A Status Report on Turbulence Warning Technology

Rod Bogue - NASA Dryden Flight Research Center

October 24, 2001

Briefing Outline

- The Turbulence Hazard
  - Sources of Turbulence
  - Accident Statistics
  - Accident/Injury Characteristics
  - Cabin Accelerations
  - Costs
- Turbulence Issues
- Approach to Risk/Injury Reduction
  - Cabin Procedures/Training - Cabin Design
  - Warnings
- Warning Issues
  - Existing Warnings
  - Advanced Time

Briefing Outline (cont.)

- **Remote Warning Technology**
  - **General Principles/Operating Concept**
  - **Radar**
    - **Hardware/Testbed Aircraft**
    - **Operating Parameters**
    - **Warning Display**
    - **Flight Test Summary**
  - **Lidar**
    - **Hardware/Testbed Aircraft**
    - **Operating Parameters**
    - **Flight Test Display**
    - **Flight Test Summary**
- **Warning Technology Summary**

Sources of Turbulence

- **Natural Turbulence**

Convective Induced


Mountain-wave Induced

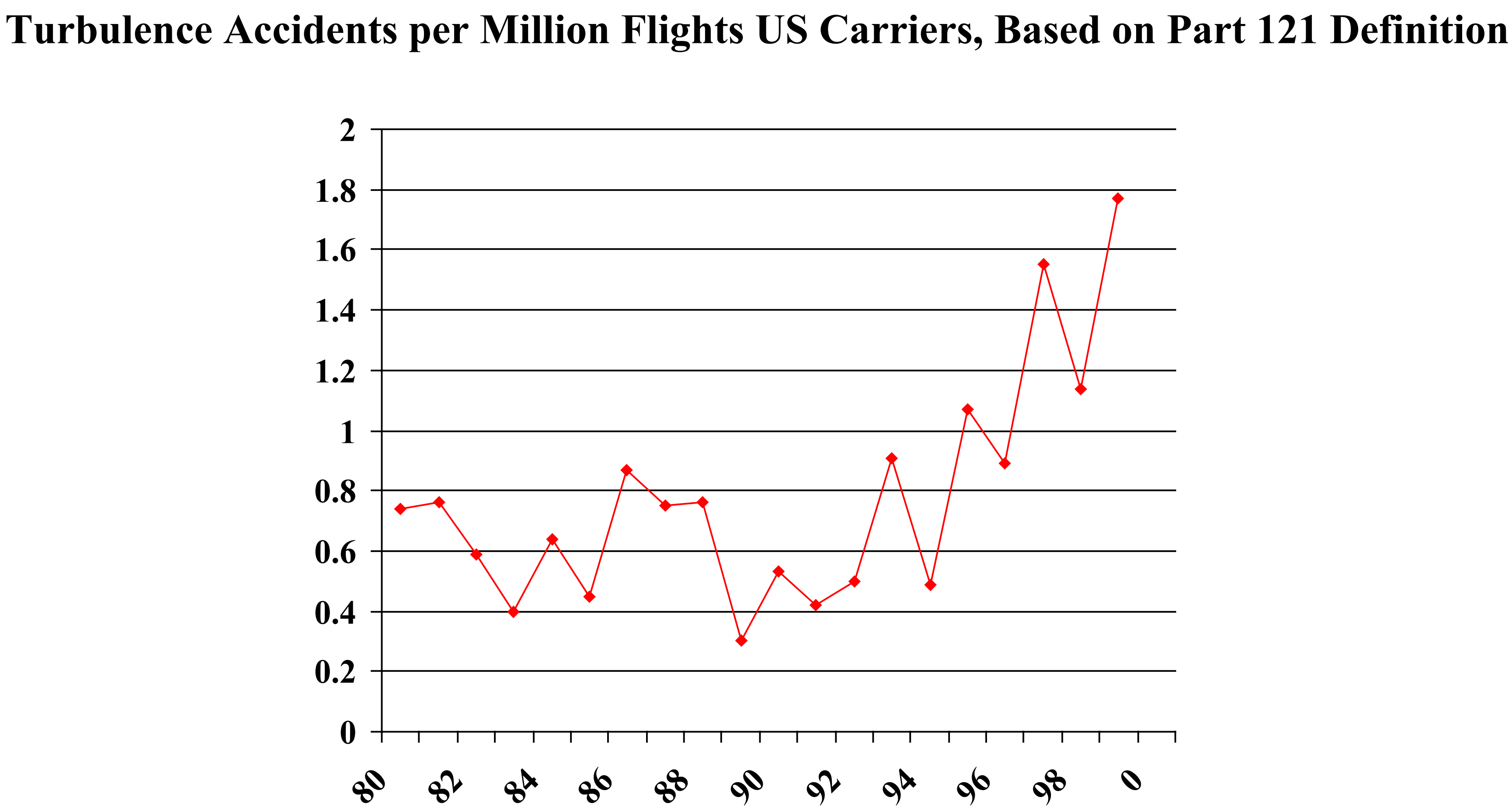

Jet-stream Induced

- **Man-Made Turbulence**

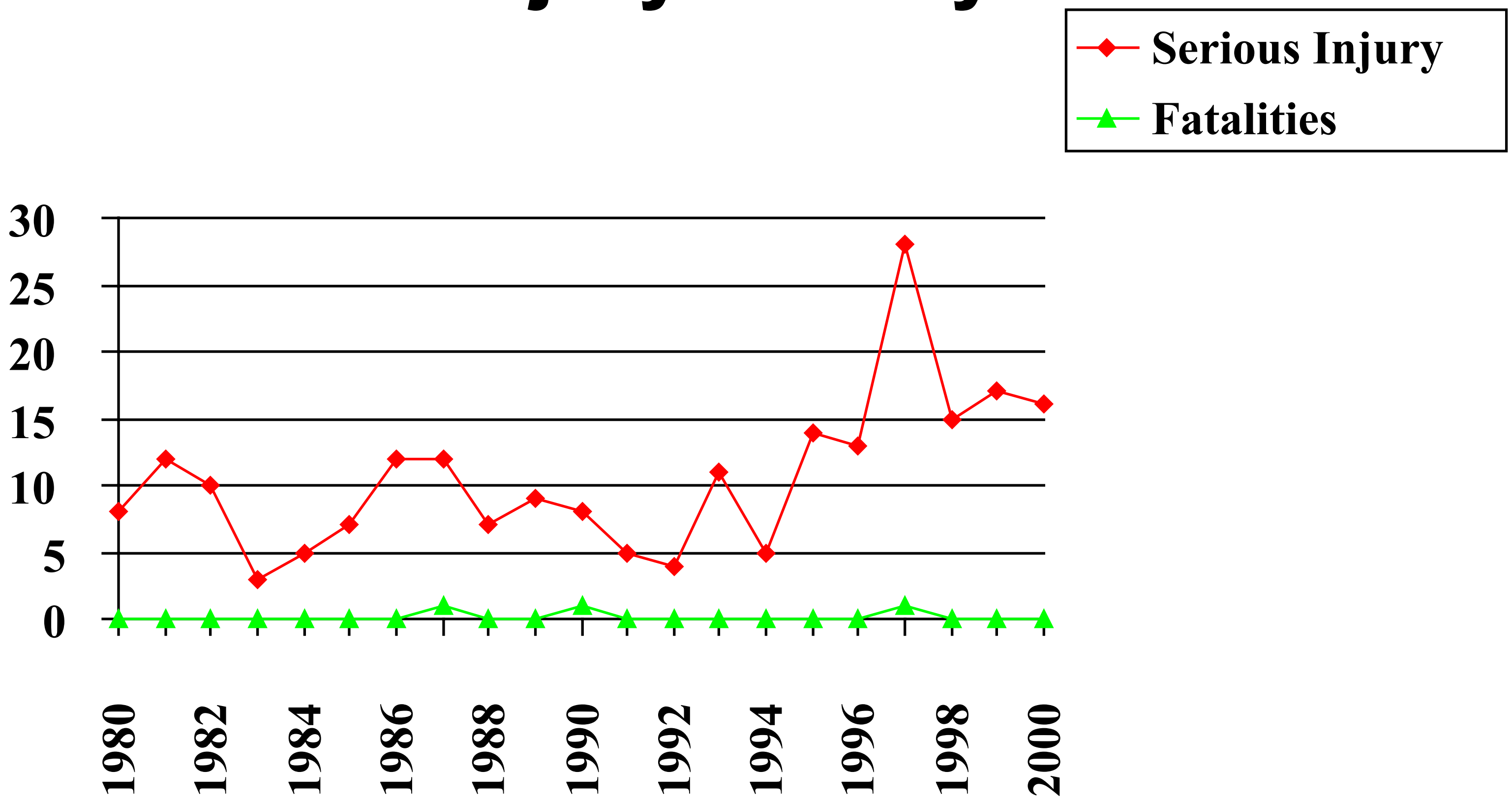


Enroute Wake Vortex

Turbulence Accident Trends



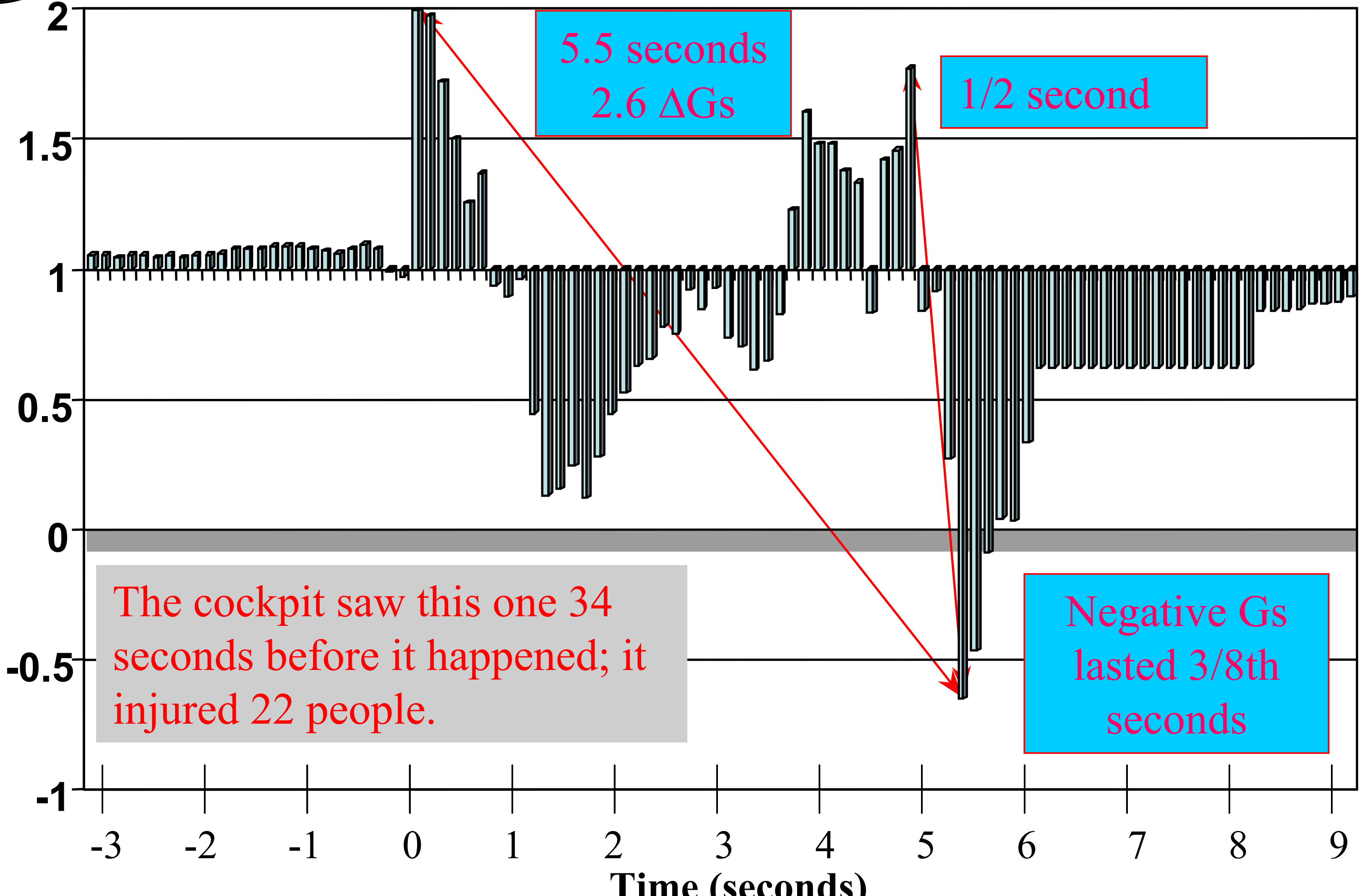
Serious/Fatal Turbulence Injury History



Aspects of Turbulence Accidents/Incidents

- **Few commercial aviation fatalities (1 each 1987, 1990, 1997)**
- **Many serious Flight Attendant and Passenger injuries and numbers growing**
  - Average 6-7 accidents and 8 serious injuries per year, 1980 to 1995
  - Sudden rise, 1995-2000 to 12 accidents and 16 serious injuries per year
  - 70 minor injuries for every serious injury (est.)
- **Negligible aircraft damage and hull loss**
- **Numerous shallow but few data-rich accident/incidents**
- **Successful avoidance or mitigation of turbulence is heavily dependent upon information that is often:**
  - Unavailable,
  - Inaccurate, or
  - Unreliable

Example of Severe Turbulence Encounter Cabin Acceleration



Turbulence Costs

(Difficult to quantify)

- **One Airline's Experience**

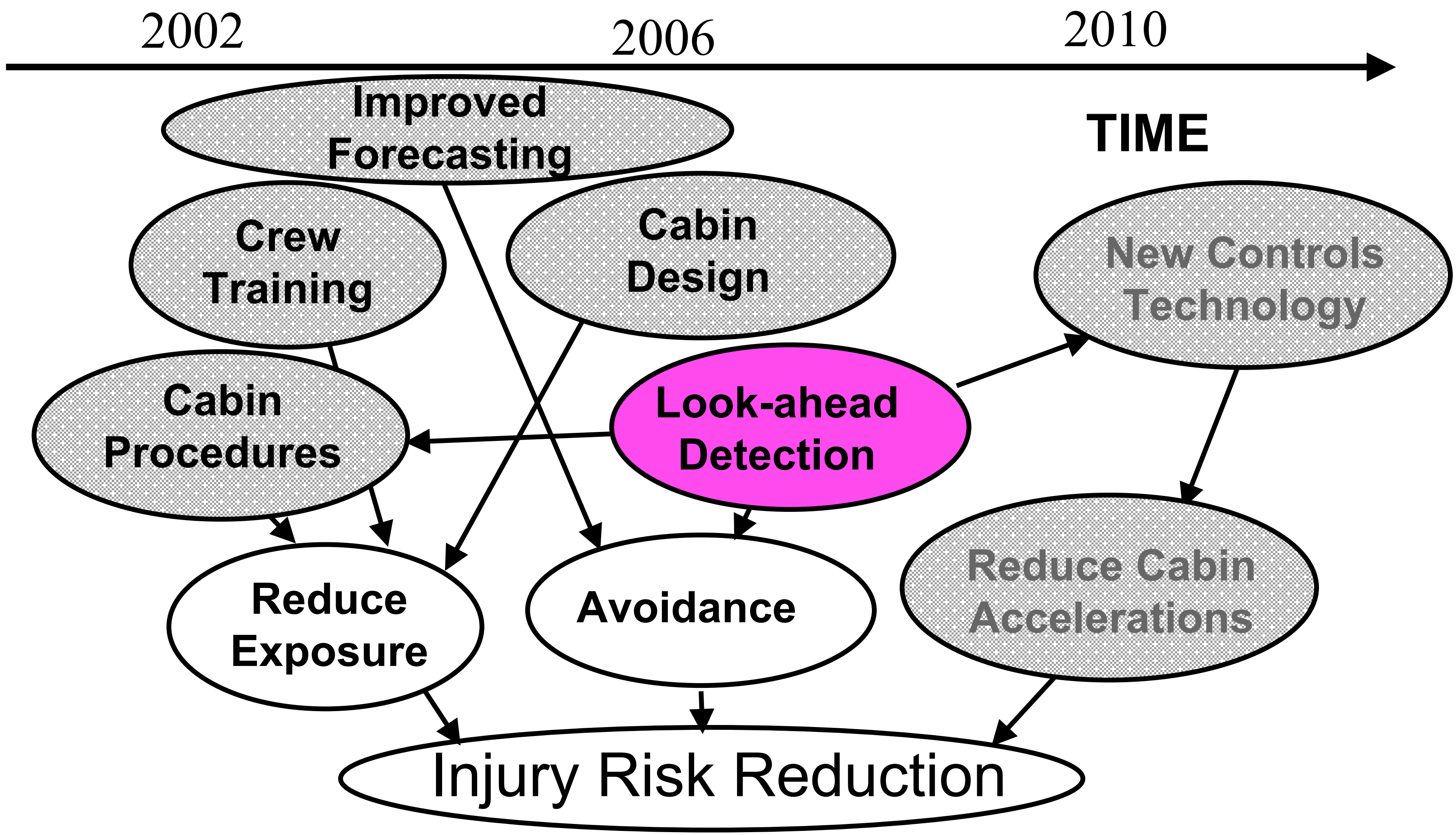
  "…on an annual basis it (AA's turbulence costs) is in the double-digit millions of dollars….last year we had 235 workers compensation claims related to turbulence encounters; those claims resulted in some 7,000 days of injury-related disability or lost time…the equivalent of 21 work-years at American alone."

  – **Robert Baker, VP Operations, American Airlines.**
- **50% of injuries are to Flight Attendants**
  - **Average 10,000 lost workdays/year through 1994**
  - **Average 15,000 lost workdays/year since 1994**
  - **For each injury, 11 workdays lost (est.)**
- **Estimated >$ 100M yearly**
- **<u>One carrier</u> averages 9 turbulence encounters resulting in 24 injuries per month**
- **Leading cause of in-flight injuries**
- **Major contributor to passenger's fear of flying**

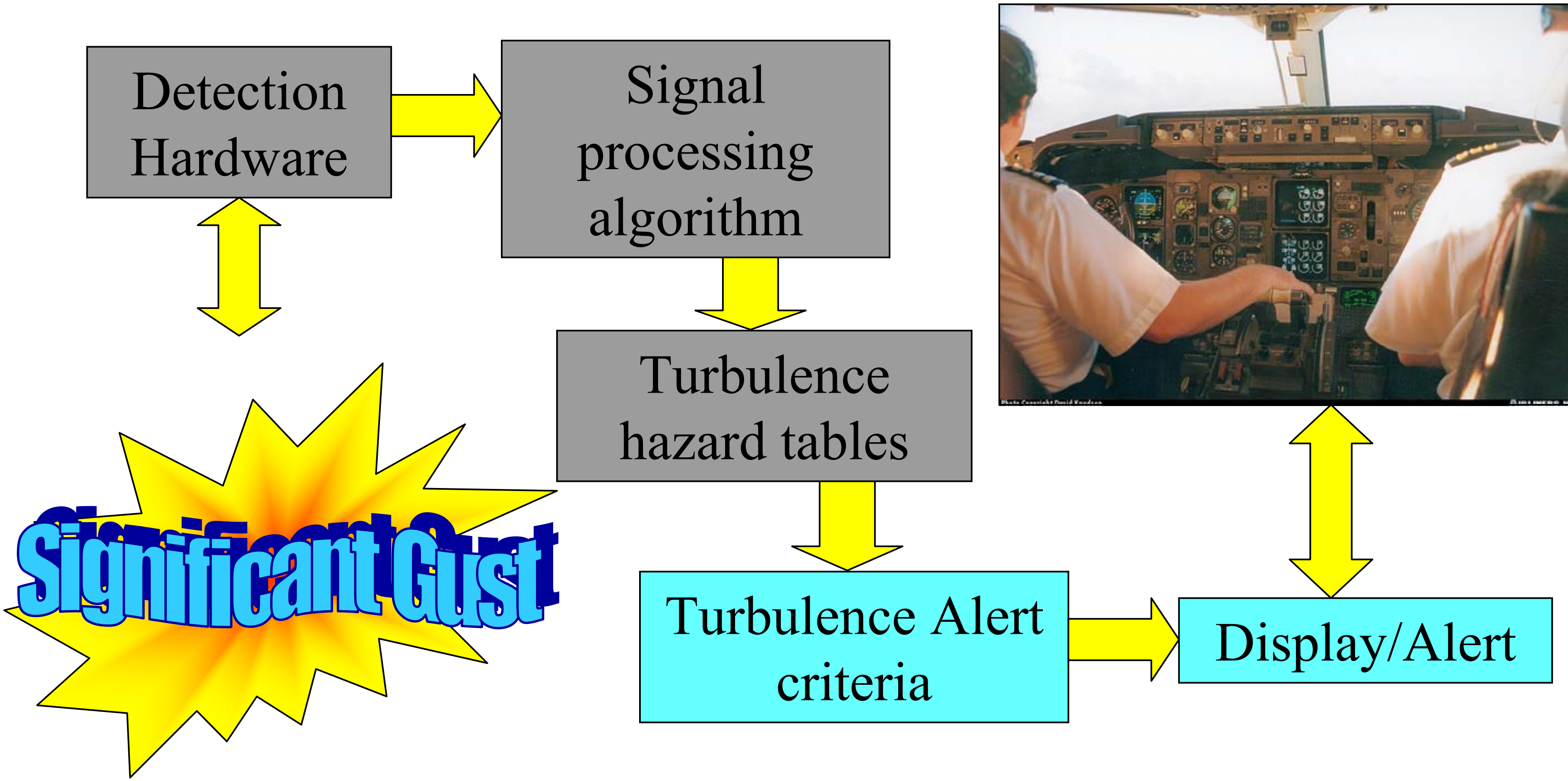
Turbulence Issues

- Challenges
  - Characterization
    - Buildup & Decay cycle
    - Persistence
  - In-situ testing
    - Finding turbulence
    - Measurement standardization (Eddy Dissipation Rate /Cabin Acceleration)
- Understood
  - Injury-producing motion
    - Vertical Acceleration (-g most dangerous)
    - Rear cabin most susceptible
  - Protection strategy
    - Fasten seat belt!!!
    - Heed Crew Warnings

Coordinated Approach to Turbulence Injury Risk Reduction



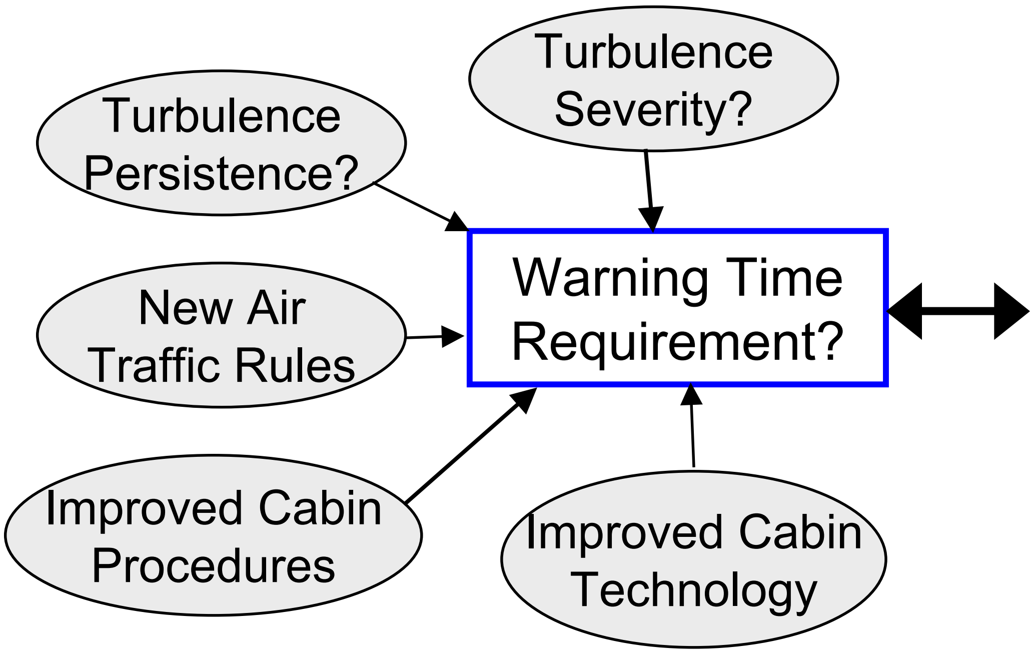
An End-to-End Turbulence Warning System

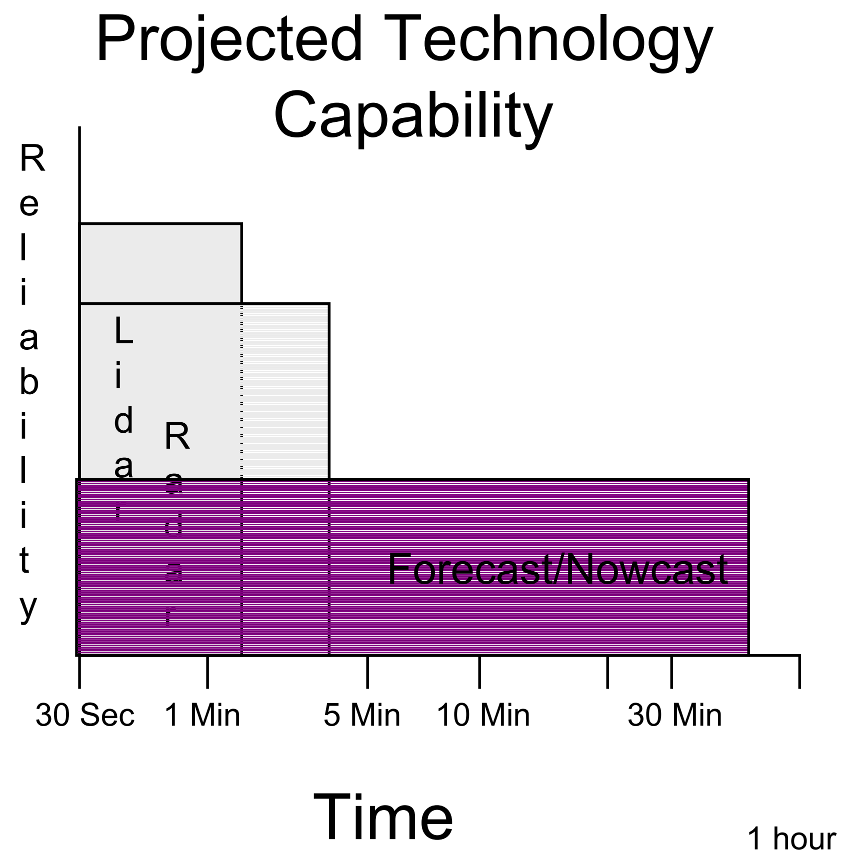


Current Turbulence Warnings

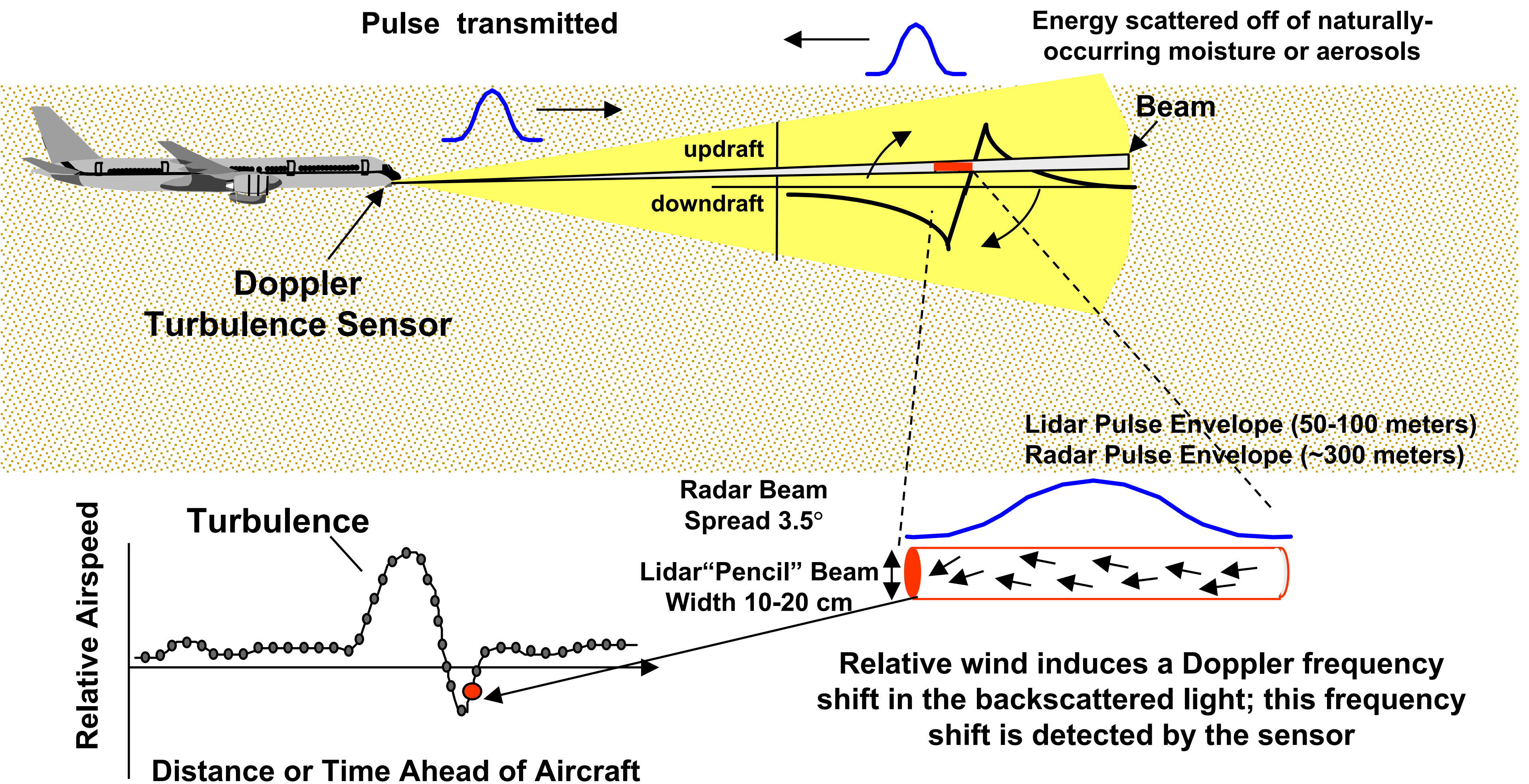
- **Forecasts**
  - – Broad, non-specific location
  - \+ Substantial work on-going and accuracy improving
- **Visual Cues**
  - Vicinity of Convective activity
  - Cirrus cloud patterns
    - Jet Stream boundaries
    - Mountain Waves
- **Pilot Reports**
  - – Observing/Ownship Dependent
  - – Subjective
  - – Spotty Capture & Dissemination
  - \+ Direct Experience

The Question of Warning Time

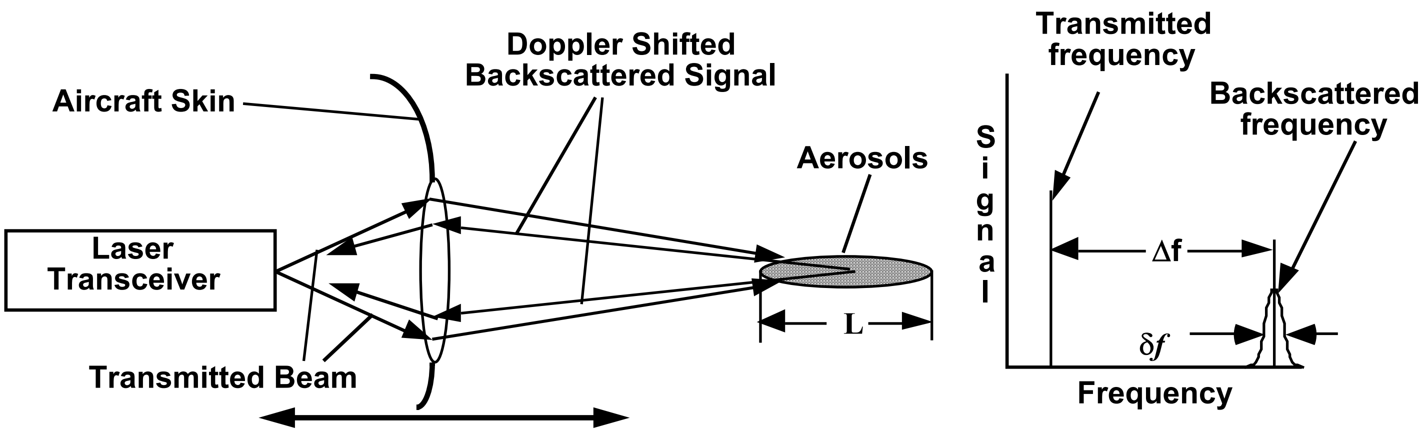




General Principle of Doppler Radar/Lidar Turbulence Measurement



Doppler Radar/Lidar Operating Concept



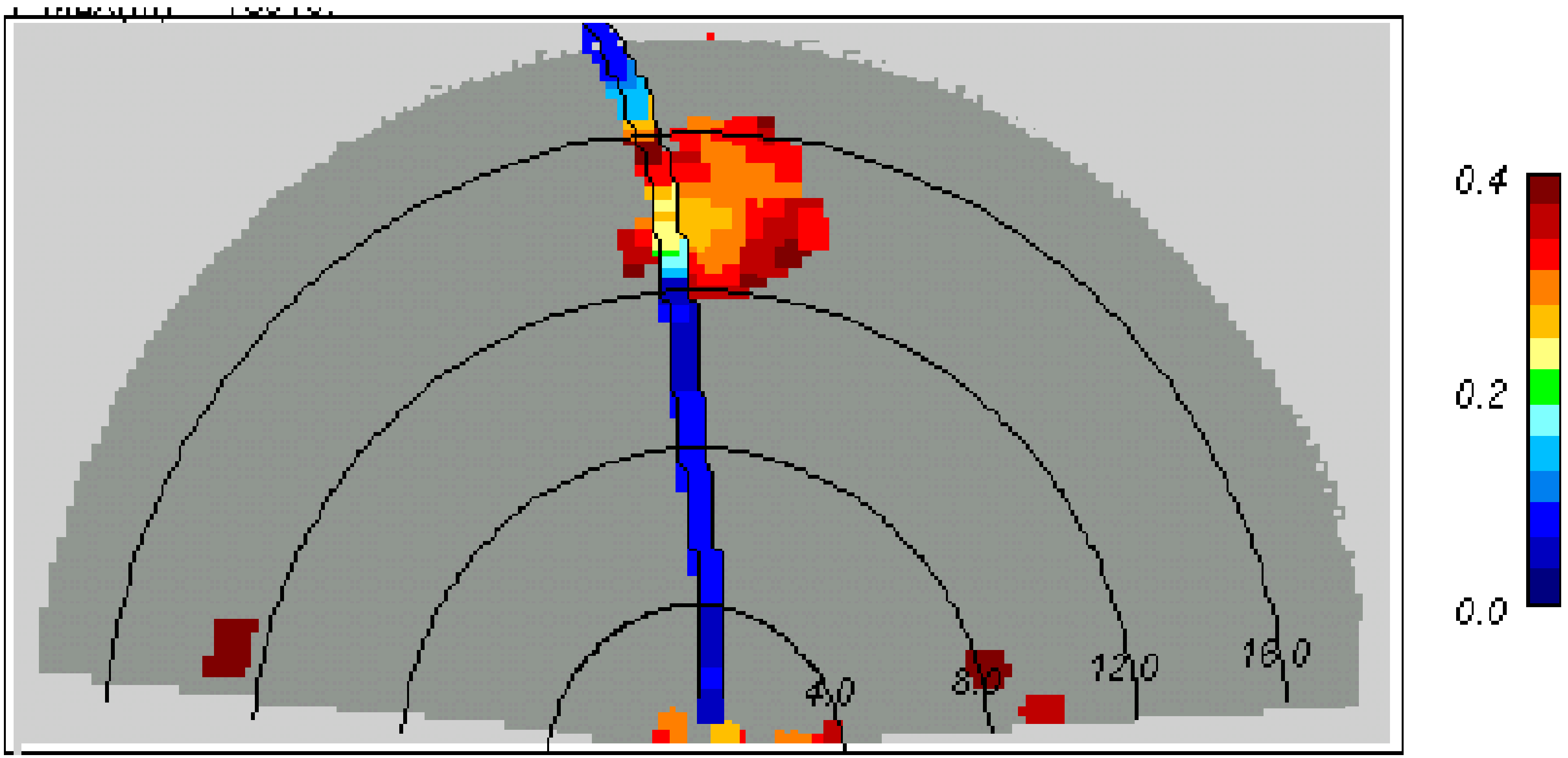
A = λ∗Δf   T = ΔA = λ∗δf

Note: At long ranges L is determined by pulse length.
δ*f* is an index of airspeed variation over length L.

NASA Langley B757 Radar Testbed Aircraft

Research Weather Radar

g-Loading (rms g) Event 191- 06



Radar Flight Test Summary

- 4 flights totaling 15 hours on NASA 757
- Flight Conditions Encountered
  - 5,000-30,000 ft MSL altitude operation
  - Mostly clear, occasional clouds
  - Encountered moderate to severe turbulence
    - 18 Convective Events
    - 1 Severe Event with - g’s

NCAR Electra
Lidar Testbed Aircraft

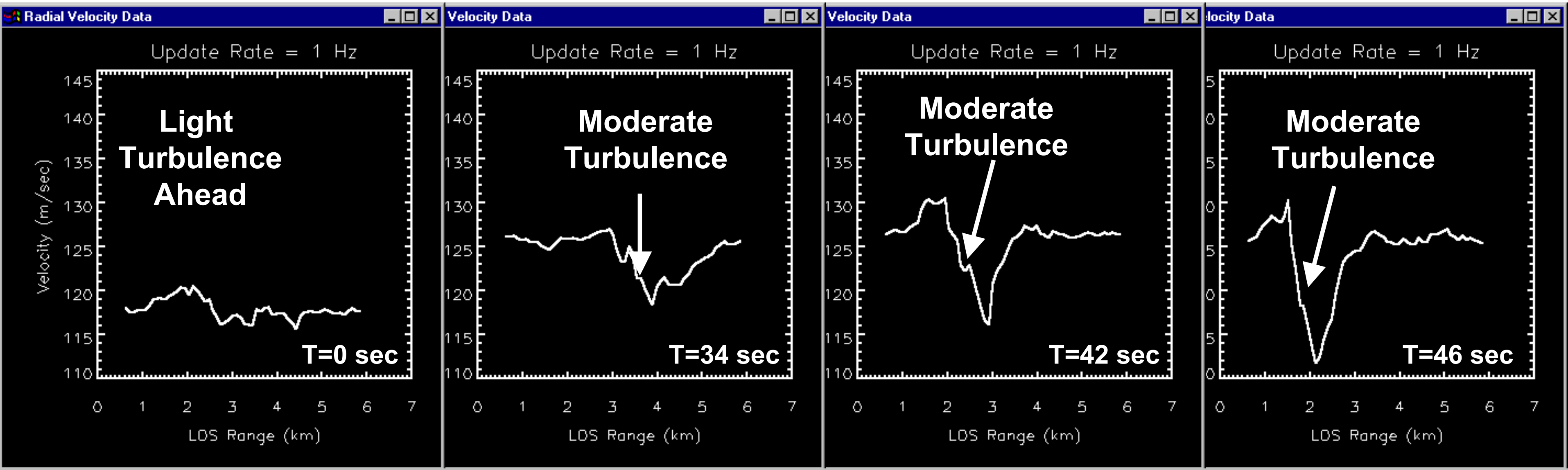
NASA Dryden DC-8
Lidar Testbed Aircraft

Lidar on DC-8

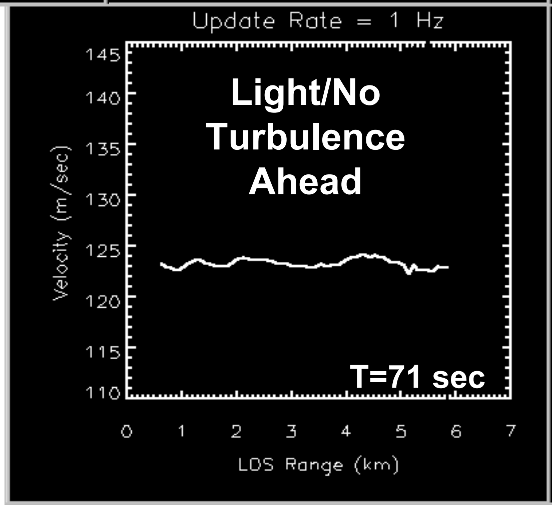
DC-8 Outside Periscope

A Status and Progress Report on Turbulence Warning Technology

LIDAR Airspeed Results in Turbulence Encounter



- ”Isolated” moderate turbulence region in light turbulence
- Detected ahead and observed as aircraft approached
- Moderate turbulence observed aboard aircraft (25 sec later)
- Aircraft traversed through turbulence and into smoother air



Sample Turbulence Encounter

Lidar Flight Test Summary

- 5 flights totaling 15 hours on NCAR Electra
- Flight Conditions Encountered
  - 5,000-25,000 ft MSL altitude operation
  - Mostly clear, occasional clouds
  - Encountered light to moderate turbulence
    - Mountain-wave-induced
    - Convective
    - Cloud/Virga
- 13 flights totaling 83 hours on NASA DC-8
- Flight Conditions Encountered
  - 24,000-39,000 ft MSL attitude operation
  - Mostly convective conditions, occasional dry air
  - Encountered light to severe turbulence in/out of cloud

Lidar Flight Test Summary (Cont.)

- Sensor readily capable of detecting light or stronger turbulence ahead of the aircraft
  - Measures apparent strength of turbulence as well as time to encounter
  - Positive correlation with on-board in-situ sensors
  - Range performance compares favorably with expectations
    - 4-6 miles for 11,000-15,000 ft MSL
    - 2 miles for 25,000-39,000 ft MSL and cloudless conditions

Turbulence Hazard Summary

- Turbulence is the leading cause of in-flight injuries and is estimated to cost the airline industry > $100M/year
- The turbulence hazard is not completely characterized from an atmospheric perspective but understanding is improving
- The approach to risk reduction includes cabin design, cabin procedures, improved forecasting as well as warning technology development
- Progress is being made with warning technology
  - Enhanced Weather Radar
    - Implemented with software change in existing Weather Radar sets
    - Most mature technology, Available 2-3 years
  - Lidar
    - Implemented with Lidar transceiver and signal processing hardware
    - Hardware integration an issue for existing fleet aircraft
    - Requires increased transmitted pulse energy
    - Available est. 5-7 years

Out-of-Scope "Turbulence"

Out-of-Scope "Turbulence" (cont.)