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## Session I. NASA Flight Tests

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NASA Wind Shear Flight Test In Situ Results

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# NASA WINDSHEAR FLIGHT TEST
# IN SITU RESULTS

Presented By:
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# OUTLINE

- **BACKGROUND**
  - OBJECTIVES
  - DESIGN REQUIREMENTS
- **IMPLEMENTATION**
- **RESULTS**
  - ALGORITHM TESTING
  - MICROBURST FLIGHTS
- **SUMMARY**

# OBJECTIVES

- PROVIDE MEASUREMENT STANDARD FOR FORWARD-LOOK SENSOR EVALUATION

- DEMONSTRATE OPERATIONAL UTILITY

The main objectives in developing the NASA in situ windshear detection algorithm were to provide a measurement standard for validation of forward-look sensors under development, and to demonstrate the algorithm's ability to operate with a suitably low nuisance alert rate. It was necessary to know exactly how the algorithm was implemented and what parameters and filtering were used, in order to be able to fully test its effectiveness and correlate in situ results with forward-look sensor data.

# DESIGN REQUIREMENTS

- MINIMIZE AIRCRAFT-INDUCED HAZARD INDEX DUE TO:
  - CONFIGURATION CHANGES
  - THRUST EXCURSIONS
  - MANEUVERING FLIGHT
  - TURNS IN STEADY WIND

- MINIMIZE NON-HAZARDOUS ATMOSPHERE-INDUCED HAZARD INDEX
  - TUNE TO APPROPRIATE SCALE OF MOTION
  - GUST REJECTION / TIME-TO-ALERT TRADE-OFFS
  - LOW NUISANCE ALERT RATE

- EMPLOY CURRENTLY AVAILABLE STANDARD SHIP-SET SENSORS

The major design requirements are 1) minimize effects of aircraft-induced motions, such as those shown in the first bullet item, and 2) minimize the effects of non-hazardous atmospheric motions, which is done using gust-rejection filters. The second item shows the major issues addressed in development of the filters, such as tuning the filters to the larger-scale motions associated with windshear, choosing an acceptable trade-off between improving the gust-rejection characteristics and decreasing the latency in the system, and maintaining a low nuisance alert rate; 3)implementing the system using currently available, standard sensors, to make the implementation feasible on any inertially-equipped airplane.

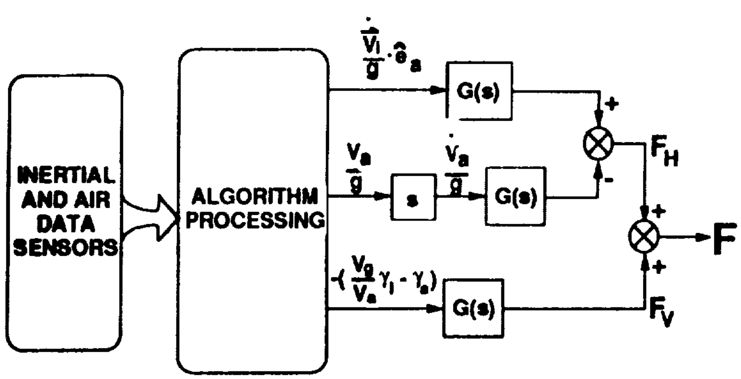
# WIND SHEAR HAZARD INDEX

- **THEORY**
  - **POTENTIAL CLIMB ANGLE** $\gamma_p = \frac{T-D}{mg} - F$
  - **HAZARD INDEX** $F = \frac{\dot{\underline{w}} \cdot \underline{e}_a}{g} - \frac{w_h}{V_a}$
- **IN SITU IMPLEMENTATION**

$$F = \left\{ \frac{\dot{\underline{V}}_I \cdot \underline{e}_a - \dot{V}_a}{g} \right\} - \frac{w_h}{V_a}$$

The method for quantifying the windshear hazard is by computing the windshear hazard index (F-factor), which is shown as it relates to an airplane's potential climb angle and ratio of thrust-minus-drag to weight. The definition of F-factor (second equation) is shown as a function of the wind vector dot product with a unit vector in the direction of the airspeed vector, vertical wind component, and true airspeed. The bottom equation shows the general full 3-dimensional implementation of an in situ algorithm, with F computed from aircraft-measured parameters such as inertial velocity rate and airspeed rate, rather than wind measurements. The NASA implementation was realized in full 3-D form, to not degrade its performance in any flight regime.

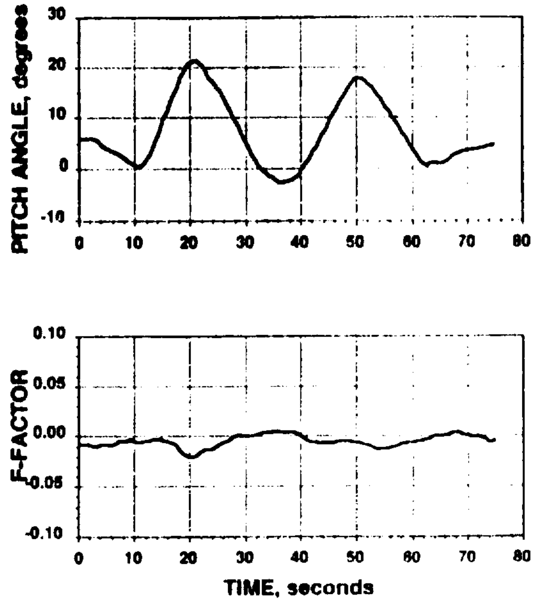
**CONCEPTUAL REPRESENTATION OF NASA IN SITU F-FACTOR ALGORITHM**




This shows the how the in situ algorithm is implemented on NASA's B-737-100, where the Algorithm Processing represents the first part of the in situ algorithm, which produces the three terms shown. These terms are then filtered (shown as G(s) boxes) to give horizontal, vertical, and total in situ F-factor.

## PUSHOVER/PULL-UP

(FLIGHT DATA, 23 MAY 91)




The in situ algorithm was flight-tested locally, with maneuvers intended to induce significant changes in specific state variables to ensure the algorithm's ability to reject aircraft maneuvering effects. This figure shows a pushover/pullup maneuver, where the airplane was pitched up and down in a porpoising type of motion to induce high normal acceleration changes. Ideally, F-factor (bottom plot) should be close to zero, with allowances for acceptable levels of turbulence and signal noise, and well below the FAA-established alert threshold level of F=0.105. As shown, there was no adverse effect of the pitching motion on the in situ F-factor measurement.

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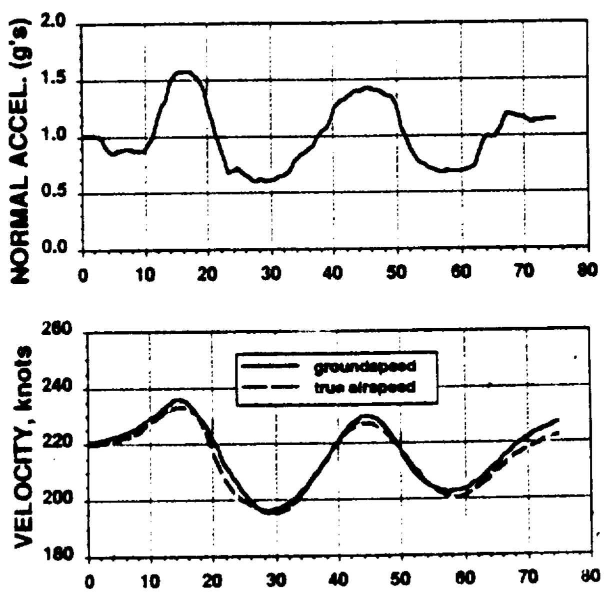
## PUSHOVER/PULL-UP

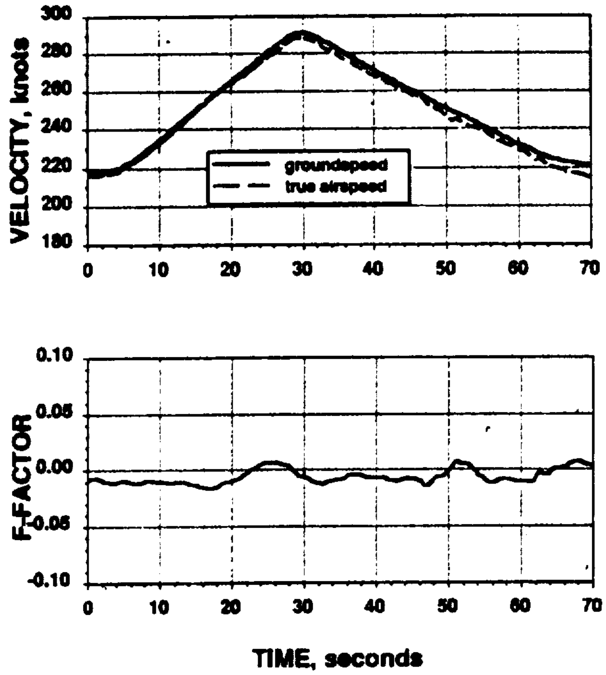
(FLIGHT DATA, 23 MAY 91)




The top figure shows the range of measured normal acceleration, which equals 1.0 g in level, unaccelerated flight. This maneuver induced an increase of 0.6 g and decrease of 0.4 g from the nominal value. True airspeed and groundspeed (bottom plot) are close in value, indicated there was no significant wind.

## ACCELERATION/DECELERATION

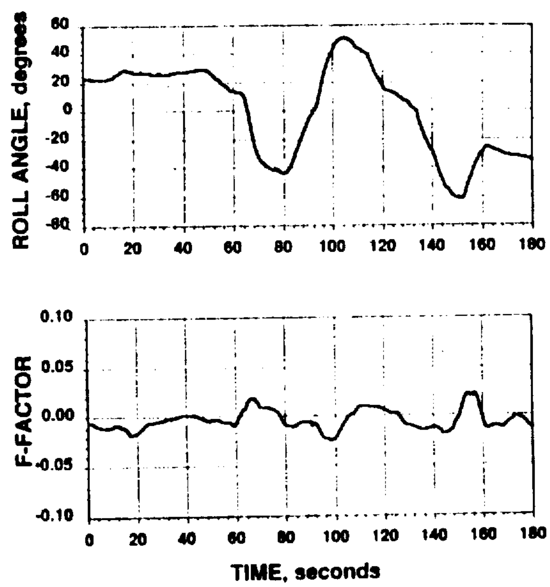
(FLIGHT DATA, 29 MAY 91)




The effect of changing longitudinal acceleration was tested by executing abrupt accelerations and decelerations, where the maximum rate of change was sustained over at least 50 knots change in airspeed. The effect of this motion did not appear to cause any adverse effect on the F-factor (bottom plot) computed by the algorithm.

## TURNING FLIGHT

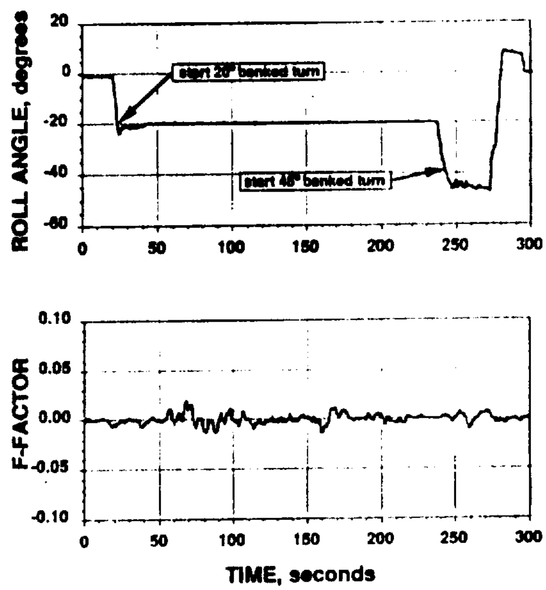
(FLIGHT DATA, 23 MAY 91)




The effectiveness of the 3-D implementation was tested by executing turns at high bank angles. The top figure shows a number of partial turns, at high bank angles and through abrupt changes in direction.

## TURNING IN STEADY WIND

(FLIGHT DATA, 2 OCT 90)




A final manuevering test was turning in a steady wind condition. The top plot shows the bank angle for the two turns executed in a steady wind of greater than 60 knots. The first was through a 360° heading change at 20° bank, the second through 180° heading at 45° bank. F-factor (bottom plot) shows no adverse effect of this manuever.

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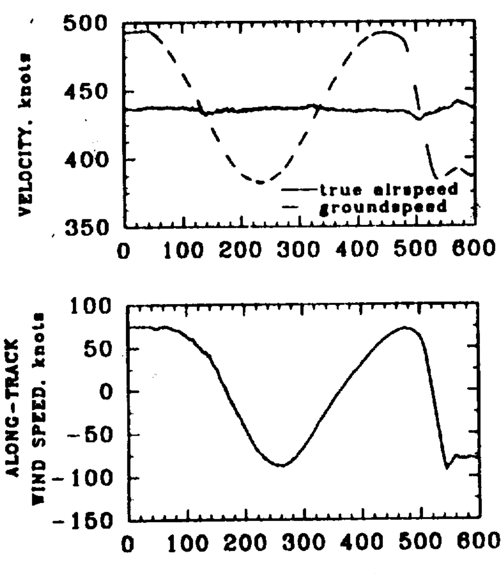
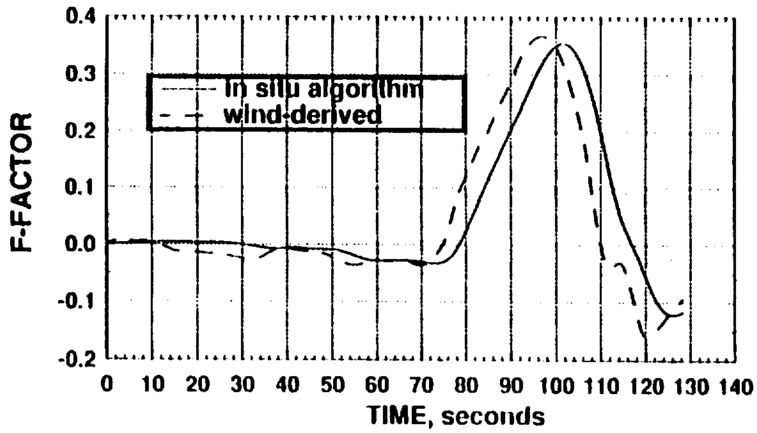
TURNING IN STEADY WIND

(FLIGHT DATA, 2 OCT 90)




These plots show the effect of the turns in steady wind on the airplane's velocity. The top plot shows true airspeed was constant, while groundspeed varied throughout the turns. The bottom plot shows the along-track wind measured by the airplane, varying by 150 knots over 20 seconds (t=250 to 270 sec), and indicates the algorithm's ability to reject the change of longitudinal wind, rather than measure it as a shear.

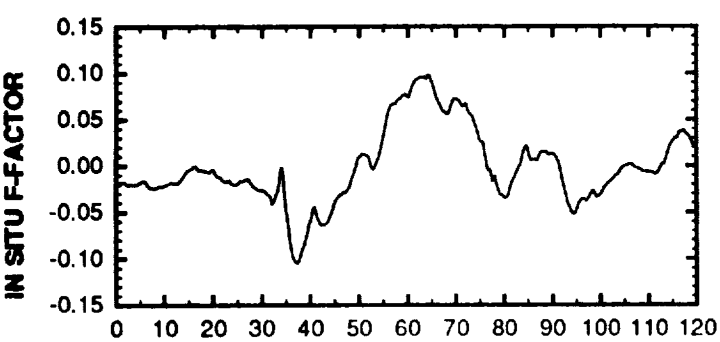
# LANDING APPROACH THROUGH MICROBURST (SIMULATOR DATA)



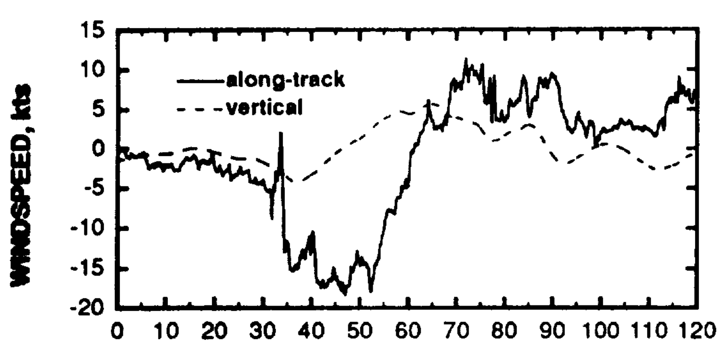

After having shown in flight that the algorithm rejected aircraft maneuvering effects, it was necessary to show that it could also detect a windshear, which was done in simulation, as shown. The in situ F-factor shows some lag and attenuation of the peak, which is primarily due to the effect of the gust-rejection filters, and was expected. Wind-derived F-factor is an instantaneous F-factor computed directly from the known winds.

## MICROBURST PENETRATION

FLIGHT DATA, 20 JUN 91



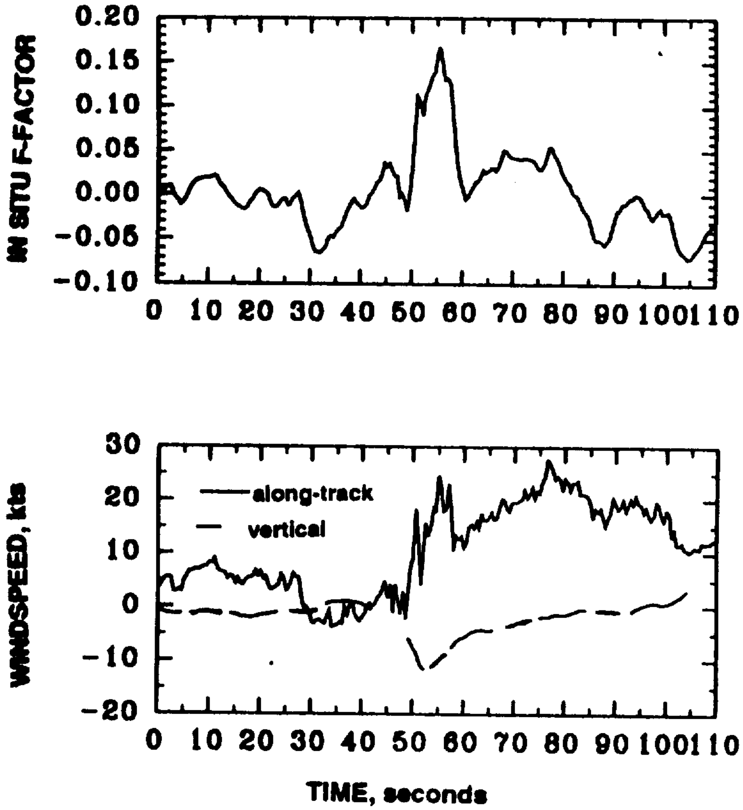

Data shown is for a microburst penetration during the 1991 NASA windshear flights; this particular case was catalogued as event #142, during which in situ F-factor approached the alert threshold of F=0.105, and showed good correlation with the observed change in along-track windspeed (bottom).




TIME, seconds

## MICROBURST PENETRATION

FLIGHT DATA, 17 JUN 91




Data shown is for microburst penetration, event #143, with a peak in situ F of 0.167. Along-track and vertical wind time histories show characteristics of passing near the core of a microburst.

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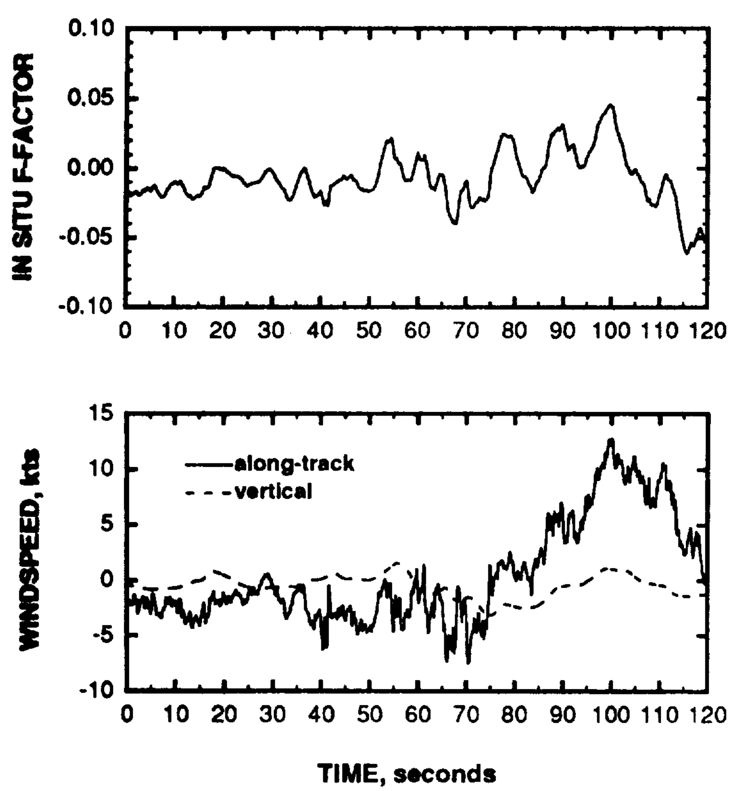
## MICROBURST PENETRATION

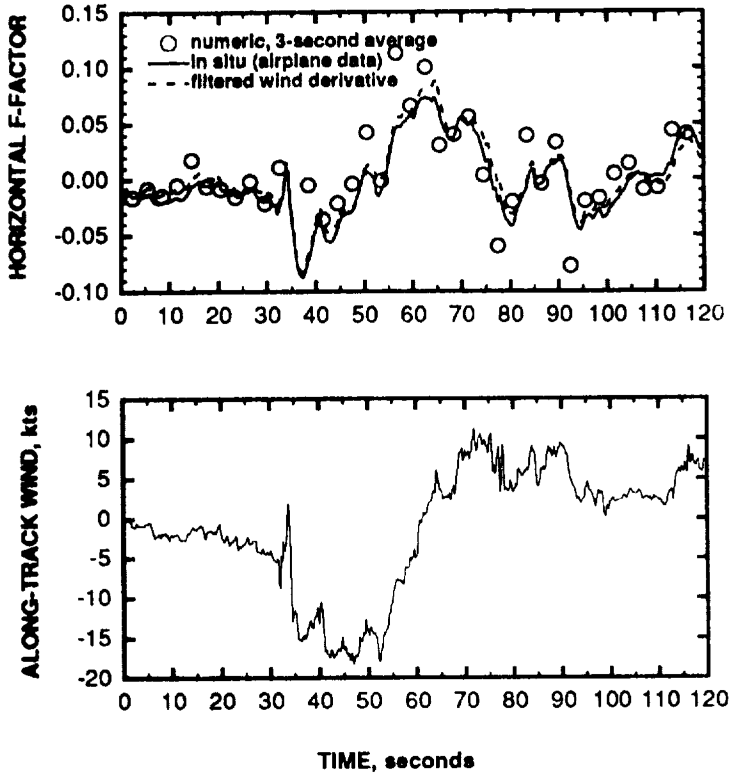
FLIGHT DATA, 17 JUN 91




Data shown is for microburst penetration, event #97. In this case, in situ F peaked at about 0.05, though along-track wind shows a general headwind-to-tailwind trend. The time scale of this event shows that the in situ algorithm is tuned to windshear that is hazardous to the airplane's climb performance, whereas this event was over a longer time scale (or distance), and as such was not a hazard to the airplane. The smaller-scale fluctuations in along-track wind (period of about 10 sec) are evident in the in situ F-factor plot (between t=75sec and end of run).

## MICROBURST PENETRATION

FLIGHT DATA, 20 JUN 91




To demonstrate how in situ F and wind-derived F correlate in-flight, F was computed from aircraft-measured along-track winds, and differentiated with a gust-rejection filter identical to the one used in the in situ algorithm. This is plotted along with the horizontal portion of in situ F-factor (top plot), and an unfiltered numerical differentiation of averaged along-track wind (wind data was averaged over 3-seconds, then differentiated). All three curves show very similar characteristics, indicating that F-factor from the in situ algorithm is nearly equivalent to the along-track wind derivative. Data shown is from event #142.

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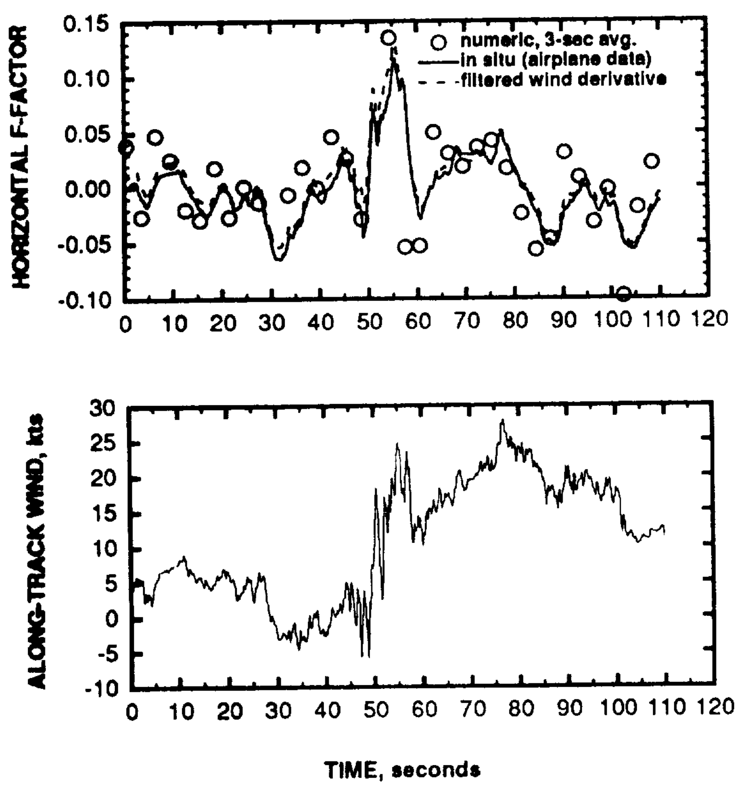
## MICROBURST PENETRATION

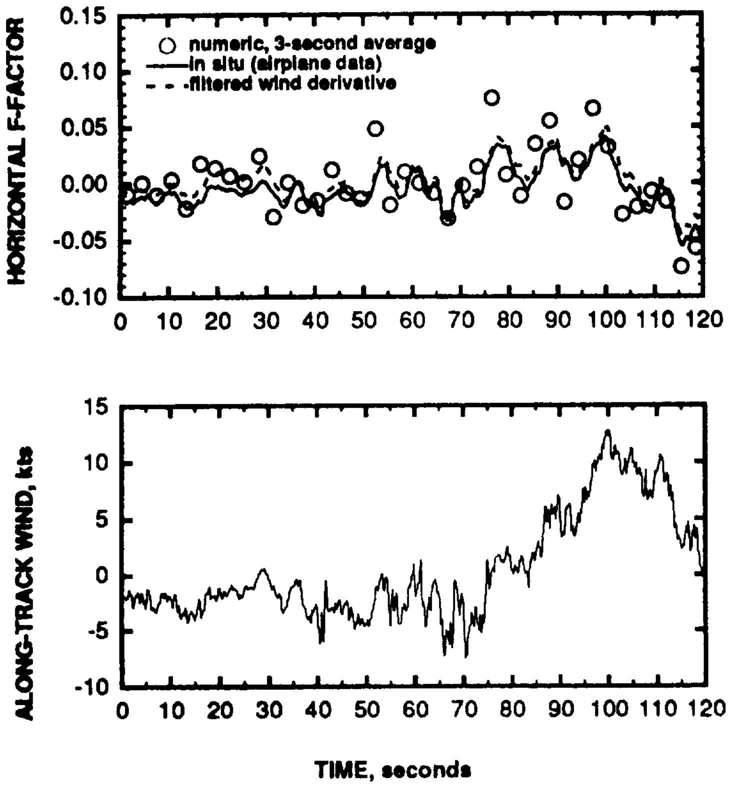
FLIGHT DATA, 20 JUN 91




Same analysis method as previous case, for event #143.

## MICROBURST PENETRATION

FLIGHT DATA, 17 JUN 91




Same analysis method as for previous case, for event #97.

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# ALGORITHM PERFORMANCE TO DATE

- OVER 100 FLIGHT HOURS COMPLETED
- APPROXIMATELY 320 TAKE-OFFS AND LANDINGS
- NO NUISANCE ALERTS GENERATED
- ALERTS GENERATED DURING MICROBURST PENETRATIONS CONFIRMED BY GROUND RADAR
- IN SITU HAZARD INDEX CONFIRMED BY WIND MEASUREMENTS

The in situ algorithm's performance is summarized as shown. The algorithm has operated on NASA's B737 for over 100 flight hours, included over 320 take-offs and landings. No nuisance alerts were generated during low-level flight (below 1400'AGL), which included flight in convective weather, gust fronts, and aggressive maneuvering; alerts were generated during microburst penetrations, and confirmed by an independent measurement (ground radar); analysis of in situ hazard index measurement showed that it compared well with hazard index from measured along-track wind.

# SUMMARY

## OBJECTIVES MET

- VALIDATED IN SITU ALGORITHM AS MEASUREMENT STANDARD FOR FORWARD-LOOK SENSOR EVALUATION
- DEMONSTRATED OPERATIONAL UTILITY

## DESIGN REQUIREMENTS MET

- MINIMIZED AIRCRAFT MANEUVER-INDUCED ERRORS IN HAZARD INDEX
- MINIMIZED EFFECTS OF TURBULENCE AND NON-HAZARDOUS ATMOSPHERIC MOTIONS
- STANDARD SENSOR IMPLEMENTATION

Results can be summarized by re-stating objectives and design requirements, which were satisfied as originally set forth.

## NASA Wind Shear Flight Test In Situ Results

Questions and Answers

**Q: Pete Sinclair (Colorado State University)** - I think you might want to be a little cautious about estimating the total F-factor from just the long track winds. Our flight measurements indicate that the vertical term can be as large or larger than the horizontal component and that can throw the F-factor to values above 0.15. Yours looks like that is suppressed quite a bit in the traces you have shown us.

**A: Rosa Oseguera (NASA Langley)** - Maybe there is a little bit of a misunderstanding. The overall F-factor that we were showing; the first one I showed, is a total F-factor. We are including the vertical term in there. The last slides that I showed where strictly for comparison purposes with the along-track winds. In those slides I was just using the horizontal portion of the F-factor to compare with. That is really all that we are computing from along-track winds. For the purpose of comparing with the forward-look sensors and for providing the alert, the total F-factor was used and that included the vertical term. In fact, that was shown on the block diagram. I just did not clearly point it out. The third term that was computed there was the vertical part of the F-factor.

**Q: Pete Sinclair (Colorado State University)** - How do you measure the vertical component?

**A: Rosa Oseguera (NASA Langley)** - It is computed from the difference between inertial flight-path angle and airmass flight-path angle, and groundspeed and airspeed. Roland did you want to expand on that?

**Roland Bowles (NASA Langley)** - The whole point is that we want to reject certain scales of motion. This measurement is the difference between the airmass and the inertial flight-path angles. This was a fourteen knot peak downdraft in that microburst. When you look at the airplane performance loss the In Situ system peaked out at about fourteen hundred feet per minute, which is about fourteen knots. In other words, that was the measurement of that microburst.

**Pete Sinclair (Colorado State University)** - What I am saying Roland, is that your system may not be seeing all of the vertical term?

**Roland Bowles (NASA Langley)** - We don't want it to see all of the vertical term. We don't want small scale turbulence to trip the system. We are not making a wind measurement, we are making a total energy change measurement on the airplane. That is what is hazardous to the airplane.

**Pete Sinclair (Colorado State University)** - But that vertical term is part of the total hazard to the airplane.

**Roland Bowles (NASA Langley)** - Sure, at the right scale. This was a small scale microburst. The vertical channel there shows you how the vertical term is estimated. Notice, we are not making wind measurements and processing winds. We are pulling from the backbone sensors on an airplane, the accelerometers and air-data system. We are not making a wind measurement and then processing the winds. You do not see winds anywhere in there. That's the key.

**Q: Jim Evans (MIT)** - There is a different issue which I think one has to be concerned about and that is the altitudes at which this testing was done. We know that some microburst have big thick outflows and some of them have much stronger outflows near the surface. We will be showing examples of that later in the conference. One of the questions that comes up is most of this testing was done at the minimum altitude of 1,000 feet, and yet in the context of the guidance we had for TDWR/LLWAS users group, that is the altitude at which people start to get concerned about Wind Shear. One of the questions that would come up is whether the agreement would be as good if you flew down at lower altitudes were we see much more evidence of strong pitching moments. If you look at the Dallas/Fort Worth crash traces for example, you see very strong eddies and things that were definitely effecting the plane at low altitude. So one of the questions I think you would have to ask is, to what extent can you extrapolate the measurements here, at about 1,000 feet altitude, down to much lower altitudes?

**A: Roland Bowles (NASA Langley)** - That is a good question. The evidence shows that the total energy change to the airplane stays about the same, because the vertical wind component diminishes as a function of altitude were as the horizontal gradient may peak at about 80 to 100 meters, but the overall performance loss is about the same; at normal approach speeds. We were making measurements at the point at which we were testing our sensors. We are not trying to characterize the relative threat level, we were making the In Situ measurement to use as a standard of goodness to compare to the predictions made by the remote sensors.

**Dan Vicroy (NASA Langley)** - The other point I would like to make is that the F-factor is a performance measurement and in reference to your comment about the pitching moment, that is more of a handling qualities problem and the F-factor is not going to reflect that at all.

**Roland Bowles (NASA Langley)** - Again, it is a scale of motion you are trying to identify.

**Pat Adamson (Turbulence Prediction Systems)** - This is just a point of clarification. The F-factor that you guys are talking about is slightly larger because of the airspeed you were flying. The airspeed plays a big factor in the magnitude of F.