

**FY02 TPAWS RADAR NASA B757 FLIGHT  
CAMPAIGN SUMMARY**

**CONTRIBUTIONS PREPARED BY:**

**NASA-Langley**

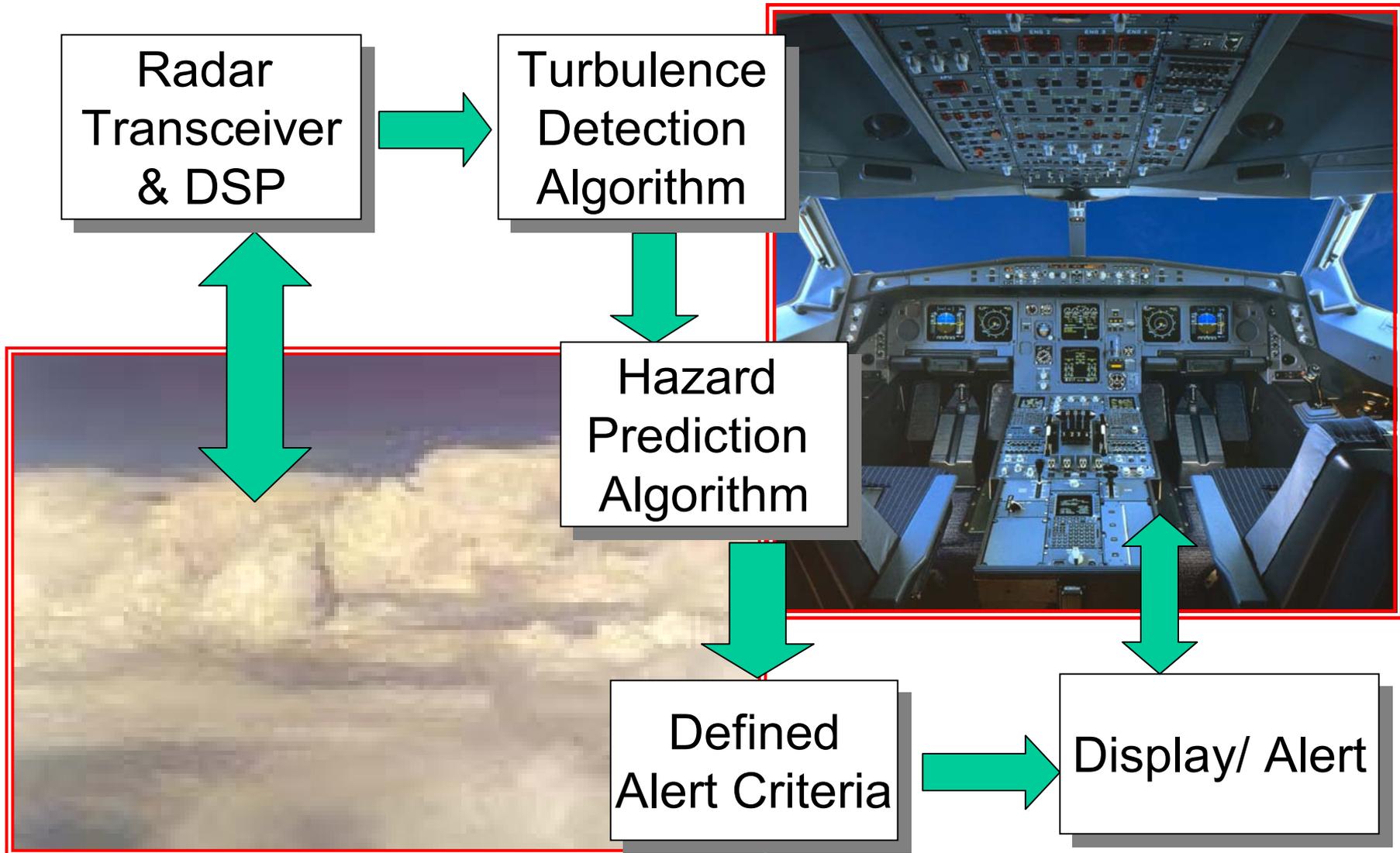
**NCAR**

**AERO TECH RESEARCH INC.**

# **OUTLINE**

- **TURBULENCE PREDICTION & WARNING SYSTEM (TPAWS) CONCEPT**
- **FY02 FLIGHT CAMPAIGN TURBULENCE CHARACTERIZATION**
- **A “SHOW CASE EVENT” CASE STUDY (R232-10)**
  - **FLIGHT OPERATIONAL SITUATION**
  - **WX - SITUATION / AIRCRAFT INSITU MEASUREMENTS**
  - **TPAWS RADAR PERFORMANCE**
- **TPAWS PERFORMANCE SUMMARY FOR FY-02 FLIGHT CAMPAIGN**
- **CONCLUDING REMARKS**
- **WHERE DO WE GO FROM HERE**

# TPAWS End-to-End System Concept



# TPAWS DESIGN FEATURES

HAZARD METRIC: PREDICTED  $\sigma_{\Delta\eta}$  BASED ON RADAR OBSERVABLES

DESIGN THRESHOLDS :

- THEORETICAL BASIS EXISTS
- AIRCRAFT CENTERED
- UNIFORM APPLICATION TO PART 121 FLEET
- SCALES WITH FACTORS WHICH PRODUCE INJURIES

**MUST NOT ALERT** ----- < .2 g

**MAY ALERT CAUTION** ----- ≥ .2 g

**MUST ALERT CAUTION** ----- ≥ .3 g

FAA MINIMUM PERFORMANCE STANDARDS :

Advance warning of ≥ 30 sec. with POD ≥ 80% for turbulence phenomena with reflectivity ≥ 15 dBz.

KEY CONCERN :

Unintended consequences of over-warning due to nuisance alerts.

# **FY02 TPAWS Flight Campaign**

## **Meteorology and Turbulence Characterization**

Presented by

**David Hamilton**

***NASA Langley Research Center***

***Hampton, Virginia***

with contributions from  
Fred H. Proctor, Ph.D.

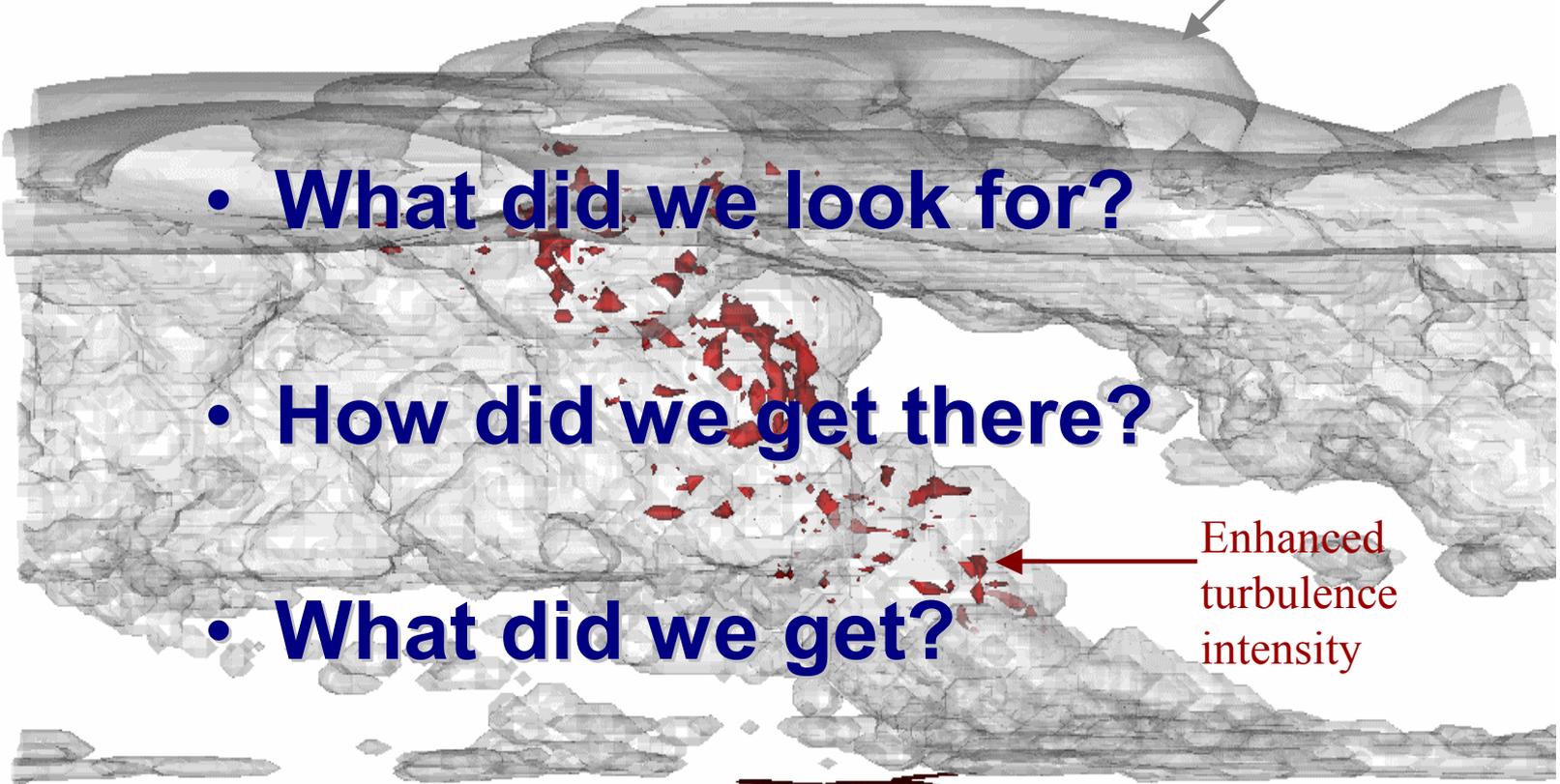
NASA Weather Accident Prevention Annual Project Review 2002  
November 20 - 21, 2002  
MIT Lincoln Lab, Lexington, MA

# Outline

Cloud  
top

- What did we look for?
- How did we get there?
- What did we get?

Enhanced  
turbulence  
intensity



# What did we look for?

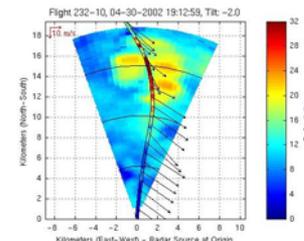
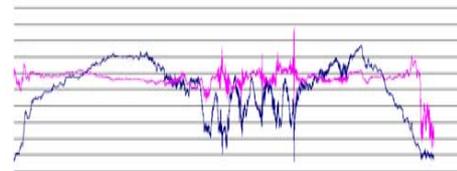
- **CIT – Convectively Induced Turbulence**
- **Turbulence regions**
  - hazardous to aircraft
  - in vicinity of thunderstorms
  - with measurable hydrometeors  
i.e. radar reflectivity

# How did we get there?

- **NASA-Langley's ARIES B-757**  
Airborne Research Integrated Experiments System



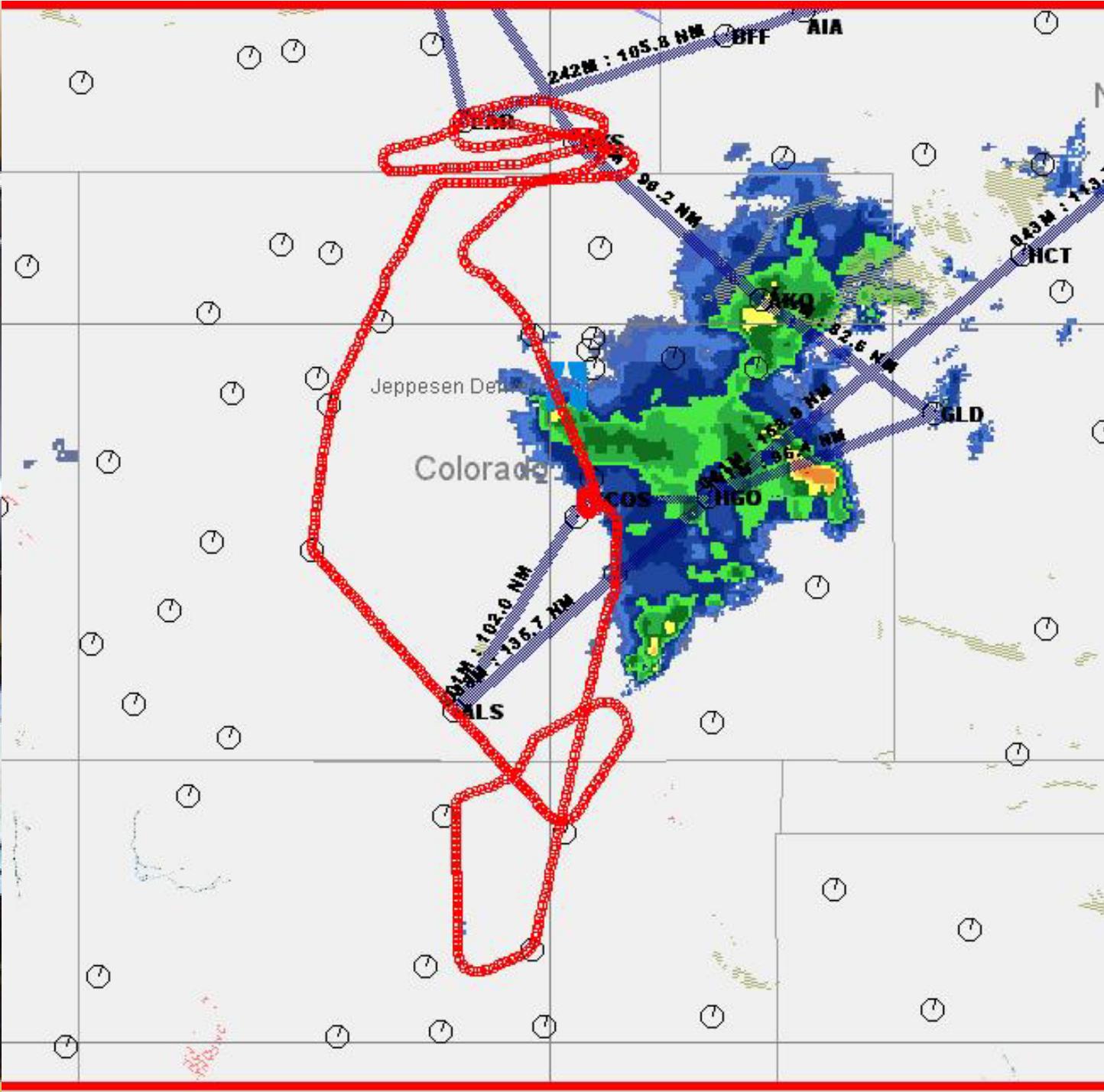
- **Airborne Turbulence 'Tools'**
  - *In situ* sensors measure wind, temperature and acceleration
  - Onboard Doppler radar for forward turbulence detection



# How did we get there?

- **Turbulence locations forecast by Langley Meteorology team**
  - Brief researchers
  - Brief pilots for flight planning
- **Meteorologist on board provided guidance into turbulent regions**
  - Onboard internet “weather” products via skyphone
- **Meteorologist on ground monitored “weather” progress and aircraft position**
  - Remained “on call”





# **Flight Requirements**

## **The Do's**

- **Locate CIT within a day's flight range of NASA Langley**
- **Operated under normal air traffic constraints**
- **Approach convection visually**
- **Obtain turbulence measurements of light and moderate intensity**

# Flight Requirements

## The Don'ts

- **Avoid**
  - **Severe turbulence**
  - **Regions with radar reflectivity greater than Level 3, i.e.  $RRF \geq 40$  dBZ**
  - **Lightning**
  - **Icing conditions**

# What did we get?

- **Convectively induced turbulence data collected throughout the southeastern CONUS**
- **10 flights between 2 Apr – 17 May, 2002 with significant turbulence**
- **Variety of convection encountered:**
  - **squall lines**
  - **sea breeze convection**
  - **tropical convection**
  - **multicellular convection**
  - **isolated “airmass” convection**

# What did we get? (cont.)

- **84 estimated penetrations into convection**
- **49 events of significant turbulence measured *in situ***
- **Strongest events associated with penetration of updrafts. Peak loads on periphery of updraft**
- **Two encounters in ‘clear air’**
- **PIREPS indicated commercial encounters with turbulence in vicinity of 6 research flights; 227, 229, 231, 232, 233, and 234**

# What did we get? (cont.)

## Video

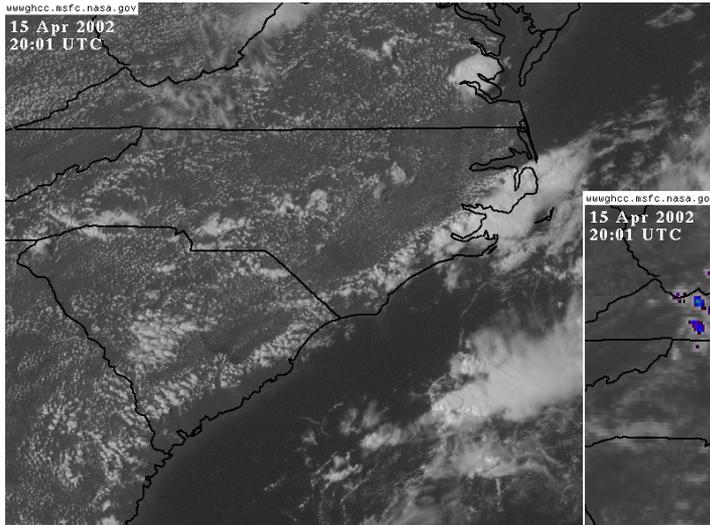


# What did we get? (cont.)

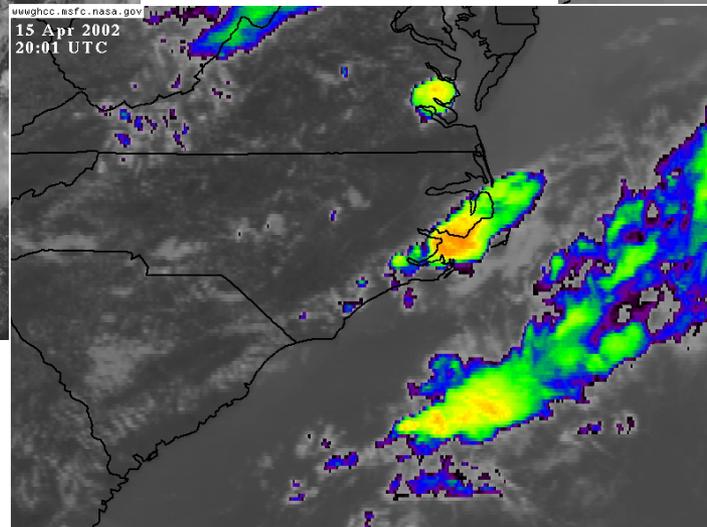
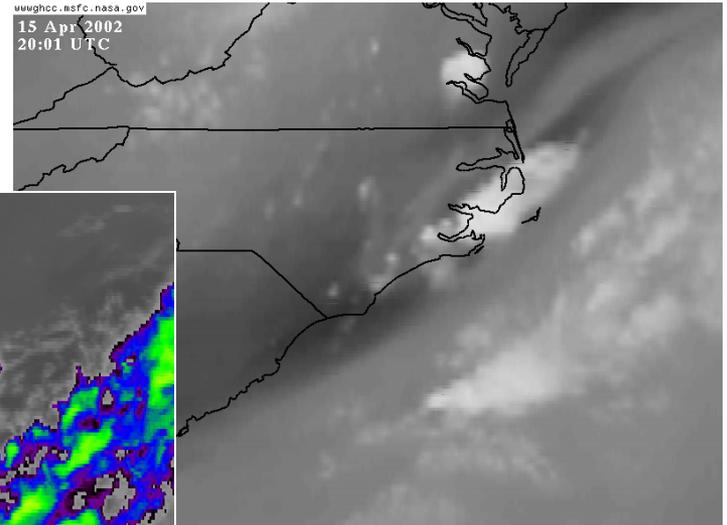
## Met. Data

- Satellite

**1 km Vis**



**4 km WV**

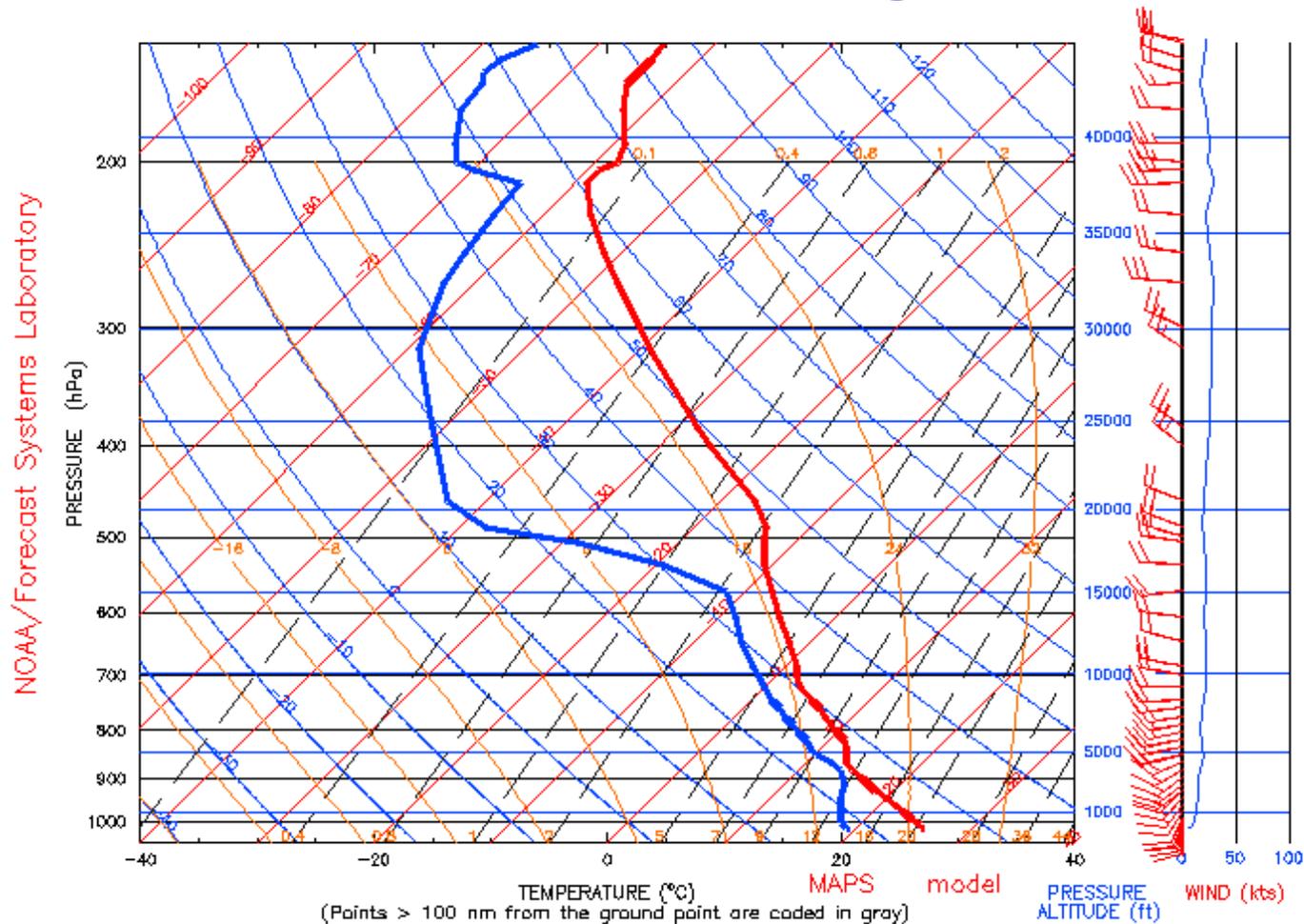


**4 km IR**

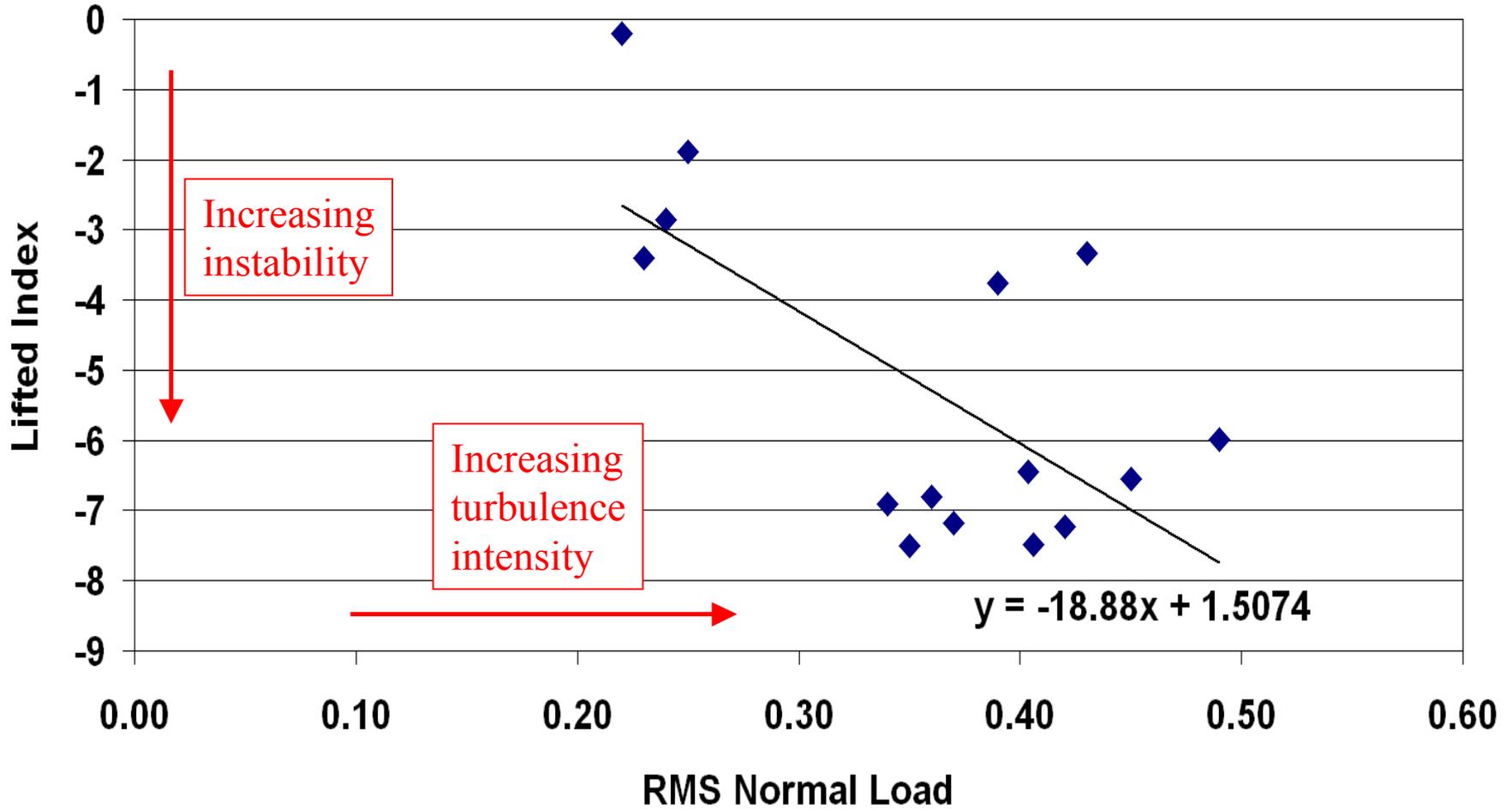
# What did we get? (cont.)

## Met. Data

- Model Sounding Data



# RMS Normal Load vs. Model Lifted Indices



# What did we get? (cont.)

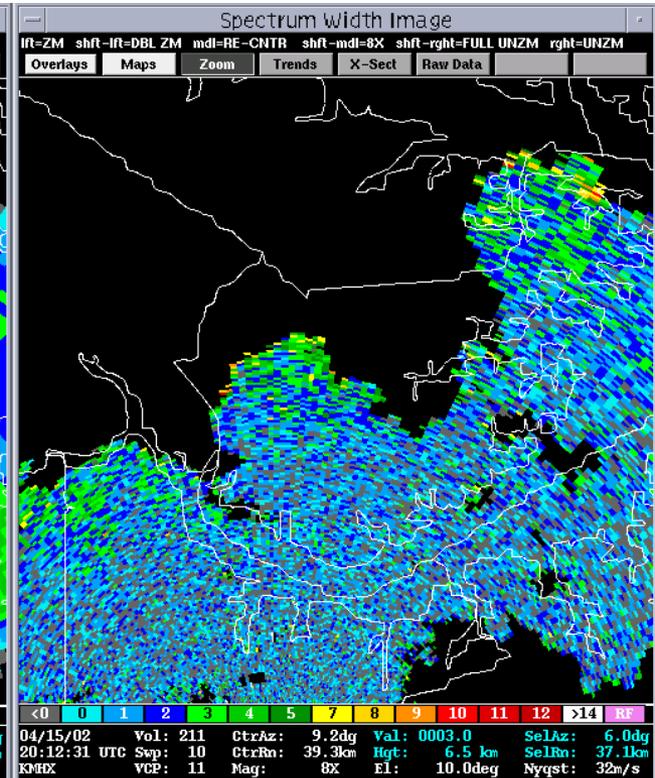
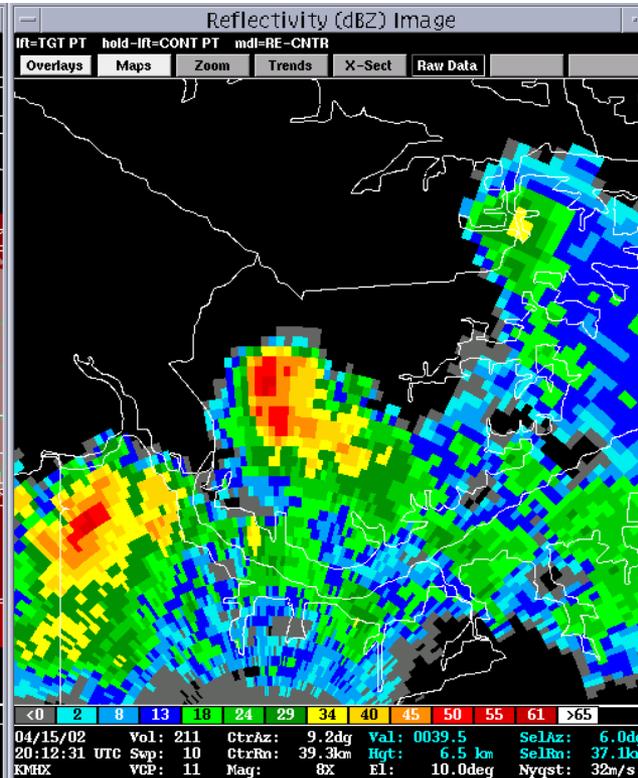
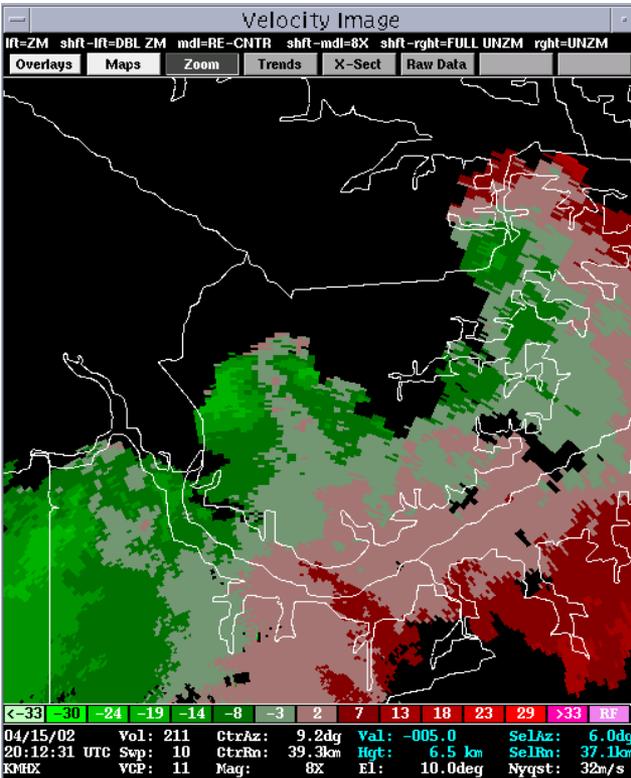
## Met. Data

- Nexrad Level II Data

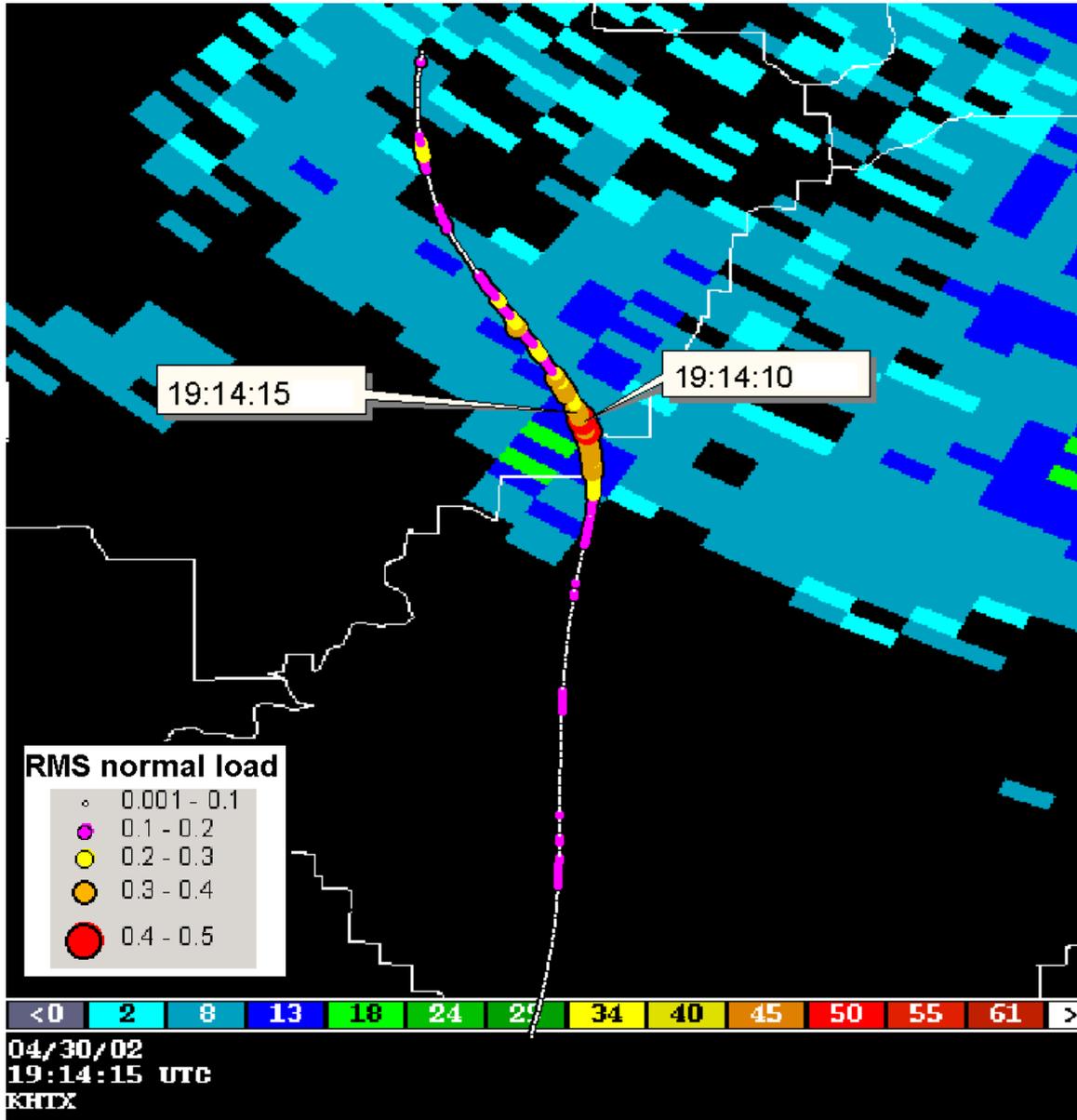
Radial Velocity

Base Reflectivity

Spectral Width



# What did we get? (cont.)



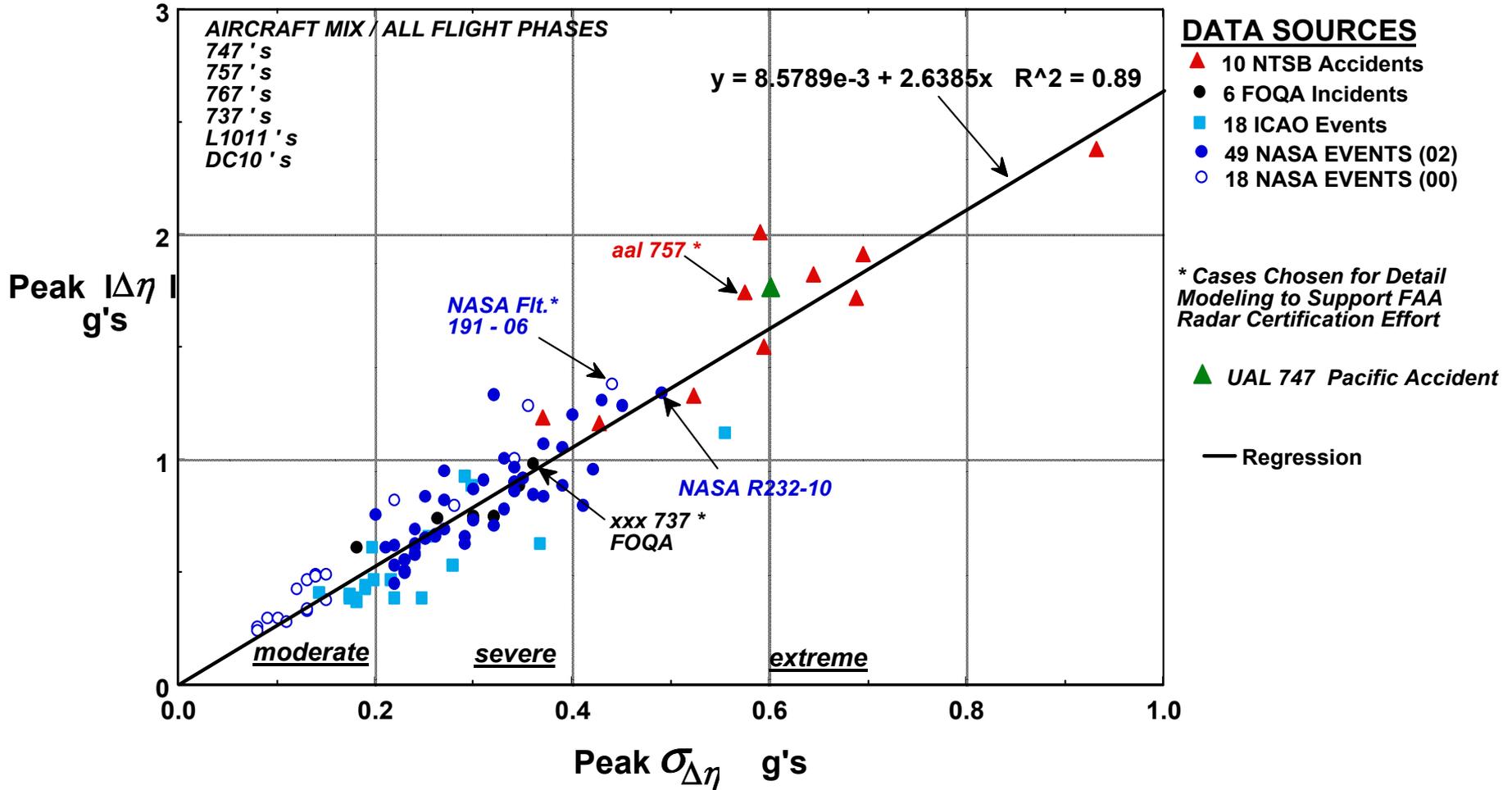
- Along path loads on Nexrad Reflectivity

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# Correlation of Peak Load With Peak RMS Load ( 5 sec. window)

Based on Measurements for 102 Turbulence Encounter Cases



**ESTIMATED FROM RADAR OBSERVABLES FOR TPAWS CONCEPT**

# **R232-10 IS A “SHOW - CASE” EVENT**

## **PREVAILING OPERATIONAL**

### **SITUATION**

- IMC - see and avoid convection not a reliable option
- Low reflectivity convection in area with localized embedded severe turbulence
- Conventional “ships” radar-display painting black & green
- Turbulence PIREPS reported by commercial traffic in the contiguous area
- Low - reflectivity environment precluded identification of “escape path” prior to encounter

**QUESTION: Where is the turbulence relative to flight path, and is it hazardous?**

**ANSWER: TPAWS TECHNOLOGY ! Exactly the tactical scenario for which the TPAWS design is expected to provide operational safety benefits.**

# Characterization of Case Environment

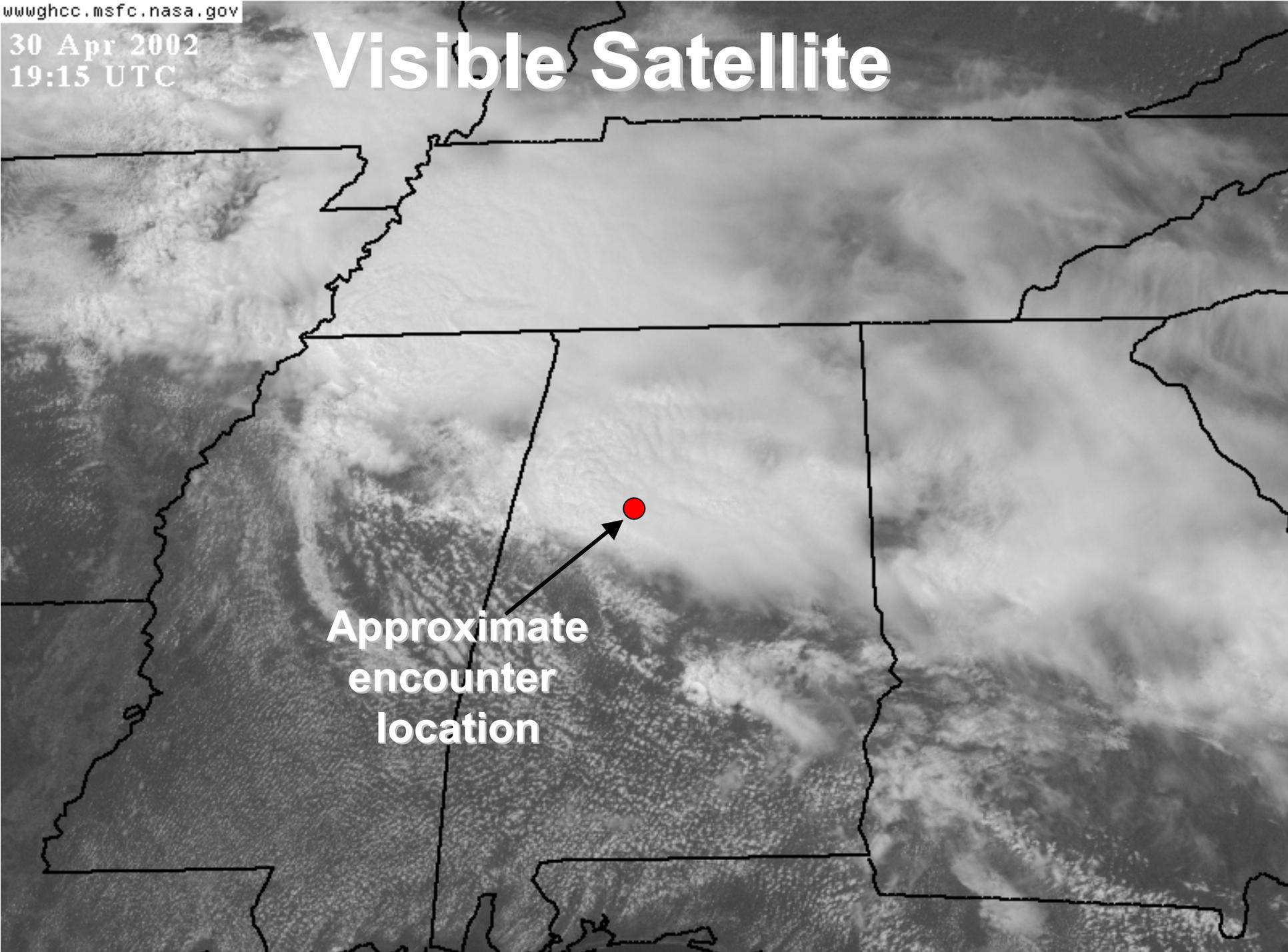
- Narrow line of convective cells detected by ground radar
  - Extends east-west across Alabama.
  - Storm Tops between 35,000 and 40,000 feet.
  - Cell motion: towards ESE at 25 knots
- Visibility: IMC due to blow off from upstream storms
- Flight level winds: from WNW at 100 kts
- Turbulence Potential – Airmet for moderate turbulence north of convection

# Characteristics at Flight Level

- Radar reflectivity between 12 and 30 *dBz*
- Rising storm tops
- Precipitation in the form of ice crystals
- Continuous light chop in surrounding environment
- Severe turbulence associated with rising storm tops

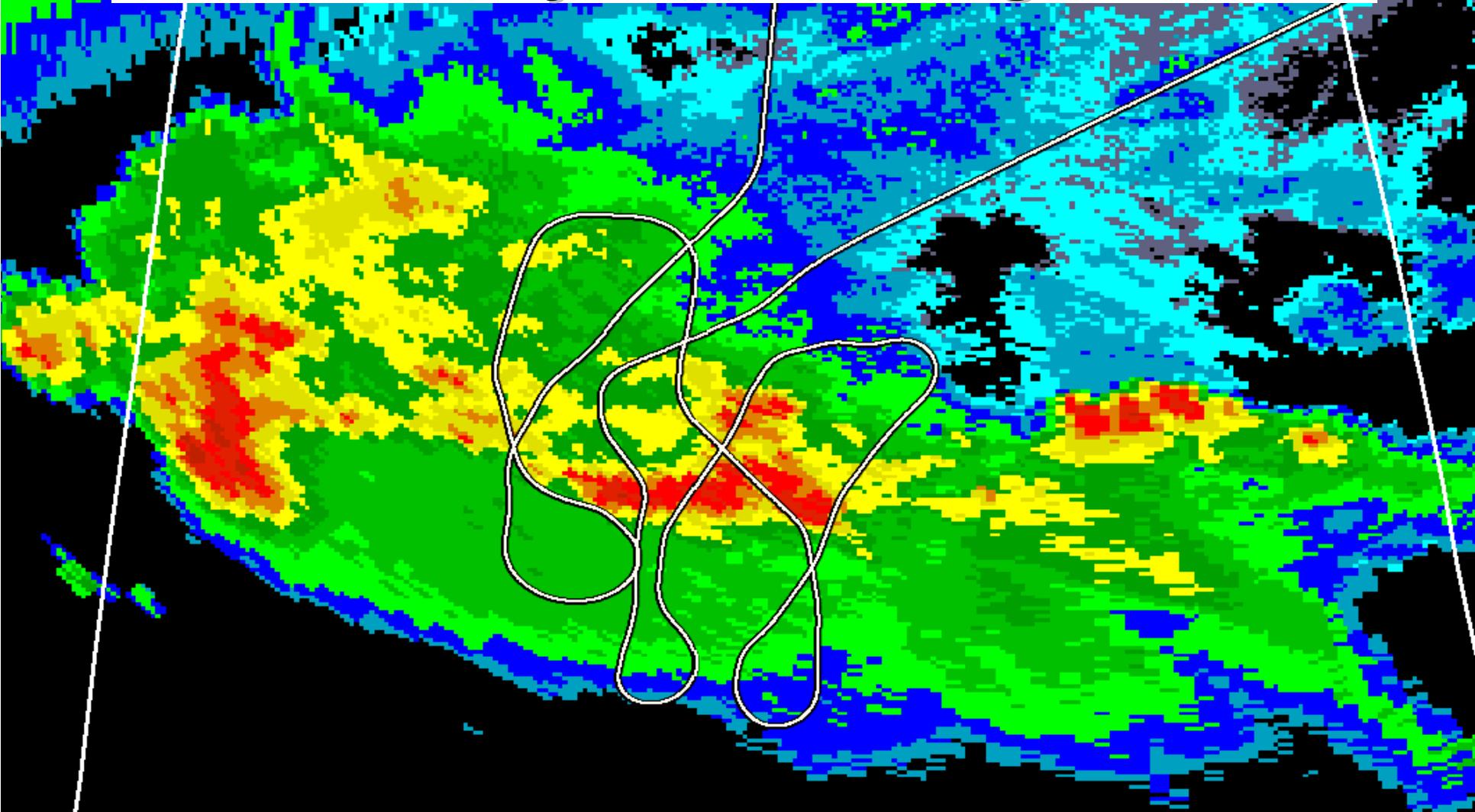
30 Apr 2002  
19:15 UTC

# Visible Satellite



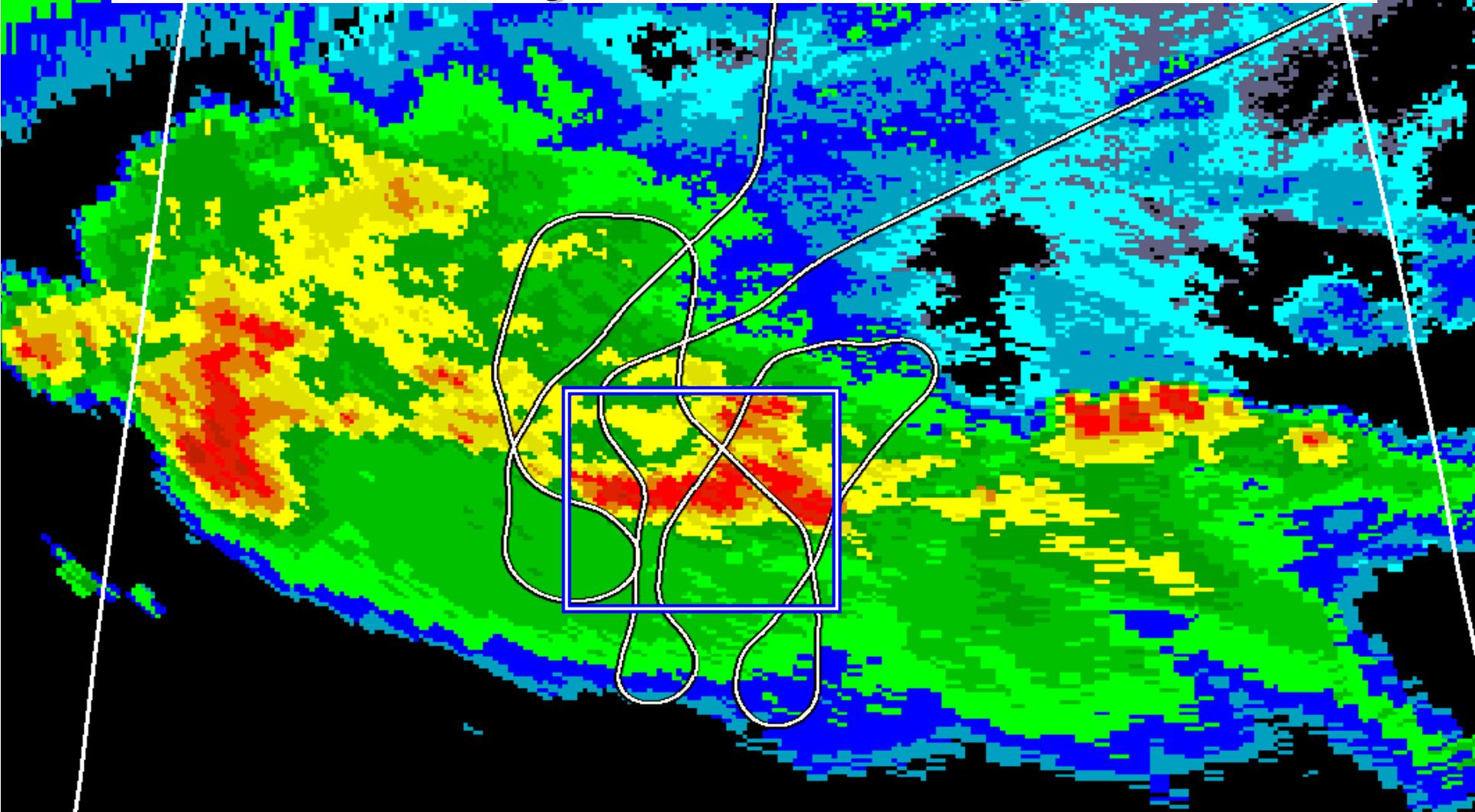
Approximate  
encounter  
location

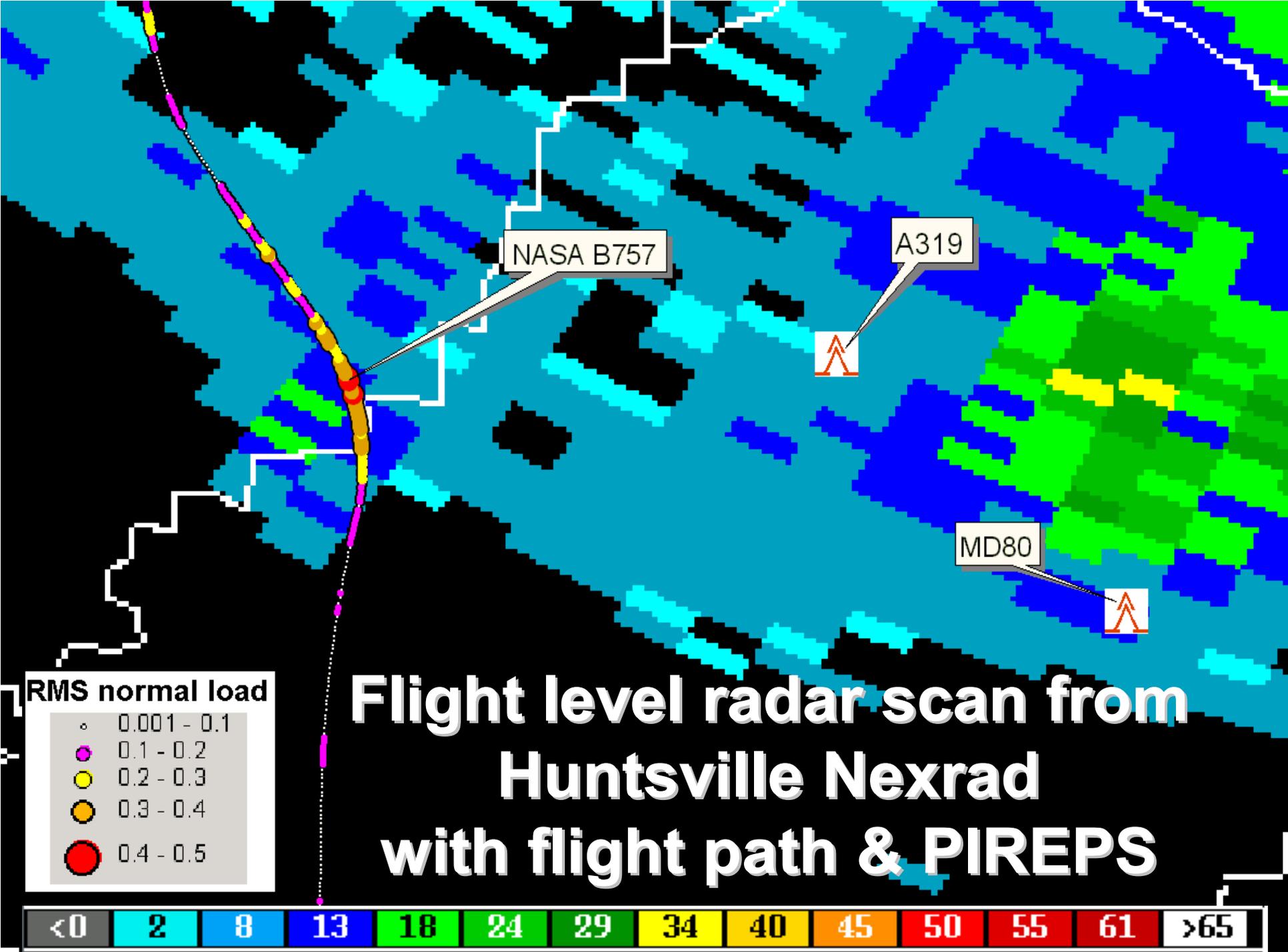
# 19:12 UTC Huntsville Composite Radar Reflectivity with R232 Flight Path



<0	2	8	13	18	24	29	34	40	45	50	55	61	>65
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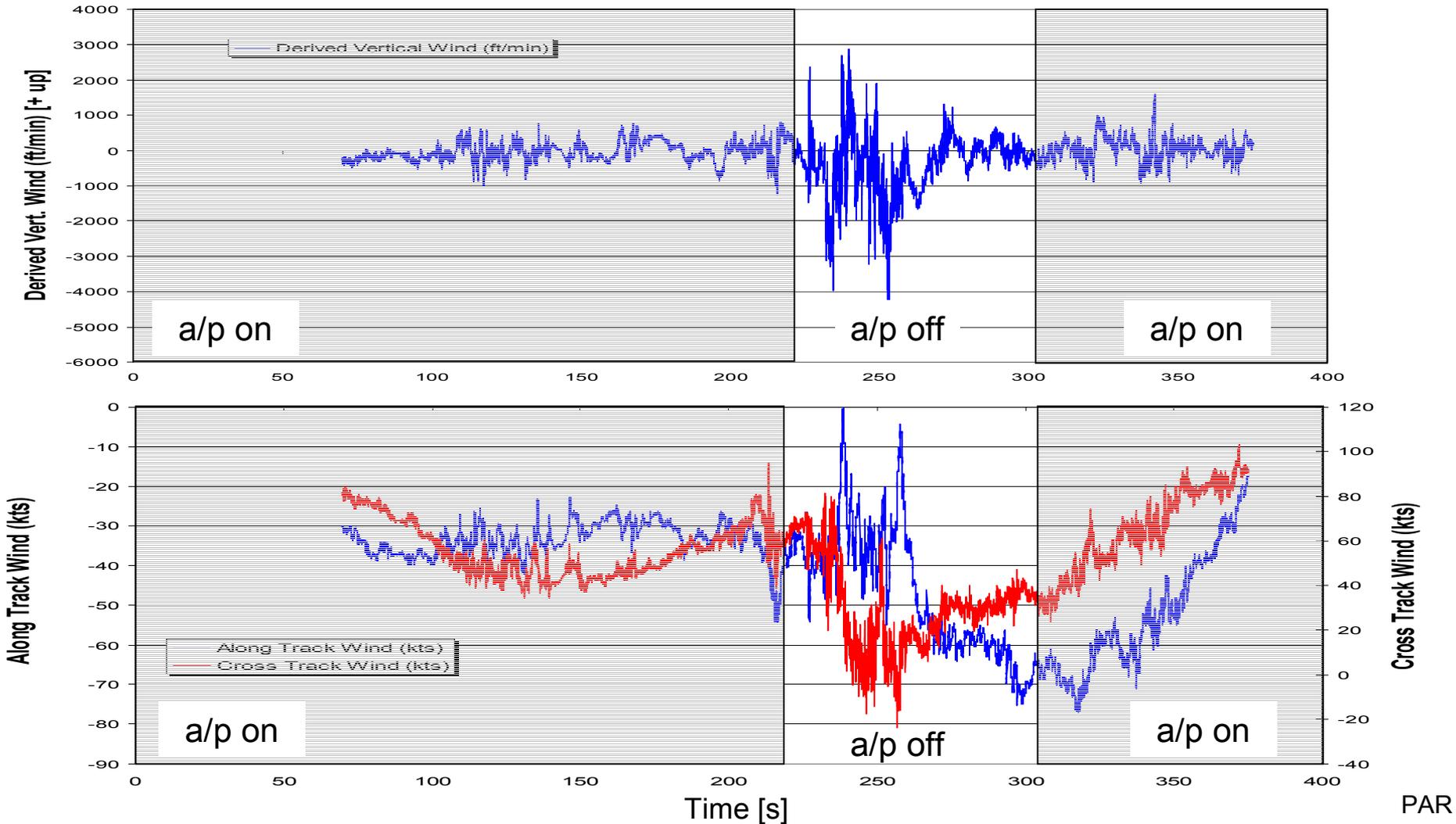
# 19:12 UTC Huntsville Composite Radar Reflectivity with R232 Flight Path



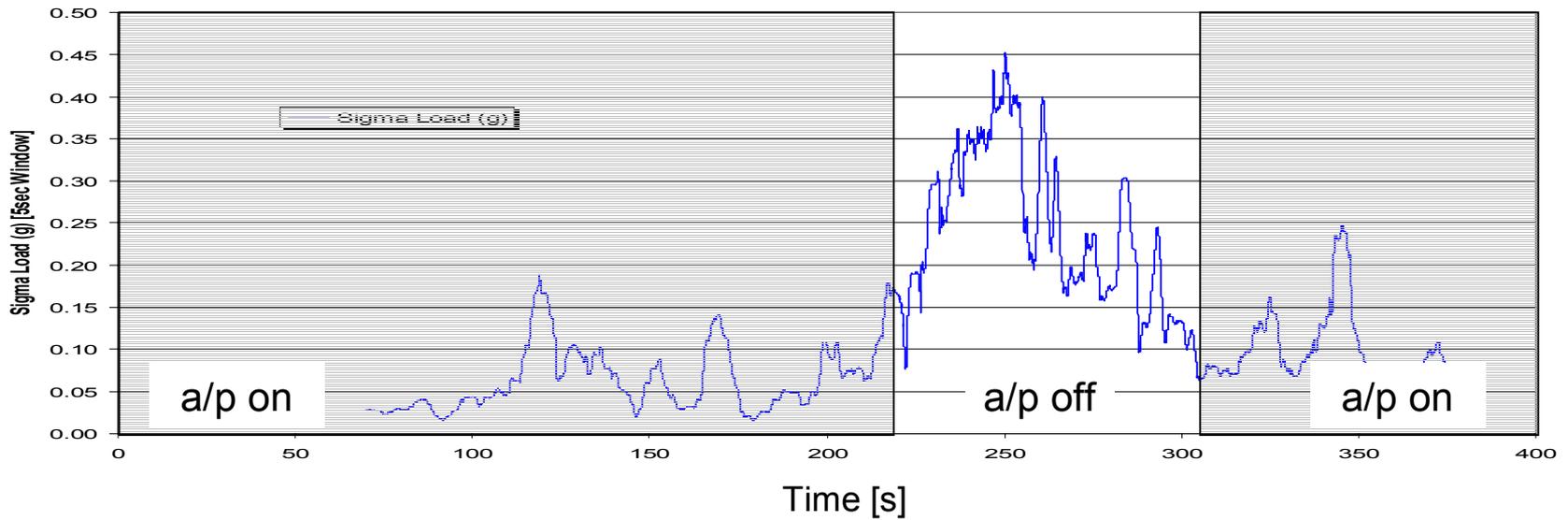
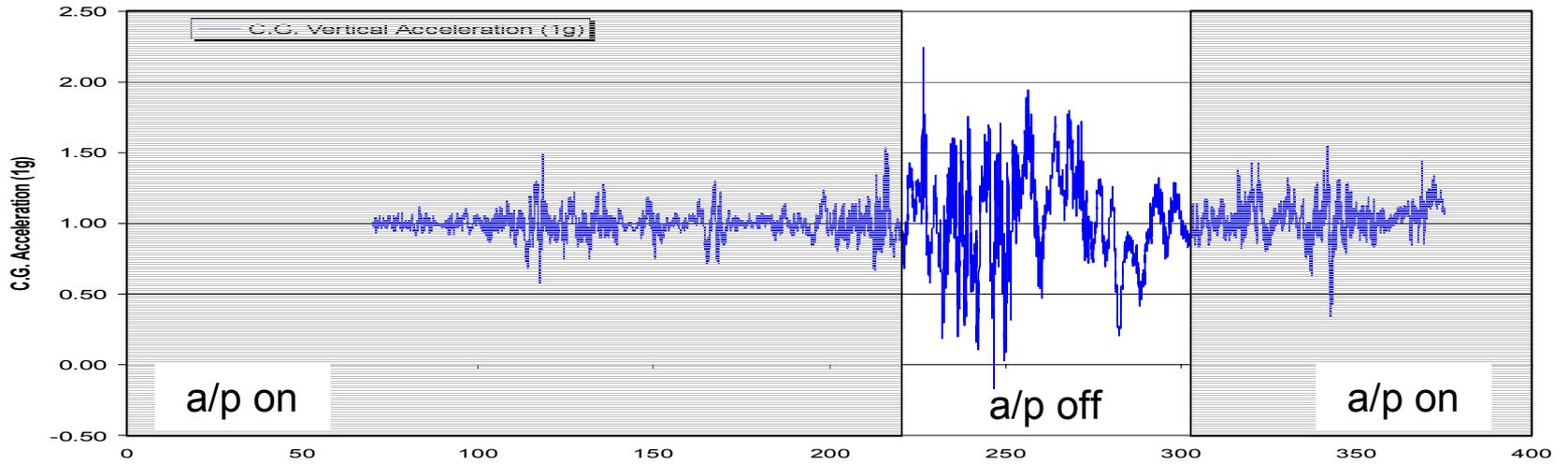


# 3-D Derived Wind Estimation

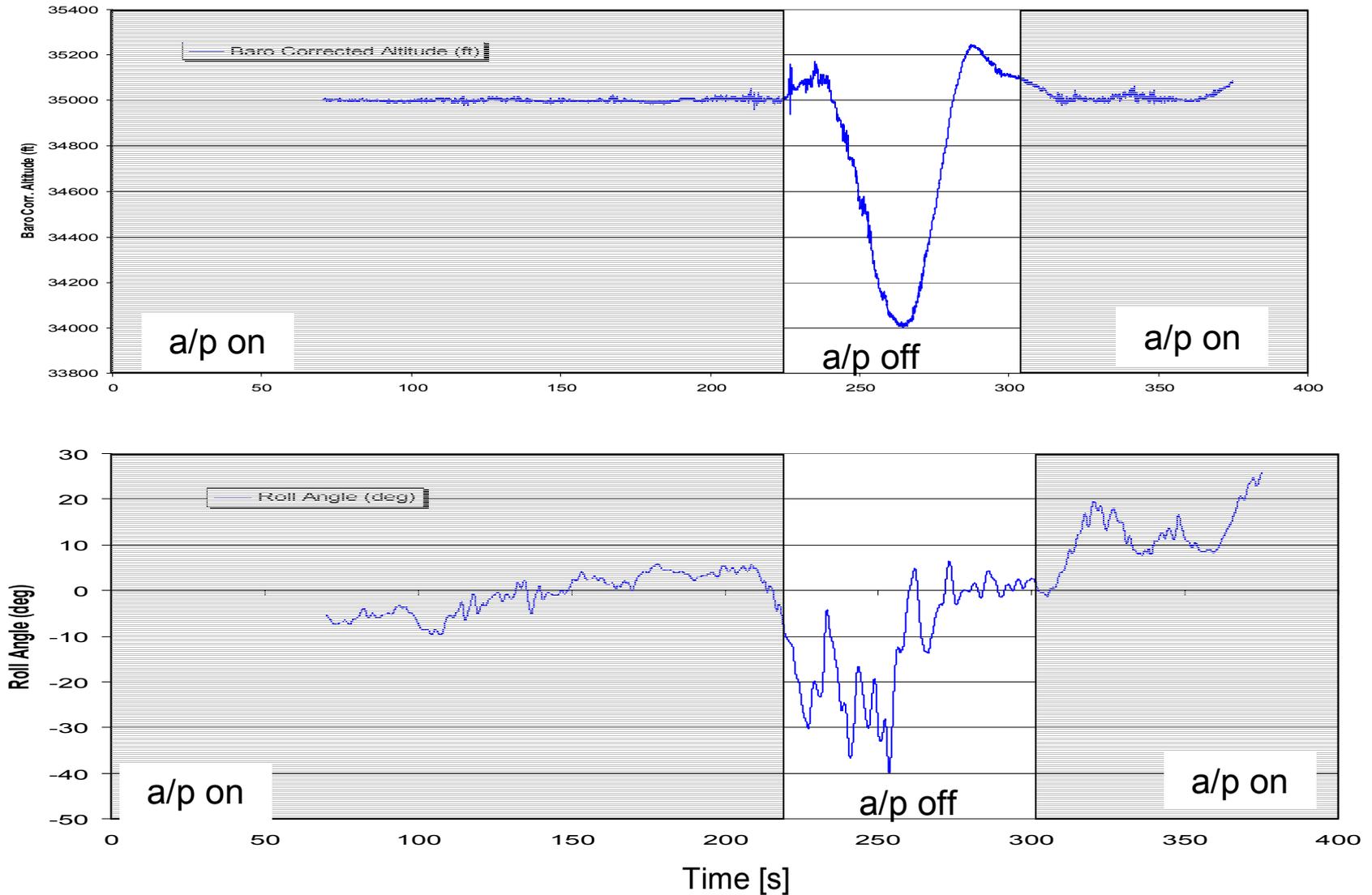
An experimental high-frequency gust estimator developed to support the TPAWS experiments



# Aircraft C.G. Loads

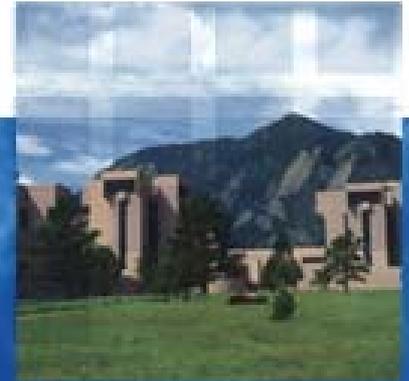
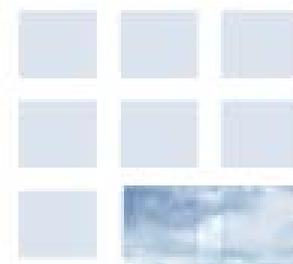


# B-757 Aircraft Parameters





NCAR



# Turbulence Prediction and Warning System FY02 Flight Test Data Analysis

Larry Cornman

National Center for Atmospheric Research

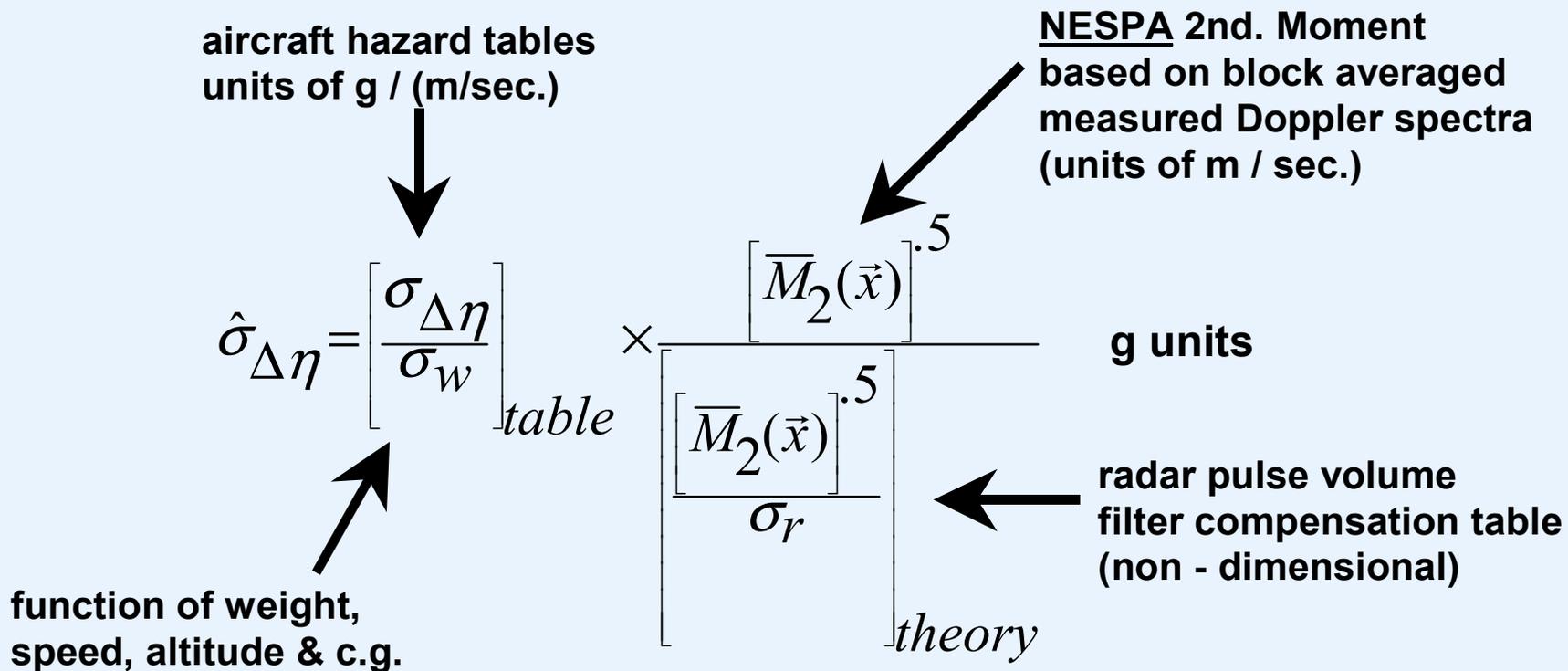
# Turbulence detection and hazard estimation from airborne radars

- The problem is to take radar observables and make an estimate of the rms of the aircraft's vertical acceleration,  $\sigma_{\Delta n}$ .
- This is done in two parts:
  - Conversion of spectrum widths into an estimate of the variance of the horizontal wind component,  $\sigma_u$ .
  - Assuming  $\sigma_u = \sigma_w$ , conversion of  $\sigma_u$  into  $\sigma_{\Delta n}$

# Quality Control Methods

- Spectra were averaged over range and azimuth to improve signal detection.
- The NCAR Efficient Spectral Processing Algorithm (NESPA), a multi-stage, real-time algorithm for producing moments and associated quality control indices, was then used.

# Hazard Prediction Based On Radar Observed Second Moments



**HAZARD PREDICTION : TURB. DETECTION**

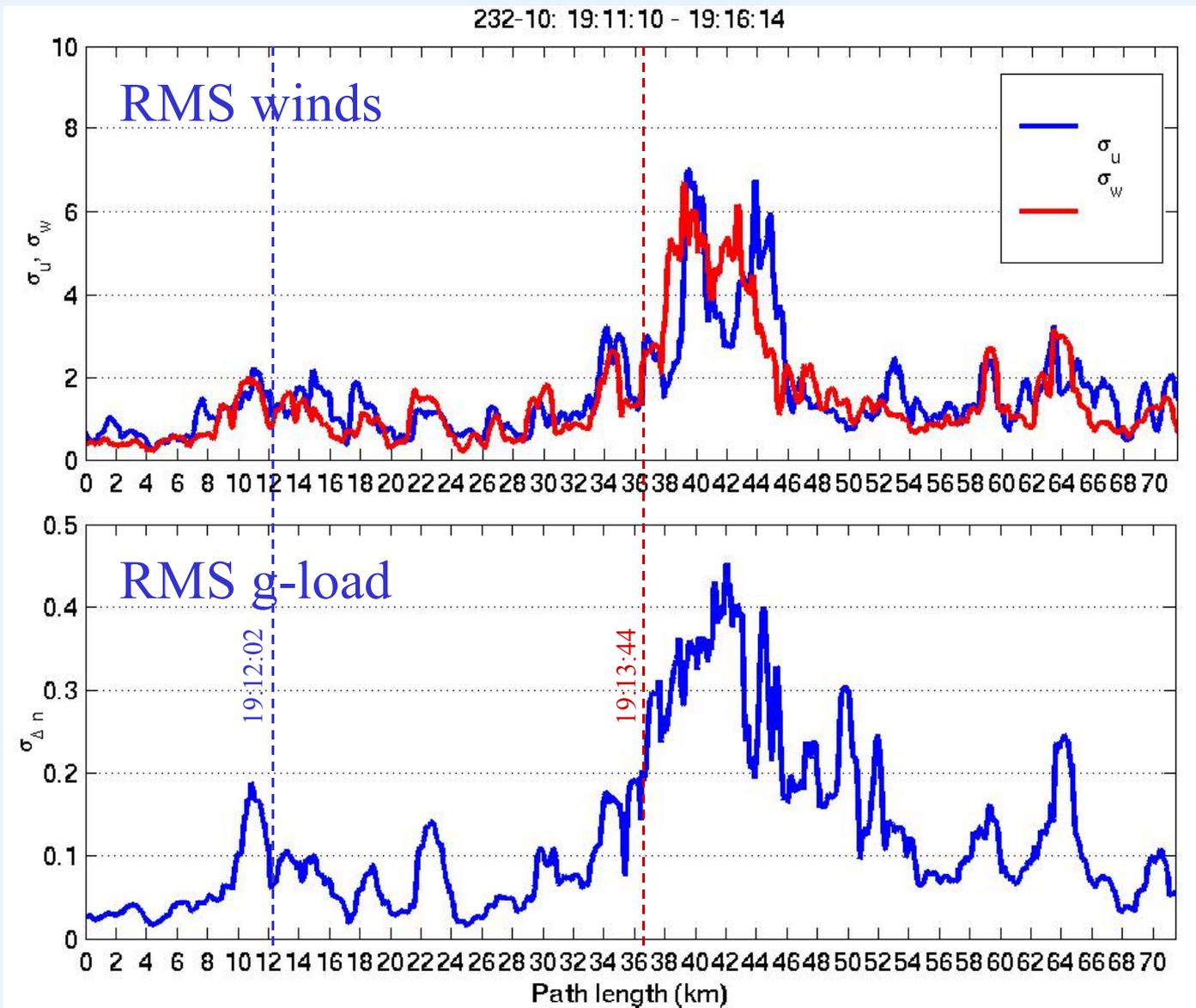
# Radar data processing and scoring

- **Three turbulence scans performed between weather scans (12-sec intervals)**
  - **standard 0, -2, -4° tilts, two interleaved frequencies**
- **Radar data processed using**
  - **timeseries editing**
  - **5x5 spectral averaging**
  - **NESPA to produce moments and confidences**
  - **hazard algorithm to predict g-loads**

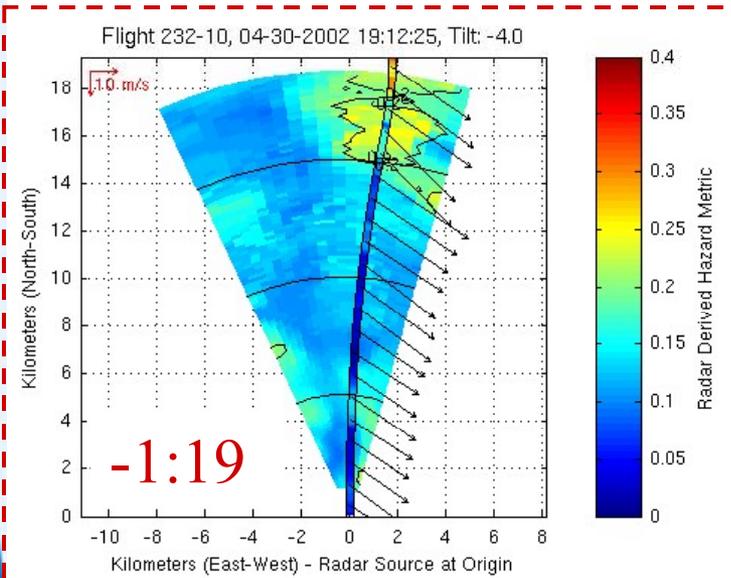
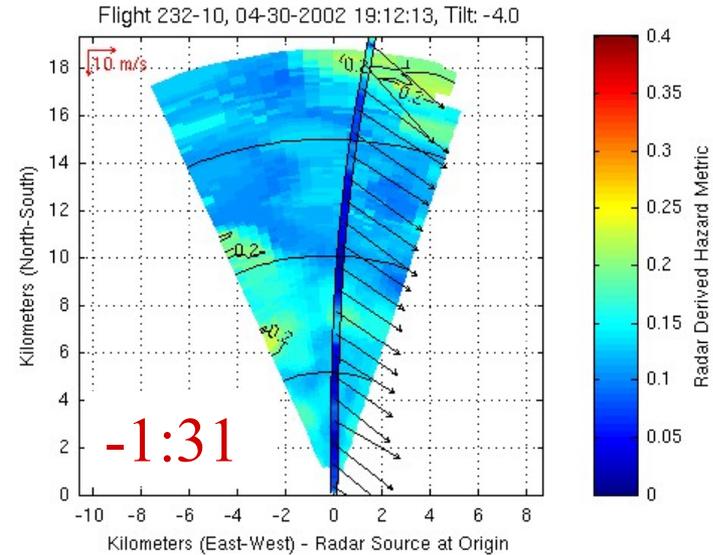
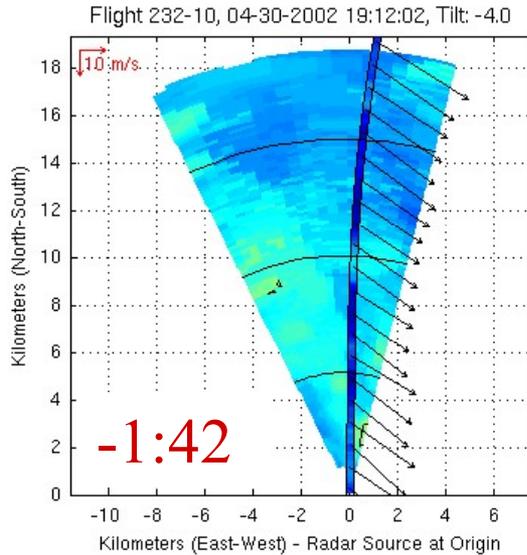
# Case 1: 232-10

- **Clear detection 80 seconds (18 km) before encounter.**
- **Reflectivities less than 20 dBZ at initial detection.**
- **Persistent detection.**

# Event 232-10 (30 April 2002, 19:11:10 – 19:16:14)

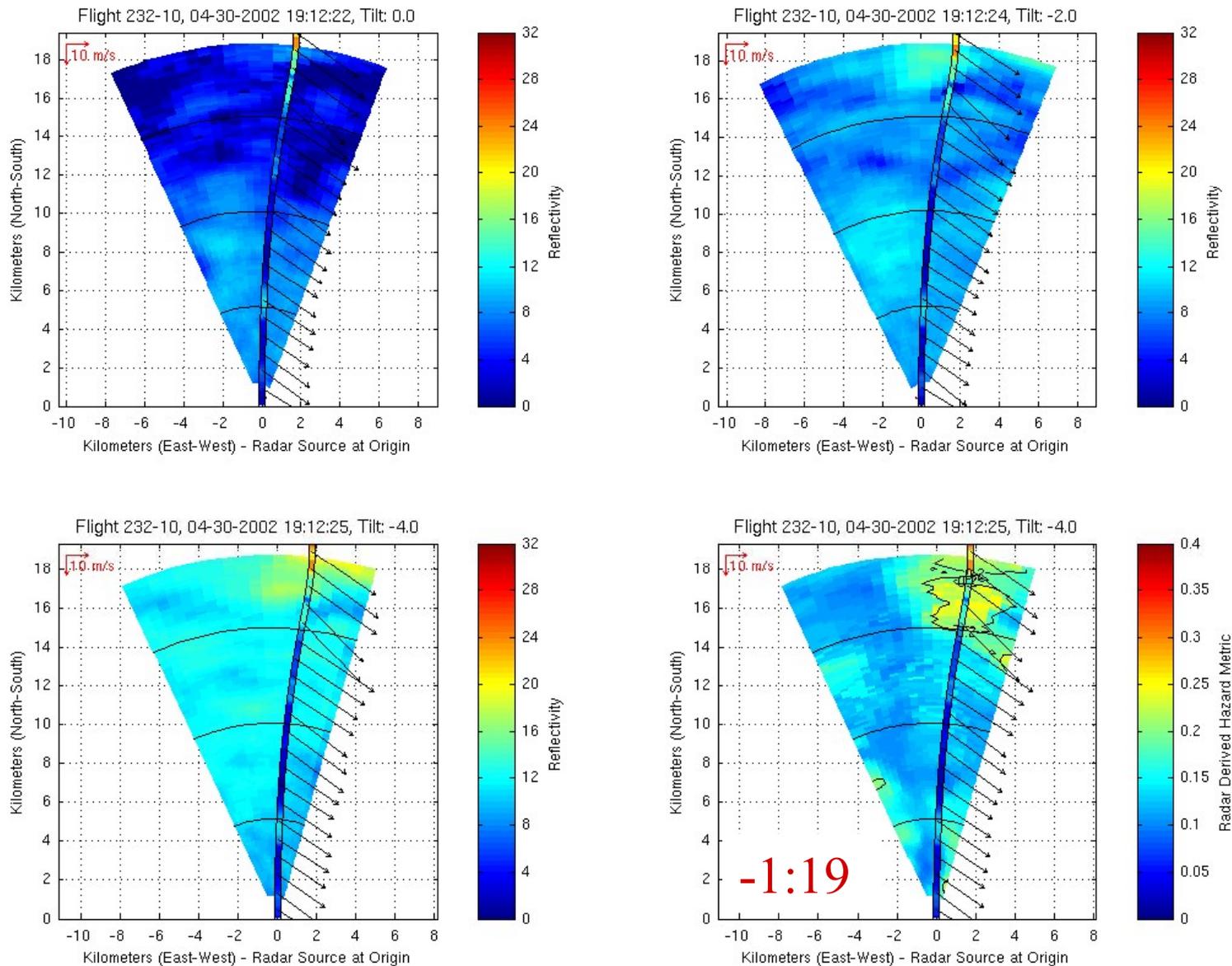


# Event 232-10 (19:12:02, 19:12:13, 19:12:25)

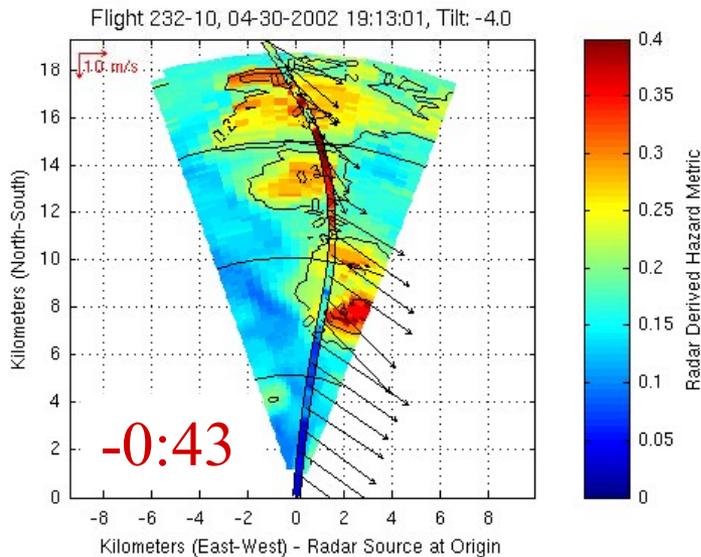
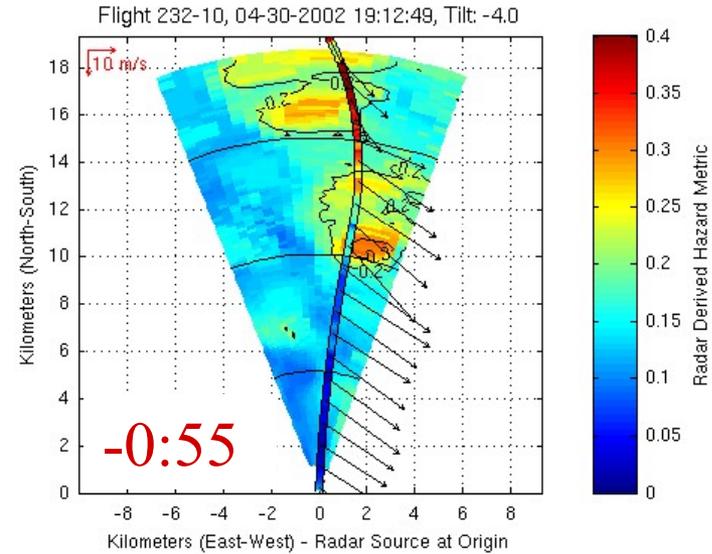
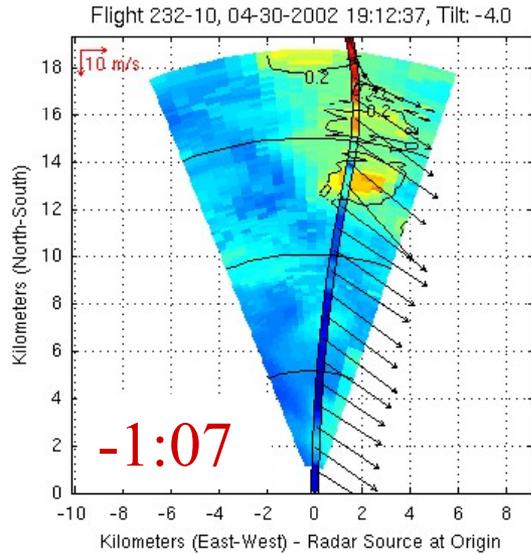


← Hazard detected  
1:19, 18 km to encounter

# Event 232-10 (reflectivities at 19:12:25)

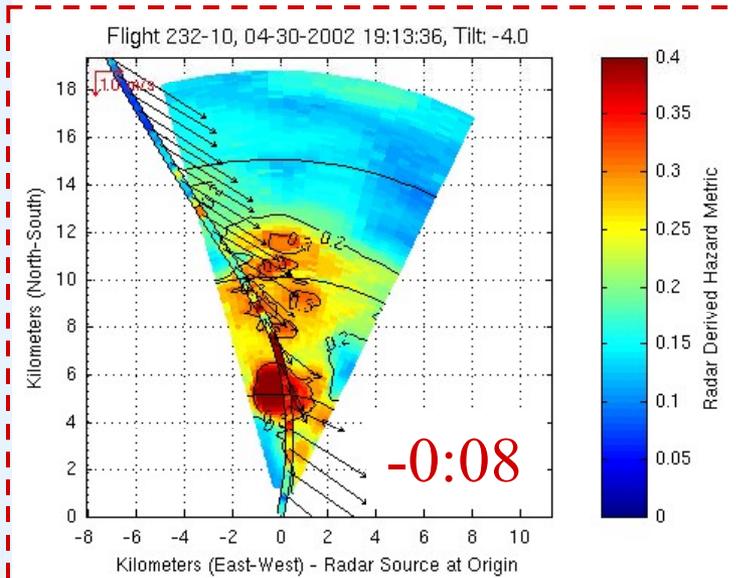
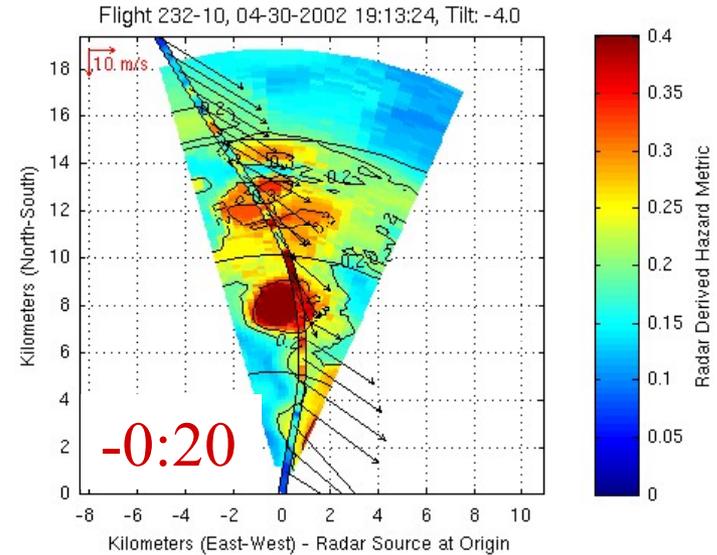
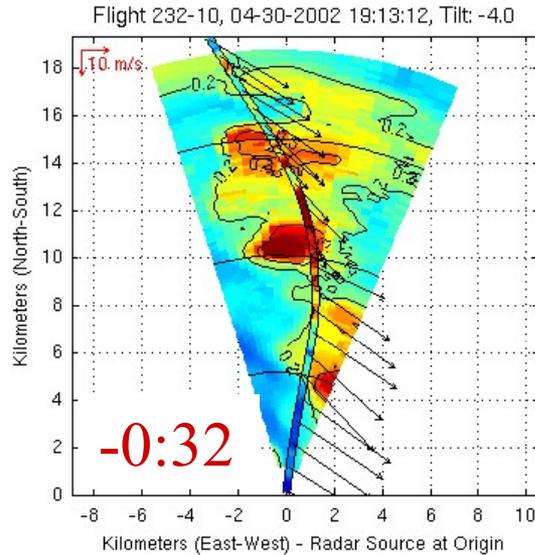


# Event 232-10 (19:12:37, 19:12:49, 19:13:01)



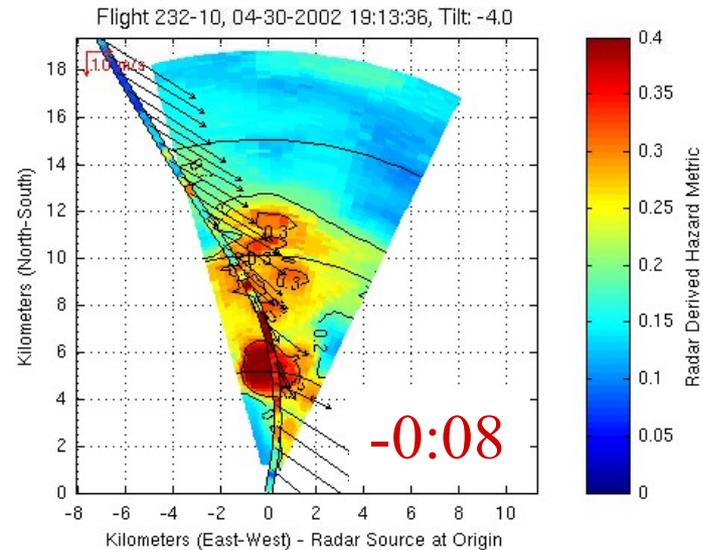
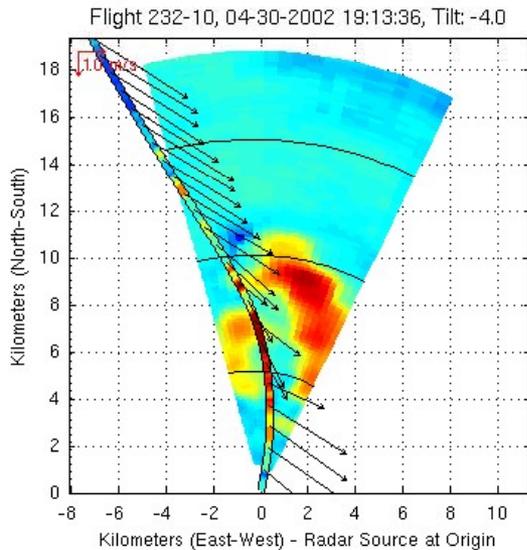
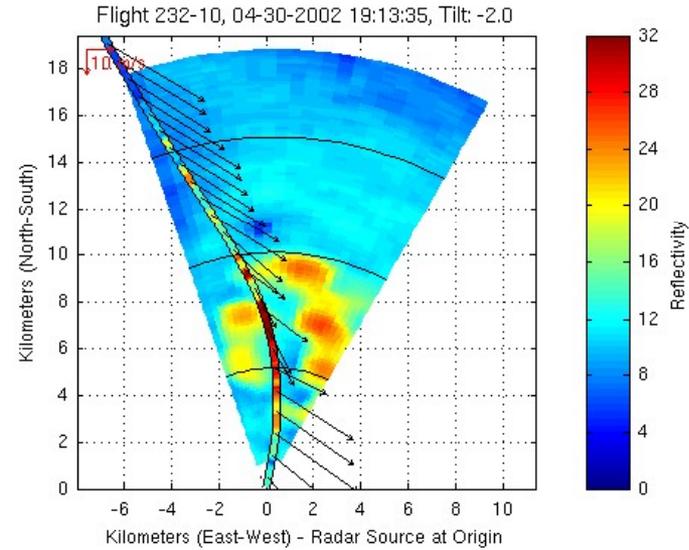
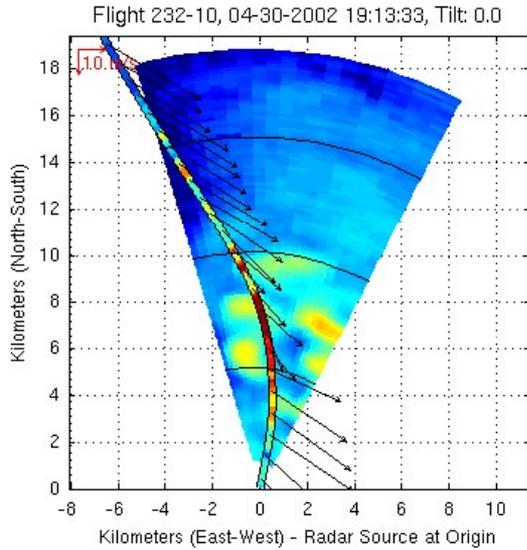
Persistent detection

# Event 232-10 (19:13:12, 19:13:24, 19:13:36)

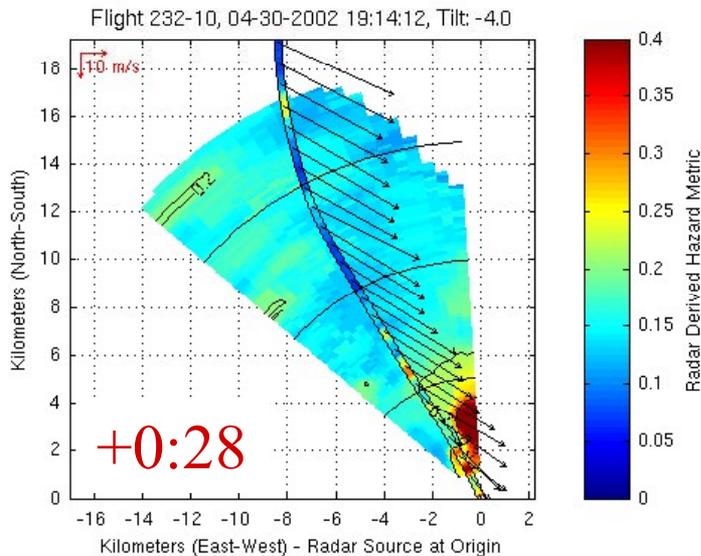
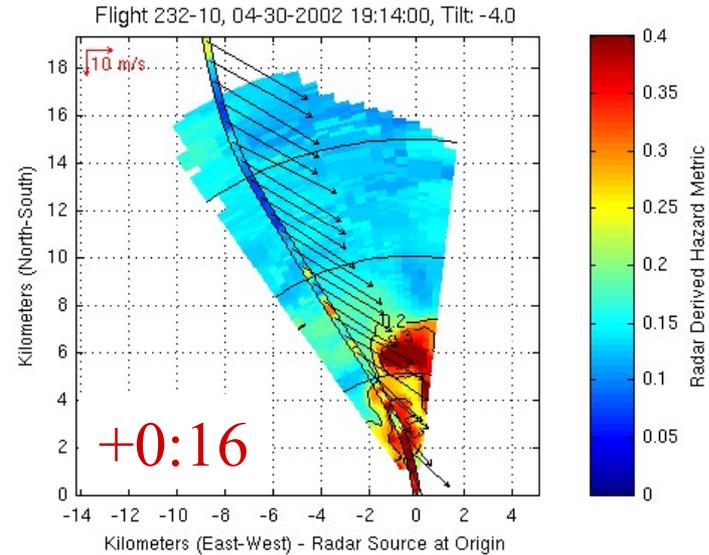
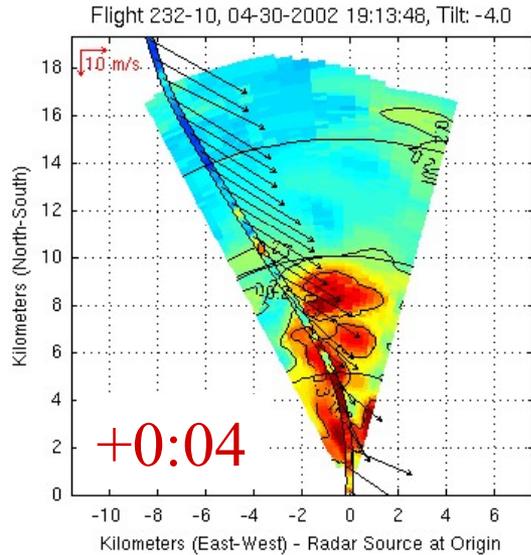


Persistent detection

# Event 232-10 (reflectivities at 19:13:36)



# Event 232-10 (19:13:48, 19:14:00, 19:14:12)



Persistent detection

# Radar data processing and scoring

- Human scoring based on *in situ* turbulence encounter “events”
  - aircraft 5-second RMS g-load is “truth”
  - radar prediction magnitude, proximity, extent, and persistence considered
- Contingency table was created based upon scoring team consensus.

# Radar data processing and scoring

- Events were classified as Detection, Miss, Nuisance or Null, and also whether:
  - The spatial registration was poor
  - The intensity was under/overestimated
  - The event was marginally missed
- Threshold was chosen as  $\sigma_{\Delta n} = 0.2g$
- Not all of the correct null events were scored for the table.

# TPAWS FY02 test flight contingency table

		R A D A R			
		Detected		Not Detected	
A	Hit	230-23 - 2 u	228-04 - u	230-06 - 2 ?	
I		230-19 - u	228-12 - u	230-10 - 2 m	
R		230-21 - 0 u	228-10 -	230-08 - 2 m	
C		230-15 - u	228-11 -	230-04 -	③
R		230-20 - u	228-06 -	230-24 - 2 m	
A		231-10 -	228-09 -	233-05 - m	
F		231-08 - ①	232-10 -	229-05 - m	②
T		233-07 - u	232-04 -	231-04 - u	
		233-01 -	232-03 -		
		233-06 - ⑤	232-08 -		
		233-04 - r	232-05 - o		
		234-06 -	235-03 - u		
		234-11 -	235-02 -		
		234-12 -	240-03 -		
		234-09 -	240-09 - u		
		234-05 -	232-06 -		
		230-12 - u	233-09 -		
		Total:	34	Total:	8
	Not hit	234-02		229-02	234-10 -
		240-04 - m		229-03	234-13
		240-05	④	229-04	231-06 - n
		233-08 - m		229-06	228-07 - n
				241-01	
		Total:	4	Total:	9

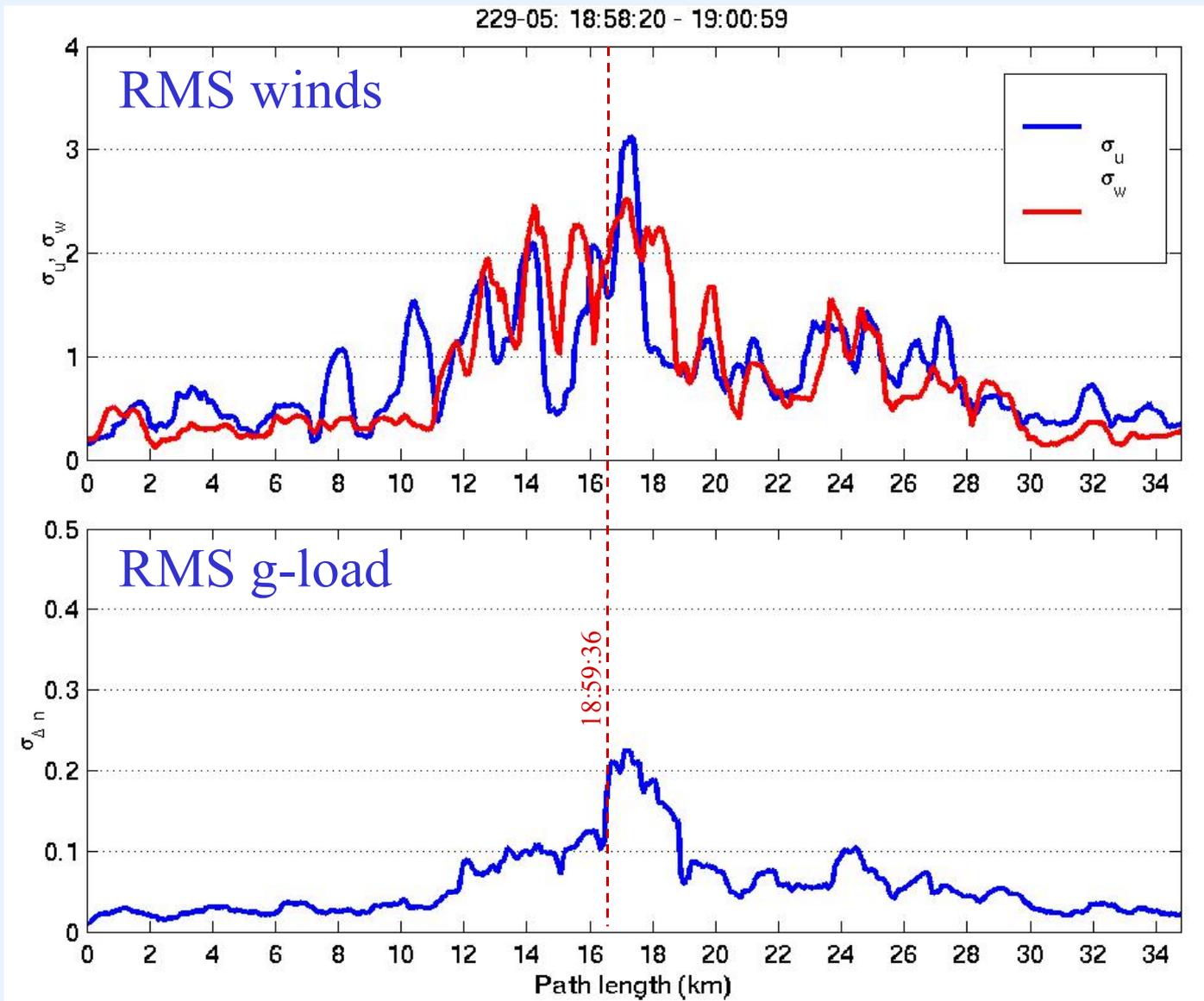
## Key

r - registration poor	
u - underestimate	
o - overestimate	
m - marginal miss	
0 - 0 tilt only	
2 - -2 tilt only	
? - not enough data	
n - non-validated detection (moved off)	
- - consensus agreement	

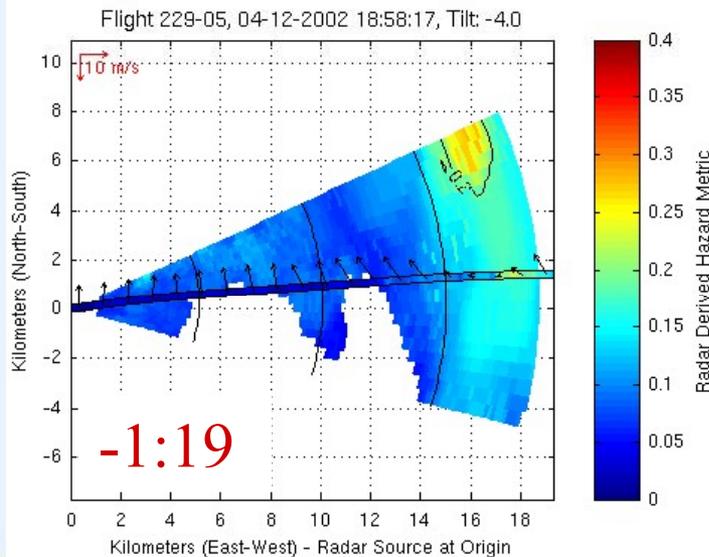
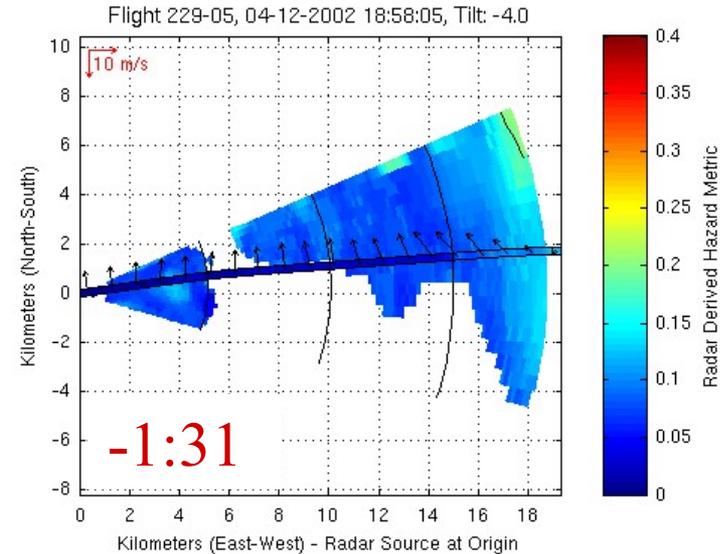
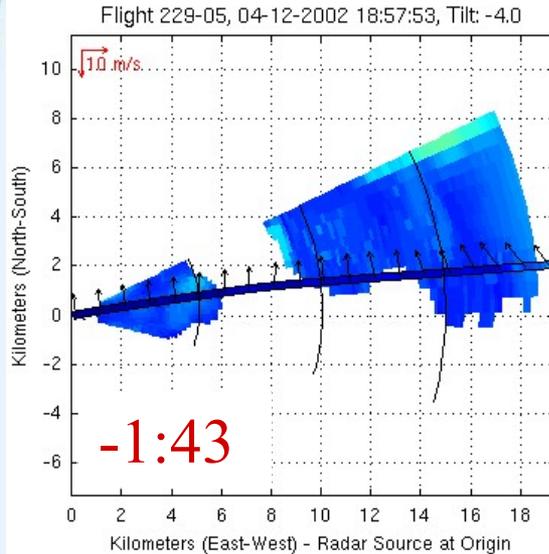
## Case 2: 229-05

- “Near miss”
- Aircraft detection was just over threshold, radar measurements
- Reflectivities greater than 20 dBZ at initial detection.

# Event 229-05 (12 April 2002, 18:58:20 – 19:00:59)

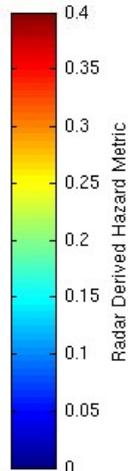
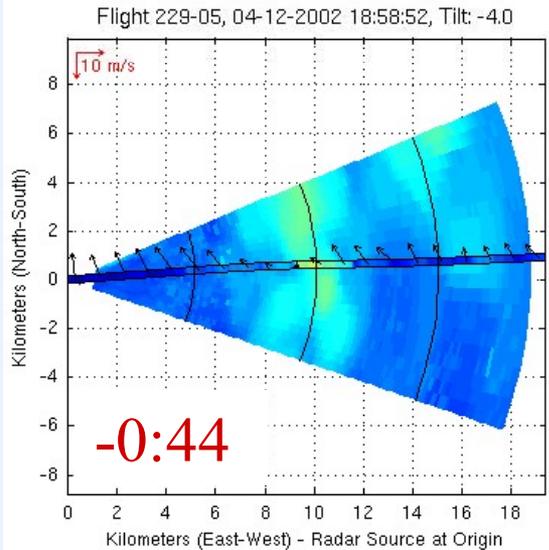
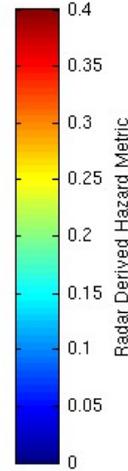
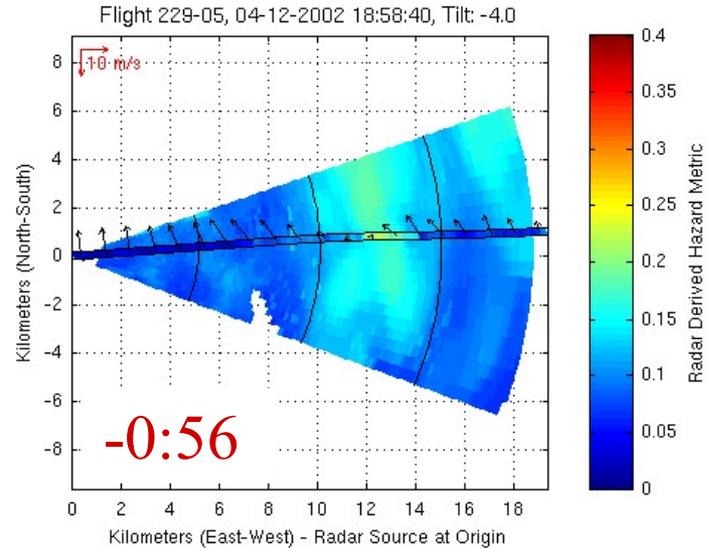
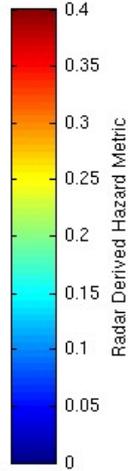
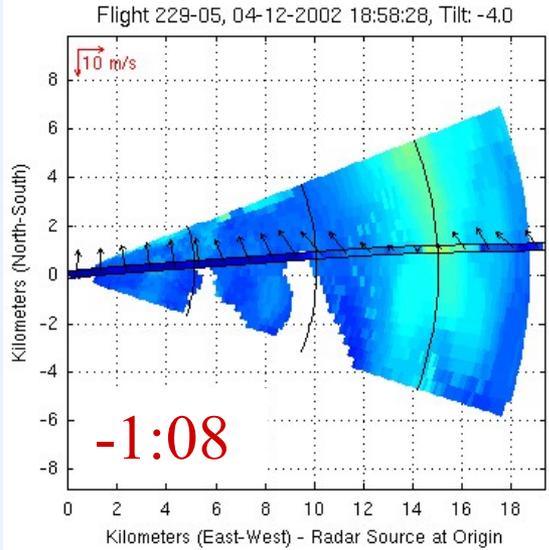


# Event 229-05 (18:57:53, 18:58:05, 18:58:17)



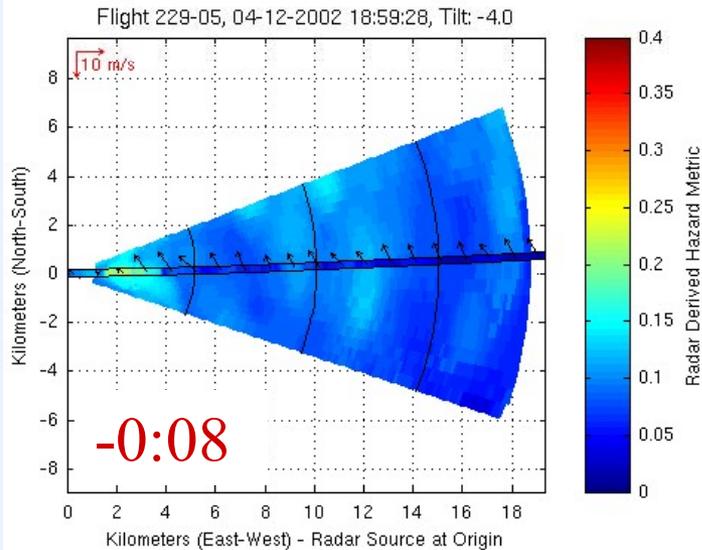
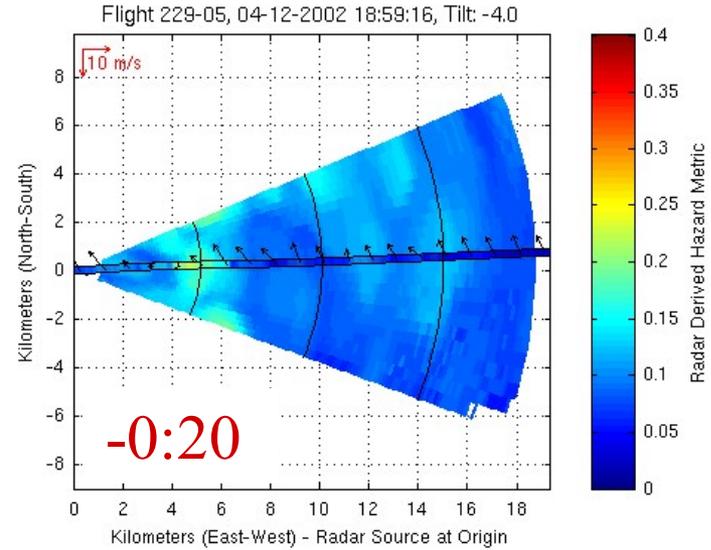
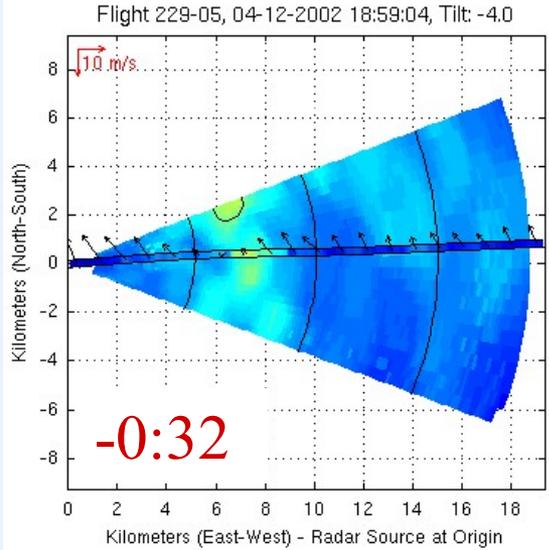
No detection

# Event 229-05 (18:58:28, 18:58:40, 18:58:52)



No detection

# Event 229-05 (18:59:04, 18:59:16, 18:59:28)

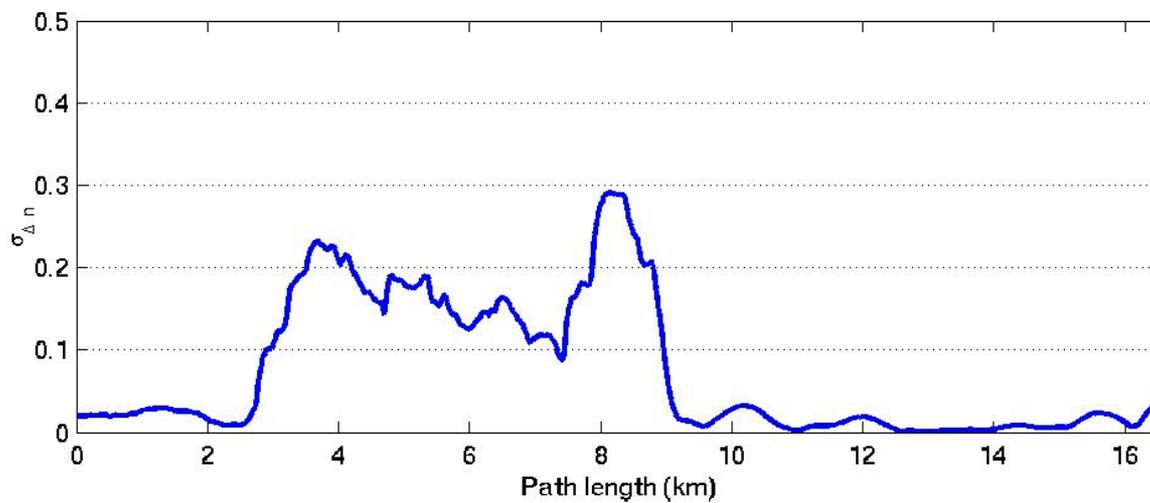
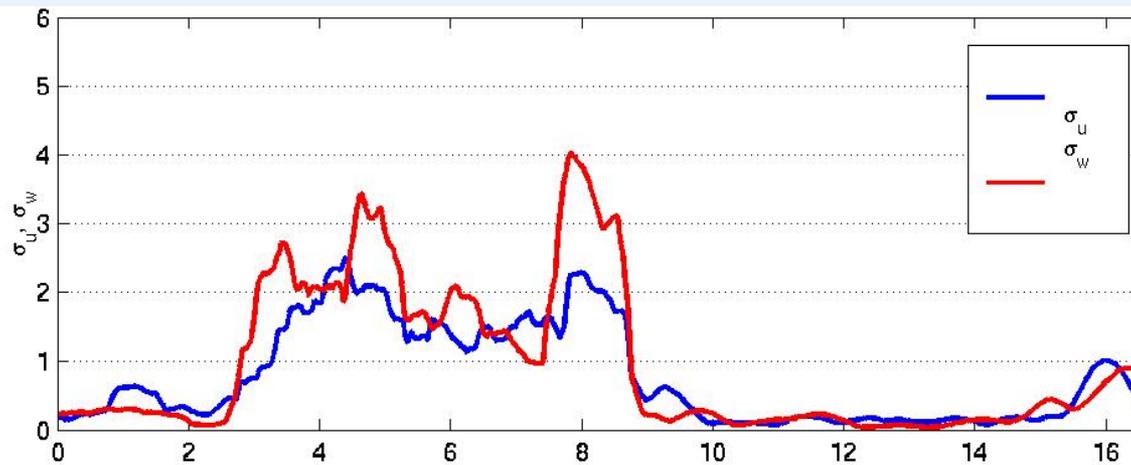


No detection

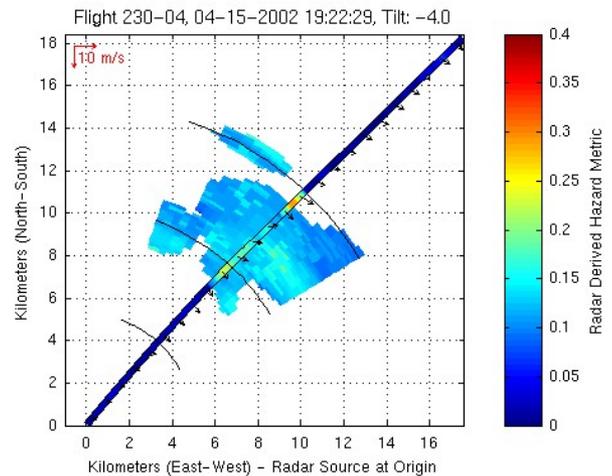
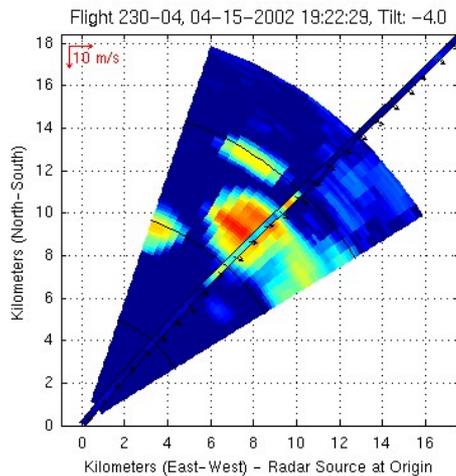
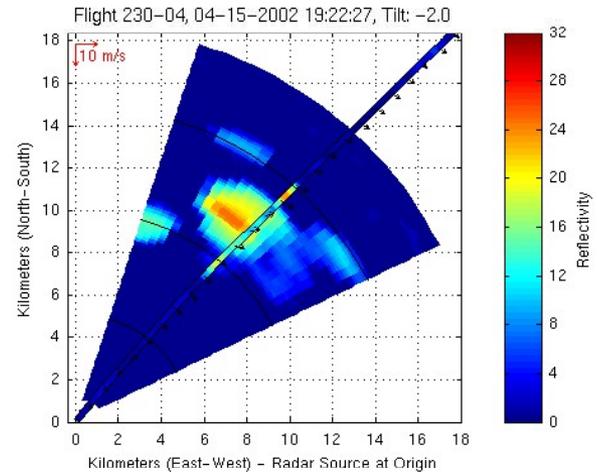
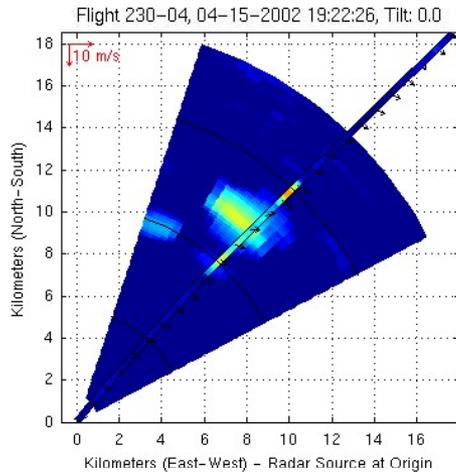
## **Case 3: 230-04**

- **The only non-marginal missed detection.**
- **The turbulence was on the edges of a convective cell, but in very low reflectivity.**

# Flight 230-04



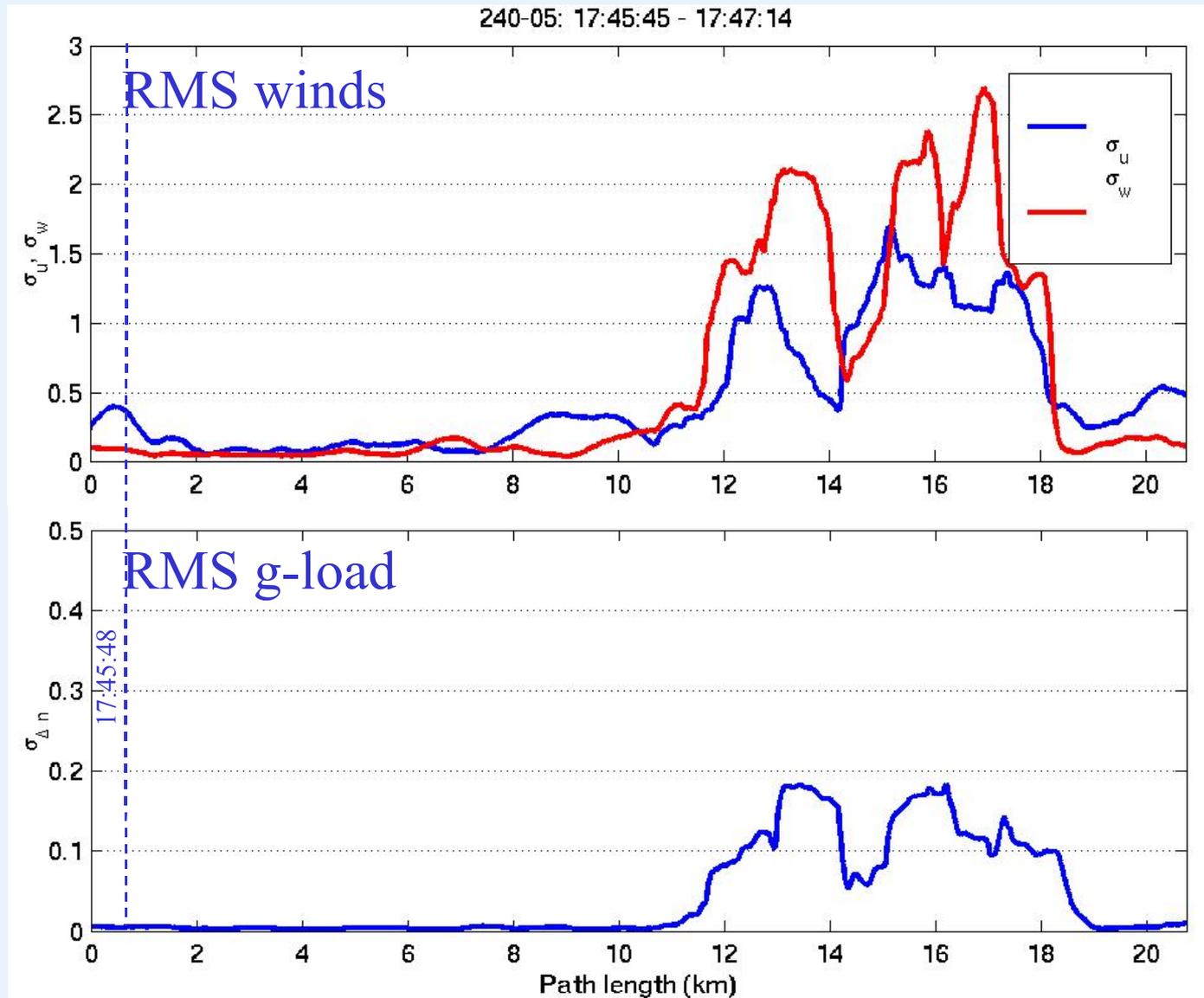
# Flight 230-04



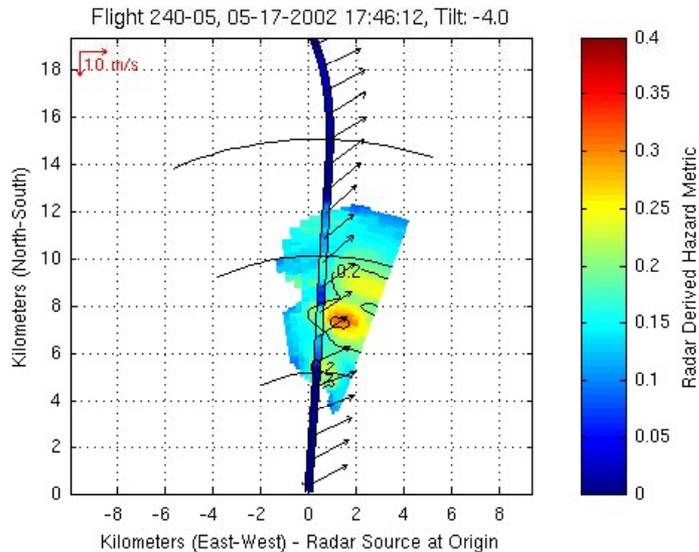
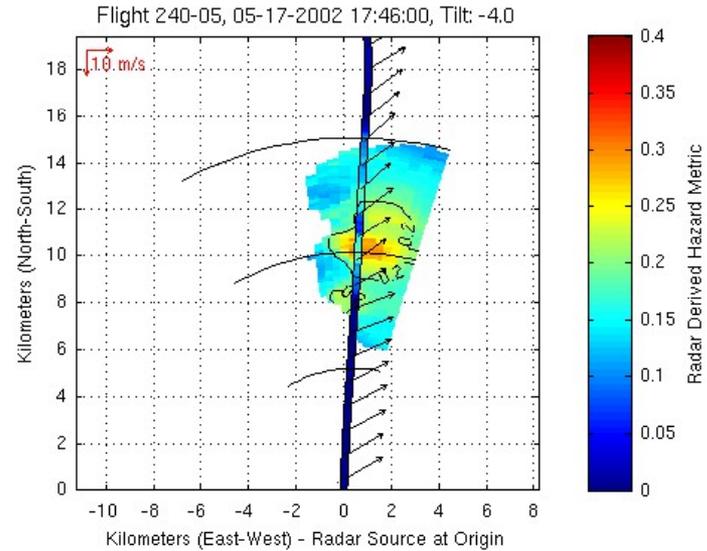
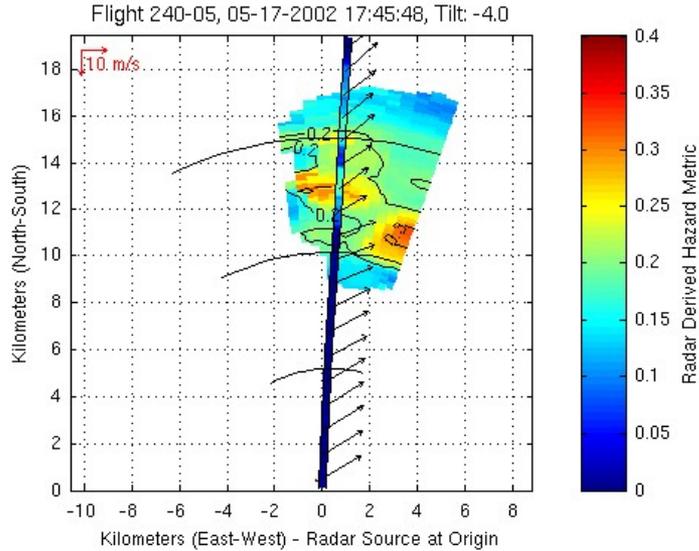
## **Case 4: 240-05**

- **Nuisance alert.**
- **Aircraft values were just below threshold.**
- **Radar values were well-above threshold – however the event was moving out of the flight path.**

# Event 240-05 (17 May 2002, 17:45:45 – 17:47:14)

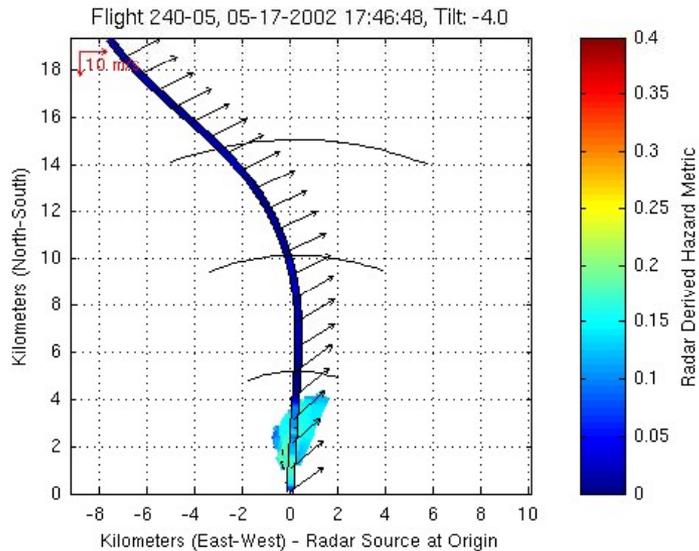
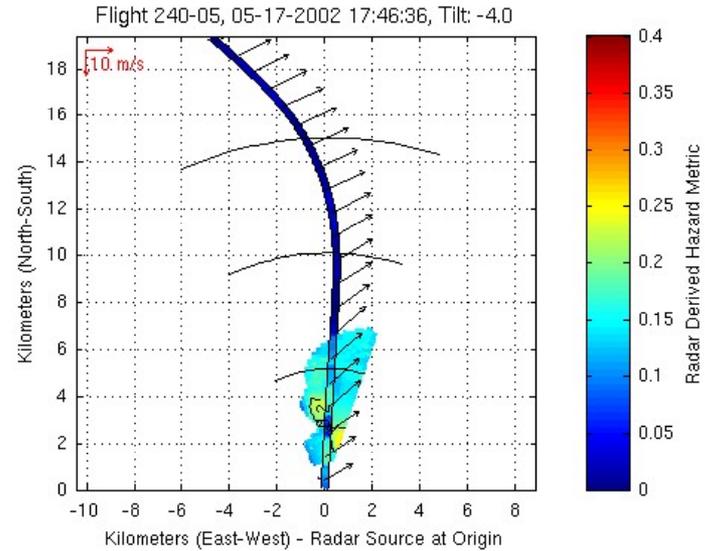
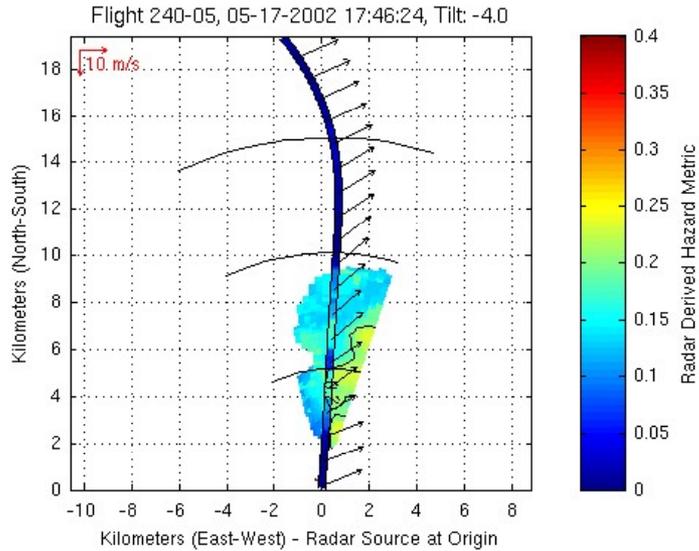


# Event 240-05 (17:45:48, 17:46:00, 17:46:12)



Nuisance alert

# Event 240-05 (17:46:24, 17:46:36, 17:46:48)

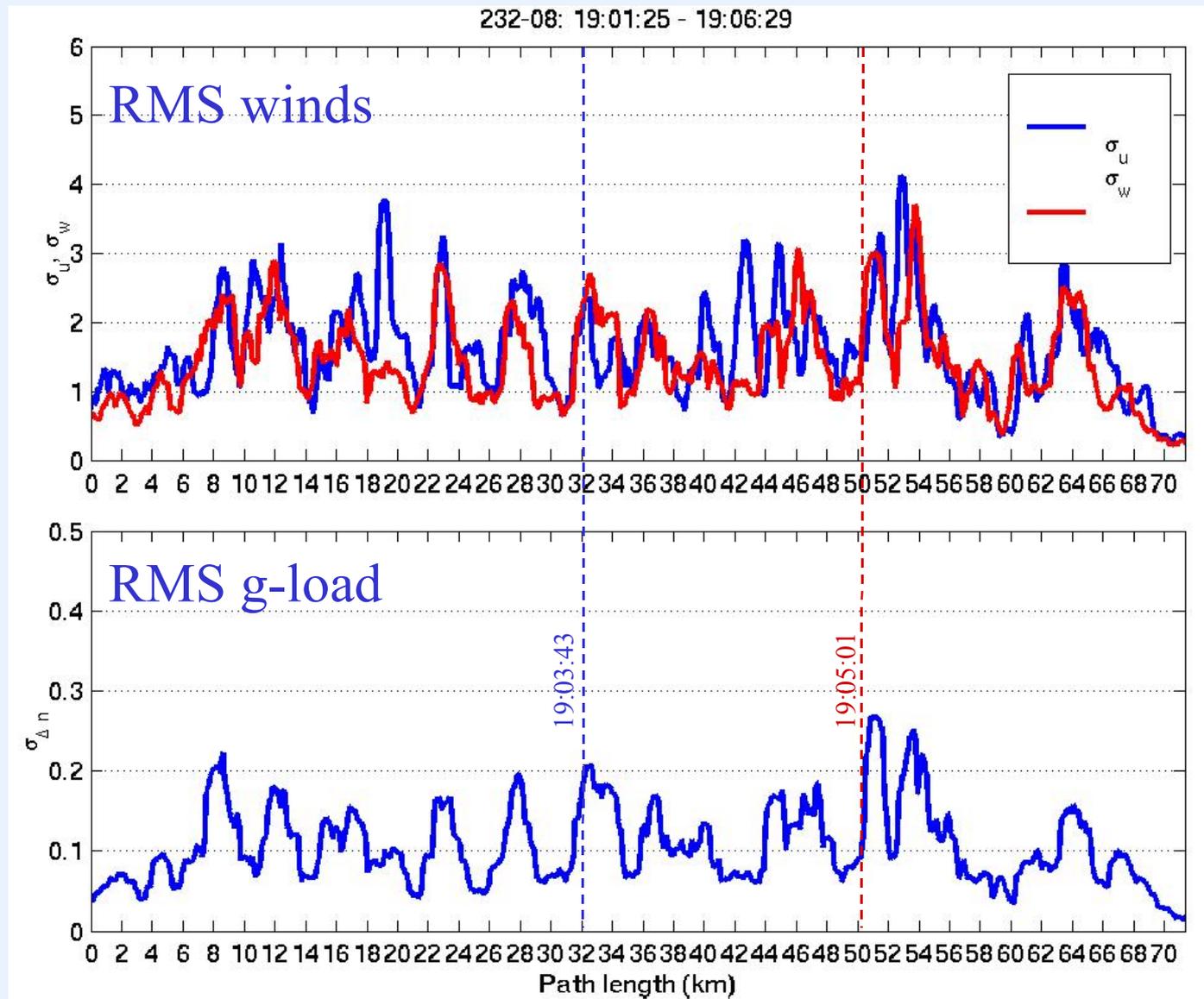


**Nuisance alert**

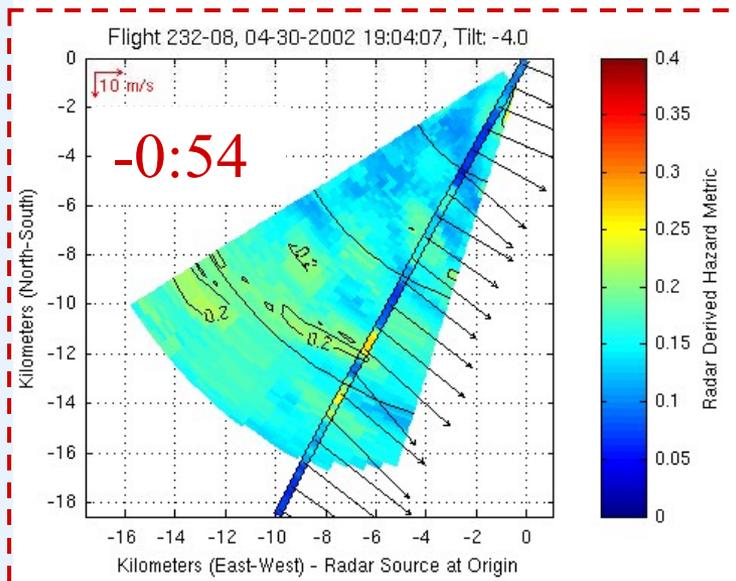
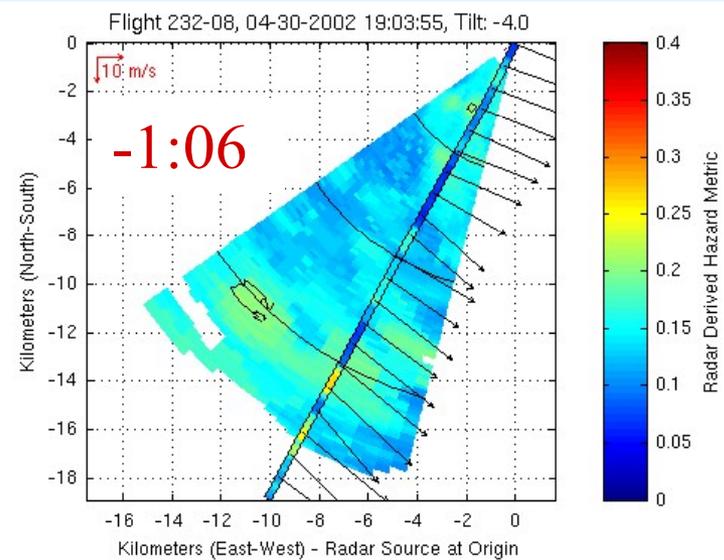
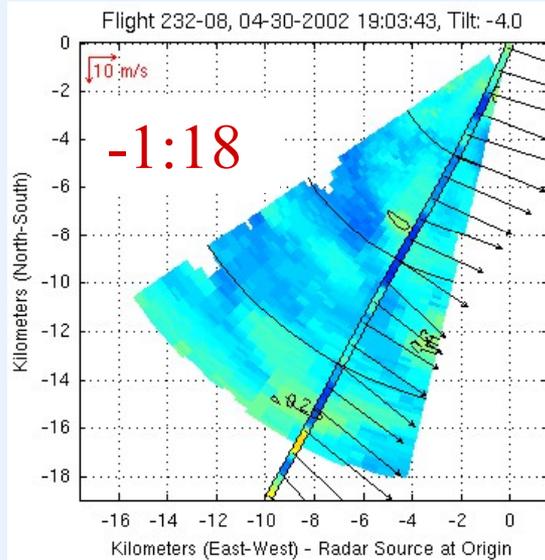
# Case 5: 232-08

- **Event detection at reflectivities below 15 dBZ.**

# Event 232-08 (30 April 2002, 19:01:25 – 19:06:29)

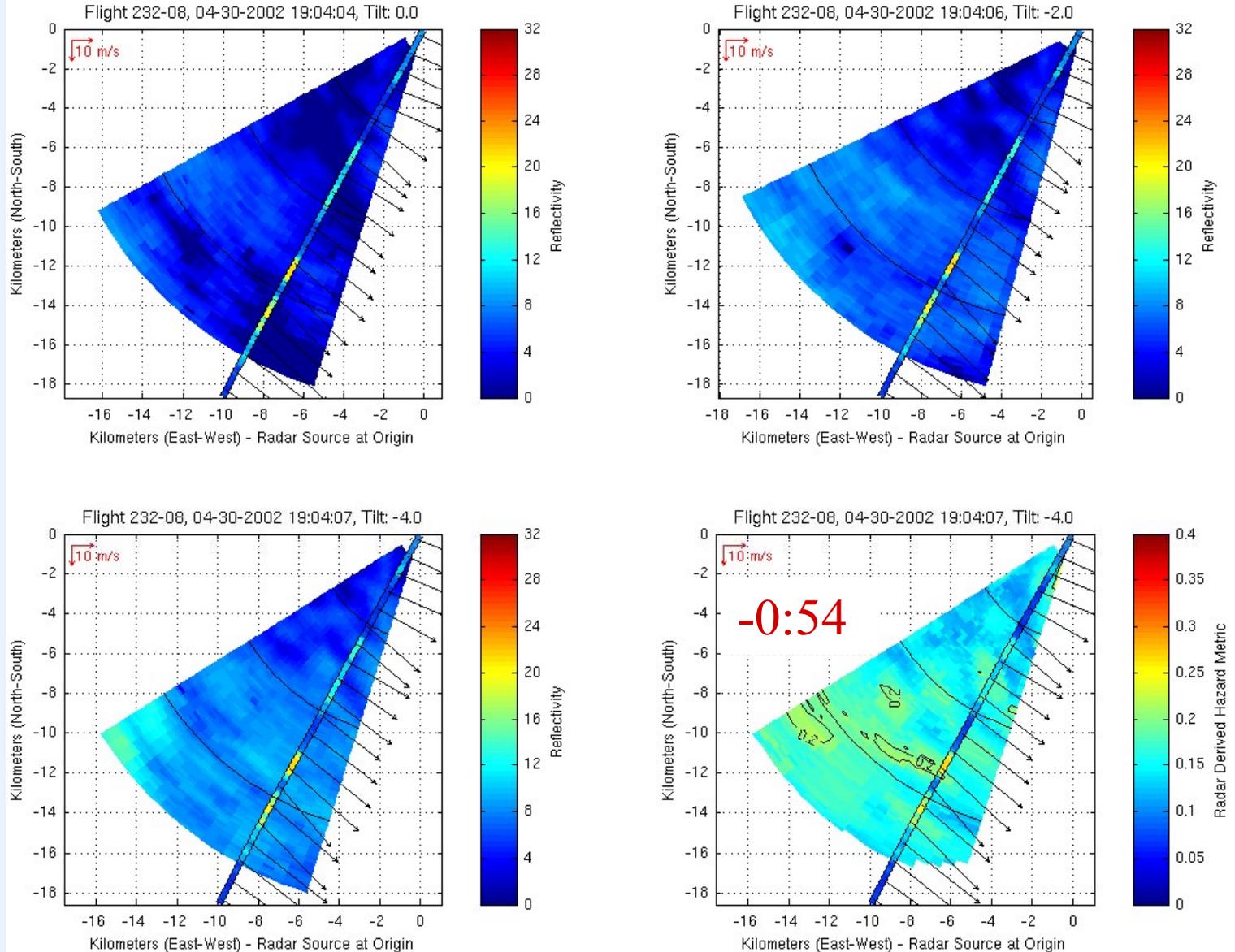


# Event 232-08 (19:03:43, 19:03:55, 19:04:07)



← Hazard detected  
0:54, 12 km to encounter

# Event 232-08 (reflectivities at 19:04:07)



# Summary

- **55 cases were analyzed for the contingency table.**
- **The overall results are very encouraging.**
  - **Most of the missed detections were marginal ones.**
  - **Very few nuisance alerts – and those were marginal, or the aircraft was turning away from the cell.**

# TPAWS PERFORMANCE SUMMARY

## 55 CASES FY-02 FLIGHT EXPERIMENT

		<i>Radar</i>	
		$\geq .2 \text{ g's}$	$< .2 \text{ g's}$
<i>In-situ</i>	$\geq .2 \text{ g's}$	<b>Correct Alerts</b> <i>POD</i> = 80.95 %	<b>Missed Alerts</b> 19.047 %
	$< .2 \text{ g's}$	<b>Nuisance Alerts</b> 10.53%	<b>Correct Nulls</b> 69.23%

***Overall % correct radar detection's = 78.18 %***

# **SUMMARY CONCLUSIONS**

- **Successful detection of hazardous turbulence convincingly demonstrated.**
- **NESPA detection performance in low reflectivity conditions considered good.**
- **Hazard prediction in general agreement with measured in-situ “truth” g-loads.**
- **Overall system performance exceeds current FAA minimum perf. standards.**
- **Radar system performance for FY-02 flight test demonstrates feasibility of TPAWS technology.**

# WHERE DO WE GO FROM HERE

## KEY NASA FOCUS :

*Provide scientific basis, test & evaluation methodologies, and a verifiable “tool - set” necessary to certify airborne radar turbulence detection & warning system concepts; and promote application of the technology into the U.S. civil airspace system.*

## MAJOR ACTIVITIES IN SUPPORT OF FAA /NASA / INDUSTRY TPAWS CERTIFICATION INITIATIVES

- Deliver verified high resolution 3D turbulence numerical models for selected accident cases & NASA research flight events
- Deliver verified engineering simulation model of airborne pulsed Doppler radar systems antenna characteristics & related DSP functions
- Develop and justify turbulence hazard tables to enable prediction of aircraft loads based on radar observables & recommend implementation guidelines for Part 121 fleet
- Develop and justify statistically based scoring methodology to evaluate radar detection performance
- Conduct flight deck integration simulation studies to assess compliance of baseline TPAWS concept to “intended function” for defined crew procedures

# TPAWS DEVELOPMENT - TEAM RELATIONSHIPS VESTED INTERESTS

ELAPSED  
TIME

## AVIONICS / AIRFRAME INDUSTRY

- DESIGN & MANUFACTURE
- CERTIFY & COMMERCIALIZE

RADAR  
SENSOR  
REQTs.

SYSTEM REQTs.

### FLIGHT DECK INTERFACE

- ALERT PROTOCOL
- DISPLAY
- CREW PROCEDURES

INTENDED FUNCTION

OPERATIONAL FACTORS

AVIATION HAZARD / THREAT DEFINITION

## GOV. FAA / NASA

- CERTIFICATION
- RESEARCH
- TECHNOLOGY FEASIBILITY
- TECHNOLOGY TRANSFER

## AIRLINES

- OPERATIONAL NEEDS
- SAFETY BENEFITS
- TECHNOLOGY "BUY IN"
- TRAINING & EDUCATION