



# Flight Test Results for a Turbulence Detection Radar

Weather Accident Prevention  
Second Annual Review  
June 5-7, 2001

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# Presentation Outline

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Introduction
- Flight Configuration
- Flight Operations Summary
- Event Summary
- Data Report and Analyses by Flight
- Flight Test Summary
- CY01 Flight Plans



# Aviation Safety Program Organization

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

**Aviation Safety Program Office**  
1.0  
Mike Lewis

Government/Industry  
Program Leadership  
Team

**Technical Integration**  
1.1  
Vince Schultz (LaRC)

Level 1- Program

**Aviation System Monitoring & Modeling**  
2.1  
Yuri Gawdiak (ARC)

**System-Wide Accident Prevention**  
2.2  
Dave Foyle (ARC)

**Single Aircraft Accident Prevention**  
2.3  
John White (LaRC)

**Weather Accident Prevention**  
2.4  
Shari Nadell (GRC)

**Accident Mitigation**  
2.5  
Doug Rohn (GRC)

**Synthetic Vision**  
2.6  
Dan Baize (LaRC)

Level 2- Projects

**Aircraft Icing**  
(Base Program)

**Aviation Weather Information (AWIN)**  
2.4.1  
Paul Stough (LaRC)

**Weather Information Communication (WINCOMM)**  
2.4.2  
Gus Martzaklis (GRC)

**Turbulence Detection & Mitigation (TDAM)**  
2.4.3  
Rod Bogue (DFRC)

Level 3- Elements



# Turbulence Detection Level 4 Sub-element

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



- Sensor Performance Assessment
- Sensor Development
- Algorithm Development
- Demonstration & Verification

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# Objectives

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

## **W<sub>x</sub>AP Objective #3**

Provide commercial aircraft sensor with 90% probability of detection of severe Convective and Clear Air Turbulence thirty seconds to two minutes before encounter.

## **W<sub>x</sub>AP Milestone #2**

Flight demonstrate certifiable forward-looking on-board turbulence warning system with Type-I and Type-II error probability commensurate with airborne wind shear technology. [TRL/IRL of 7/4]

## **Goal for NASA/FAA/Industry**

Advance warning of  $\geq 30$  sec. with POD  $\geq 80\%$  for phenomena with reflectivity  $\geq 15$  dBz.



# Flight Operations Summary

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Weather Support
  - Forecasting and pre-flight recommendations
    - 2-, 1-, and day of operation forecasts
  - Pilot briefings
  - Onboard tactical recommendations
  - Real-time observations
- *In Situ*
  - Data Collection
  - Real-time engineering displays
  - Post-flight processing
- Turbulence Radar
  - Data collection
  - Real-time engineering displays
  - Aircraft response algorithms
  - Post-flight processing

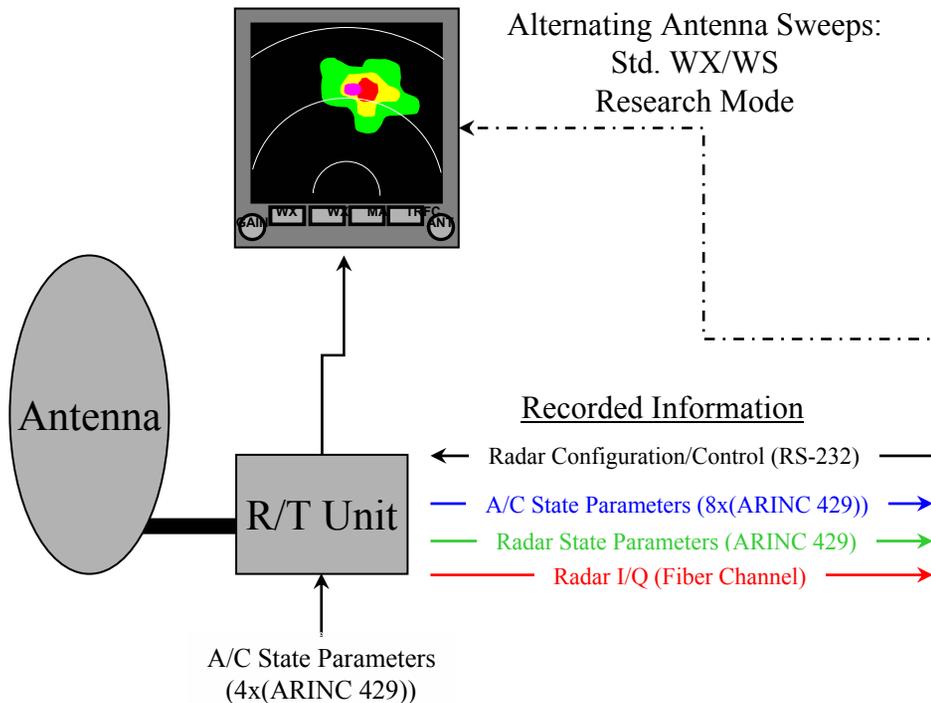


# Radar Data Collection

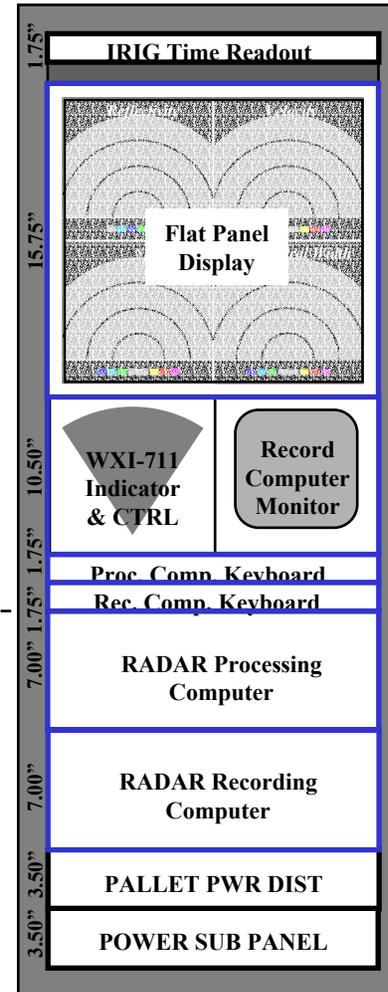
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

## CY'00 Radar Flight Test Objectives

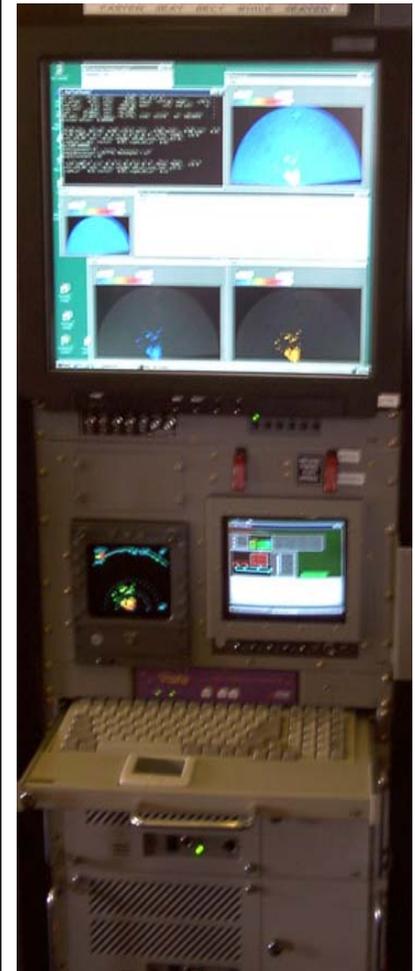
- Collect airborne radar signatures of turbulence (along with aircraft response) to enable characterization and algorithm development/refinement.
- Assess the performance of the latest-generation turbulence detection and hazard estimation algorithms.



## Design Layout



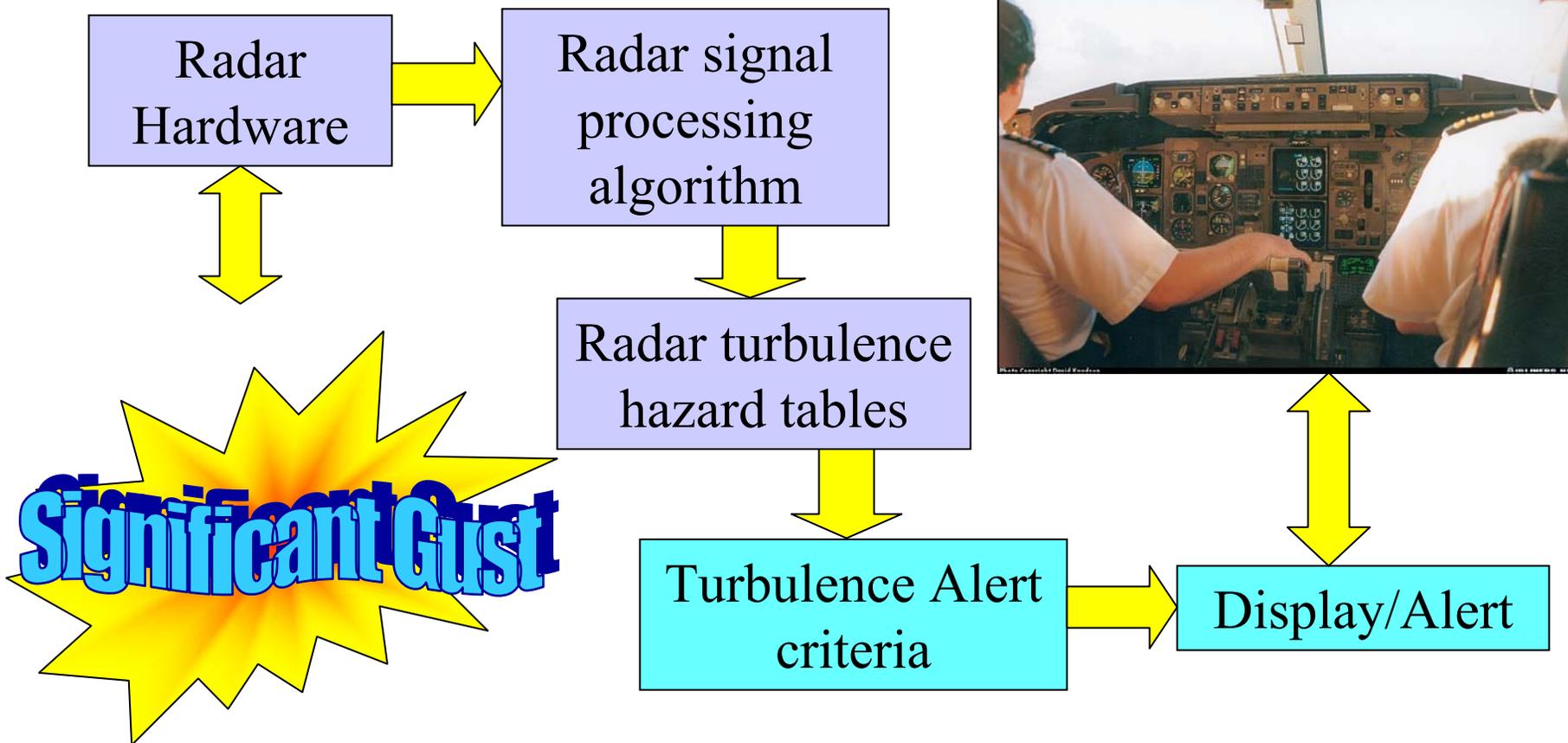
## As Built





# An End-to-End Turbulence Radar System

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation





# Baseline Algorithm Methodology

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Includes time-domain interference-rejection filter
- Frequency/Doppler-velocity domain spectral width estimation
- Optional averaging over range and/or azimuth
- Estimates turbulence correlation length
- Thresholding using CFAR (constant false alarm rate) threshold calculated from the spectra
- Estimates point variance from spectral width and bin-to-bin variance of average velocity
- Uses Hazard Tables to predict RMS accelerations from point variance



# NCAR Algorithm Methodology

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- The NCAR Efficient Spectral Processing Algorithm (NESPA) is a multi-stage approach to finding high-quality Doppler moments in real-time.
- Data quality is improved by averaging the spectra over multiple azimuths and ranges.
- Hazard metrics are produced by scaling the second moment estimates using tables and combining the results from three elevation angles.
- Confidence measures based on many different indicators (e.g. SNR, continuity, etc.) of data quality are used in the multi-stage processing and are also used in the calculation of the hazard metrics.



# Radar Hazard Tables

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Relate radar estimates of spectral width or point variance to predicted variance of aircraft accelerations
- Key part of system to go from radar data processing algorithm output to aircraft effects



# Hazard Levels: RMS Vertical Acceleration

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Light ➤ less than 0.2 g
- Moderate ➤ 0.2 to 0.3 g
- Severe ➤ greater than 0.3 to 0.6 g
- Extreme ➤ over 0.6 g



# Proposed Alert Criteria

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

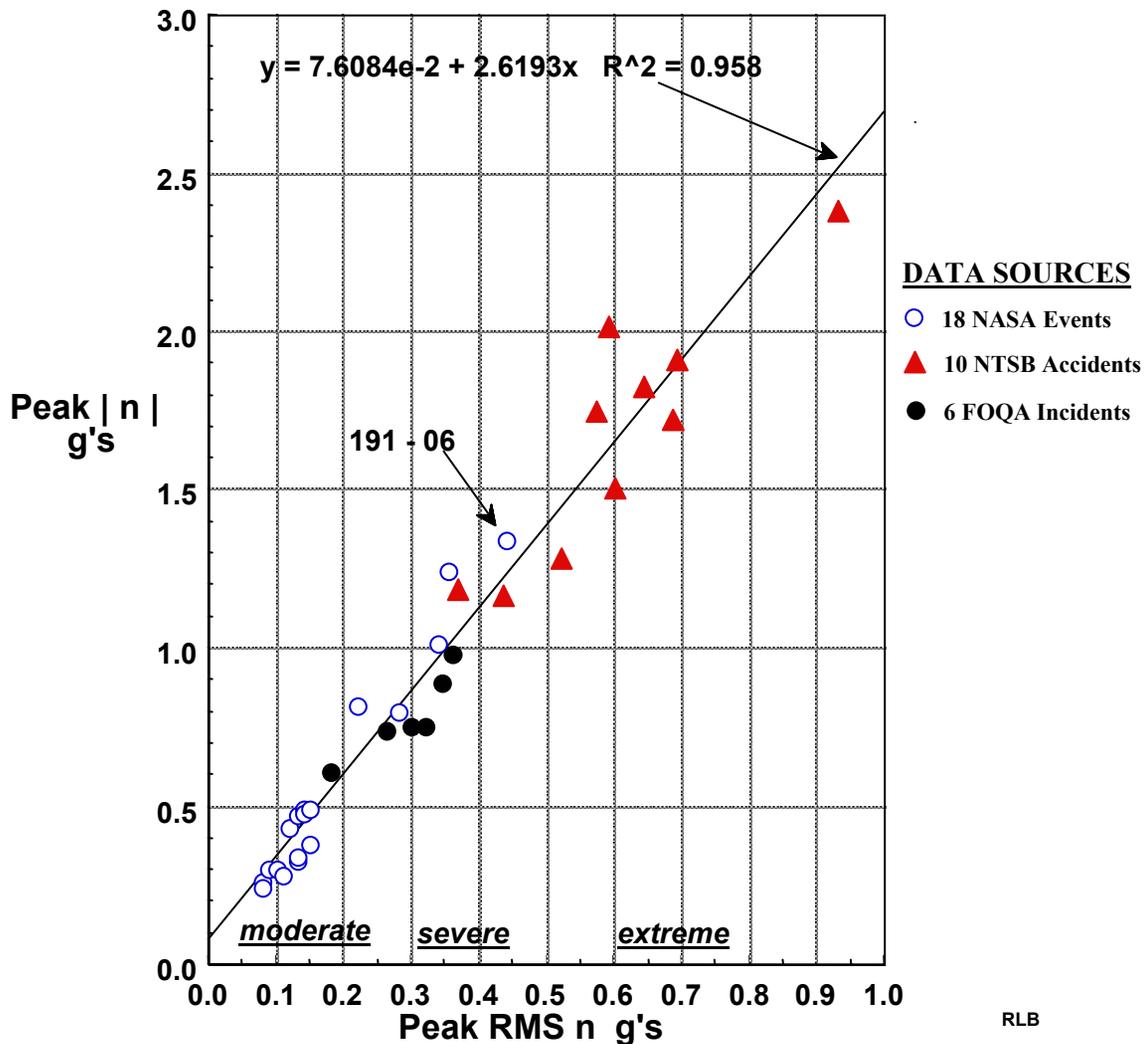
**Goal:** Advance warning of  $\geq 30$  sec. with  $\text{POD} \geq 80\%$   
for phenomena with reflectivity  $\geq 15$  dBz.

<u>Alerts Based on Radar Observables</u>	<u>Predicted Hazard</u>
<b>No Alert</b>	$\sigma_{\Delta n} < 0.2g$
<b>May Alert</b>	$0.2g \leq \sigma_{\Delta n} < 0.3g$
<b>Must Alert</b>	$\sigma_{\Delta n} \geq 0.3g$



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

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



Based on Measurements for 34 Turbulence Encounter Cases



# Flight Test Summary

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Checkout/ferry flights (154, 155, 169)
- 3 Data flights
  - 181: 3 to 4 very low reflectivity encounters with light turbulence
  - 190 & 191: low reflectivity encounters with light to severe turbulence
- 18 *in situ* events identified from data flights
- 7 events selected for detailed radar analysis



# 18 Event Summary Table

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

<i>Flight-event</i>	<i>No Alert &lt; 0.2 g</i>	<i>0.2 ≤ Alert &lt; 0.3 g</i>	<i>Alert ≥ 0.3 g</i>	<i>Notes</i>
181-01	X			
181-02	X			-10 deg roll
181-03	X			
181-04		X		+/- 30 deg roll
181-05	X			30 deg roll
181-06	X			-30 deg roll
181-07	X			+/- 30 deg roll
181-08	X			
190-02	X			
190-03	X			
190-04		X		30 deg roll
190-05	X			50 deg roll
190-06			X	40 deg roll
190-07	X			35 deg roll
191-03			X	30 deg roll
191-04	X			---
191-05	X			30 to 50 deg roll
191-06			X	30 deg roll



# 7 Event Summary Table

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

Flight-event	In Situ $\sigma\Delta n$	NESPA	Baseline	Hazard
181-07	0.15	< 0.2	> 0.2	light
181-08	0.16	< 0.2	0.32	light
190-04	0.28	< 0.2	< 0.27	moderate
190-06	0.2 & 0.35	< 0.2	0.3	severe
191-03	0.34	0.2	0.32	severe
191-04	0.14	< 0.2	low reflectivity	light
191-06	0.44	0.32	near 0.4	severe



# Weather Summary

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

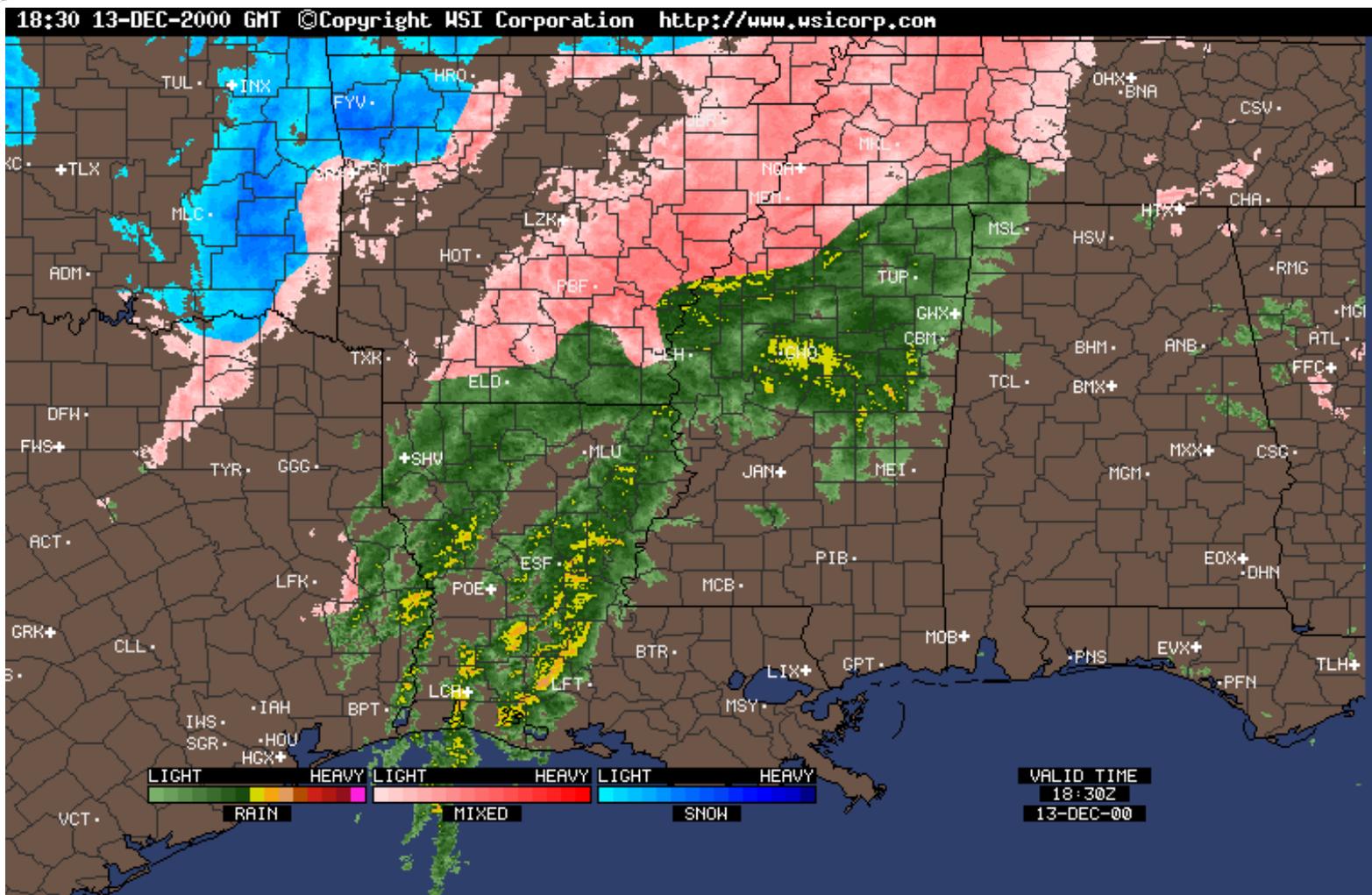
<b>Flight/Day</b>	<b>Weather</b>	<b>Primary Region of Interest</b>	<b>Peak Storm Tops</b>	<b>Cell Movement (from)</b>
<b>FI- 181 16 Nov 2000</b>	Broad Area of Rain with Embedded Convective Cells	Southern Mississippi & Louisiana	30,000 feet	WSW at 45 kts
<b>FI -190 13 Dec 2000</b>	Broad Area of Rain and Convective Cells with Embedded Thunderstorms	Northeast Louisiana	43,000 feet	SW at 65 kts
<b>FI -191 14 Dec 2000</b>	Narrow Line of Convective Cells/Thunderstorms	Florida Panhandle & South Georgia	40,000 feet	SW at 40 kts





# Flight 190 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



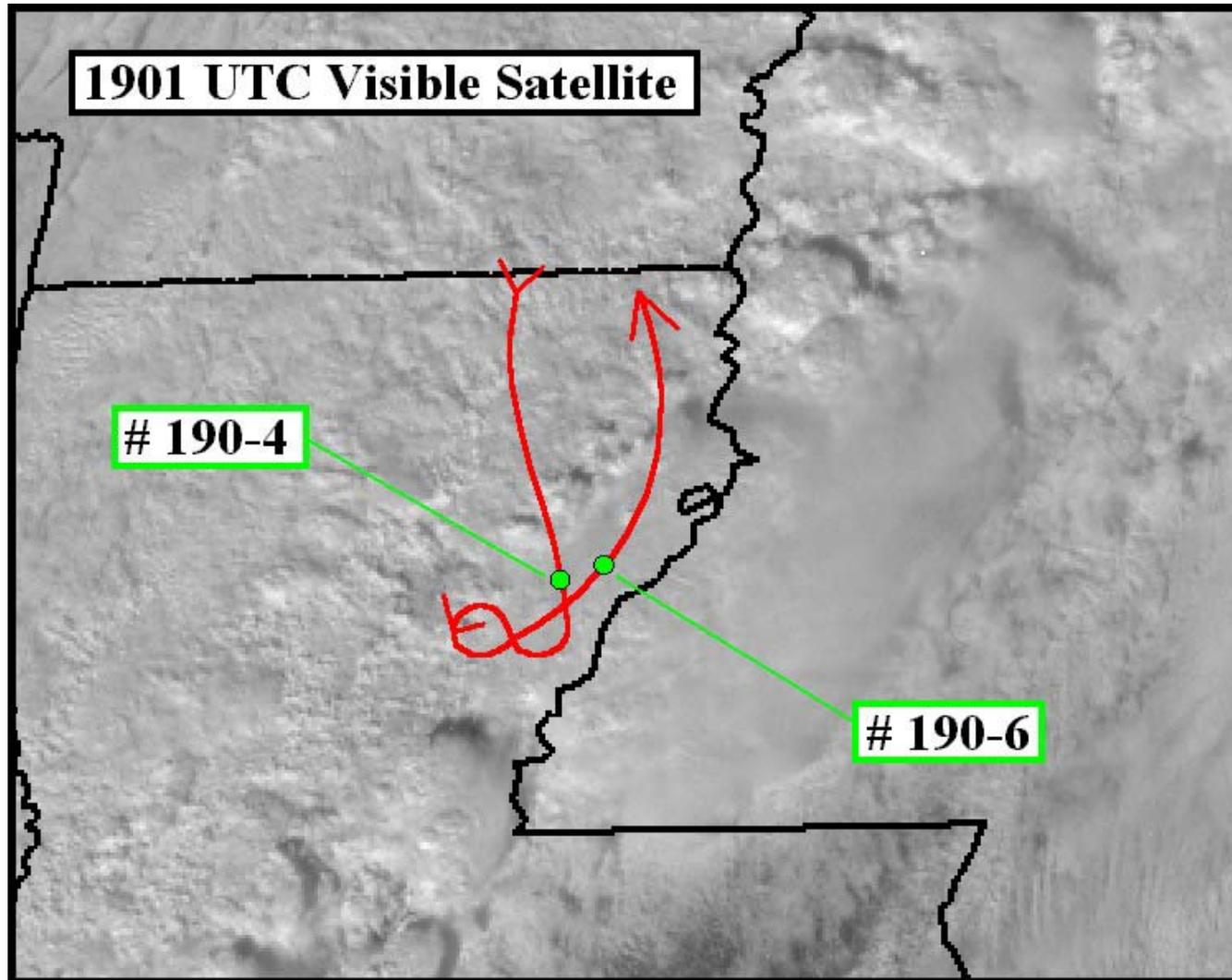
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# Flight 190 Satellite Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



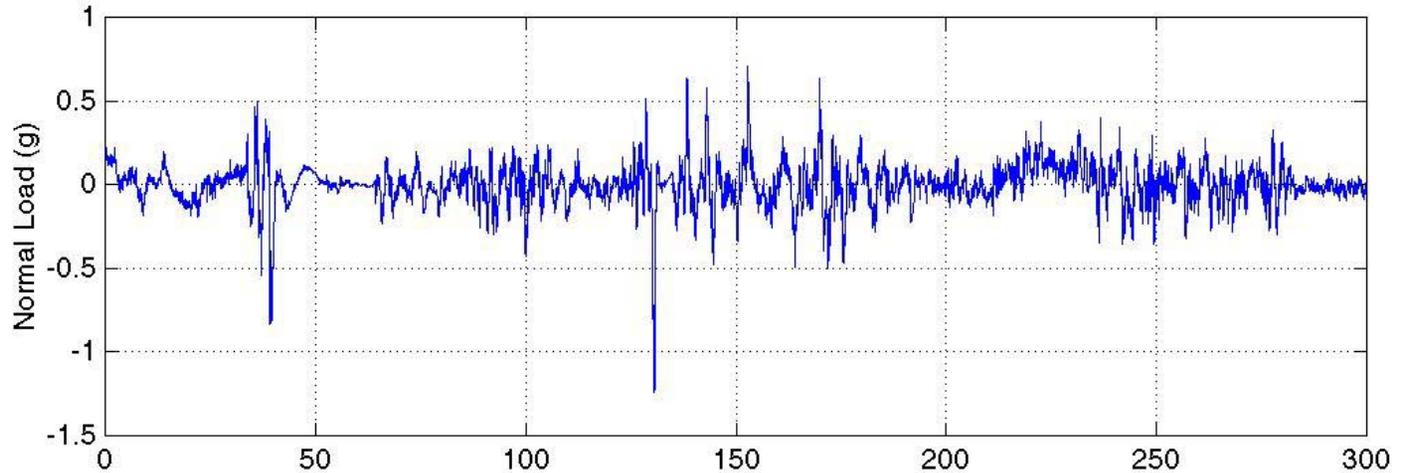
July 25, 2003

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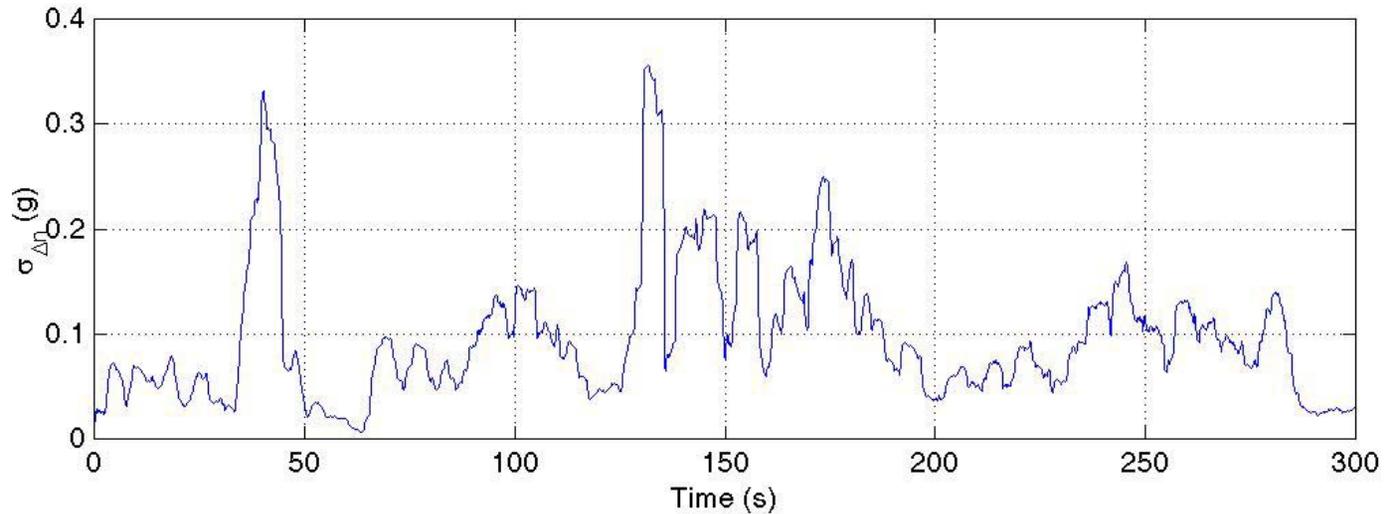
# Flight 190 Event 06 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



68080 sec.

68170 sec.

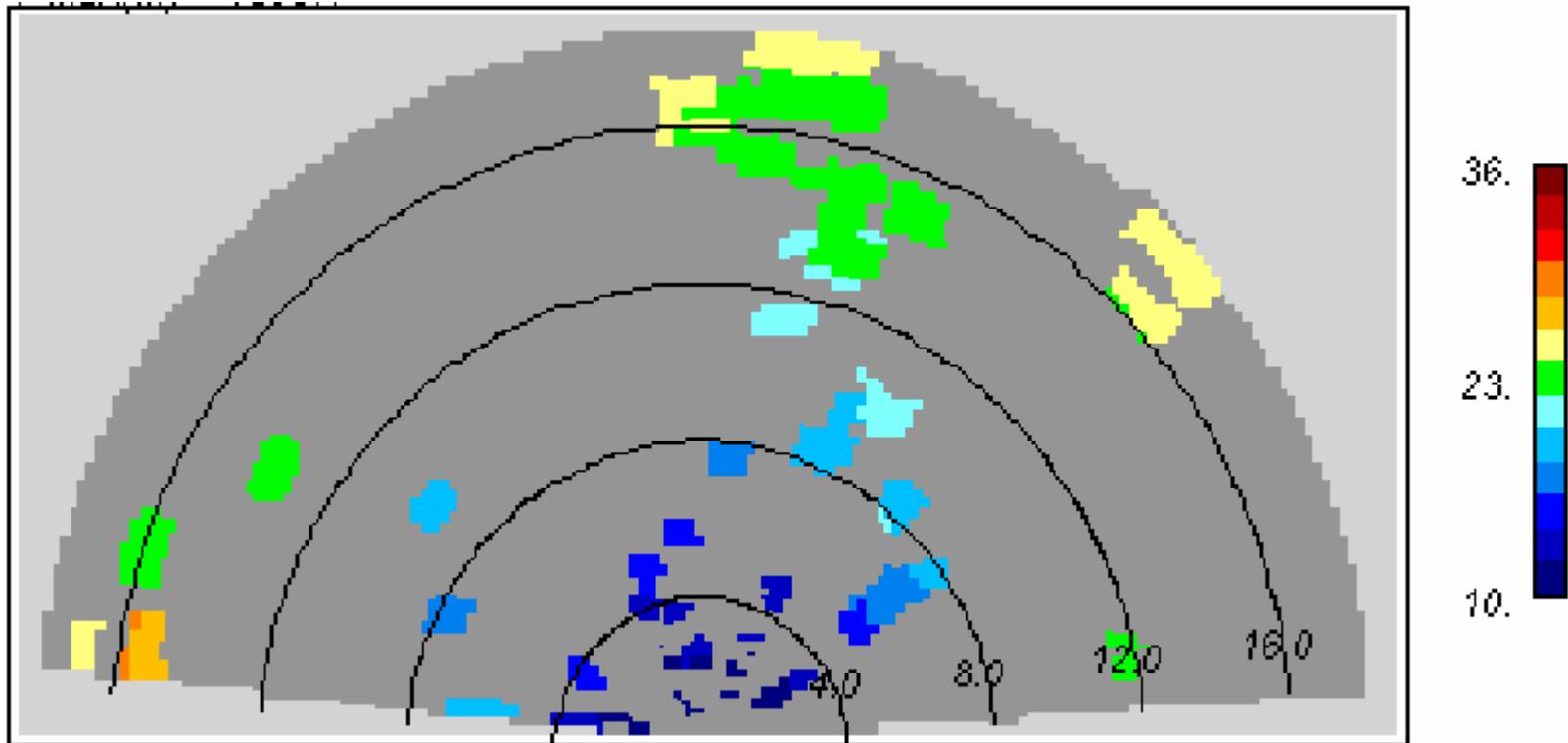




# Reflectivity (dBZ) Event 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:45:21 or 67521 seconds



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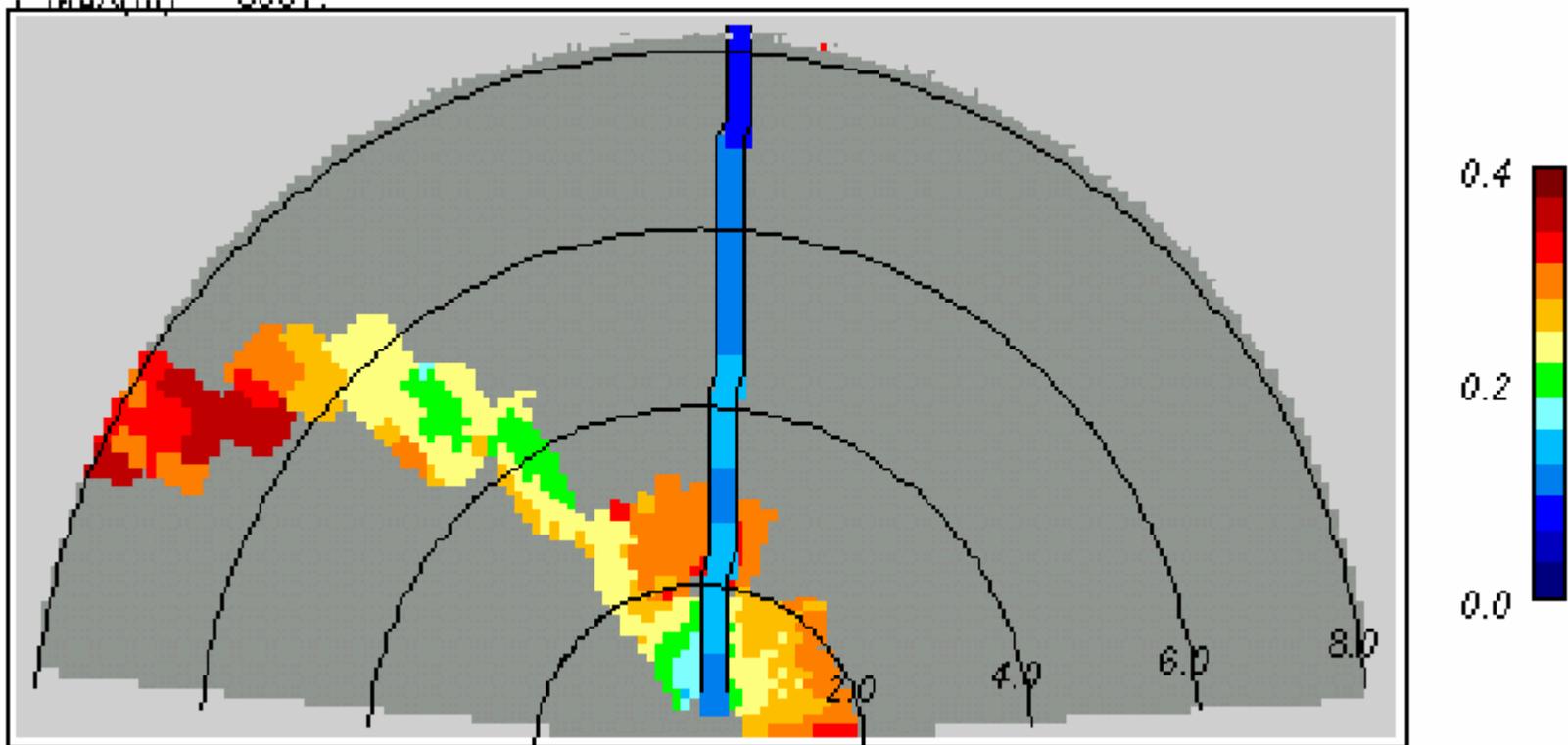
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# g-Loading (rms g) Event 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:55:30 or 68130 seconds

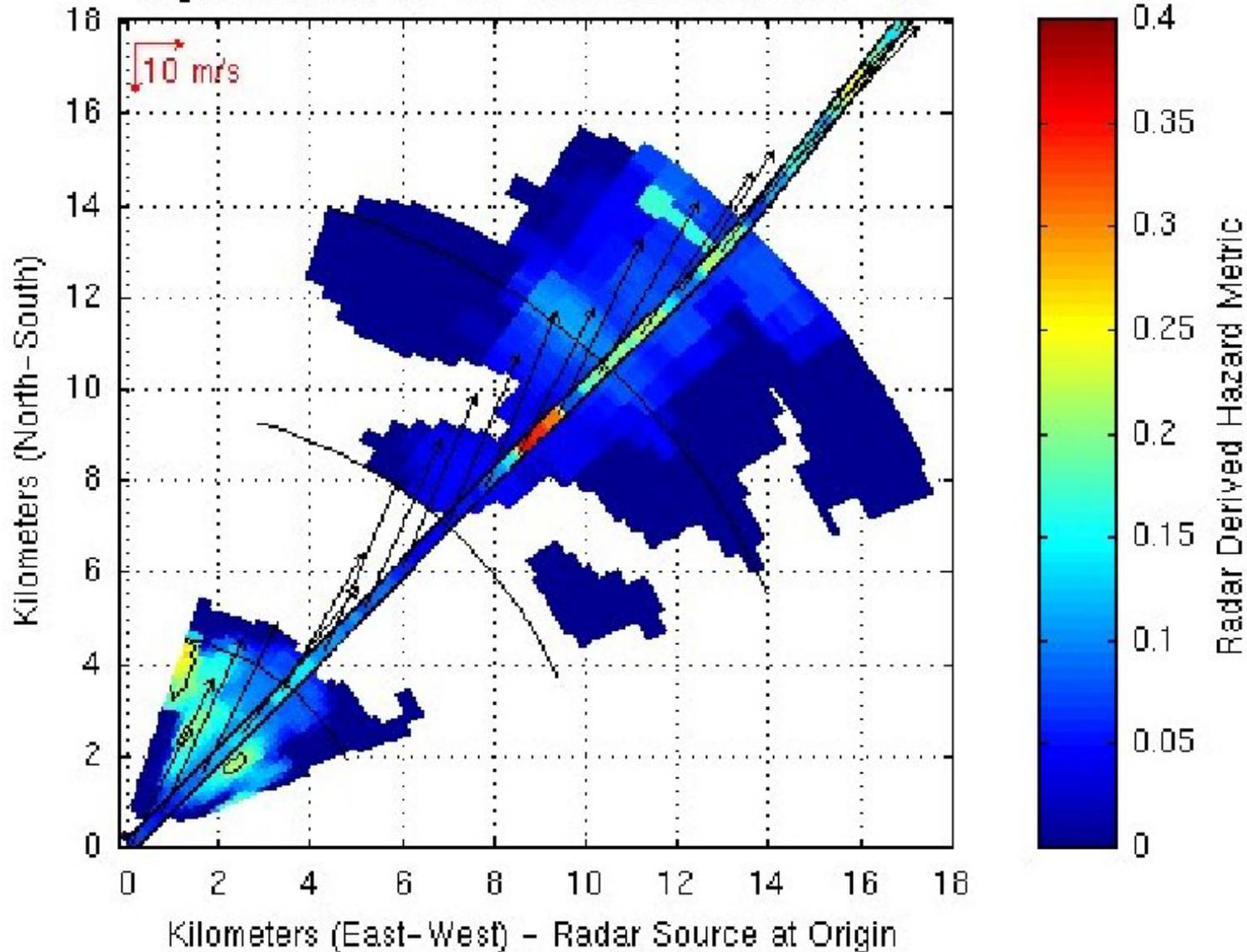


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Flight 190-06, 12-13-2000 18:55:20, Tilt: -4.0



July 25, 2003

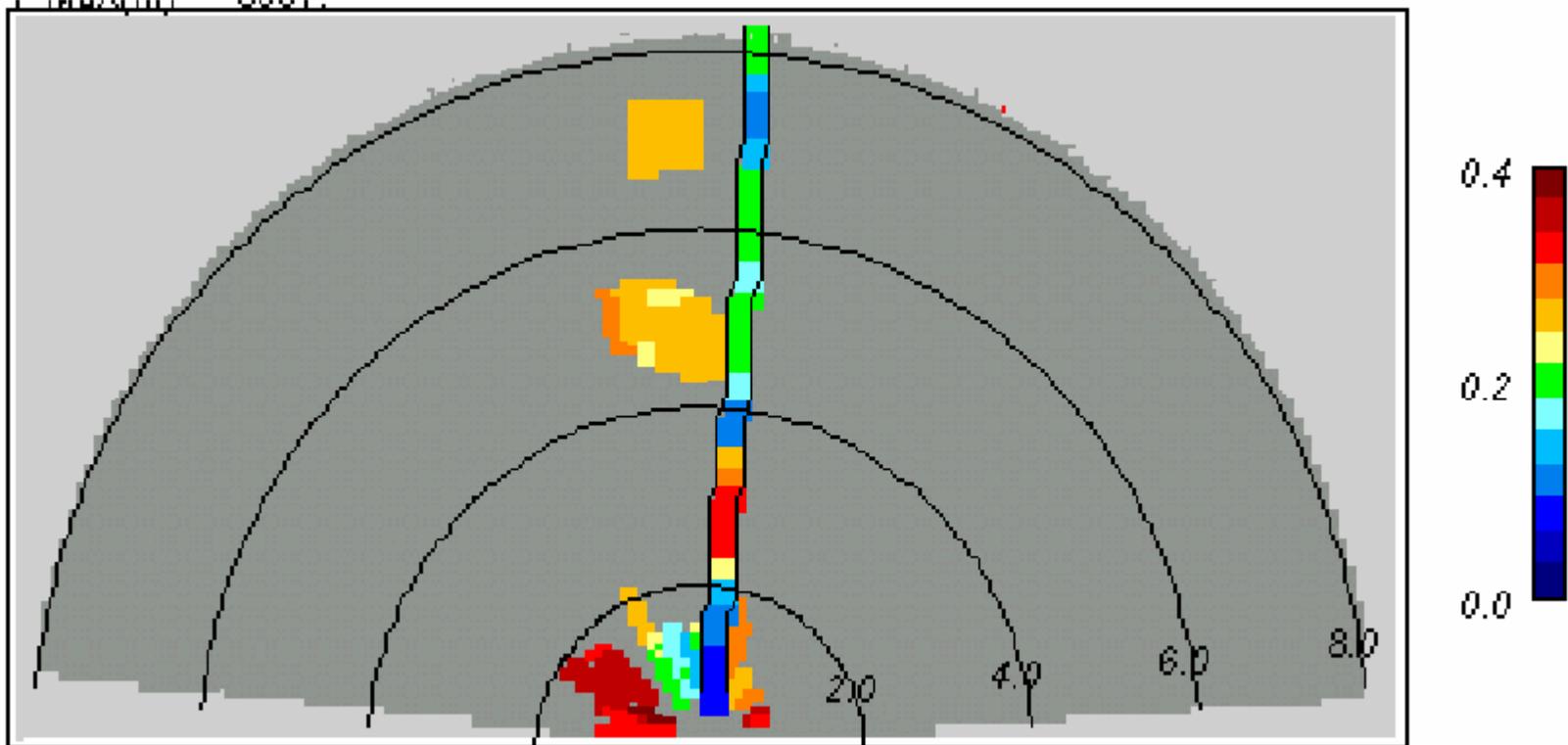
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# g-Loading (rms g) Event 190-06

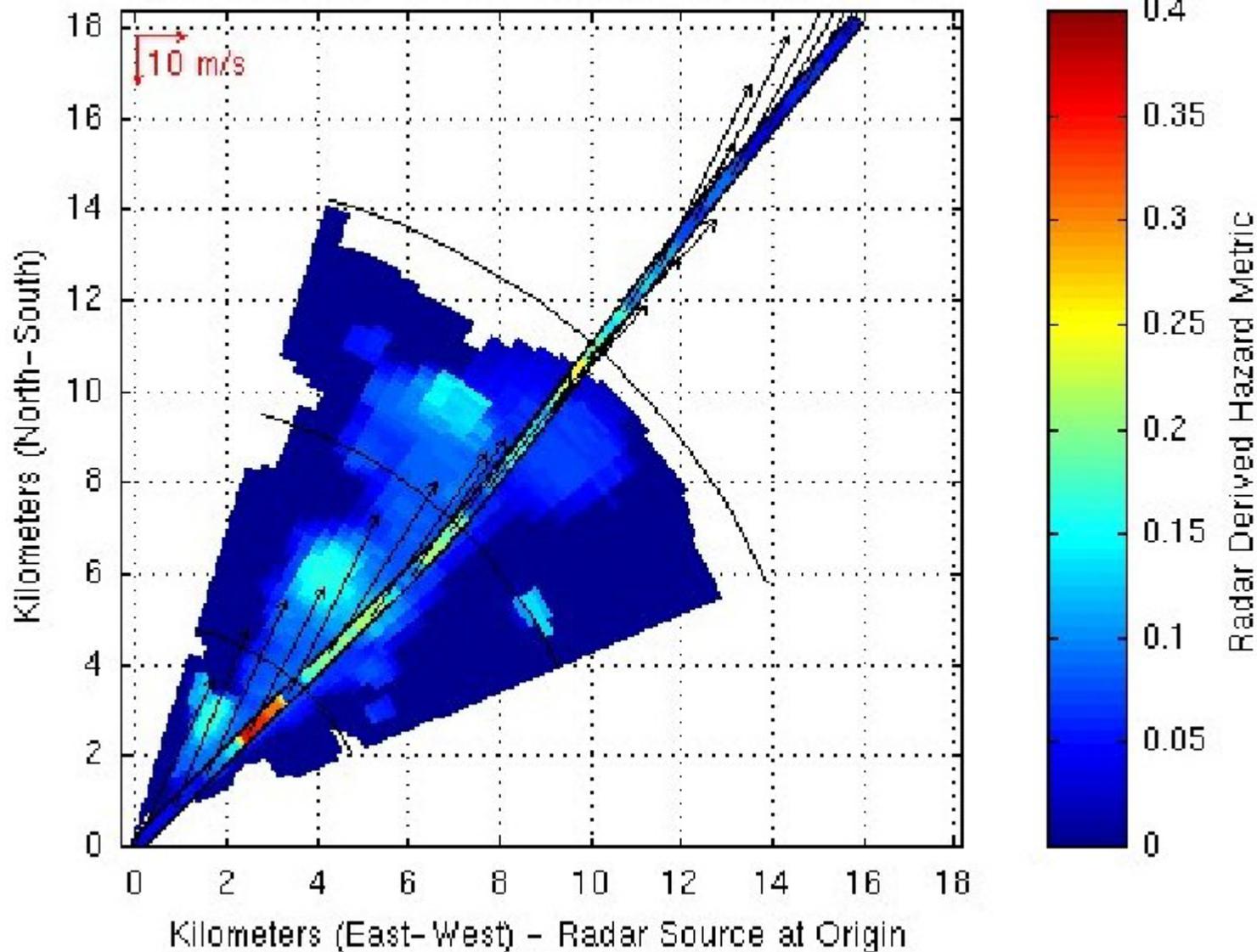
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:56:05 or 68165 seconds





Flight 190-06, 12-13-2000 18:55:55, Tilt: -4.0





## Summary - Case 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- **Little reflectivity within scan range**
- ***In situ* peak rms g ~ 0.33 at 68170 seconds**
- **Missed prediction of in situ peak**
- **Detection of ~0.35 g 5 km (20 seconds) ahead at 68177 seconds where in situ shows ~0.25**
- **Many areas >0.3 off track**



# Flight 191 Weather

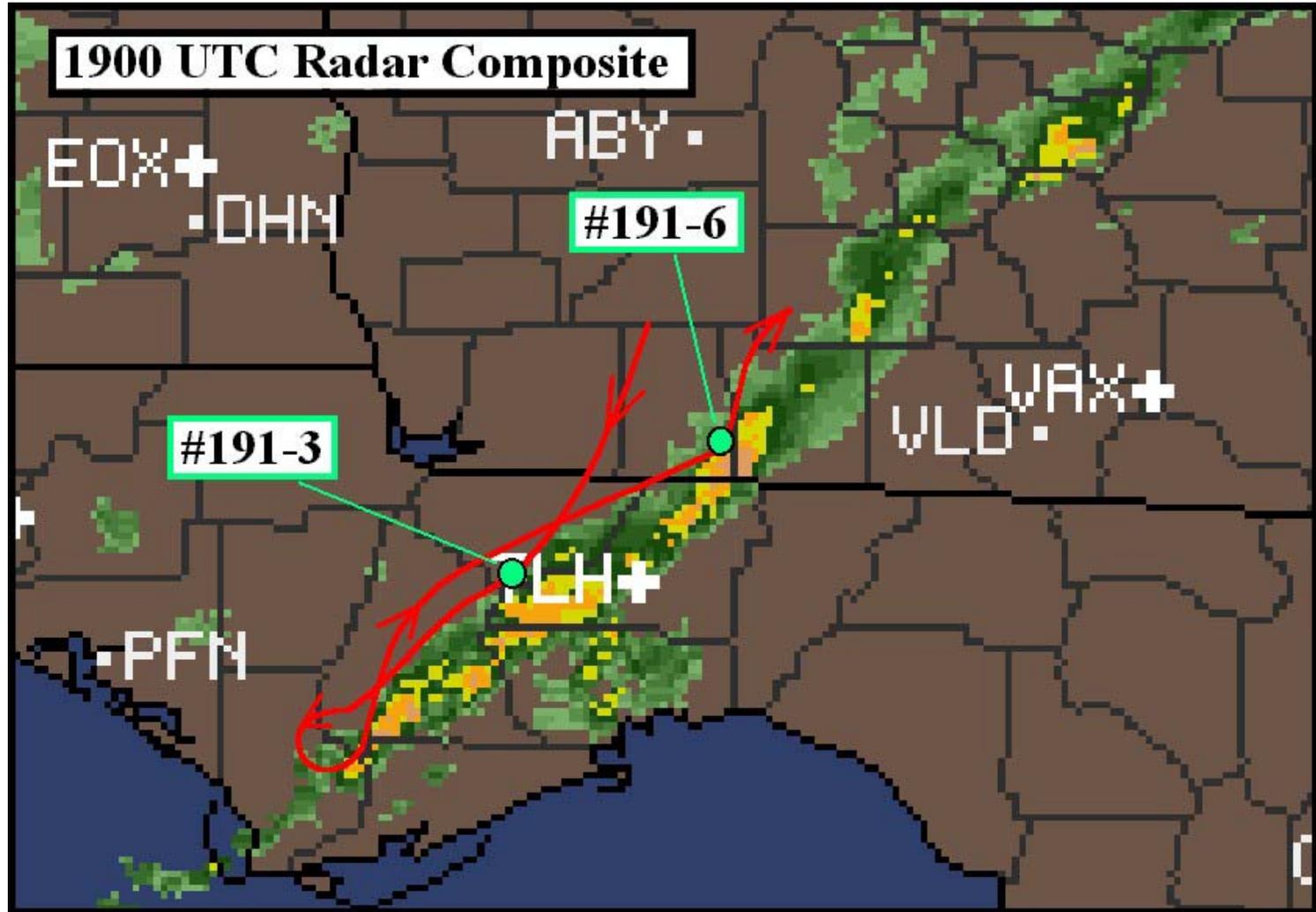
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation





# Flight 191 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



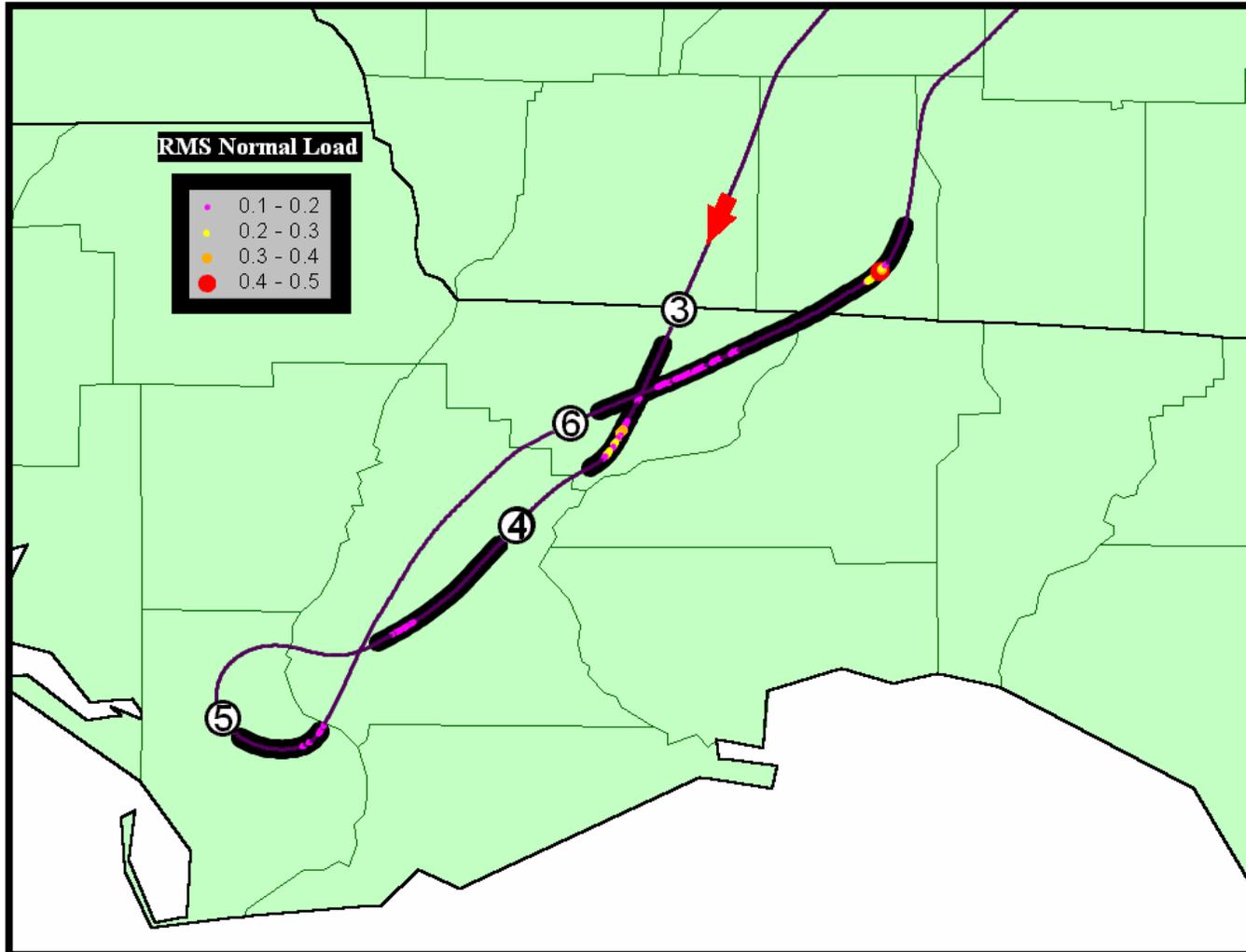
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# 191 Path Flight

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



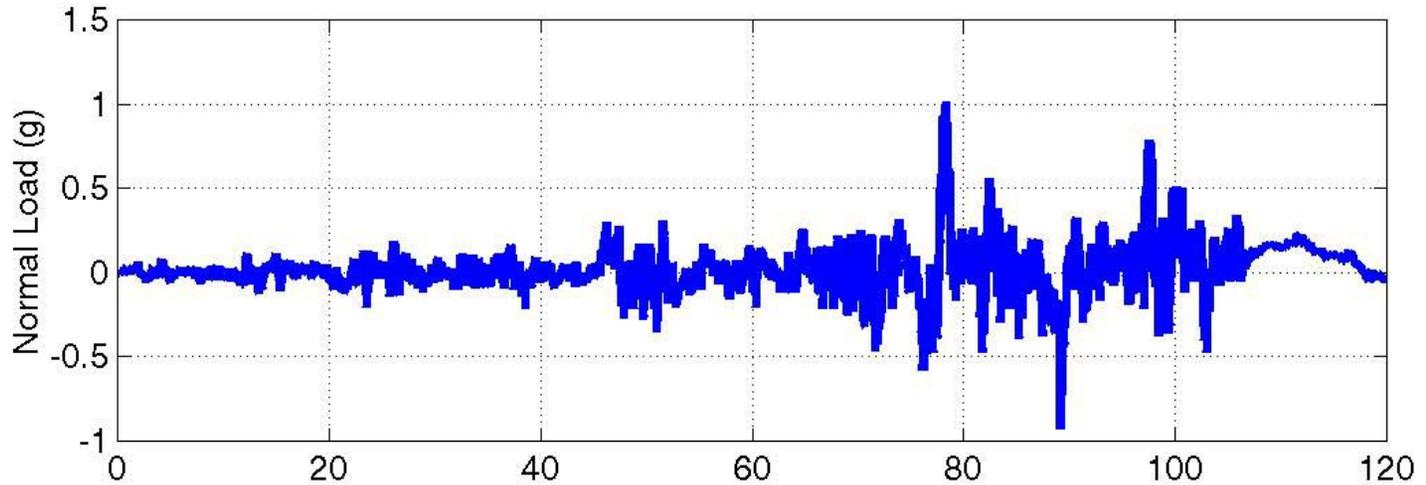
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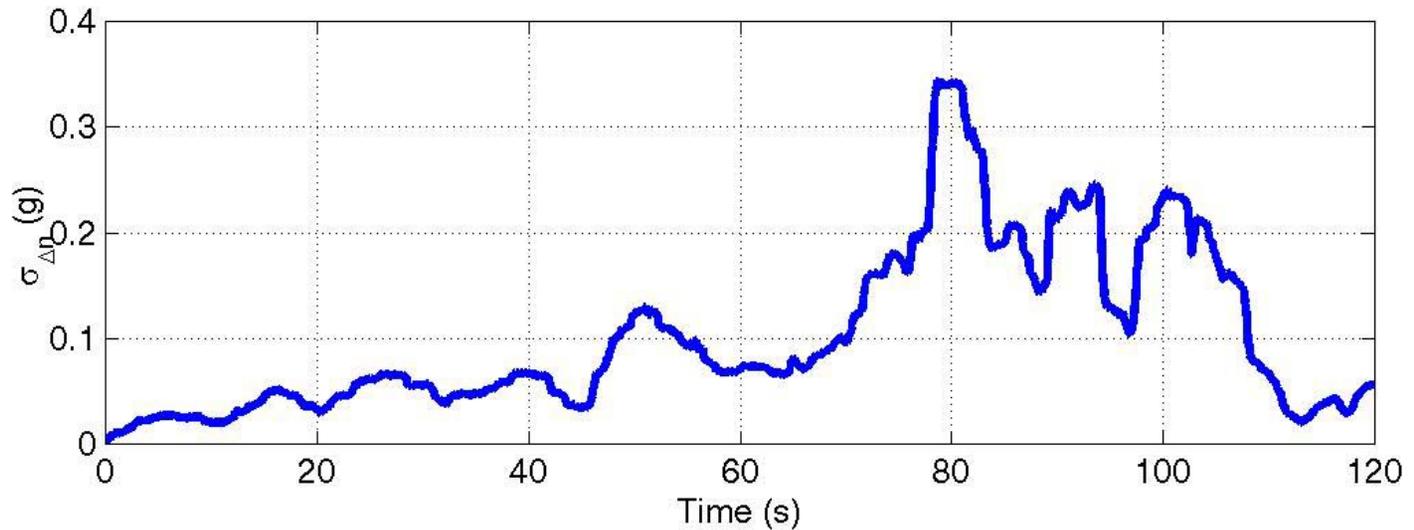


# Flight 191 Event 03 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



66470

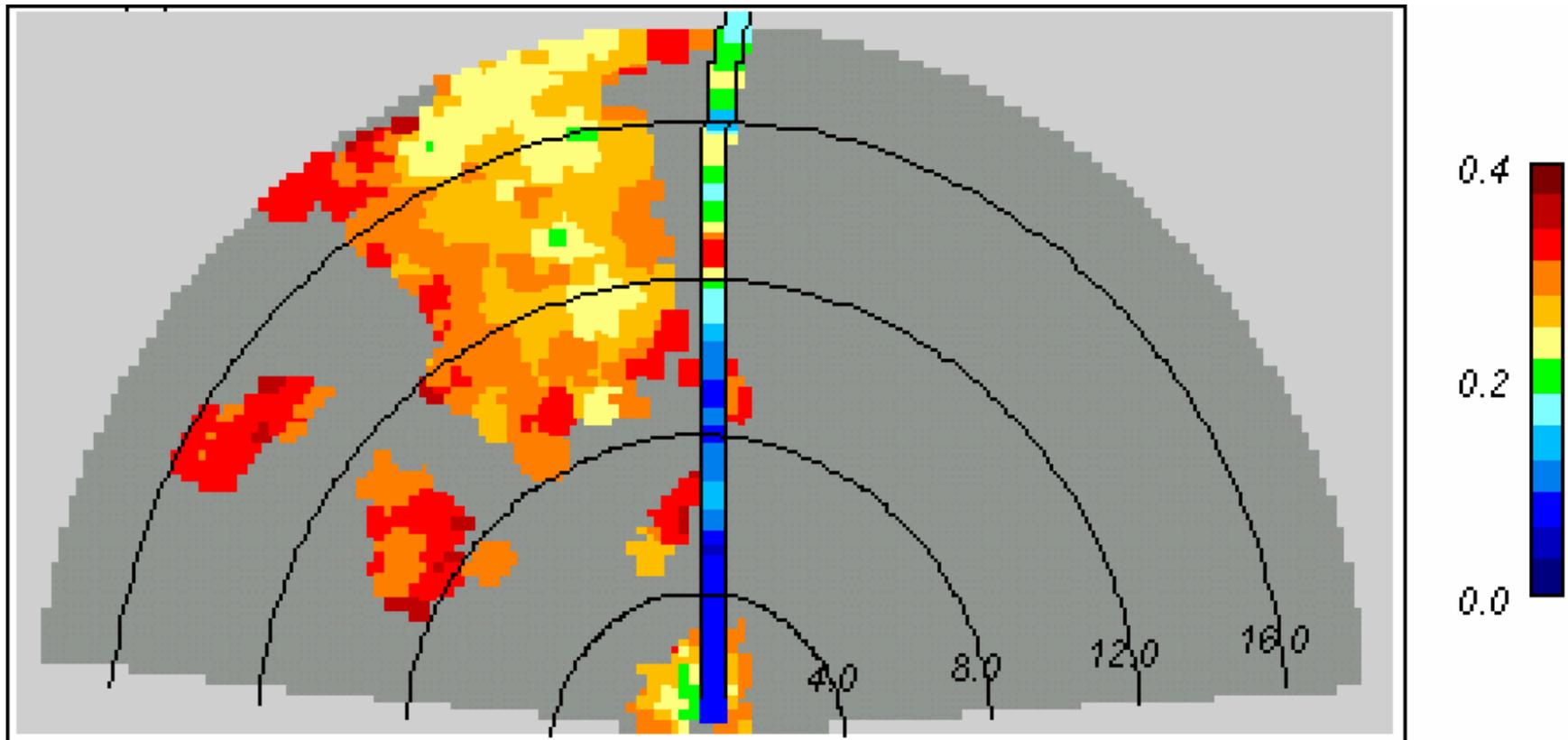




# g-Loading (rms g) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:26:54 or 66414 seconds

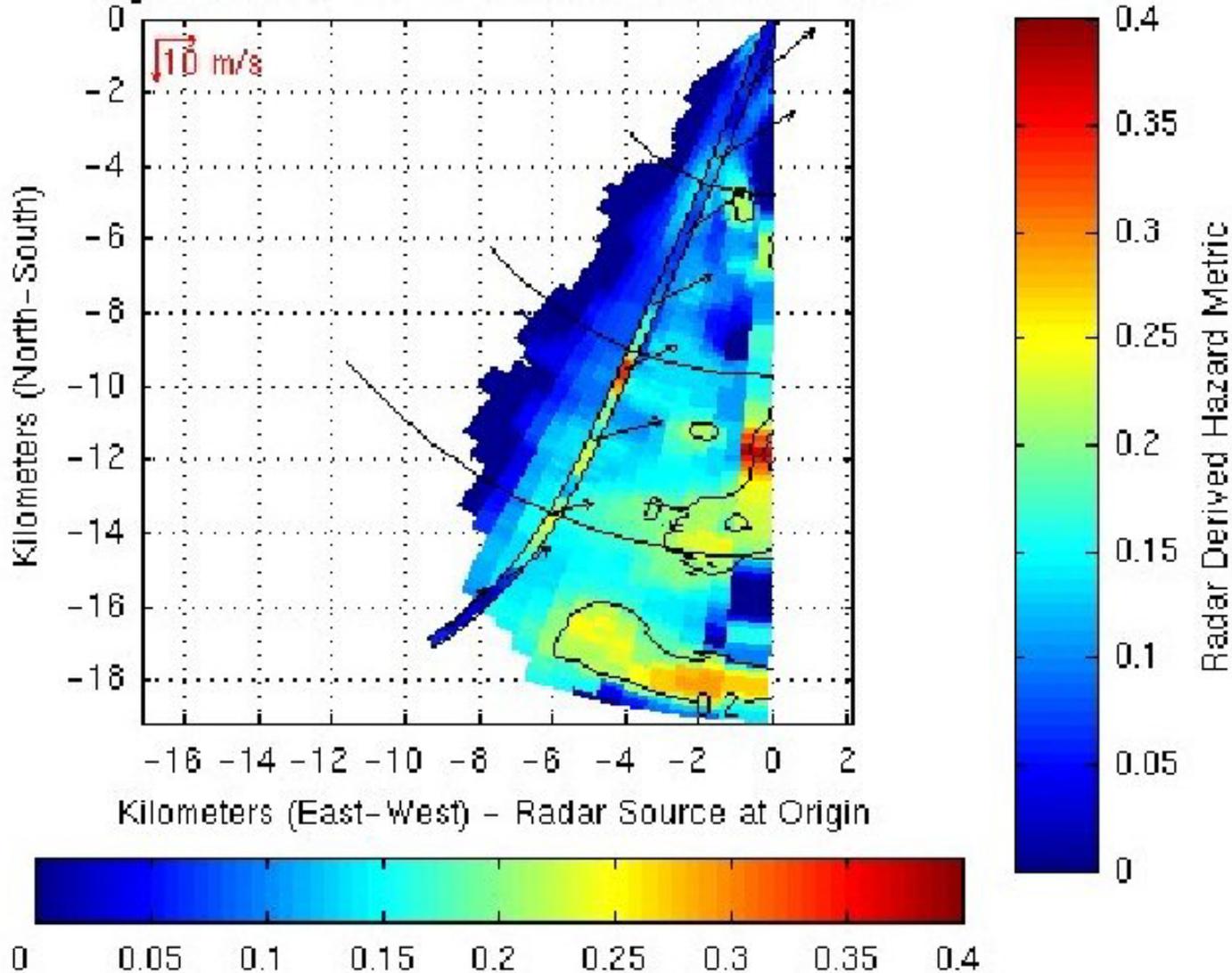


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Flight 191-03, 12-14-2000 18:26:59, Tilt: -2.0



RMS Aircraft Vertical Acceleration (g) - Temporal Window: 5 seconds

July 25, 2003

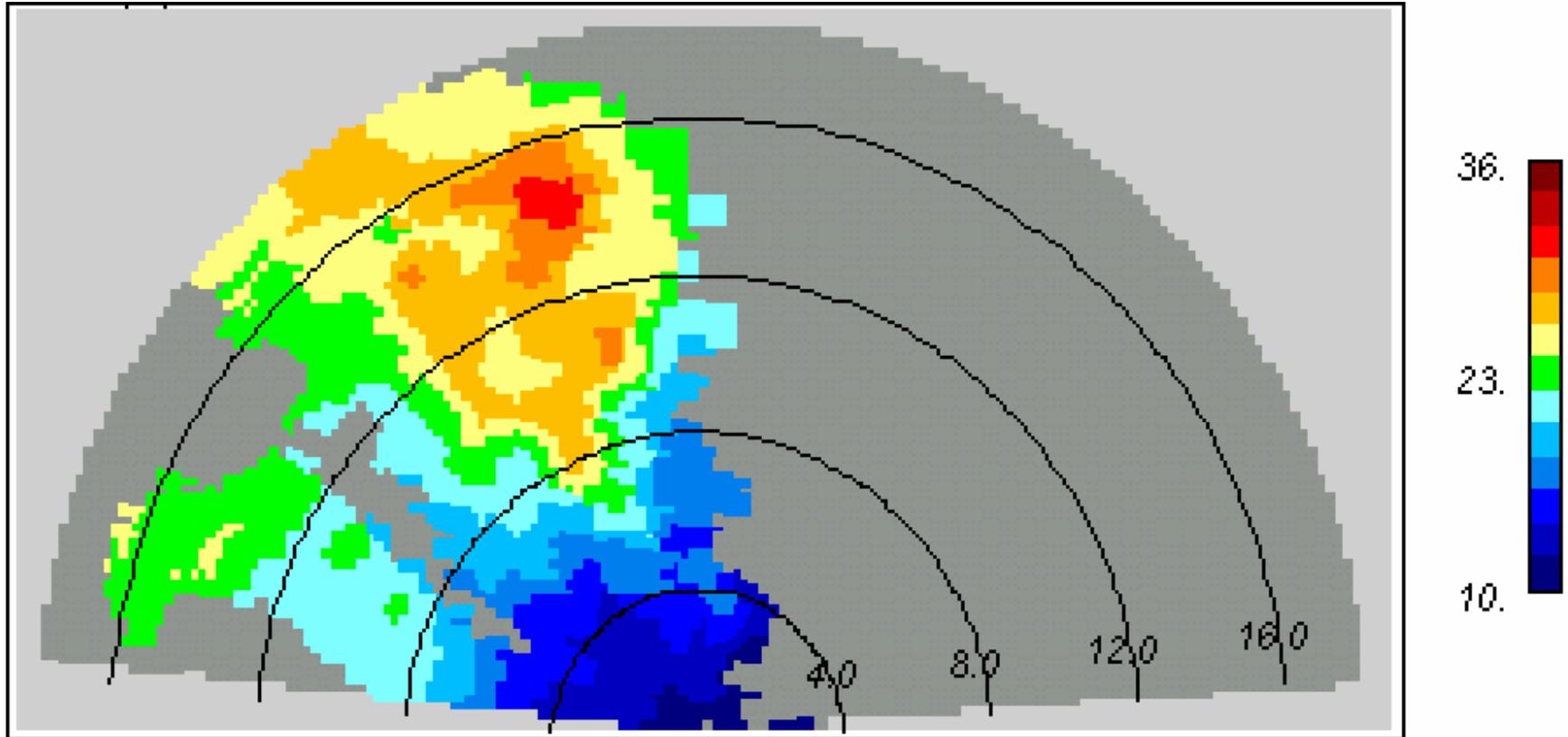
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# Reflectivity (dBZ) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:27:11 or 66431 seconds



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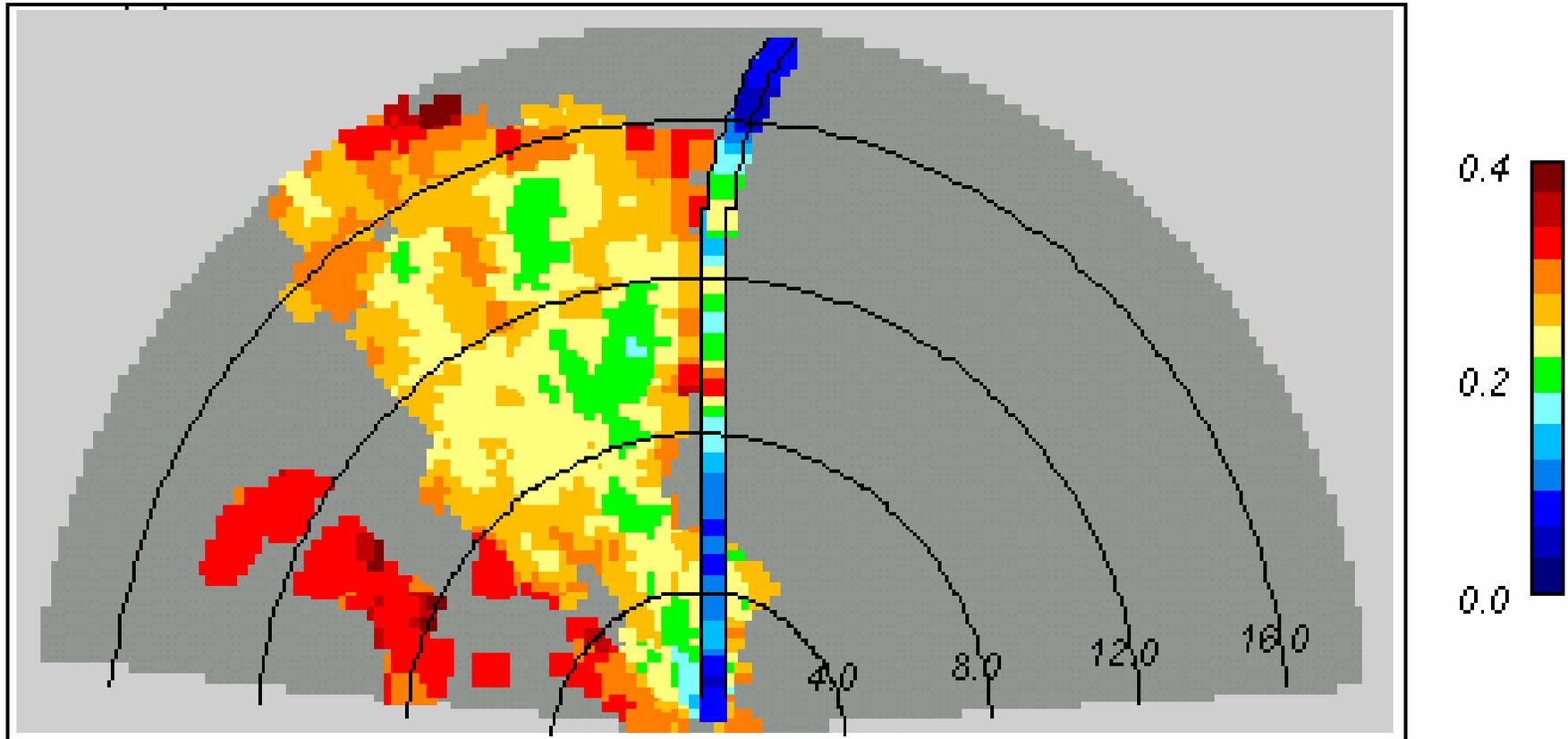
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# g-Loading (rms g) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:27:09 or 66429 seconds

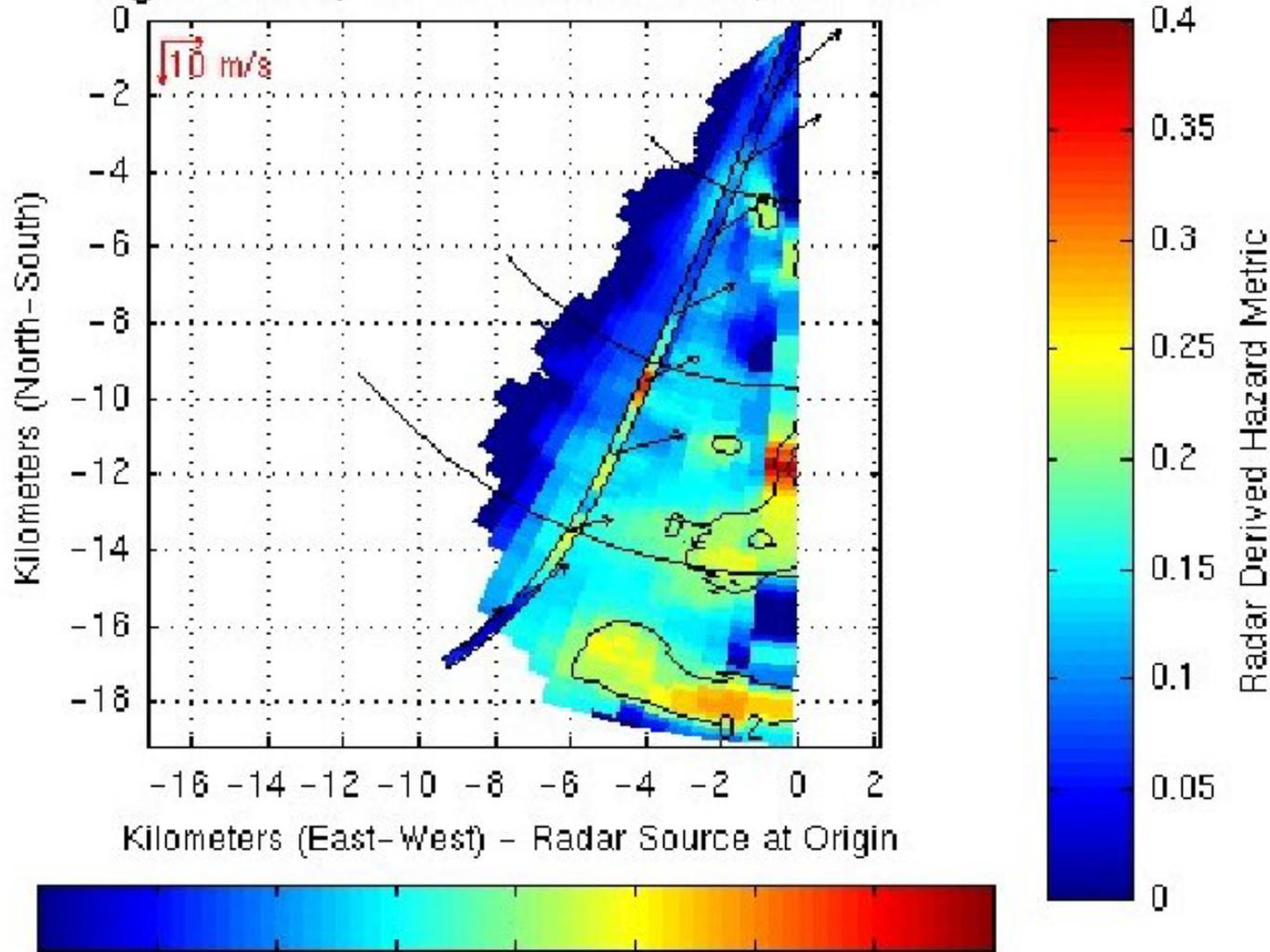


July 25, 2003

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Flight 191-03, 12-14-2000 18:26:59, Tilt: -2.0



RMS Aircraft Vertical Acceleration (g) - Temporal Window: 5 seconds

July 25, 2003

NASA Langley Research Center



# Summary - Event 191-03

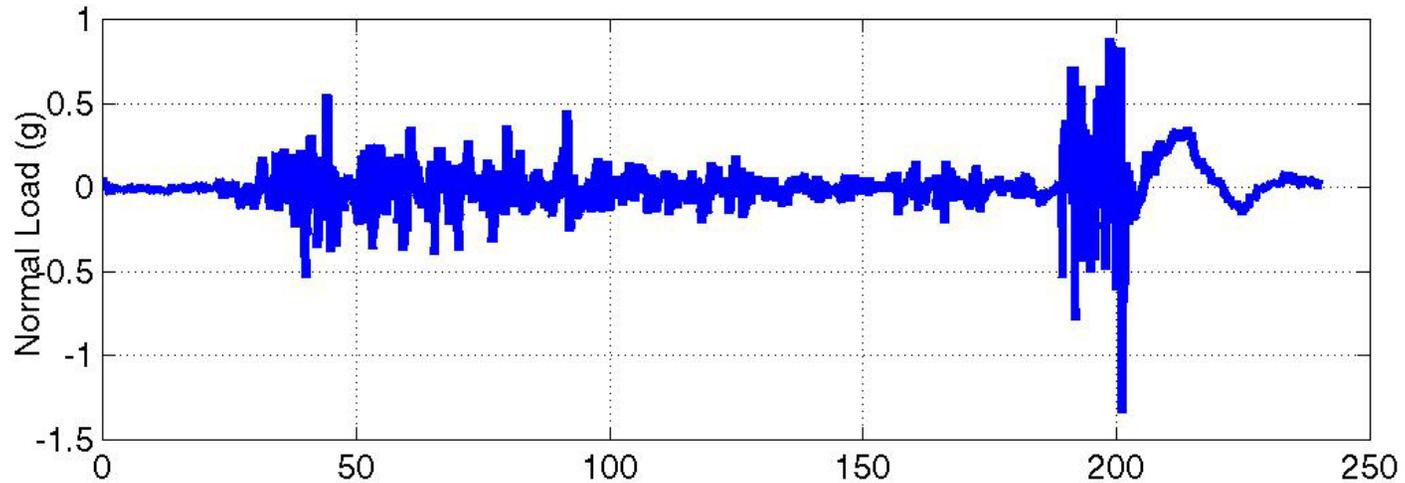
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- **Good reflectivity on port side near path, low reflectivity along path at beginning of run**
- ***In situ* peak rms g ~ 0.33 at 66470 seconds**
- **Predictions of  $> 0.32$  g along path at 66429 9.5 km (44 seconds) ahead**
- **Multiple hits on successive scans down to ~ 5 km**

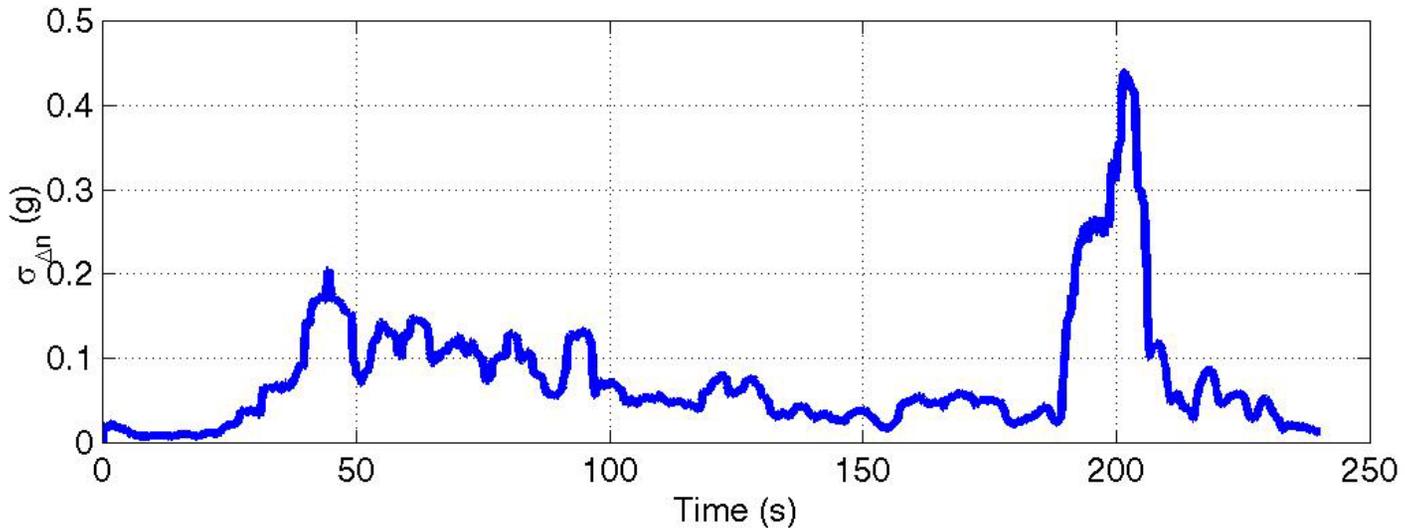


# Flight 191 Event 06 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



67458 sec.

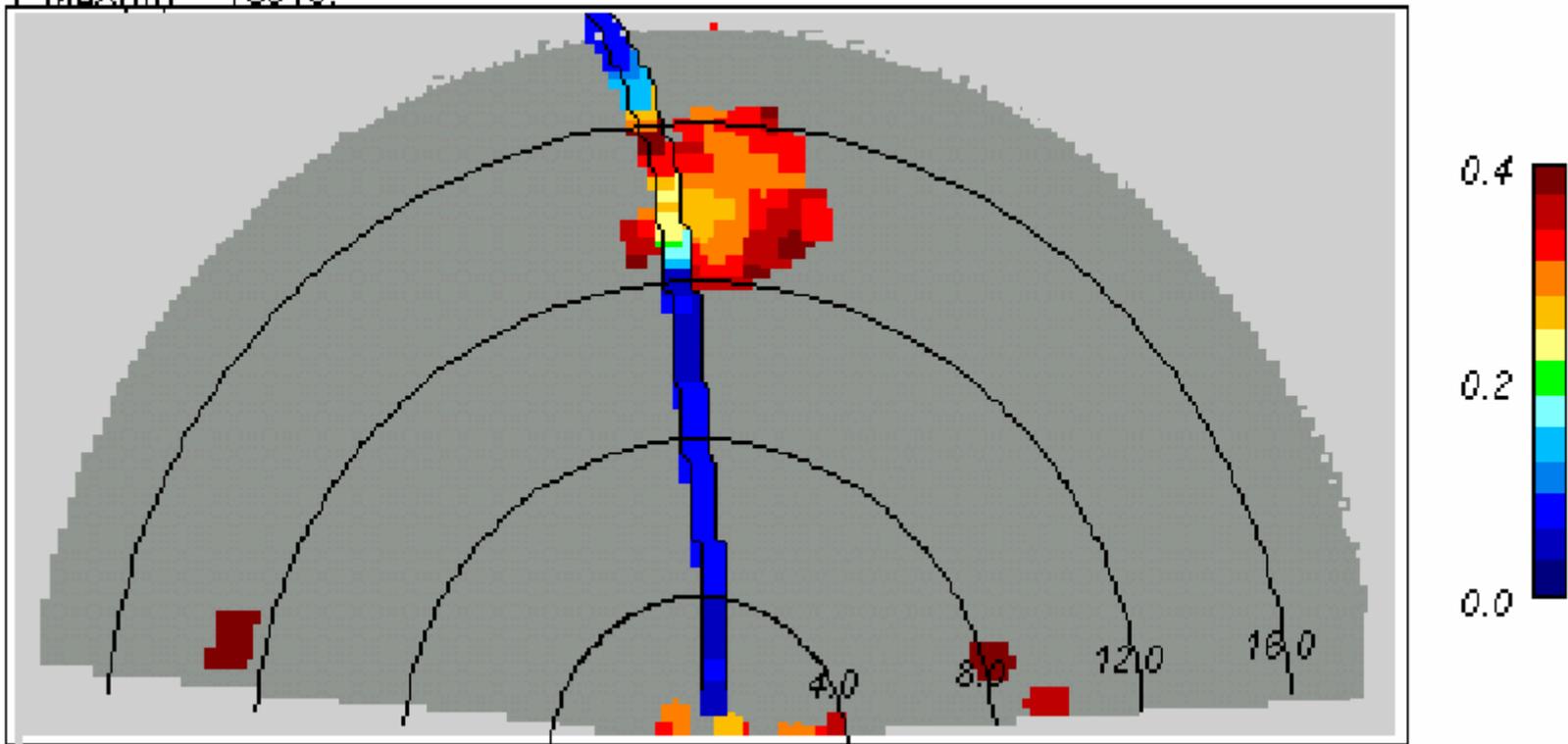




# g-Loading (rms g) Event 191- 06

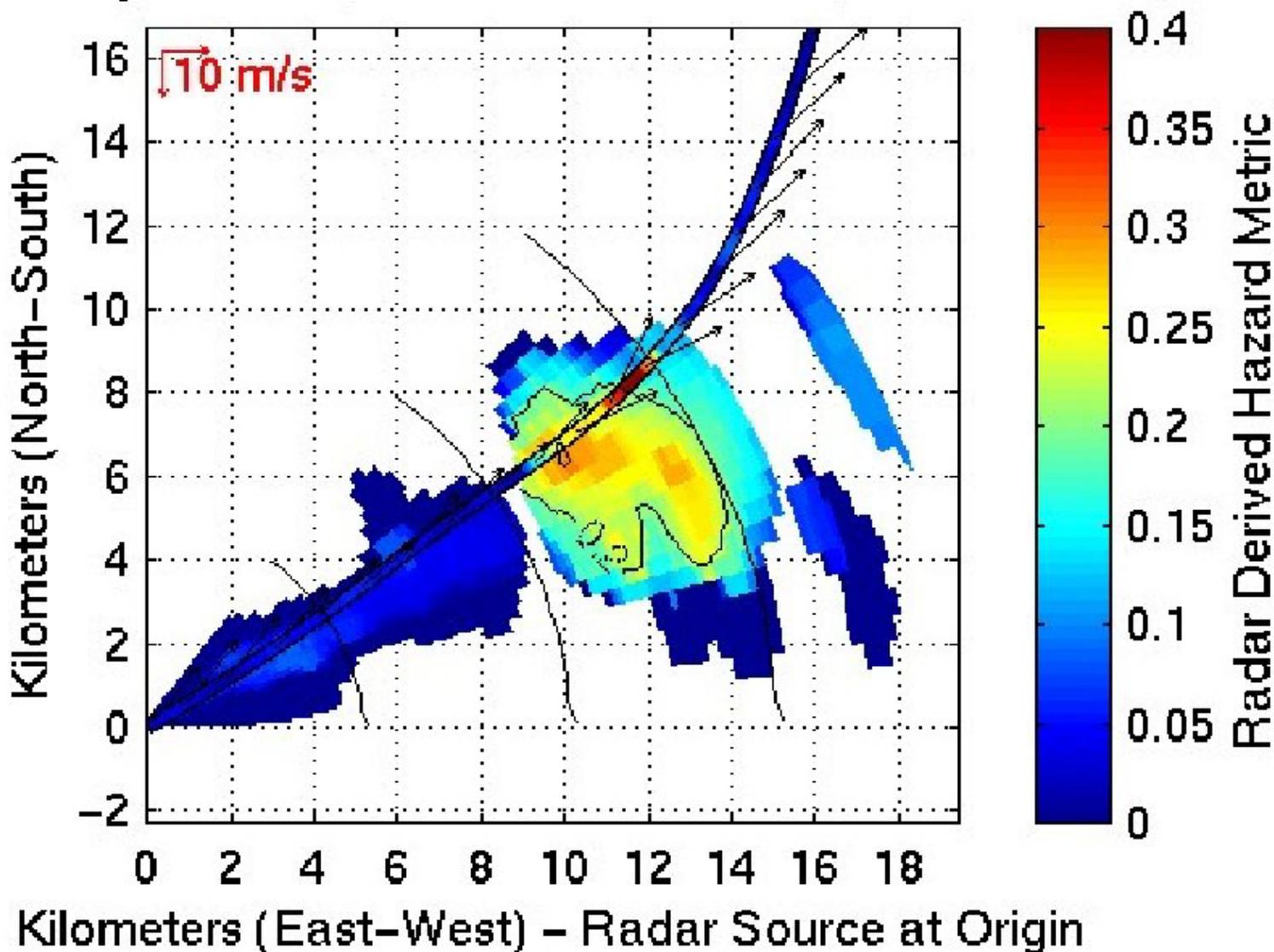
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:43:22 or 67402 seconds





Flight 191-06, 12-14-2000 18:43:24, Tilt: -2.0

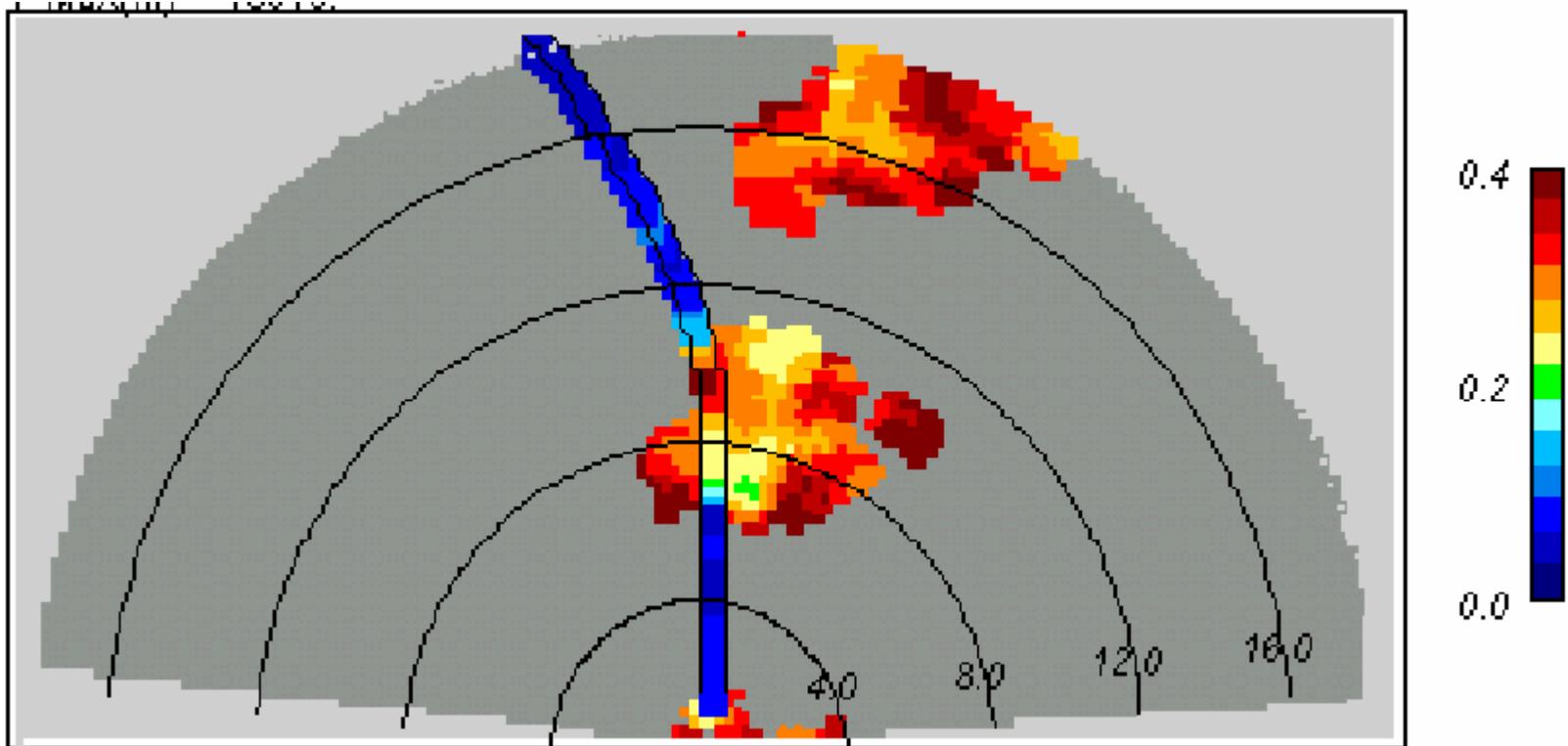




# g-Loading (rms g) Event 191- 06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:43:46 or 67426 seconds

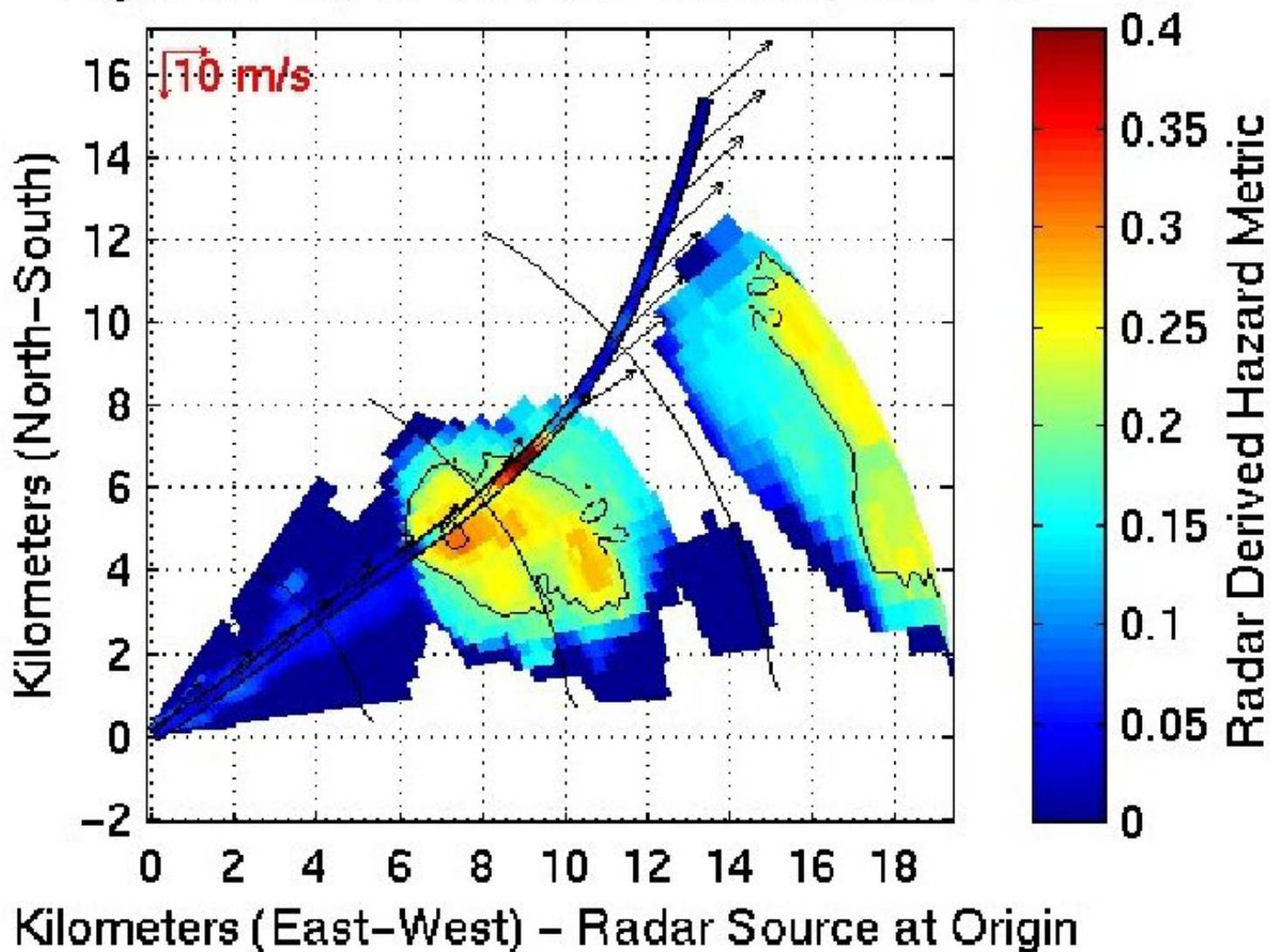


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Flight 191-06, 12-14-2000 18:43:36, Tilt: -2.0





# Summary - Event 191-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- **Two major “blobs” of reflectivity 25- 40 dBZ**
- ***In situ* peak rms g ~ 0.43 at 67458 seconds**
- **Prediction of ~ 0.4 g at 16km (63 seconds) ahead at 67402 seconds**
- **Multiple detections until 67450 seconds**



# Type I and Type II Errors

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- I: Missed Detections/Alerts
- II: False Detections/Nuisance Alerts
- Insufficient Data to Predict Performance
- Performance Predictions Will Require Modeling and Analysis
- Unlikely to Acquire Sufficient Experimental Data to Allow Statistical Analysis



# Turbulence Radar Results Summary

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

## Combined Event Based *A'Posteriori* Scoring for 7 Radar Events

	In Situ	Radar	Low dBZ
Bumps	5	4	3
Nulls	3	3	1



# Conclusions

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- **Use and method of averaging/filtering will be a key factor in detection and reduction of false alarms**
  - Lack of averaging may cause over-alerting
  - Averaging can reduce peak load estimates
- ***In Situ* truth not available for large part of data**
  - Validated models would enable more thorough algorithm evaluation
  - Modeling/simulation will support error analysis
  - Lidar can provide comparison data



# CY01 Flight Objectives

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- **S/W and H/W upgrades**
- **Flight objectives**
  - **40 events 0.2 g or better**
  - **Vary radar pulse configuration**
  - **Weather variety**
  - **Sufficient reflectivity for radar detection**
  - **Record I & Q and aircraft data**
  - **Test detection algorithms in real time**
  - **Research turbulence display for NASA pilots**