NASA/CP—2002-210964

Flight Test Results for a Turbulence Detection Radar

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

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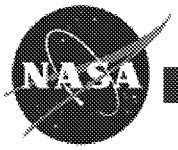
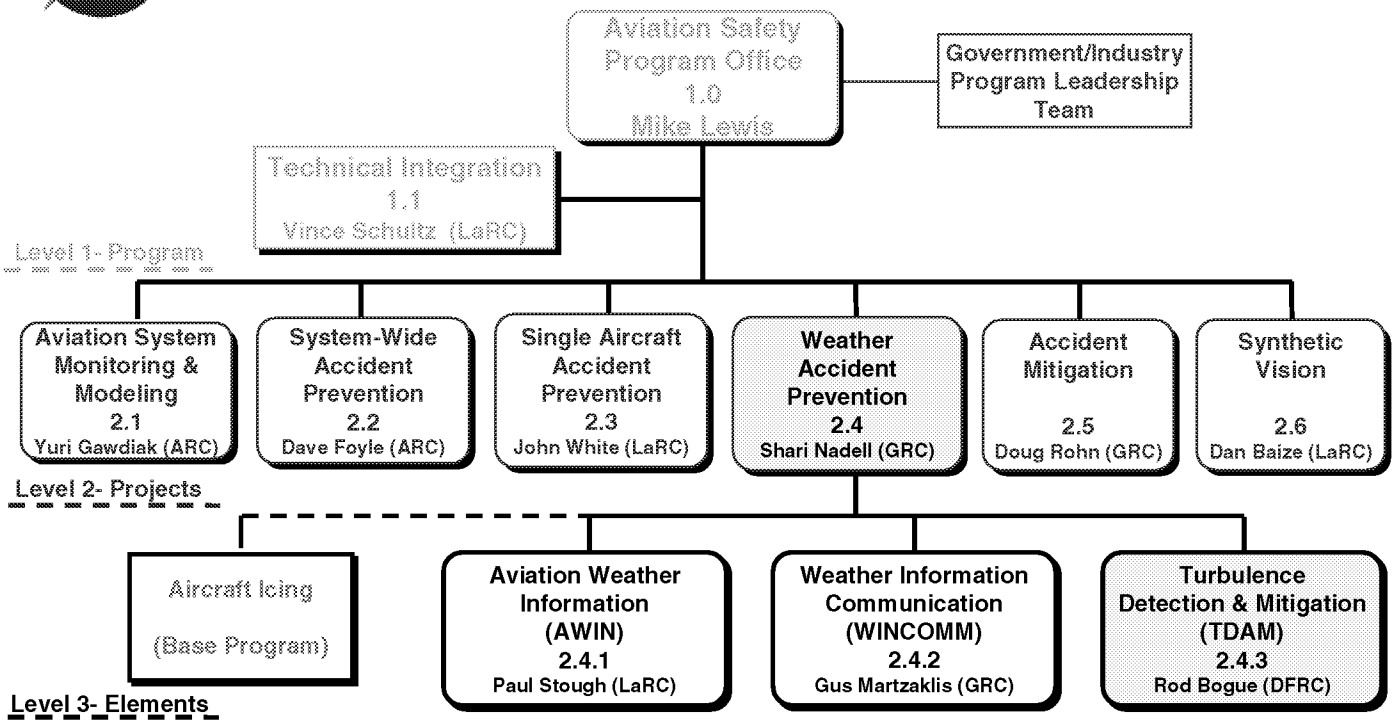


Presentation Outline

- 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



Turbulence Detection Level 4 Sub-element

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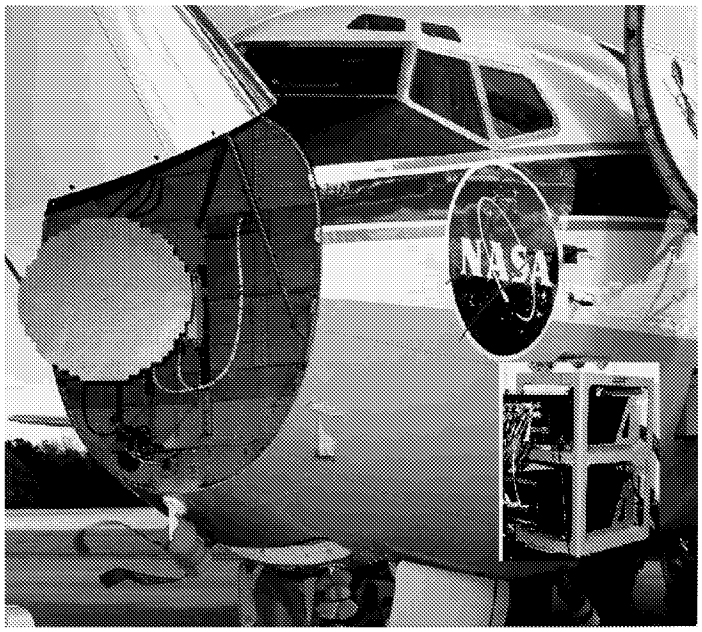
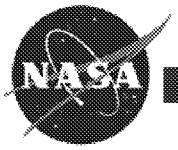


- Sensor Performance Assessment
- Sensor Development
- Algorithm Development
- Demonstration & Verification



Objectives

WxAP Objective #3

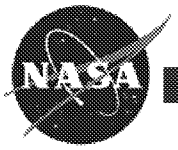
Provide commercial aircraft sensor with 90% probability of detection of severe Convective and Clear Air Turbulence thirty seconds to two minutes before encounter.

WxAP 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 ≥ 30 sec. with POD ≥ 80% for phenomena with reflectivity ≥ 15 dBz.



Flight Operations Summary

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

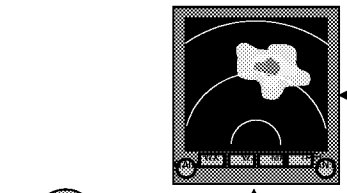
- Weather Support
  - Forecasting and pre-flight recommendations
    - 2-, 1-, and day of operation forecasts
  - Pilot briefings
  - Onboard tactical recommendations
  - Real-time observations
- *In Situ*
  - Data Collection
  - Real-time engineering displays
  - Post-flight processing
- Turbulence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



Alternating Antenna Sweeps:
Std. WX/WS
Research Mode

Antenna

R/T Unit

A/C State Parameters
(4x(ARINC 429))

Recorded Information

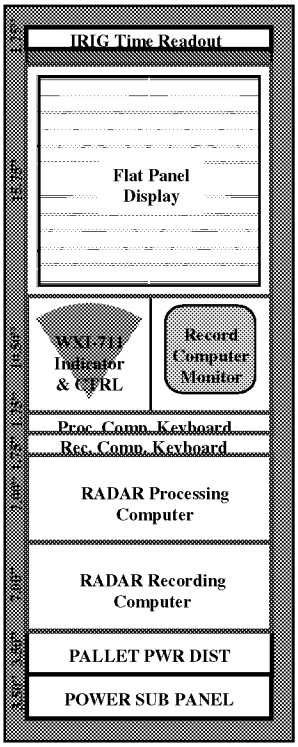
Radar Configuration/Control (RS-232)

A/C State Parameters (8x(ARINC 429))

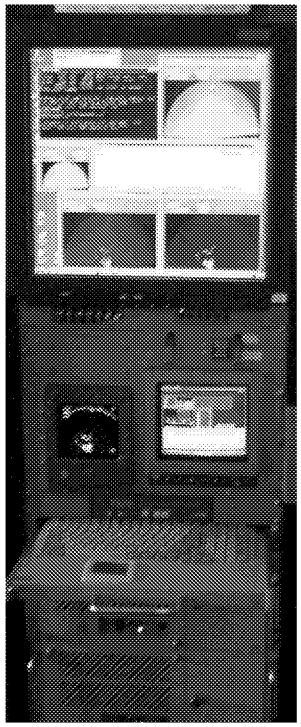
Radar State Parameters (ARINC 429)

Radar I/Q (Fiber Channel)

Design Layout

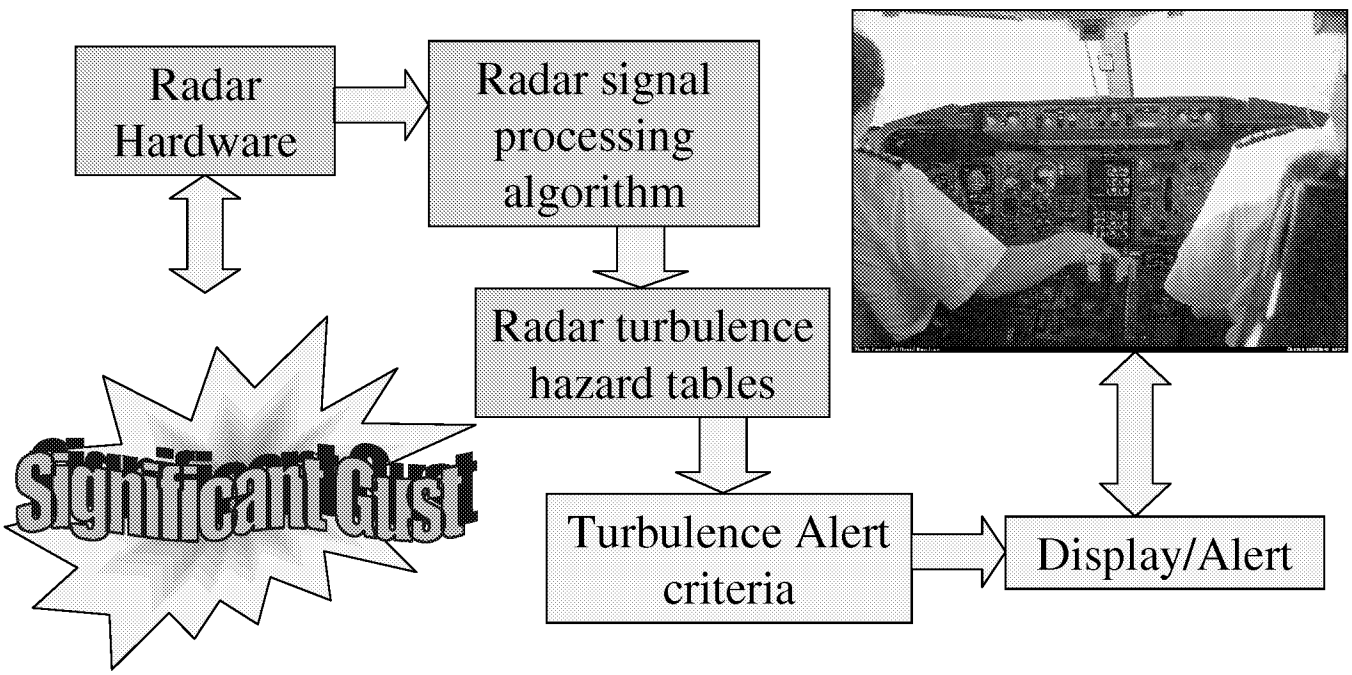


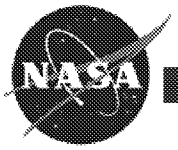
As Built



An End-to-End Turbulence Radar System

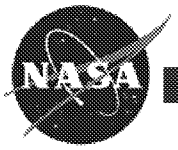
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation





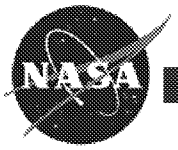
Baseline Algorithm Methodology

- 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



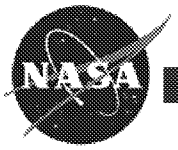
NCAR Algorithm Methodology

- 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.



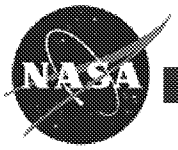
Radar Hazard Tables

- 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

• 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

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

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

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

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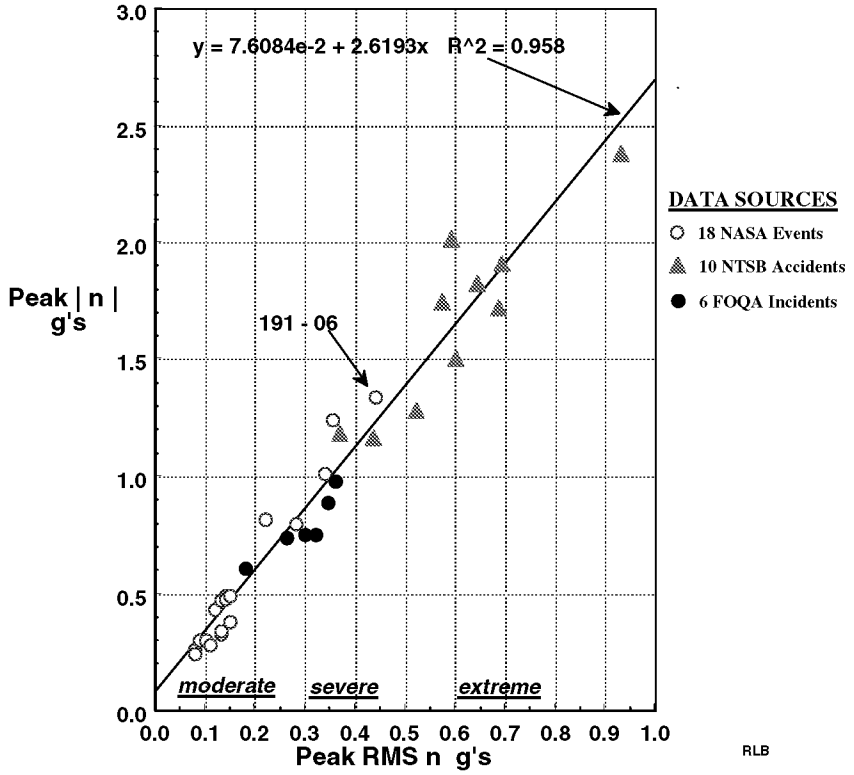

Based on Measurements for 34 Turbulence Encounter Cases

Flight Test Summary

- 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

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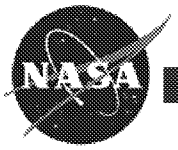


18 Event Summary Table

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

Flight-event	*No Alert < 0.2 g*	*0.2 <= Alert < 0.3 g*	*Alert >= 0.3 g*	*Notes*
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

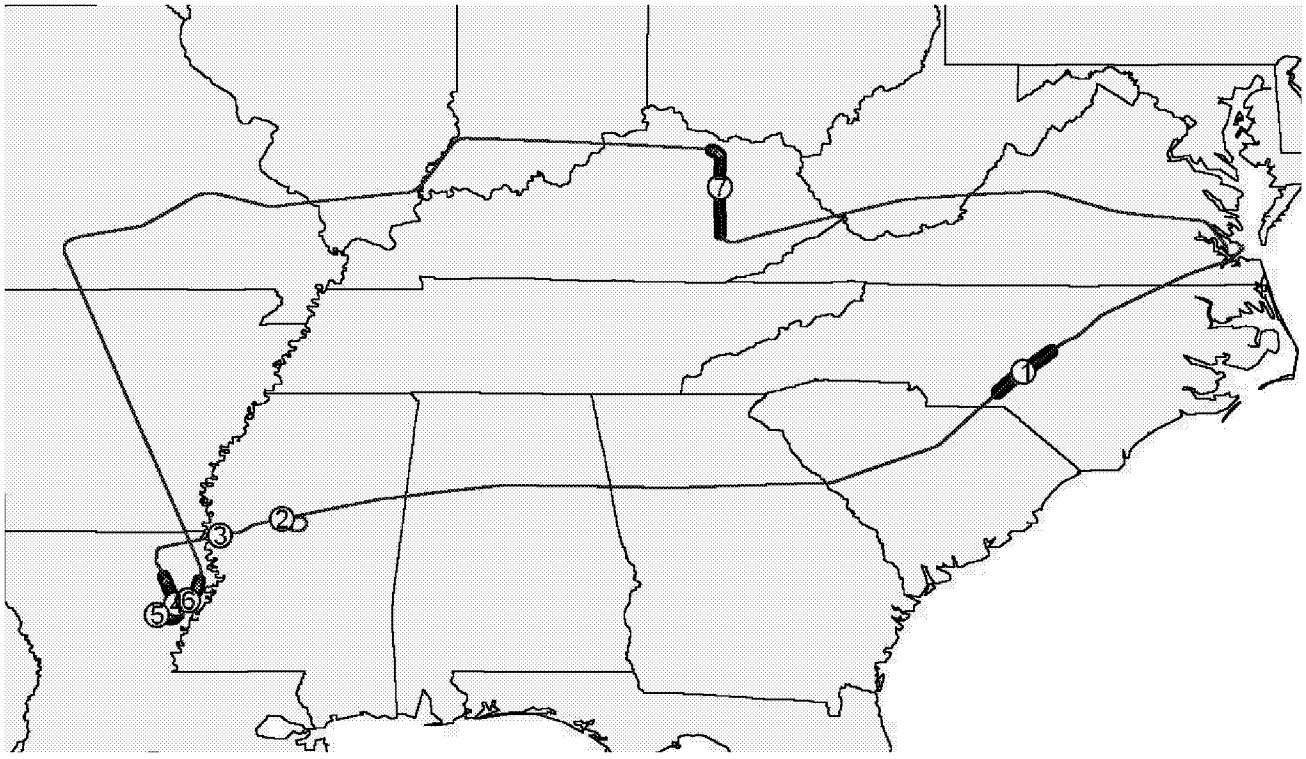
Flight-event	In Situ σΔn	NESPA	Baseline	Hazard
181-07	0.15	< 0.2	> 0.2	light
181-08	0.16	< 0.2	0.32	light
190-04	0.28	< 0.2	< 0.27	moderate
190-06	0.2 & 0.35	< 0.2	0.3	severe
191-03	0.34	0.2	0.32	severe
191-04	0.14	< 0.2	low reflectivity	light
191-06	0.44	0.32	near 0.4	severe

Weather Summary

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

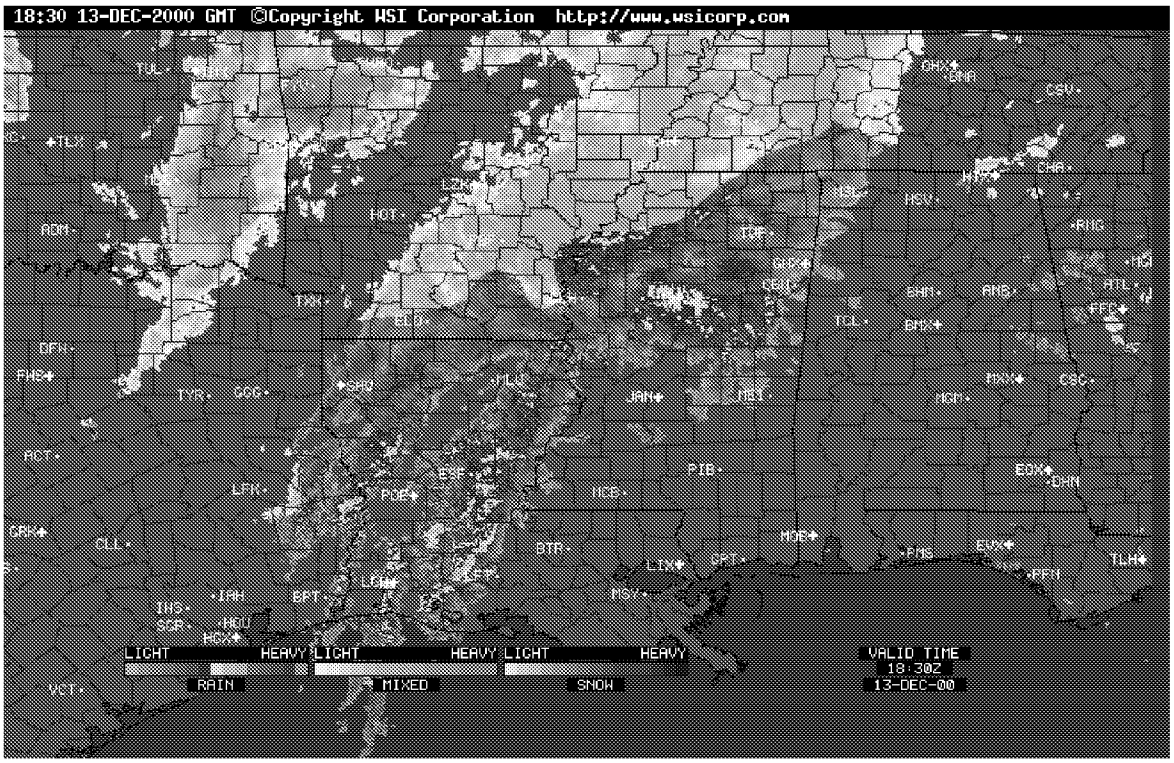
Flight 190 Path

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



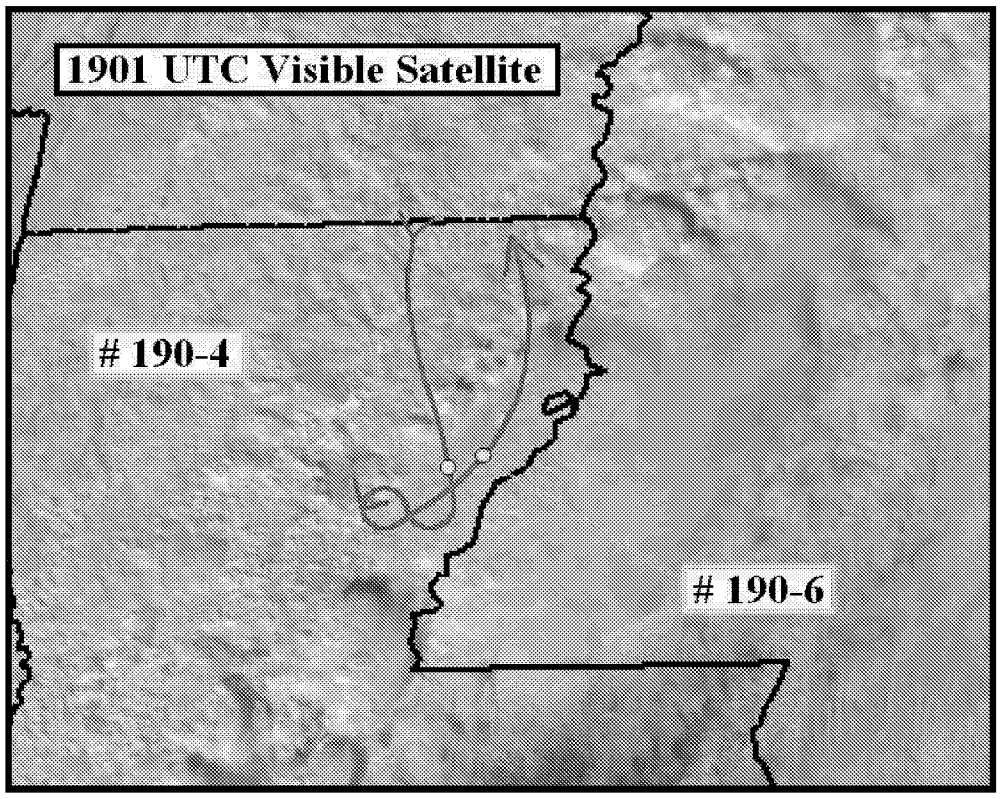
Flight 190 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



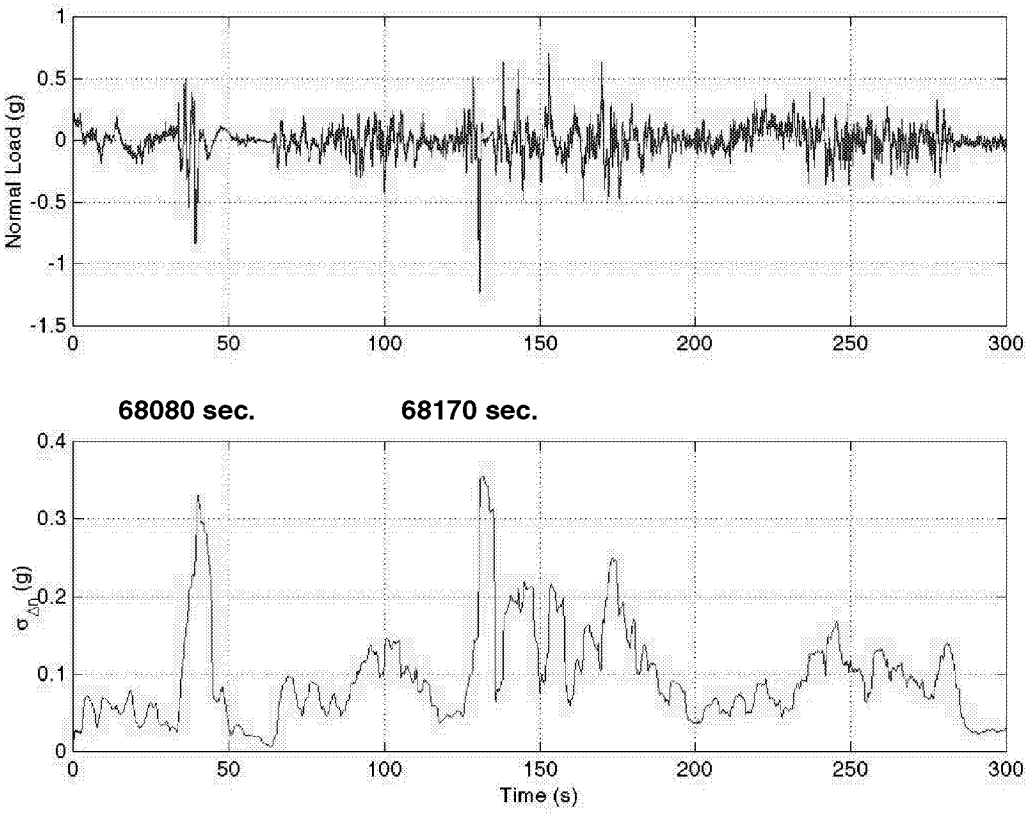
Flight 190 Satellite Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



Flight 190 Event 06 Normal Loads

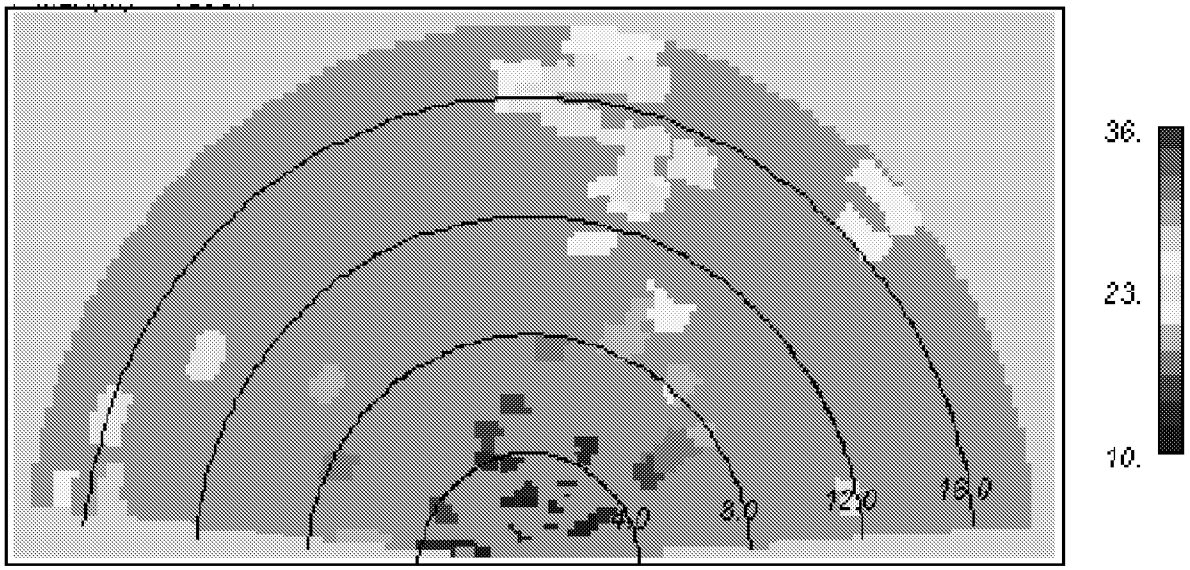
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



Reflectivity (dBZ) Event 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

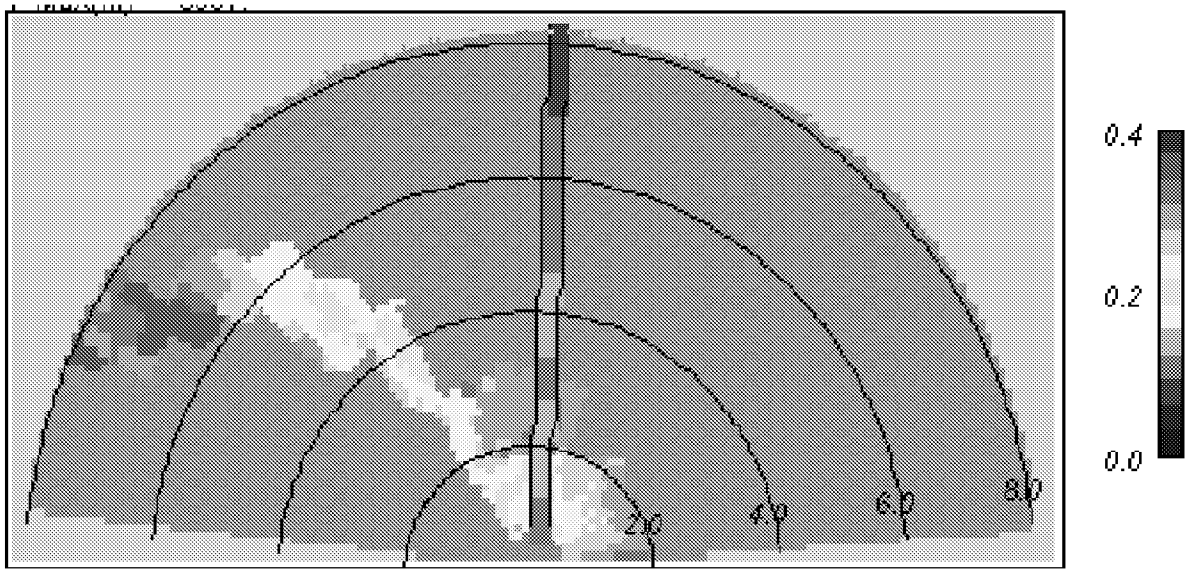
18:45:21 or 67521 seconds

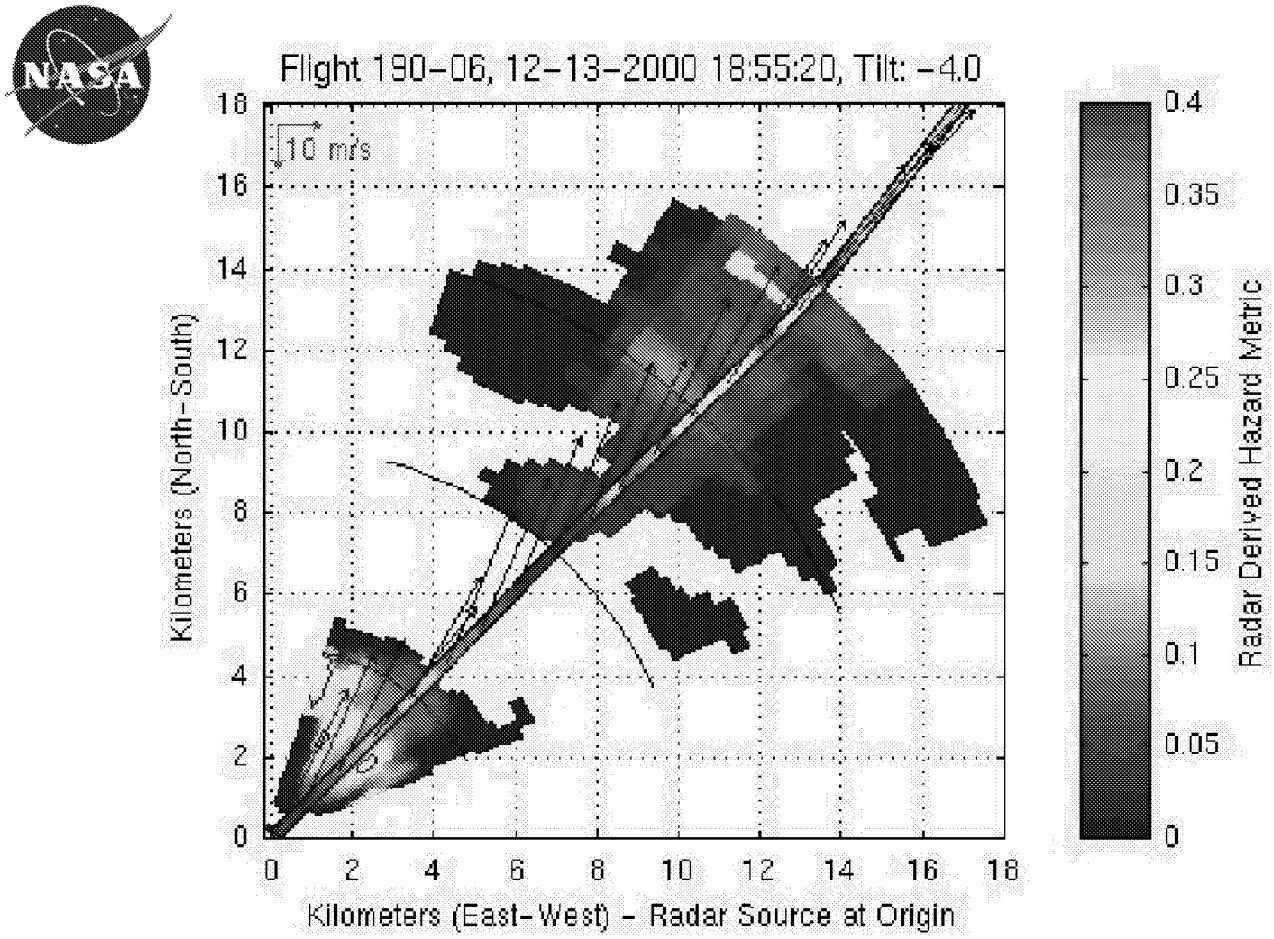


g-Loading (rms g) Event 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:55:30 or 68130 seconds

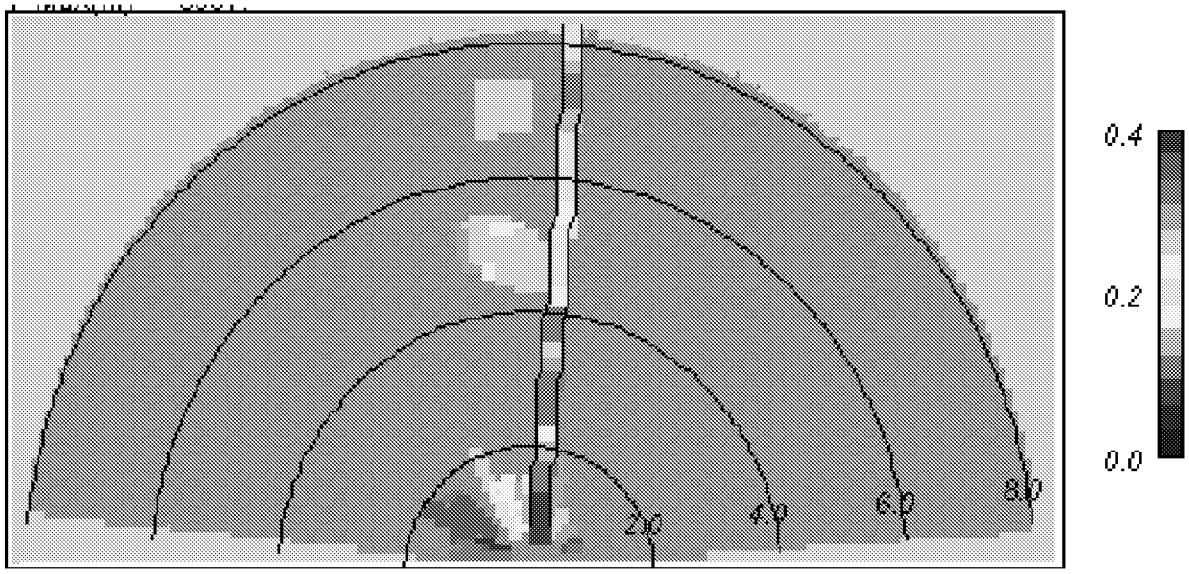


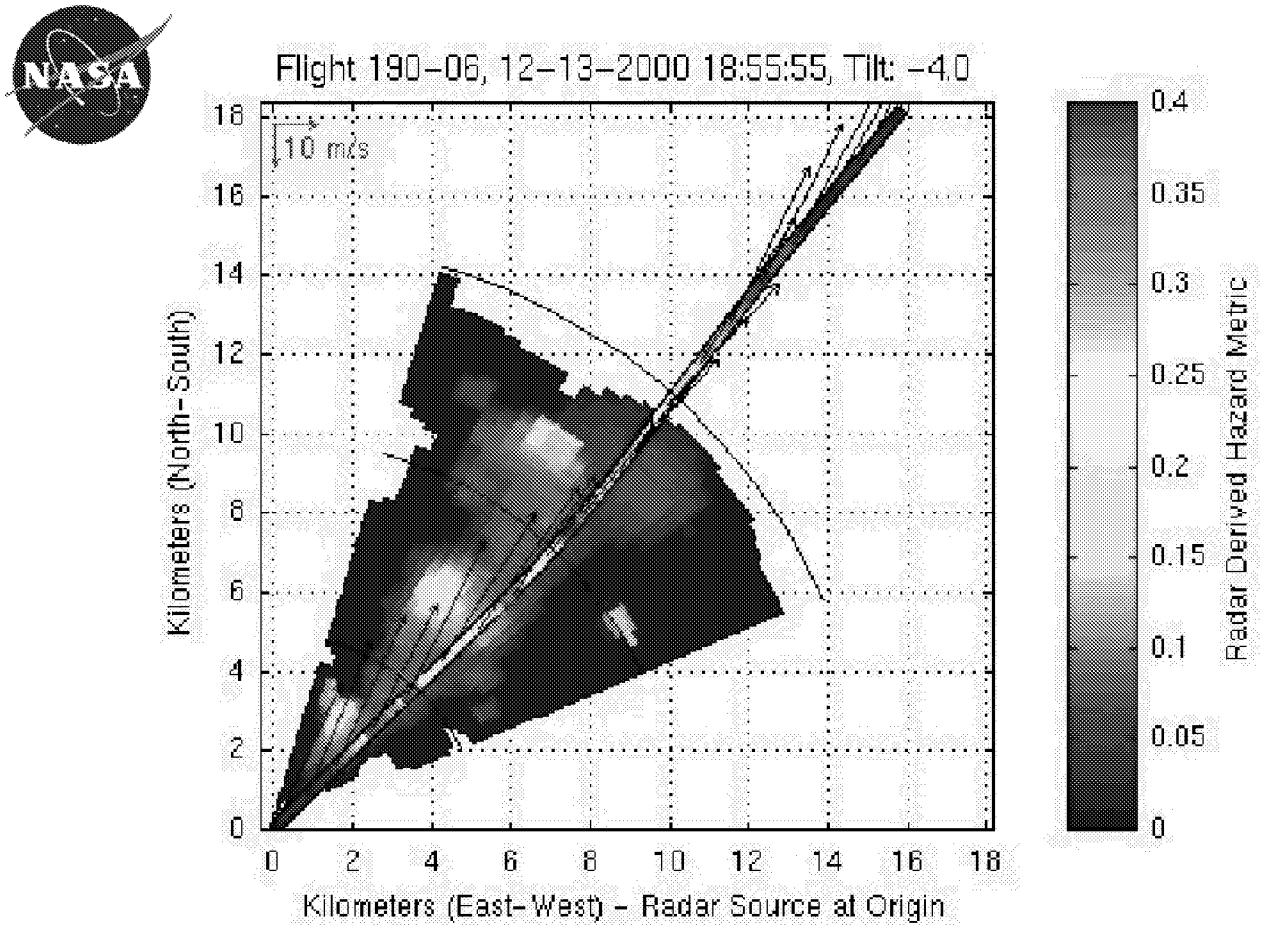

Flight 190-06, 12-13-2000 18:55:20, Tilt: -4.0
10 m/s
Kilometers (North-South)
Kilometers (East-West) - Radar Source at Origin
Radar Derived Hazard Metric
0
2
4
6
8
10
12
14
16
18
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

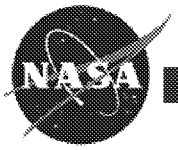
g-Loading (rms g) Event 190-06

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
10 m/s
Kilometers (North–South)
Kilometers (East–West) – Radar Source at Origin
0
2
4
6
8
10
12
14
16
18
Radar Derived Hazard Metric
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

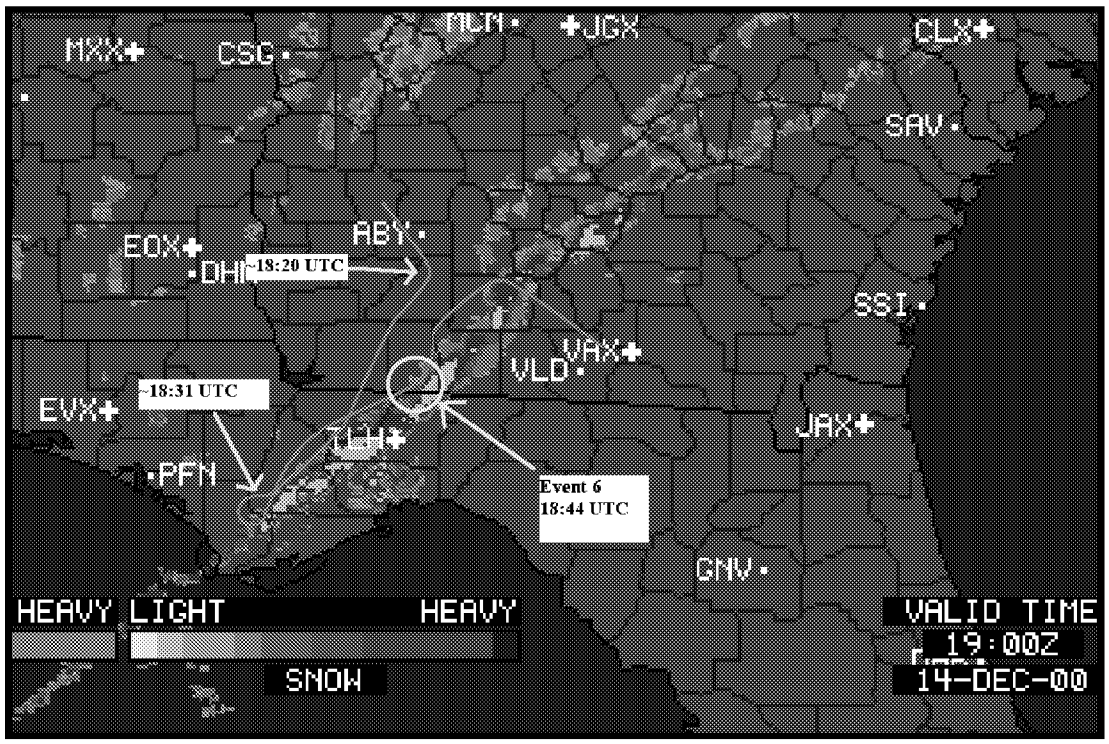


Summary - Case 190-06

- **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**

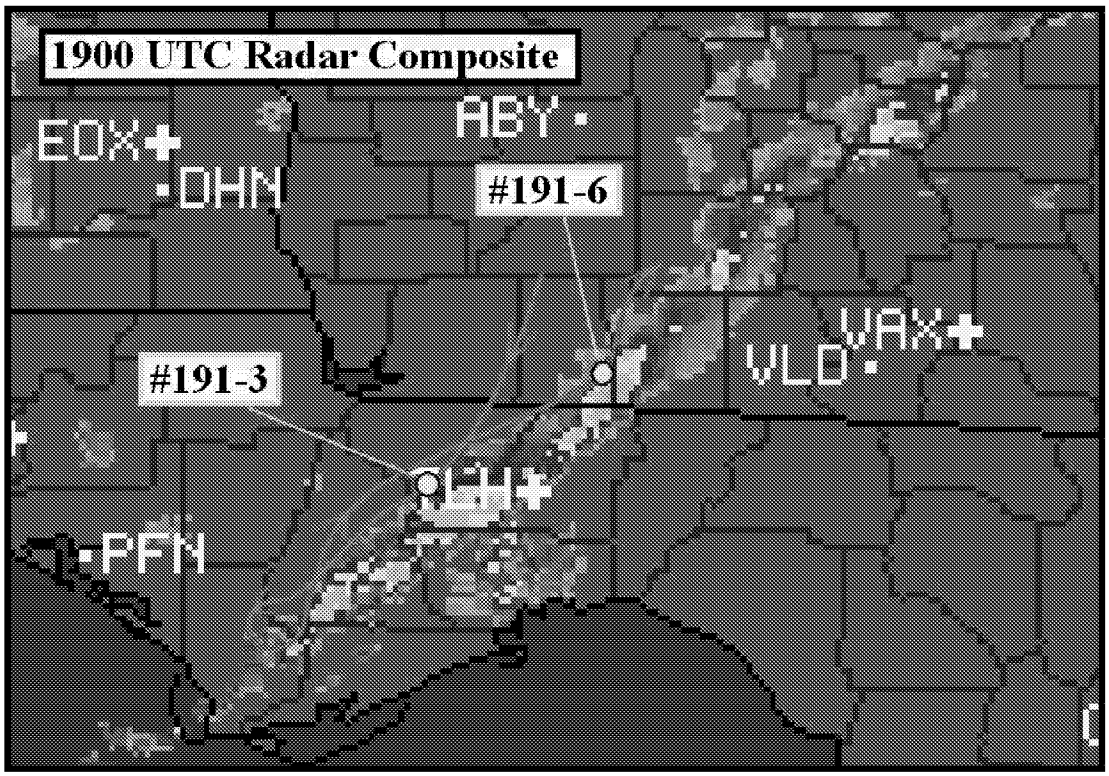
Flight 191 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



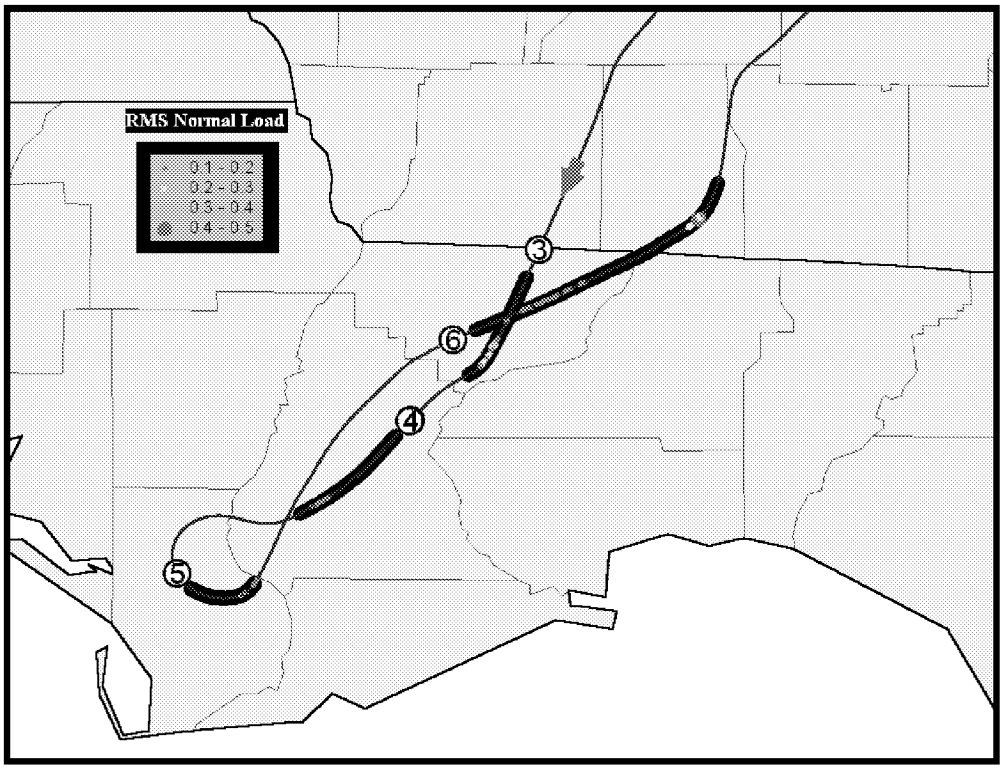
Flight 191 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



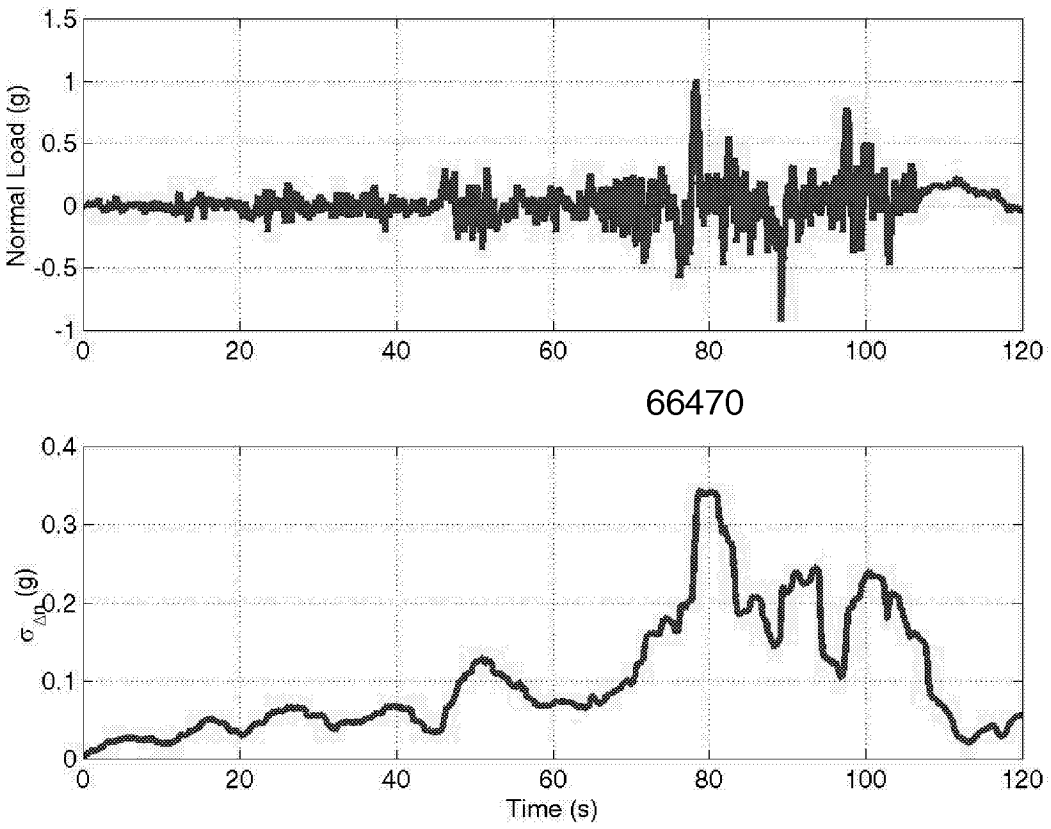
191 Path Flight

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation



Flight 191 Event 03 Normal Loads

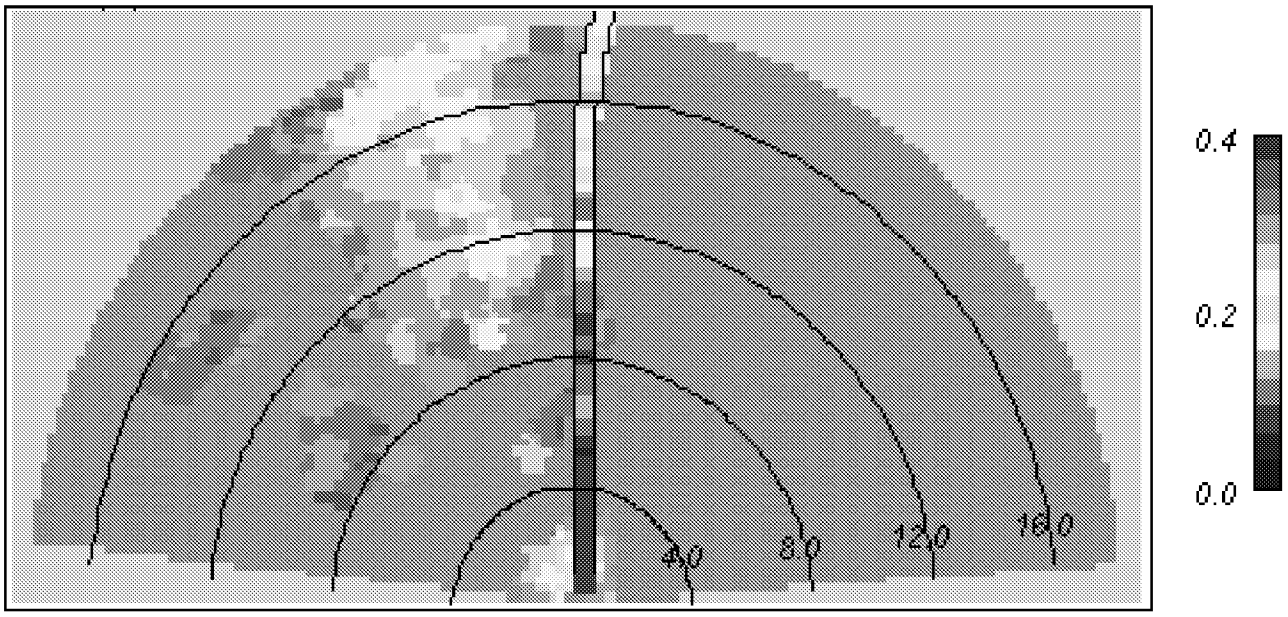
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

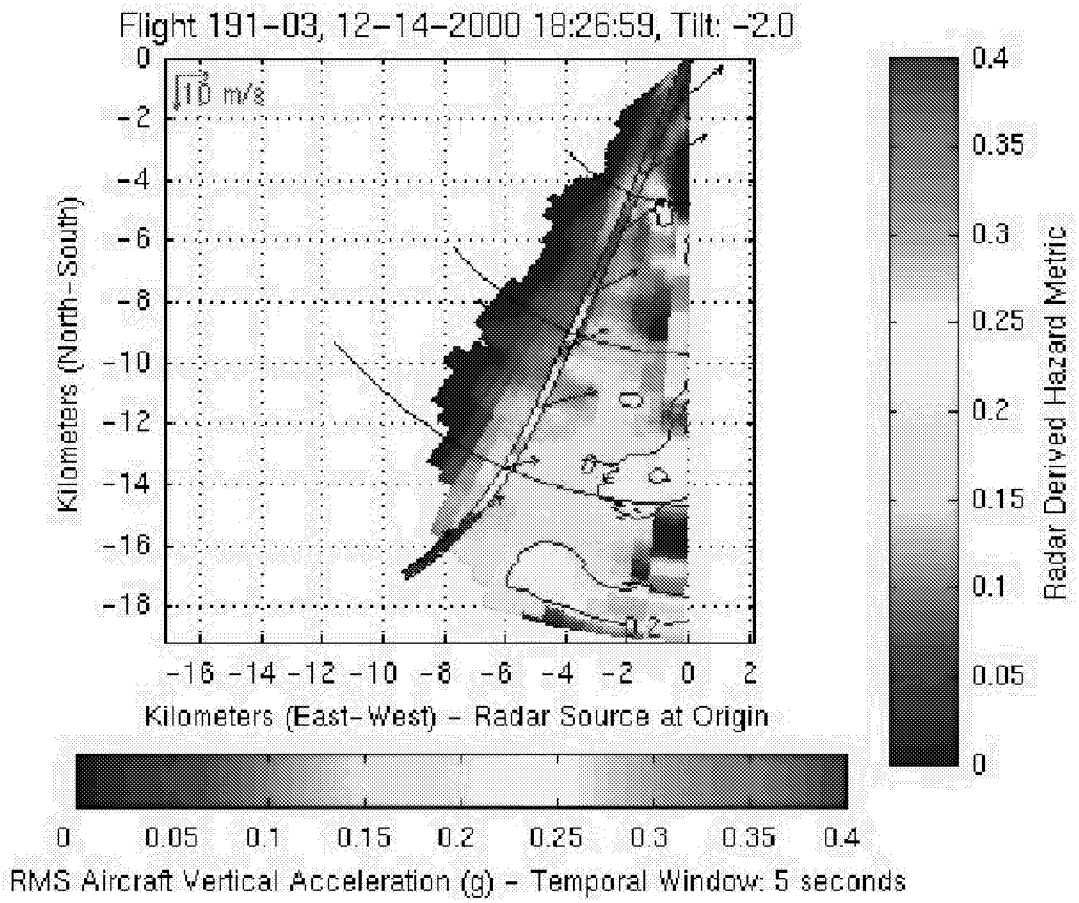


g-Loading (rms g) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:26:54 or 66414 seconds

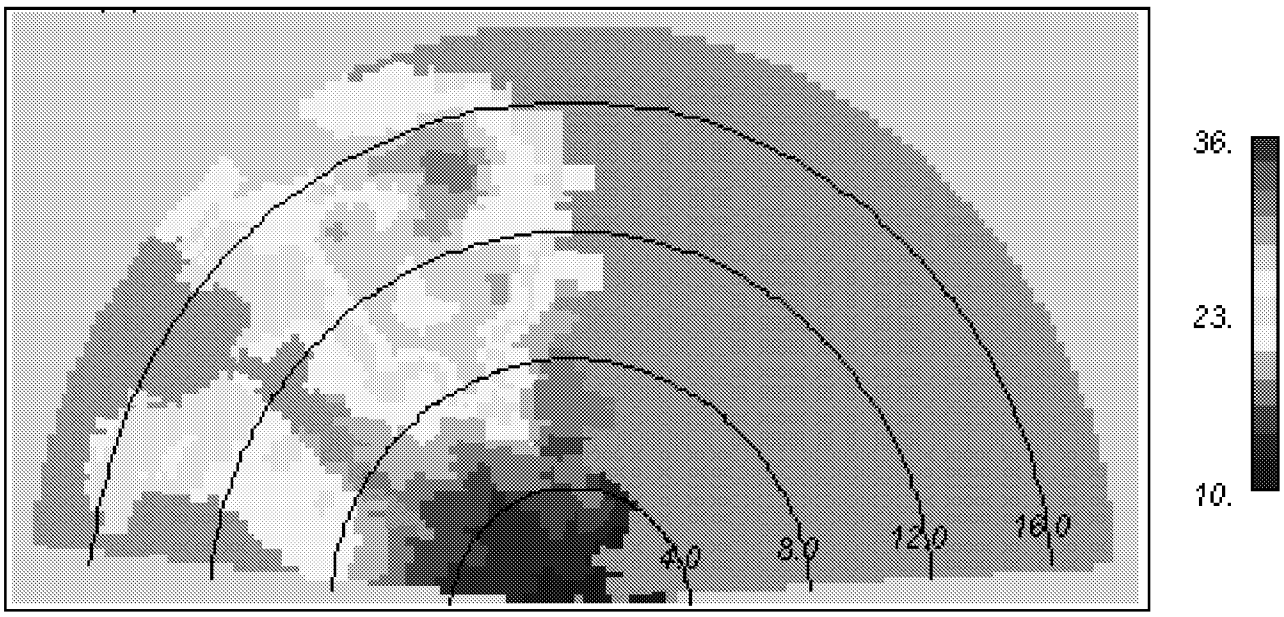



Flight 191-03, 12-14-2000 18:26:59, Tilt: -2.0
10 m/s
Kilometers (North-South)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-16 -14 -12 -10 -8 -6 -4 -2 0 2
Kilometers (East-West) - Radar Source at Origin
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
RMS Aircraft Vertical Acceleration (g) - Temporal Window: 5 seconds
Radar Derived Hazard Metric
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

Reflectivity (dBZ) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

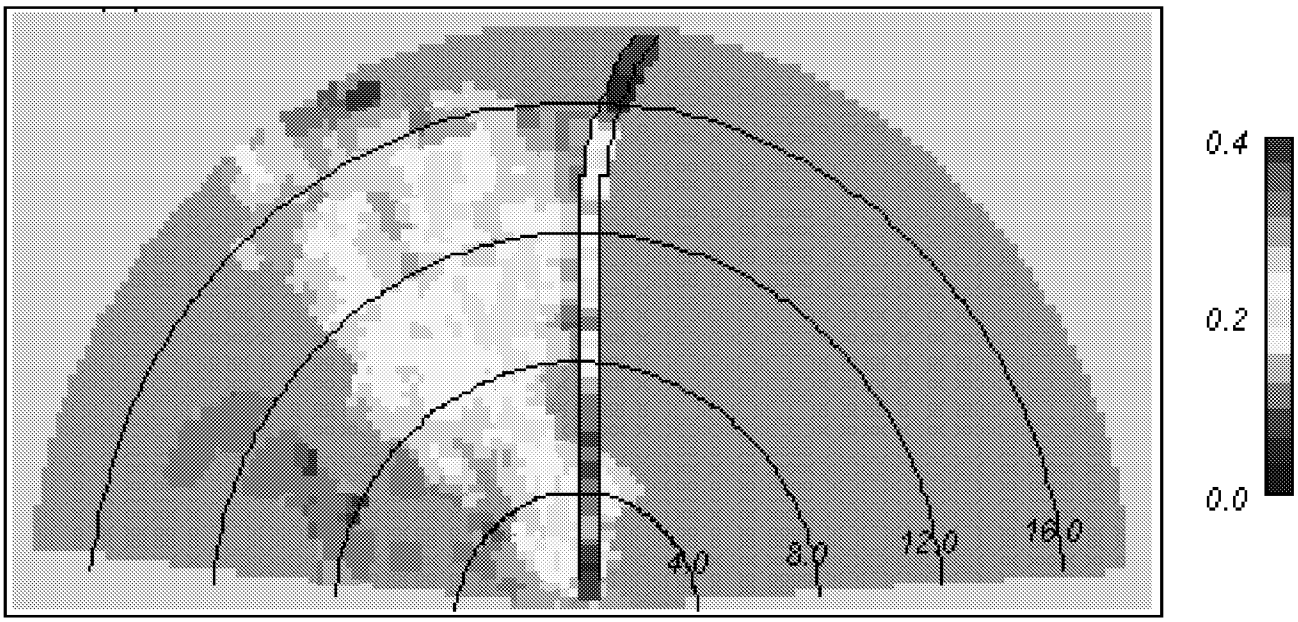
18:27:11 or 66431 seconds

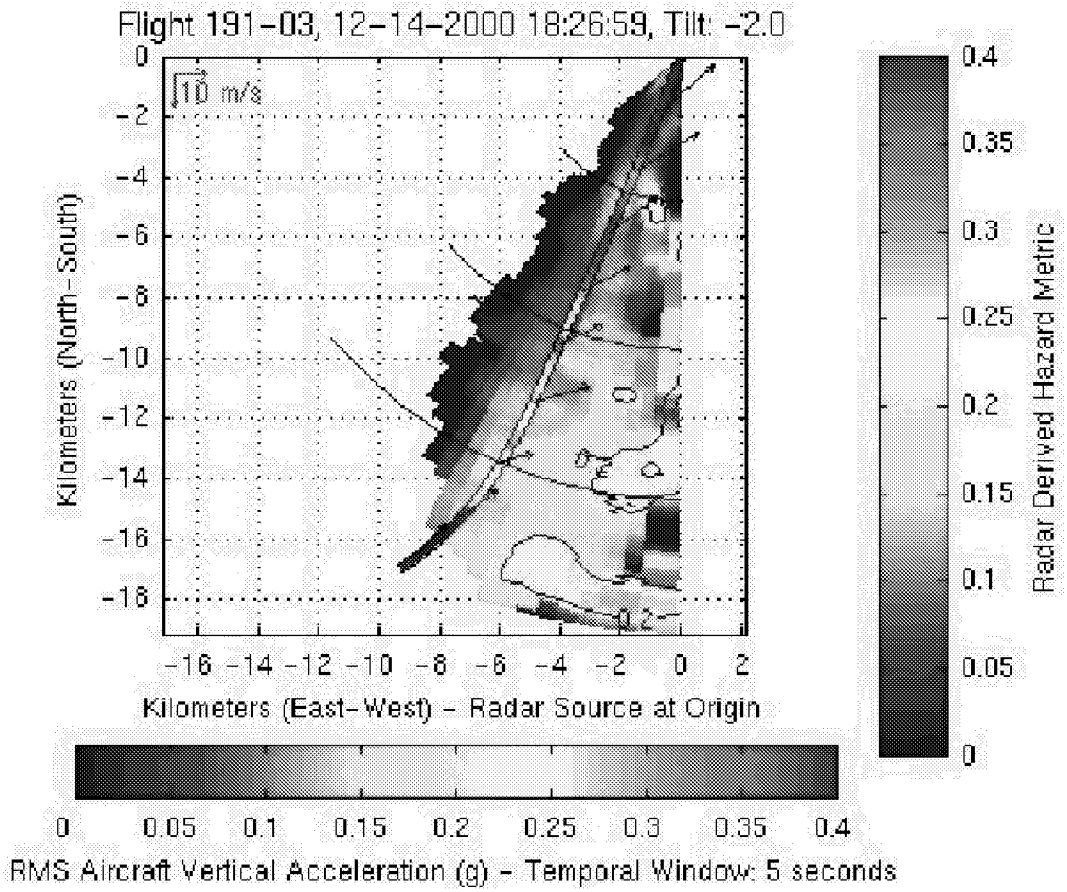


g-Loading (rms g) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:27:09 or 66429 seconds



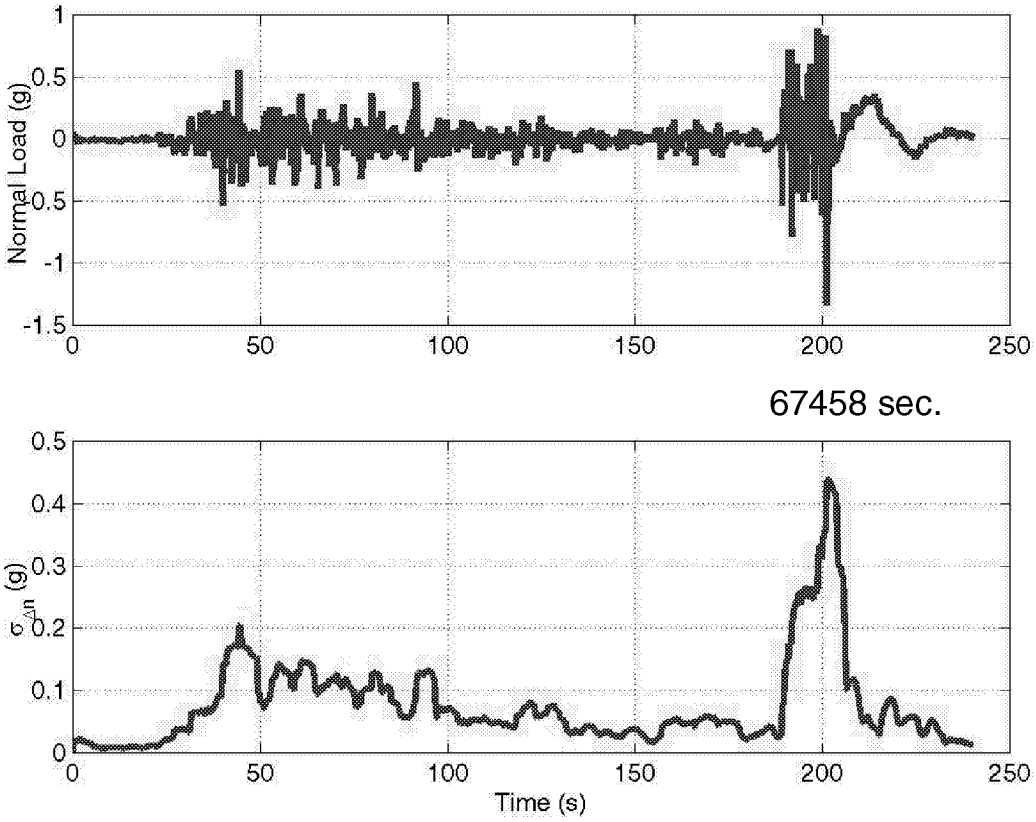

Flight 191-03, 12-14-2000 18:26:59, Tilt: -2.0
10 m/s
Kilometers (North-South)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-16 -14 -12 -10 -8 -6 -4 -2 0 2
Kilometers (East-West) - Radar Source at Origin
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4
RMS Aircraft Vertical Acceleration (g) - Temporal Window: 5 seconds
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Radar Derived Hazard Metric

Summary - Event 191-03

- **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

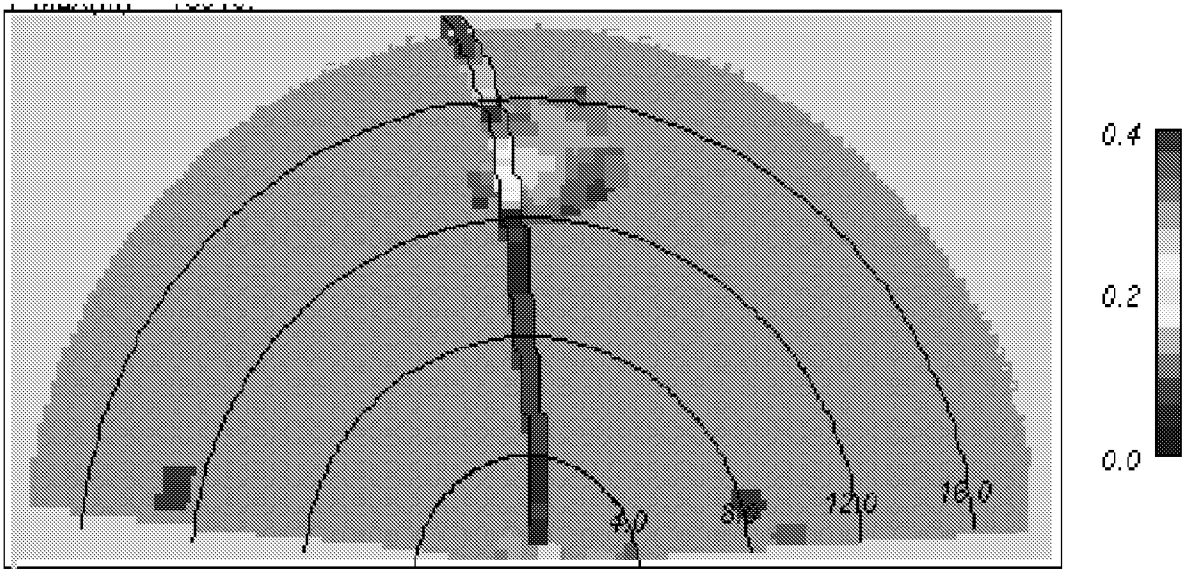
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

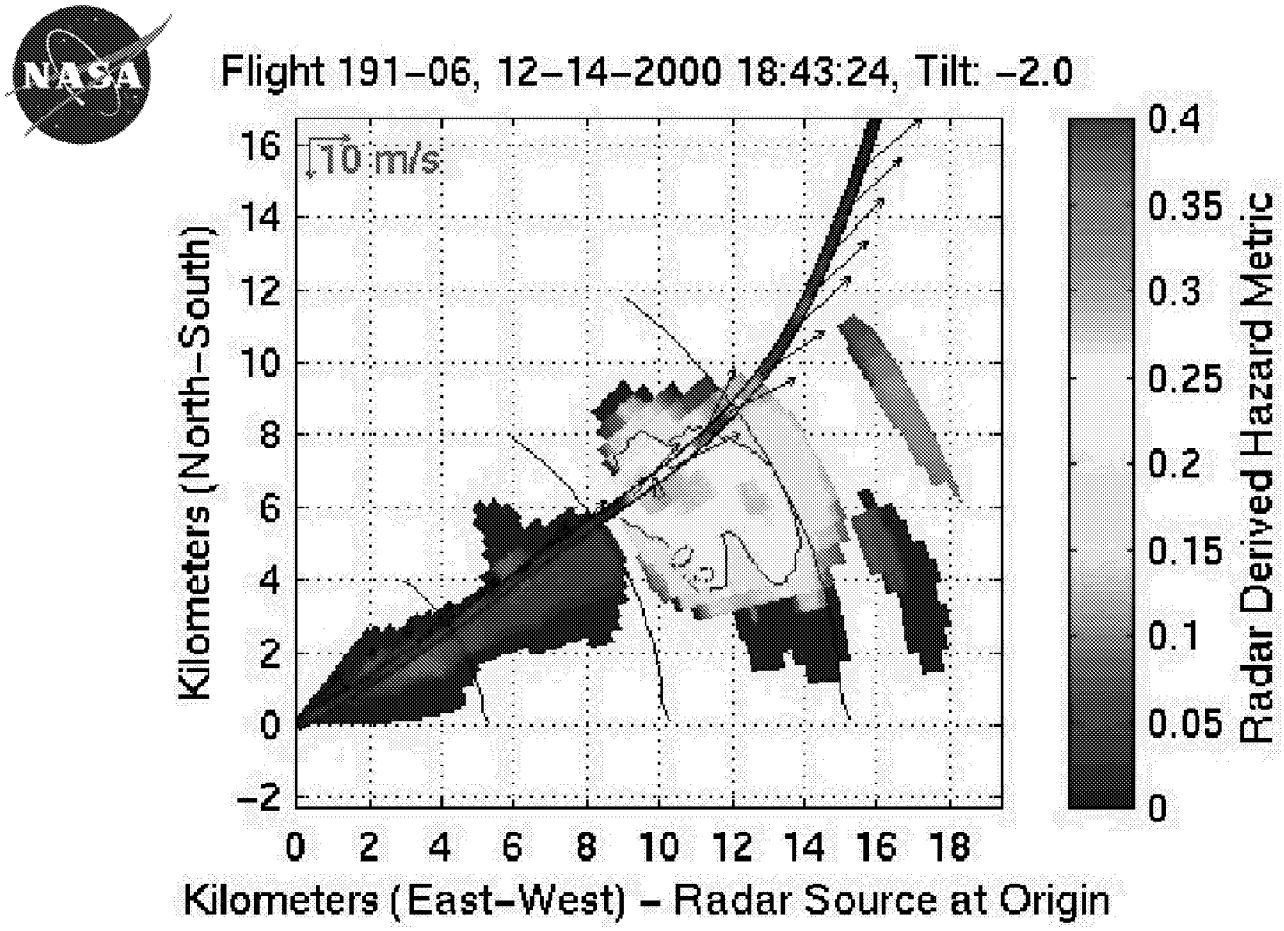


g-Loading (rms g) Event 191- 06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:43:22 or 67402 seconds

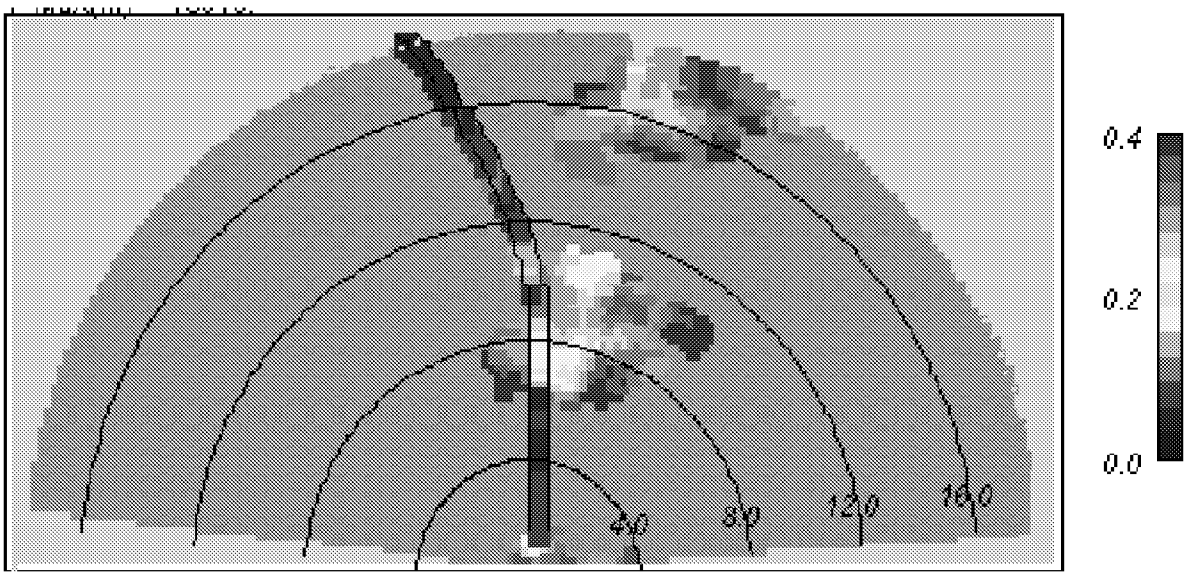


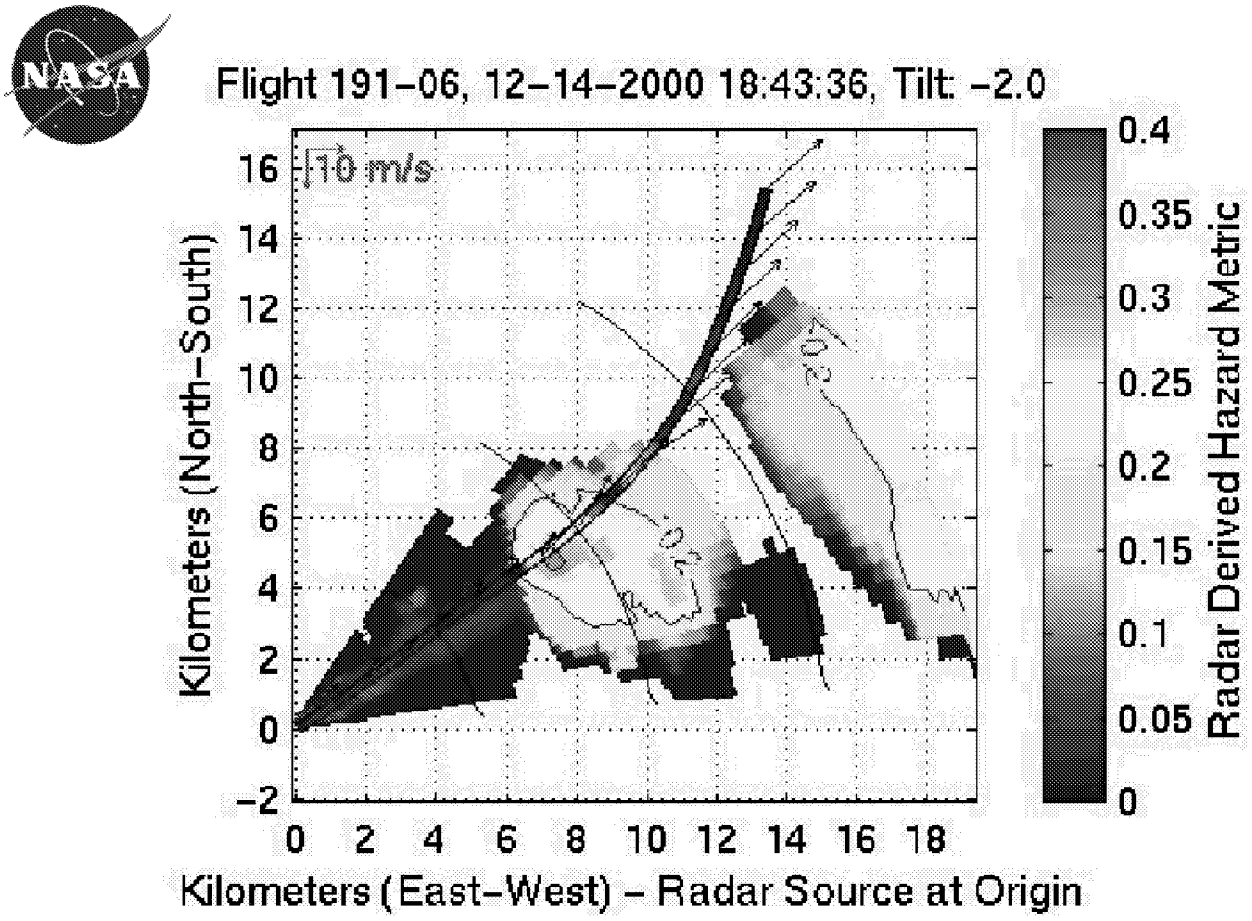

Flight 191–06, 12–14–2000 18:43:24, Tilt: –2.0
10 m/s
Kilometers (North–South)
Kilometers (East–West) – Radar Source at Origin
Radar Derived Hazard Metric
0
2
4
6
8
10
12
14
16
18
–2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

g-Loading (rms g) Event 191- 06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

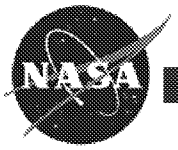
18:43:46 or 67426 seconds




Flight 191–06, 12–14–2000 18:43:36, Tilt: –2.0
10 m/s
Kilometers (North–South)
Kilometers (East–West) – Radar Source at Origin
Radar Derived Hazard Metric
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.2
0.3
16
14
12
10
8
6
4
2
0
–2
0
2
4
6
8
10
12
14
16
18

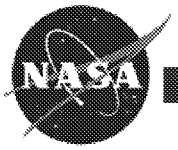
Summary - Event 191-06

- 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

- 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

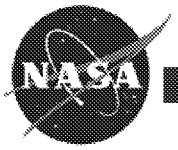


Turbulence Radar Results Summary

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

- **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**