# In situ and remote sensing of turbulence in support of the aviation community


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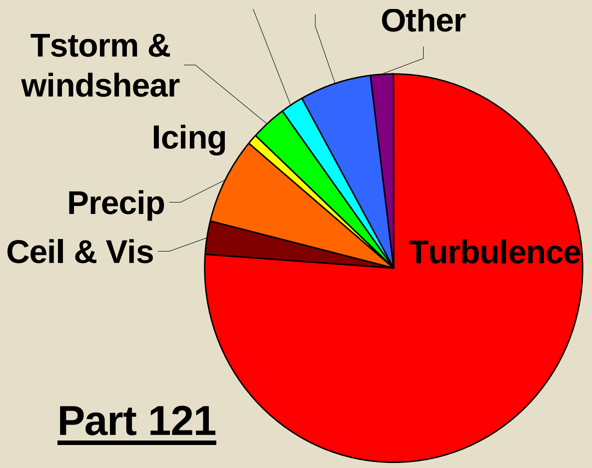
# The Motivation

- Turbulence is the main cause of in-flight injuries – for both passengers and flight attendants.
- After a severe encounter, the airline has to perform a structural check on the aircraft.
- Pilots will try to re-route around an area if there have been reports of moderate or greater turbulence.

**Bottom-line: Turbulence is a safety problem as well as having a large financial impact on the airlines.**




**Weather-related accidents for large transport aircraft**

# DC-8 Cargo Aircraft Damaged Due to Extreme Turbulence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# The Turbulence Problem for Aviation (Grossly Oversimplified)

"Turbulent eddies larger than 100 meters and smaller than 3000 meters (approximately) produce aircraft motions which can be difficult -- or impossible -- to control.

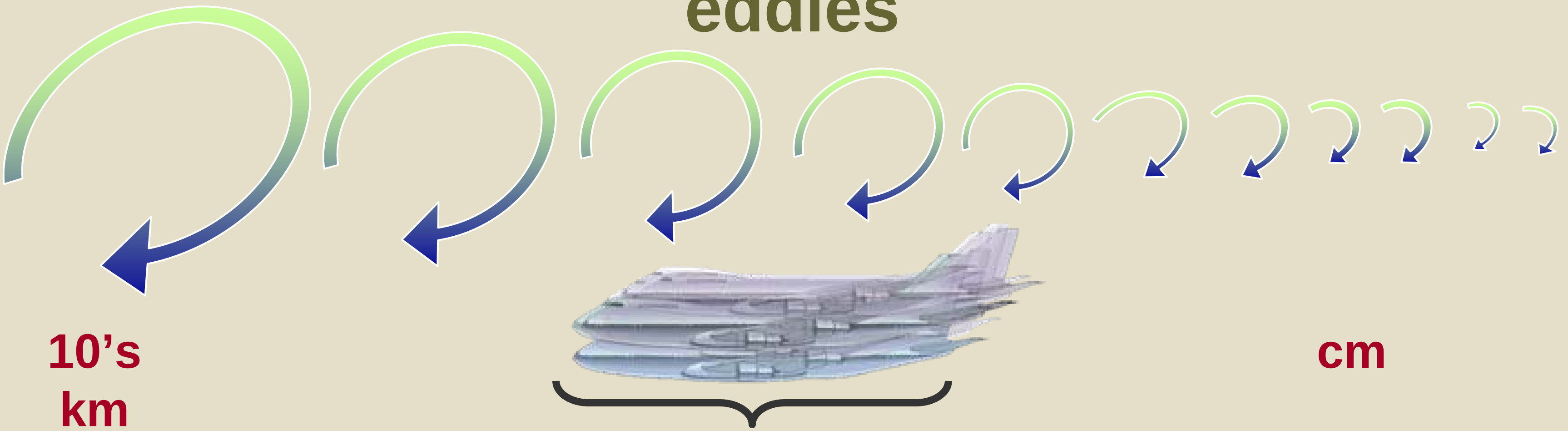
With small-amplitude eddies, these induced motions may be simply uncomfortable to passengers. Large amplitude eddies, on the other hand, can result in passenger injuries or even structural damage to the aircraft."

# Turbulence Scales of Motion

Large eddies

"Turbulent" eddies

Small eddies



10's km

cm

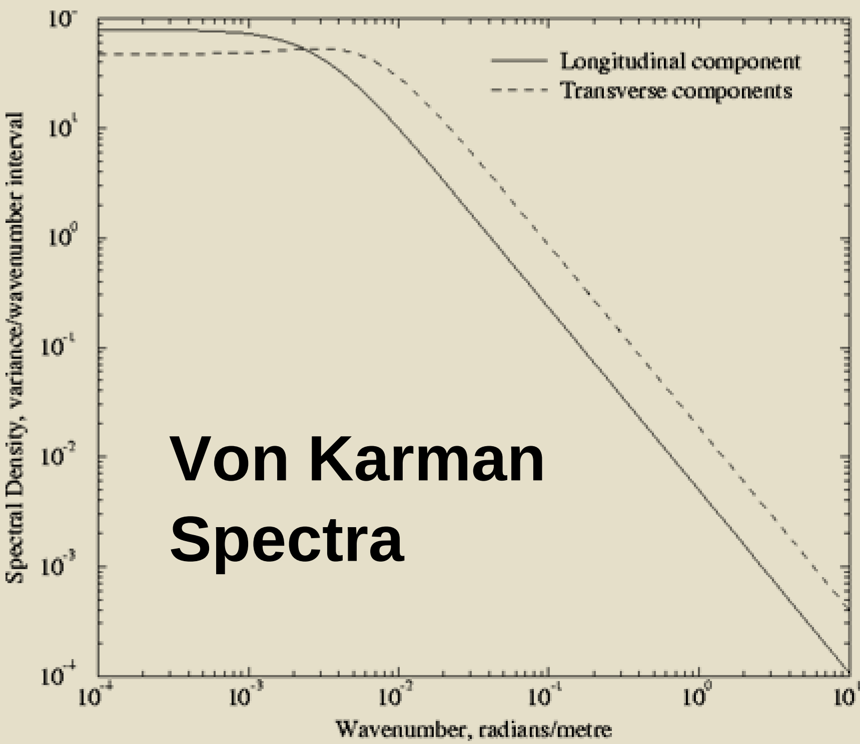
Aircraft responds to scales from approx. 100 m – 3 km

NWP resolution

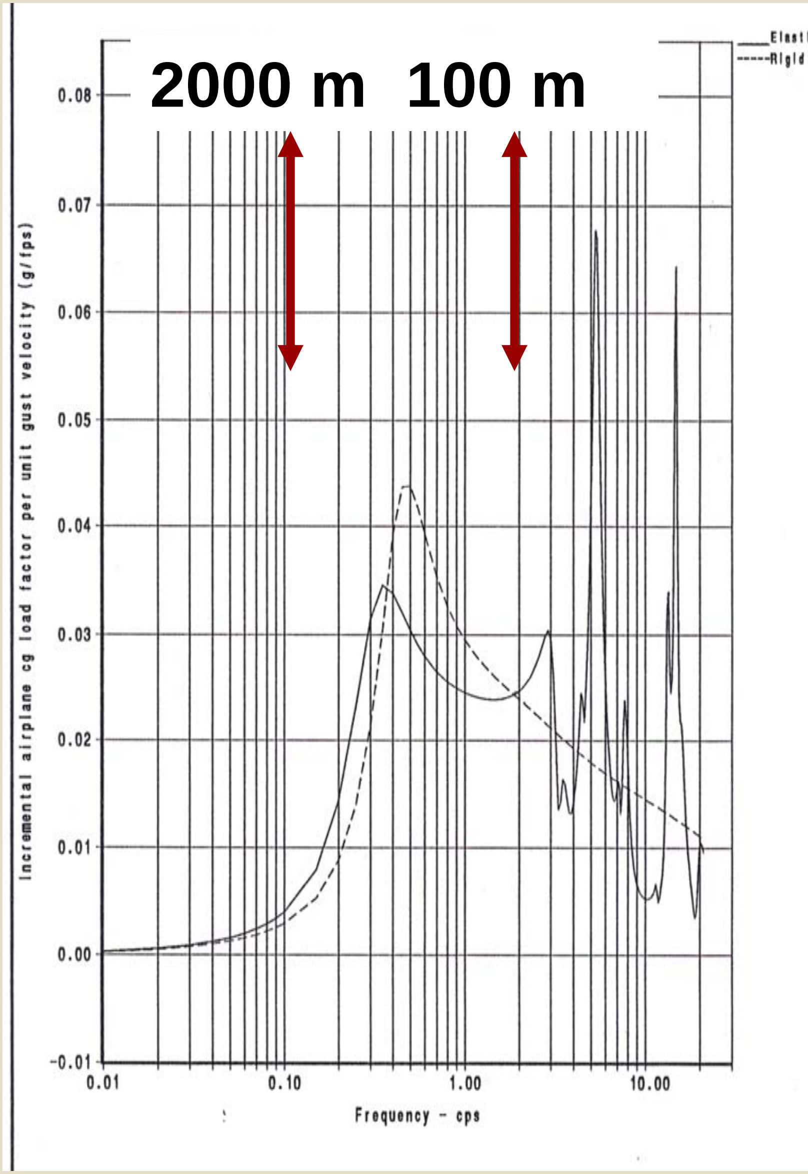
Mesoscale model resolution

Fine-scale model resolution

The product of the response function and the wind spectrum gives the output spectrum.




## Response Function for Transport Aircraft



# The Need For Turbulence Measurements

- **Tactical**:
  - Real time alerts of eminent encounter (< 1 min.)
    - Turn seat belt sign on.
    - Get passengers seated and in seatbelts.
    - Get service carts stowed and flight attendants seated.
  - Real time alerts/nowcast of impending encounter (< 15 min.)
    - All of the above.
    - Change altitude.
    - Change flight path.

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# The Need For Turbulence Measurements

- **Strategic**:
  - Nowcast/Forecast of potential encounter (en route)
    - Increase pilot awareness.
    - Discussions with airline Dispatch personnel.
    - Discussions with en route air traffic personnel.
    - Consider altitude/course change.
  - Forecast of potential encounter (pre-flight)
    - Pre-flight awareness for pilot/Dispatch.
    - Consider re-routing flight path.

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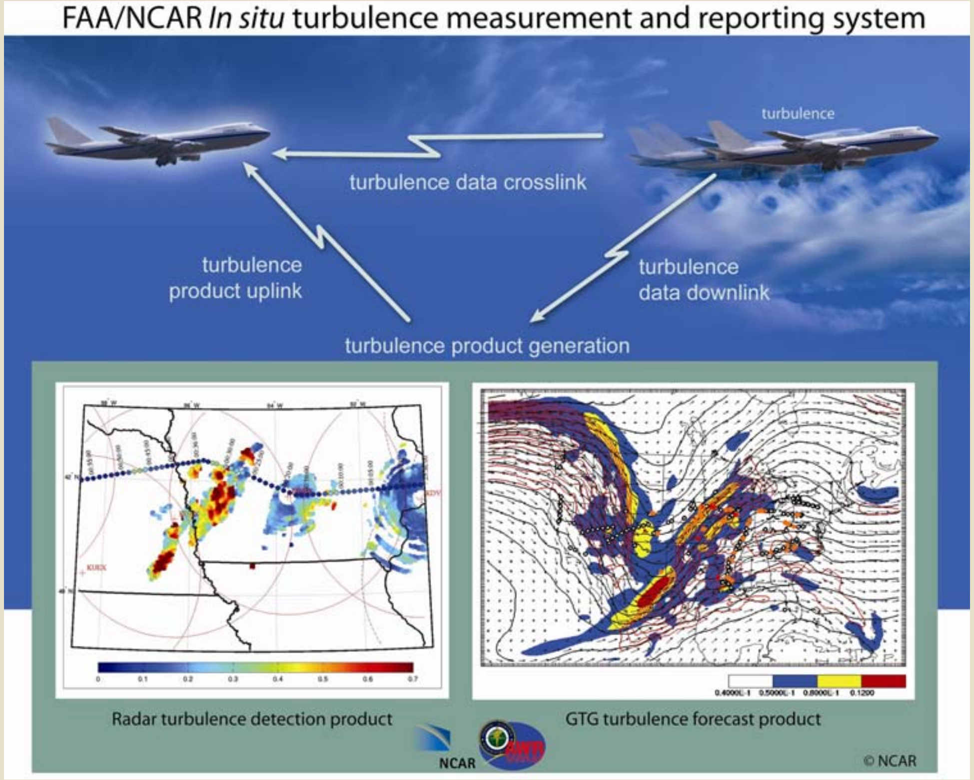
# *In situ* Turbulence Measurement and Reporting System

**Goal:** To augment/replace subjective PIREPs with objective and precise turbulence measurements.

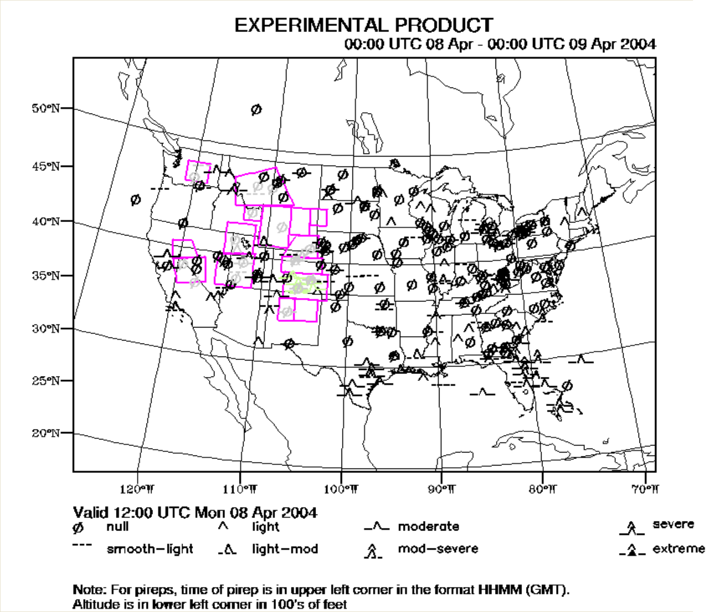
**Features:**

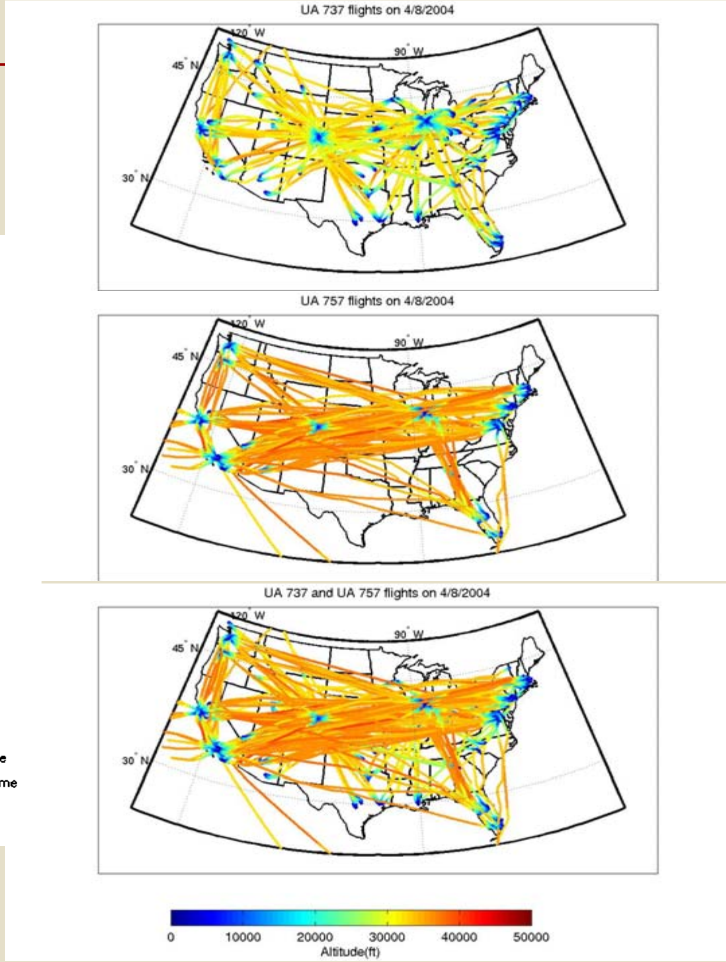
- Atmospheric turbulence metric: eddy dissipation rate (EDR).
- EDR can be scaled into aircraft turbulence response metric (RMS-g).
- **Adopted as ICAO Standard**



# Increase in Spatial/temporal Coverage: UAL EDR Reports Compared to pireps

**1.3 million EDR reports/month from 100 or so aircraft - compared to 55k pireps from all aircraft.**



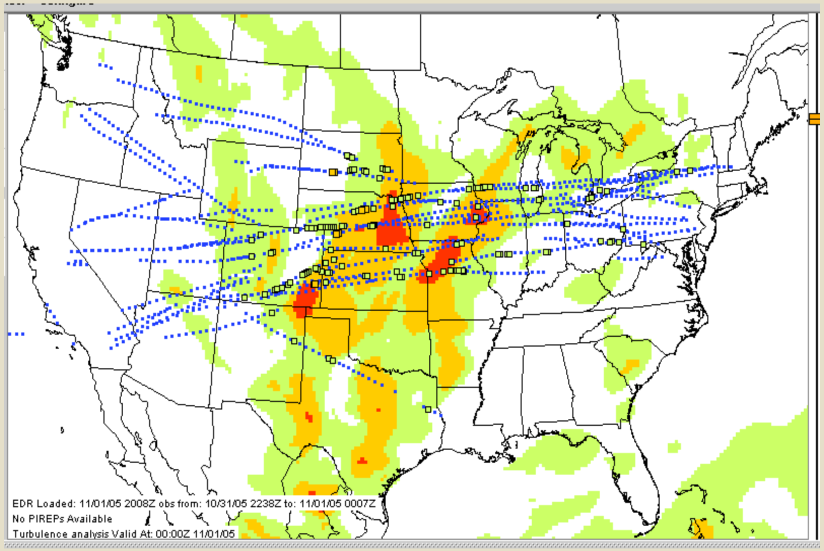

**737**

**757**

**737**
**+**
**757**

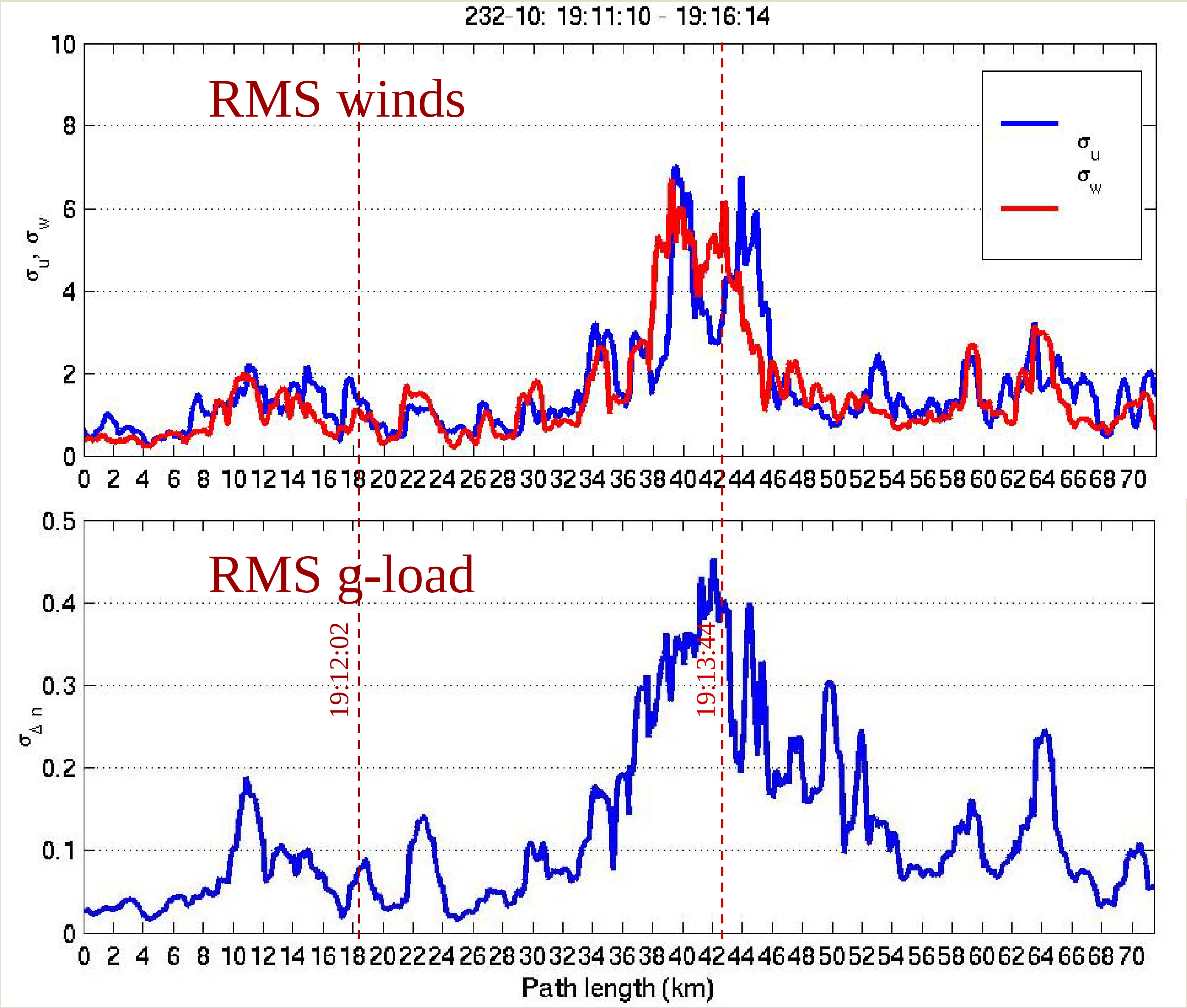
# *In situ* measurement and reporting system

- Implemented on ~ 200 UAL aircraft since 2000
- Implementation status
  - SWA: Fleet implementation on ~ 280 737-700s in CY08
  - DAL: Fleet implementation on ~ 120 737-800s in CY08
  - NWA: Discussions ongoing for implementation on ~ 140 Airbus 319/320s and 56 787s
  - UAL: 757 ACMS replacement
  - AAL: Discussions ongoing



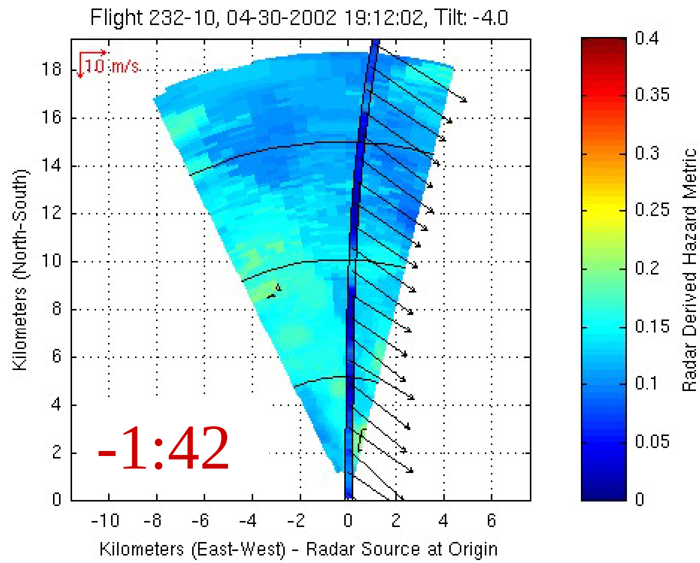

Website: UAL 757 edr flight tracks overlaid on GTG forecasting product

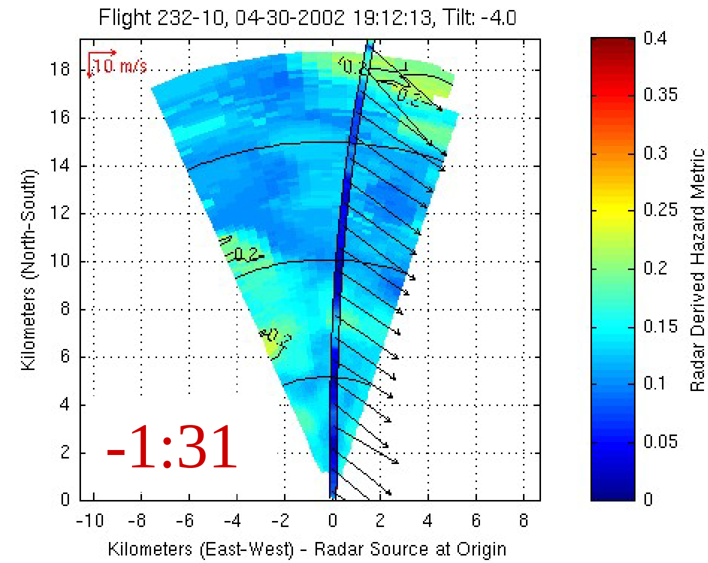
# NASA Airborne Radar Detection of Turbulence Program

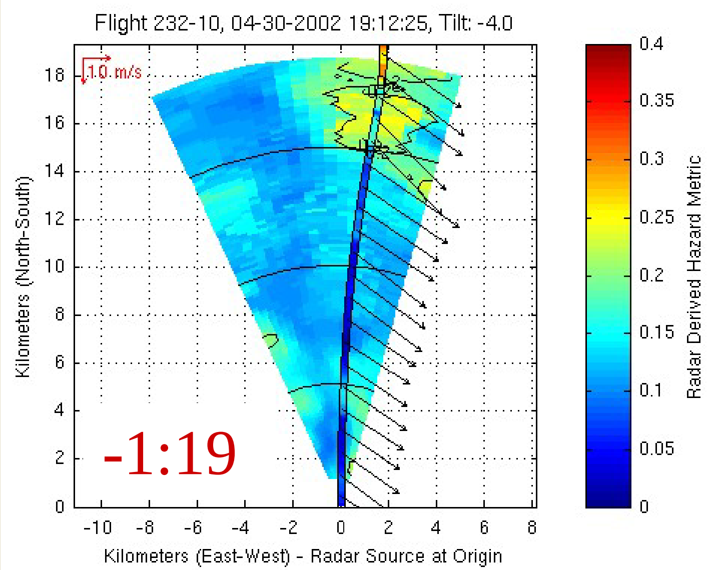



**From NASA B-757 Aircraft**

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



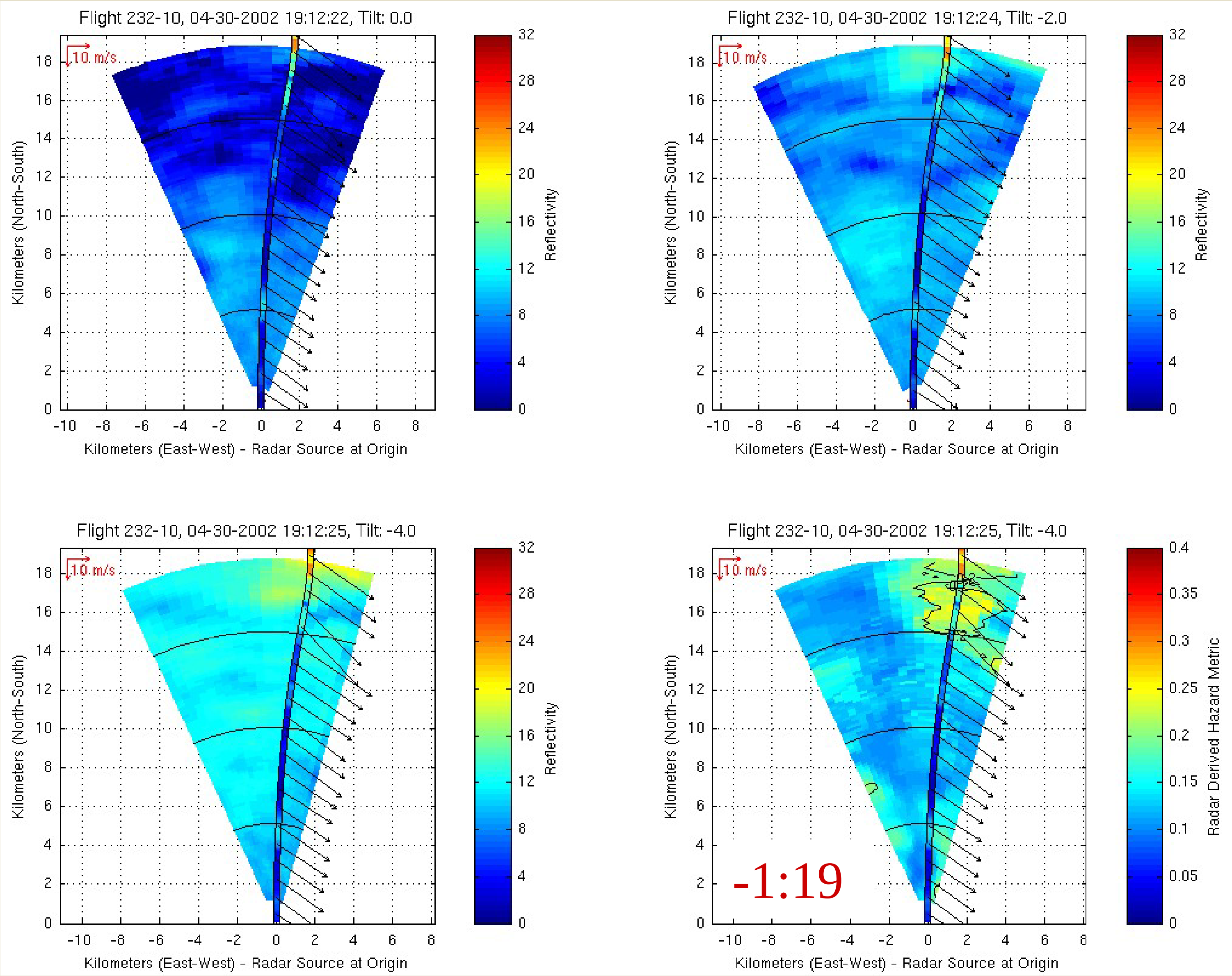



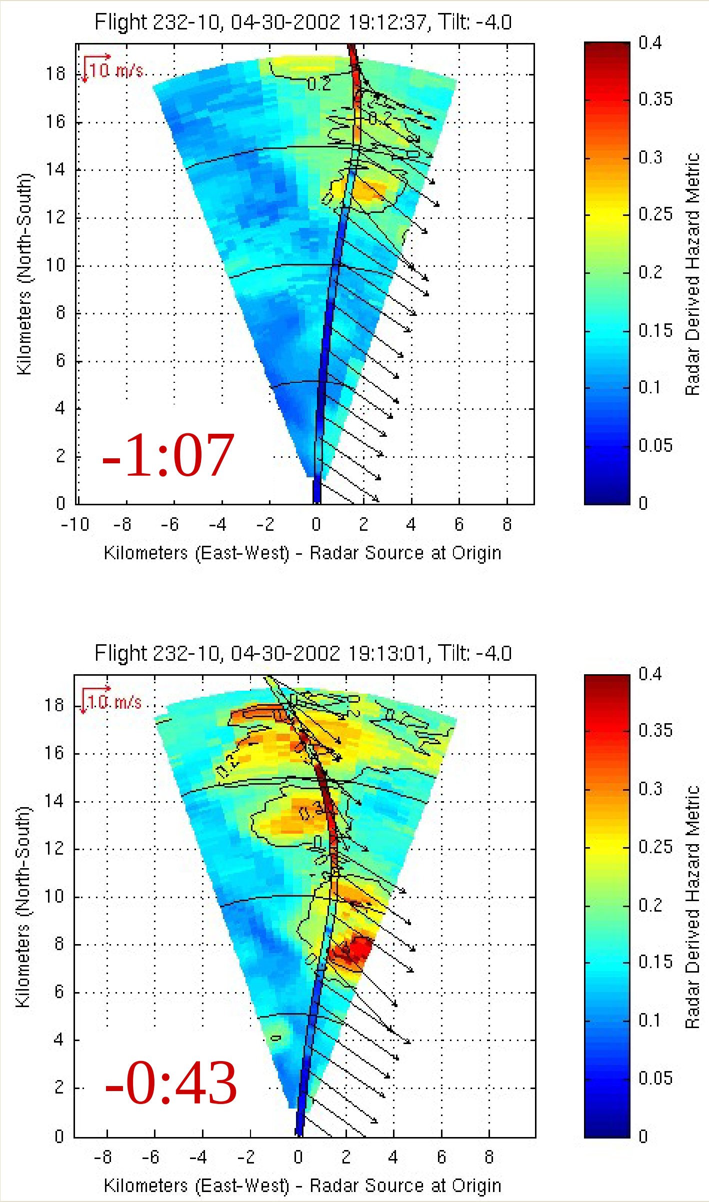

**Hazard detected**

**1:19, 18 km to encounter**

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

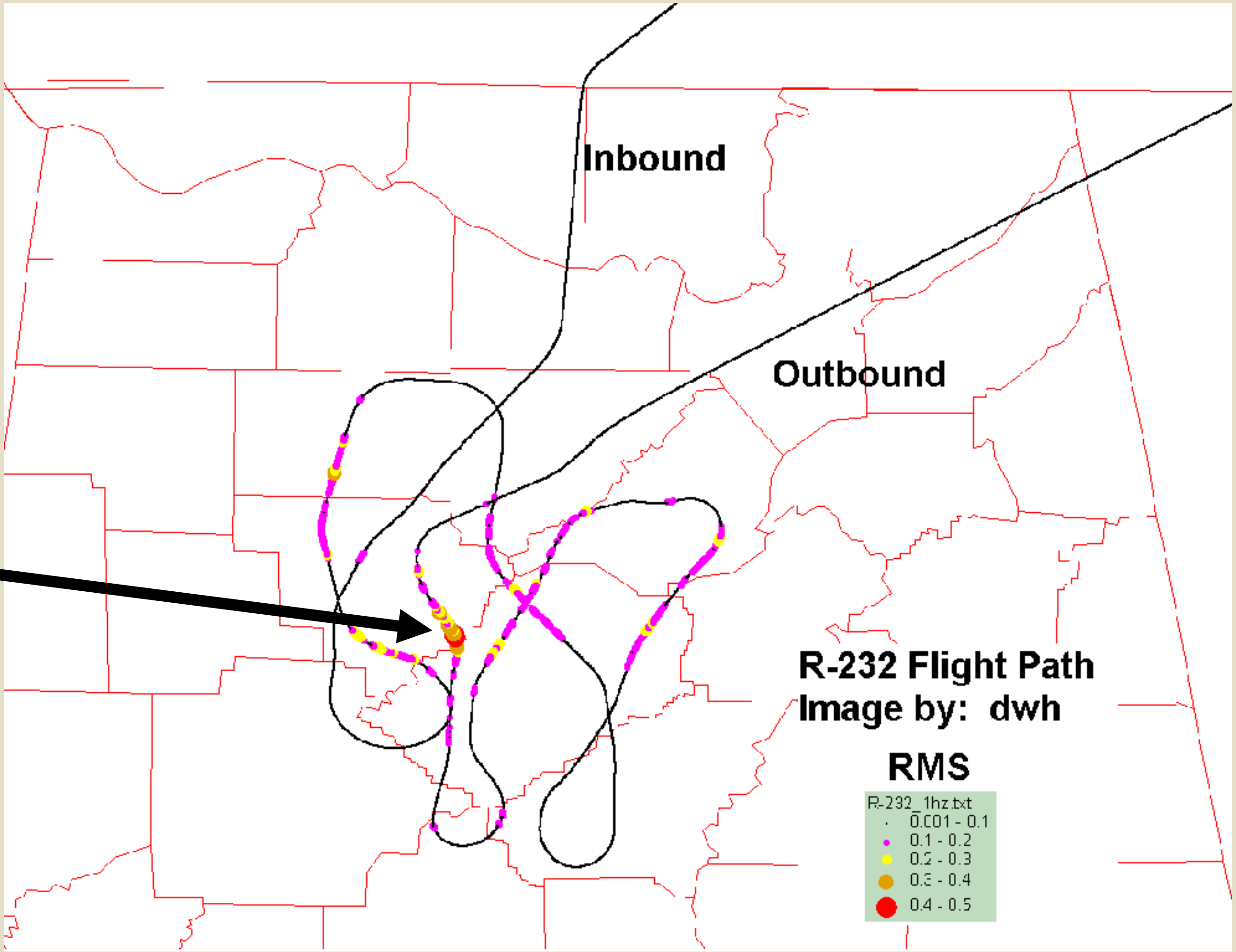


# Event 232-10 (19:12:37, 19:12:49, 19:13:01)




**Persistent detection**

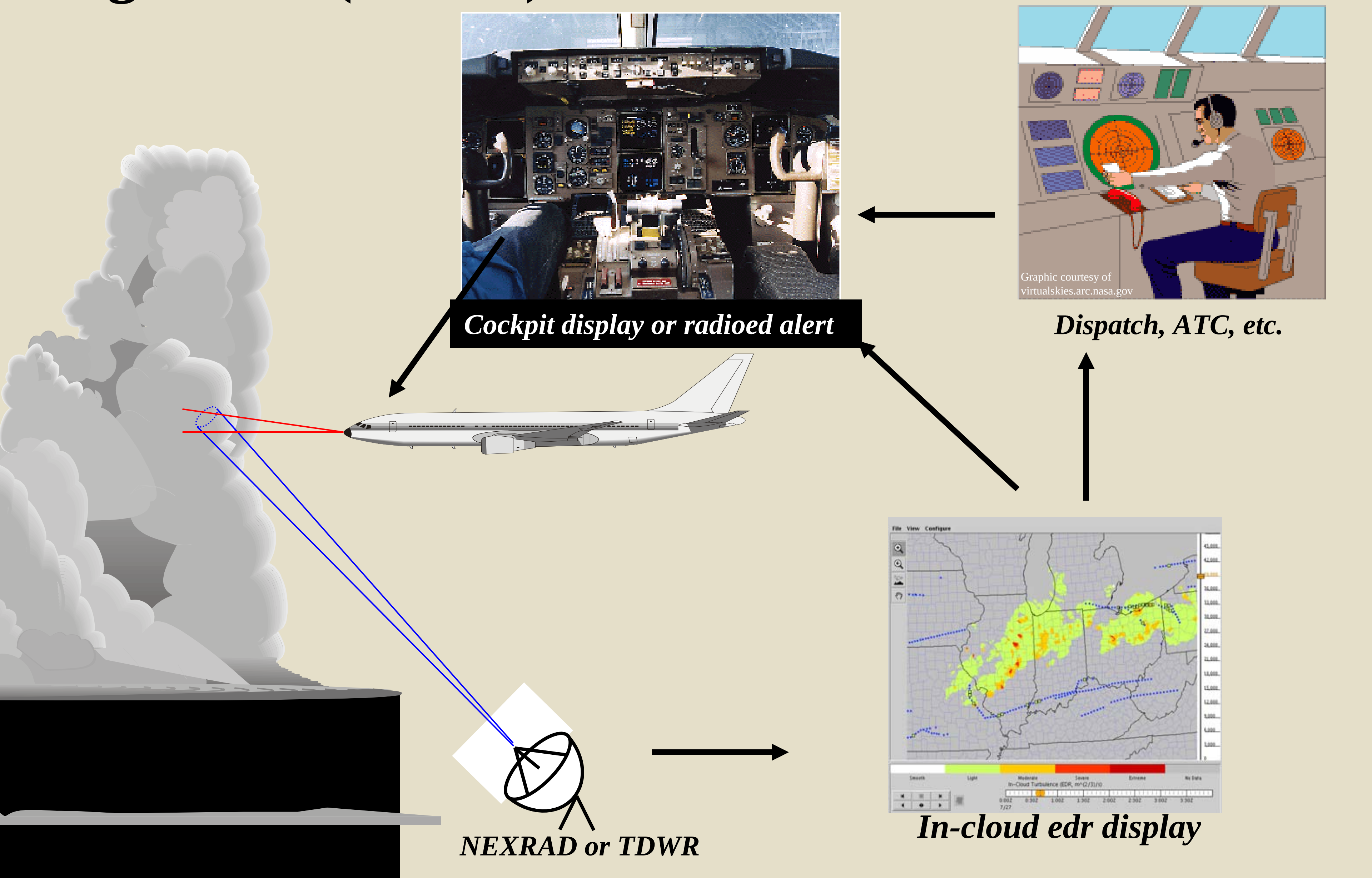
# Flight Track for NASA flight R232




**Event R232-10**

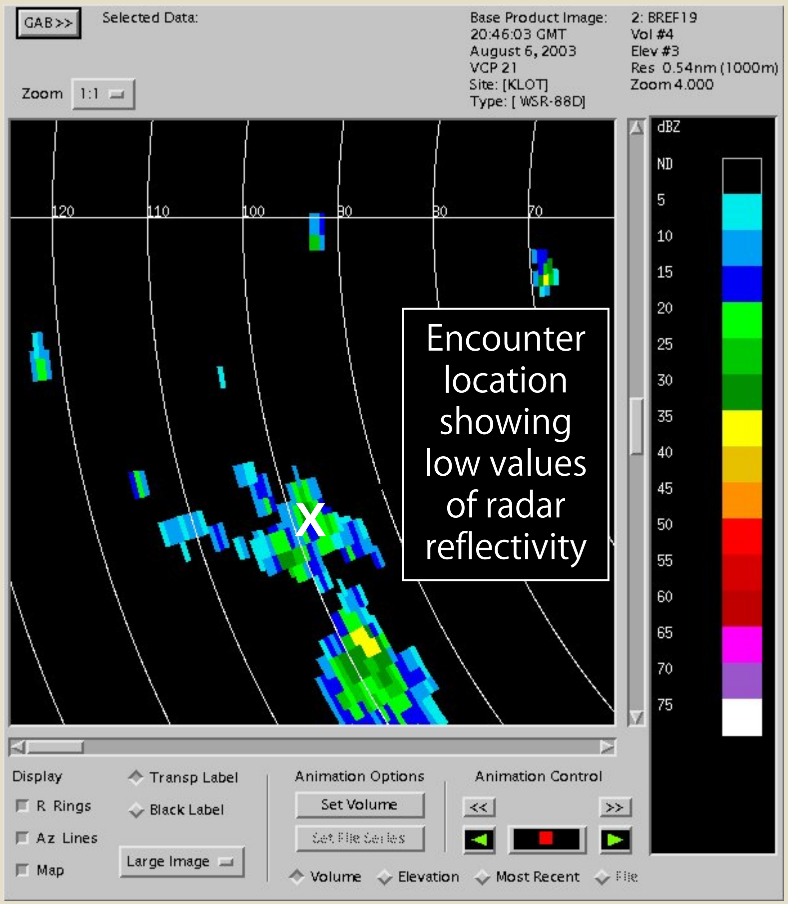
**North-Central Alabama**

# NEXRAD in-cloud turbulence detection algorithm (NTDA)

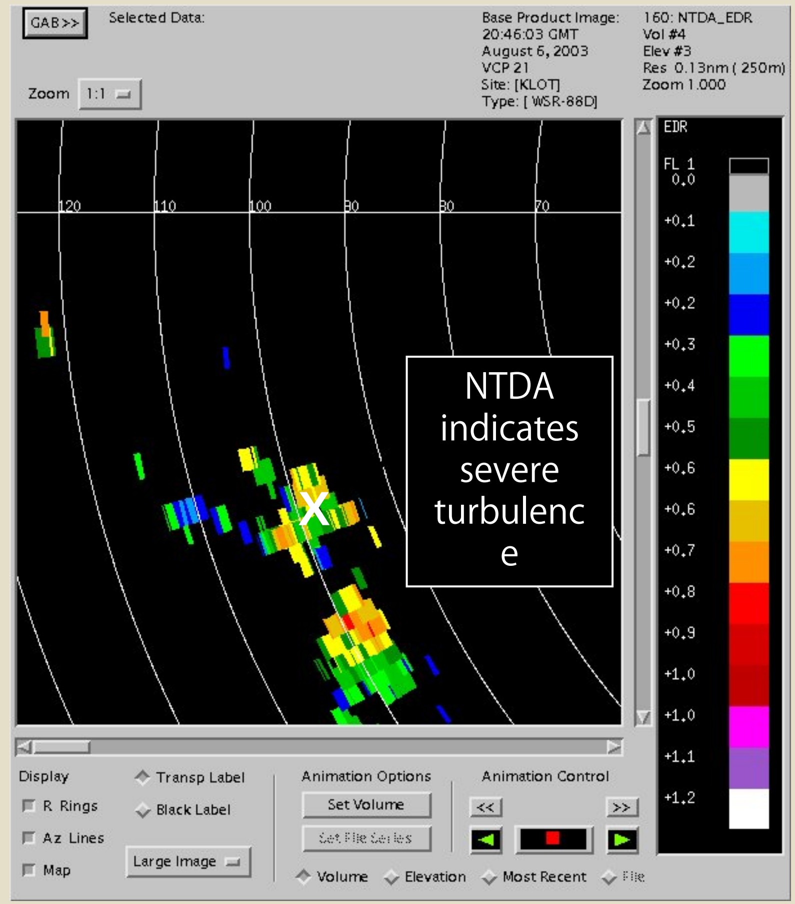


# Case Study: Severe turbulence encounter at FL 310 over NE Arkansas

- Vertical acceleration from -0.9 g to +2.3 g in about 3 seconds
- 43 minor injuries, two serious; cabin damage
- 8 min. warning could have reduced/eliminated injuries



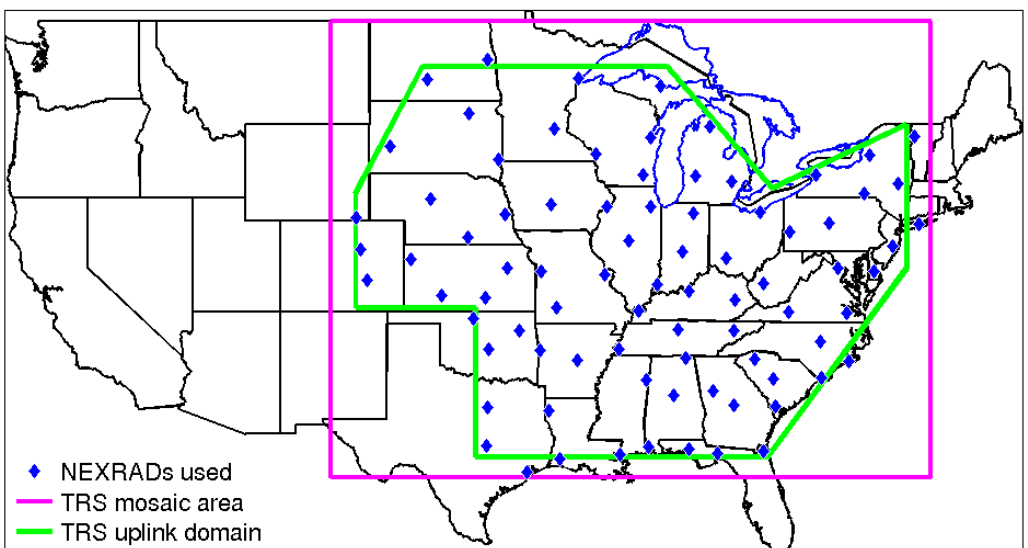

KPAH reflectivity 8 minutes prior: 15-30 dBZ




NTDA EDR: 0.55-0.65 $m^{2/3}\ s^{-1}$ (severe)

# NTDA uplink demonstration

- **Uses data from 83 NEXRADs, covering eastern US**
- **3-D EDR mosaic updated every 5 minutes, displayed via Experimental ADDS**
- **ACARS text uplinks to UAL cockpits for flights registered on NCAR webpage**
- **Pilot feedback via webpage**
- **September press release garnered significant attention**




```
/EXPERIMENTAL TURBULENCE FI UAL[redacted]/AN N[redacted]UA UPLINK
-- 05 Sep 2006 21:38:13Z  FL 300  orient. 83 deg
'+'=waypoint, '*'=route, 'X'=aircraft at 38.3N, 80.6W
' '=no_data, 'o'=smooth, 'l'=light, 'M'=mod, 'S'=severe
----------------------(52 to IAD)-------------------------
       |                    *
       |                    *
MM     |                     *
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MM     |lllllllllllllll  l     *
lll    |lllllllllollllllll      *
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llM    |      MM  lMlllll       *           l
-------|---------valid-|--------X--------|----------------
-90 +90|Left 40  2135Z  (18 from 3819N/8058W)      Right 40
```

Flight information

Legend

Route

Waypoint

Severe turbulence

Moderate turbulence

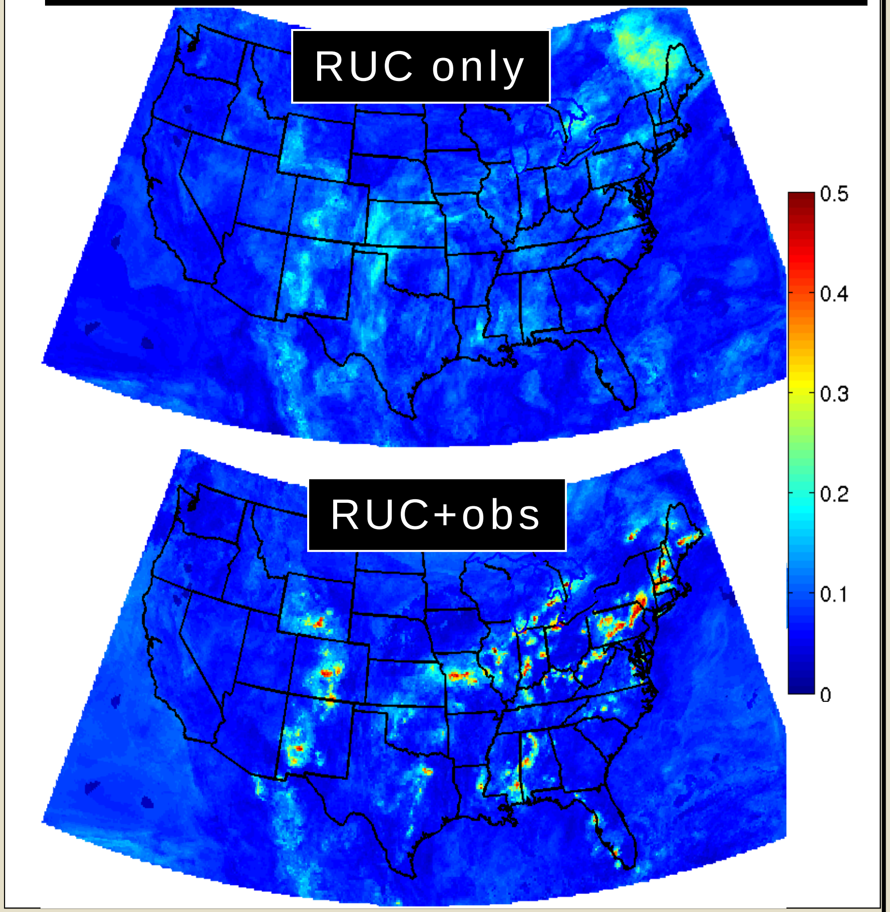
Aircraft position

Vertical cross-section

# Diagnosis of convectively-induced turbulence (DCIT)

- Near-storm environment and turbulence diagnostics from RUC
- Storm location, morphology, and observations from satellite, radar (dBZ and EDR), and lightning
- Associations with *in situ* EDR reports used to tune an empirical model (random forest)
- DCIT provides tactical 3-D gridded EDR, Prob MoG and Prob SoG assessments
  - for use in GTGN
- DCIT real-time prototype running in RAL since August

**DCIT: Prob MoG (uncalibrated)**
**27 June 2007 2300 UTC, FL 300**



# Turbulence Detection via Airborne GPS Receivers: The Concept

- Airborne receivers would be a platform of opportunity to collect occultations in the cruise regime of commercial aviation, e.g., 20-40 kft. AGL.
- The turbulence measurements from these occultations would probably not be used as stand-alone information, but integrated into operational nowcast/forecast products.

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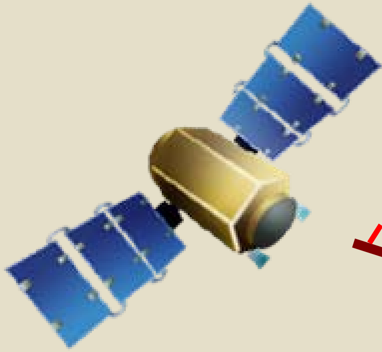
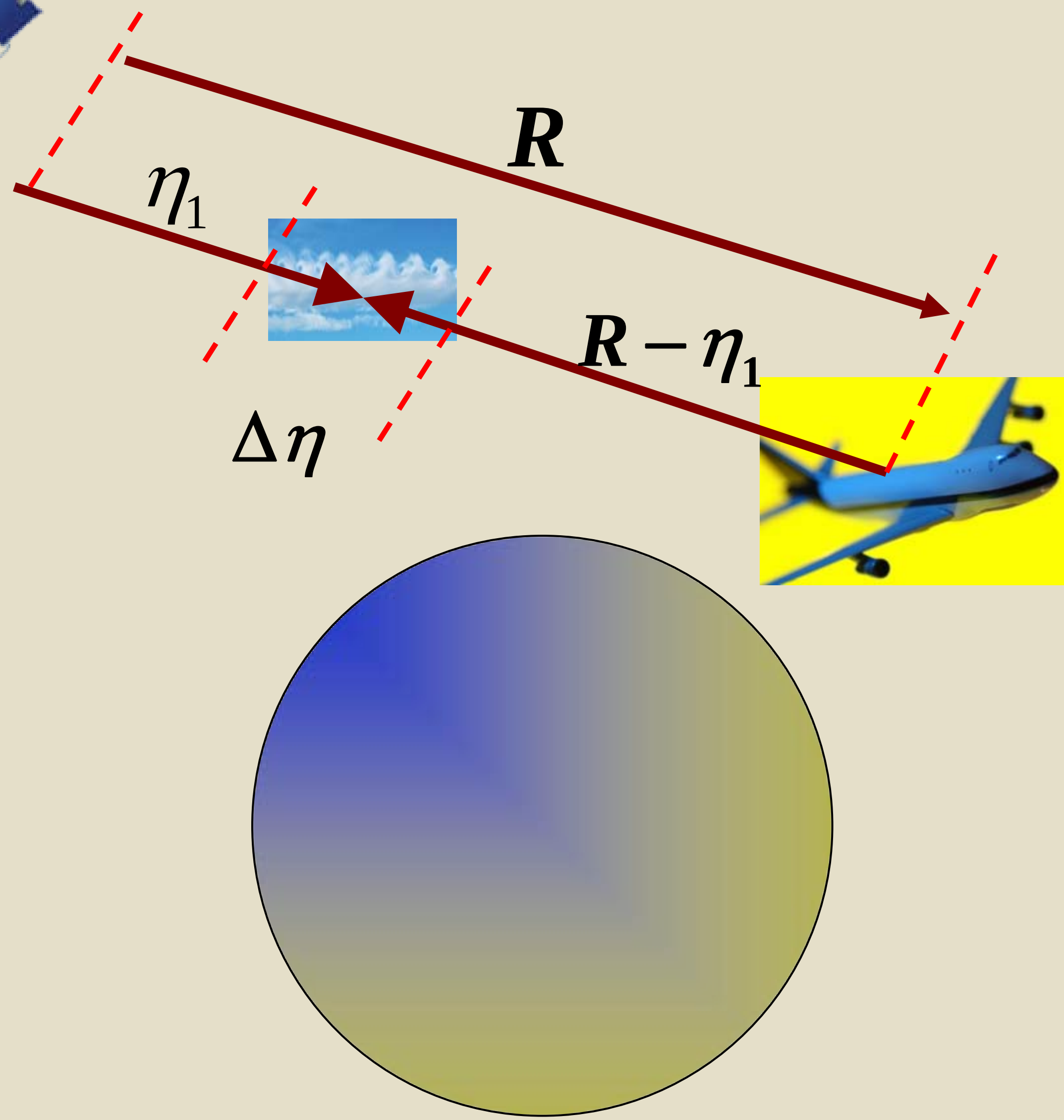
# Geometry of the Problem





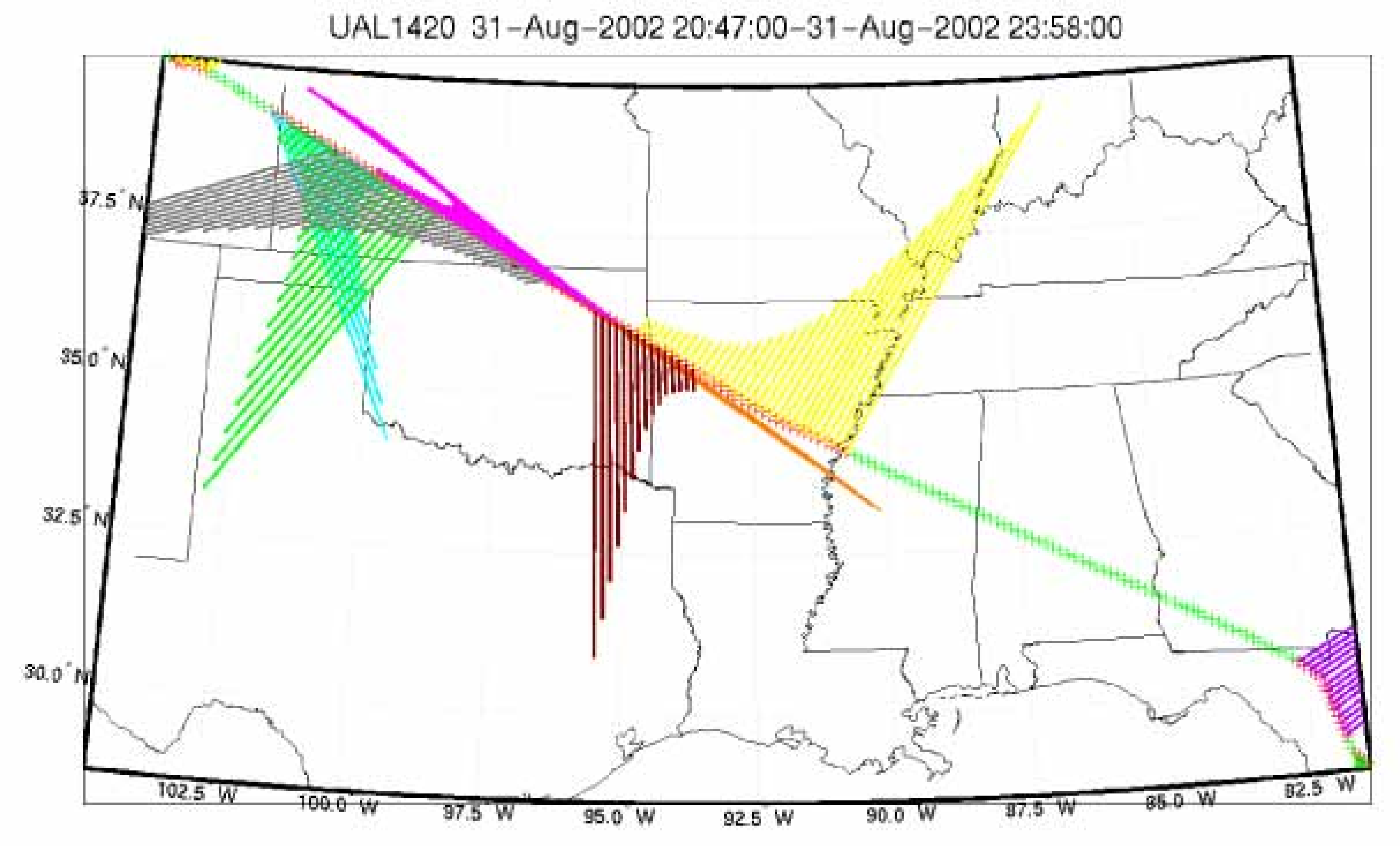

$\eta_1$ is the distance, along the LOS, from the satellite to the center of the turbulence patch.

**R** is the distance from the satellite to the aircraft receiver along LOS.

$\Delta\eta$ is the width of the turbulence patch along LOS.

$R-\eta_1$ is the distance from the aircraft to the turbulence patch.

# Aircraft Flight Track with GPS Occultations

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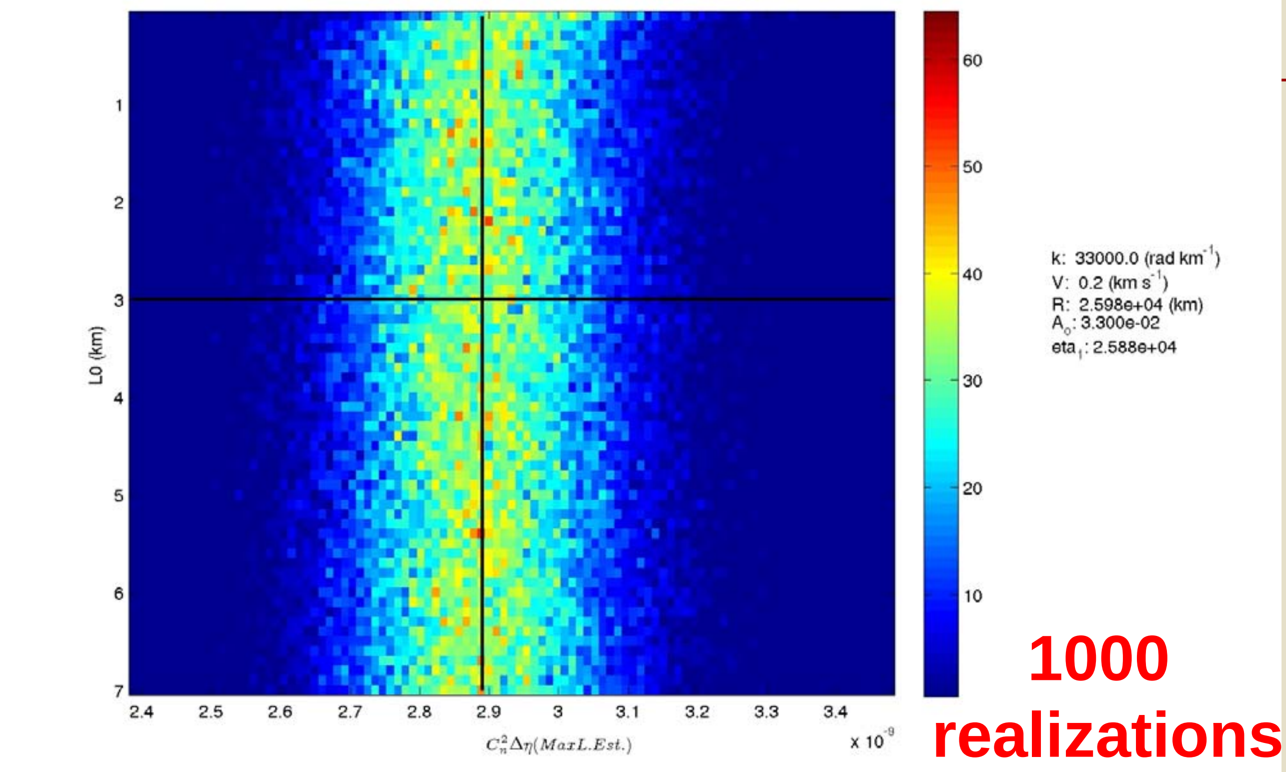
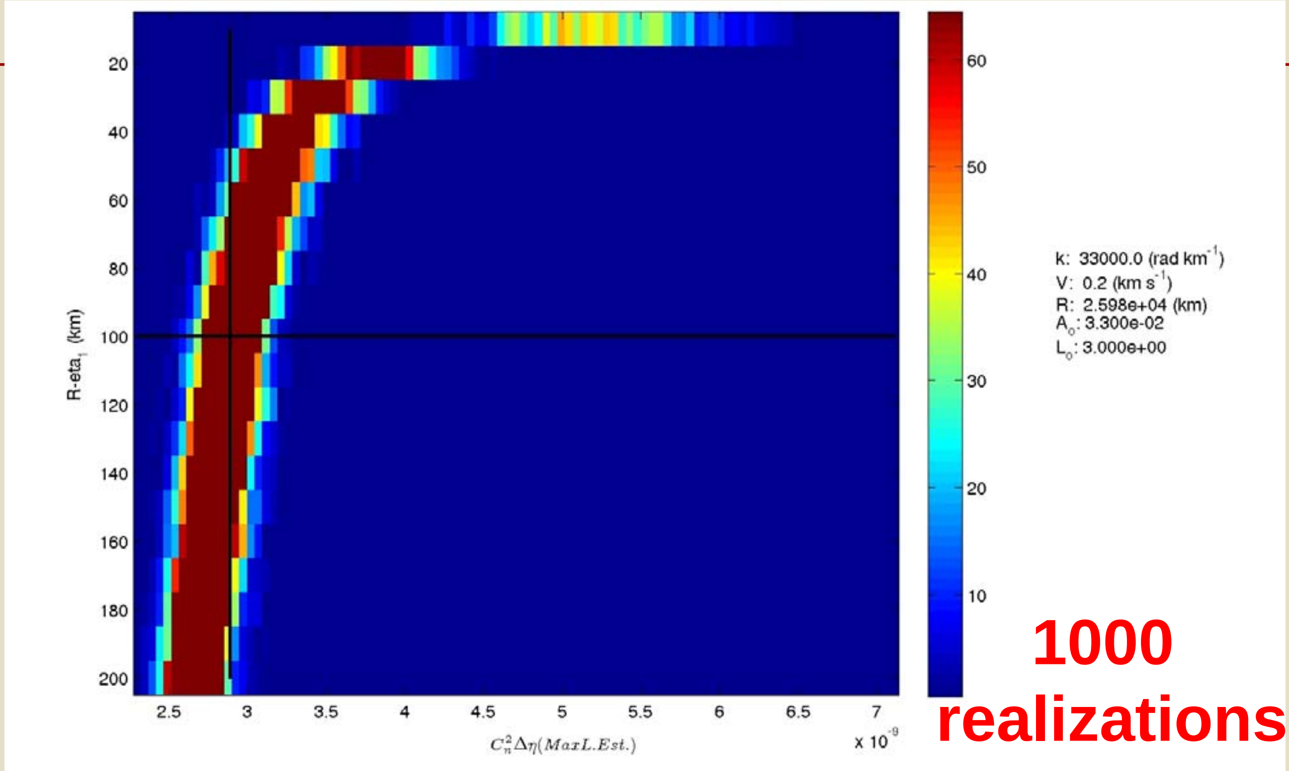
# Parameter Estimation




**1000 realizations**

**Maximum Likelihood (ML) estimation of intensity with fixed $R-\eta_1 = 100\ km$ while varying $L_0$. Horizontal and vertical lines are simulated (i.e., "true") values.**

# Parameter Estimation (cont’d)




**1000 realizations**

**ML estimation of intensity with fixed $L_0 = 3\,km$ while varying $R - \eta_1$ .**

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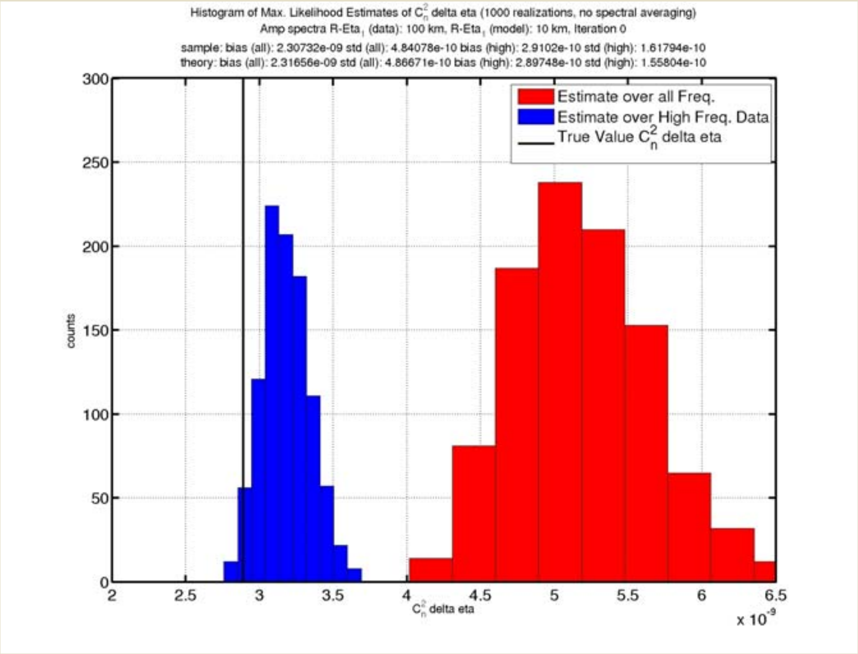


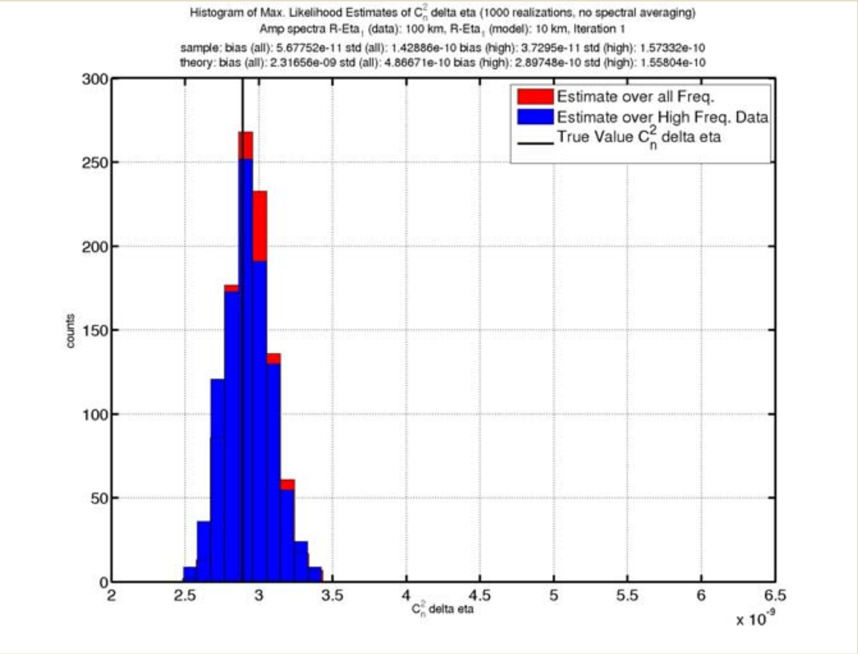


- **Initial ML estimation of intensity (left) and using an estimate of $\eta_1$ (right).**
- **Solid vertical line is true value.**
- **Blue values are from using the high-frequency portion of the spectrum, red values use all the spectral points.**
- **Simulated $R-\eta_1$ value is 100 km, "guess" is 10 km - i.e., an *underestimate – hence the overestimate of the intensity.***

# Detection of Turbulence Using an Airborne Forward-Looking IR Sensor

- Possible Approach:
  - Derive equation that relates the statistics of the atmospheric turbulence (e.g., temperature field) to those of the sensor measurables.
  - Consider the irradiance (H) at a given frequency, measured at the aircraft (x=0):

$$H(0) = \int_L^0 W_B(T(x)) f(x) dx$$

Where $W_B$ is the Planck function, *L* is the path length over which the measurement is made, and *f* is a combined function of the non-turbulent atmosphere and the response characteristics of the sensor.

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# Detection of Turbulence Using an Airborne Forward-Looking IR Sensor

- Next, consider the same measurement when the aircraft has moved a distance $\rho$ :

$$H(\rho) = \int_{L+\rho}^{\rho} W_B(T(x)) f(x) dx$$

- Assuming that the Planck function is linear in the temperature, the correlation function of the irradiances can be computed:

$$\langle H(0)H(\rho)\rangle = K \int_{L}^{0} \int_{L+\rho}^{\rho} \langle T(x)T(x')\rangle f(x) f(x') dx dx'$$

# Detection of Turbulence Using an Airborne Forward-Looking IR Sensor

- Assuming that standard turbulence theory applies, $\left\langle T(x)T(x')\right\rangle = C_T^2 g(x'-x)$, where $C_T^2$ is the intensity parameter of the turbulent temperature field. In principle the turbulence intensity parameter is given by:

$$C_T^2 = \frac{\left\langle H(0)H(\rho)\right\rangle}{K\int_L^0 \int_{L+\rho}^{\rho} g(x'-x)\, f(x)\, f(x')\, dx\, dx'}$$

# Detection of Turbulence Using an Airborne Forward-Looking IR Sensor

- Issues:
  - Aircraft respond to vertical wind motions, not temperature fluctuations - the relationship between the two is not well-understood.
  - To what spatial scales are these IR devices sensitive?

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# Turbulence Forecast Product: Graphical Turbulence Guidance (GTG)

- **Based on RUC NWP forecasts**
- **Uses a combination of turbulence diagnostics, merged and weighted according to current performance (pireps, EDR)**
- **Current work areas:**
    - Probabilistic forecasts of moderate-or-greater (MOG) turbulence
    - Optimal use of *in situ* reports
  - Output probability of MOG,SOG > some EDR threshold
  - Improve forecasts of severe turbulence

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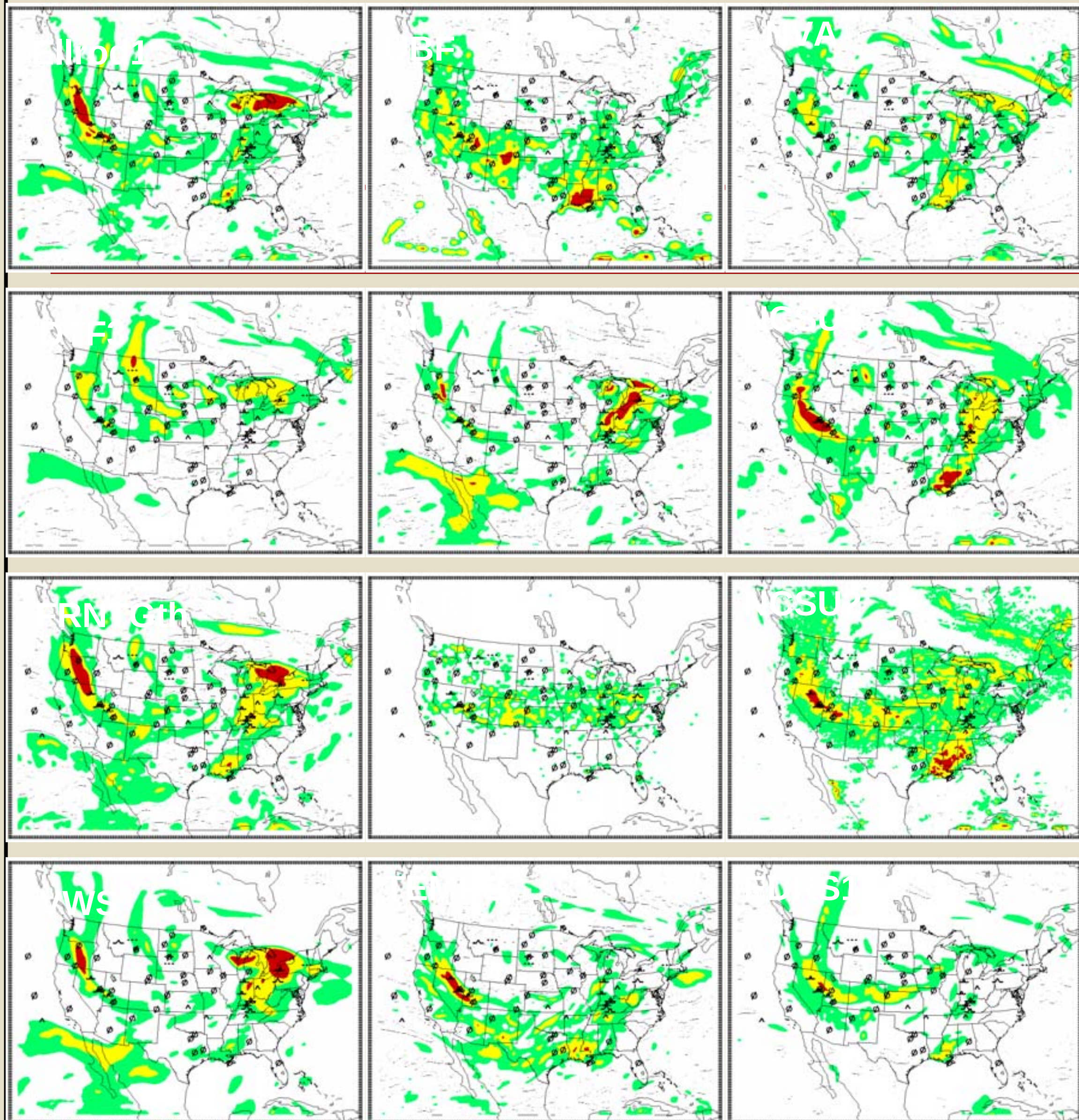
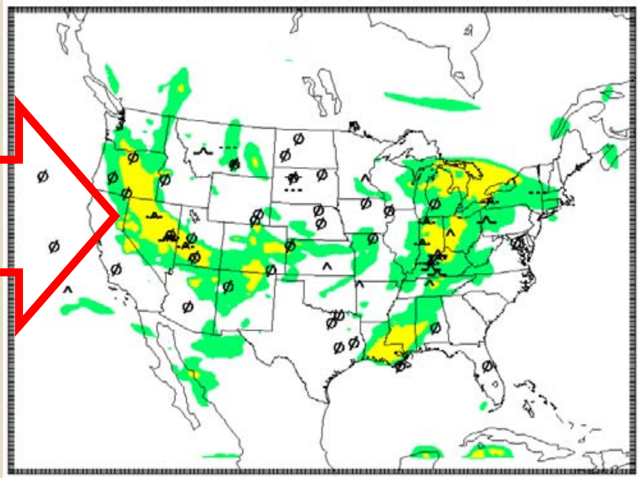
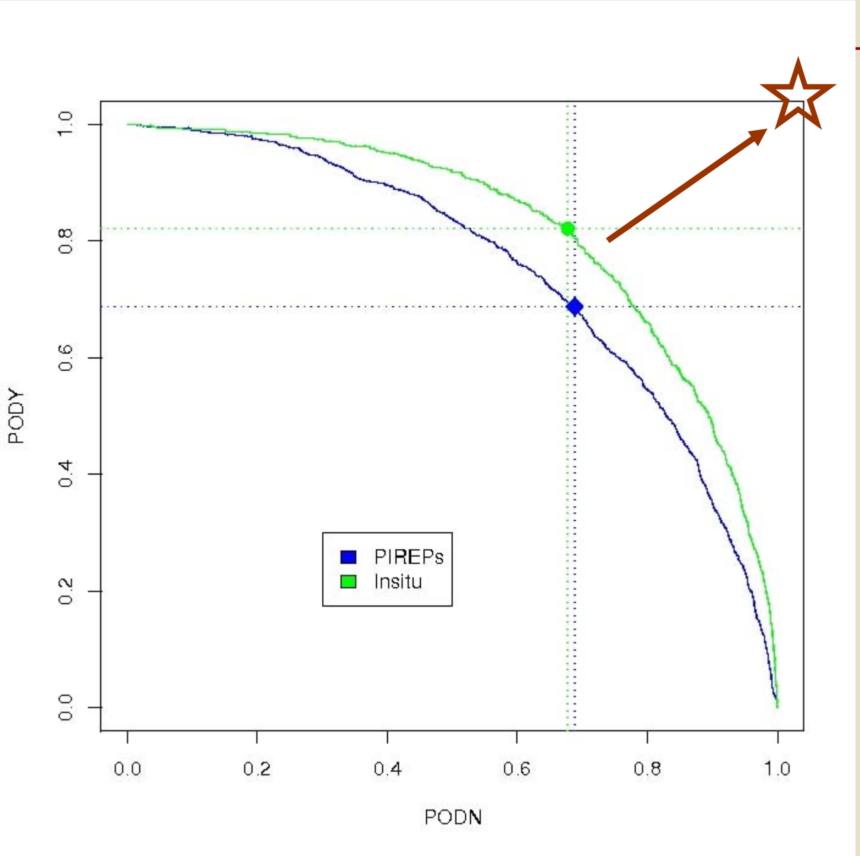
# GTG = Weighted ensemble of turbulence diagnostics



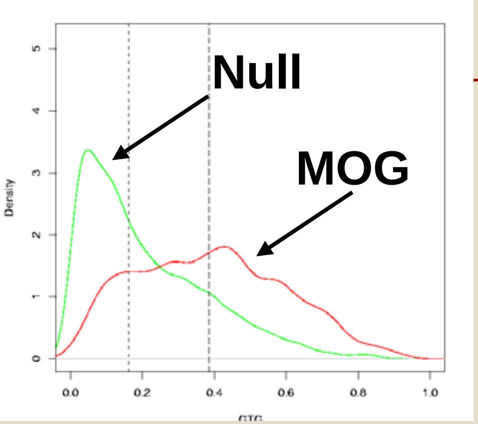


0 h forecast valid at 22 Sep 2006 15Z

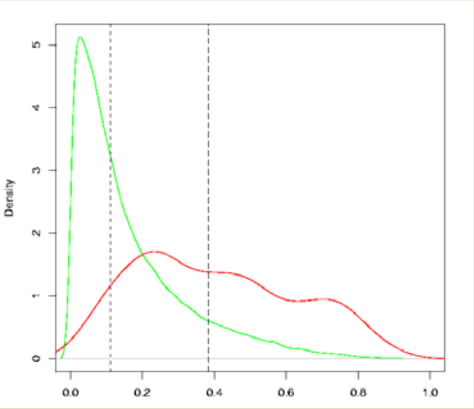
# GTG improvement using *in situ* data over pireps




**ROC Curve**




**w/ Pireps**




**w/ *In Situ***

**Intensity Discrimination**

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# Turbulence Nowcasting System (GTG-N) Overview

- Motivation:
  - GTG updates are tied to the model runs (once per hour).
  - Turbulence can vary dramatically over small space/time intervals.
  - We will have more observational data and rapid-update diagnostic products in the near future.
  - This implies the need for a rapid-update (e.g., every 15 min) gridded turbulence product, GTG-N

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# GTG-N Overview

- Approach (nominal):
  - Start with GTG grid.
  - Incorporate:
    - DCIT/NTDA
    - *In situ* Reports
    - Pireps
    - Lightning data
    - Satellite data.
    - Other…
  - Compute confidences for all inputs (diagnostic and measurements).
  - Use an intelligent merging procedure to create a unified turbulence nowcast gridded product.

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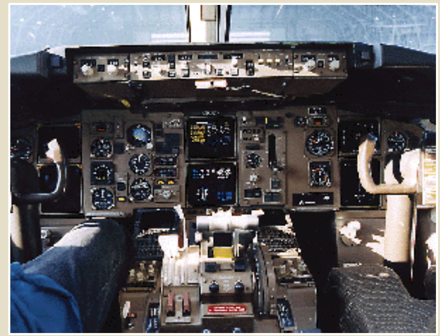
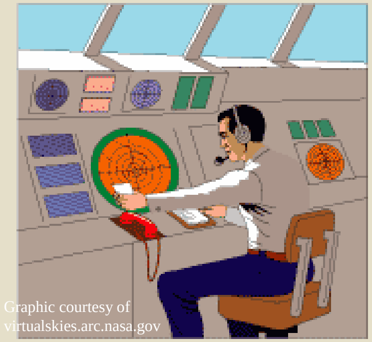
# Turbulence Nowcasting System: GTG-N

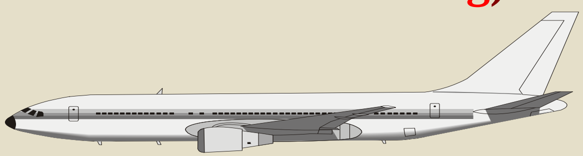
**Merges all current turbulence observations with forecast grids.**






*Cockpit display or alert* (**EDR** or **RMS-g**)

*Dispatch, ATC, etc.*



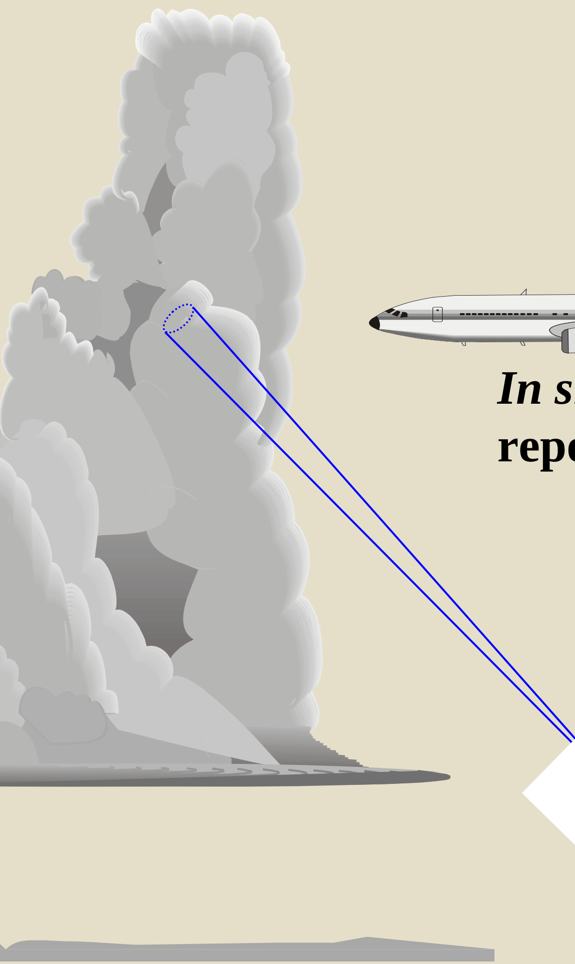
*In situ* **EDR** reports, *PIREPs*,

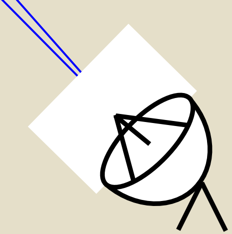
**4D data cube updated every ~15 min**

***GTG forecast grids (EDR)***

***Convective turbulence diagnostic (EDR)***

***Wx satellite data***

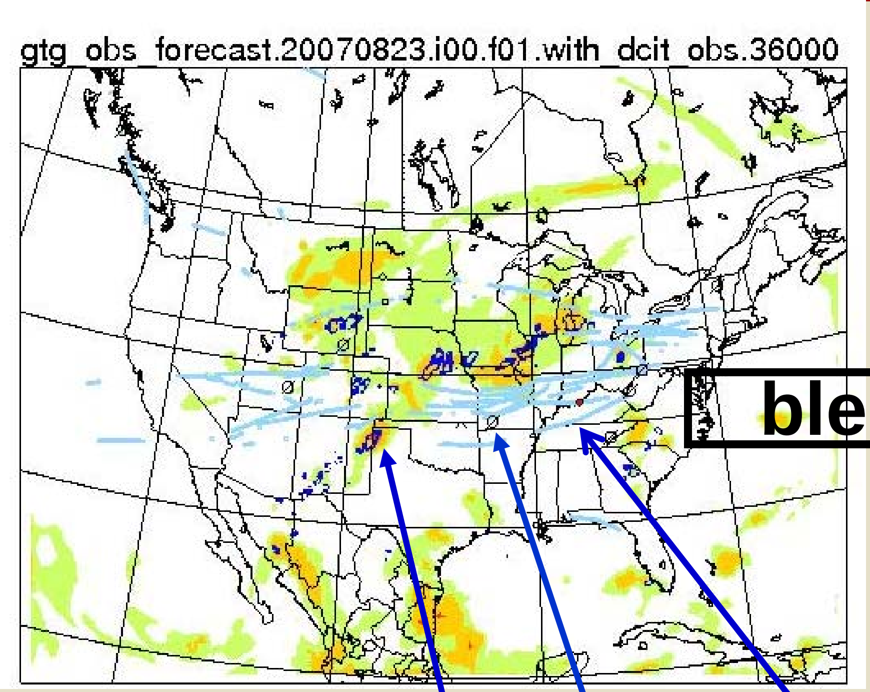




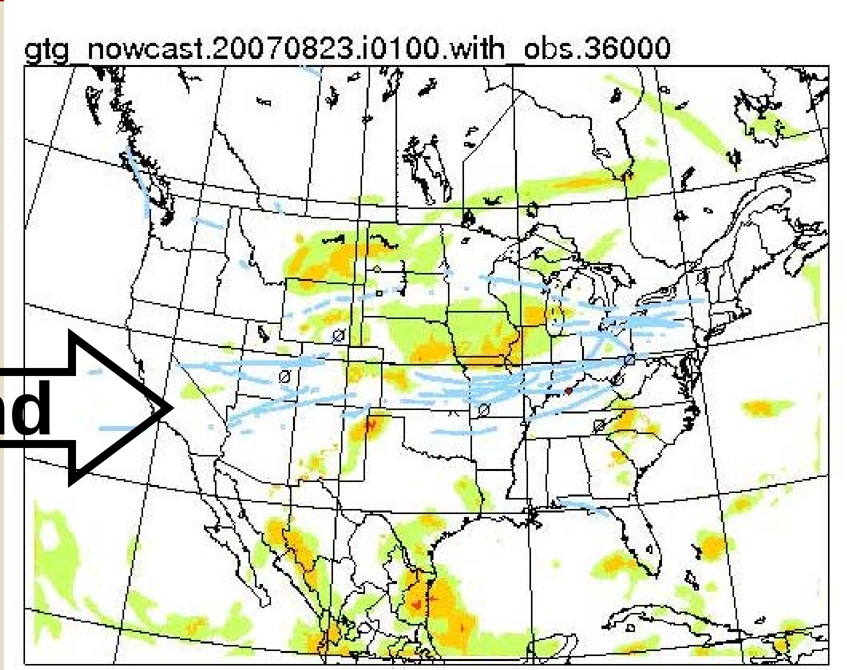
**Radar (NTDA) turbulence grids (EDR)**

# GTG-N Example

**GTG 1 hr forecast**




**blend**




**pireps**

DCIT

*In situ* tracks

# Summary

- Turbulence measurements are critical in providing accurate and operationally useful tactical and strategic information to users.
- *In situ* turbulence measurements are now available and used operationally – more to come.
- A number of proof-of-concept sensor demonstrations have occurred, with positive results.
- Other technologies in development/evaluation:
  - Airborne lidar
  - Satellite
  - GPS/Iridium
  - Airborne IR

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