In Situ and Remote Measurements of Turbulence

Larry B. Cornman

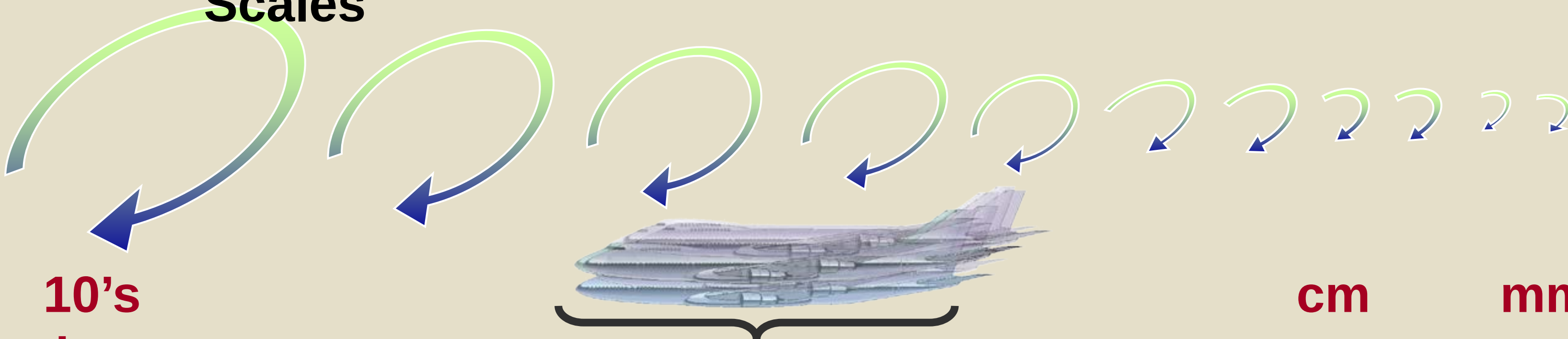
National Center for Atmospheric Research

NCAR

Aircraft Response to Turbulence

Energy Production Scales

Dissipation Scales



10’s km

cm

mm

Aircraft responds to scales from 10’s m – few km

Aircraft can adjust pitch angle and airspeed to ride smoothly over “waves”

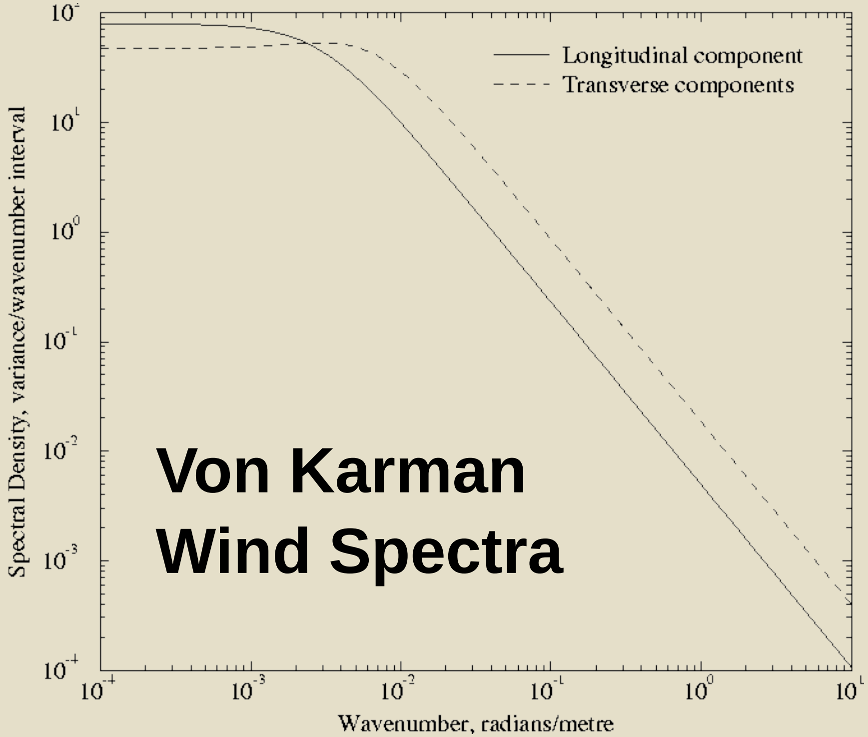
Excites rapid pitching and vertical motions

Excites flexible modes – but typically small amplitude

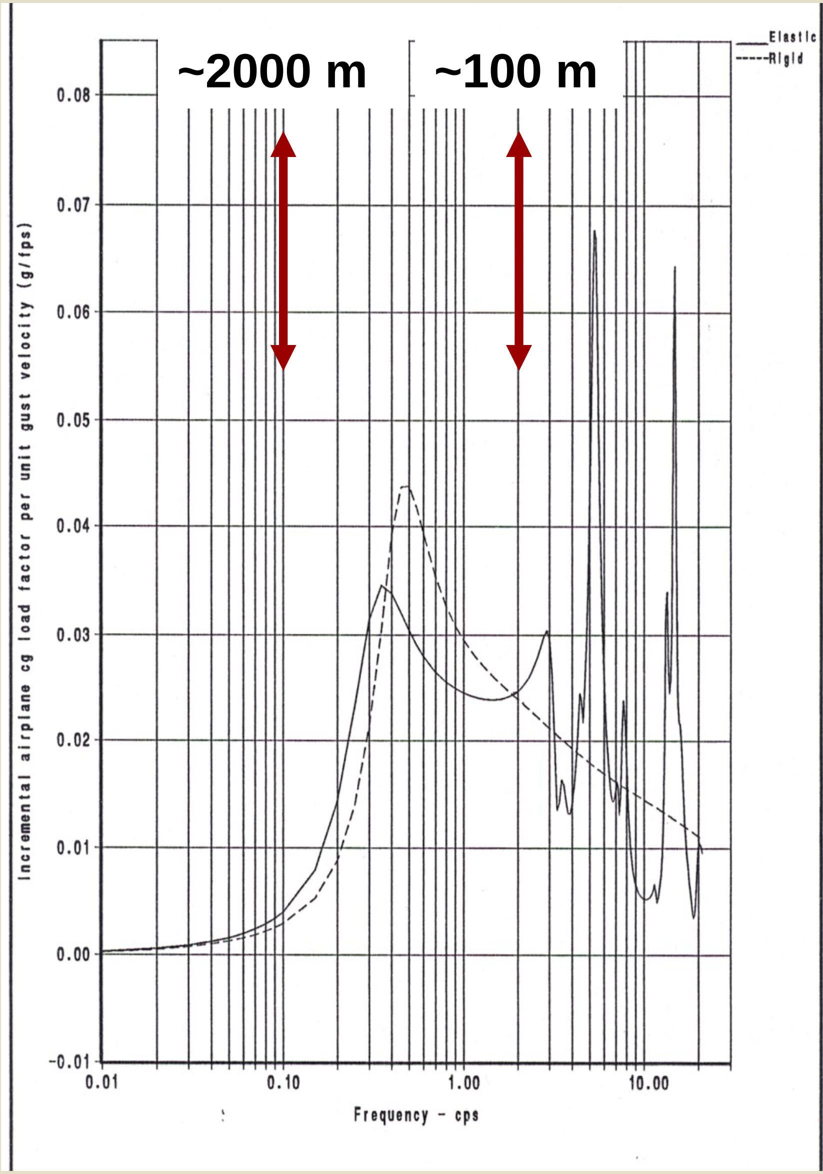
NCAR

Aircraft acceleration is a function of the wind spectrum and aircraft response function.

Response Function for Transport Aircraft



X



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.

NCAR

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.

NCAR

Importance of energy dissipation rate as an intensity parameter

- Under appropriate simplifications the turbulent kinetic energy equation can be written as:

$$\frac{de}{dt} = -\varepsilon$$

- Furthermore, for isotropic turbulence in the inertial subrange, is given by the Kolmogorov energy spectrum :

$$E(k) = A\,\varepsilon^{2/3} k^{-5/3}$$

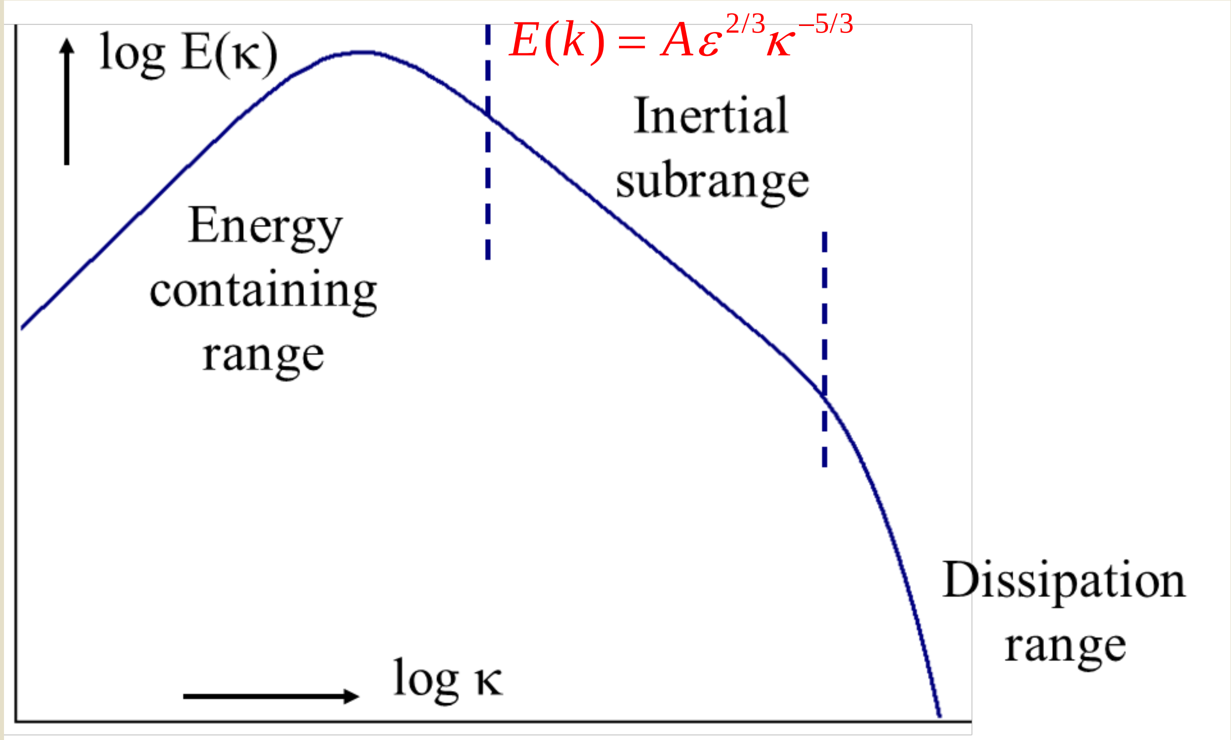
Notation: EDR = $\varepsilon^{1/3}$

NCAR

Energy Scales in Wavenumber Space

KEY: In the inertial subrange,
the turbulence can be described via EDR (and κ)

$$\kappa = \frac{2\pi}{l}$$



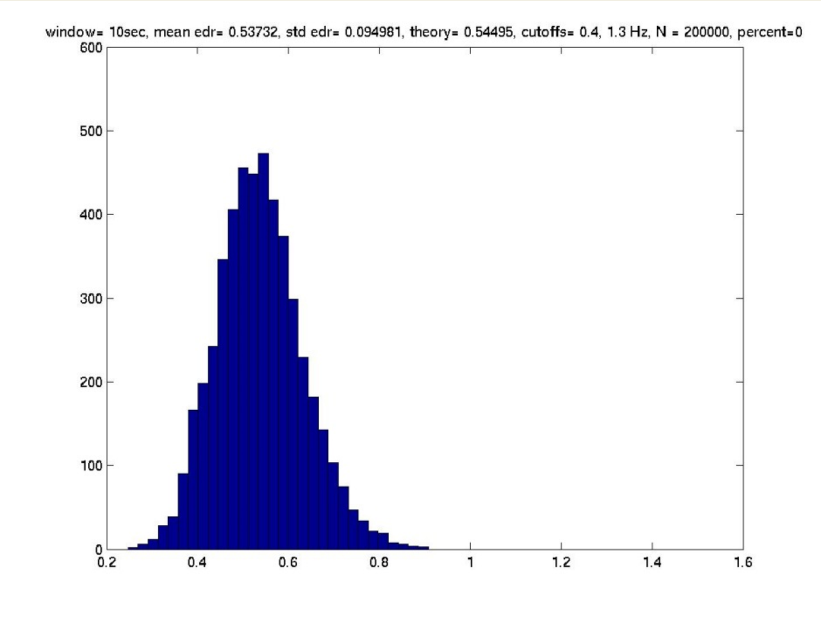
Important Considerations with Turbulence

- Turbulence is a random process, and hence statistical measures are required.
- "More samples = better results" (for homogenous turbulence).
- EDR is a calculated – not measured - quantity, and so how it is computed is important.

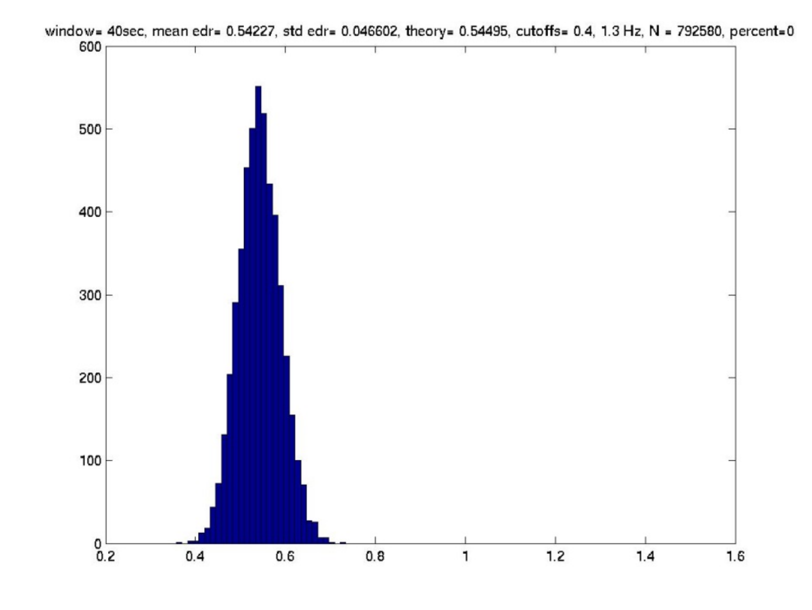
NCAR

Homogeneity and sample size statistics:
Histogram of $\varepsilon^{2/3}$ over 10 and 40 second intervals.

10 Second Windows



40 Second Windows

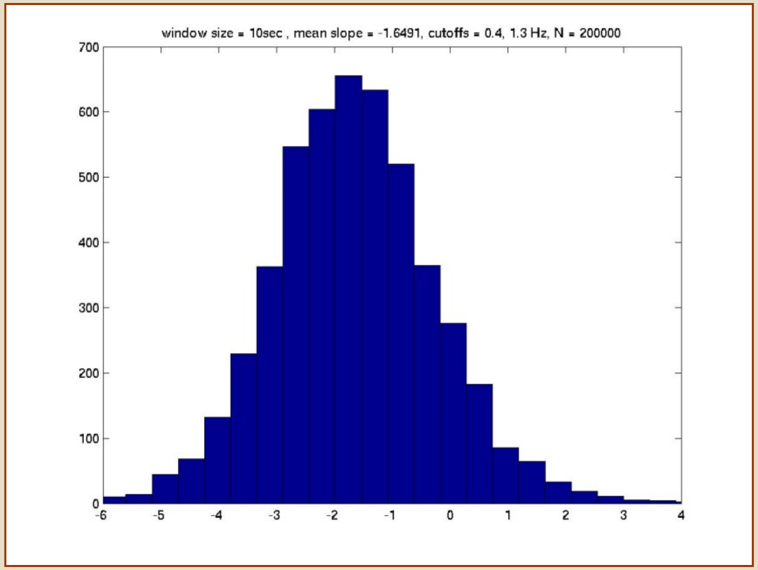


NCAR

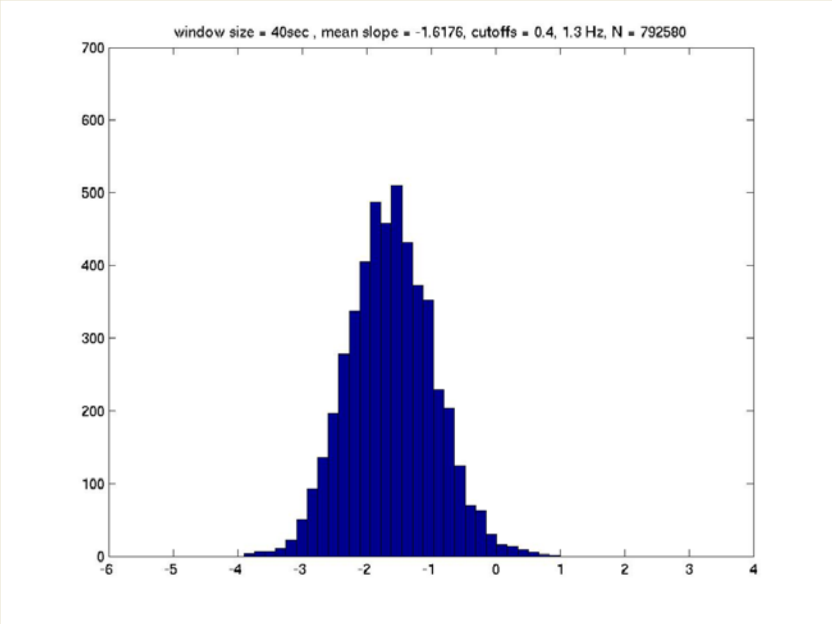
Kolomogorov energy spectrum: $E(k) = A\varepsilon^{2/3}k^{-5/3}$

Hence, the slope in log-log should be -5/3 – *on average*.

10 Second Windows

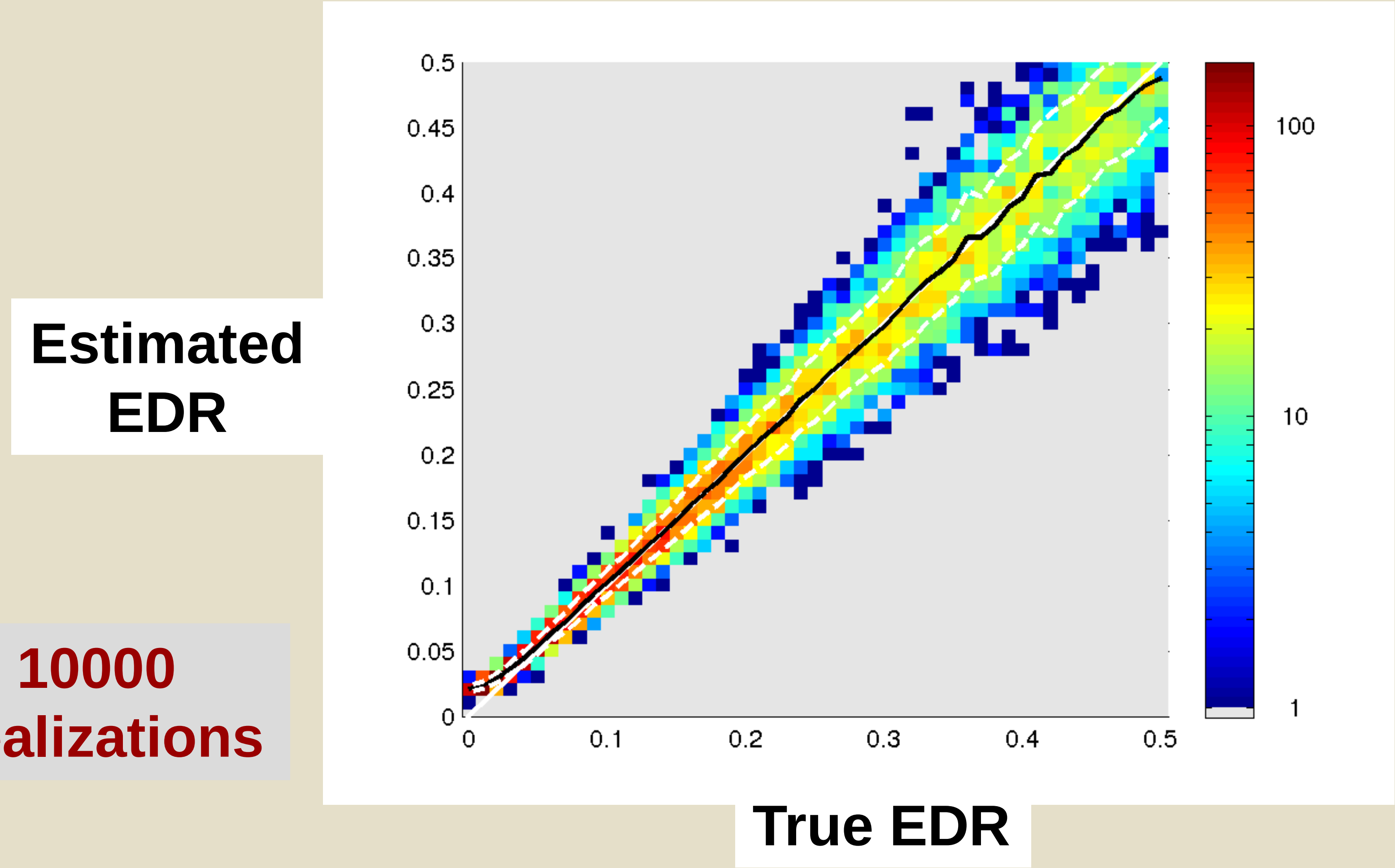


40 Second Windows



NCAR

Random Error is Proportional to Intensity Level



10000 Realizations

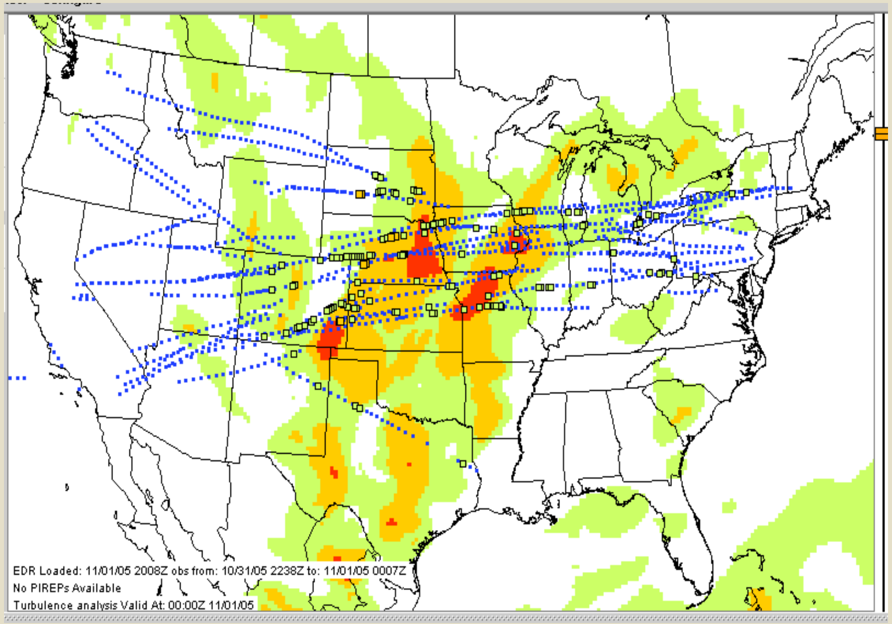
In Situ Turbulence Reporting System

- **Driver:**

  Augment/replace subjective PIREPs with objective state-of-the-atmosphere turbulence measurements.

- **Features:**

  - Atmospheric turbulence metric: energy dissipation rate (EDR).
  - ICAO and NextGen standard.
  - Can be converted into aircraft-dependent measure (RMS-g).
  - Position accuracy within 2-3 km vs average 50 km pireps.



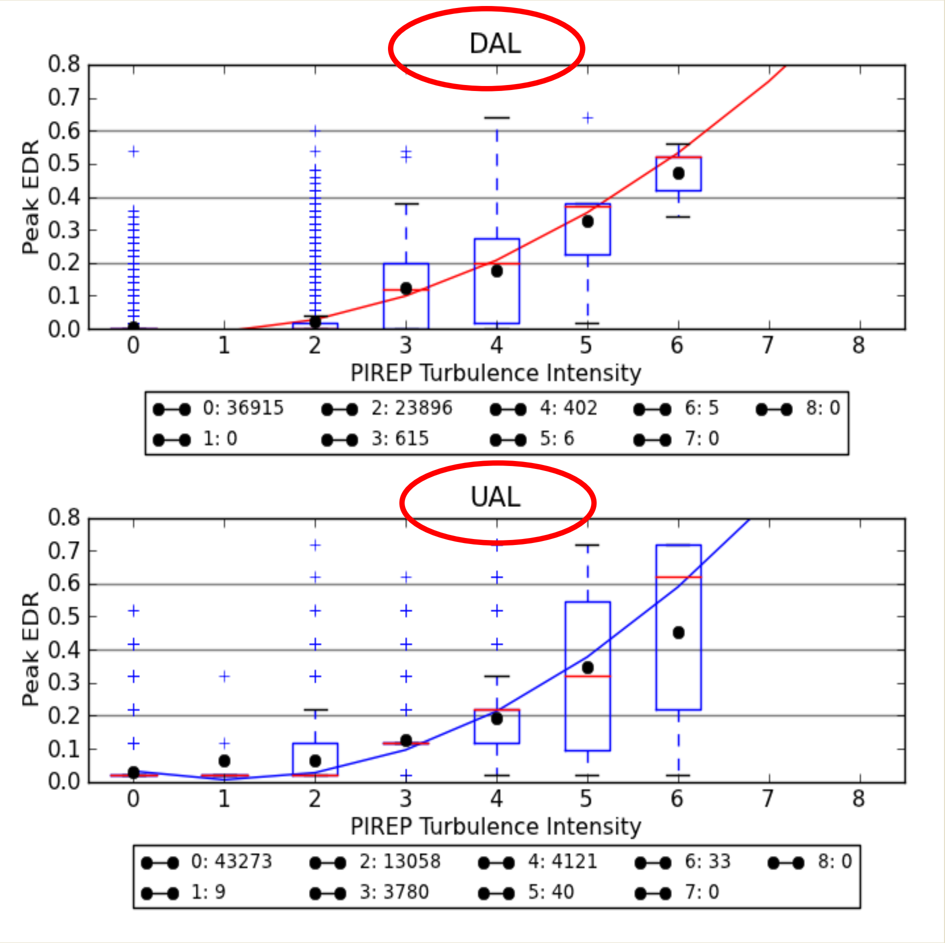
Experimental ADDS website

Current EDR Implementations

Implementer	Alg. Type	Airlines	Number
WSI/ATR	Vert. Accel.	AA & others	>500
FAA/NCAR	Vert. Wind	SWA & DAL	323
FAA/NCAR	Vert. Accel.	UAL	54
PAC	TAS	Regional	256

NCAR

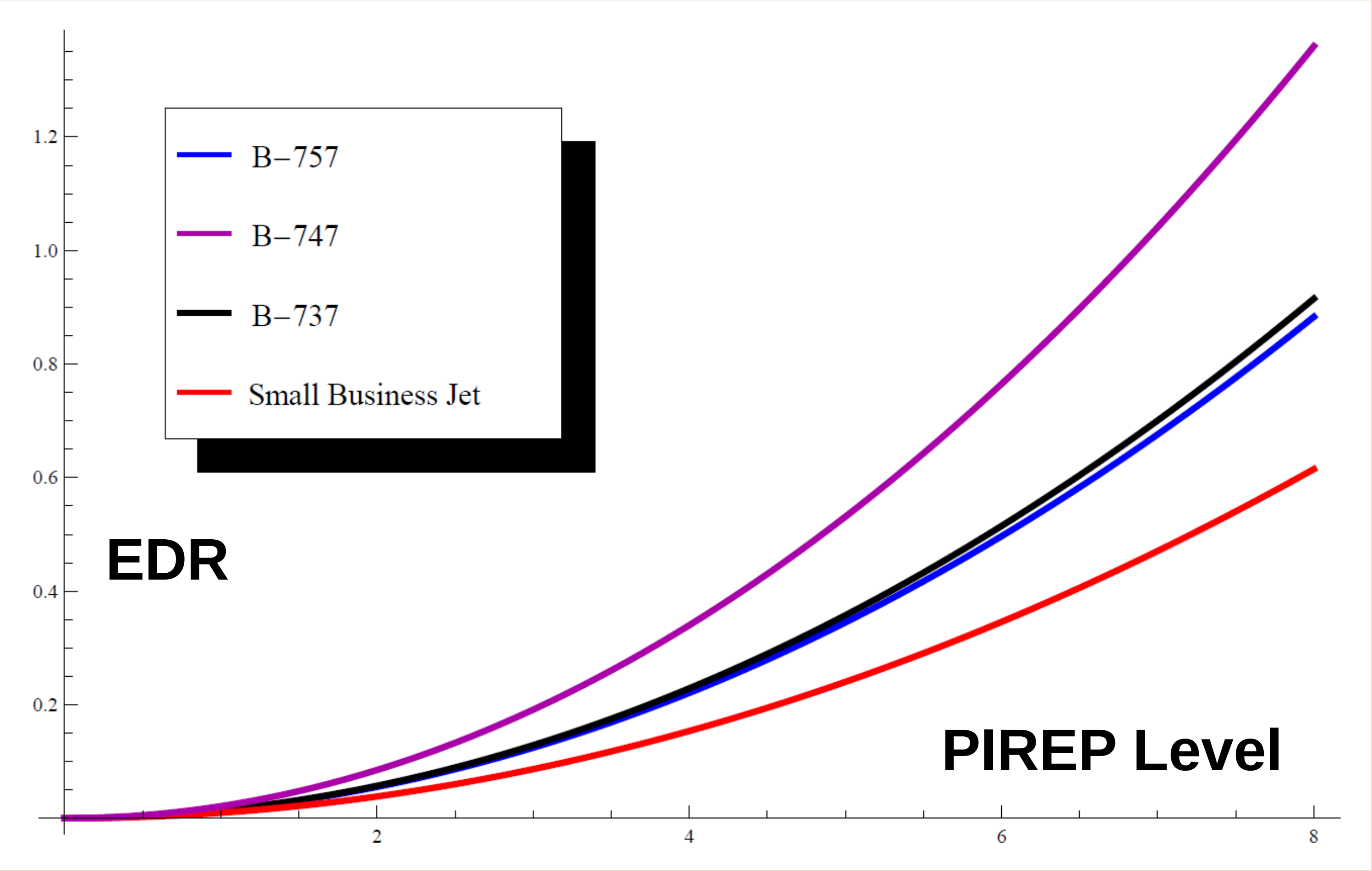
PIREP-EDR Comparisons



Goal: Mapping between Pirep levels (0-8) and EDR values.

Based on 60,000 UAL B-757 and 50,000 DAL B-737 Pirep/EDR matches.

Scaling Pirep-EDR Curves



NCAR

EDR *and* RMS-g, Not *either-or*

- EDR is a measure of the turbulent state of the atmosphere, i.e., aircraft independent.
- RMS-g is the response of a given aircraft – at a given flight condition – to the turbulence.

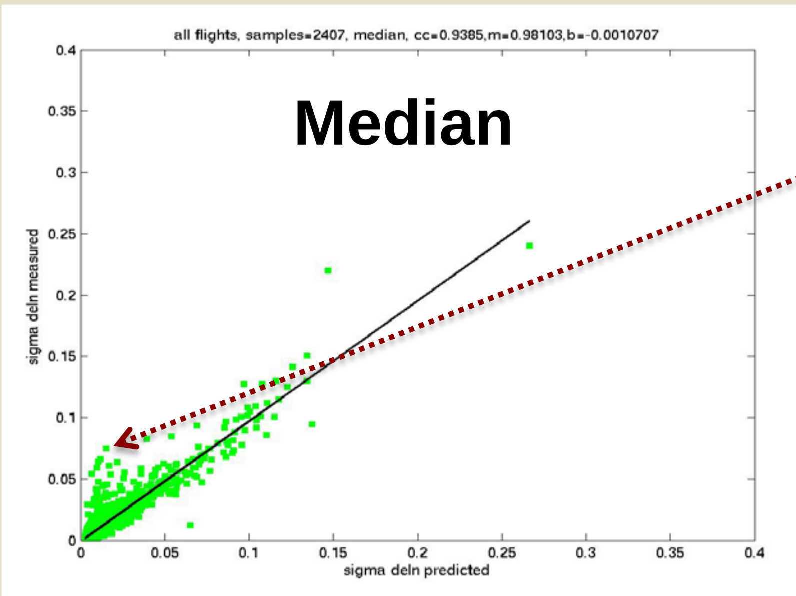
Both are valid quantities

- Given knowledge of aircraft type, airspeed, altitude and weight, EDR can be converted into RMS-g with reasonable accuracy.
- Recommendation: Use EDR as the reporting metric for air-ground, air-air, and ground-air
  - EDR populates the NextGen 4D data cube.
  - If a specific user wants RMS-g, convert EDR at their location.

NCAR

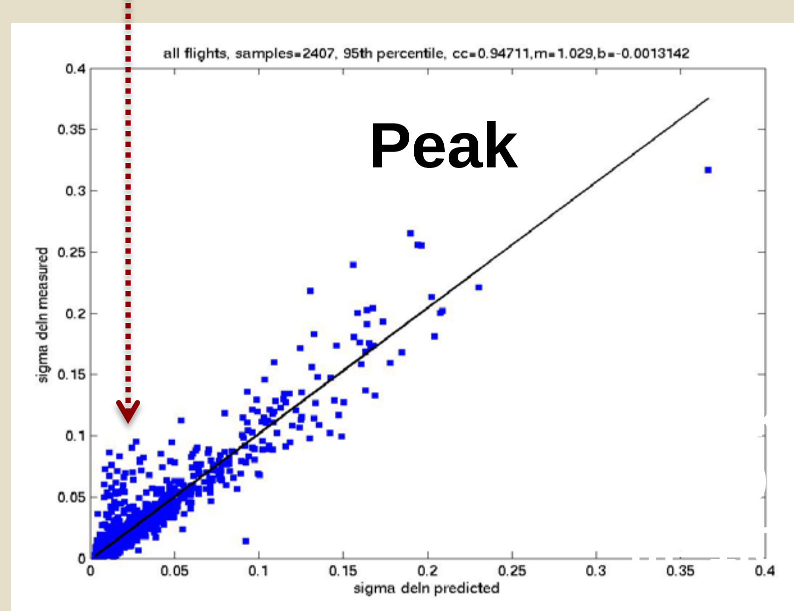
Conversion Between EDR and RMS-g: Illustrated with Data from NASA B-757 Aircraft

Measured RMS-g



EDR-calculated RMS-g

Maneuver Loads

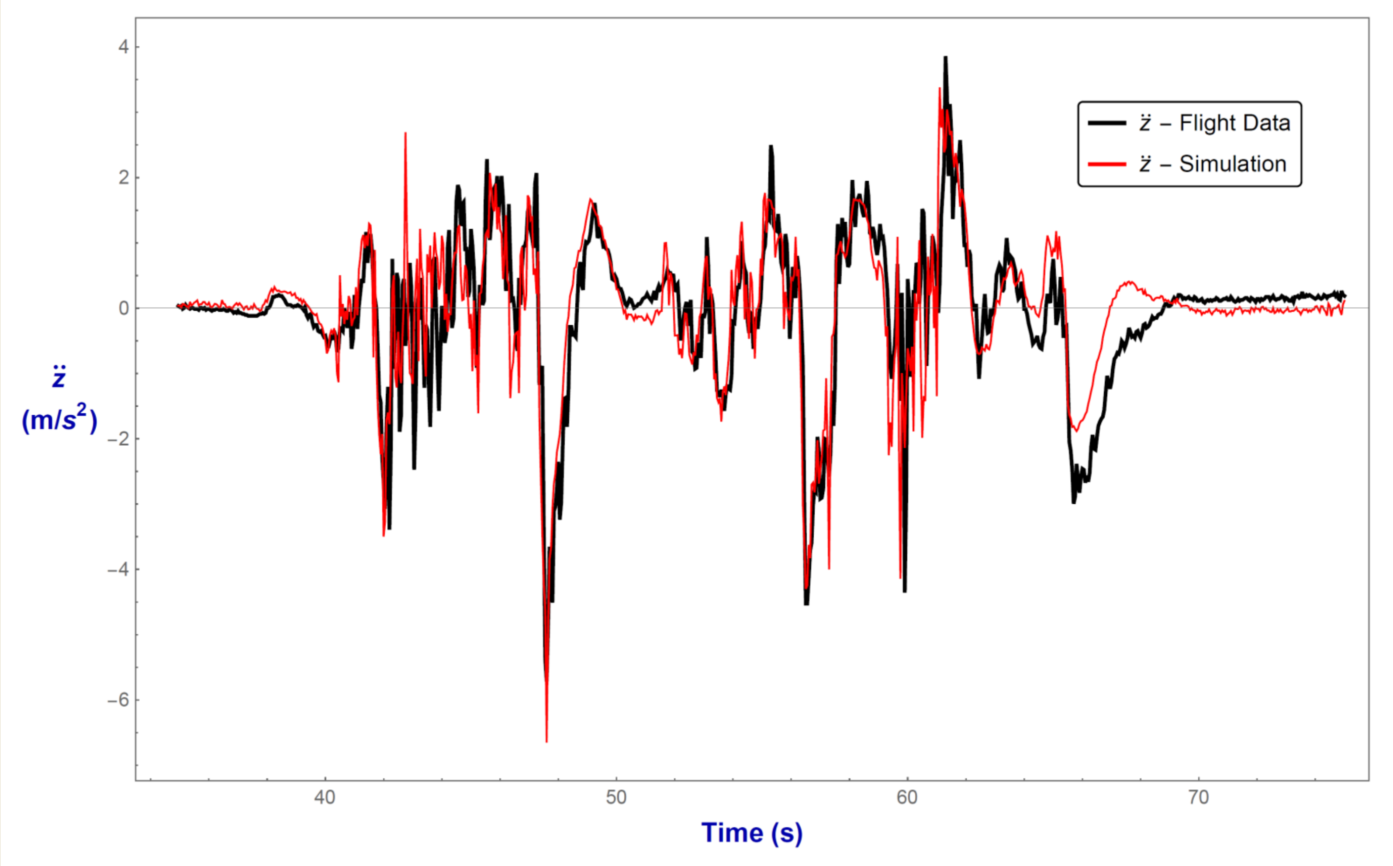


2407 one-minute samples

NCAR

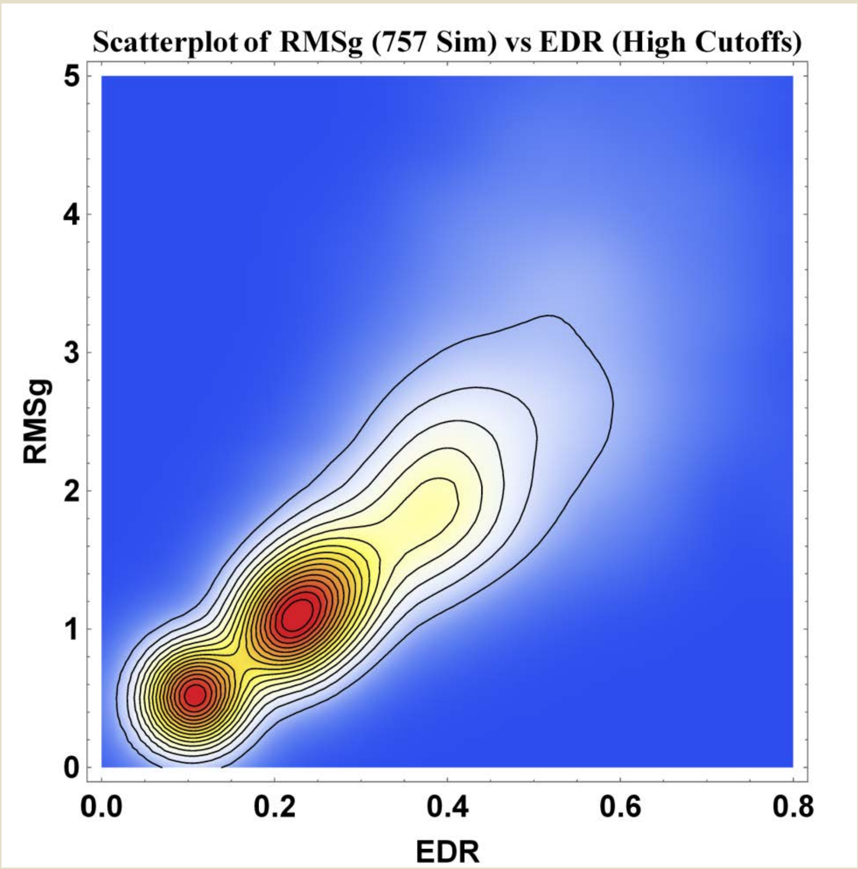
EDR vs. RMSg: 757 Simulation

Measured and simulated vertical accelerations:
20 Hz. NASA 757 flight data

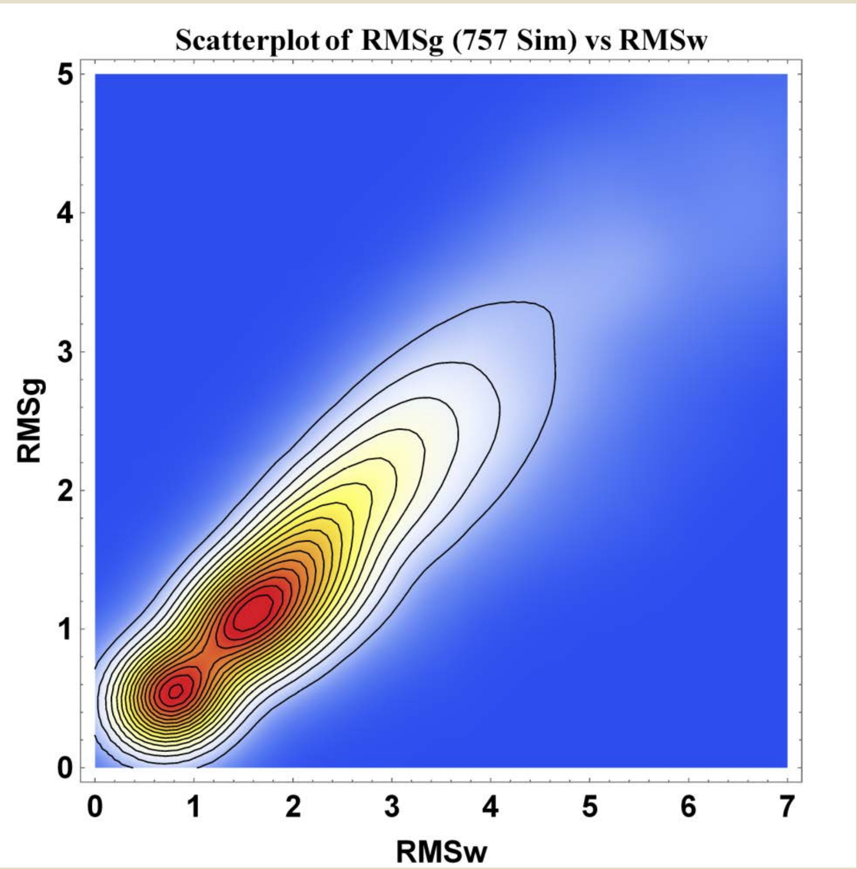


EDR vs. RMSg: 757 simulation. > 7500 10 sec. samples.
Weaker homogeneous and stronger inhomogeneous wind fields

RMSg vs. EDR



RMSg vs. RMSw



Statistical correlation is similar between EDR and RMSw

NCAR

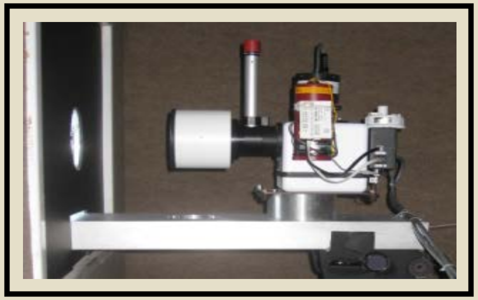
Remote Sensing of Turbulence: An Inverse Problem

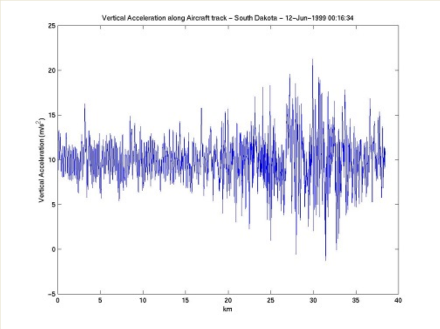
"Sensor as turbulence filter"

Input signal
(turbulence)

Sensor

Output signal
(sensor measurements)





<u>But, we want to go backwards</u>:

Given statistics of the sensor output – and a model of how the sensor "filters" the turbulence – estimate the statistics of the turbulence.

NCAR

Remote Sensing of Turbulence: A Primer

- Measuring turbulence with *active sensors* can be broken-down into two types of problems:
  - Backscatter. Transmitter and receiver are typically at the same place.
  - Propagation. Transmitter and receiver are on opposite sides of the sample volume.

Remote Sensing of Turbulence: A Primer

- Typical backscatter devices include: radars, lidars, and sodars.
  - Radars reflect microwaves (mm to m) off of hydrometeors (rain, snow, ice, etc.) and index of refraction fluctuations (typically, temperature or humidity variations). Ground-based and airborne.
  - Lidars reflect photons off of aerosols (micron-sized particulates). Ground-based and airborne.
  - Sodars reflect acoustic waves off of index of refraction fluctuations (typically, temperature variations). Ground-based.

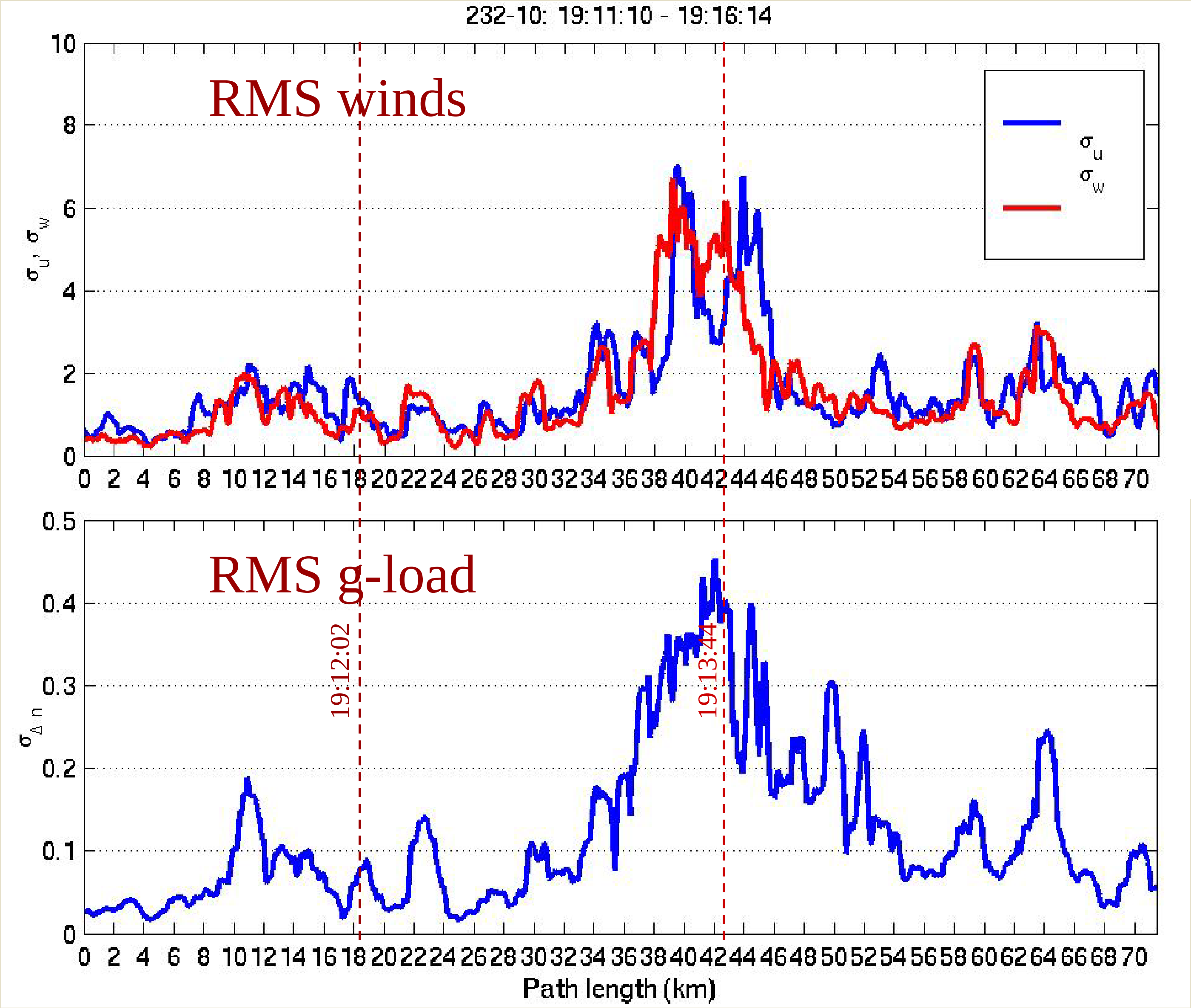
NCAR

Remote Sensing of Turbulence: A Primer

- Typical propagation measurements of turbulence are obtained by mm-m radio waves, optical and acoustic waves which are diffracted by temperature and/or humidity fluctuations in the index of refraction.

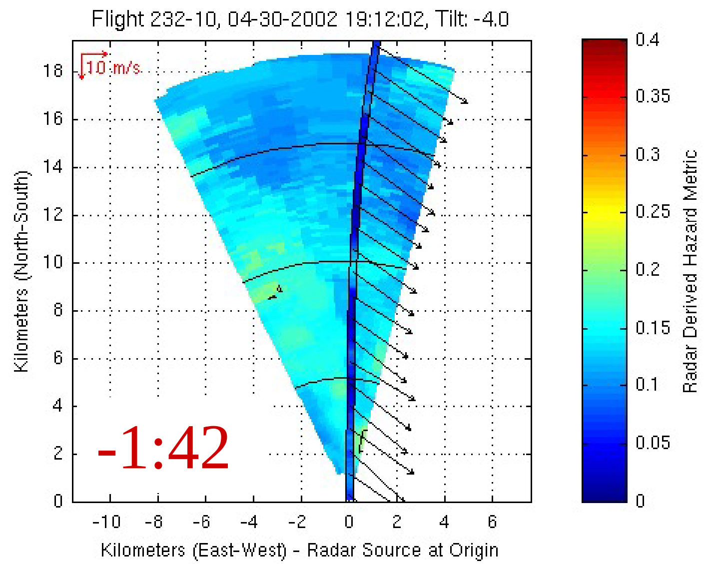
NCAR

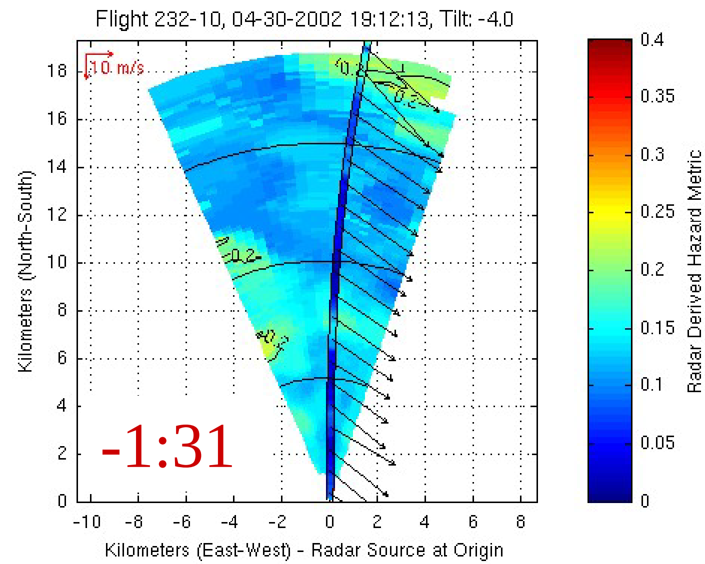
NASA Airborne Radar Detection of Turbulence

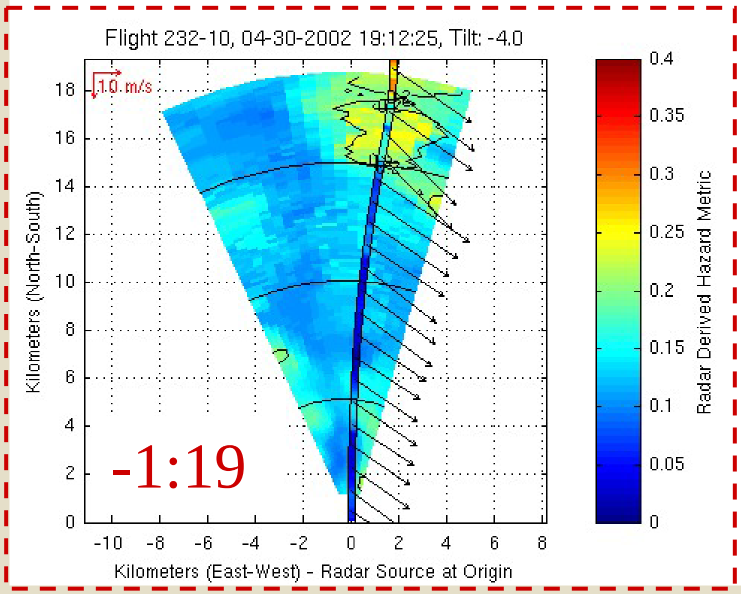


From NASA B-757 Aircraft

NCAR-Developed Turbulence Detection Algorithm: EDR converted into RMSg



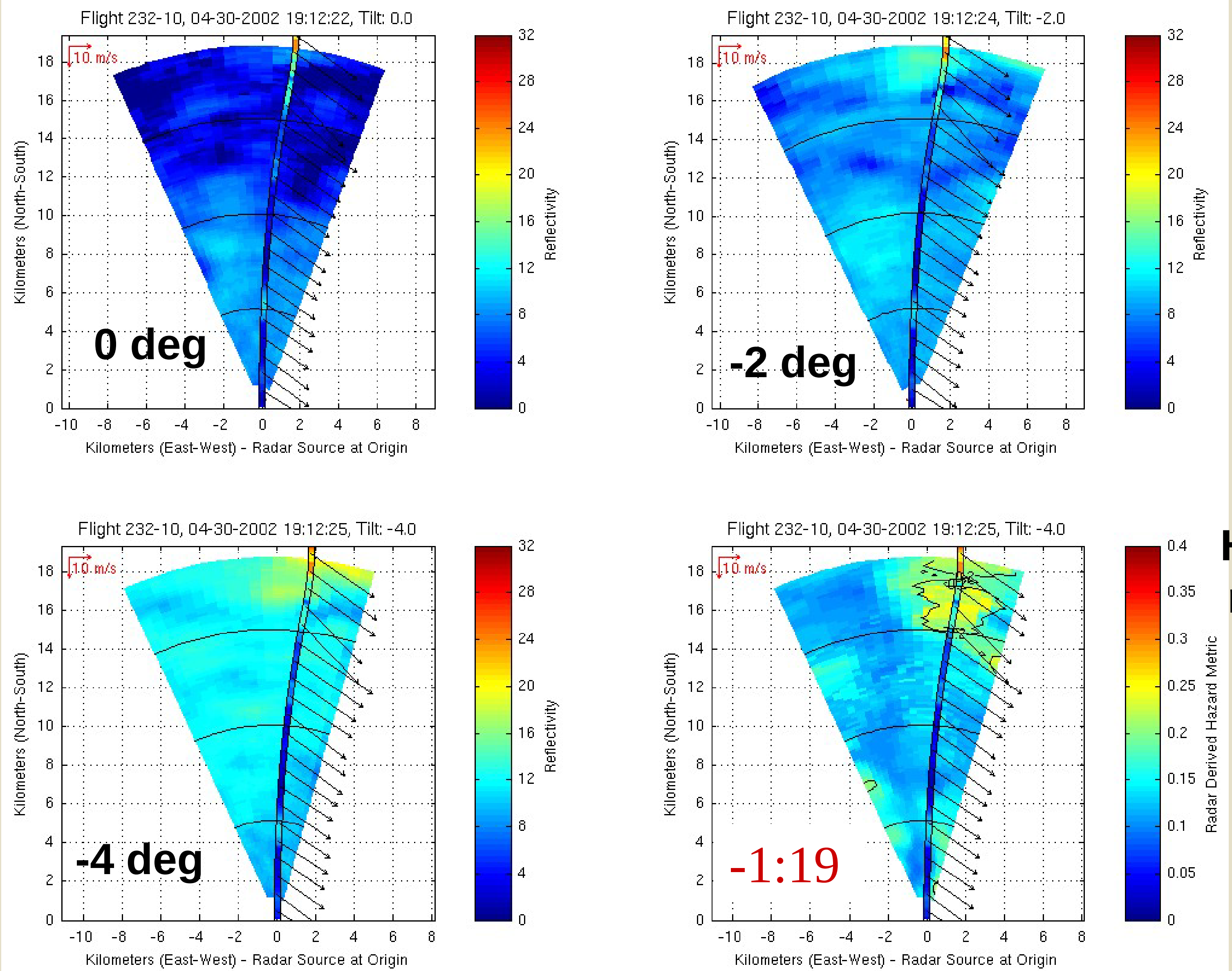




Hazard detected

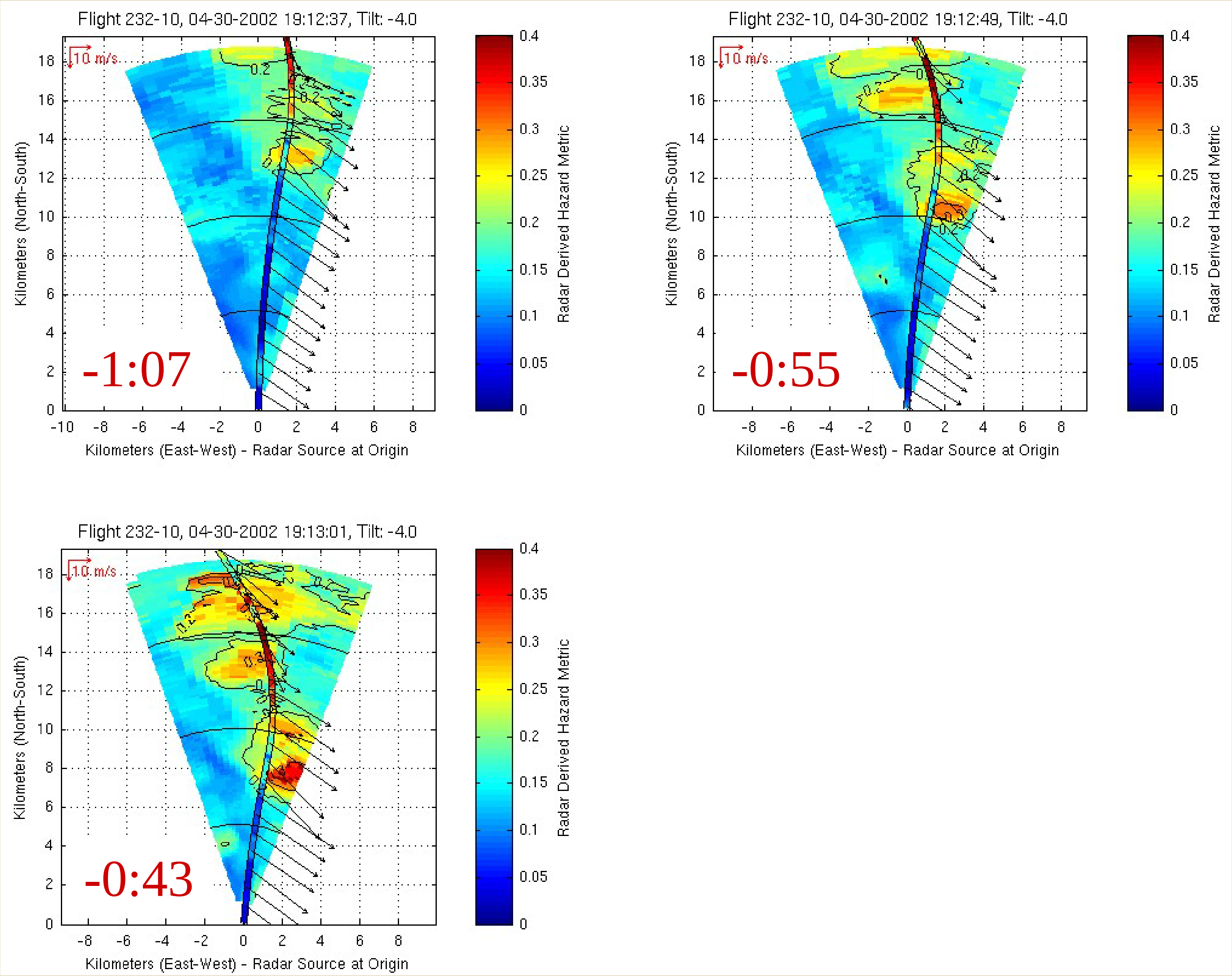
1:19, 18 km prior to encounter

Reflectivities (Note scale)

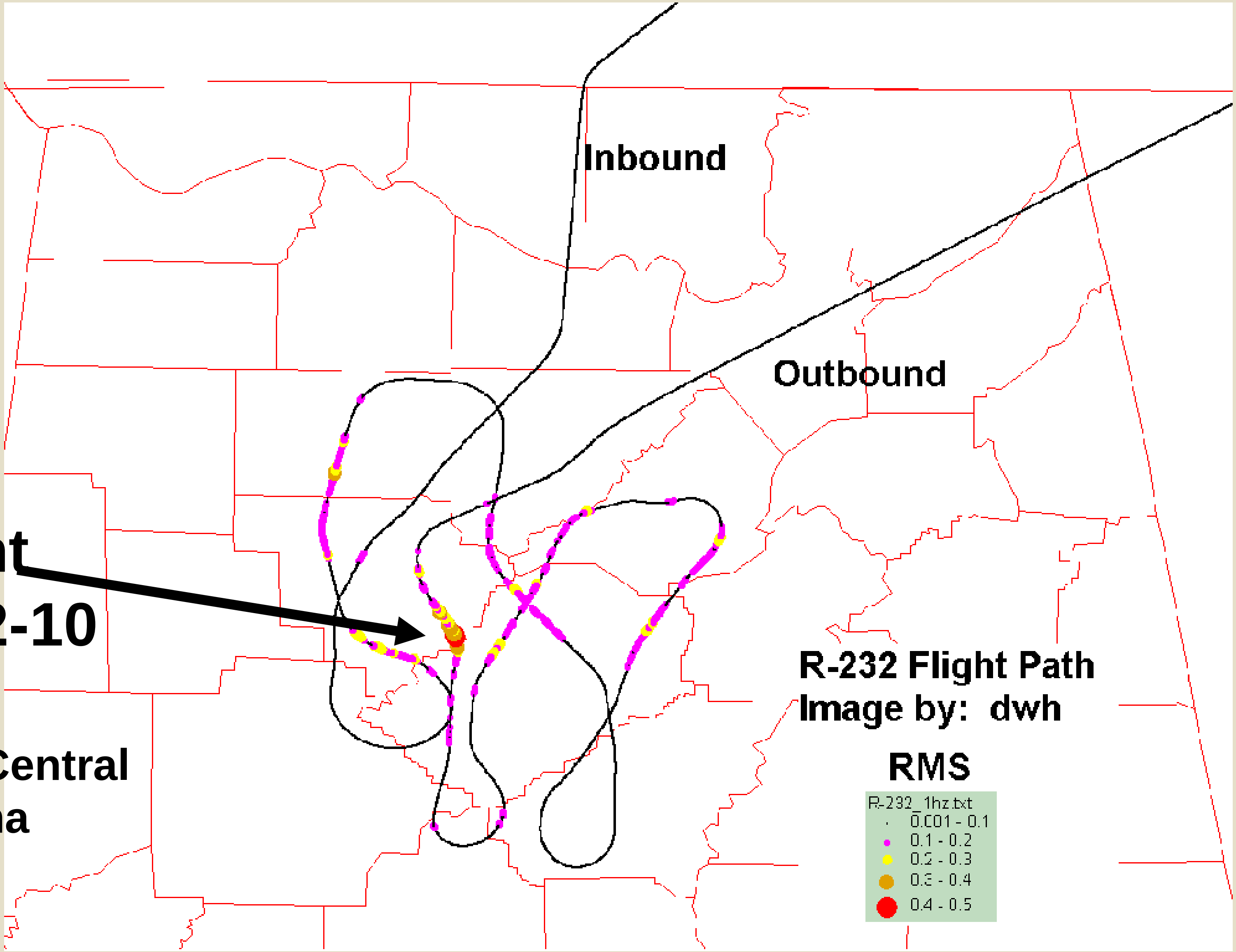


Hazard metric

Persistent detection



Flight Track for NASA flight R232



Event R232-10

North-Central Alabama

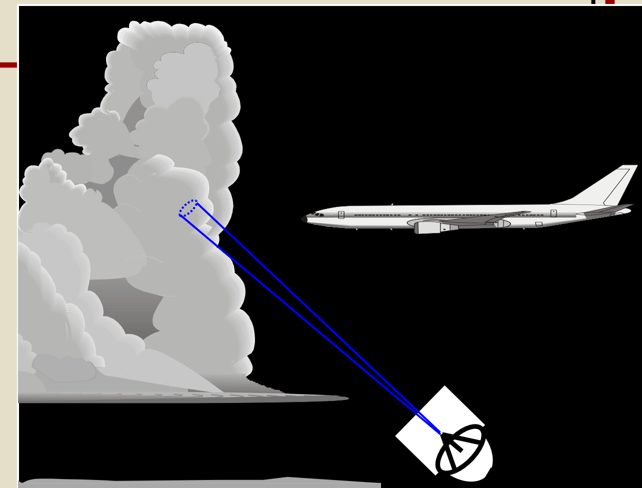
NCAR/NEXRAD Turbulence Detection Algorithm

Motivation

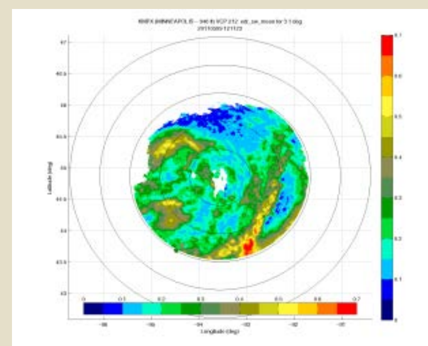
- Reflectivity (dBZ) is NOT a reliable indicator of turbulence location
- Convective turbulence can be small-scale and evolve quickly, making it difficult to predict
- Remote in-cloud EDR measurements are valuable for real-time hazard identification and for training and verifying turbulence inferences

Approach

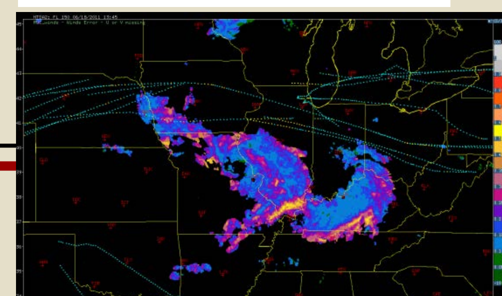
- Quality control the Doppler data and use spectrum width measurements to compute EDR for each sweep
- Merge data from multiple radars to create a 3-D “mosaic” of turbulence



Level 2
NEXRAD data



NTDA
(Radar by Radar)

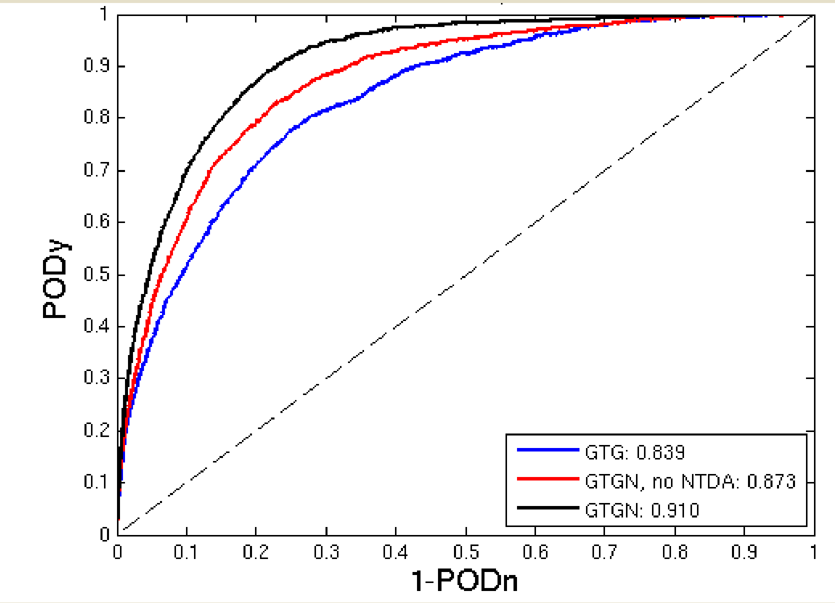


NTDA
Mosaic

NCAR

NTDA Status

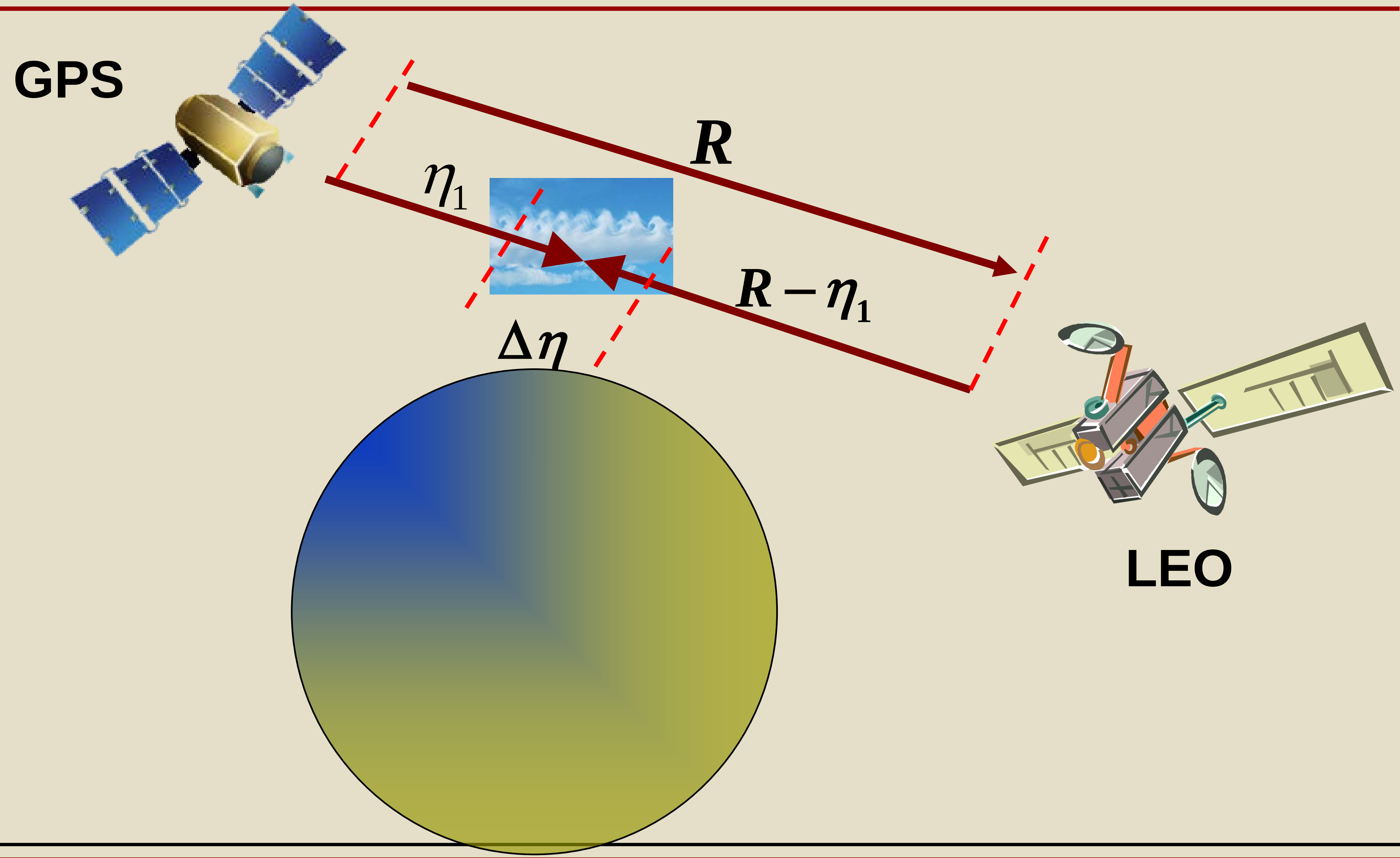
- NTDA modified for Gematronik radars and implemented in the Advanced Operational Aviation Weather System in Taiwan
- Processing and mosaic with 142 CONUS NEXRADs now runs at NCAR/RAL on a single server, producing 2 km x 3,000 ft in-cloud EDR grids every 5 minutes
  - Real-time NTDA mosaics also generated for Alaska, Hawaii and Puerto Rico
- "NTDA-enhanced GTG Nowcast" product to provide basis for planned cockpit turbulence alerts in FAA WTIC Tactical Turbulence project



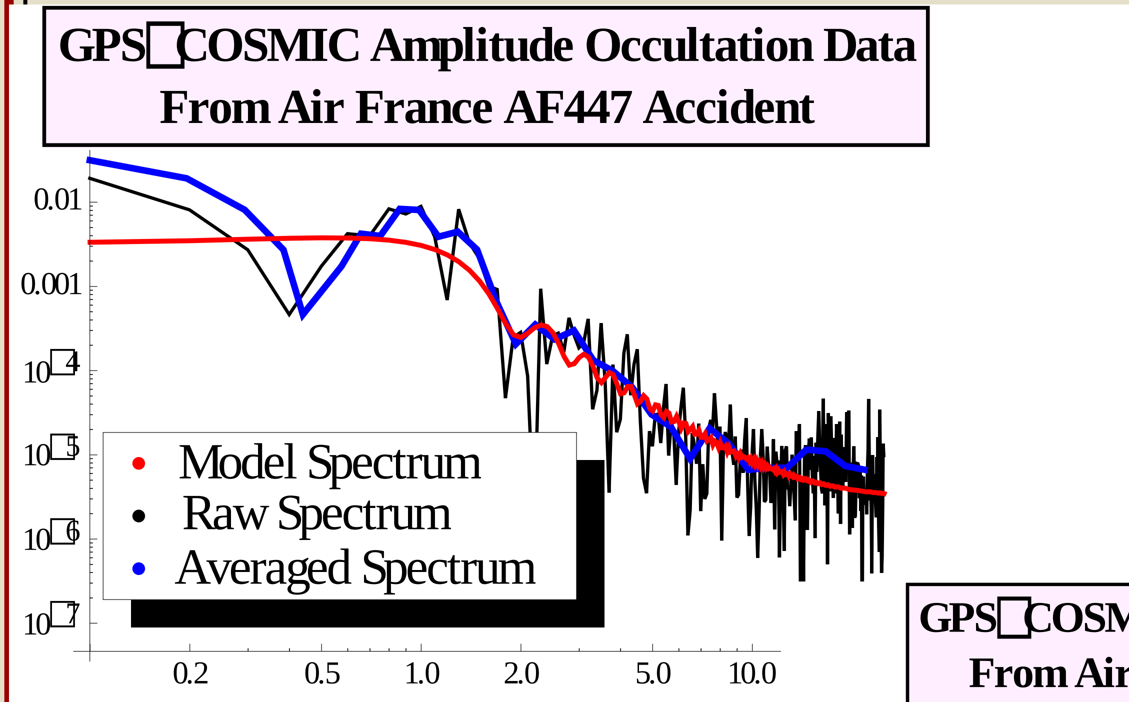
Incorporation of NTDA in GTG-Nowcast significantly improves product skill

NCAR

GPS-LEO Measurements of Turbulence

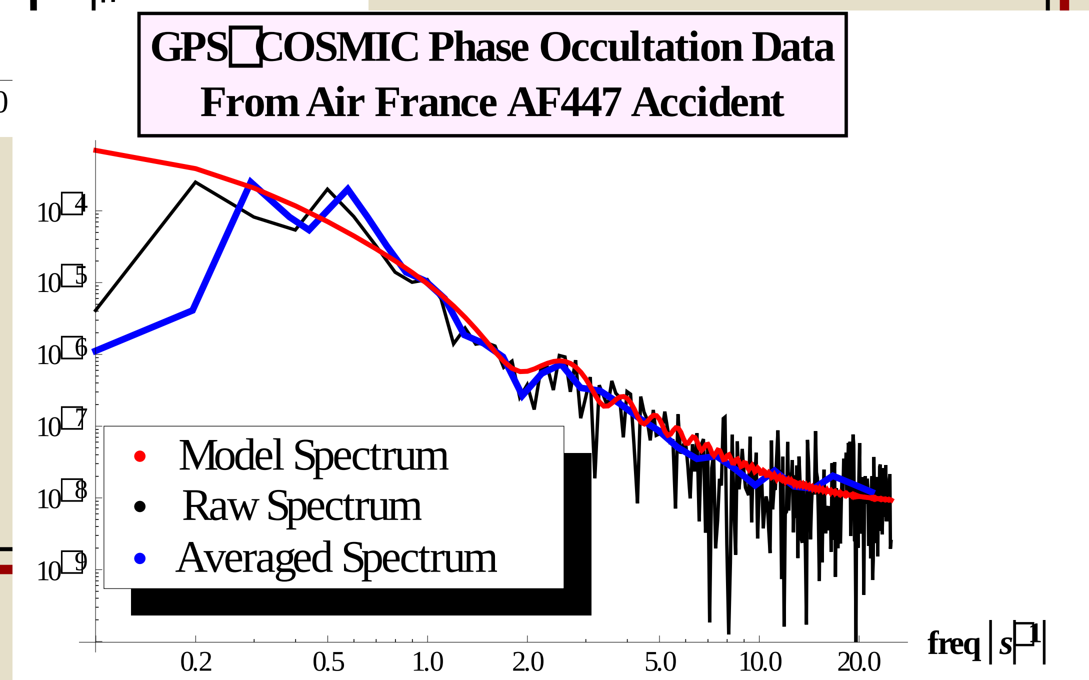


GPS Turbulence: Measurement vs. Theory



Amplitude

Phase



NCAR

Remote Sensing: Gap Analysis

- Turbulence can be such a variable (space & time) phenomena; hence, there will always be a measurement gap for tactical aviation purposes.
- This is due to:
  - Lack of all-weather sensors.
  - Economics of getting sensors onboard aircraft.
  - Limited range for many sensors.

NCAR

Gap Analysis, cont'd.

- So, what can we do in the near-term?
  - Downlink EDR from airborne Doppler radars.
  - Apply WSR-88D algorithm (NTDA) to TDWR radars.
  - Continue GPS (esp. airborne application) & IR studies.
  - More/better use of satellite information (esp. for future deployments).
  - Incentives for manufacturers/airlines to improve/employ technologies (economy of scale).

NCAR