Universal Atmospheric Hazard Criteria

In the context of the UFO project

Peter van der Geest

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• Why do we need a universal metric?
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The UFO project (Ultra Fast windsensOrs)

Addresses a wide range of new Lidar/Radar wind sensors for detecting/monitoring/alerting of atmospheric hazards:

• Wake vortices
• Wind shear
• Turbulence
Atmospheric Hazard Metrics

UFO sensors establish a 3D windfield (windcube) and need to extract the severity the various atmospheric hazards.

The various atmospheric hazards are defined by various specific metrics:

• **Wake vortex**
  • Circulation strength, induced rolling moment, roll disturbance, etc.

• **Wind shear**
  • F-Factor

• **Turbulence**
  • Induced loadfactor, standard deviation of turbulence velocities, Eddy Dissipation Rate, etc.
Why a Universal Metric?

UFO system requires consistent assessment of the various hazards:

• Specified thresholds, defining the severity of encounter (e.g. minor, major, hazardous, catastrophic)

Ideally we would like to have for each atmospheric hazard:

• One specific metric with following characteristics:
  • Good discriminative power (strong correlation between metric value and severity)
  • Aircraft independent
  • Meaningful
  • Computable (without need for access to proprietary data)
  • Absolute
Severity and probability

• **No safety effect** (P > 10^{-3})
  • No effect on safety, no impact on crew/ATC workload

• **Minor** (10^{-3} \geq P > 10^{-5})
  • Slight reduction in safety margins, well within crew/ATC capabilities, slight increase in crew/ATC workload

• **Major** (10^{-5} \geq P > 10^{-7})
  • Significant reduction in safety margins, significant increase in crew/ATC workload, crew efficiency impaired, discomfort/physical distress of passengers

• **Hazardous** (10^{-7} \geq P > 10^{-9})
  • Large reduction in safety margins or functional capabilities, excessive crew/ATC workload, small number of occupants possibly injured

• **Catastrophic** (P \leq 10^{-9})
  • Uncontrollable, fatal injuries, loss of aircraft
Wake vortex severity metrics

- Wake Vortex Circulation ($\Gamma$), [m$^2$/s]

- Induced Rolling Moment Coefficient ($C_l$), [-]

- Roll Control Ratio (RCR) $\frac{C_l}{C_l\delta_a \delta a_{max}}$, [-]

- Equivalent Roll Rate (ERR) $\frac{C_l}{C_{l_p}}$, [-]
Metrics evolution

Wake vortex encounter severity criteria are evolving from severity of initiating event (circulation strength) to more risk based metrics:

\[
\text{Risk} = \text{Hazard} \times \text{Probability}
\]
Circulation Strength

Easy to compute, less meaningful, not absolute, and aircraft dependent:

Same circulation strength may cause different induced rolling moment, depending on characteristics of generator aircraft
Rolling Moment Coefficient based metrics

\[ IRM = \frac{1}{S_b} \int_{-b/2}^{b/2} c_{eff}(y) C_{Lo} \Delta \alpha_{wv}(y) y dy \]

\[ RCR = \frac{IRM}{C_{l_{\delta a}} \delta_{\alpha_{max}}} \]

\[ ERR = \frac{\int_{-b/2}^{b/2} c_{eff}(y) \Delta \alpha_{wv}(y) y dy}{2 \int_{-b/2}^{b/2} c_{eff}(y) \frac{y^2}{b} dy} \]

Provided by UFO sensors

Aircraft dependent aerodynamic parameter

Only aircraft geometric parameters
Maximum ERR @ ICAO separation

Maximum ERR at minimum ICAO WV separation (61 A/C types) (RECAT-1 decay)

Equivalent Roll Rate [deg]

Span [ft]

Light
Medium
Heavy
Super

L/M
M/H
H/S

Light
Medium
Heavy
Super
Impact on Maximum ERR due to RECAT1

Maximum ERR at minimum RECAT1 WV separation

- Cat. F
- Cat. E
- Cat. D
- Cat. C
- Cat. B
- Cat. A

Equivalent Roll Rate [deg]

Span [ft]

ICAO
RECAT
Probability of encounter

Probability of encounter ERR = 4.5 deg is estimated as:

\[ P_{\text{encounter}} = P_{\text{calm}} \times P_{\text{worst}} \times P_{\text{exposure}} \times P_{\text{duration}} = 10^{-5} / \text{flight hour} \]

Thus:

\[ ERR = 4.5 \text{ deg constitutes minor/major boundary} \]
Proposed ERR severity thresholds

Based on correlation with RCR and available literature:

• No safety effect: \( \text{ERR} \leq 1.5 \text{ deg} \)
• Minor encounter: \( 1.5 \text{ deg} < \text{ERR} \leq 4.5 \text{ deg} \)
• Major encounter: \( 4.5 \text{ deg} < \text{ERR} \leq 6.0 \text{ deg} \)
• Hazardous encounter: \( 6.0 \text{ deg} < \text{ERR} \leq 7.5 \text{ deg} \)
• Catastrophic encounter: \( \text{ERR} > 7.5 \text{ deg} \)

To be further validated by planned simulator investigation (Eurocontrol)
Wind shear

Wind shear severity metric (F-factor):

\[ F = \left( \frac{\dot{w}_x}{g} - \frac{w_z}{V} \right) \]

Where: \( \dot{w}_x \) change in horizontal wind velocity

\( w_z \) vertical wind velocity
TSO C-117 alerting boundaries

- Must ALERT
- May ALERT
- Must NOT ALERT

- 20 kt windspeed change
- Wind gradient 2 kt/s
- Wind gradient 0.78 kt/s

Exposure Time (sec)

Avg. Factor (-)
Proposed wind shear severity thresholds

Exposure Time (sec)

Factor (-)

Catastrophic
Hazardous
Major
Minor
No safety effect

M u s t  A L E R T

Must NOT A L E R T

2 kt/s
1.4 kt/s
0.78 kt/s
30 kt speed loss
20 kt speed loss
7 kt speed loss
3 kt/s
236x150
240x100
244x152
Turbulence intensity is determined in terms of Eddy Dissipation Rate (EDR), as laid down in ICAO Annex 3.

EDR is strongly correlated with the Total Kinetic Energy and therefore a metric for turbulence intensity

ICAO Annex 3:
- Severe turbulence : $EDR > 0.7$
- Moderate turbulence : $0.4 < EDR \leq 0.7$
- Light turbulence : $0.1 < EDR \leq 0.4$
- Nil turbulence : $EDR \leq 0.1$

 Applies to medium-sized transport aircraft, en-route
## Turbulence intensity vs. Encounter severity

<table>
<thead>
<tr>
<th>Turbulence Intensity</th>
<th>Encounter severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nil</td>
<td>No safety effect</td>
</tr>
<tr>
<td>Light</td>
<td>Minor</td>
</tr>
<tr>
<td>Moderate</td>
<td>Major</td>
</tr>
<tr>
<td>Severe</td>
<td>Hazardous</td>
</tr>
<tr>
<td>Extreme</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>
Turbulence Auto PIREP System (US)

relation in situ EDR and Pilot reported turbulence intensity

Peak EDR [m$^{2/3}$/s]

ICAO Annex 3, Severe

ICAO Annex 3, Moderate

ICAO Annex 3, Light

PIREP, Severe

PIREP, Moderate

PIREP, Light

PIREP Turbulence intensity scale
Aircraft dependency

PIREP Turbulence intensity scale

- Boeing 737
- Boeing 747
- Small Businessjet

Peak EDR \([m^{2/3}/s]\) vs. PIREP Turbulence intensity scale
Aircraft dependency

Current research indicates that turbulence encounter severity scales with the aircraft short period frequency.

Short period frequency:

\[ \omega_{sp} = \sqrt{-\frac{C_{m\alpha} g}{C_L k_y \bar{c}}} \]

**A/C chord c is the dominant parameter**

Generalised EDR:

\[ GEDR = EDR \sqrt{\frac{1}{\bar{c}}} \quad [m^{1/6}s^{-1}] \]
GEDR and Turbulence Intensity

Relation Generalised EDR and Pilot reported turbulence intensity

- Boeing 737
- Boeing 747
- Small Businessjet
### Proposed turbulence encounter severity

<table>
<thead>
<tr>
<th></th>
<th>En-route</th>
<th>Approach phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>No safety effect:</td>
<td>GEDR &lt; .03</td>
<td>GEDR &lt; .02</td>
</tr>
<tr>
<td>Minor:</td>
<td>.03 ≤ GEDR &lt; .12</td>
<td>.02 ≤ GEDR &lt; .08</td>
</tr>
<tr>
<td>Major:</td>
<td>.12 ≤ GEDR &lt; .26</td>
<td>.08 ≤ GEDR &lt; .17</td>
</tr>
<tr>
<td>Hazardous:</td>
<td>.26 ≤ GEDR &lt; .46</td>
<td>.17 ≤ GEDR &lt; .31</td>
</tr>
<tr>
<td>Catastrophic:</td>
<td>EDR ≥ .46</td>
<td>EDR ≥ .31</td>
</tr>
</tbody>
</table>
Conclusions

• Metrics to assess atmospheric hazards have been proposed:
  • Equivalent Roll Rate for Wake Vortex encounters
  • F-Factor for Wind Shear
  • Generalised EDR for Turbulence intensity

• Severity thresholds have been defined for each metric

• The proposed metrics are aircraft independent and require only aircraft geometric data for their calculation

• The proposed metrics can be used in the UFO sensor system to monitor and alert for various atmospheric hazards in a consistent way.

• More background in UFO deliverable D50.1 Part C, Universal Atmospheric Hazard Criteria