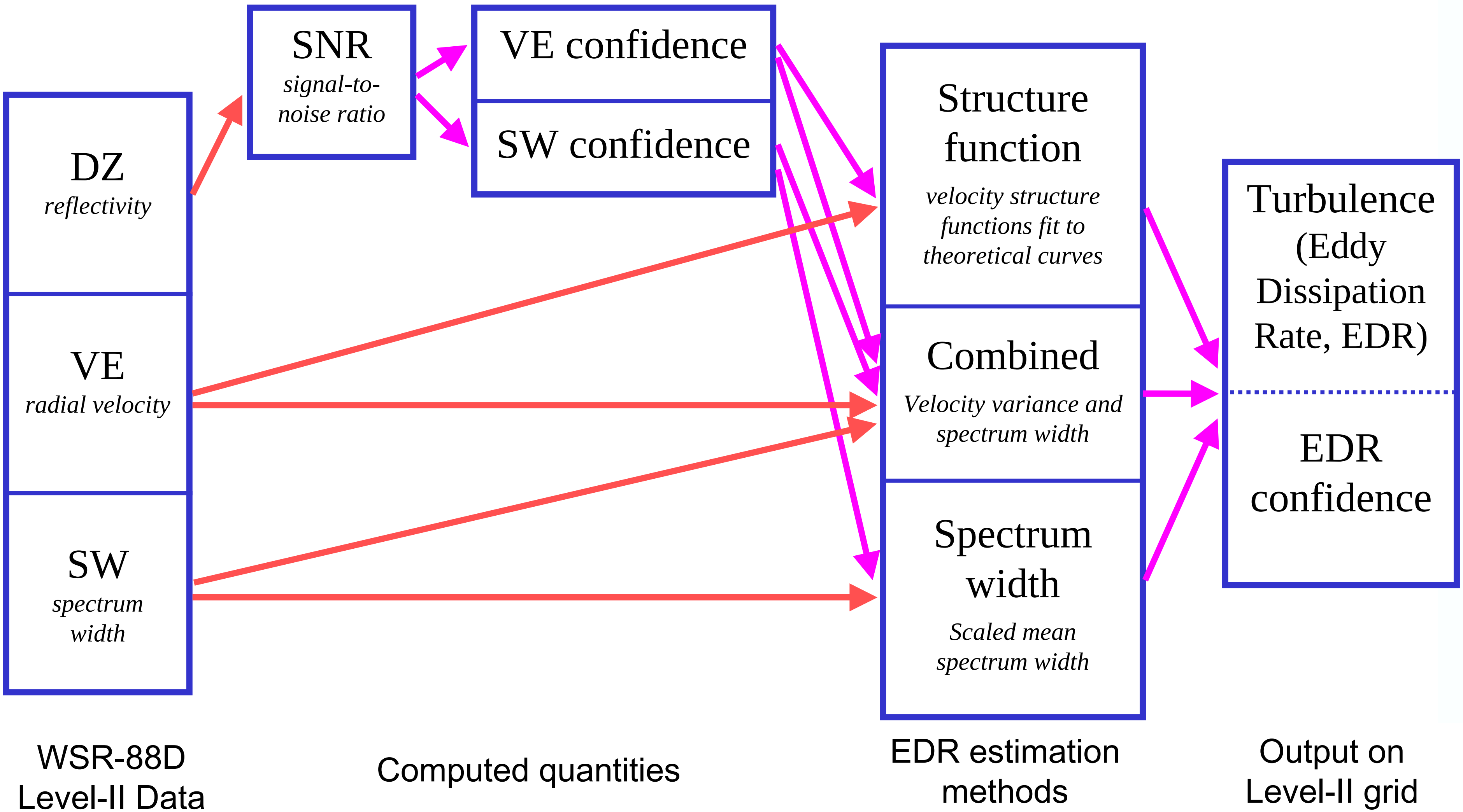
Radar Turbulence Detection Challenges

- Radars measure mostly horizontal wind fluctuations, but vertical have greatest effect on aircraft
- Convectively-induced turbulence may not be well-developed and may not satisfy theoretical models
- Ground-based scans are slow, have poor resolution at large distances (at 60 miles, $1° \approx 1$ mile), and have large gaps between sweeps at high angles
- Radar data are contaminated by non-atmospheric and measurement noise
- Radar spectrum width not extensively tested/tuned
- Turbulence is a statistical quantity—measurements must be averaged to be meaningful

Data quality challenges

- Don Burgess and Kim Elmore (Nov. 2000 FAA AWRP PMR): “NEXRAD spectrum width data may be unusable.”
- OSF Engineering reports (Dale Sirmans, et al., 1997-98)
  – Signal clipping/receiver saturation at high SNR
  – Improper noise compensation at low SNR
  – Overlaid echo thresholds too low
- Dick Doviak, Dusan Zrnic, personal communications
  – Low SNR thresholds for SW yield high error
  – Automatic Gain Control (AGC) works incorrectly
  – Pulse-pair method produces zeros on failure
- Additional artifacts sometimes appear

NCAR Turbulence Algorithm (NTDA)

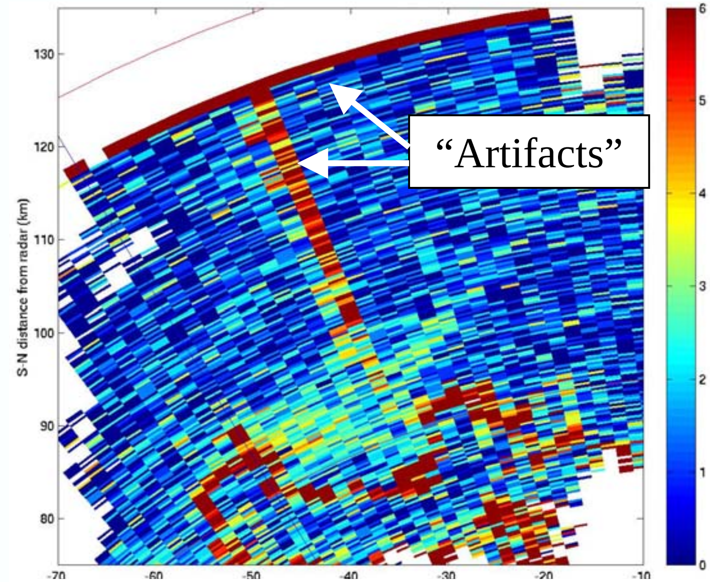


"Fuzzy logic" algorithm methodology

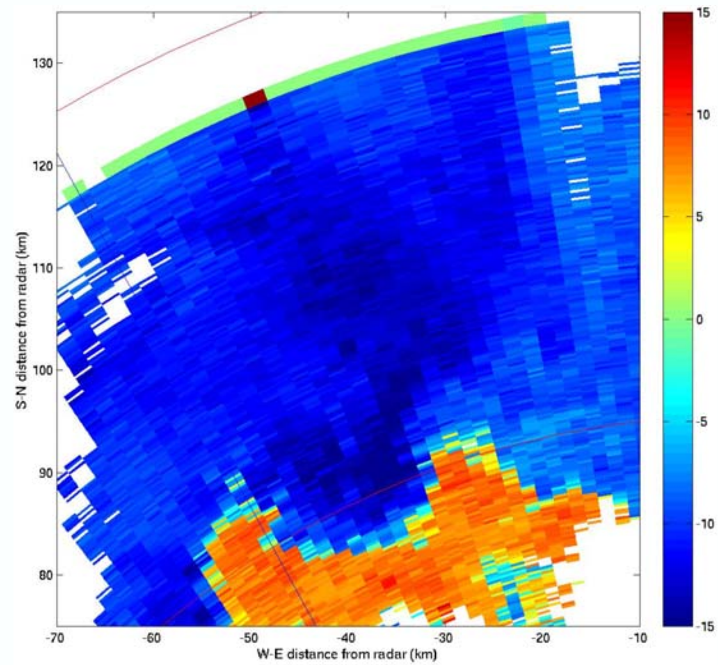
NCAR

SW confidence

- Interest maps
  - Feature detection identifies artifacts (none $\rightarrow$ good)
  - Local variance of spectrum width (small $\rightarrow$ good)
  - Spectrum width values (>0 $\rightarrow$ good)
  - Signal-to-noise ratio (large $\rightarrow$ good)
- Combine via fuzzy logic approach $\Rightarrow$ confidence c_i



KGLD 2.4° sweep SW (0 to 6 m/s)



KGLD 2.4° sweep VE (-15 to 15 m/s)

Spectrum width EDR computation

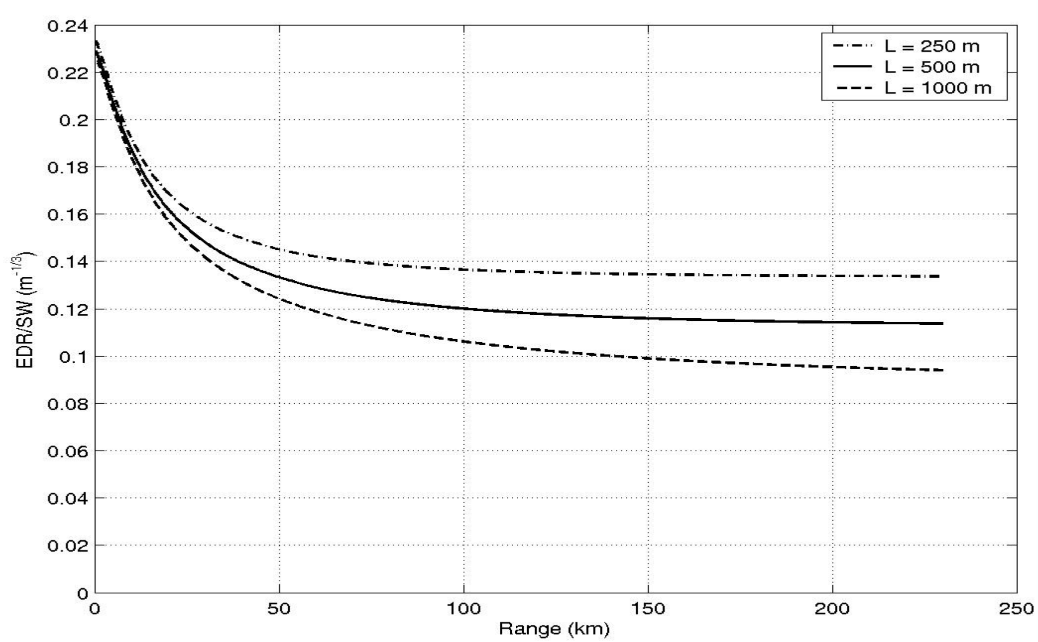
- Let $\varepsilon_i^{1/3} = s_i\, f(r_i)$

raw EDR "estimate"

measured spectrum width

"scale" factor for range r_i computed by assuming von Karman turbulence with L_0 = 500 m

- At a given range and azimuth, EDR is $\varepsilon^{1/3} = \dfrac{\sum_{i\,\in\,\mathrm{disc}} c_i\, \varepsilon_i^{1/3}}{\sum_{i\,\in\,\mathrm{disc}} c_i}$



SW to EDR "scaling" function $f(r)$ for WSR-88D

Case study: CRJ extreme turbulence encounter on 17 November 2002, 2300 UTC

- CRJ-2 encountered extreme turbulence at 18,000 ft in decent to Washington National Airport
- Vertical acc. from -2.0 to +4.4 g in about 2 seconds (max. allowable +2.5 g, -1.0 g)
- From the NTSB Factual Report:

  At 1759:53, Comair 109 reported an encounter with severe turbulence…. The controller replied that this was the first severe turbulence report he had received in the last 40 minutes.

  (FA): "we had extremely severe turbulence that lasted 8 to 10 seconds. Rocking back and forth, up and down and dropping. I saw passengers hit their heads on the overhead bins and I had one passenger tossed out of his seat onto the floor….I yelled back 'stay calm, stay on the floor, passengers around, hold him down.'
- The aircraft was taken out of service for extensive inspection

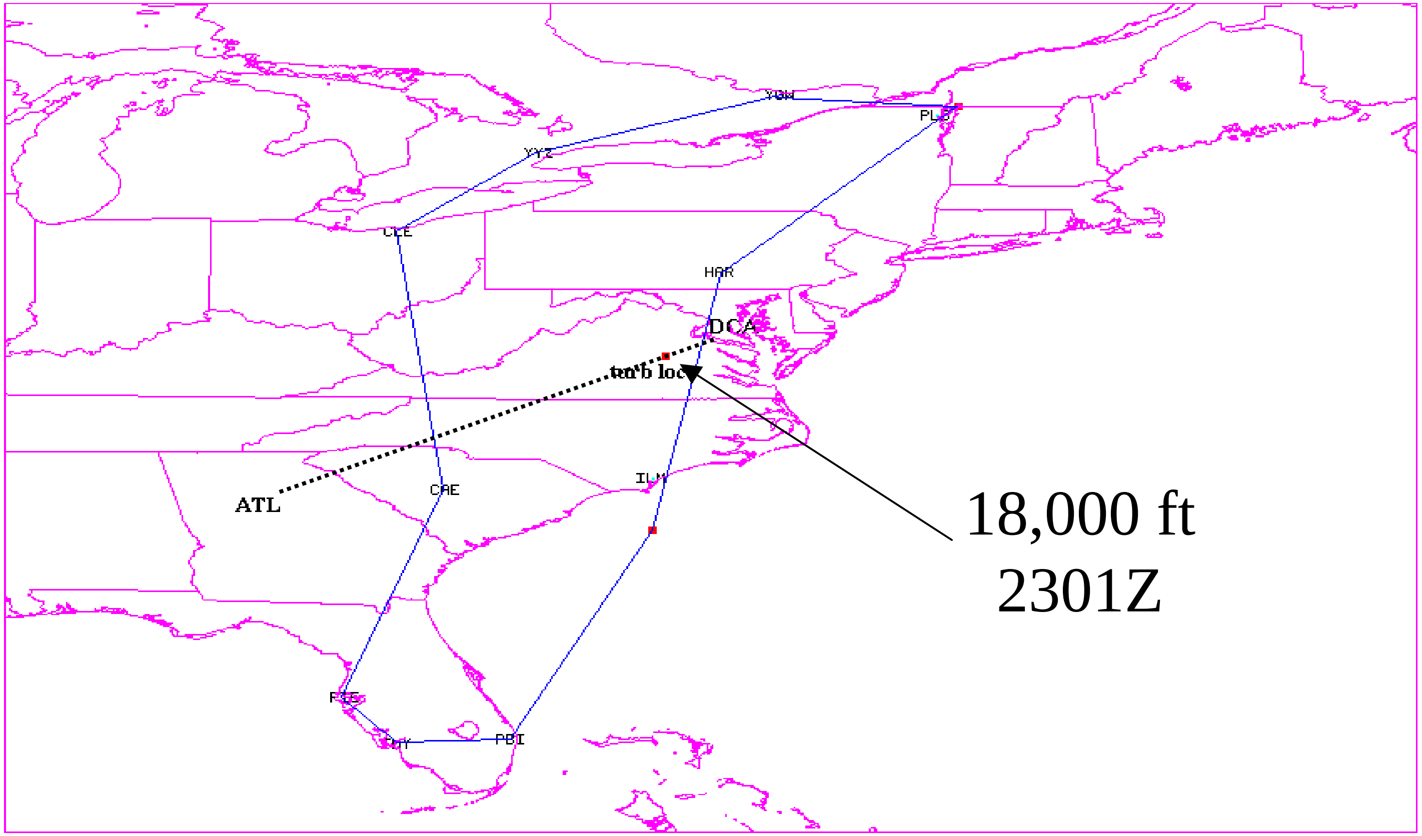
Case study: CRJ-2 aircraft

Canadair CL-600-2B19 (CRJ-2)

AWRP

NCAR

Case study: SIGMET from Flight Release

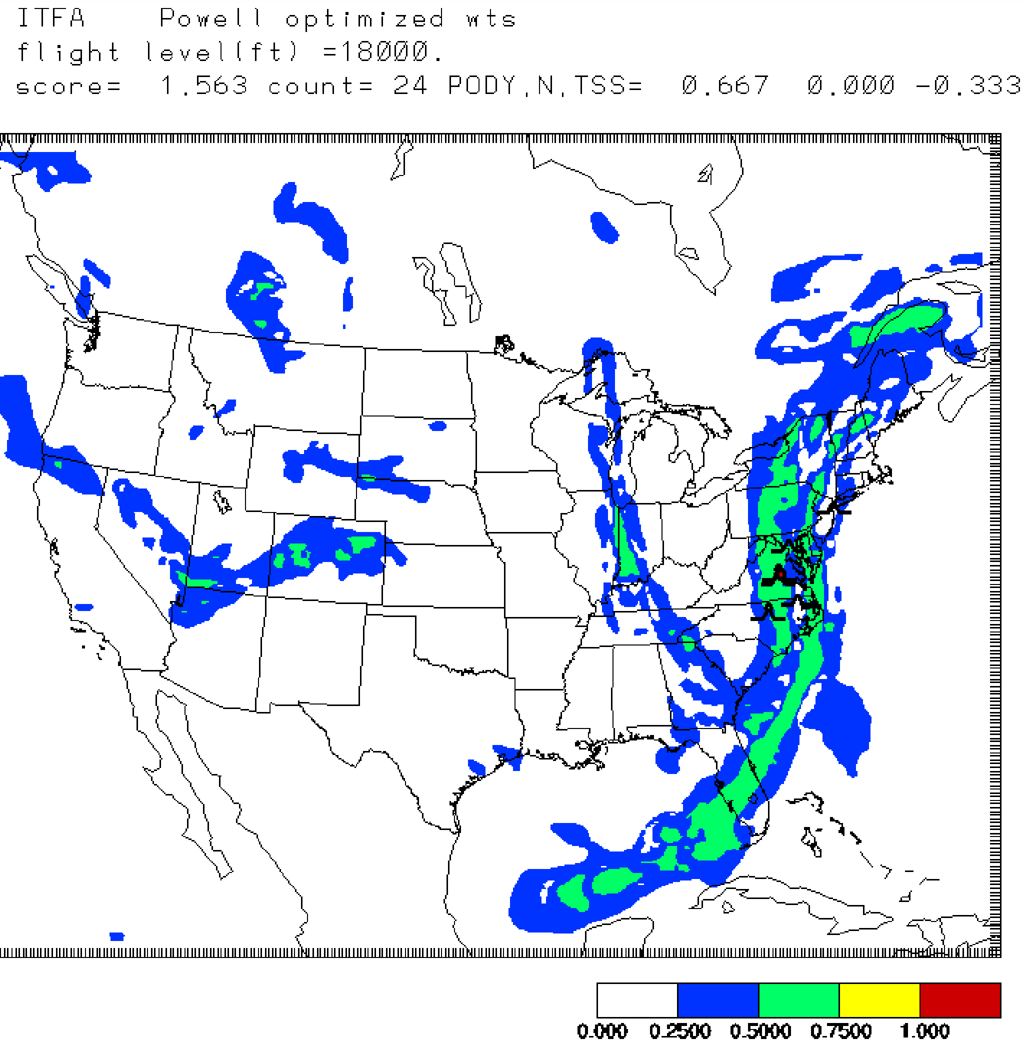


SIGMET WHISKEY 9 -- OCNL SEV TURB BTN 130 AND FL280 17/1920Z TO 17/2320Z

SIGMET issued 17 November 2002 at 1920Z and valid until 2320Z.

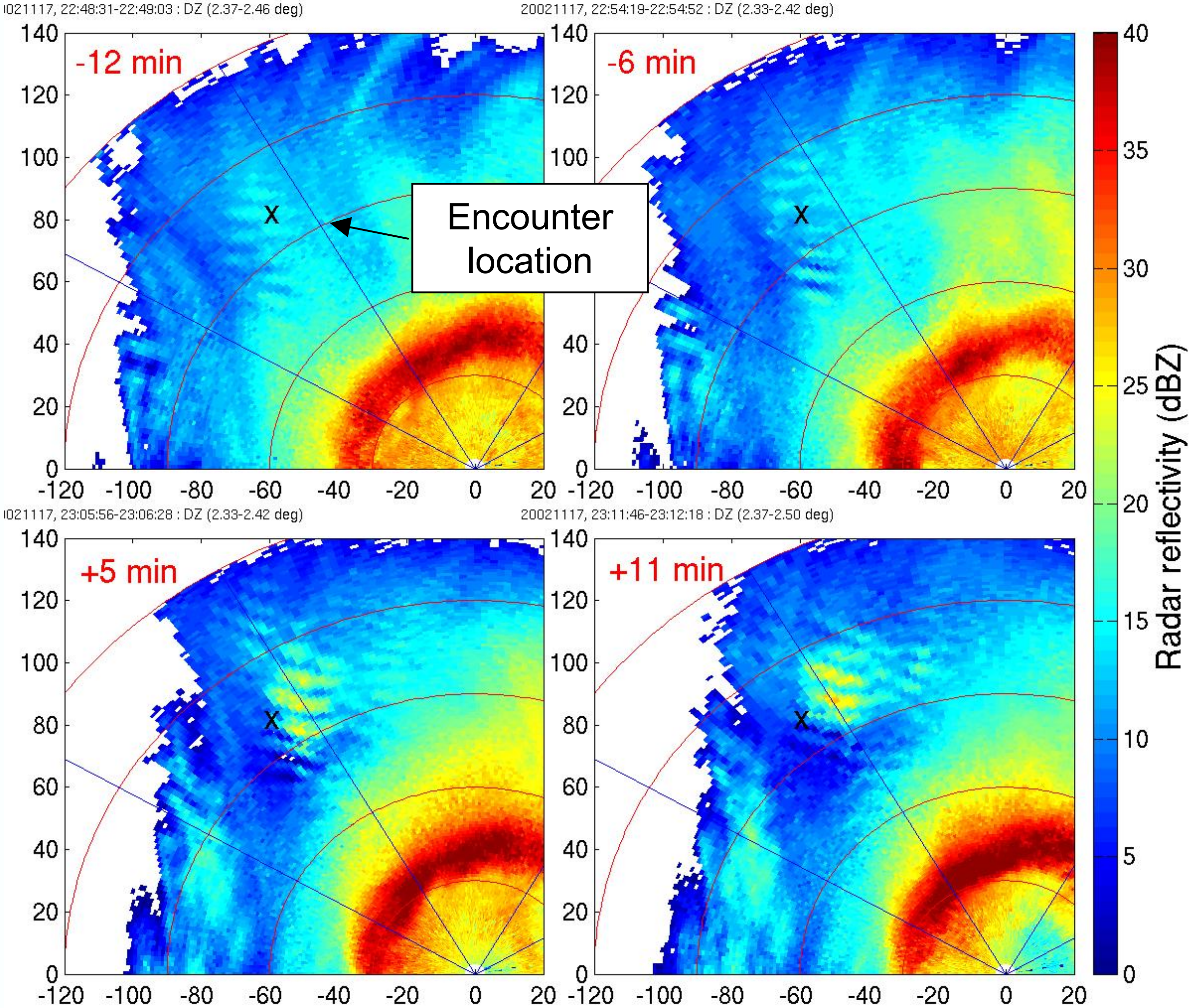
"Occasional severe turbulence between 13,000 and 28,000 feet due to windshear associated with jetstream and middle / upper trough."

Case study: ITFA diagnosis (FL180)



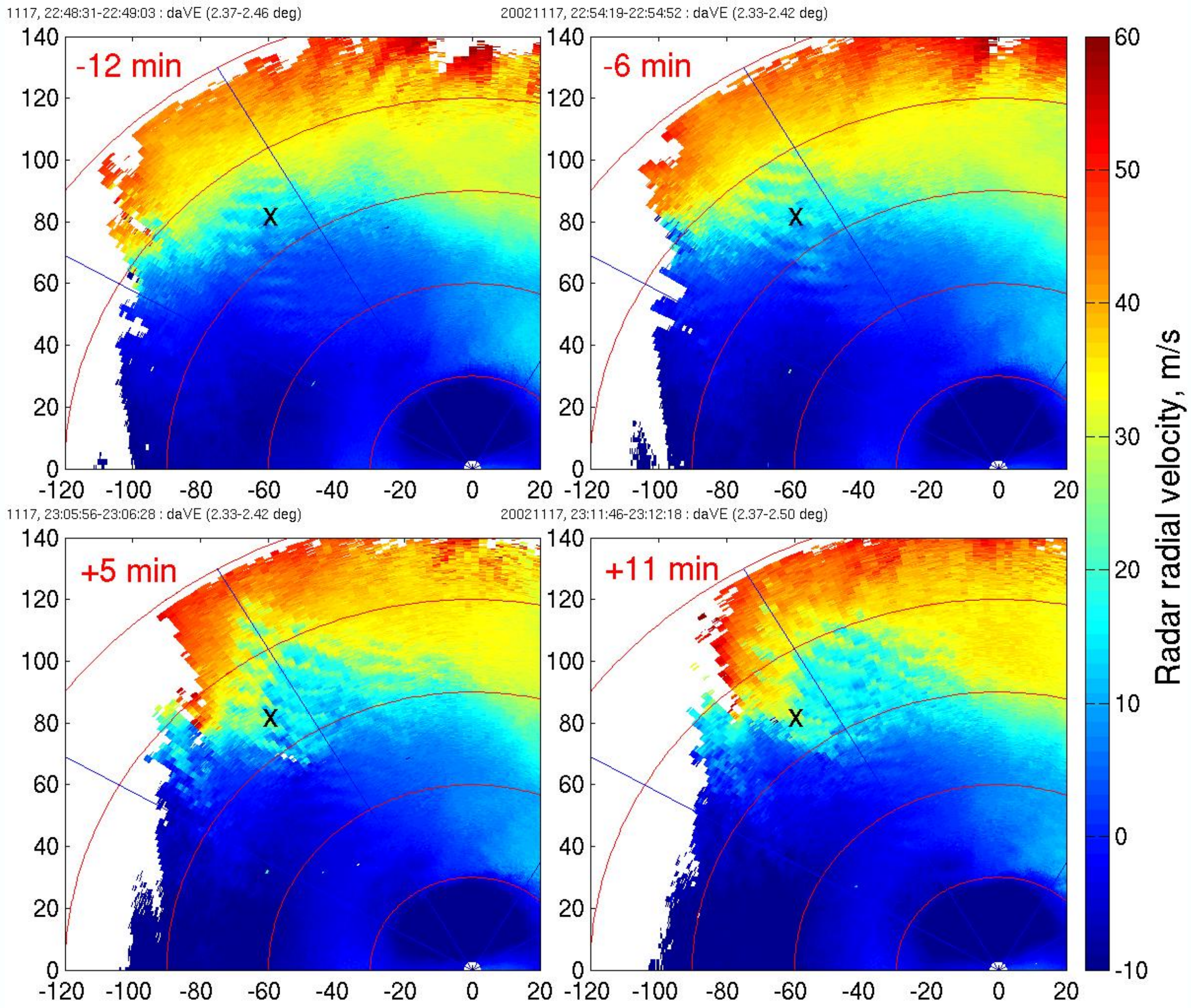
ITFA (now Graphical Turbulence Guidance, GTG)
“turbulence potential” for 18,000 ft and time 2300Z

Case study: Radar data - reflectivity



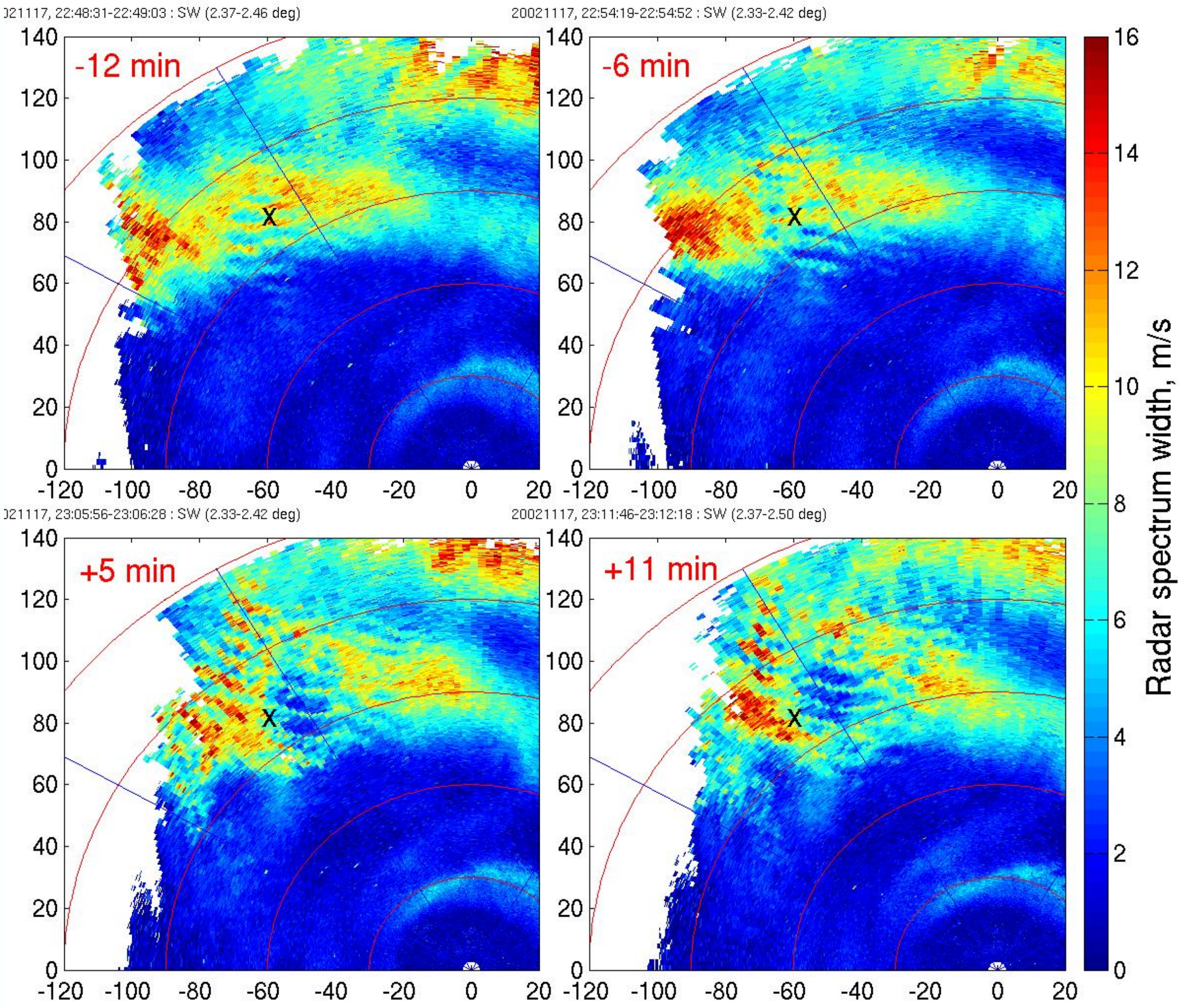
KAKQ 2.4° sweep radar reflectivity (0 to 40 dBZ)

Case study: Radar data – velocity



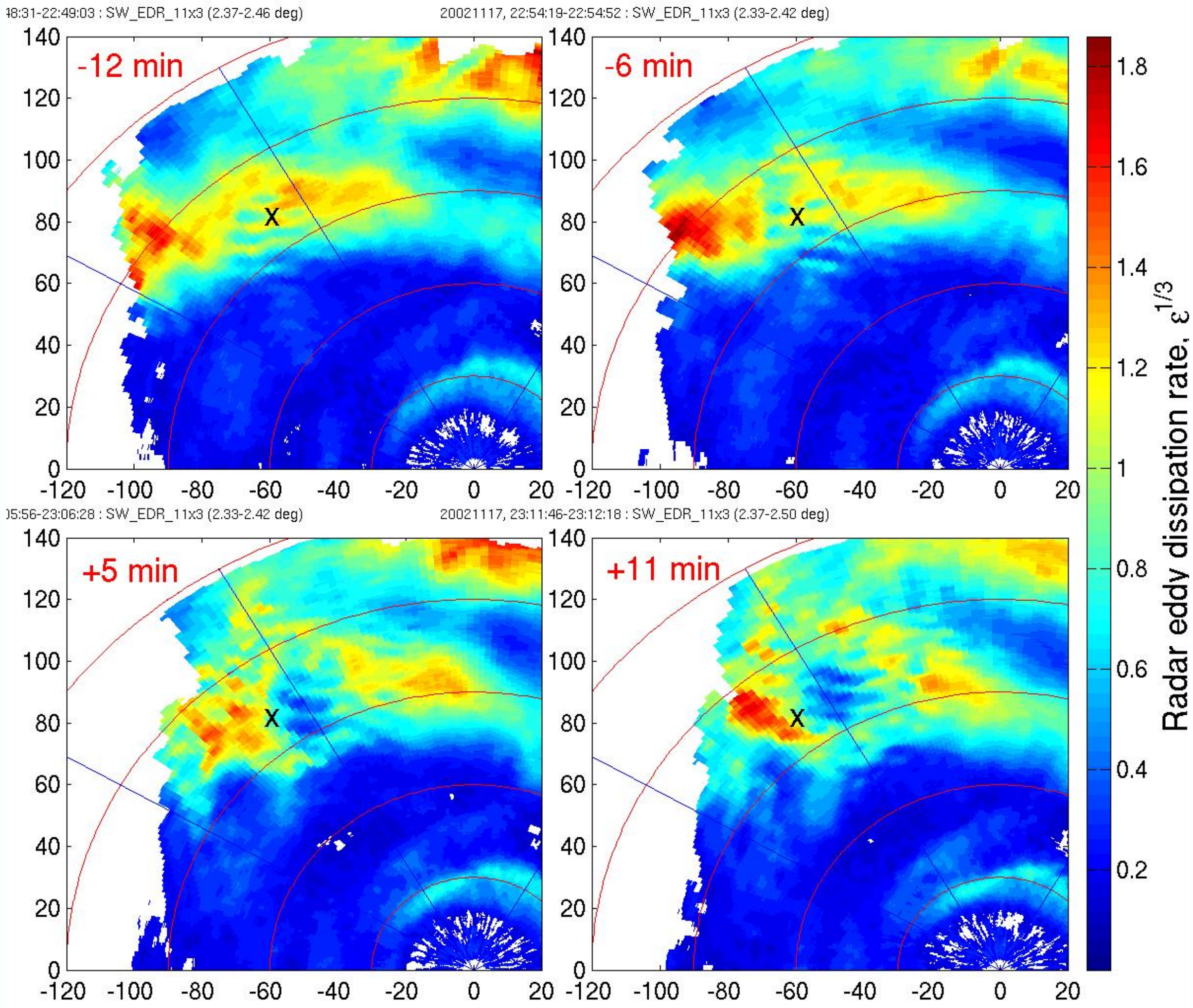
KAKQ 2.4° sweep radial velocity (-10 to 60 m/s)

Case study: Radar data – spectrum width



KAKQ 2.4° sweep spectrum width (0 to 16 m/s)

Case study: Radar data – NCAR EDR



KAKQ 2.4° sweep NTDA EDR ($\varepsilon^{1/3}$, 0 to 1.85 $m^{2/3}/s$)

AWRP

NCAR

Case study: Airbus A340 severe turbulence encounter on 6 August 2003

- Encounter at FL 310 over NE Arkansas, 20:57 UTC
- Vertical acceleration from -0.9 to +2.3 in about 3 seconds
- 43 minor injuries, two serious
- From the NTSB Factual Report:

…the flight crew noticed "a change in density, but did not get any radar echoes." A few seconds later, the flight encountered severe turbulence.

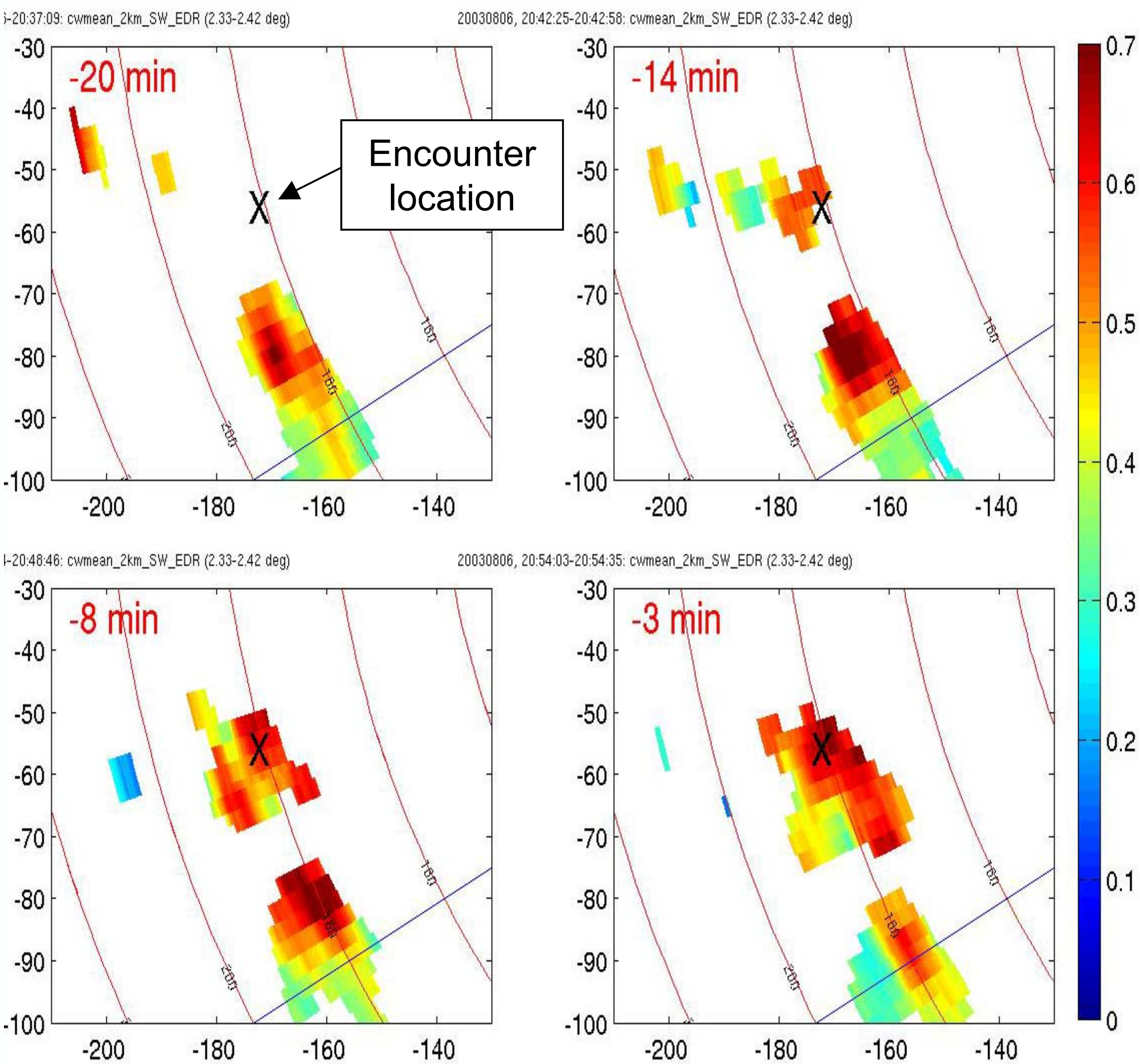
…seven FA's hit the cabin ceiling and then the floor, one FA hit the ceiling then an armrest, and two FA's were tossed through a galley. The trolleys…were lifted from the floor. Numerous food service items were tossed and broken throughout the cabin.

The FAA inspectors…found damage to cabin interior, ceiling, seats, and galley. Ceiling panels were loose, hanging down, or pushed upward...aircraft structure and cables were exposed.

AWRP

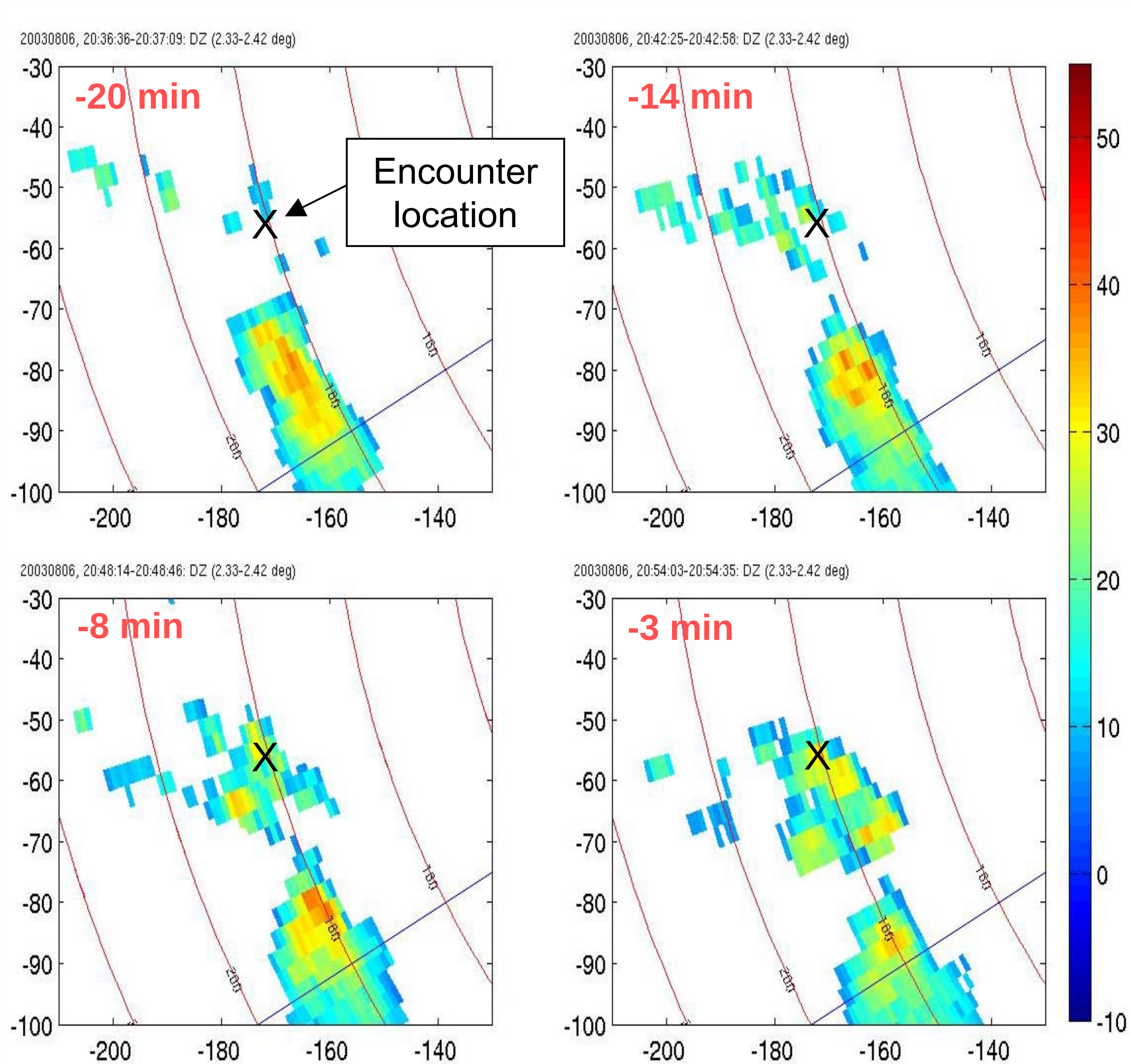
NCAR

Case study: NTDA EDR



KPAH 2.4° sweep NTDA EDR ($\varepsilon^{1/3}$, 0 to 0.7 $m^{2/3}/s$)

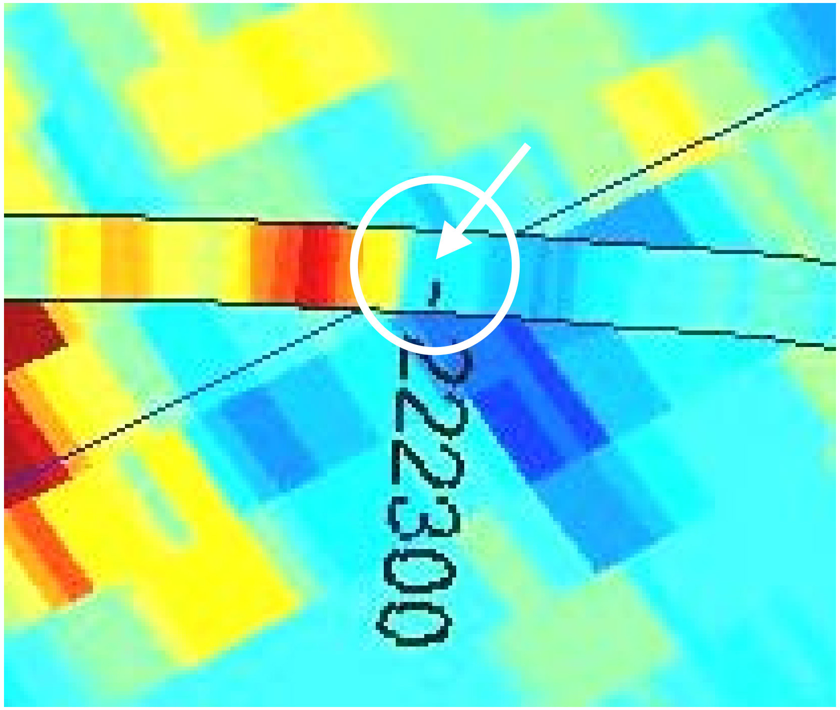
Case study: reflectivity



KPAH 2.4° sweep DZ (-10 to 55 dBZ)

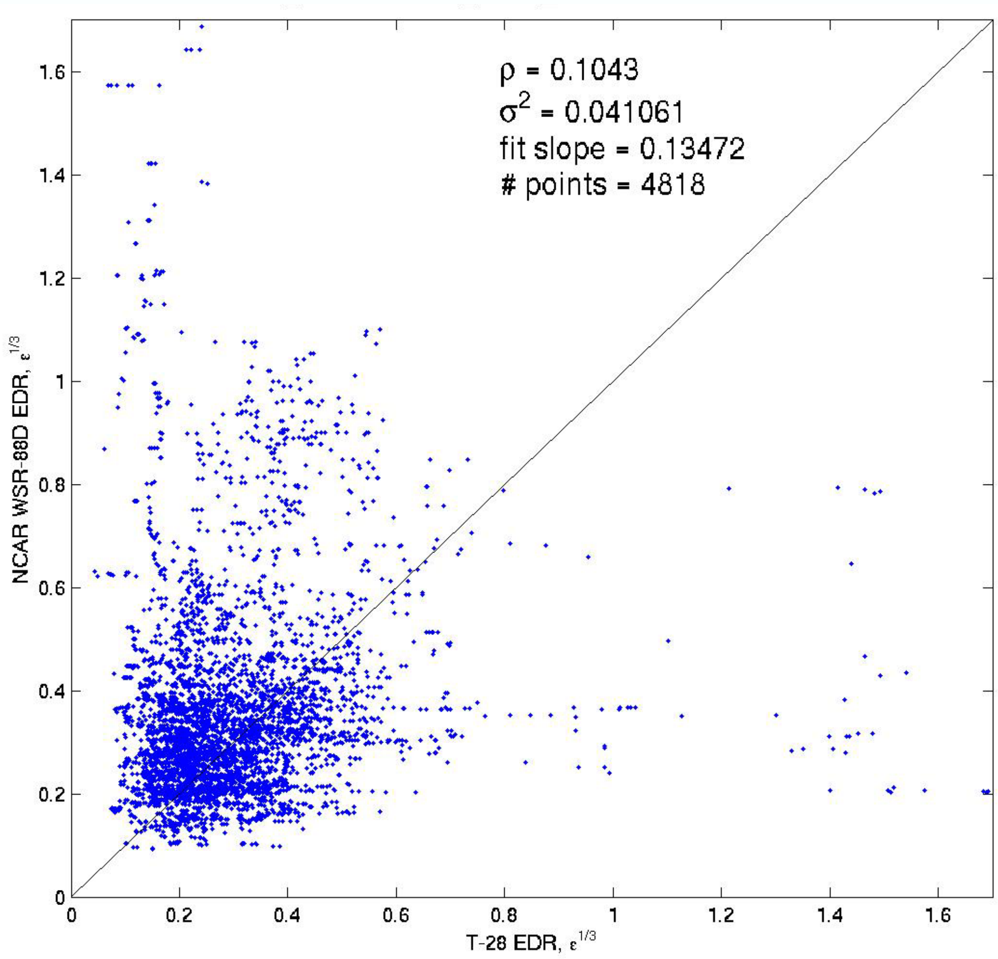
STEPS-2000 Field Program

- Severe Thunderstorm Electrification and Precipitation Study, May 17 - July 20, 2000, Goodland, Kansas
- SDSMT T-28 research aircraft flew 12 flights into
  - major downburst storms
  - mesoscale convective system
  - tornadic storms
  - supercell storms
- Ran NTDA on Level II data from WSR-88D (KGLD)
- Compared each in-situ value with statistic from surrounding disc on near scan



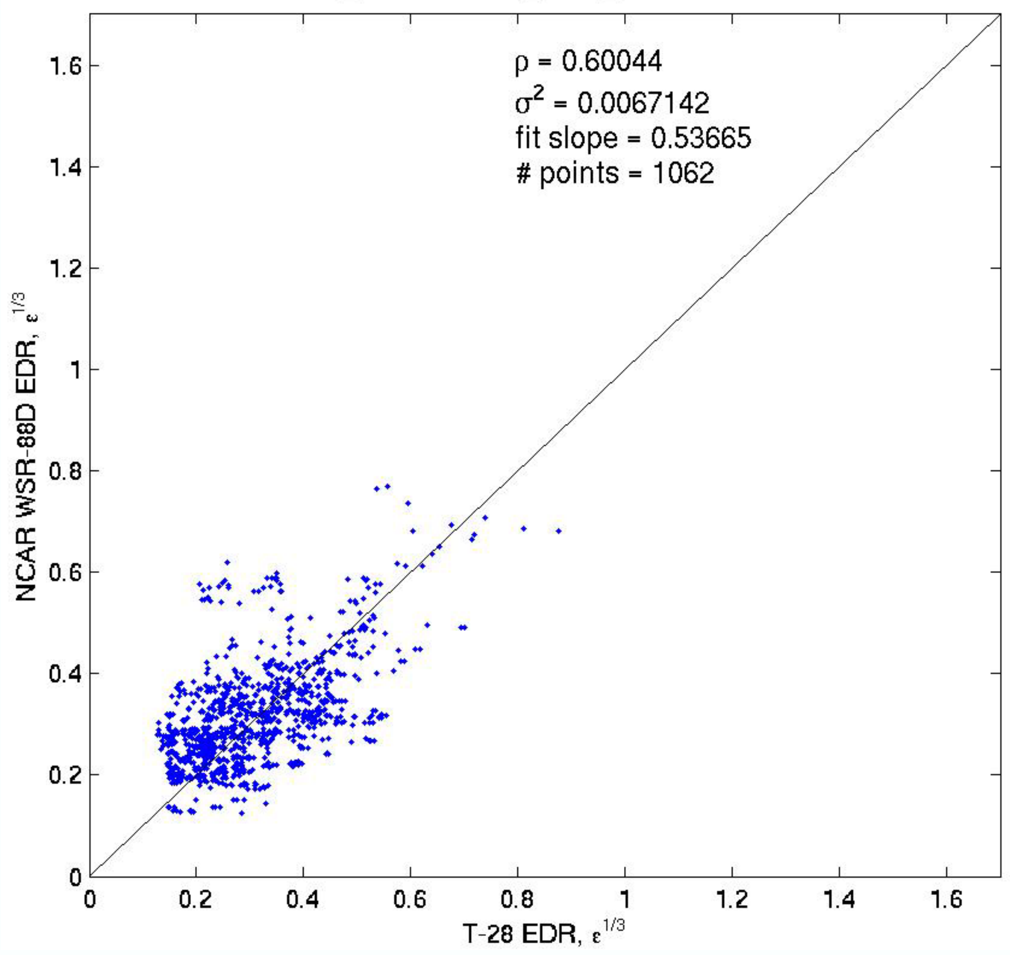
Example: The *in situ* EDR at 22:30 is compared to the median of radar values in a 1-km disc surrounding its location projected onto the nearest sweep

STEPS-2000: NTDA performance



NTDA "combined" method EDR with minimal QC (1 km disc median) vs. *in situ* EDR, all STEPS flights

STEPS-2000: NTDA performance, cont.



NTDA "combined" method EDR with more extensive QC (1 km disc median) vs. *in situ* EDR, all STEPS flights

NASA B-757 flight tests, spring 2002

- 11 flights over south-eastern US between 3 April and 18 May, 2002 with 55 turbulence encounter “events”
- Obtained Level II data for all NEXRADs along flight path from NCDC archives
- Ran NTDA
- Computed *in situ* EDR from vertical winds data
- Created overlay plots and timeseries plots
- “Scored” detection of turbulence encounters
- Created EDR mosaics for one flight

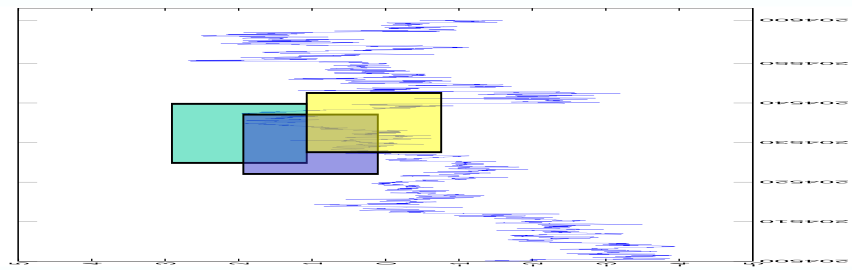
The NASA Langley B-757 aircraft

AWRP

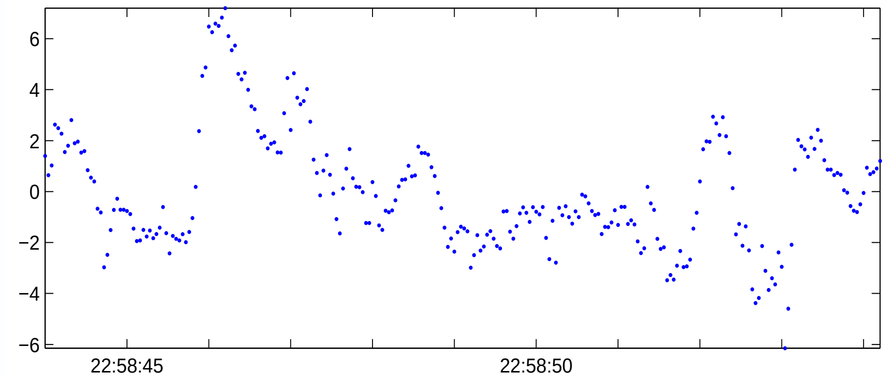
NCAR

In situ EDR

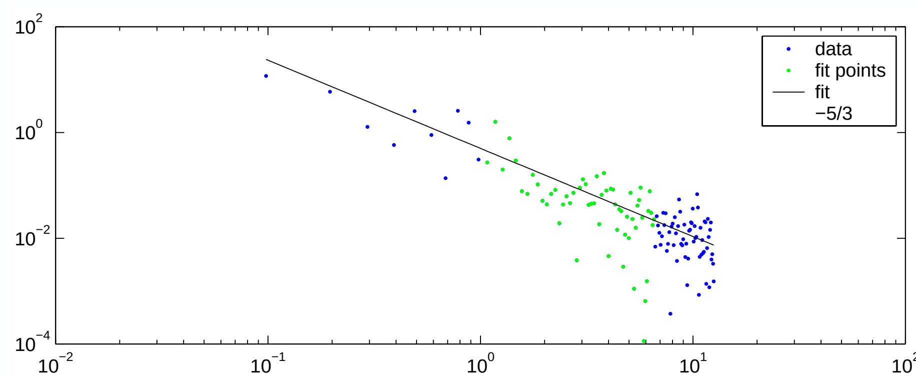
- Eddy Dissipation Rate is an aircraft-independent metric for the turbulence intensity in a volume of air
- Used vertical <u>winds-based</u> calculation method
- Maximum-likelihood, Von Karman model



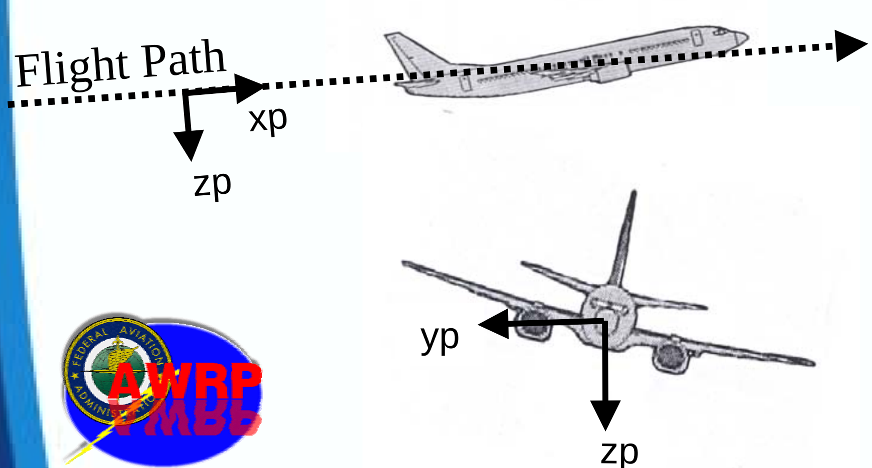
Sliding 256-point windows in *z*-wind timeseries



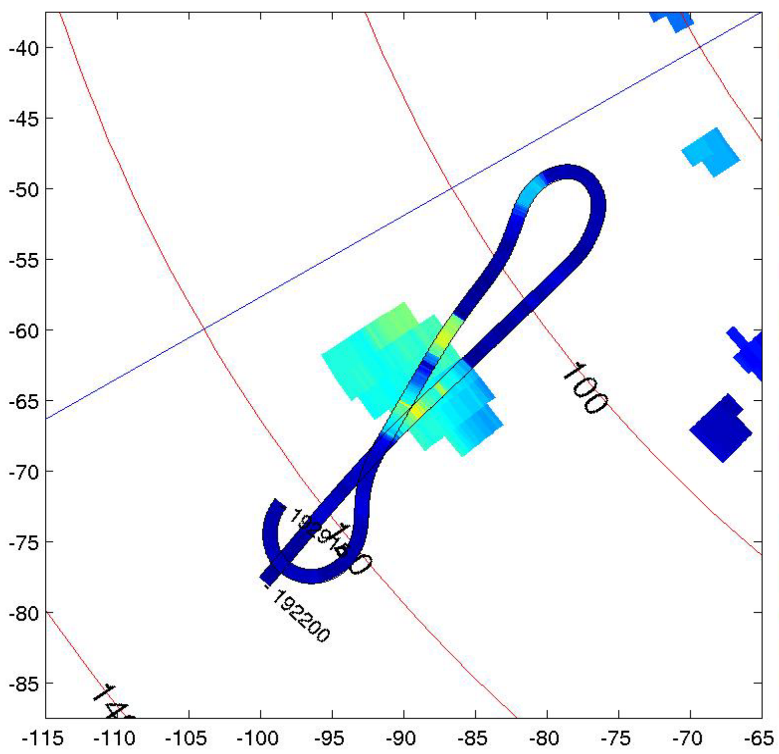
z-wind timeseries data



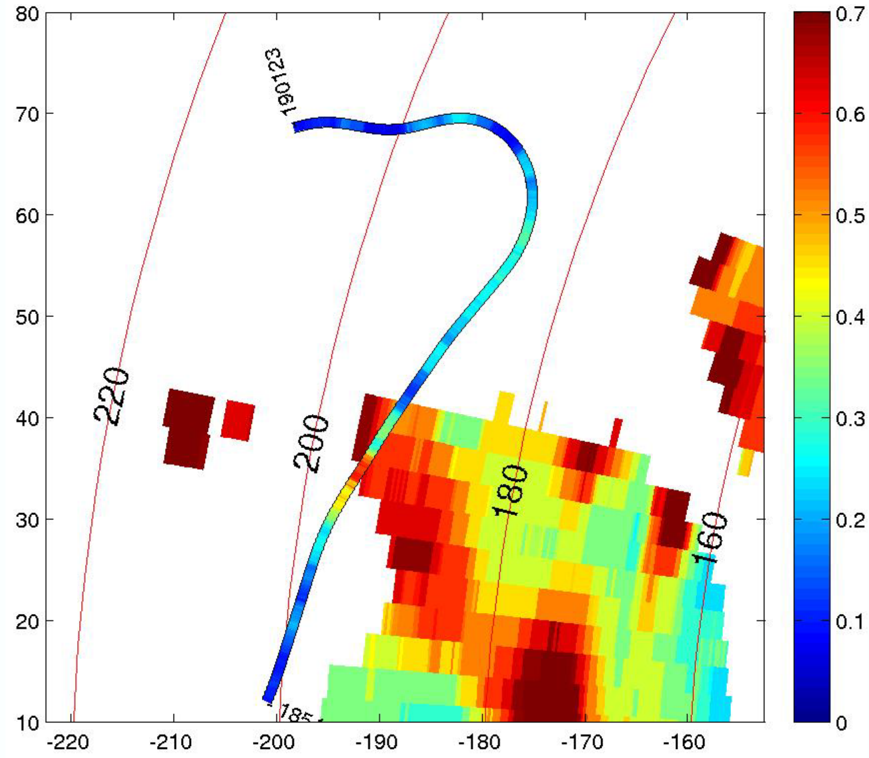
Resulting spectrum and maximum-likelihood fit



NASA B-757 turbulence flight tests, spring 2002



B-757 EDR (0 to 0.7 $m^{2/3}/s$) from 15 April 2004, 19:22–19:29 overlaid on 19:26 KLTX 2.4° NTDA EDR (refl. between 5-30 dBZ)

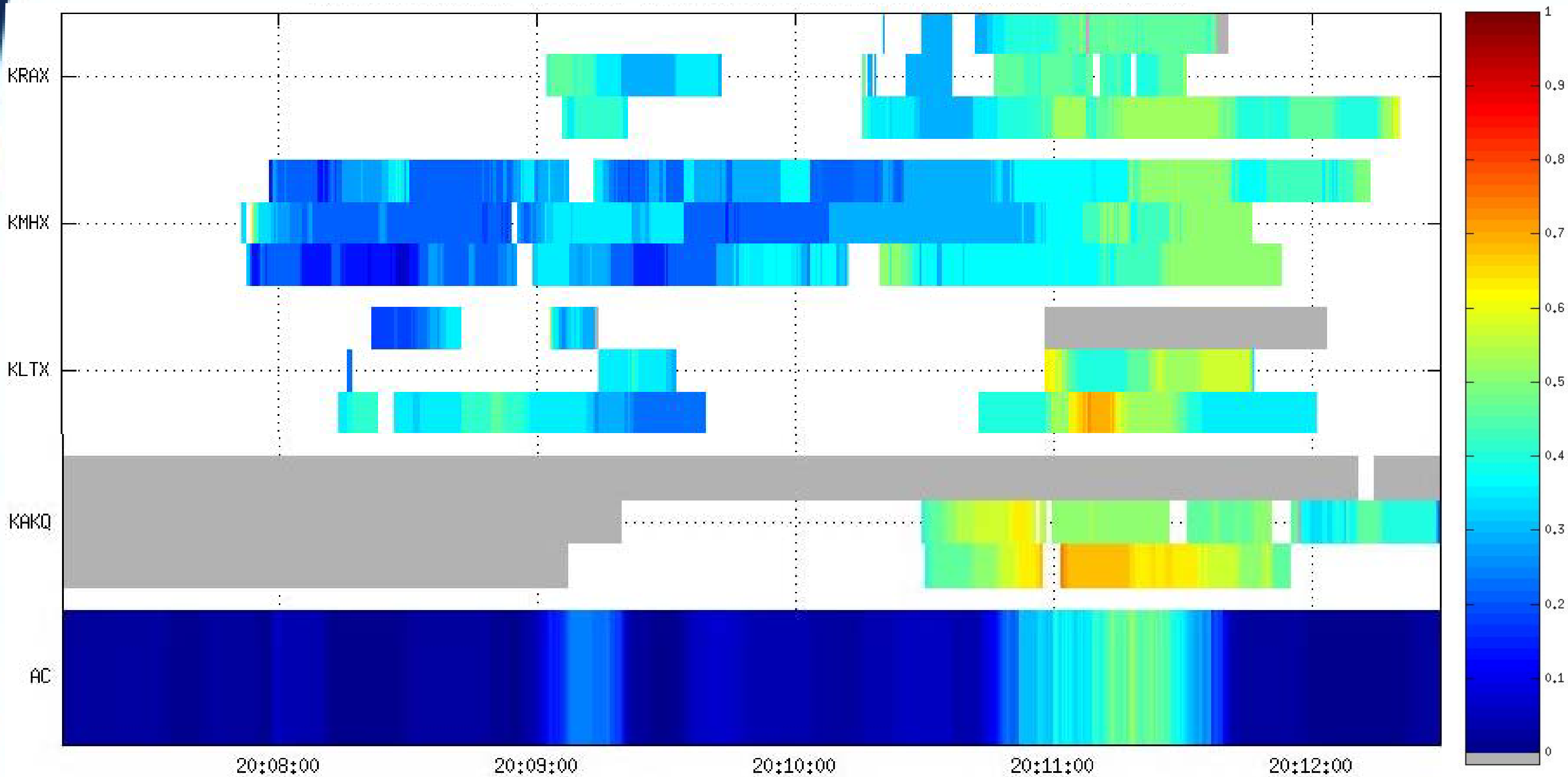


B-757 EDR (0 to 0.7 $m^{2/3}/s$) from 30 April 2004, 18:55–19:01 overlaid on KFFC 2.4° NTDA EDR (refl. between 5-15 dBZ)

AWRP

NCAR

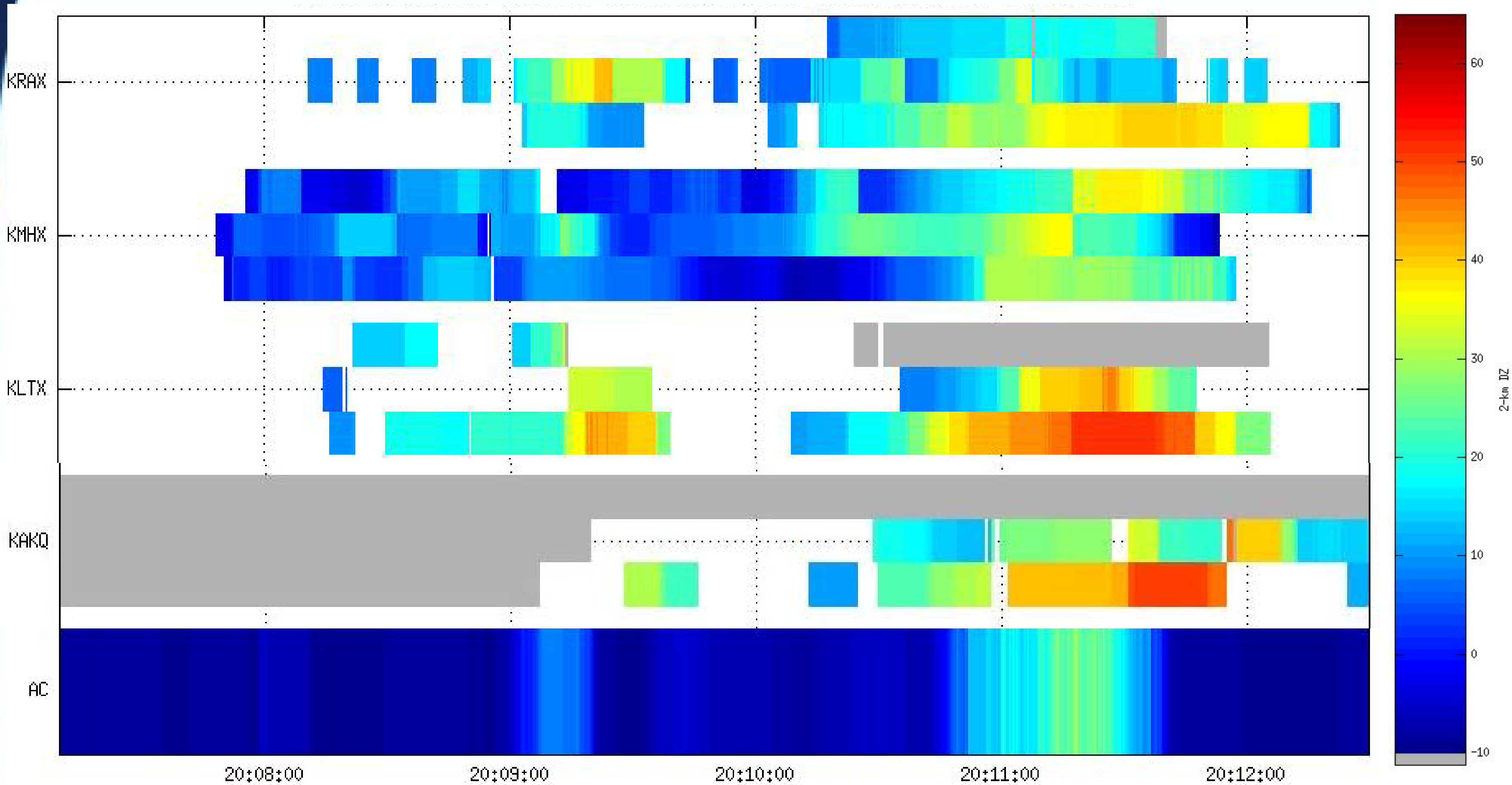
NASA B-757: “stacked-track” EDR



NASA B-757 aircraft EDR timeseries (bottom) and 2-km disc median NTDA EDRs (0 to 1 $m^{2/3}/s$) along aircraft track from nearest 3 sweeps of multiple NEXRADs,15 April 2002

NCAR

NASA B-757: "stacked-track" DZ



NASA B-757 aircraft EDR timeseries (0 to 1 $m^{2/3}/s$, bottom) and 2-km disc median radar reflectivity (-10 to 65 dBZ) along aircraft track from nearest 3 sweeps of multiple NEXRADs,15 April 2002

NCAR

Scoring NASA B-757 flight tests

AIRCRAFT \ RADAR NTDA	Detected	Not Detected
Turbulence	32	2
No turbulence	6	0

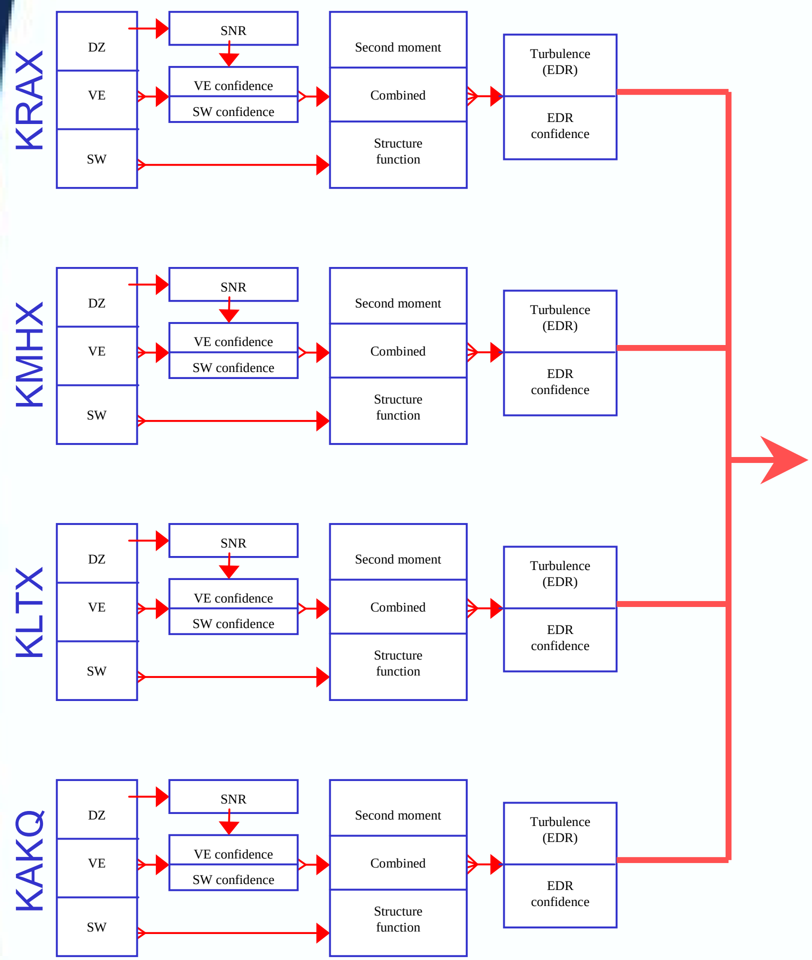
- Probability of Detection = 94%
- Nuisance Alarm Rate = 16%

But:

- 15 of 55 aircraft “events” had no available archived NEXRAD data
- these cases may not be representative of commercial aircraft encounters

$\Rightarrow$ Need to use PIREP or (better) *in situ* data to perform more comprehensive verification

Merging data from multiple radars

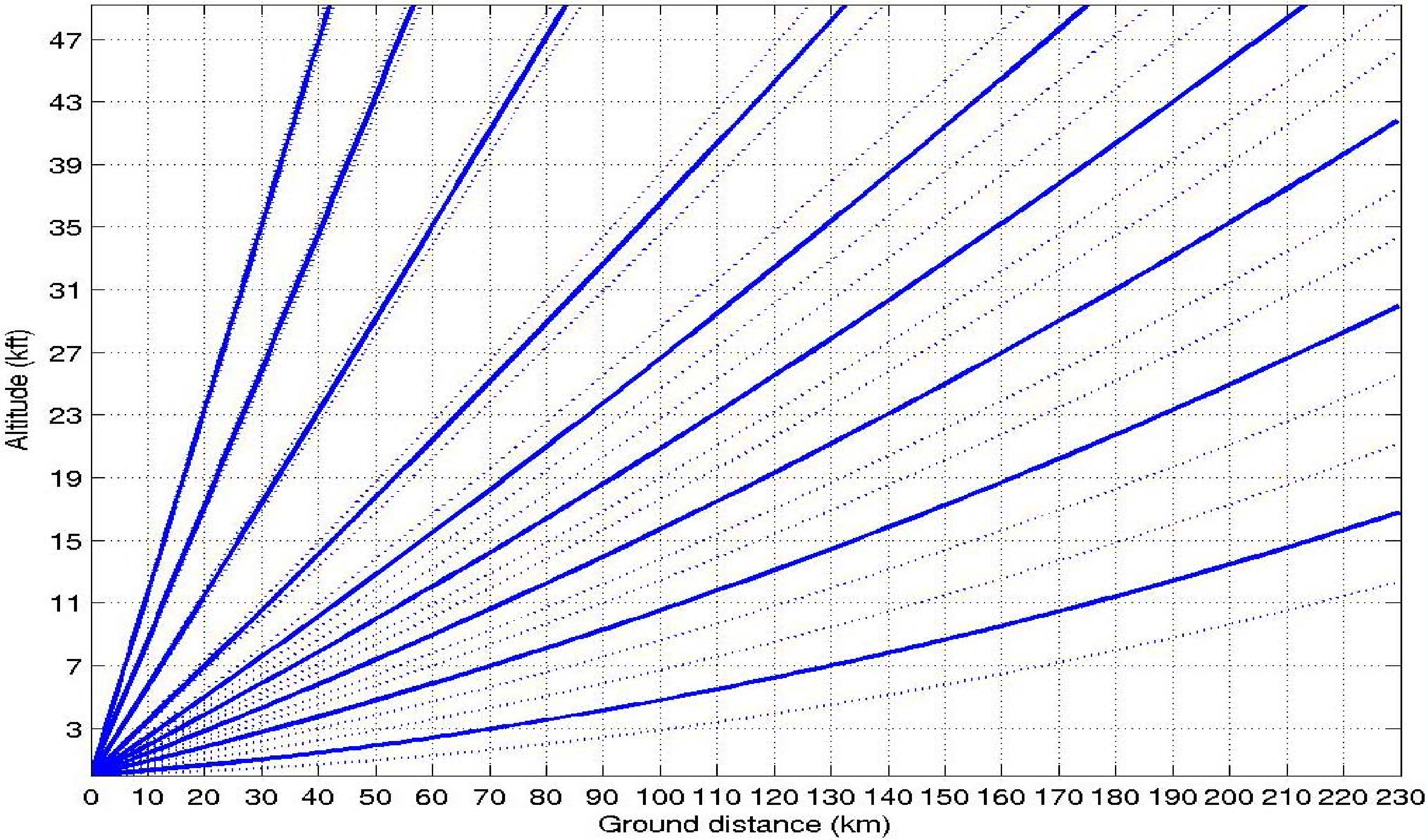


Distance*- and confidence-weighted mean EDR on grid†
Distance*-weighted mean confidence on grid†

* *Distance weights are Gaussian with $\sigma_{hor.}$ = 2 km, $\sigma_{vert.}$ = 2 kft*

† *Grid is regular lat-lon-alt of approximately 2 km x 2 km x 2 kft*

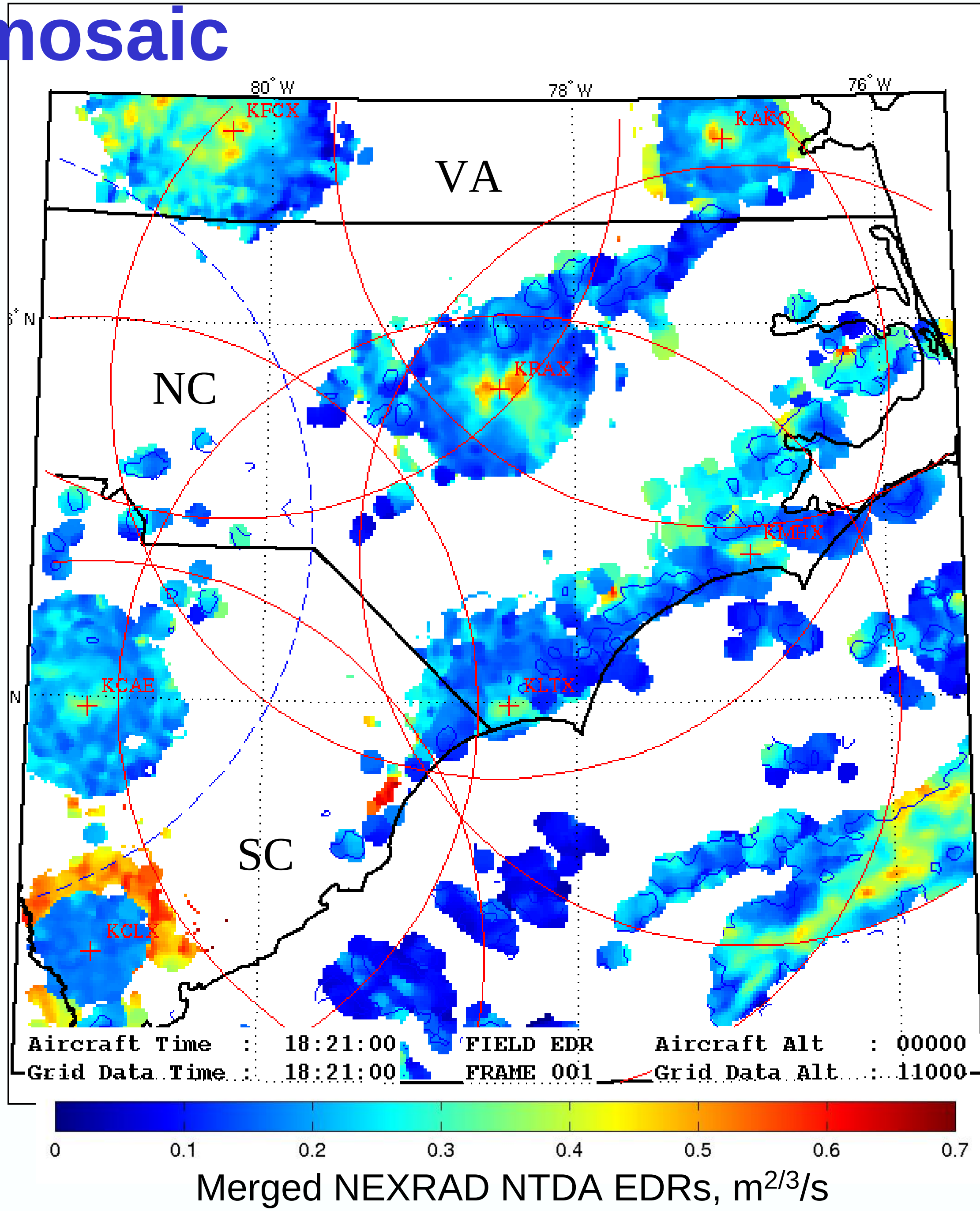
Challenge: radar geometry



Altitude above radar for 0.5, 1.5, 2.4, 3.3, 4.3, 6.0, 9.9, 14.6, and 19.5° tilts as a function of ground distance. Dotted lines represent ±1/3° beam paths.

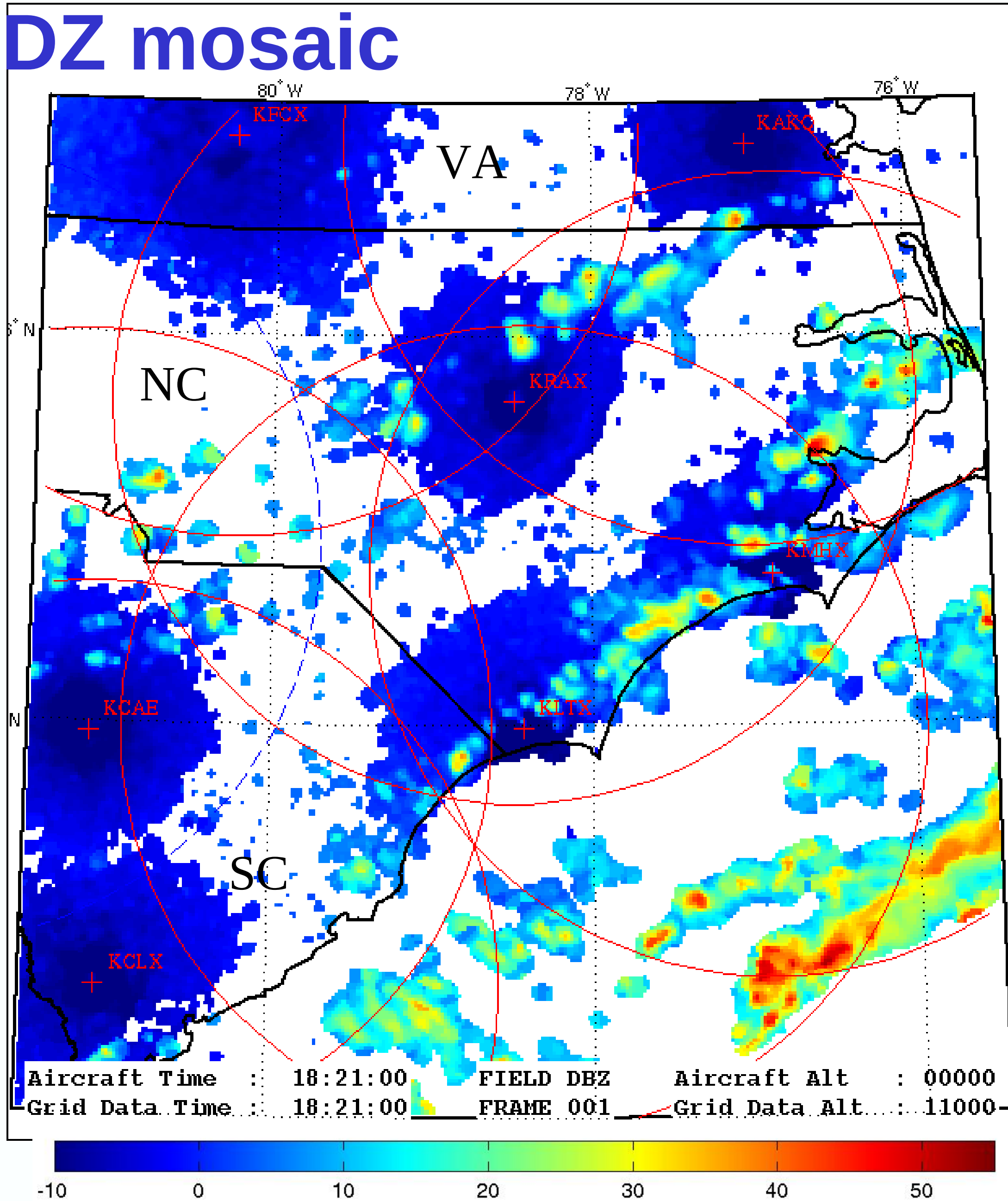
Example EDR mosaic

- Merged data from 5 NEXRADs covering B-757's 2:40 flight path through VA, NC, and SC on 15 April 2004
- Only EDRs with confidence > 0.1 are shown
- Contours are drawn at 15 dBZ reflectivity level
- Animation shows 5 lead and 5 trailing minutes of aircraft EDR ($\varepsilon^{1/3}$, 0 to 0.7 $m^{2/3}/s$)
- Grid level is determined by aircraft altitude (above 11,000 ft)



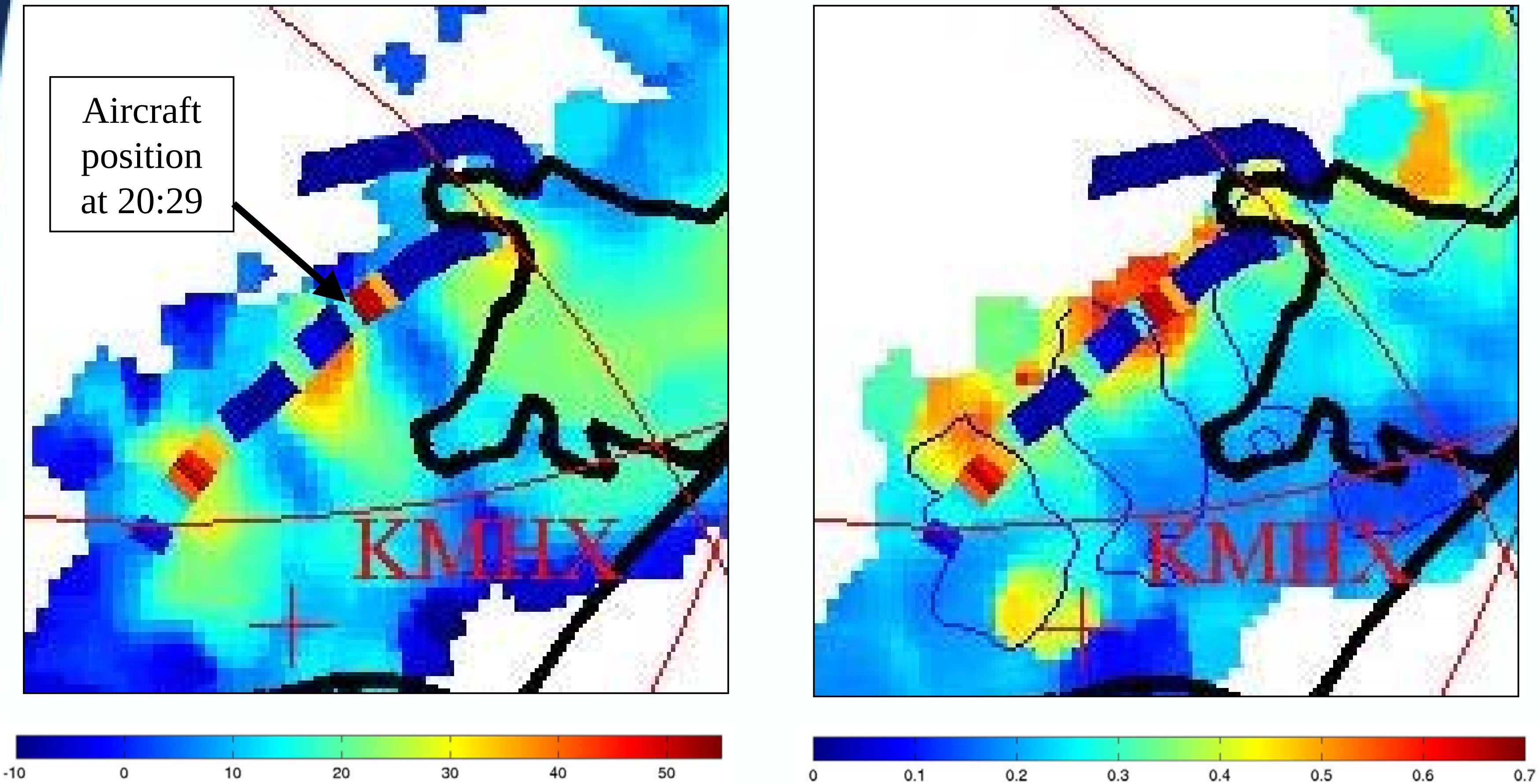
Corresponding DZ mosaic

- Merged data from 5 NEXRADs covering B-757's 2:40 flight path through VA, NC, and SC on 15 April 2004
- Only DZs with confidence > 0.5 are shown
- Animation shows 5 lead and 5 trailing minutes of aircraft EDR ($\varepsilon^{1/3}$, 0 to 0.7 $m^{2/3}/s$))
- Grid level is determined by aircraft altitude (above 11,000 ft)



Merged NEXRAD DZs, dBZ

Mosaic comparisons



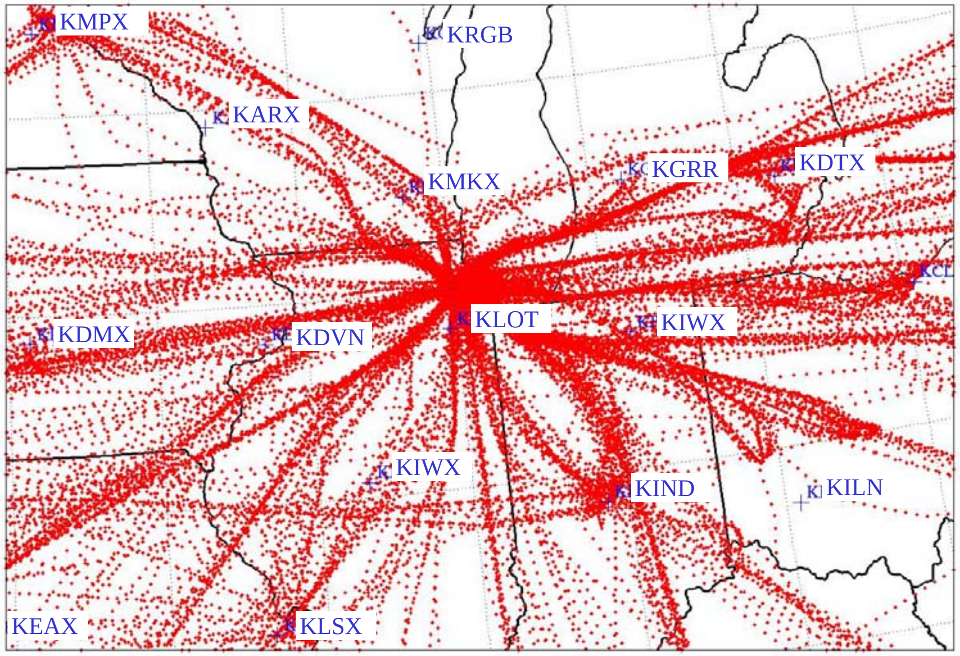
Merged NEXRAD DZs, dBZ

Merged NEXRAD NTDA EDRs, $m^{2/3}/s$

Overlay plot for 15 April 2004,
grid time 20:27, aircraft time 20:29

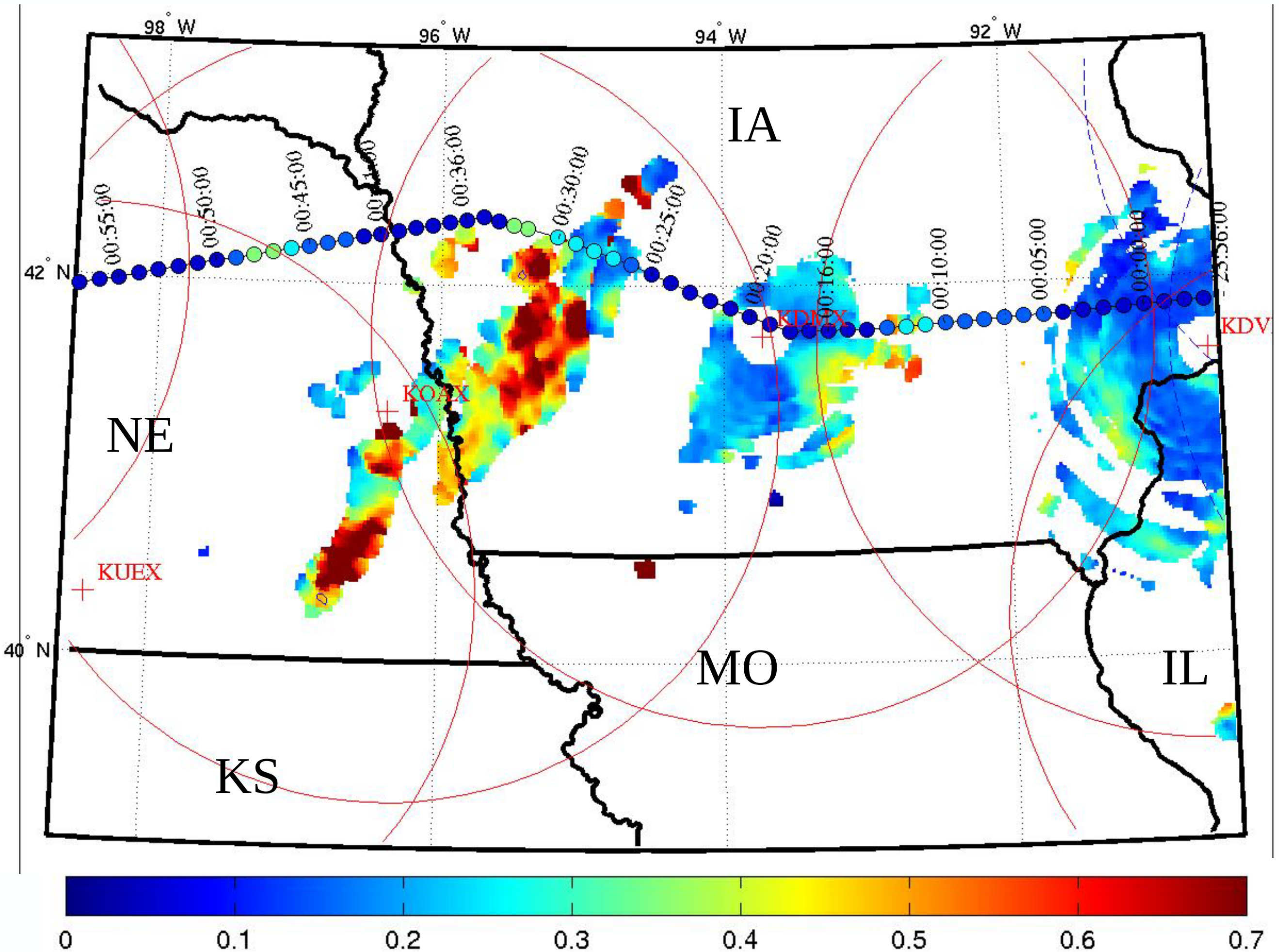
Future plans—FY05

- Real-time turbulence detection demonstration in Summer ’05: Chicago area, 3-6 radars
- Real-time web display at NCAR/RAP site
- EDR uplink to ACARS printer on select aircraft
- Verification and tuning using *in situ* EDRs from commercial aircraft
- Feedback solicited from potential users



Locations of *in situ* turbulence measurements near Chicago during November, 2003

Example: *In situ* comparison



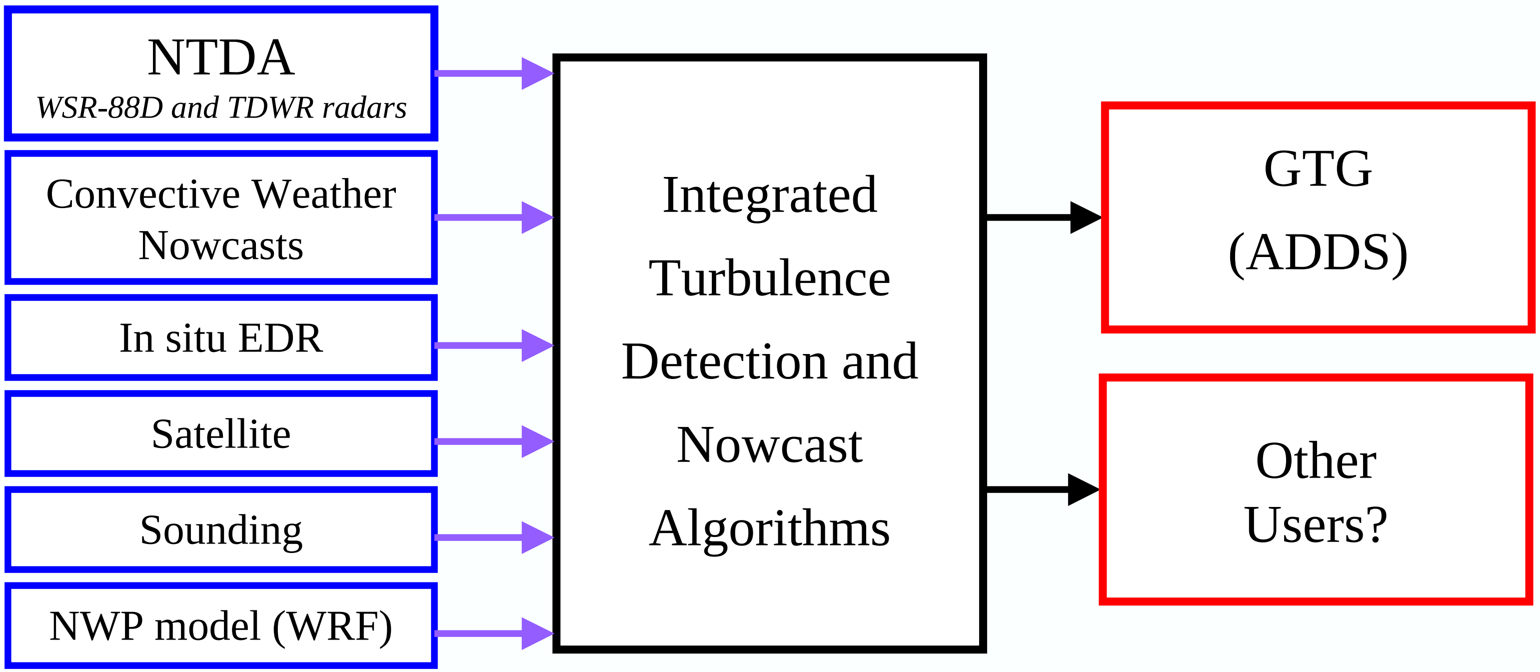
Merged NEXRAD NTDA EDRs and overlaid *in situ* EDRs , $m^{2/3}/s$

18 November 2003, 00:30 UTC grid, 31,000 ft
with ORD to SLC flight *in situ* EDRs overlaid

NTDA Proposed Implementation Timeline

- **FY05**
  - NTDA informational briefing presented to NEXRAD TAC
  - NTDA CODE implementation, mods to accommodate OpenRDA changes, and continued verification
- **FY06**
  - NTDA decision briefing presented to NEXRAD TAC
  - NTDA CODE implementation approval briefing to NEXRAD SREC
- **FY07**
  - NTDA deployment on WSR-88D radars
  - NTDA turbulence diagnoses merged and integrated into GTG
- **FY08**
  - NTDA implementation on TDWR and ASR radars
- **FY09**
  - Advancement to AWRTT-approved experimental status for GTG5

Future work: Integrated system for in-cloud and out-of-cloud turbulence nowcasts and forecasts



Goal: Demonstration FY06, deployment FY09

AWRP

NCAR

NTDA future technical needs

- Reliable spectrum width measurements (esp. in low dBZ)
  - Spectral QC and moment estimation methods
- Ability to trade SW resolution for accuracy
  - Oversampling, spectral averaging
- Freedom to choose censoring threshold
  - QC "confidence" fields supplied for Level-II variables
- Polarimetric data for
  - Improved QC
  - Additional turbulence diagnostic
  - PID to support mitigation of hydrometor inertial effects

Future information needs

- Guidance on what verification studies, other steps are required before NTDA can be approved for deployment
- “In the loop” on proposed NEXRAD OpenRDA/RPG changes that may affect NTDA
  - R/V ambiguity mitigation techniques (e.g., SZ, staggered PRT)
  - Data quality improvement and censoring
- Collaboration on advanced QC and processing techniques?

Acknowledgements

- Many thanks to
  - the FAA's Aviation Weather Research Program for funding this work
  - NASA Langley Research Center for making available the TPAWS field program data
  - the National Transportation Safety Board for providing FDR and other accident information
  - the National Climate Data Center for supplying archived NEXRAD Level II data
  - Larry Cornman for being the chief creative force behind the project
  - and my colleagues Steve Carson, Danika Gilbert, and Jaimi Yee