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

Larry B. Cornman
National Center for Atmospheric Research
USA
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

Missing Something?
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

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

10’s km

cm

NWP resolution

Mesoscale model resolution

Fine-scale model resolution
The product of the response function and the wind spectrum gives the output spectrum.

**Von Karman Spectra**

Response Function for Transport Aircraft

2000 m 100 m
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.
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.
**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 topireps

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

Note: For pireps, time of pirep is in upper left corner in the format HHMM (GMT). Altitude is in lower left corner in 100s of feet.
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

Hazard detected

1:19, 18 km to encounter
Event 232-10 (reflectivities at 19:12:25)

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
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
```

```
RUC only
```

```
RUC+obs
```

NCAR
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.
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
Parameter Estimation

Maximum Likelihood (ML) estimation of intensity with fixed $R - \eta_1 = 100 \text{ km}$ while varying $L_0$. Horizontal and vertical lines are simulated (i.e., “true”) values.
Parameter Estimation (cont’d)

ML estimation of intensity with fixed $L_0 = 3 \text{ km}$ while varying $R - \eta_1$.
- 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.
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:

$$\langle H(0)H(\rho) \rangle = K \int_{L}^{\rho} \int_{L+\rho} \langle T(x)T(x') \rangle f(x)f(x') dx dx'$$
Assuming that standard turbulence theory applies, 
\[ \langle T(x)T(x') \rangle = C_T^2 g(x' - x), \]
where \( C_T^2 \) is the intensity parameter of the turbulent temperature field. In principle the turbulence intensity parameter is given by:

\[
C_T^2 = \frac{\langle H(0)H(\rho) \rangle}{K \int_{L}^{L+\rho} \int_{L}^{\rho} g(x' - x) f(x) f(x') dx dx'}
\]
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?
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
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

Intensity Discrimination

w/ Pireps

w/ In Situ
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
GTG-N Overview

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

Merges all current turbulence observations with forecast grids.

In situ EDR reports, PIREPs,

4D data cube updated every ~15 min

Cockpit display or alert (EDR or RMS-g)

Dispatch, ATC, etc.

GTG forecast grids (EDR)

Convective turbulence diagnostic (EDR)

Wx satellite data

Radar (NTDA) turbulence grids (EDR)

Graphic courtesy of virtualskies.arc.nasa.gov
GTG-N Example

GTG 1 hr forecast

DCIT

pireps

blend

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