Turbulence Mitigation Using Existing Aircraft Controls

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Scott Shald (Coherent Technologies)

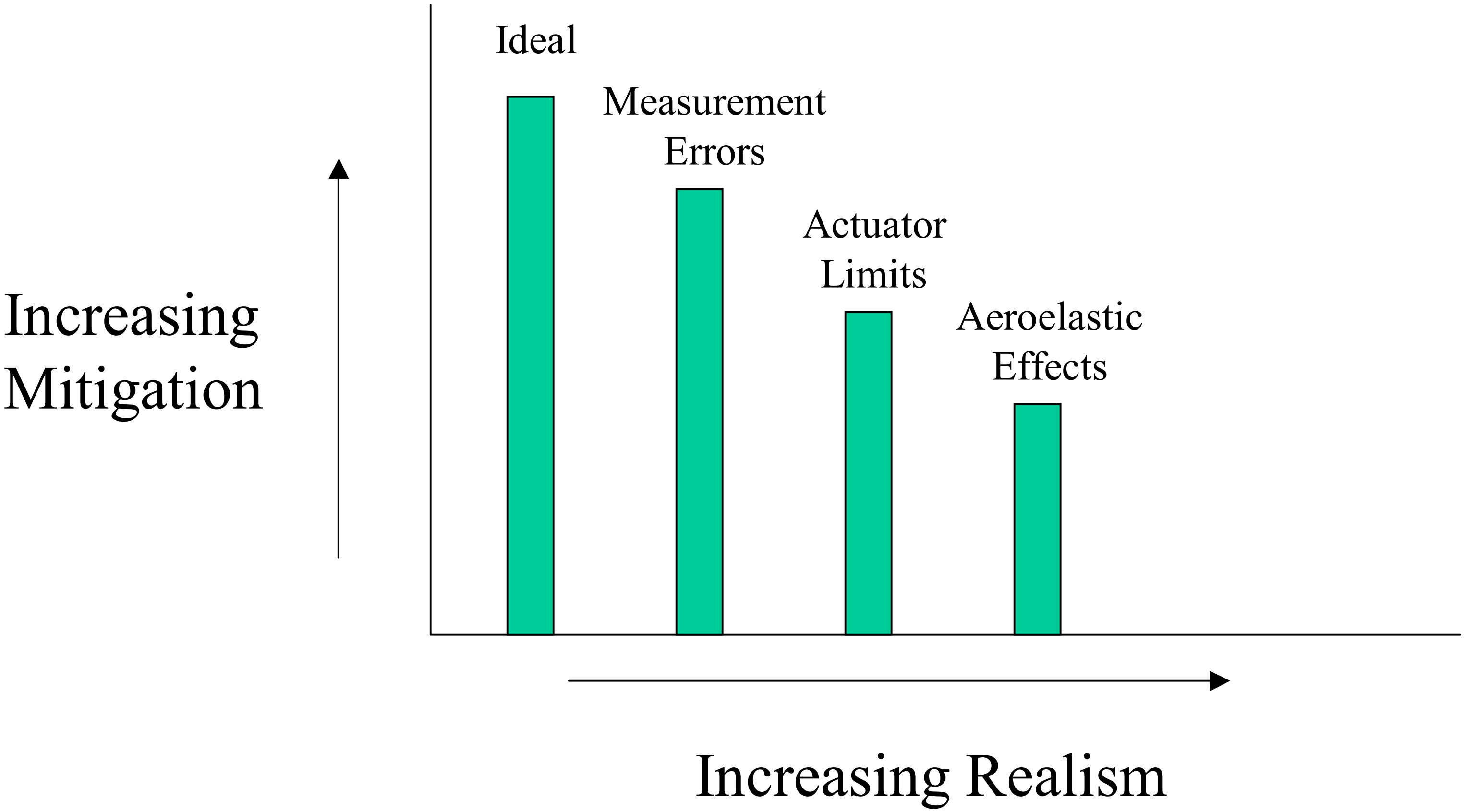
Outline

- Background
- Boeing research (Chris Borland)
- Coherent Technologies research (Scott Shald)
- NASA Research
- Summary
- Recommendations

Mitigation Challenges

- Economics
  - Software changes to autopilot control laws
  - Hardware changes (sensors, actuators, control surfaces)
- Certification Requirements
- Laws of Physics

Study Realism



“Turbulence Encounter Mitigation Using Existing Control Actuators”

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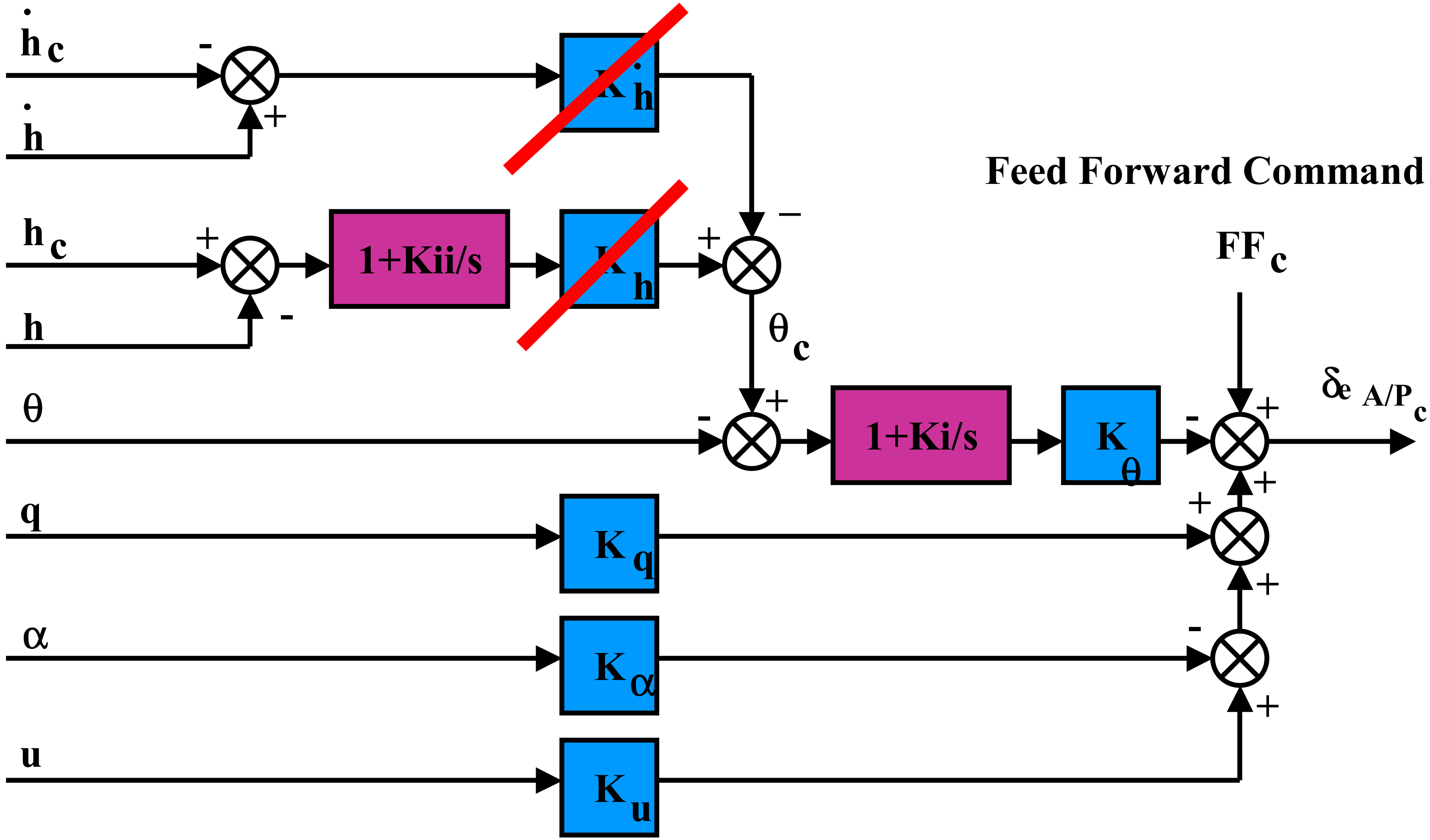
3rd NASA Weather Accident Prevention Review
November 20-21, 2002

- **Task 2 - Benefits of Feedback and Feedforward Control**
  - **Feedback using existing inertial / air data sensors**
  - **Feedback and feedforward sensor integration**
  - **Alternate control laws to improve performance**

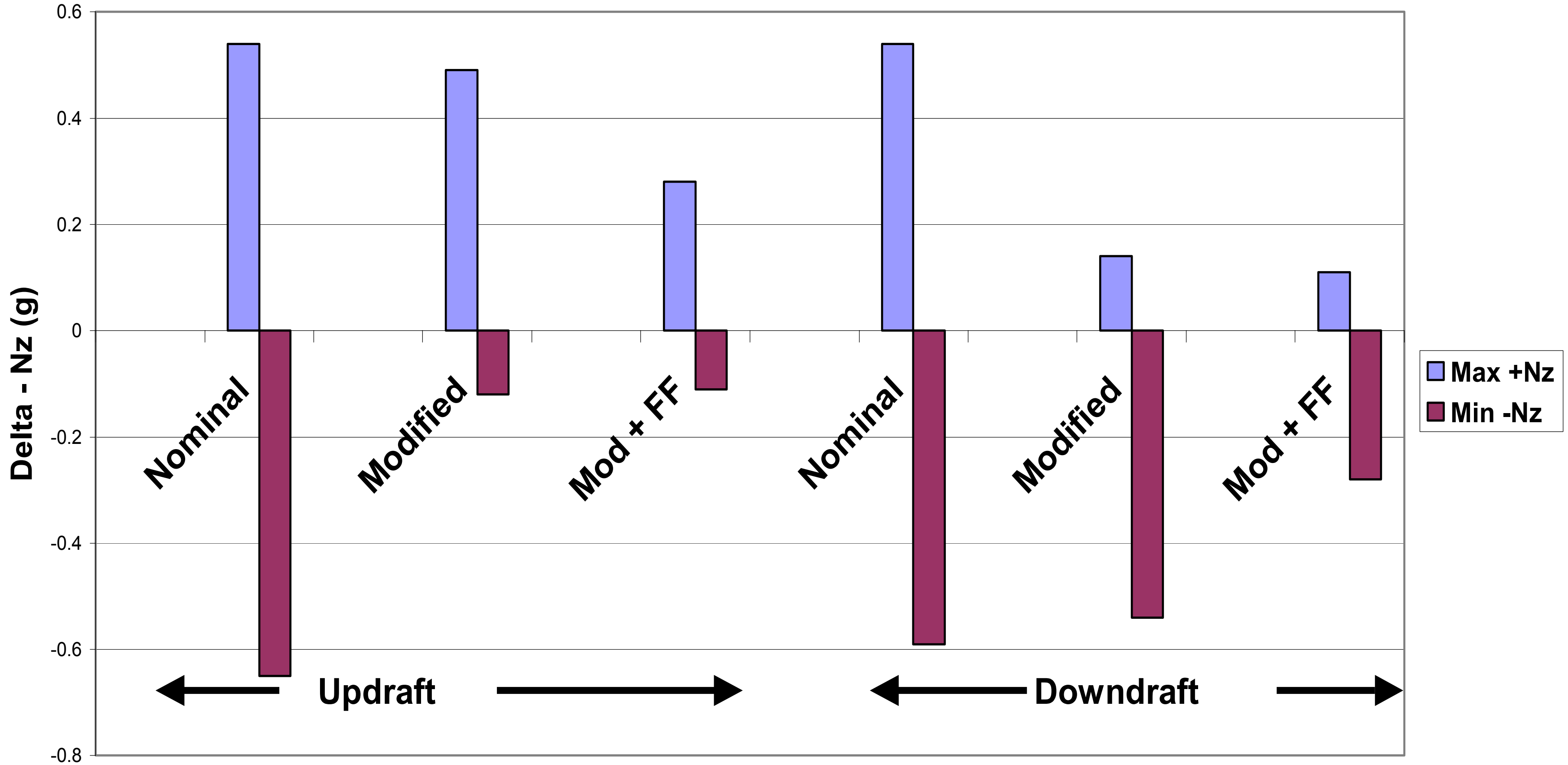
Development of Alternate Control Laws to Improve Turbulence Response

- Existing 757-200 autopilot model showed inadequate performance during severe turbulence
- Several modifications tried using existing inputs and gains
- Alternate control gains with additional sensor inputs improved response
- Combining with forward feed controller improved response further

Simplified Linear Autopilot Model (Enhanced Autopilot)



Effect of Autopilot Modification on Aft Cabin Acceleration Response



Conclusions:

1) Response of airplanes to turbulence can be improved by autopilot control law modifications. However, a "warning" signal would probably be required to engage.

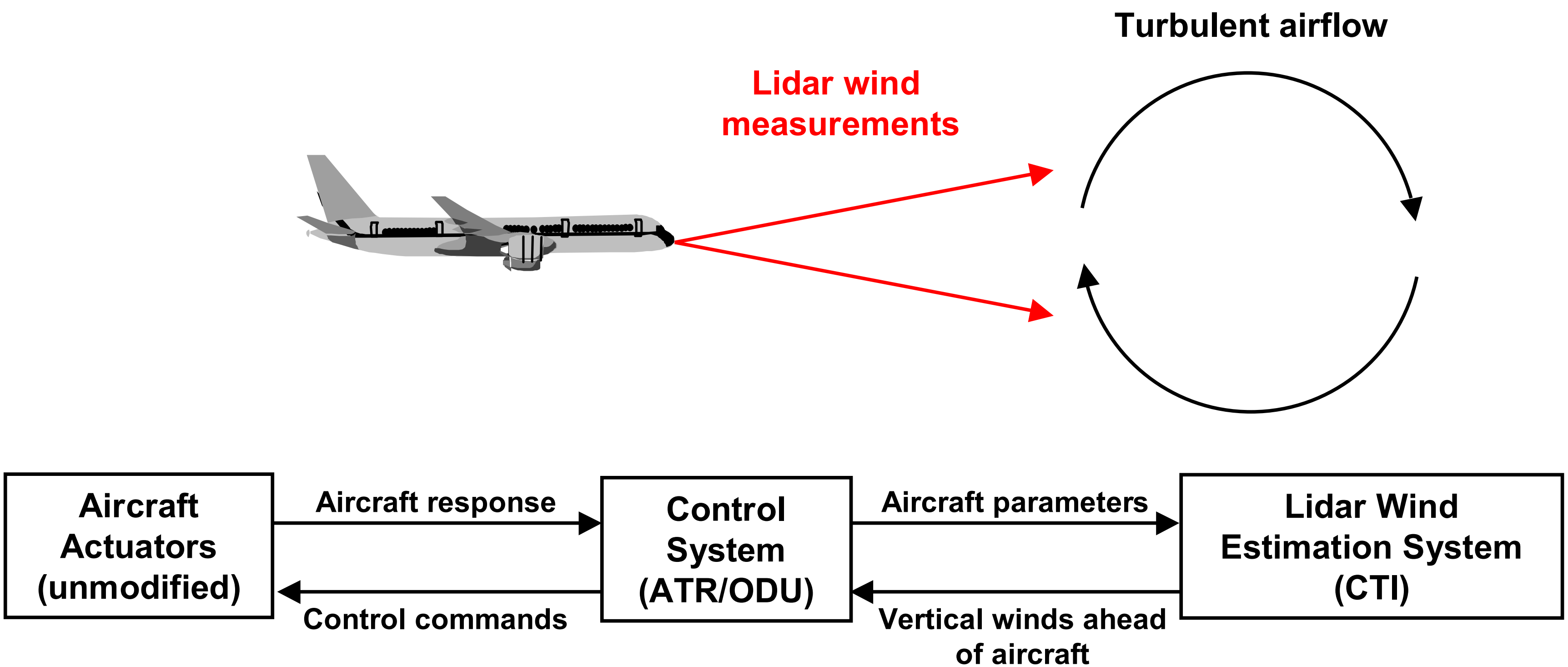
2) Response can be further improved by addition of a forward-looking sensor to measure the oncoming vertical gust profile (est. 400-1000 ft look-ahead).

3) Mitigation of severe (injury-causing) gust levels (60-150 ft/sec peaks) will probably require (in addition) system modifications to increase control authority, or providing protection against autopilot saturation.

Feed Forward Turbulence Mitigation with Coherent Doppler Lidar

Scott Shald, Coherent Technologies
Phil Gatt, Coherent Technologies
Paul Robinson, AeroTech Research
Brett Newman, Old Dominion University

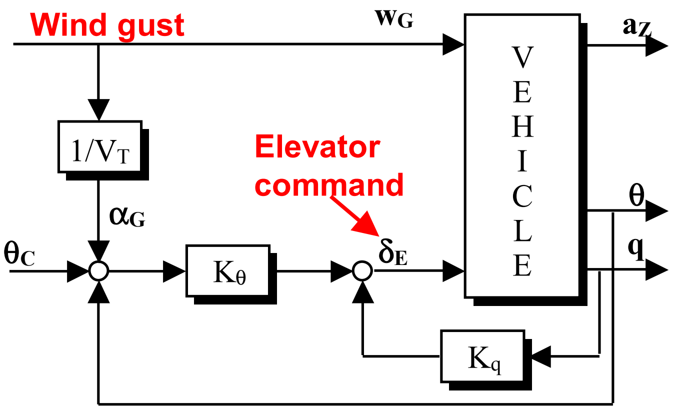
Feed Forward Turbulence Mitigation



- Estimate vertical winds using multiple lines-of-sight
- Pass wind estimates to control system
- Modify control systems to reduce loads through event
- No change to aircraft actuators

Scalar Feed Forward Control

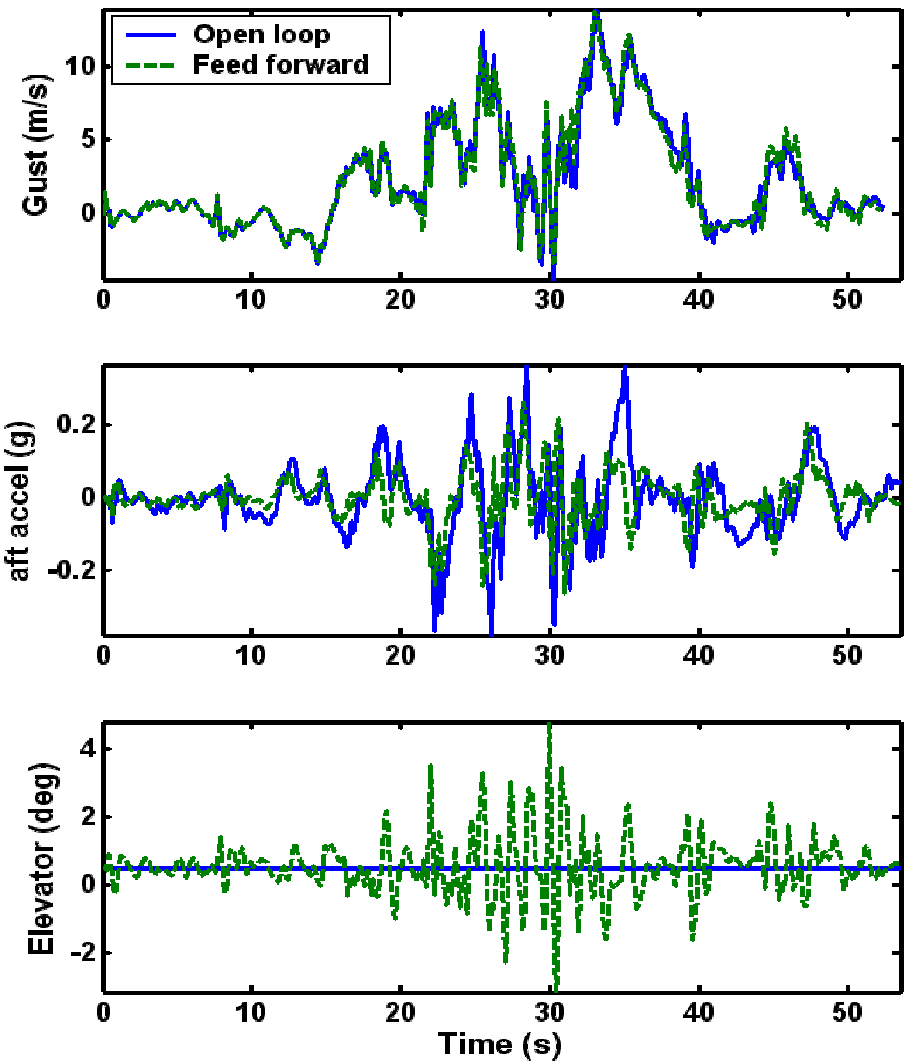
$$\delta_E = K_\theta(\theta_c + \alpha_G - \theta) - K_q q$$



- Simple flight control law generates elevator command based upon wind measurement at one fixed distance ahead of the aircraft
- Straightforward to implement

SCALAR FEED FORWARD CONTROL INITIAL RESULTS

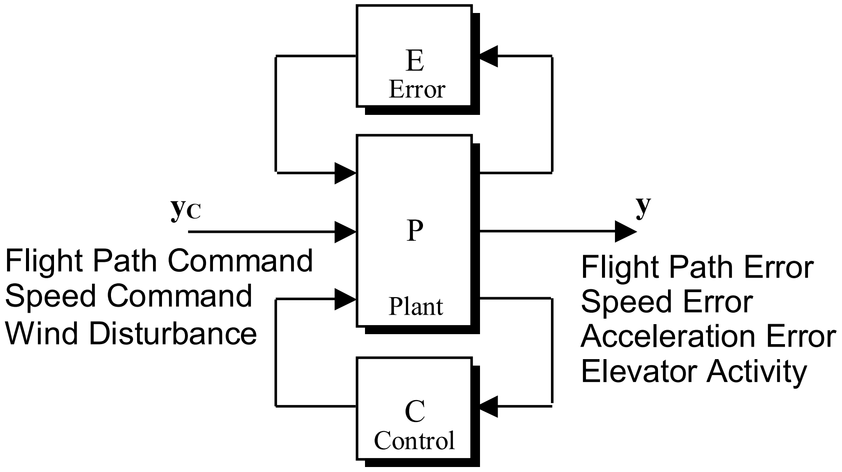
- NASA simulated 3D wind field†
- Look ahead time of 0.3 s
- Reduction in max load from 0.36 g to 0.26 g (28%), reduction in sigma load from 0.10 g to 0.069 g
- Reduction limited by actuator
- Improvement possible in two ways
  - Increase actuator authority (undesirable)
  - Further improve flight control law and sensor to use multiple look ahead distances



†Proctor, F. H., D. W. Hamilton, and R. L. Bowles, 2002: Numerical Study of a Convective Turbulence Encounter. 40th AIAA Aerospace Sciences Meeting & Exhibit, 14-17 January, Reno, NV, Paper No. AIAA-2002-0944, 14 pp.

VECTOR FEED FORWARD CONTROL

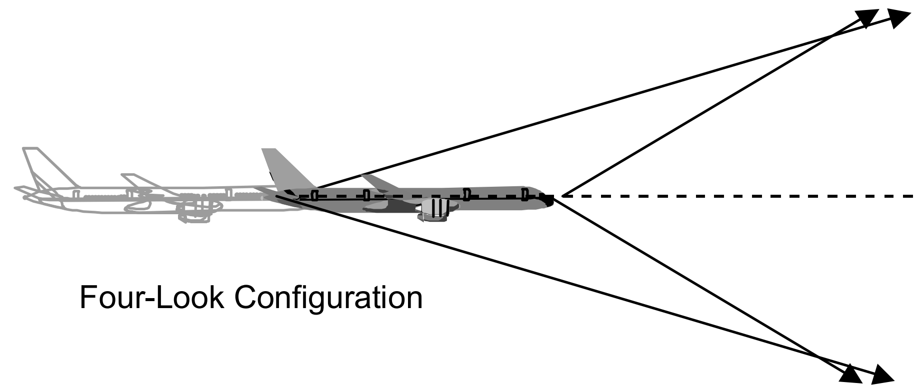
- Lidar system estimates wind at multiple distances ahead
- Flight control law must process a vector of wind estimates
- Optimizes path through turbulence event
- Further reduction of loads anticipated



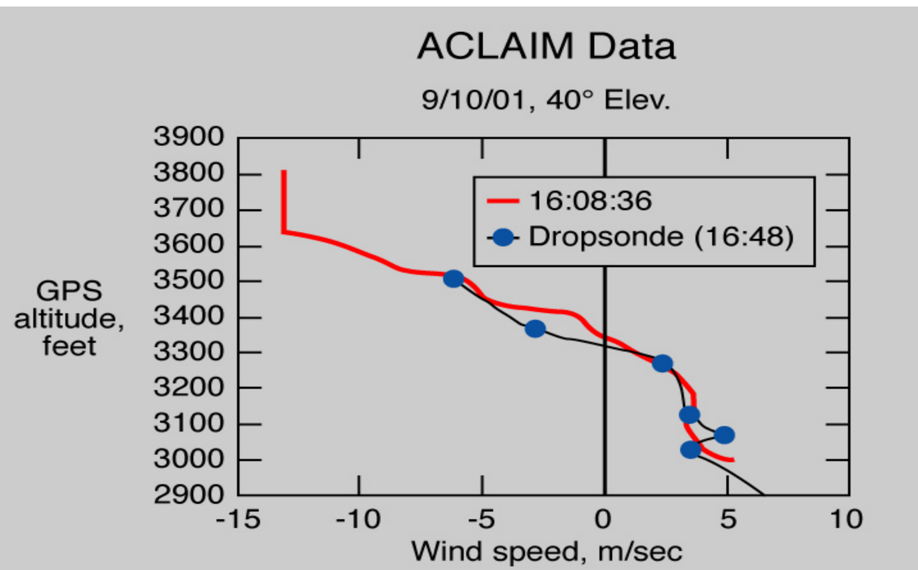
$$\min \|y / y_C\|$$

$$\min \|y\|$$

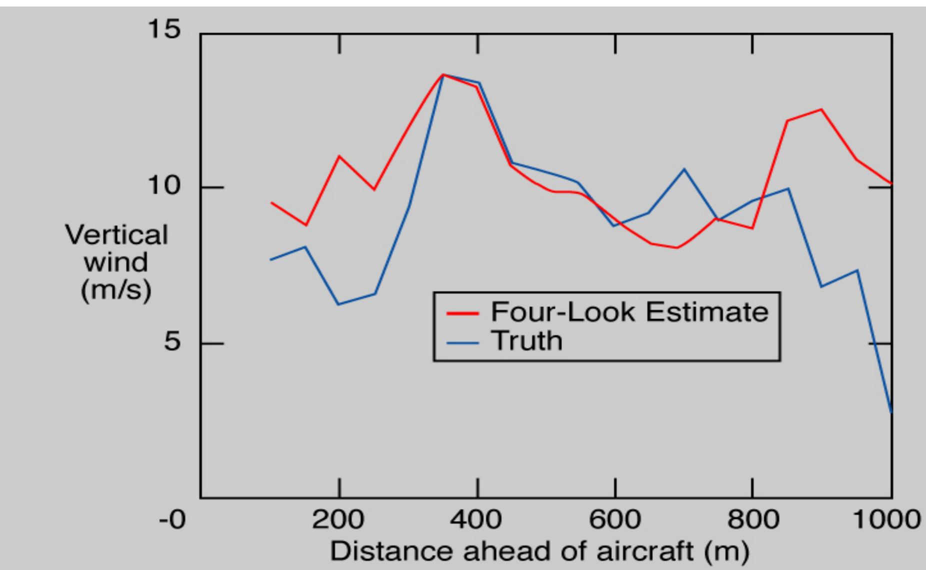
LIDAR WIND ESTIMATION ACCURACY



Collected Radial Velocity Data



Simulated Wind Vector Estimation



CONCLUSIONS

- Measurements of the wind field ahead of an aircraft allows for significant reduction in loads using existing actuators
  - Reduction of ~30% in simulation
  - Requires measurement accuracy on the order of 2 m/s
- Scalar feed forward control law provides load reduction, but is limited by current actuator authority
- Vector feed forward control law under development
- Lidar produces accurate measurements of radial velocity, and wind vector estimation methods under development
- Lidar based turbulence mitigation system may be fielded in 5-10 years

Turbulence Tolerant Autopilot Control Laws

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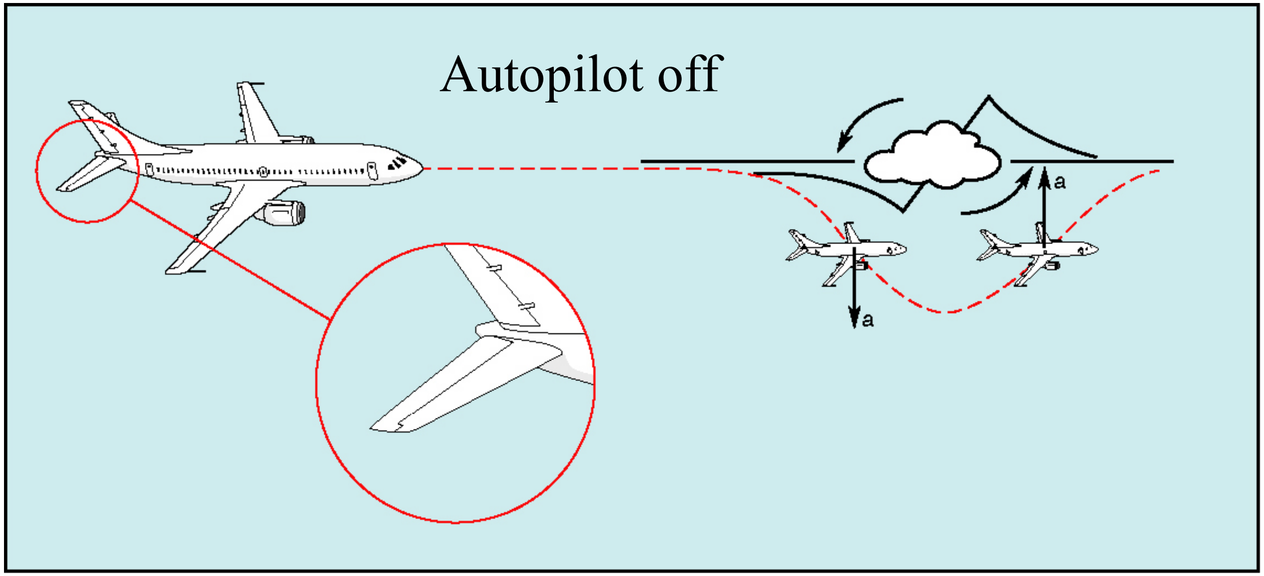
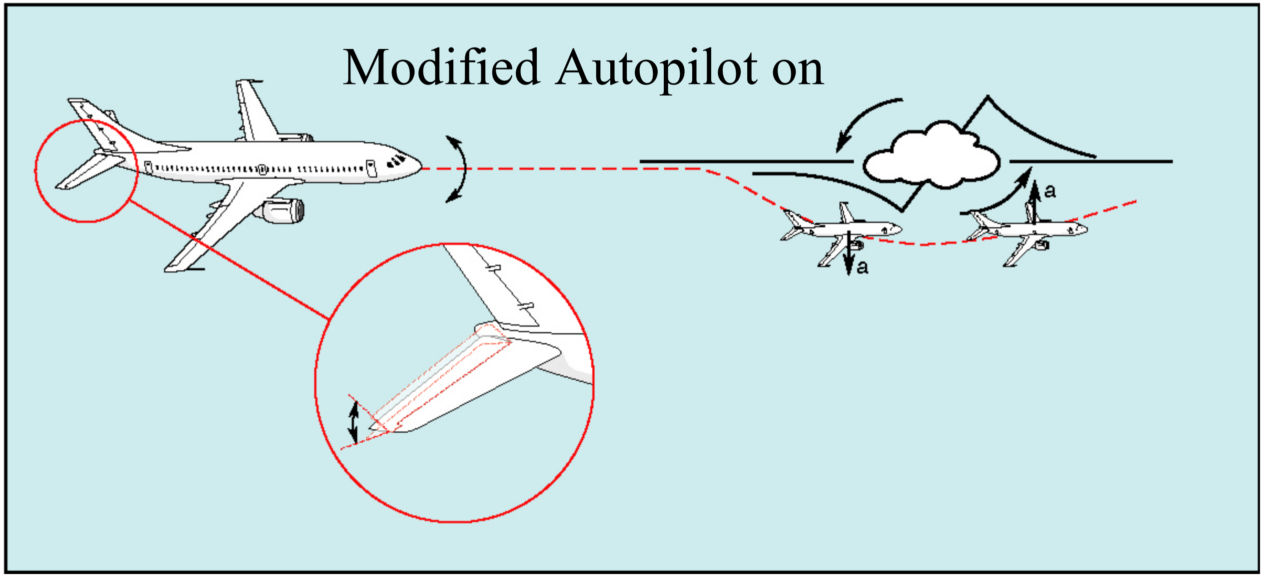
Approach

- Use NASA non-linear real time simulation of Boeing 757 on Integration Flight Deck
- Modify operational autopilot control laws
- "Fly" simulator through 6 different gust profiles
  - 1-cosine
  - 5 gust profiles derived from NTSB FDR of actual accidents

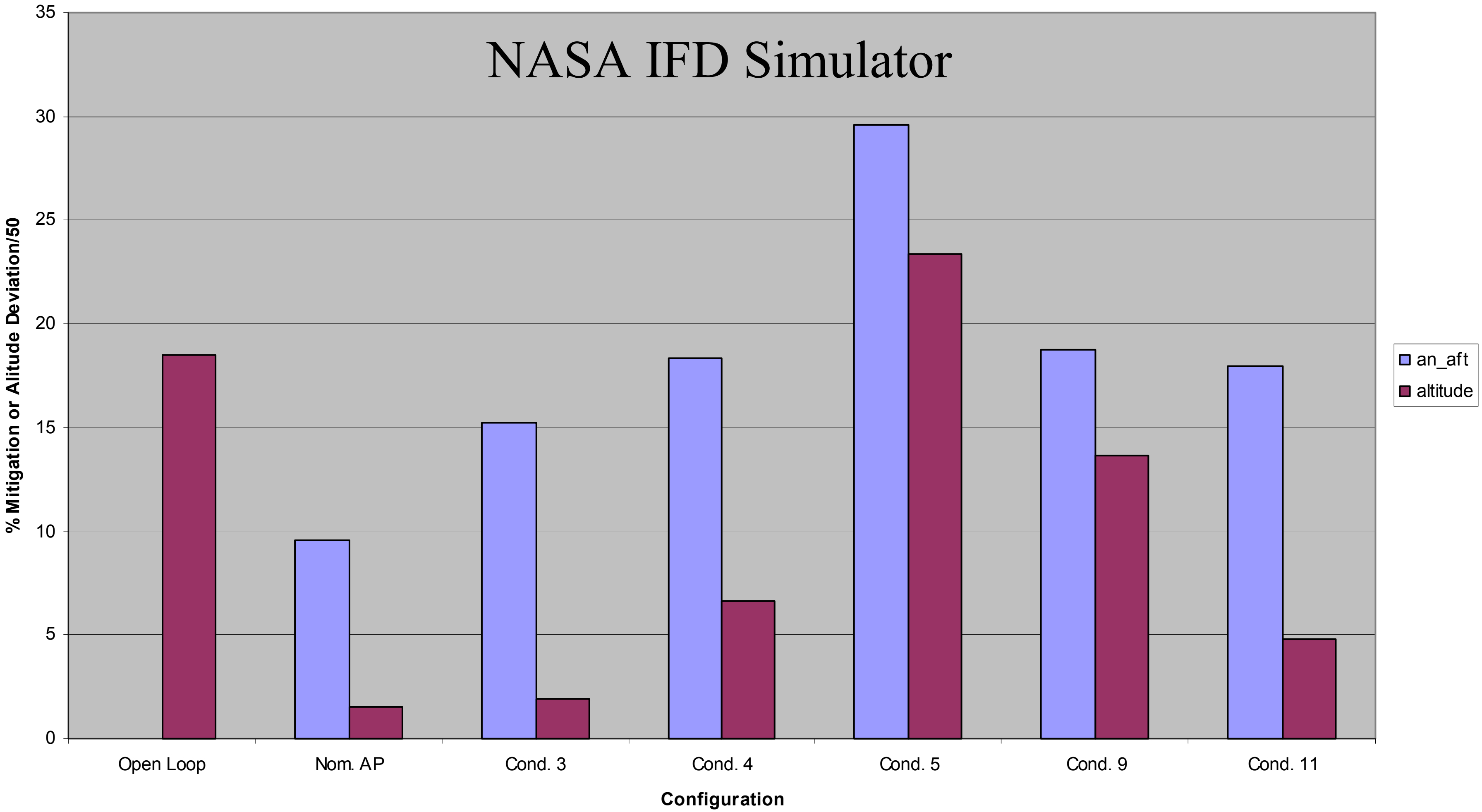
Turbulence Response Mitigation



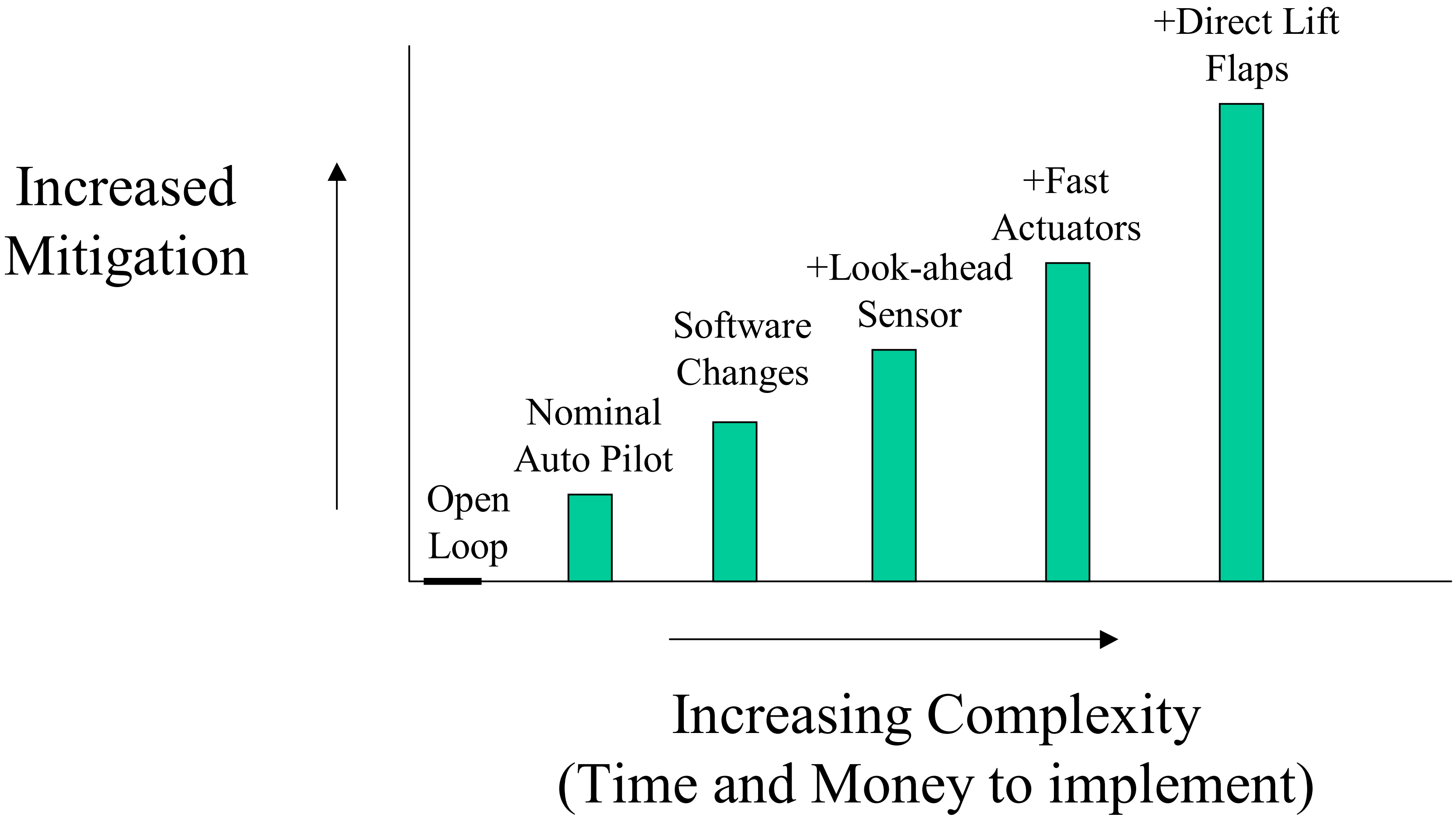


A/P Software Changes Only

(Averages for 6 Gust Profiles)



Research Summary



Recommendations

- Use a phased approach to further research:
  - Phase I: Software changes to Autopilot. Can be implemented on aft flight deck of NASA's 757 available in FY 04
  - Phase II: Add Lidar Feed Forward to Autopilot depending on maturity
  - Phase III: Increase actuator authority depending on Phase II results