Airborne Wind Shear Detection and Warning Systems

Fourth Combined Manufacturers' and Technologists' Conference

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NΛSΛ

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(NASA-CP-10105-Pt-2) AIRBORNE WIND
SHEAR DETECTION AND WARNING
SYSTEMS. FOURTH COMBINED
MANUFACTURERS' AND TECHNOLOGISTS'
CONFERENCE, PART 2 (NASA) 416 p

FOREWORD

The Fourth Combined Manufacturers' and Technologists' Conference was hosted jointly by NASA Langley Research Center (LaRC) and the Federal Aviation Administration (FAA) in Williamsburg, Virginia on April 14-16, 1992. The meeting was co-chaired by Dr. Roland Bowles of LaRC and Robert Passman of the FAA. Dan Vicroy of LaRC served as the Technical Program Chairperson and Carol Lightner of the Bionetics Corporation was the Administrative Chairperson.

The purpose of the meeting was to transfer significant ongoing results of the NASA/FAA joint Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements.

The present document has been compiled to record the essence of the technology updates and discussions which followed each. Updates are represented here through the unedited duplication of the vugraphs, which were generously provided by the respective speakers. When time was available questions were taken form the floor; if time was not available questions were requested in writing. The questions and answers are included at the end of each presentation. A general question and answer session was conducted at the end of each day and is included at the end of report along with closing remarks.

TABLE OF CONTENTS

Part 1*

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* Published under separate cover.

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Part 2

Session VII. Airborne LIDAR Technology

N93-14845

Two Micron Laser Development for Atmospheric Remote Sensing
at NASA Langley Research Center

Philip Brockman, NASA Langley Research Center

2 μm Laser Development for

Atmospheric Remote Sensing

at NASA Langley Research Center

Philip Brockman

Fourth Combined Manufacturers' and
Technologists' Airborne Wind Shear
Review Meeting
April 14-16, 1992

EYE SAFETY
REVISION OF INFRARED MPE

CURRENT ANSI STANDARD

λ	PULSE LENGTH (t)	MPE		LAWS
1.4 to 1000 μm	1 ns to 100 ns	10^{-2}	J/cm^2	0.015 J/cm^2 (2.1 μm, 600 ns)
	100 ns to 10 s	$0.56\ t^{1/4}$	J/cm^2	0.023 J/cm^2 (9.1 μm, 3 μs)
1.54 μm	1 ns to 1 μs	1.0	J/cm^2	

REVISED ANSI STANDARD

λ	PULSE LENGTH (t)	MPE		LAWS
1.4 to 1.8 μm	1 ns to 10 s	1.0	J/cm^2	0.1 J/cm^2 (2.1 μm, 600 ns)*
1.8 to 2.6 μm	1 ns to 1 ms	0.1	J/cm^2	
1.8 to 2.6 μm	1 ms to 10 s	$0.56\ t^{1/4}$	J/cm^2	
2.6 μm to 1 mm	1 ns to 100 ns	0.01	J/cm^2	0.023 J/cm^2 (9.1 μm, 3 μs)
2.6 μm to 1 mm	100 ns to 10 s	$0.56\ t^{1/4}$	J/cm^2	

*NOTE, MPE AT 2.1 μm INCREASED BY FACTOR OF 6

FOR 20-JOULE TRANSMITTER PULSE, 2-MICRON FLUX IS 1/133 OF NEW ANSI STANDARD AND 9-MICRON FLUX IS 1/575 OF NEW ANSI STANDARD.

Tm:Ho DYNAMICS CHARACTERIZATION

- **Spectroscopy**
  - absorption
  - emission
  - time / temperature dependent

- **Laser Experiments**
  - laser pumped
  - flashlamp pumped
  - reduced temperature

- **Modeling**
  - resonators
  - thermal
  - quantum mechanical
  - energy transfer dynamics

Q.M. MODEL CALCULATION

- Energy levels

- Electric and magnetic dipole transition probabilities

- Lifetimes

- Branching ratios

- Absorption spectra

- Emission spectra

Tm - Ho Energy Transfer Processes Being Considered

Inter-ionic Processes

Electronic Transitions
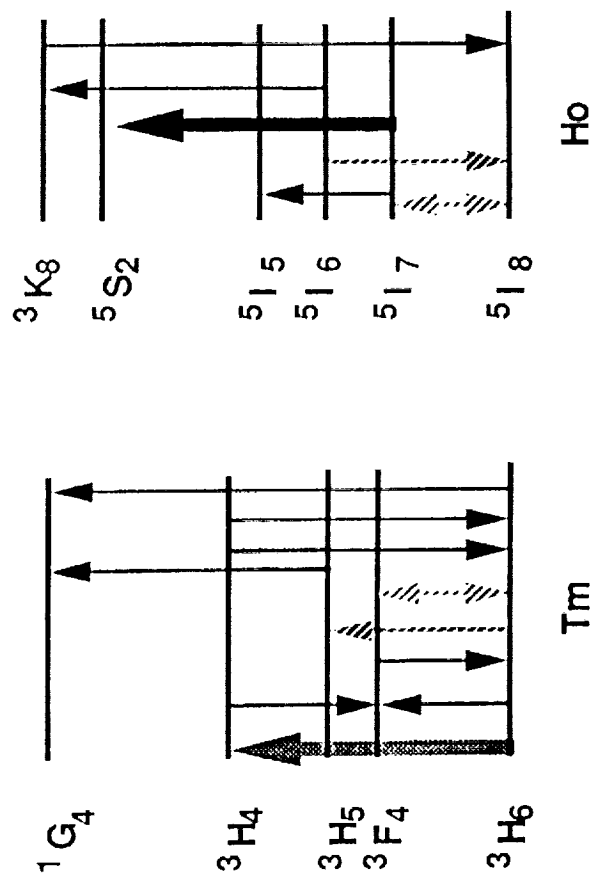
Processes connected to upper levels are newly added to model

Upconversion from the 5I7 Manifold Can Limit the Maximum Stored Energy
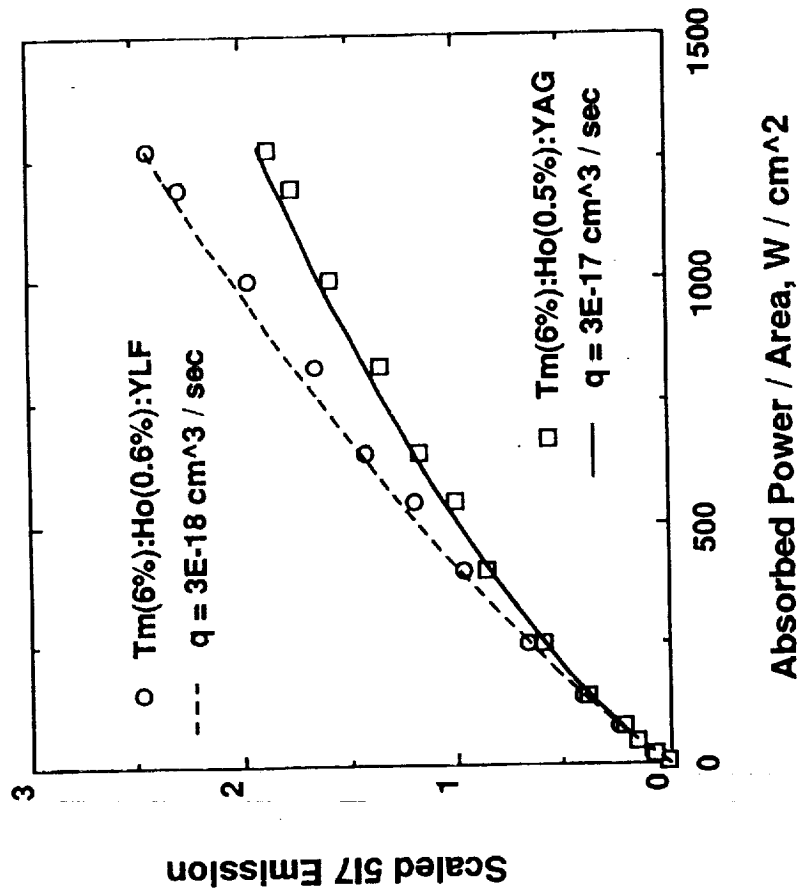
- CW diode excitation simplifies analysis

- Upconversion rate an order of magnitude less in YLF

- At higher pump fluences must include effects of ground state depletion

Scaled 5I7 Emission vs. Absorbed Power / Area, W / cm^2

○ Tm(6%):Ho(0.6%):YLF
- - - q = 3E-18 cm^3 / sec

□ Tm(6%):Ho(0.5%):YAG
q = 3E-17 cm^3 / sec

623

Maximum Energy Extraction Efficiency Can Be Optimized for the Disk Amplifier

N/\S/
Langley Research Center

Oscillator Radius = 0.1 cm

Pump Energy = 1.2 J

Room Temperature
Maximum Energy
Extraction Efficiency

9	> 4.0
8	0.36 - 0.40
7	0.32 - 0.36
6	0.28 - 0.32
5	0.24 - 0.28
4	0.20 - 0.24
3	0.16 - 0.20
2	0.12 - 0.16
1	0.08 - 0.12
0	< 0.08
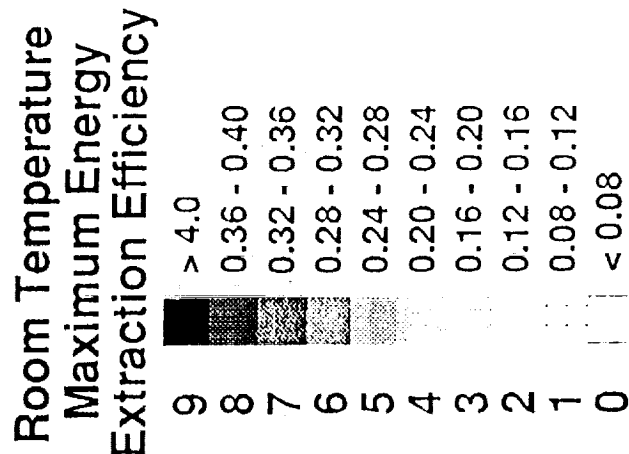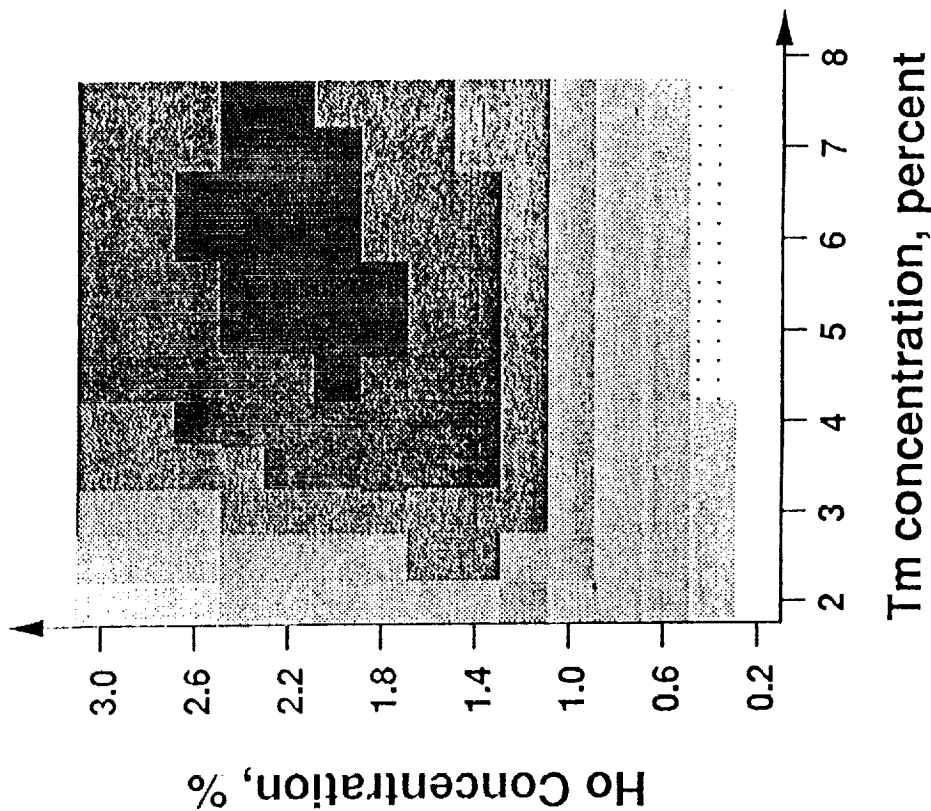
At fixed Ho concentration, efficiency rolls off due to diminished Tm-Ho transfer

At fixed Tm concentration, efficiency rolls off due to ground state absorption

Ho Concentration, %

Tm concentration, percent

624

Heat Propagation in a Laser Rod

End-pumped Single Pulse
Gaussian Cross Section

Time = 0.0 Seconds

Time = 0.01 Seconds

Time = 0.02 Seconds
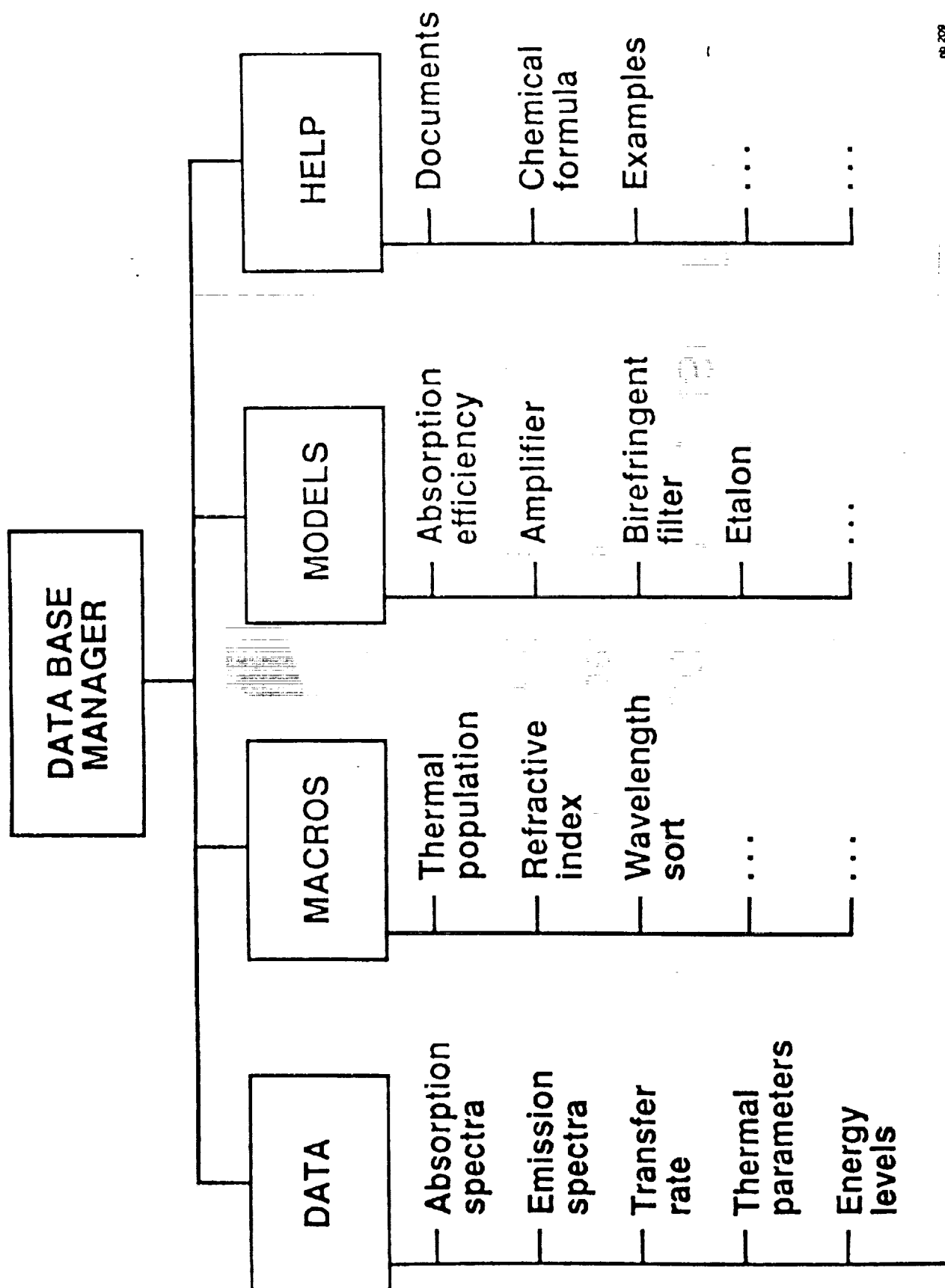
INJECTION LOCKED OSCILLATOR-AMPLIFIER SYSTEM

PROVIDES SINGLE FREQUENCY SOLID STATE LASER

627
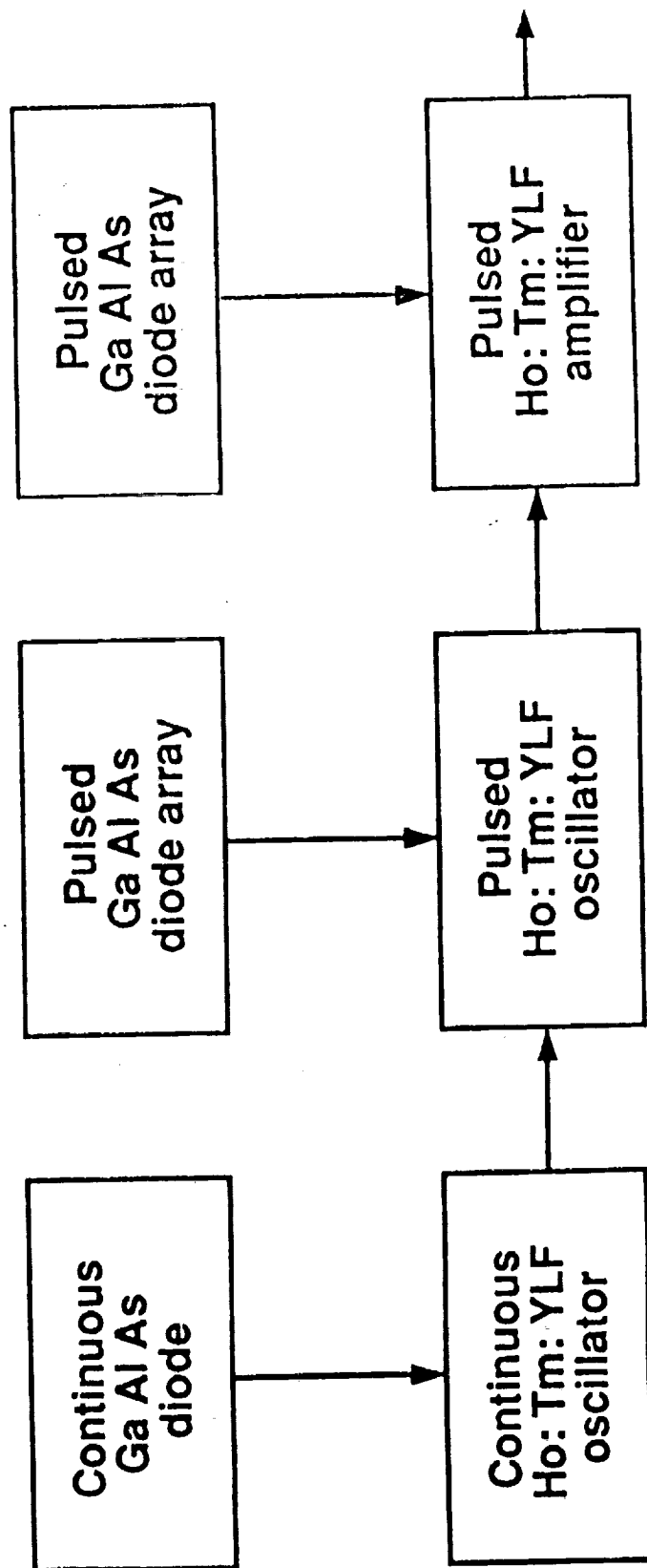
- Seed laser
  - single frequency demonstrated
  - 10 mW demonstrated

- Power oscillator
  - $1.0 \mu sec$ pulselength at 30 mJ
  - diode pumped laser head fabricated

- Amplifier
  - Ho and Tm concentration optimized
  - disk configuration selected

- Supporting activities
  - Cr: Be Al_2O_4 pumped Ho: Tm: YLF
  - spectroscopy
  - quantum mechanical model

628

4% Duty Cycle
0.4 mm Pitch (6) Bar Array
on 0.5 cm x 1 cm Cooler

The figure is a plot of Power (W) versus Current (A).

- Y-axis: Power (W), with marks at 0, 100, 200, 300
- X-axis: Current (A), with marks at 0, 20, 40, 60, 80, 100

Annotations:
- 360 Watts
- 4% Duty Cycle
- 1500 W/cm^2
- (Stack S052)

630
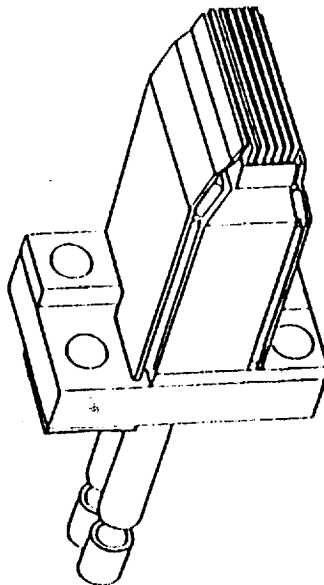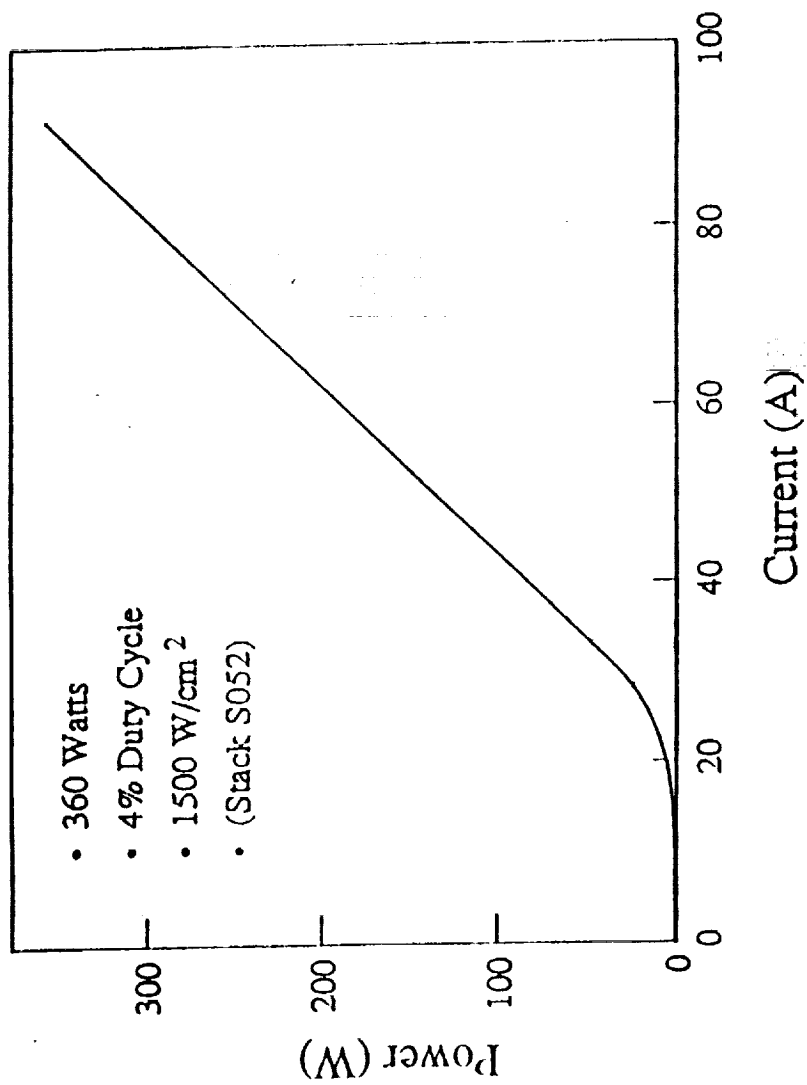
I_{op} = 80 A
$T_{coolant}$ = 16°

τ_{PW} = 200 µs
f = 200 Hz

τ_{PW} = 500 µs
f = 80 Hz

τ_{PW} = 1000 µs
f = 40 Hz

780   785   800

Wavelength (nm)
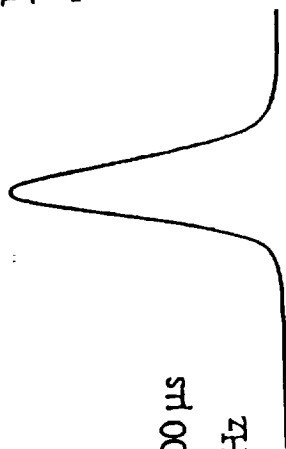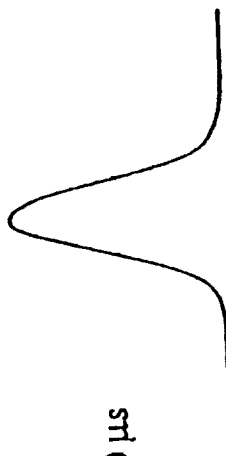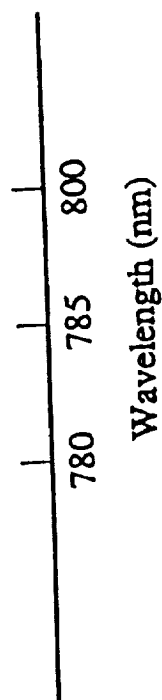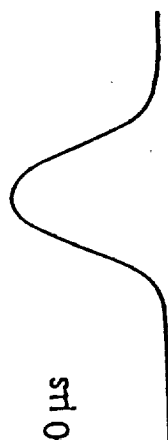
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NASA/LMSC Instrument Design & Fabrication

Dr. Russel Targ, Lockheed Missiles and Space

CLASS

COHERENT LIDAR AIRBORNE SHEAR SENSOR

WINDSHEAR AVOIDANCE

APRIL 1992

Prepared by

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CLASS-10 FLIGHT TEST PROGRAM

- **OBJECTIVE IS FOR NASA/FAA TO EVALUATE PERFORMANCE OF LIDAR TO DETECT AND CHARACTERIZE WINDSHEAR EVENTS**

  - USE OTHER SENSORS: X-BAND DOPPLER, INFRARED RADIOMETER, REACTIVE SENSORS

  - GROUND TRUTH PROVIDED BY TDWR AND LLWAS

- **FLIGHT TEST PROGRAM IN SUMMER 1992**

  - WET MICROBURSTS AT ORLANDO

  - DRY MICROBURSTS AT DENVER

- **THREE ENGINEERING FLIGHTS TO DATE**

  - WIND VELOCITY DATA TAKEN AT 10-km RANGE

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AIRBORNE WINDSHEAR DETECTION:
GENERAL REQUIREMENTS

- **MEASURE LINE-OF-SIGHT COMPONENTS OF WIND VELOCITY FROM AIRCRAFT**

- **DETECT THUNDERSTORM DOWNBURST EARLY IN ITS DEVELOPMENT**

- **EMPHASIZE AVOIDANCE RATHER THAN RECOVERY**

- **RESPOND IN REAL TIME WITH LOW FALSE-ALARM RATE**

- **MONITOR APPROACH PATH, RUNWAY, AND TAKEOFF PATH**

- **OPERATE IN BOTH RAIN AND CLEAR-AIR CONDITIONS**

- **OPERATE RELIABLY WITH MINIMUM MAINTENANCE IN AIRCRAFT ENVIRONMENT**

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CLASS SYSTEM REQUIREMENTS

- **RANGE OF THE SYSTEM SHOULD BE:** 4 km IN CLEAR AIR

  2 km IN RAIN 0.5 in./h

- **WARNING — AT LEAST 20 s IN ADVANCE TO PILOT**

- **RANGE RESOLUTION SHOULD BE 300 m, FOR MICROBURST STRUCTURE**

- **MAXIMUM RADIAL VELOCITY ERROR <1 m/s, FOR F-FACTOR HAZARD**

- **DESIGN OF SYSTEM SHOULD BE CONSISTENT WITH COMMERCIAL AVIATION USE**

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APPLICATIONS OF ONBOARD LIDAR

- DETECTION AND AVOIDANCE OF WINDSHEAR AND TURBULENCE HAZARDS

- COLLISION AVOIDANCE ON THE GROUND IN FOG

- DETECTION OF WAKE VORTICES FROM OTHER AIRCRAFT

- DETECTION OF VOLCANIC ASH

- GROUND PROXIMITY INDICATION

- LOAD ALLEVIATION

- CLEAR-AIR TURBULENCE DETECTION AT ALTITUDE (WITH SOMEWHAT INCREASED LASER ENERGY)

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DOPPLER WIND-VELOCITY MEASUREMENT

The CLASS coherent detection system uses a CO_2 laser that transmits a train of 2.0-μs pulses at a 100-Hz rate. These transmitted pulses, at a frequency f_t, will be scattered by the aerosols in the air being illuminated. The frequency of the optical signal will be Doppler shifted by an amount of f_w, which is proportional to the wind velocity. An additional frequency shift f_p, will be caused by the plane's velocity.

This signal, at a frequency $f_t + f_w + f_p$, will be received by the transmitting telescope. It will then be detected and mixed with a stable laser local oscillator at a frequency of $f_t + 70$ MHz, to place the resulting beat well above baseband and retain the direction as well as the velocity of the wind being sensed.

After photodetection, the signal will be mixed with a radiofrequency (RF) signal f_p determined by the onboard flight computer. This will subtract out the frequency component due to the plane's velocity. The resulting frequency will be the desired Doppler shift introduced by the wind velocity.

DOPPLER WIND VELOCITY MEASUREMENT

AEROSOLS AT WIND VELOCITY V_w

$f_t + f_p \pm f_w$

f_t

LASER TRANSMITTER

$f_t - 70$ MHz

LASER LOCAL OSCILLATOR

DETECTOR

$f_w + f_p + 70$ MHz $\simeq 90 \pm 5$ MHz

MIXER

$\pm f_w + 70$ MHz $\simeq 70 \pm 5$ MHz

f_p

GROUND SPEED

X00047/001PGM

641
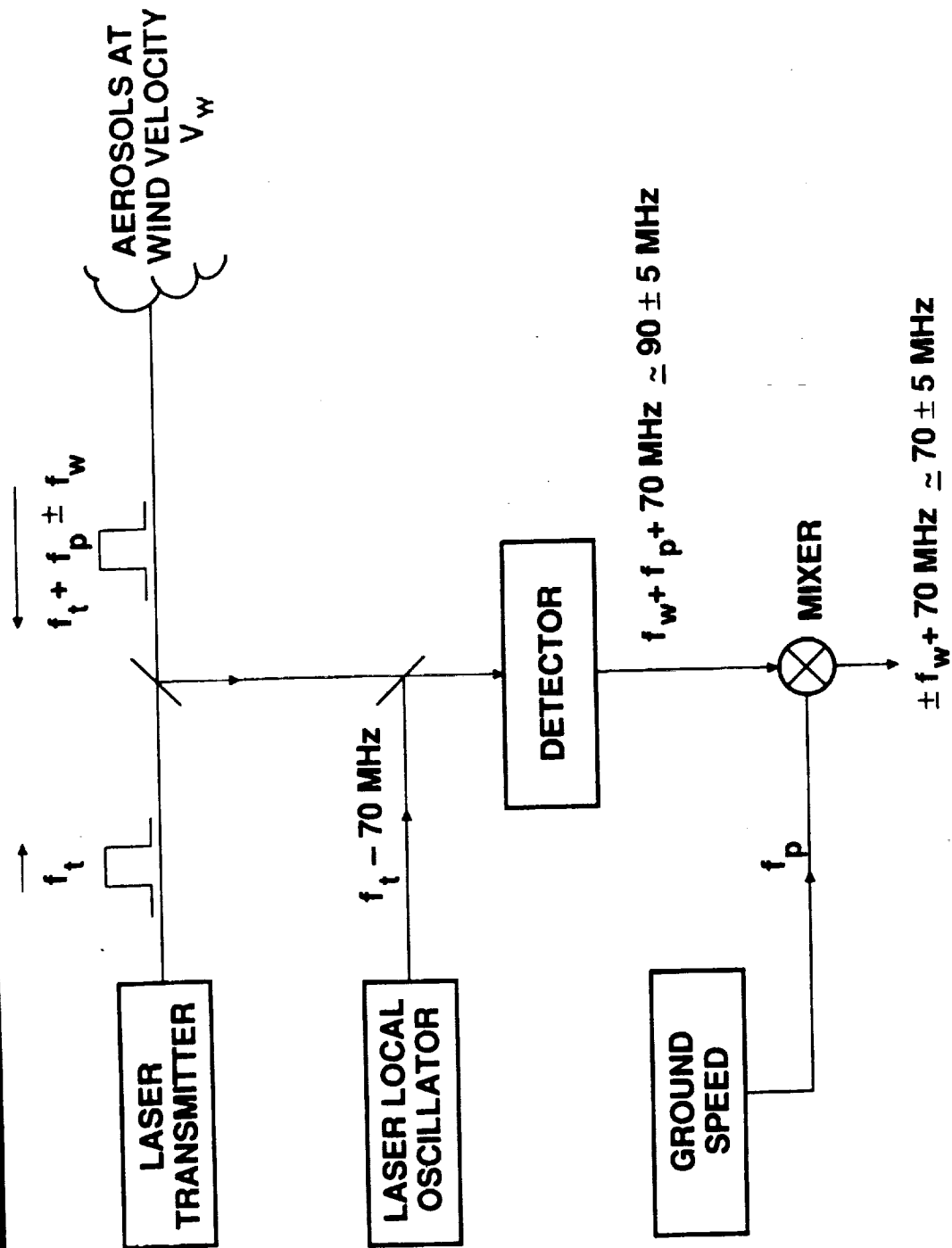
COHERENT DETECTION WITH A Q-SWITCHED CO$_2$ LASER

The CLASS system uses a Q-switched RF-excited CO$_2$ laser as its signal source. A small frequency-stabilized CO$_2$ laser local oscillator controls the output frequency of the laser transmitter and maintains a precise frequency offset. The lasers are sealed and are capable of 2,000 h of operation. The HgCdTe detector is cooled by a mechanical cooler. Neither liquid-nitrogen nor compressed-gas cooling is used. All signal processing of the Doppler wind data is completed in real time by the CLASS onboard computer, built by Lassen Research.

The entire laser package has a volume of 2.5 ft^3 and weighs less than 100 lb. It is designed and built by United Technology Optical systems.

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642

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BLOCK DIAGRAM USING PULSED LASER

ATMOSPHERE

SCANNER

TELESCOPE

QUARTER WAVE PLATE

ν

$\nu + \Delta\nu$

BREWSTER WINDOW BEAM SPLITTER

SCAN AND PULSE CONTROL

Q-SWITCHED LASER

LOCAL OSCILLATOR LASER

PZT FREQUENCY CONTROL

OFFSET LOCKING LOOP

DETECTOR

IF AMPLIFIER

SIGNAL PROCESSOR

ON-LINE COMPUTER COMPARATOR

DISPLAY

SIGNAL PROCESSOR AND DISPLAY

X00237ML

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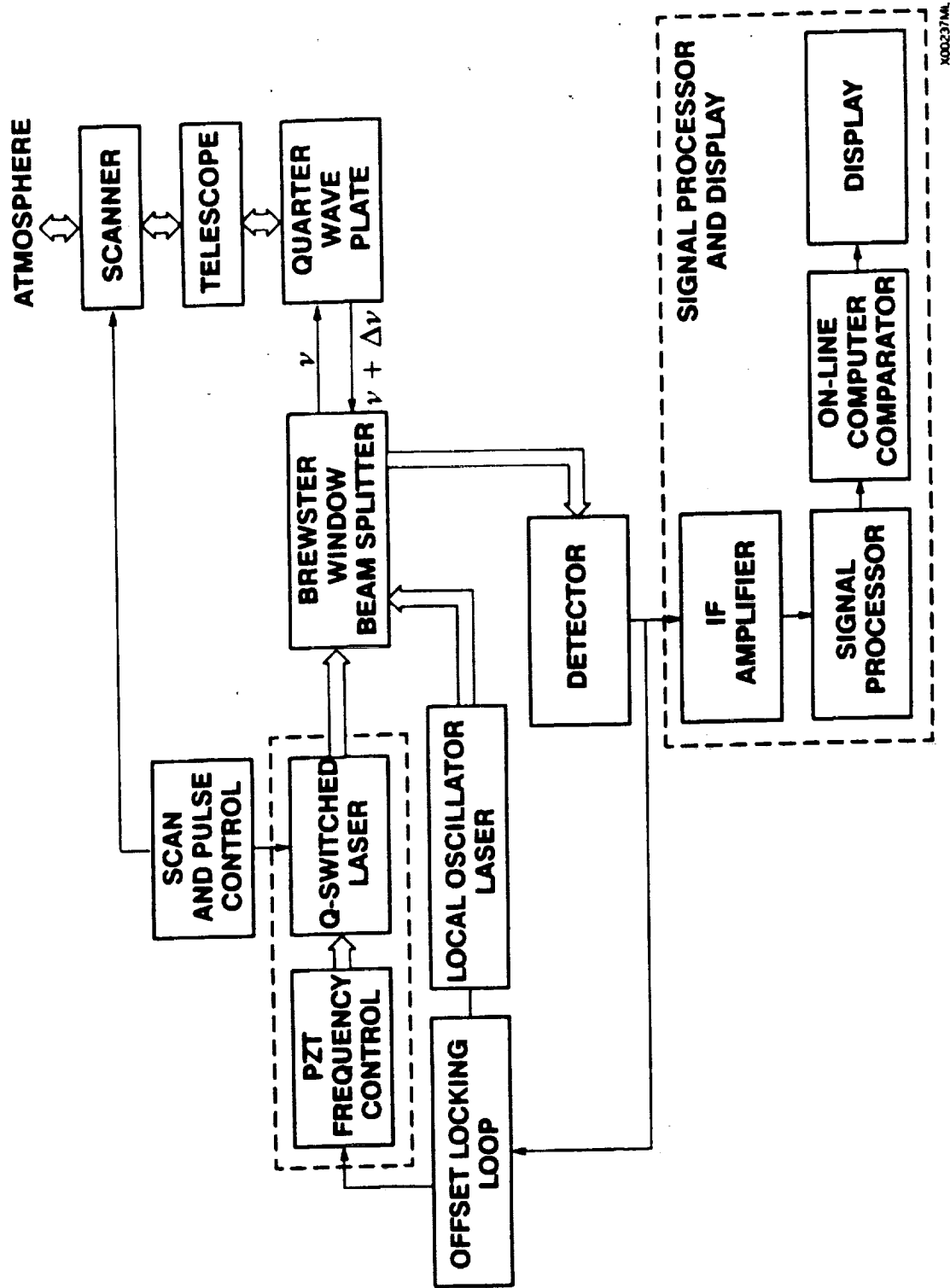
SYSTEMS SPECIFICATIONS RATIONALE

DESIGN ELEMENT	SELECTION	REASON
WAVELENGTH	10.6 μm	EYE SAFETY/MATURITY
LASER TYPE	RF-WAVEGUIDE	RELIABILITY
PULSE ENERGY	10 mJ	4-km RANGE
PULSE DURATION	2 μs	300 m RES./ <1 m/s VELOCITY ERROR
PULSE REPETITION RATE	100 Hz	COVERAGE/PULSE AVERAGING
DETECTOR	PV HgCdTe	QUANTUM NOISE LIMITED PERFORMANCE
COOLING	LIN. MECH. REFRIG.	NO EXPENDABLES
TELESCOPE DIAMETER	15 cm	APPROPRIATE FOR 4-km RANGE
TELESCOPE TYPE	OFF-AXIS PARABOLOID	COST
SCANNING CAPABILITY	50° NOMINAL	MICROBURST GEOMETRY
SIGNAL PROCESSOR	POLY-PULSE PAIR	EXPERIMENTAL FLEXIBILITY
LASER LIFETIME	>2000 h	DEMONSTRATE OPERATIONAL PERFORMANCE

SIGNAL-TO-NOISE EQUATION FOR REMOTE ATMOSPHERIC SENSING LASER VELOCIMETER

$$SNR\ (R) = \frac{E\eta\beta(R)\lambda K^2 \pi D^2}{8\ hB_N R^2}\left[1 + \left(\frac{D}{2S_0}\right)^2 + \left(\frac{\pi D^2}{4\lambda R}\right)^2\left(1 - \frac{R}{F}\right)^2\right]^{-1}$$

where:

E = laser pulse energy (J)

D = telescope diameter (m)

$\beta(R)$ = backscatter coefficient ($m^{-1}\ sr^{-1}$)

λ = laser wavelength (m)

η = detector heterodyne and quantum efficiency

K = extinction for range R (1/m)

B_N = system narrow bandwidth ($1/\tau$)

h = Planck's constant

S_0 = transverse coherence length of the received field (m)

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VARIATION OF SIGNAL-TO-NOISE RATIOS AND
TRUE WIND VELOCITY WITH DISTANCE

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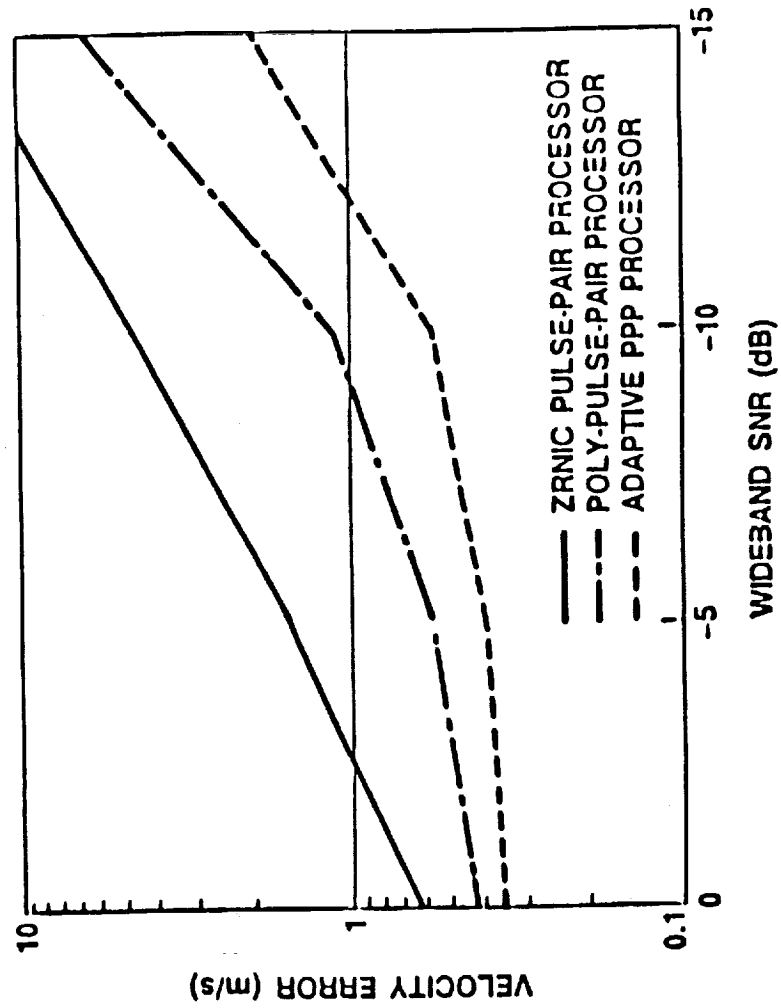
FINAL CLASS OPTOMECHANICAL DESIGN
ON NASA B/737

Lockheed

RADD

FUSELAGE

POWER SUPPLIES
AND COOLER

PALLET

LASER TRANSCEIVER

OUTPUT BEAM

55 in.

FOLD MIRROR

AZIMUTH
DRIVE MOTOR

TAIL FAIRING

SCANNER

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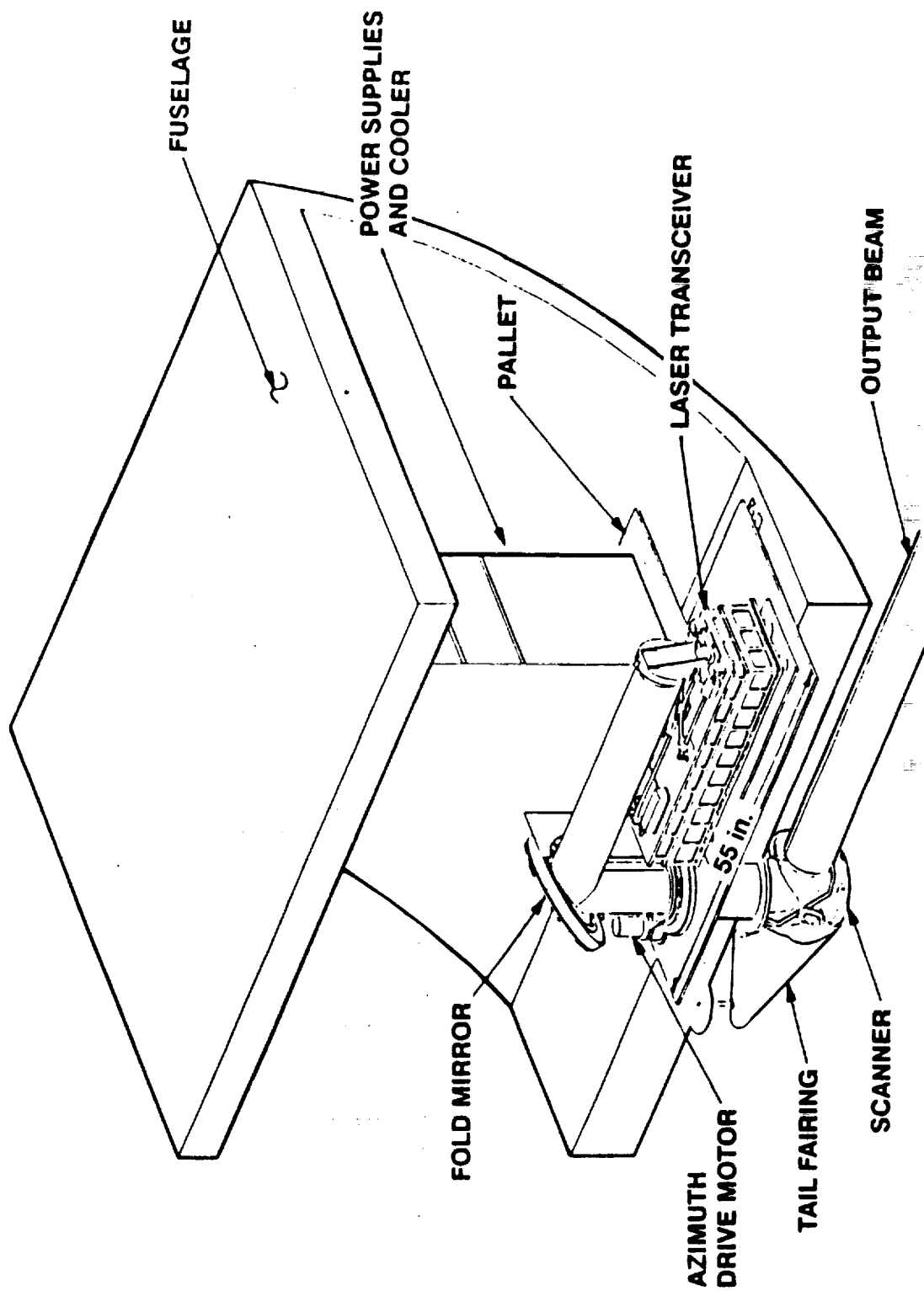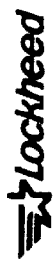
CLASS LASER WINDSHEAR DETECTOR BLOCK DIAGRAM

R&DD

SIGNAL PROCESSOR rack
- RF-IF Board
- Signal Processor
- CPU & 12 bit A to D
- Output & Memory

OPTICAL HEAD CRH50 DAY
- Laser & Receiver
- Scanner
- Control Unit

Signal

Signal

POWER & COMMAND

status/hsk

DIGITAL EXABYTE VCR TAPE RECORDER (2.3 GIGABYTES) rack

Ethernet

GROUND STATION
- Exabyte Recorder
- Sun Workstation
- Hard Copy Facility
- Fusion Facility

Operator Console rack
- Terminal
- Floppy Drive
- Color Monitor
- Cockpit Display
- Power & DATAC Input & A/D Conversion
- Control & Display of Laser & Scanner

AIRCRAFT (NASA 515)
- DATAC & Power
- Cockpit Instrumentation

649

RANGE-AZIMUTH DISPLAYS

The following page shows simulated range-azimuth displays for a 30-knot "dry" Denver/Stapleton microburst illuminated by a 5-mJ CO_2 lidar which is 4 km from the core of the microburst. (The simulations are by Coherent Technologies, Inc.)

The top figure is a **50°** segment of a plan position indicator (PPI) scan with a scan angle of $\pm 25°$ (in 5° increments). The "dry" microburst is clearly delineated. The range resolution is 300 m, and wind velocities are measured out to 7 km.

The lower figure shows the windshear hazard index in red for values of F greater than 0.1. Under these conditions, a modern twin-engine passenger jet can no longer maintain level flight.

HAZARD INDEX

Outputs from the windshear computer will include wind-velocity information for each measured range increment. Thus, the change in w_x (the radial wind vector) will be calculated. The value of w_h (vertical wind) is not measured.

The onboard windshear detector must be given the aircraft's attitude and air speed from the inertial navigation system in order to provide a continual update of its calculation of the hazard index F:

$$F = \dot{w}_x/g - w_h/V$$

where $\dot{w}_x$ is the d/dt of the radial wind, w_h is the vertical wind, V is the aircraft's air speed, and g is the acceleration due to gravity (20 knots per second).

The lidar, together with an algorithm for inferring w_h, gives a complete picture of the windshear hazard.

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RANGE-AZIMUTH DISPLAY FOR A 30-kt "DRY" DENVER STAPLETON MICROBURST, ILLUMINATED BY A 5-mJ CO_2 LIDAR 4 km FROM THE MICROBURST CORE
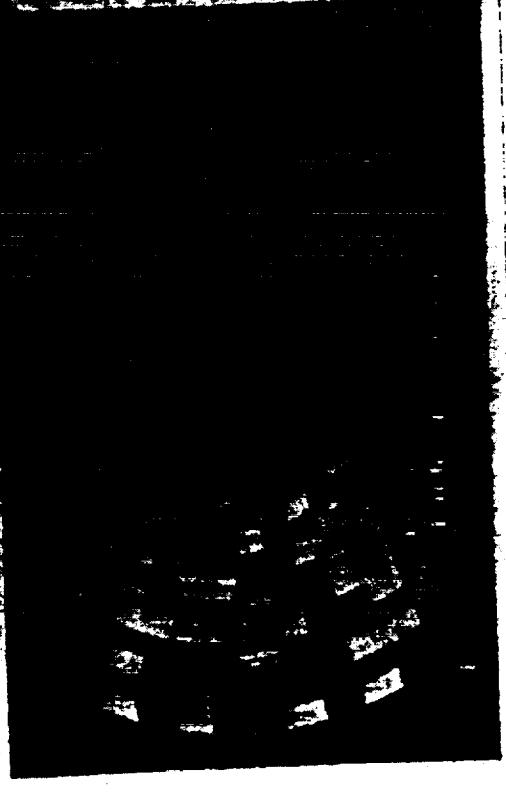
COHERENT LIDAR AIRBORNE SHEAR SENSOR (CLASS) SNR VS. RANGE: 10.6 μm, 8.5 mJ, 10 km AEROSOL RETURNS AT NASA, HAMPTON, VA

Lockheed

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652

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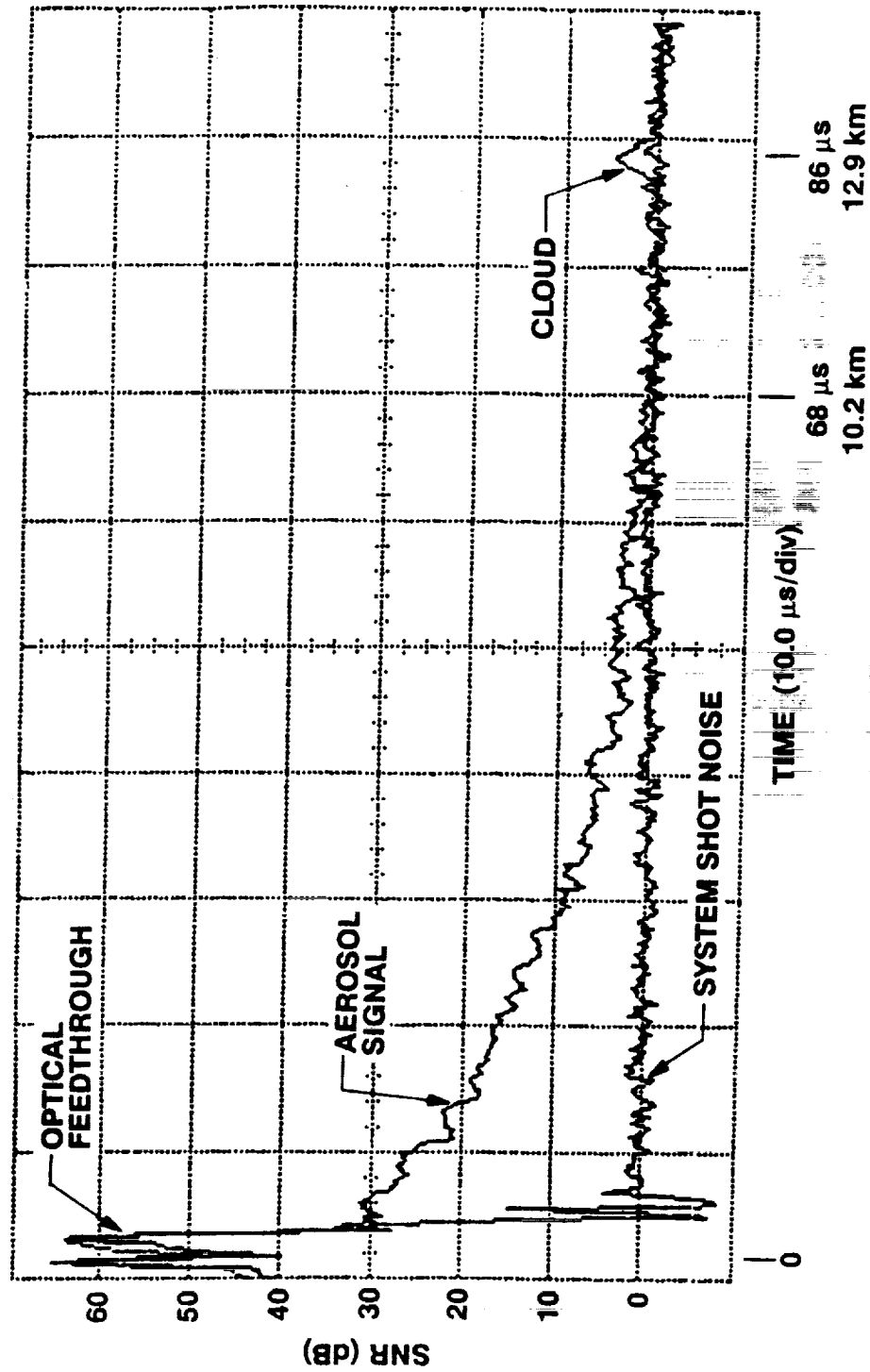
ATTENUATION DUE TO FOG

The data shown here illustrate the measured attenuation experienced by lasers of three different wavelengths. The critical fact to notice is that as the fog increases in density to the point where the red laser, with a 0.63-μm wavelength, is attenuated by more than 40 decibels, the CO_2 laser, at 10.6-μm wavelength, has less than 3-decibel loss.
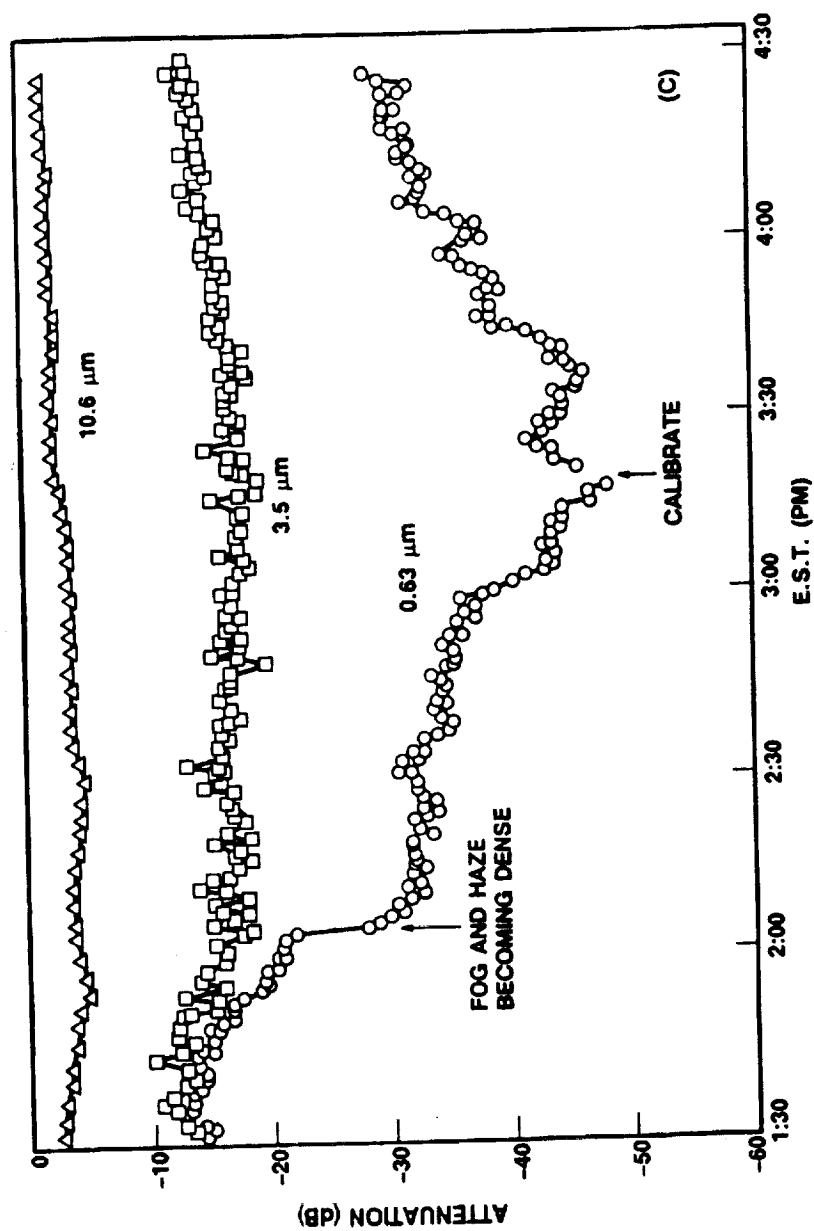
ATTENUATION DUE TO RAIN AND FOG

The data in this figure show the attenuation due to rain and fog for signals across the electromagnetic spectrum. Of particular interest is the attenuation for infrared radiation at 10.6 μm. At this wavelength, and a rain rate of 1 in. per hour, the attenuation is approximately 8 decibels per kilometer.
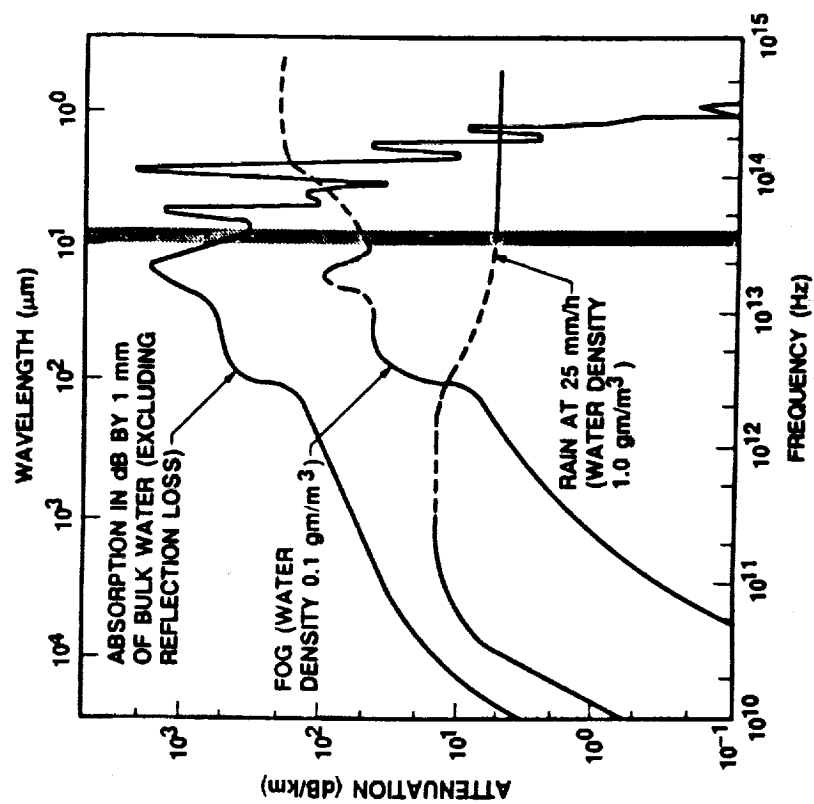
From T. S. Chu and D. C. Hogg, BSTJ, May 1968

RANGE IN RAIN OF A 10.6-μm SYSTEM WITH A 10-mJ CO_2 LIDAR

It is well known that the 10.6-μm radiation from CO_2 lasers is attenuated by rain, and that will limit the usefulness of such systems in conditions of heavy rain. A systems analysis of an integrated windshear detection and avoidance system will take this into account. The figure shows the effects of rain on range, and indicates that a 10-mJ CO_2 lidar is able to penetrate rain of moderate levels for a sufficient distance to give a warning of 10 to 20 s to a pilot flying into a potentially dangerous situation.

655
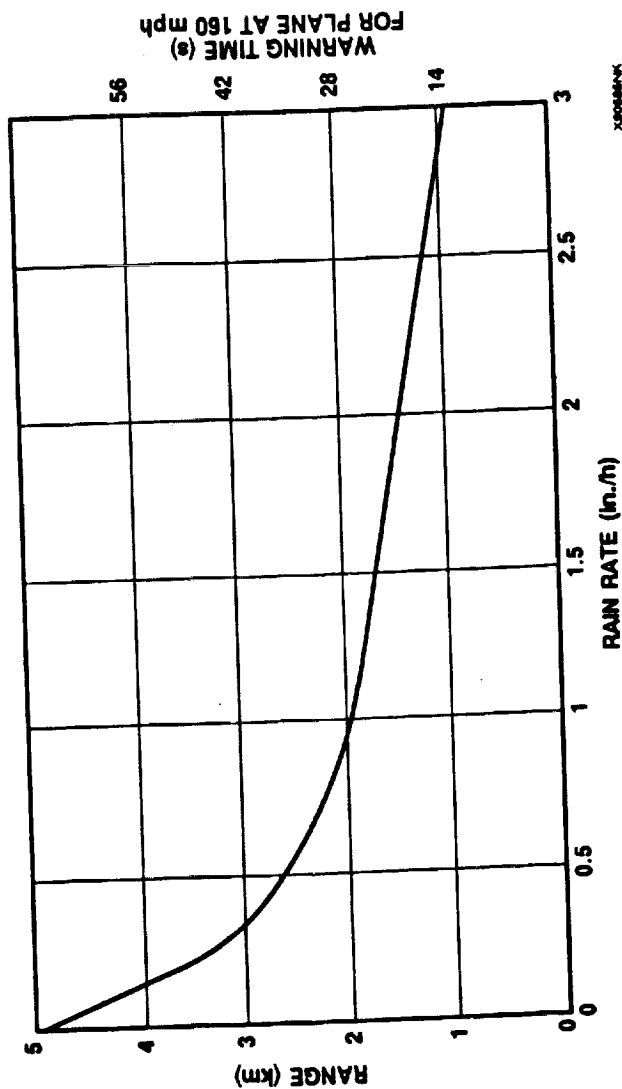
NASA/LMSC Instrument Design & Fabrication
Questions and Answers

Q: Bob McMillan (Georgia Tech) - Unless it has been improved lately, the NOAA LIDAR has had some problems maintaining alignment. Specifically, it is difficult to keep the receiver spot and the local oscillator single mode pattern aligned on the detector. How are you going to be able to solve these problems considering that your LIDAR operates in a harsher environment?

A: Russell Targ (Lockheed) - It is a two part question, one part pertains to the laser that we built with United Technology, the other part is the design of the laser that we are building with CTI now. The laser that we are presently operating on the NASA aircraft is a CO_2 laser that resides in a monolithic aluminum shell. The laser itself has very carefully designed mirrors, and a low center of gravity. The mirror spacing and alignment of the laser cavity is actively measured and compensated for. We are not troubled with problems of thermal drift because the laser is water cooled with a very carefully regulated chiller and any residual motion is taken out by the active frequency stabilization. The cavity is carefully controlled with regard to its expansion by the chiller and the alignment of the inner phorometer doesn't change once this thing has come up to equilibrium. This is a fair question, recognizing that we have a meter long aluminum block and aluminum should basically be considered as butter if it is sitting out in the atmosphere. But the ordinary commercially available chiller is able to maintain the temperature even in the harsh environment of the cargo bay to within a quarter degree centigrade. Our experience is that even in that terrible environment where the air temperature is varying over 20 degrees centigrade we are able to maintain the system in alignment for the duration of a flight. The reason that we are having better success than the NOAA laser, which has done yeoman service for many years, is that the mounts of the NOAA laser are basically lollipop kind of mounts, up on stands, using commercial equipment. That laser is indeed maintained by several PhD's who have grown up and lived with the laser. Where as, ours is designed specifically to have very stable operation.

Q: Kim Elmore (NCAR) - How mature is laser technology compared to the set it and forget it state of radar technology? When will such a system be commercially available? How will this system compare with radar system costs? How sensitive is such a system to the degradation from bugs and dirt that would get on the window? How much power does it consume?

A: Russell Targ (Lockheed) - Well radar technology is 50 years old and laser technology is 30 years old. So, radar technology is more mature. On the other hand, there are things that a 30 year old can do that a 50 year old can't do as well. There are hundreds of thousands of lasers in CD players and tens of thousands of lasers in supermarkets and thousands of laser range finders in tanks, none of which get any maintenance at all. The supermarket checker does not have to touch his laser scanner, the GI in the tank does not have to touch his laser range finder. So, a lot of progress has been made in the optimechanical design of laser radar systems and laser systems are in general. It took about a decade for people to realize how you build kinematic mounts and apply them to lasers, how you provide frequency stabilization, and how you solve those kinds of problems. I would say that with regard to many laser systems they have achieved the set it and forget it technology. When will such a system be commercially available? I presume that such a system pertains to an airborne laser radar for wind shear measurement. The system that I showed,

which is a 200 pound, kilowatt consuming, CO_2 system, is not intended as a commercial system for the world airline fleet. I think that would not be a sensible application. We are developing together with CTI a two micron system that would meet the same performance requirements as I described earlier. That system will be certified we anticipate in 1995 and available for sale at that time. How will this system compare with radar system costs? I of course have no idea what radar systems cost. We have spoken to a number of airline executives and they have described what they would consider as an acceptable price for a solid state laser system that can measure wind shear as well as clear air turbulence. We are able to build a system and sell it for prices that airlines consider acceptable. If you need more information there are two people here from Lockheed Austin Division who will be happy to discuss it with you and take your order. How sensitive is such a system to the degradation from bugs and dirt that would get on the window? No doubt about it, you are going to have to wipe off the window just as you have to wipe off the windshield. In our limited experience, flying now through three flights, the hard coated window of our scanner is simply wiped off with a rag. It has not had any special attention and we have not observed degradation of the performance. How much power does it consume? The answer is about three hundred watts. That would be the commercial unit.

Q: Jim Evans (MIT) - How does one determine the dBZ for lasers, and make it equivalent to radar dBZ as a function of rain intensity. Since the rain drops are much greater than the wave length. dBZ is usually measured only for Rayleigh scattering?

A: Russell Targ (Lockheed) - It is all perfectly true. We don't measure dBZ for LIDAR. We erroneously showed an intensity chart with dBZ which is simply left over from its previous incarnation from a radar system. What we are plotting in the color bar on the right side, is dB of the signal noise ratio received at our coherent receiver. The signal to noise ratio goes typically from 50 dB for hard targets to zero dB where we can no longer use it. A proper scale should say is zero to fifty dB and not dBZ at all. That is our error. LIDAR aren't measuring things in dBZ.

Q: Jim Evans (MIT) - What is the pulse spacing of your LIDAR? I don't understand how pulse pair approaches can be used with lasers given the very high Doppler velocities and the long distance between pulses.

A: Russell Targ (Lockheed) - The pulse spacing is ten milliseconds because of the hundred hertz laser. I have almost nothing useful to say about the algorithms behind the poly pulse pair processor. I think that I know just enough to answer your question. The poly pulse pair processor is really misnamed. It is not a processor looking at several pulses. What it does is look at several lags and perform an autocorollation on each pulse, several times per pulse. Rather than looking at it and simply doing an FFT on that pulse. It is not a pulse comparison technique, it takes several looks at each pulse, does an autocorollation analysis and drives the answer that way. So, we are not looking at one pulse after another.

N93-14847

NASA/LMSC Coherent LIDAR Airborne Shear Sensor:
System Capabilities and Flight Test Plans

Dr. Paul Robinson, Lockheed Engineering & Sciences

NASA/LMSC Coherent Lidar Airborne Shear Sensor:

System Capabilities and Flight Test Plans

Paul A. Robinson

Lockheed Engineering & Sciences Co., Hampton, Virginia

Overall Objectives of the Flight Tests

The primary objective of the NASA/LMSC[1] Coherent Lidar Airborne Shear Sensor (CLASS) system flight tests is to evaluate the capability of an airborne coherent lidar system to detect, measure, and predict hazardous wind shear ahead of the aircraft with a view to warning flight crew of any impending dangers. On NASA's Boeing 737 Transport Systems Research Vehicle, the CLASS system will be used to measure wind velocity fields and, by incorporating such measurements with real-time aircraft state parameters, identify regions of wind shear that may be detrimental to the aircraft's performance. Assessment is to be made through actual wind shear encounters in flight.

Wind shear measurements made by the CLASS system will be compared to those made by the aircraft's in situ wind shear detection system as well as by ground-based Terminal Doppler Weather Radar (TDWR) and airborne Doppler radar. By examining the aircraft performance loss (or gain) due to wind shear that the lidar predicts with that actually experienced by the aircraft, the performance of the CLASS system as a predictive wind shear detector will be assessed.

The CLASS System

Definition

The CLASS system is required to measure wind shear ahead of an aircraft and relate that measurement to the effect on the aircraft's performance. In addition the system must be

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[1]National Aeronautics and Space Administration/Lockheed Missiles and Space Co.

able to combine these measurements with current aircraft state parameters to predict the effect on aircraft performance.

The CLASS system comprises a CO_2 laser radiating with a pulse energy of 10 mJ at a wavelength of 10.6 μm and pulse length of 2 μs, and employing optical heterodyne detection. The range resolution is 300 m, and the velocity error is required to be less than 1 m/s. The range can extend to 10 km (depending on aerosol size and density conditions), and the scan can be centered $\pm 90°$ about the aircraft nose with an azimuth sweep of up to $\pm 50°$. Velocity estimation uses a poly-pulse pair algorithm (Reference 1). The system is described in detail in Reference 2.

The capability to read data tapes recorded in flight and reproduce all events seen in flight is available on a ground-based workstation. Reprocessing of the data in order to assess alternate calculation algorithms is also possible.

Measurement Capabilities and Wind Shear Products

This section describes how the CLASS system uses wind velocities measured by the coherent lidar, and produces a higher level wind shear detection product quantifying the effect of the wind field on the aircraft's performance.

The high level measurements of interest made by the system are Doppler return intensities and line-of-sight wind velocities. The relation between the wind shear and the aircraft's performance is given by the F-factor, F, (Reference 3)

$$F = \frac{\dot{W_i} \cdot \hat{e}_i}{g} + \frac{W_z^i}{V_a}$$

The first term is the time rate of change of the inertial wind vector along and in the direction of the airspeed vector, and the second term is the ratio of the inertial vertical wind speed to the airspeed. Forward looking wind shear detectors can measure the wind field at some region ahead of an aircraft and calculate an F-factor as follows.

Doppler return frequencies are processed to provide velocities at 300 m intervals (Δr). The processing of the return signals to yield velocities is described in Reference 1. The first term in the F-factor (the 'horizontal' term, F_h) may be approximated by differencing

wind velocities, v, along a lidar measurement radial. The value at the ith range bin is given by

$$F_{h_i} = \frac{v_{i+2} - v_i}{2\Delta r}\frac{V_G}{g}$$

The differencing scheme arises from using an unweighted least-squares fit over three range bins (Reference 4). If required the velocities may be weighted in order to reduce the effect of spurious velocity returns. The computed F_{h_i} is that which the aircraft would experience if it flew along the measurement radial through the hazard at the aircraft's ground speed (V_G) at the time of measurement.

The second term in the F-factor is introduced by implementing a simple linear vertical wind estimator (Reference 5), giving the total F-factor at the ith range bin as

$$F_i = F_{h_i}\left(1 + \frac{3gh_i}{2V_a V_g}\right) + \left|F_{h_i}\right|\left(\frac{gh_i}{2V_a V_g}\right)$$

As described in Reference 6, the actual threat to an aircraft is based on the average F over approximately 1 kilometer. Therefore the above F-factor is averaged over three range bins (900 meters) giving $\overline{F_i}$ as

$$\overline{F_i} = \frac{F_{i-1} + F_i + F_{i+1}}{3}$$

It has been determined (Reference 6) that a value of $\overline{F_i} \geq 0.105$ represents a threat to the aircraft. The minimum criterion for a hazard region is at least one range bin radially with $\overline{F} \geq 0.105$, as well as another range bin on an adjacent radial contiguous with it, also with $\overline{F} \geq 0.105$ (see Figure 1). NASA's flight tests require a representational display of the hazard region on the aircraft's research cockpit navigational display. This system is described in Reference 7 for data produced by the airborne radar system. A similar technique will be used in 1992 for the CLASS system. For this purpose a box is generated with its center at the centroid as the hazard region, and with dimensions proportional to the spatial extent of the measured hazard region.

Interpretation of the Wind Shear Products

The measurements and wind shear products described above will be assessed by several means. By actually penetrating microburst wind shears the predicted location and intensity of the shears may be compared directly with those measured by the aircraft's in situ system, the latter being taken to be the measurement standard. This will allow an appraisal of the CLASS measurement accuracy. The CLASS wind shear measurement can also be corroborated by the independent ground-based wind shear measurement of the Terminal Doppler Weather Radar (TDWR). The aircraft will also be operating an enhanced airborne weather radar (Reference 7). A comparison between the CLASS measurement and this radar's measurement will provide a comparison of the relative merits of radar- and lidar-based forward-looking wind shear detection systems.

Results to Date and Future Goals

To date, flight tests have been carried out to evaluate the overall system performance prior to making actual wind field measurements. The laser has been found to be stable and reliable. The ability of the scanner to point and compensate for aircraft motion has been tested and is currently being assessed. In addition, the performance of the signal processor, computer, and data recording system is under evaluation.

Tests to be carried out include a velocity calibration. This will determine the system's capability to account for the aircraft's motion in making wind velocity measurements.

CLASS performance in obscuring and non-obscuring atmospheric phenomena will also be studied. Examples of obscuring phenomena are rain, fog, and cloud. Typical non-obscuring phenomena are planetary boundary layer shear, gust fronts, and sea-breeze fronts.

The capability of the system to detect and measure actual microburst wind shears will be evaluated this summer (1992) when the TSRV aircraft will penetrate microburst wind shears in Orlando, FL, and Denver, CO.

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6. Lewis, M. S., "Wind Shear Hazard Characterization", Fourth Combined Manufacturers' and Technologists' Airborne Wind Shear Review Meeting, Williamsburg, VA., April 14-16, 1992.

7. Hinton, D. A., "Air/Ground Wind Shear Information Integration - Flight Test Results", Fourth Combined Manufacturers' and Technologists' Airborne Wind Shear Review Meeting, Williamsburg, VA., April 14-16, 1992.
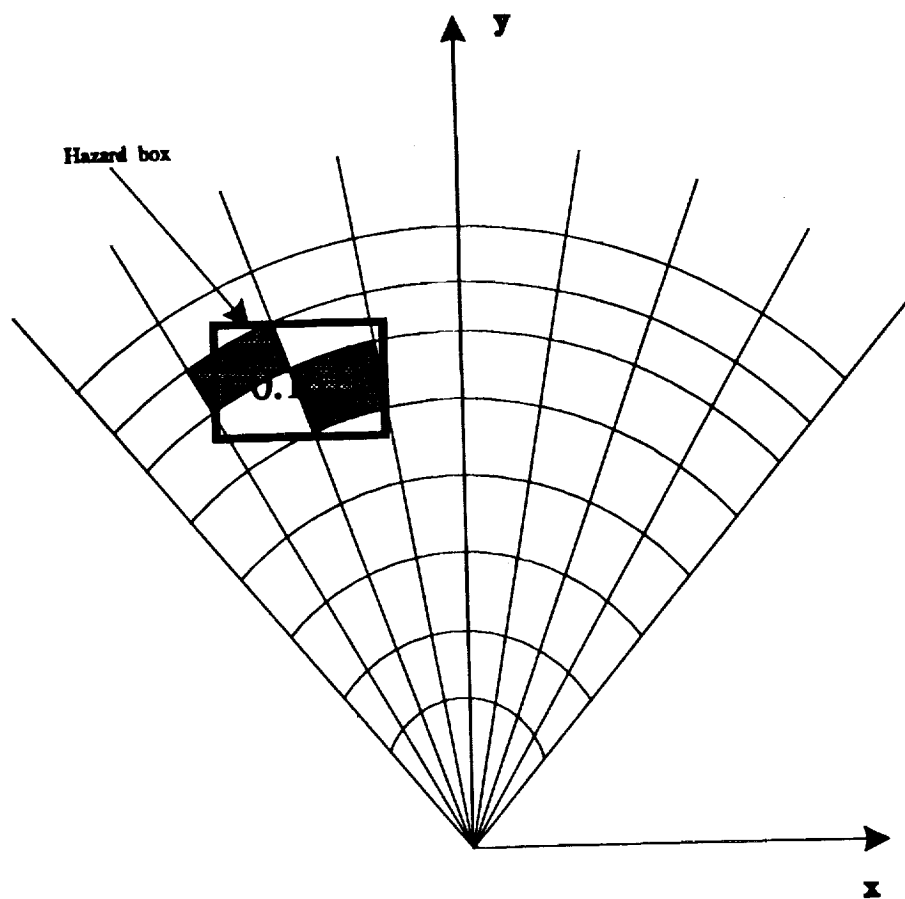
Figure 1: Hazard Region Definition on $\bar{F}$ map.

NASA/LMSC Coherent Lidar Airborne Shear Sensor (CLASS): Flight Test Evaluations

Paul A. Robinson
Lockheed Engineering & Sciences Co.

Objectives of Flight Tests

To evaluate the ability of airborne lidar technology to detect and predict hazardous wind shear ahead of an aircraft with a view to warning flight crew of impending dangers.

System Definition

To measure wind shear ahead of the aircraft and relate that measurement to an effect on the aircraft's performance.

- Measure wind shear hazard accurately at least 10 seconds ahead of an aircraft.

- Combine those measurements with aircraft state parameters to assess the effect of any wind shear on the aircraft.

In Flight Measurements

Return Intensities

Line of sight wind velocity

In Flight Products

F-factor

1 Km averaged F-factor ($\bar{F}$)

Hazard regions

Discrete alerts

667

Interpretation of Products

Location and intensity of regions of hazardous wind shear.

Comparison with airborne and ground-based radar systems.

Comparison with aircraft's in situ detection system.
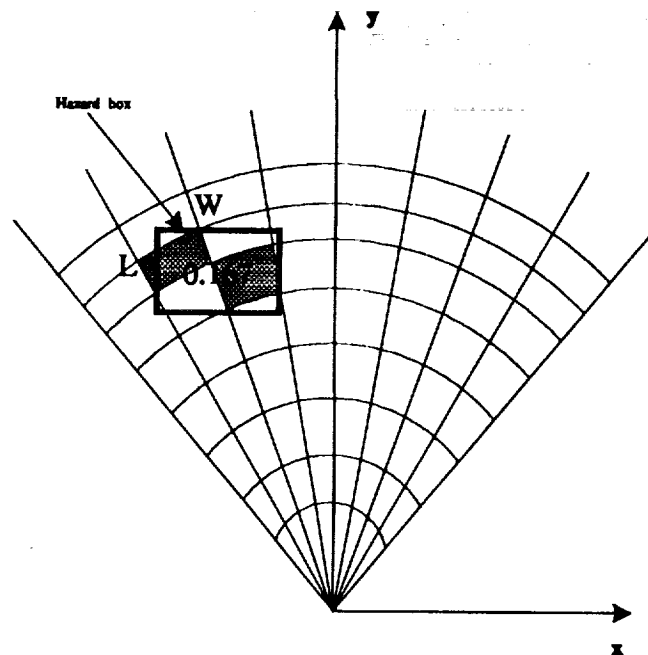
Wind Shear Hazard Region Definition

$$F = \frac{W_1 \cdot \hat{e}_a}{g} + \frac{Wf}{V_a}$$

Horizontal:
$$F_{II} = \frac{v_{i+2} - v_i}{2\Delta r} \frac{V_g}{g}$$

Total:
$$F = F_{II}\left(1 + \frac{3gh}{2V_a V_g}\right) + |F_{II}|\left(\frac{gh}{2V_a V_g}\right)$$

Averaged:
$$\overline{F_i} = \frac{F_{i-1} + F_i + F_{i+1}}{3}$$

Current Status

Laser operation and stability.

Scanner stability and positioning accuracy.

Data system operation.

669

Future Goals

1. Velocity calibration.

2. Investigation of lidar performance in obscuring and non-obscuring weather phenomena.

3. Investigation and assessment of lidar performance in hazardous wind shears.

NASA/LMSC Coherent LIDAR Airborne Shear Sensor:
System Capabilities and Flight Test Plans
Questions and Answers

Q: Pete Sinclair (Colorado State University) - In calculating the F-factor what errors magnitude do you expect from the technique used to estimate the vertical velocity term?

A: Paul Robinson (Lockheed) - The errors that were studied by Dan Vicroy and presented earlier today where from 0 to 600 meters above ground. The estimation is plus or minus 2.5 meters per second.

Dan Vicroy (NASA Langley) - The results that I presented earlier from the In Situ data showed about 2.5 to 3 meters per second RMS error in computing the vertical winds. We think we can probably do much better than that once we get into some signal processing with the radar data. We will be able to give you a more definitive number after we do the simulation with the asymmetric microburst models. We will have that answer in about two or three months. From our preliminary work, it looks like we can probably do at least 2.5 meters per second.

N93-14848

Solid-State Coherent Laser Radar Wind Shear Measuring Systems

R. Milton Huffaker, Coherent Technologies

COHERENT TECHNOLOGIES, INC.

P.O. Box 7488 Boulder, CO 80306   (303) 449-8736, FAX: (303) 449-8780

Fourth Combined Manufacturers' and Technologists'

Airborne Wind Shear Review Meeting

April 14 - 16, 1992

SOLID-STATE COHERENT LASER RADAR

WIND SHEAR MEASURING SYSTEMS

R. Milton Huffaker
Coherent Technologies, Inc.
P.O. Box 7488
Boulder, CO 80301 USA
(303) 449-8736

Coherent Technologies, Inc. was established in 1984 to engage in the development of coherent laser radar systems and subsystems with applications in atmospheric remote sensing, and in target tracking, ranging and imaging. CTI focuses its capabilities in three major areas:

- Theoretical performance and design of coherent laser radar systems

- Development of coherent laser radar systems for government agencies such as DoD and NASA

- Development of coherent laser radar systems for commercial markets

1.06 MICRON SOLID-STATE COHERENT LASER RADAR SYSTEM

- MOPA CONFIGURATION

- MAXIMUM PULSE ENERGY 200 mJ/PULSE

- PULSE DURATION 0.1 - 10 μs (adjustable)

- PRF 0.1 - 20 Hz

- TRANSMIT APERTURE 10 cm (20 cm also available)

- PROCESSING BANDWIDTH ~100 MHz (50 m/s)

- REAL-TIME DATA ACQUISITION, PROCESSING, AND DISPLAY

COHERENT TECHNOLOGIES, INC

42.5 cm

148.3 cm

AOM

AMP

12

12

B.P.

LIDAR
SIGNAL
IN

L.O.

I1

COUPLER

MASTER
OSCILLATOR
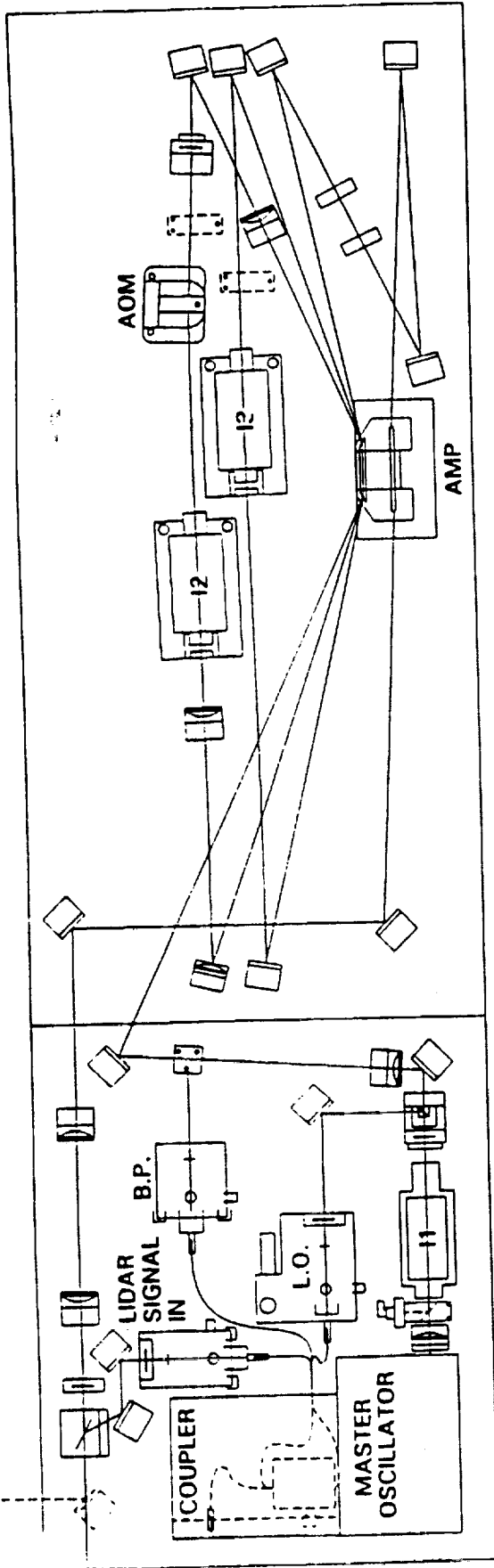
L.O.: LOCAL OSCILLATOR INPUT
B.P.: BACK PROPAGATOR INPUT
AOM: ACOUSTO-OPTIC MODULATOR

, : POLARIZERS
I1-I3: FARADAY ISOLATOR
: CYLINDER LENS

: MIRROR, HR 1um
: KINEMATIC MOUNT

: λ/2 PLATE
: LENS

677

WIND MEASUREMENT USING 1.06 MICRON SYSTEM

Udar

Rawinsonde 20
km distant

15-Sep-91 0045Z, EL 80 deg, 100 pulses

Wind direction, degrees

COHERENT TECHNOLOGIES, INC.

SMHVORTEX-14

Udar

Rawinsonde 20 km
distant

15-Sep-91 0045 Z, EI 80 deg, 100 pulses

Horizontal velocity, m/s

678
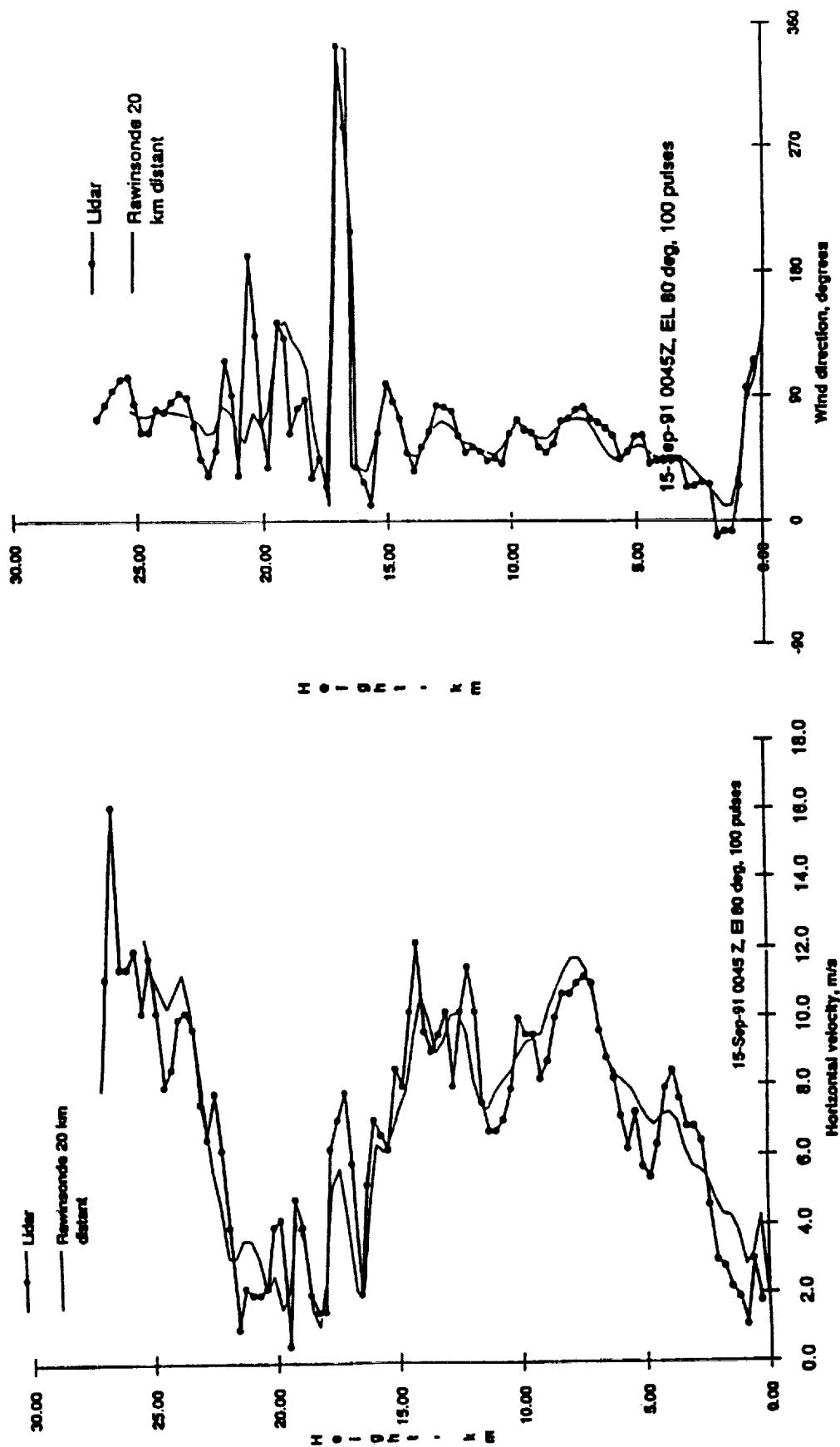
FLASHLAMP-PUMPED 2.09 MICRON SOLID-STATE COHERENT LASER RADAR SYSTEM

- Tm,Ho:YAG

- INJECTION-SEEDED (MO/SO) CONFIGURATION

- MAXIMUM PULSE ENERGY ~50 mJ/PULSE

- PULSE DURATION ~150 ns @ 50 mJ, ~220 ns @ 22 mJ

- PRF ~6 Hz

- TRANSMIT APERTURE 10 cm

- PROCESSING BANDWIDTH ~50 MHz (50 m/s)

- REAL-TIME DATA ACQUISITION, PROCESSING, AND DISPLAY

COHERENT TECHNOLOGIES, INC.

SMHVORTEX-3

400 SHOTS-14 km HILLSIDE

no shot editing

~22mT
128pt FFT

$M = 0.087$ m/s
$\sigma = 0.094$ m/sec @40 kHz

$= 5\%$ ΔU_{FWHM}
$= 2\%$ $1/\pi_{FWHM}$

FREQUENCY

VELOCITY (M/S)

RAW301-3

30mJ

RADIAL VELOCITY (M/S)

RANGE (KM)
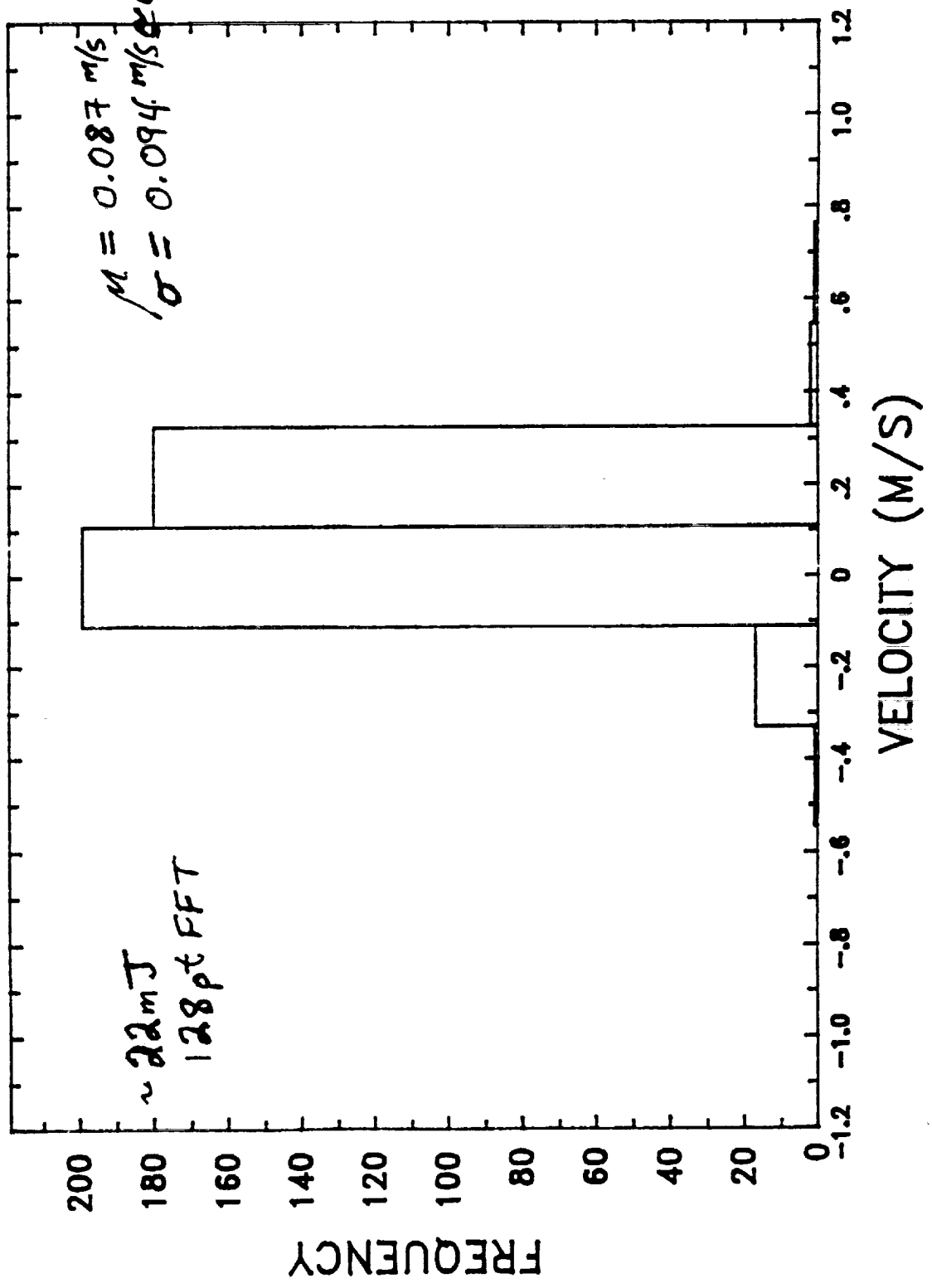
3-1-91
10 shots
128 pt FF

681
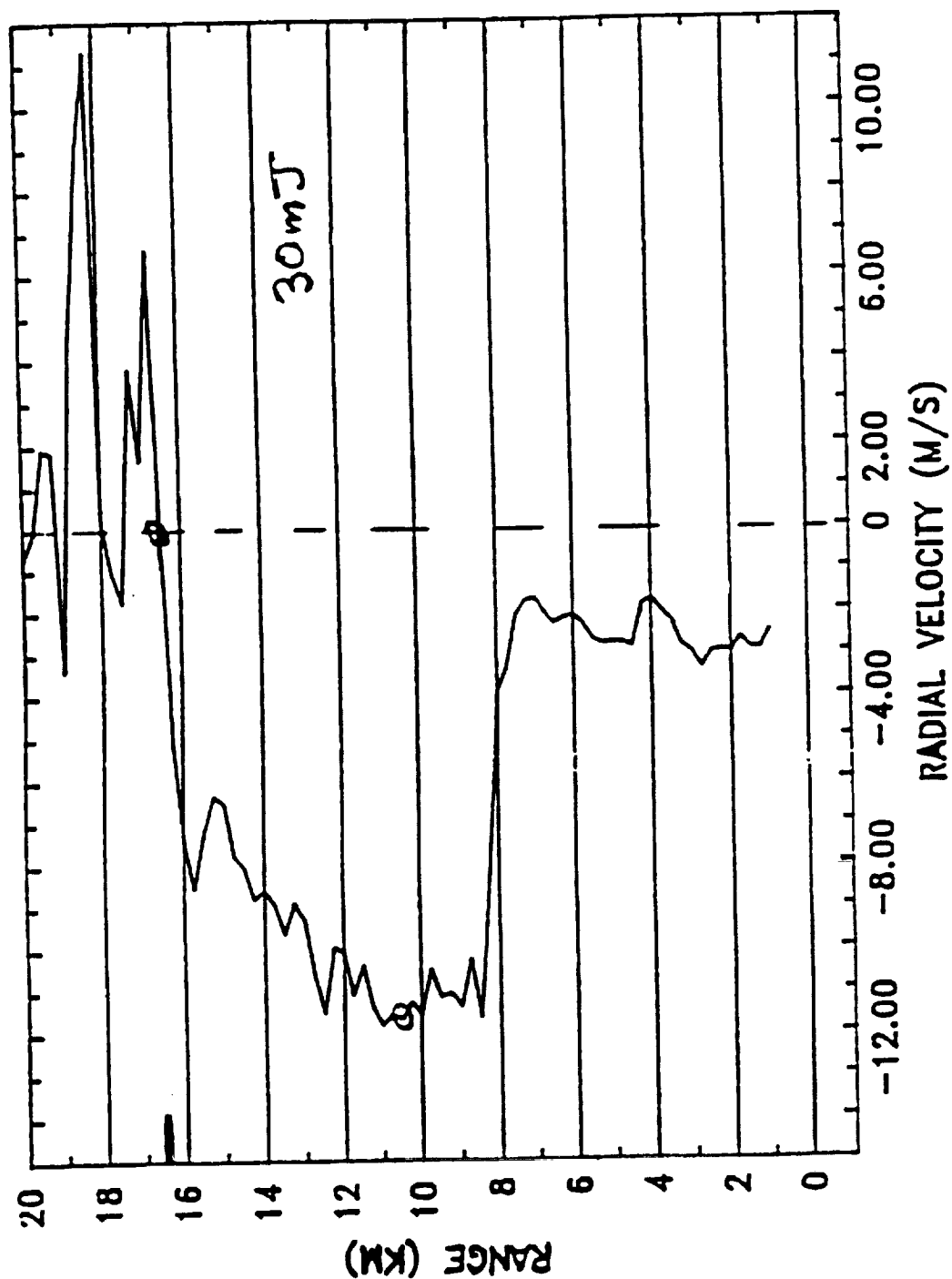
Pulse Energy vs. Time Between Pulses

5.1 mJ @ 100 Hz

4.2 mJ @ 200 Hz

1.1 mJ @ 1 kHz
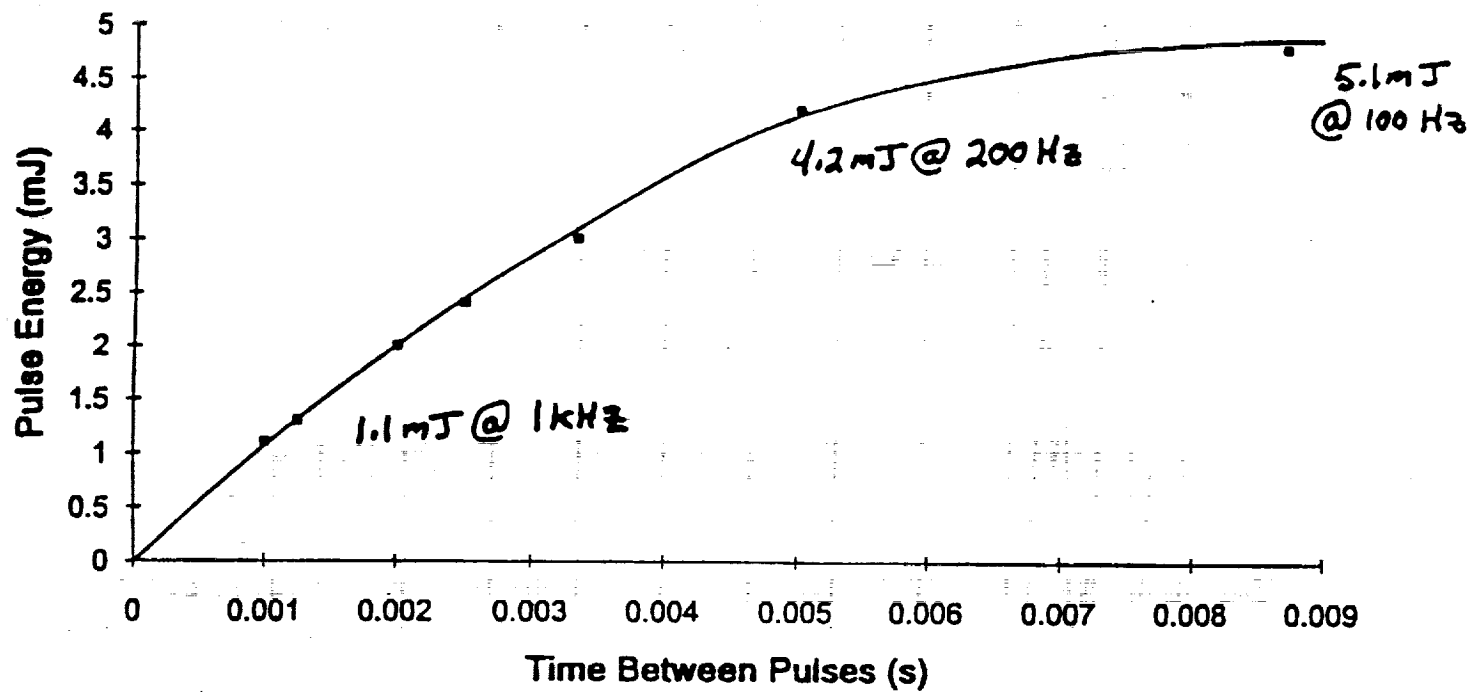
Pulse Energy vs. PRF
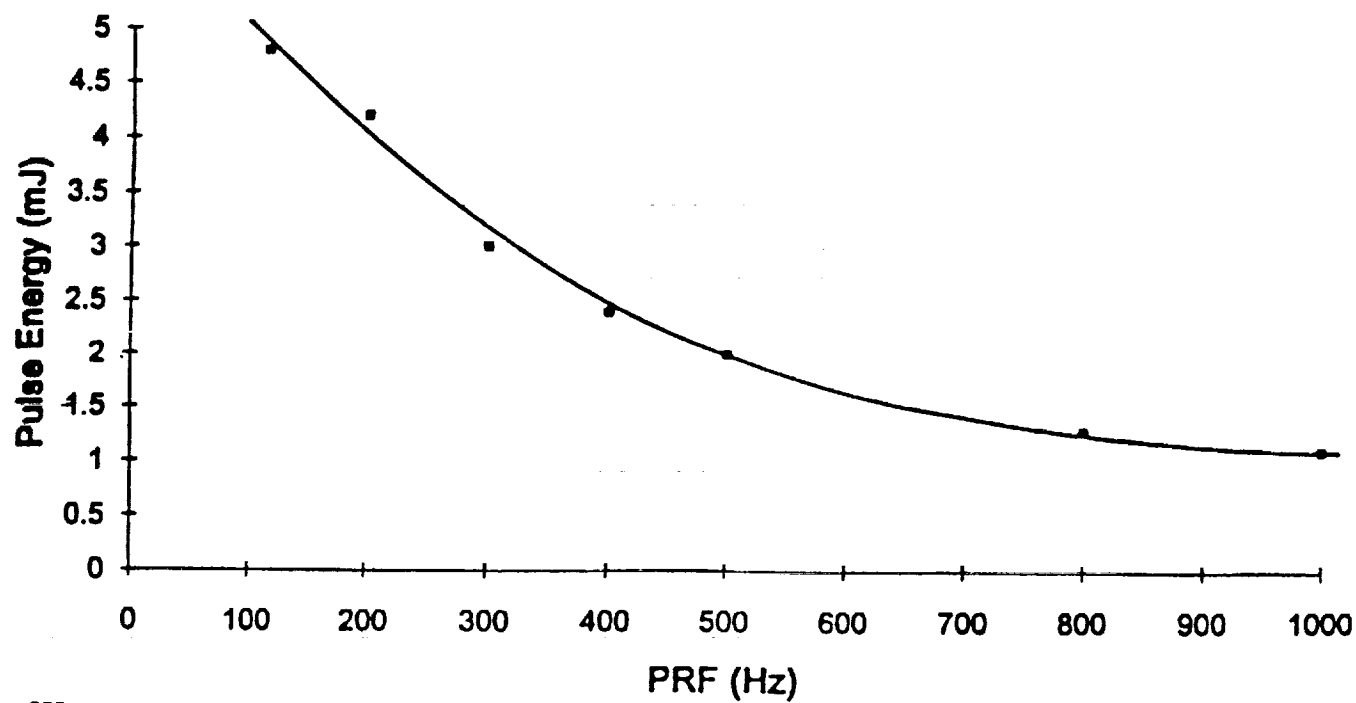
CONCLUSIONS

- A RELIABLE GROUND-BASED 2 μm COHERENT LIDAR HAS BEEN DEMONSTRATED

- DIODE-PUMPED 2 μm LASERS AT POWER LEVELS > 10W AND PULSE ENERGIES OF > 100 mJ HAVE BEEN DEMONSTRATED

- THE POTENTIAL FOR COMPACT EYESAFE ALL-SOLID-STATE COHERENT LASER RADAR SYSTEMS HAS BEEN DEMONSTRATED USING DIODE PUMPING (Complete transceiver @ 1-2 W avg. power requires ~ 1 ft^3)

Solid-State Coherent Laser Radar Wind Shear Measuring Systems
Questions and Answers

Q: Roland Bowles (NASA Langley) - Is the material damage problem solved with solid state two micron technology? Particularly if you pump it reasonably hard, like five or ten millijoules?

A: Milt Huffaker (Coherent Technologies) - I think it is. We have researched those materials and had special materials developed, and those materials have proven themselves as damage free.

Q: Roland Bowles (NASA Langley) - So that problem is behind us?

A: Milt Huffaker (Coherent Technologies) - Right.

Q: Roland Bowles (NASA Langley) - What about the availability of diodes that would put us up around the fifty to one hundred millijule capability?

A: Milt Huffaker (Coherent Technologies) - Well the diodes are there, the question right now is the cost.

Phil Brockman (NASA Langley) - We have 64 diode arrays, at 300 watts each, on order right now for Langley. They cost us $300,000 dollars when we ordered them.

Q: Roland Bowles (NASA Langley) - Is Sony making these?

A: Milt Huffaker (Coherent Technologies) - Spectra Diode Labs is the main developer here in this country. We have been using 3 watt diodes and they are working on 10 watt diodes. The technology is changing and every six months it will be cheaper.

Q: Roland Bowles (NASA Langley) - But when does it stabilize to the point we can think about practical two micron airborne systems?

A: Milt Huffaker (Coherent Technologies) - As I mentioned, we have demonstrated in the lab an all diode pumped transmitter, to the energy and power we are talking about.

Q: Roland Bowles (NASA Langley) - So we are ready to do a point design on an airborne instrument and go.

A: Milt Huffaker (Coherent Technologies) - I think we are now ready to implement that, in my opinion.

Session VIII. Passive Infrared Technology

N93-14849

Development of the Advance Warning Airborne System (AWAS)

Pat Adamson, Turbulence Prediction Systems

FOURTH COMBINED MANUFACTURERS'
&
TECHNOLOGISTS'
AIRBORNE WINDSHEAR REVIEW MEETING

APRIL 14-16, 1992

DEVELOPMENT
OF THE
ADVANCE WARNING AIRBORNE
SYSTEM
(AWAS)

PAT ADAMSON
TURBULENCE PREDICTION SYSTEMS
3131 INDIAN ROAD, BOULDER , CO 303 443-8157

ABSTRACT

DEVELOPMENT OF THE ADVANCE WARNING AIRBORNE SYSTEM (AWAS)

H. PATRICK ADAMSON
TURBULENCE PREDICTION SYSTEMS
BOULDER, COLORADO 80301

The thermal characteristics of microbursts are utilized by the AWAS IR and OAT features to provide predictive warning of hazardous microbursts ahead of the aircraft during landing or take off. The AWAS was evaluated satisfactorily in 1990 on a Cessna Citation that was intentionally flown into a number of wind shear events. The events were detected, and both the IR and OAT thermal features were shown to be effective. In 1991, AWAS units were flown on three American Airlines MD-80s and three Northwest Airlines DC-9s to study and to decrease the nuisance alert response of the system. The AWAS was also flown on the NASA B737 during the summer of 1991. The results of these flights were inconclusive and disappointing. The results were not as promising as before because NASA conducted research flights which were outside of the normal operating envelope for which the AWAS is designed to operate. In an attempt to compensate for these differences in airspeed and mounting location, the automatic features of the system were sometimes overridden by NASA personnel during the flight. Each of these critical factors is discussed in detail. The effect of rain on the OAT signals is presented as a function of the air speed. Use of a 4 pole 1/20 Hertz filter is demonstrated for both the IR and thermal data. Participation in the NASA 1992 program was discussed. FAA direction in the continuing Certification program requires the addition of a reactive feature to the AWAS predictive system. This combined system will not require flight guidance on newer aircraft. The features of AWAS-IV, with the NASA algorithm included, were presented. Expected completion of the FAA Certification plan was also described.

AWASIII
UND/TPS PROGRAM
CESSNA CITATION

Over the past five years, Turbulence Prediction Systems (TPS), in Boulder, Colorado has combined the concepts of the thermal properties of microbursts with the behavior of infrared (IR) in the atmosphere, and OAT (Outside Air Temperature) response on the aircraft flying into such events. From these studies, TPS has established an Advance Warning Airborne System (AWAS) that has proceeded through its third version, AWAS-III, and is in process of FAA certification.

INITIAL INSTALLATION 6/90

SW 2.0

66 FLTS ~100 HRS

During the summer of 1990, AWAS-III was flown on the Cessna Citation research aircraft operated by the University of North Dakota (UND) in conjunction with the FAA study of the MIT Terminal Doppler Weather Radar (TDWR) in the detection of microbursts. This provided unique opportunity for AWAS-III to predict and enter a number of wet microbursts in Orlando, Florida, and several dry microbursts in Denver, Colorado.

AWAS-III, with software version 2.0, was installed in the Citation in June of 1990. It was located in the luggage compartment in front of the pilot, and the IR from ahead of the aircraft was reflected into AWAS-III via a 2" gold coated mirror mounted outside, just below the windshield, where it did not interfere with the pilot's view. Sixty-six flights were flown in attempts to make wind shear contacts.

Turbulence Prediction Systems

Block Diagram

695
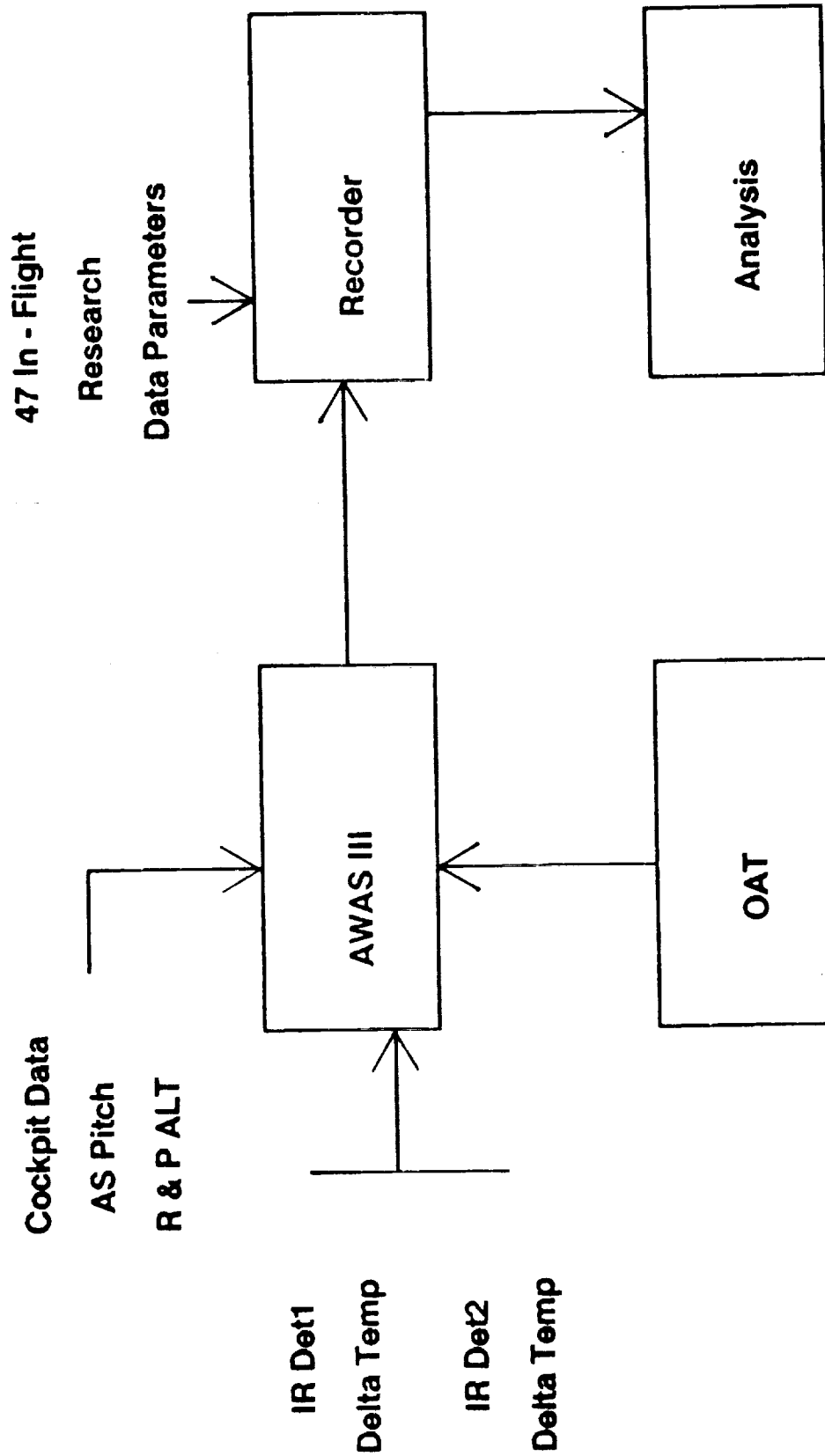
The received IR power is separated into appropriate wavelengths by a spectrometer. The IR power in these wavelengths is then registered by two IR detectors. AWAS processes the difference between far and near IR indicated temperatures to generate a "Predictive Hazard Index" that relates to the microburst's hazard. Airspeed, pitch, radio and pressure altitudes are also used. The OAT data is also used to create a "Thermal Hazard Index" relating to microbursts. For research purposes, 47 AWAS in flight and aircraft data parameters are recorded. These parameters were used for the post-flight analyses.

07/07/90 PENETRATION

F(TDWR) = 0.155

F(CITATION) = 0.17 @ 180 kts

F(AWAS) = 0.15

One of the most important microburst penetrations was on July 7th, 1990. The aircraft airspeed during approach was 180 knots, and the aircraft entered the center of the microburst. The IR created a warning at 55, and 35 seconds before that which would have been provided using a hazard index calculated from the winds recorded by the inertial system, i.e., inertial warning. The Thermal Hazard Index provided a warning 15 seconds before the inertial warning. The TDWR measured the event a few seconds before the aircraft entered the microburst. The hazard value calculated by the TDWR was 0.155, inertial hazard index was 0.17, and the AWAS IR hazard index was 0.15. This data was presented at the 3rd Combined NASA meeting in January 1991.

AMERICAN / TPS
CERTIFICATION PROGRAM

MD80 CONFORMED INSTALLATIONS
2/91

Another important aspect of the certification program was to determine the level of nuisance alerts which might occur in revenue service. American Air Lines cooperated with TPS in this phase of the program. An AWAS-III with a recorder was installed, starting in February of 1991, on 3 MD-80 aircraft. Many thousand flights have been conducted with these units on board.

INSTALLATION OF AN ALPHA JET PYLON ON AMERICAN AIRLINES MD-80
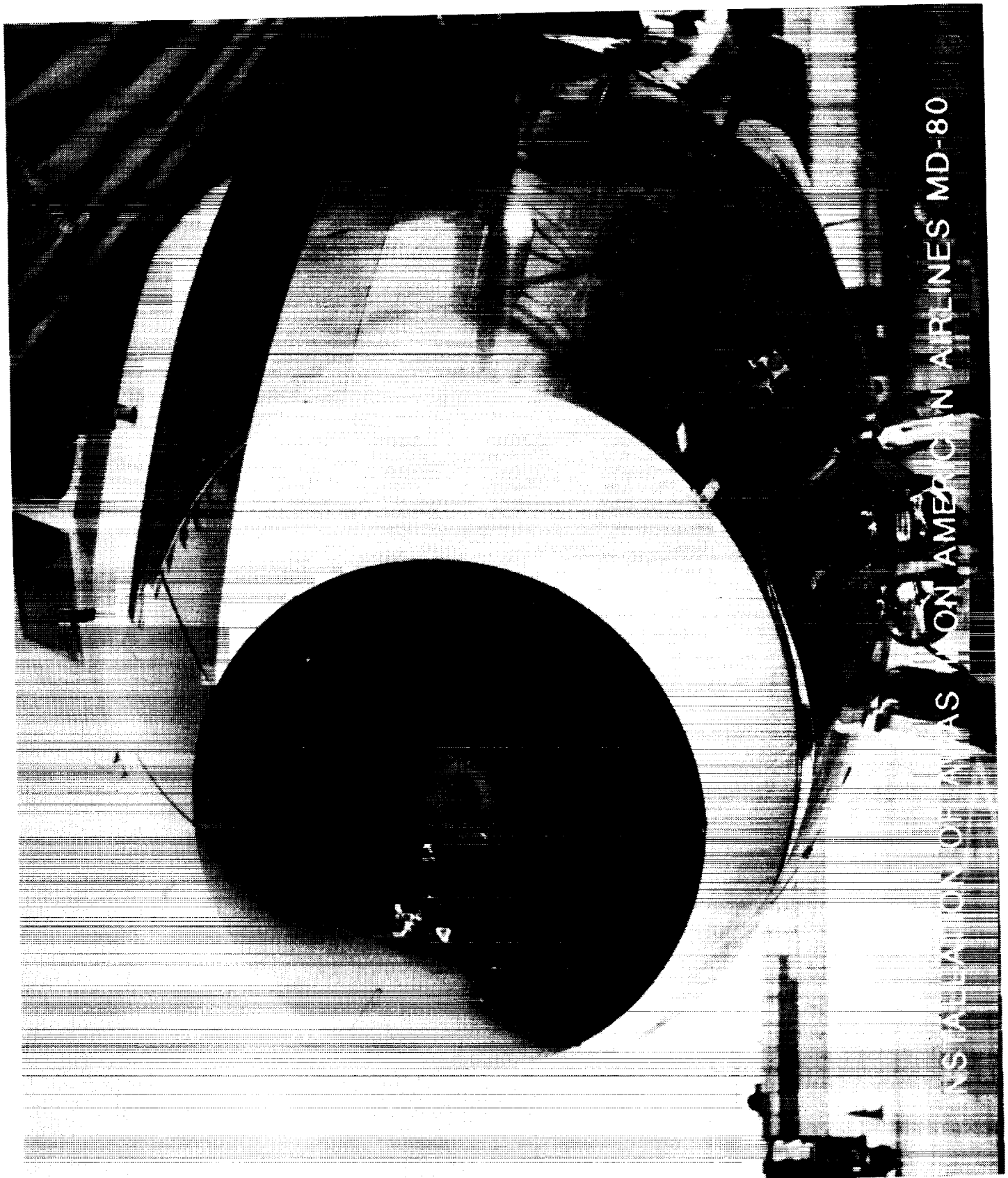
AWAS was installed in the front wheel-well of the MD-80. The mirror, which is seen lower right in the picture, has the red alignment laser beam centered on it. The laser is used in the installation to guarantee that AWAS looks out the flight line of the aircraft.

AMERICAN AIRLINES/TPS AWAS INSTALLATION DIAGRAM

MD-80

ARINC INPUT (19 ITEMS)

28 VDC

EXT MIRROR
HEATER

AWAS III
28 VDC
18 WATTS

RS 232 OUTPUT (45 ITEMS)

RECORDER
(IBM PC)

10APR92

630277 REV X

703
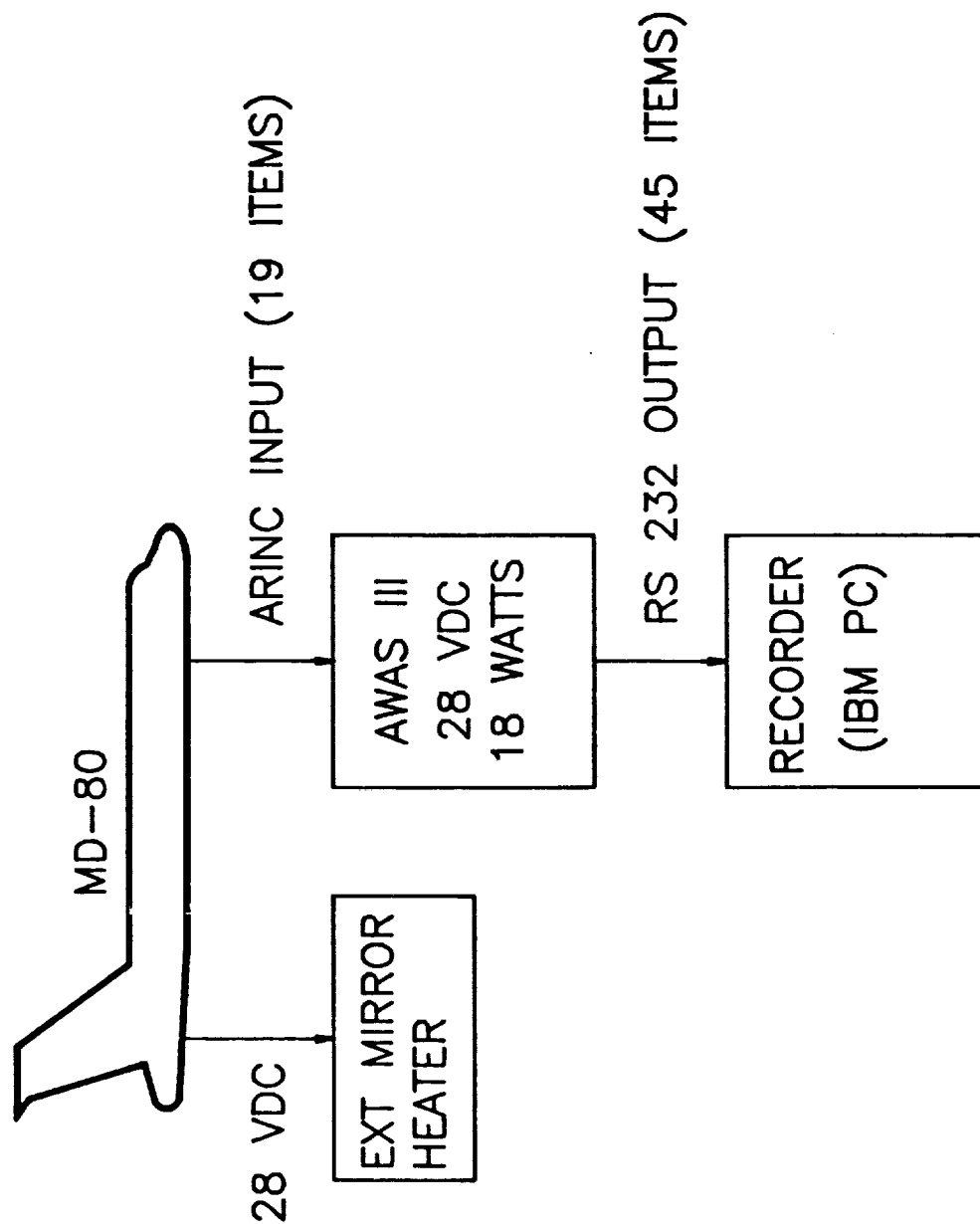
The AWAS uses 28 VDC and the mirror is also heated with 28 VDC. The AWAS receives the necessary aircraft data via ARINC. This aircraft data and the AWAS generated data is transmitted to the recorder. A lap-top computer was used as the recorder.

AA PROGRAM

SW VER	DATE	FLTS	FLT HRS
2.1.1.2	4/91 - 10/91	1336	2134
2.1.1.4	10/91 - PRESENT	1216	2047

705

From an analysis of the early data the software version was changed in October, 1991. Over a thousand flights have been recorded since these minor software changes were installed.

C-2

NORTHWEST / TPS EVALUATION PROGRAM

PROGRAM

DC9 INITIAL INSTALL 6-12/91

A second commercial airlines program involved the installation of AWAS-III with a Honeywell Windshear Computer on three DC9 aircraft. Northwest Air Lines installed these units from June to December of 1991.

This installation was also in the front wheel well, on the port side, but at a somewhat higher level.

NORTHWEST AIRLINES/TPS AWAS INSTALLATION DIAGRAM

DC-9

ANALOG INPUT (3 ITEMS)

AWAS OUTPUT (25 ITEMS)

AWAS III
28 VDC
18 WATTS

DATA
RECORDER
(WADL)

HONEYWELL
WSC

ARINC INPUT
(5 ITEMS)

28 VDC

40 DEG C
CONTROLLER

EXT MIRROR
HEATER

10APR92

630279 REV X

709
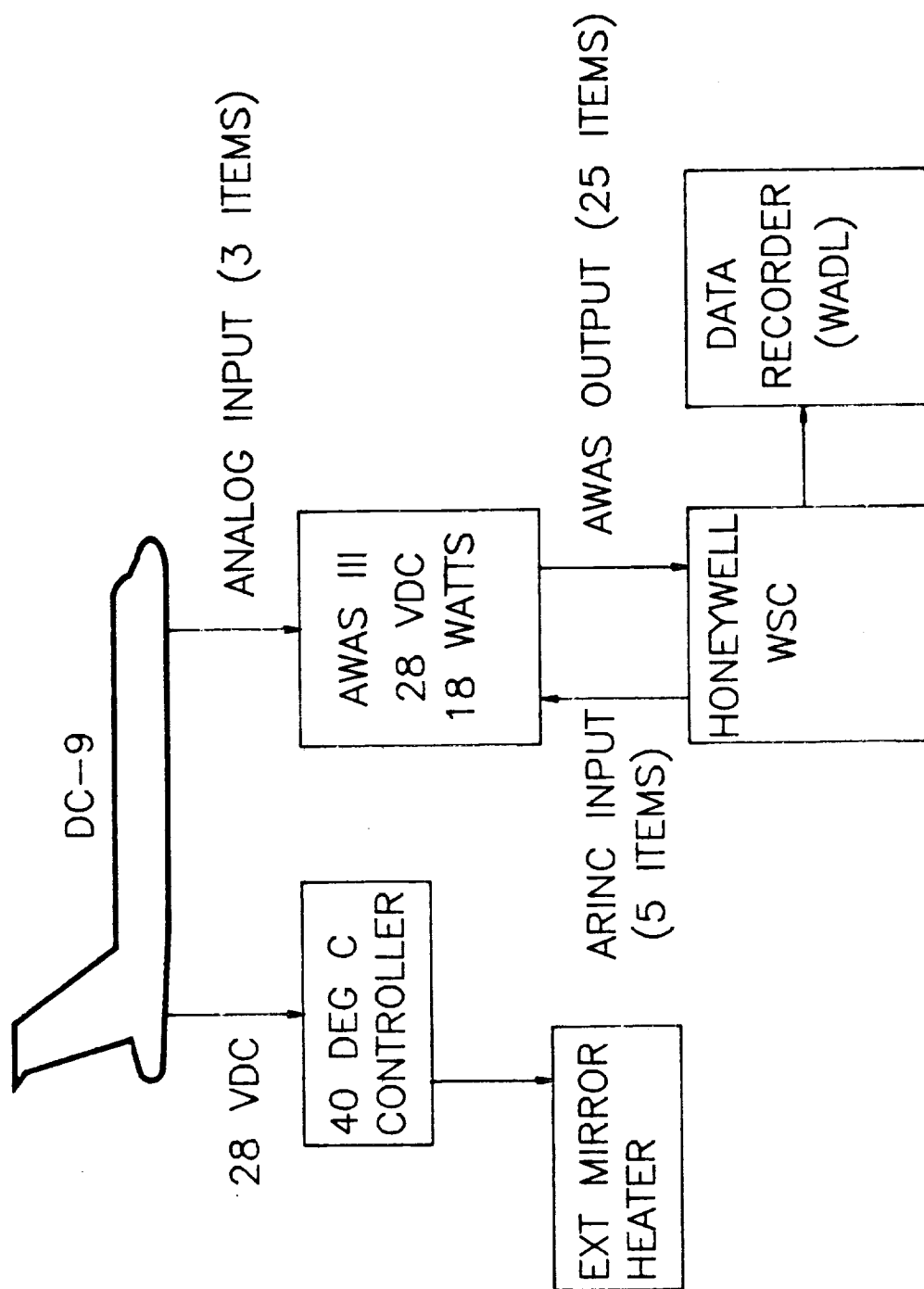
In this program, both an AWAS and a Honeywell WindShear Computer (WSC) were installed. The AWAS received three inputs from analog connections with the aircraft instruments, and five from ARINC through the WSC. These 8 input items plus 17 AWAS generated items were passed through the WSC to the recorder.

NWA PROGRAM

SW VER	DATE	FLTS	FLT HRS
3.0	6/91 - 2/92	1710	2052
3.1	2/92 - 3/92	590	708
3.2	3/92 - PRESENT	135	191

The AWAS-III software was updated twice in this program. The major changes were to prevent AWAS nuisance response to non-hazardous weather conditions.

SOFTWARE EFFECTS

ALERTS	AA 2114	NWA 3.1	NWA 3.2
LLWS	20% / FLT	12% / FLT	1 ALERT IN EVALUATION
CAT	30% / HR	0% / HR	0% / HR
FLTS	1216	590	135
HRS	2047	708	191
FLT LENGTH	1.7 hrs	1.2 hrs	1.4 hrs

713

NWA3.2 represents the latest software upgrade. These changes were to reduce nuisance from inversions, and to incorporate improved pitch correction equations.

LESSONS LEARNED

MTBF / MTBR

AWAS / WINDOW / MIRROR

ENVIRONMENTAL ENVELOPE

The operation of the AWAS has been exceptionally free of failure over more than 2 years. The IR window and the gold coated, heated mirror have been inspected regularly. While the mirrors have not required any replacement, the windows have been cleaned every 4 to 6 weeks--to eliminate these cleanings, a protective coating has been applied to one window on American Air Lines, and to all 3 windows on Northwest Air Lines. The coating, while still under study, appears to solve the problem of window degradation. Because both of the airlines testing these AWAS units have flights through a wide variety of weather conditions, it is believed that these tests are effective for establishing response to a large environmental envelope.

IR WEATHER EFFECTS

OPERATIONAL ISSUES-DEICING

717

While passive IR power may be diminished somewhat in rain, this has not appeared to be a problem during any commercial test flight. Heating the mirror within a pre-set range of temperatures is important for the proper function of the AWAS, and to prevent icing.

NASA / TPS SUMMER PROGRAM 91

SW 2.1.2.0 = 2.1.1.2 AA

In the summer of 1991, NASA included AWAS-III in its tests of radar in penetrations of microbursts. The AWAS unit operated in these flights used a software configuration comparable to the early version used in the American Air Lines flights.

NASA/TPS AWAS INSTALLATION DIAGRAM

737

ARINC INPUT (6 ITEMS)

AWAS III
28 VDC
18 WATTS

RS 232 OUTPUT (45 ITEMS)

NASA
RECORDER

TPS
RECORDER
(IBM PC)

INFLIGHT
DISPLAY
PANEL
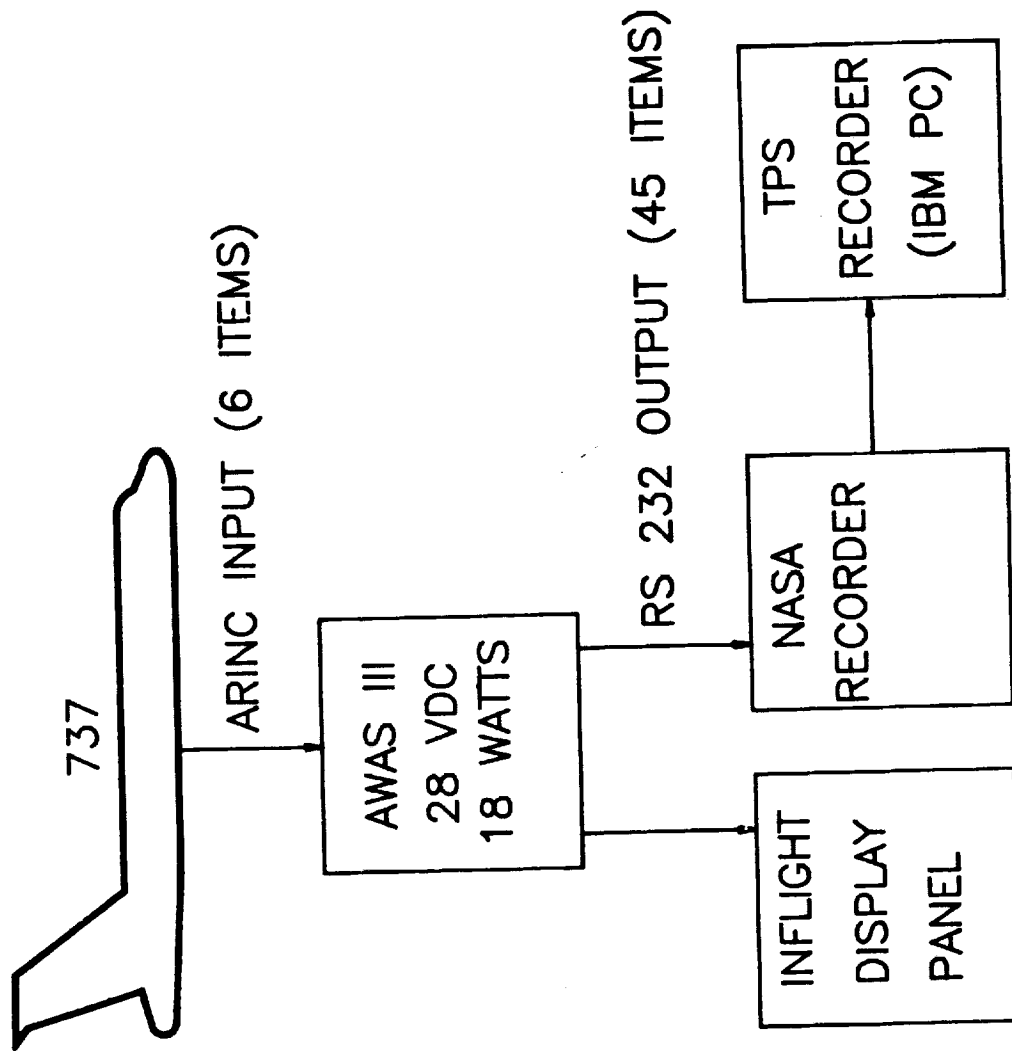
13APR92
630278 REV X1

721

WHY DID THE AWAS NOT PERFORM AS EXPECTED IN 1991 VERSUS THE GOOD PERFORMANCE IN 1990?

Normal Flight Mode:

The AWAS is programmed to operate in a normal flight pattern and not in a research mode. Consequently, the AWAS changes from one mode to another automatically as the aircraft takes off, cruises and then enters the landing phase of flight. During these phases the AWAS collects and stores data necessary for different phases of the flight. If the AWAS is rebooted (restarted), or if the modes are changed by means other than that automatically prescribed by the internal software of the AWAS, valuable data necessary for the proper functioning of the AWAS may be lost, or not be collectable again in time to provide an adequate warning. In normal flight, if the system is rebooted, the failure light is illuminated until the AWAS is again operating properly.

AWAS FLIGHT MODES:

NORMAL FLIGHT MODE

RESEARCH FLIGHT MODE

724

Research Flight Mode:

It was discovered that NASA, in an effort to assure accurate data for research purposes, overrode the automatic mode functions of the AWAS. Unfortunately, if this switching occurred shortly before an encounter with a microburst, all of the data banks would be zeroed, with the result that some of the information, e.g., lapse rate, required for the AWAS to operate properly would be lost. To date, NASA has been unable to provide TPS with the time of occurrence when the five manual overrides occurred. If this information becomes available, it may be possible to determine what effect, if any, these overrides would have had on the performance of the AWAS.

In conclusion, the 1991 test flights of the AWAS by NASA were not as successful as anticipated because the AWAS was flown in an inappropriate flight envelope.

The factors, either individually or combined, that contributed to this poor performance were:

1. The ability of NASA to override on command the AWAS automatic mode selection routine;

2. The undesirable location and method of mounting the mirror and the infrared window assembly;

3. Airspeed in excess of that which is encountered in normal landings and take offs.

The first of these, mode selection, has been discussed, and the problems with the periscope location and design, and airspeed factors, will now be discussed.

LOOK DISTANCE PERISCOPES

UND

AA

NWA

NASA

The effect on the performance of the AWAS due to the location and method of mounting of the mirror and window assembly became very apparent during the NASA 1991 summer flights. While there had been no impairment of the infrared line of sight in the earlier installations on the UND Citation II, American Airlines MD-80's, or Northwest Airlines DC9's, it became apparent when TPS analyzed the flight data received from NASA that the look distance of the AWAS was often seriously impaired.

The exact cause of this impairment has not yet been determined. In some cases it appears that it may be due to rain collecting in the periscope. Yet, in other cases where rain existed, the look distance did not appear to be affected. It was determined in the very earliest flights that extensive damage was occurring to the mirror. The damage over the summer was sufficient to require that the mirror be replaced twice. No significant damage has occurred on any of the other installations. This includes over 10,000 hours of flight in revenue service.

The effect of reduced look distance will, of course, reduce the ability of the AWAS to sense the microburst within an adequate time, and/or to measure the intensity of the event accurately.

Consequently, the impairment of the look distance during these summer 1991 flights certainly contributed to the apparent poor performance of the AWAS.

AIRSPEED

EFFECT ON WARNING TIME

EFFECT ON F FACTOR

EFFECT ON OAT SENSOR

729

Effect of Airspeed on Warning Time

Warning Time

Airspeed with Fixed Look Distance

730
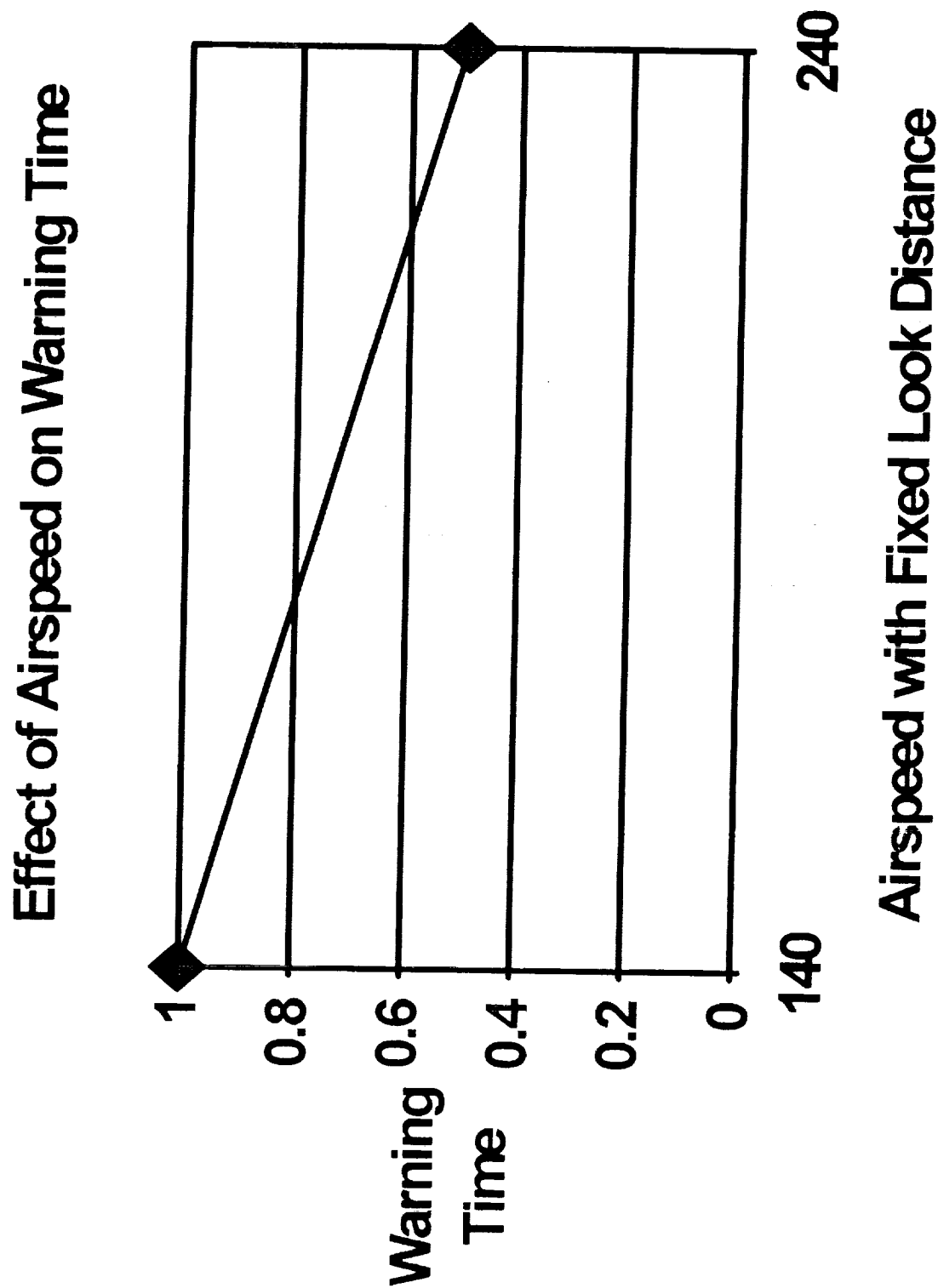
The aircraft airspeed has, as is indicated in the previous graph, a significant effect on the amount of warning time provided. This relationship is quite apparent when it is noted that the AWAS will sense the event from a given distance, but that distance will be traversed by the aircraft in less time due to the greater airspeed. Because of safety reasons, the NASA B 737 flew at airspeeds from 230 to 260 knots rather than the 130 to 160 knots flown in normal revenue service by jet aircraft. The airspeed factor was not as significant when the UND Citation II encountered microbursts during the summer of 1990 because the Citation was able to approach and penetrate the events at a much slower airspeed, e.g., 160 to 190 knots.

The distribution of landing speeds from 972 flights is depicted in the following graph.

LANDING AIRSPEED DISTRIBUTION

972 FLIGHTS AA MD-80

X-axis: AIR SPEED IN KNOTS @ 50' RALT (110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180)

Y-axis: # OF OCCURANCES (0, 10, 20, 30, 40, 50, 60, 70, 80)

732
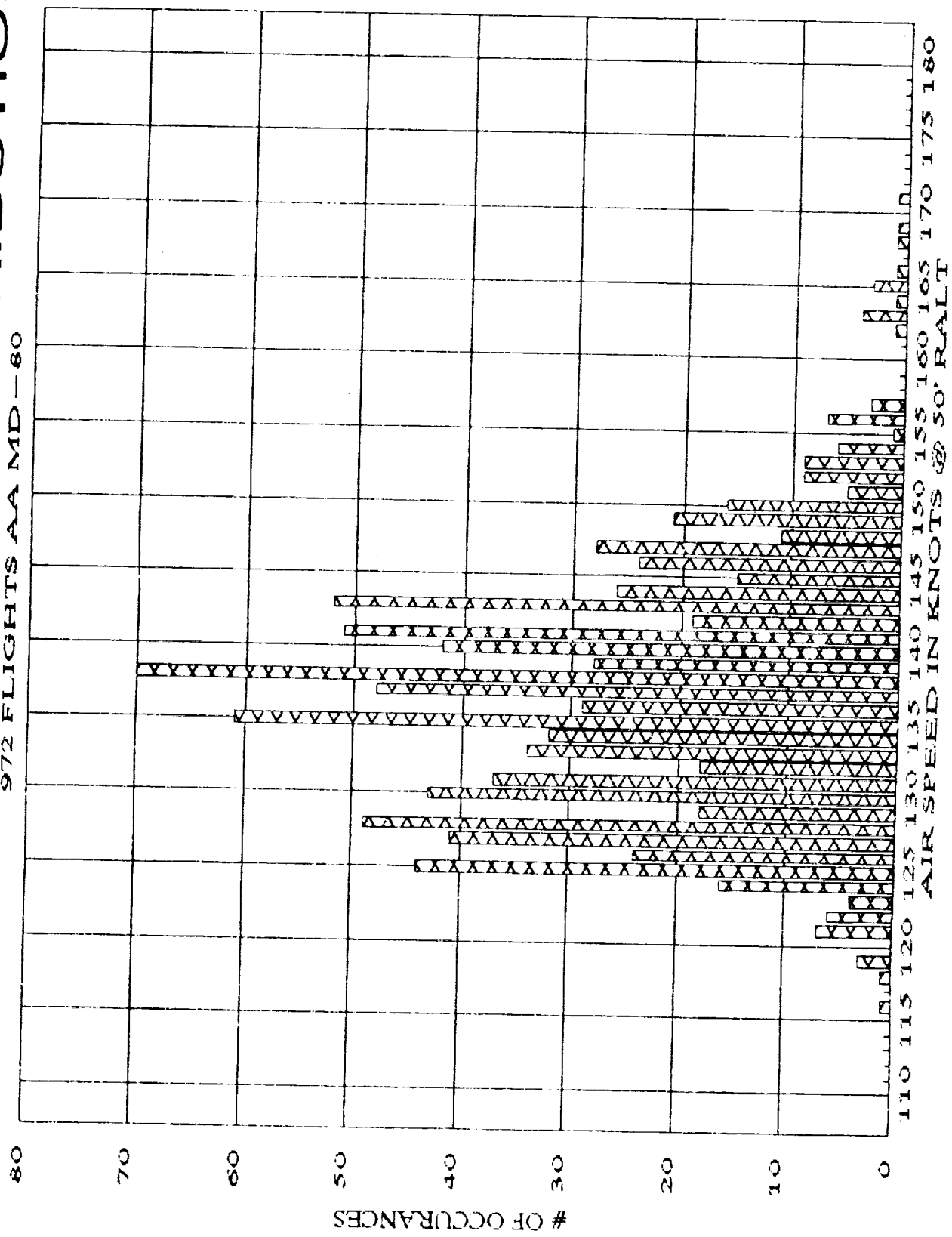
F INDEX VS AIRSPEED

AWAS F INDEX VS AIRSPEED

733

The AWAS-III was designed to estimate the hazard or F factor for use with aircraft operating at a normal landing, or take off speed of approximately 140 knots. For example, the MD-80's data shown in the previous graph indicates a central value of about 140 knots with a maximum value of 171 knots. The F factor as measured at approach speeds of up to 260 knots in the NASA research flights are not comparable with the F factor computed at the lower normal airspeeds. The effect of these differences can be understood by an analysis of the following equations.

The hazard index, F, is based upon the vertical and horizontal winds. These F factors can be appreciated more completely relative to the airspeeds if we look at the nature of the equations and the measurements.

DEFINITION OF TASS F MODEL
PAGE 1

USING THE TASS DATABASE AS INPUT:

$$F_{WIND} = F_{\dot{u}} + F_w$$

$$WHERE \quad F_{\dot{u}} = \frac{\frac{du}{dt}}{G} \quad WHERE \ dt = 1 \ second$$

$$WHERE \quad F_w = -w/AIRSPEED$$

$$F_{WIND} = (\frac{\frac{du}{dt}}{G}) + (-w/AIRSPEED)$$

$if \frac{du}{dt} > 0$ then u = tailwind / decreasing headwind -w is a downdraft

The TASS F model represents a hazard index that is separated into two terms, one related to the acceleration of horizontal winds, and the other related to the velocity of vertical winds. The acceleration of the horizontal winds are shown as a time derivative of the horizontal wind velocity. This is divided by G, which is the acceleration of gravity. This provides a first term which is independent of the dimensions. The second term contains the vertical wind velocity divided by the airspeed. This again provides a term that is dimensionless. It is important to apply the directional senses shown, in order for the F values to be of the signs anticipated. An important aspect of the TASS database used in conjunction with these equations is the continuity of time, t. This does not mean that data is present for all possible time values. It means that the data is generated from equations that could provide meaningful wind values at all possible time values, without "exploding" anywhere between time values. Values for study are provided by the instrumentation only once each second. Thus, dt is one second.

DEFINITION OF TASS F MODEL
PAGE 2

USING THE TASS DATABASE AS INPUT:

t *IS CONTINUOUS FOR THE FOLLOWING EQUATIONS*

$$WHERE\ S_{INTEGER} = \frac{1000\ METERS}{AIRSPEED_{M/S}}$$

$$1KMFT_{WIND} = \frac{\sum_{1}^{S_{INTEGER}} F_{WIND}}{S_{INTEGER}}$$

TASS IS THE TERMINAL AREA SIMULATION SYSTEM WET MICROBURST STUDY
NASA WINDSHEAR MODEL (PROCTOR 1987)

called nasaiv.dat

In order to obtain an average value of F over a kilometer of flight, we first establish the number of seconds (S) required to proceed 1000 meters. Because the data comes only each second, we choose the closest integer value for S. The lower equation shows the use of this integer, S, and the F values obtained at each second from 1 to S. This provides us with the average F value over that 1 km distance.

Peak Fwind, averaged over 1KM

Wet TASS data

Altitude (meters)

Peak 1KMfwind

0.25
0.2
0.15
0.1
0.05
0

0   100   200   300   400   500

■ 140 knots   △ 240 knots

739
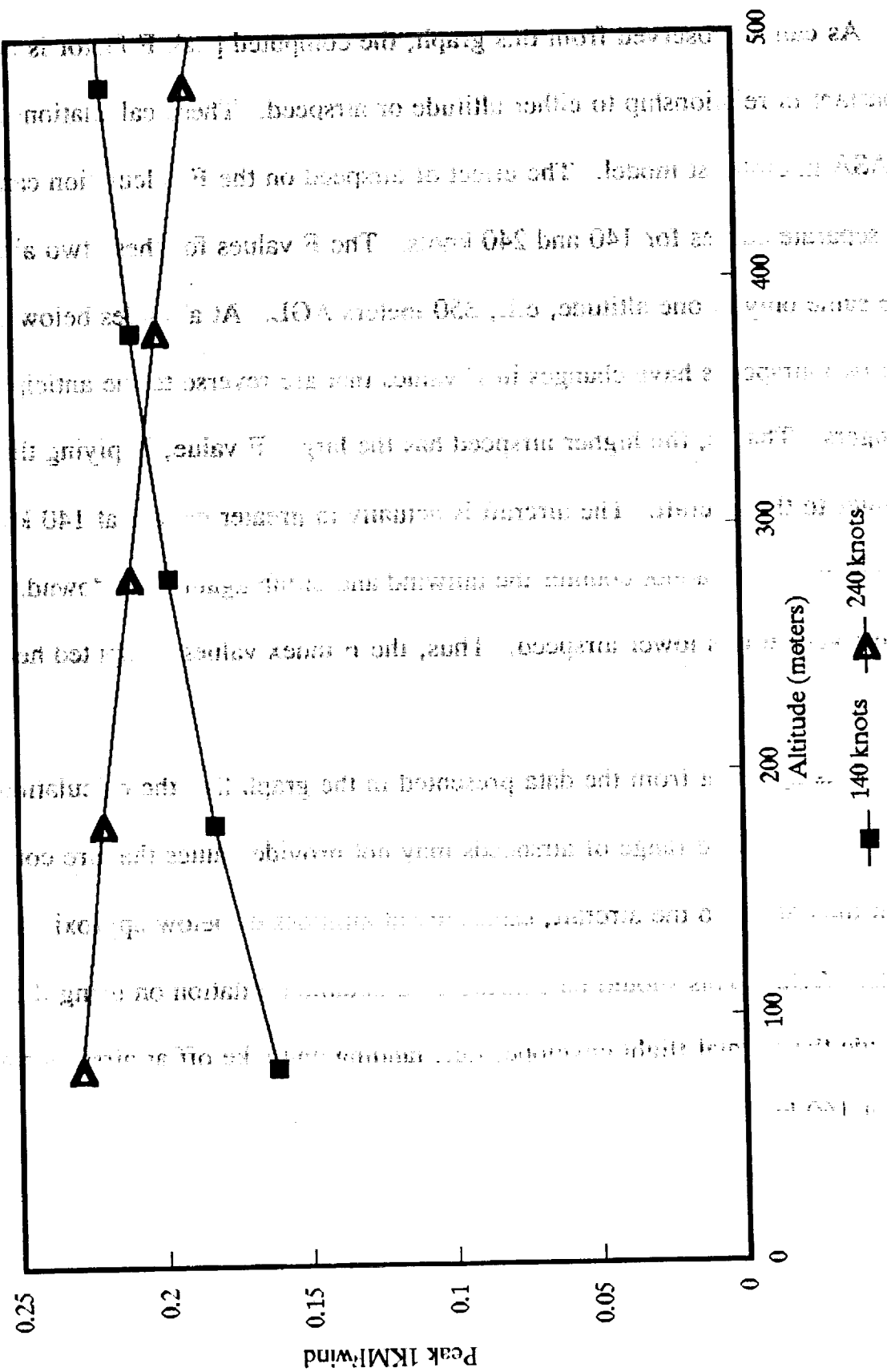
Peak F Index versus Altitude at Different Airspeeds:

As can be observed from this graph, the computed peak F factor is not a constant in relationship to either altitude or airspeed. These calculations are from a NASA microburst model. The effect of airspeed on the F calculation can be seen as separate curves for 140 and 240 knots. The F values for these two airspeeds are the same only at one altitude, e.i., 350 meters AGL. At altitudes below 350 meters the two airspeeds have changes in F values that are reverse to the anticipated dangers. That is, the higher airspeed has the larger F value, implying the greater danger to the aircraft. The aircraft is actually in greater danger at 140 knots, however, for it cannot counter the tailwind and climb against the downdraft as effectively at this lower airspeed. Thus, the F index values computed here are in error relative to the aircraft situation.

It is apparent from the data presented in the graph that the calculation of the F factor over a wide range of airspeeds may not provide values that are consistent with the danger to the aircraft, especially at altitudes of below approximately 350 meters AGL. This should be considered a notable limitation on using the F factor outside the normal flight envelope, i.e., landing and take off at airspeeds above about 160 knots.

Thus, the importance of this graph is to show that the magnitude of the F

peak value will be a significant function of the altitude of approach and the

airspeed.

WET MICROBURST LANDING AT VARIOUS AIRSPEEDS

STARTING ALT 1500 FT

DISTANCE FROM MICROBURST AXIS IN METERS

Thousands

F INDEX

Legend: 100, 140, 200, 250
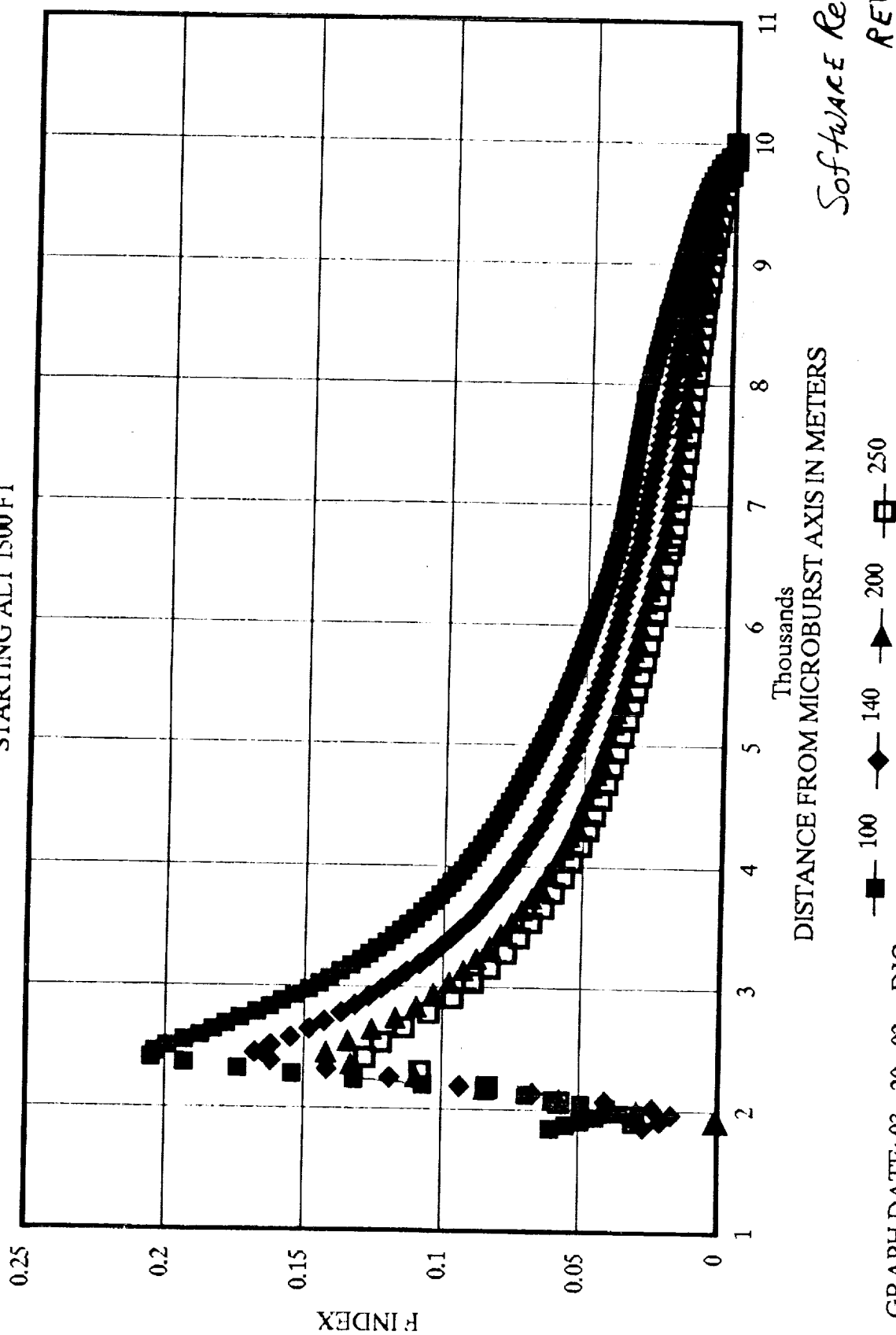
Software Rev 2.1.2.0

REV 2.1.1.2

712

When using the AWAS-III algorithm which takes advantage of thermal measurements, we obtain a rather different situation. Here, the lower the airspeed, the greater the peak value of the AWAS F index. This seems quite reasonable, for the lower the airspeed, the greater the danger to the aircraft. When the aircraft is flying fast enough, the danger is sufficiently low that a warning is not required. Also, we see that the lower the airspeed, the earlier the warning will be given. This also seems quite appropriate. Thus, we see that there is a very fundamental difference between the NASA F index, and the AWAS F index in character. These differences make it very difficult to directly compare the NASA and the TPS warning systems on a truly meaningful basis.

Effect of Airspeed on OAT

Airspeed in 1" per Hour Rain

744
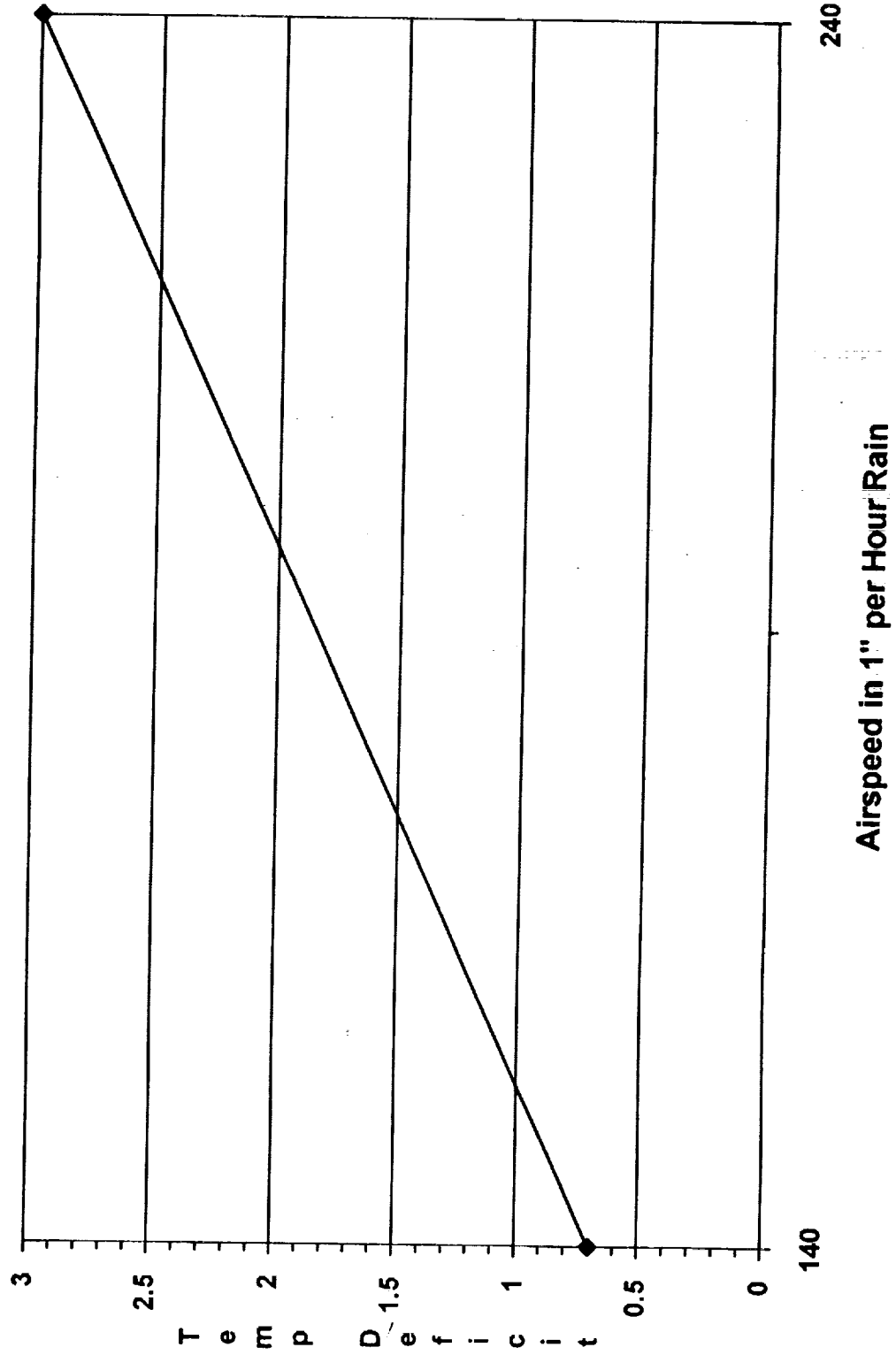
The additional concern related to the airspeed is that of the response of the OAT transducer when operating in the presence of rain. The airspeed effect on the output of the OAT is related to the presence of rain which can evaporate and provide cooling for the gauge. The amount of cooling is a direct function of the airspeed. There is very often rain associated with the microbursts, thus there can be quite different response to these events with different airspeeds. It is possible at these considerably higher than normal landing and take off speeds to obtain temperature indications that can cause nuisance alarms when there are no microbursts present. Here we see that between 2 and 3 degrees Celsius temperature change can occur due to the difference in airspeed from 140 to 240 knots when flying into one inch per hour of rain. As a result, the higher airspeed can cause a warning to be given even when there is no actual change in air temperature. This is of considerable concern, for it keeps the OAT indicated temperature from being an accurate sensor of windshear when the airspeed is significantly greater than 140 knots. The problem of evaporate cooling has not presented a serious problem on other flights at normal landing speeds.

MICROBURST PENETRATION B143

$$F(TDWR)_{140KTS} = 0.13 *$$

$$F(NASA)_{140KTS} = 0.15 *$$

$$F(AWAS)_{140KTS} = 0.13$$

*Preliminary - DH - 4/10/92

746

During the NASA penetration (B143), the IR sensor was not significantly blocked, and the IR performed as expected, when the data was adjusted for airspeed. After the data was adjusted to 140 knots, good agreement was provided among AWAS, the TDWR, and the NASA algorithm using inertial (wind) data. Noise level in the NASA algorithm is plus or minus 0.02.

HAZARD INDEX – NASA EVENT B143
IR1 (LU) WITH 4 POLE 1/20 HZ FILTER

0.15 @ 16 knots

H-INDEX

0.2
0.15
0.1
0.05
0

TIME IN SECONDS

74600   74650   74700   74750   74800   74850   74900

NASA FE3   ■ F IR1

NOTE: AIRSPEED CORRECTION APPLIED

748
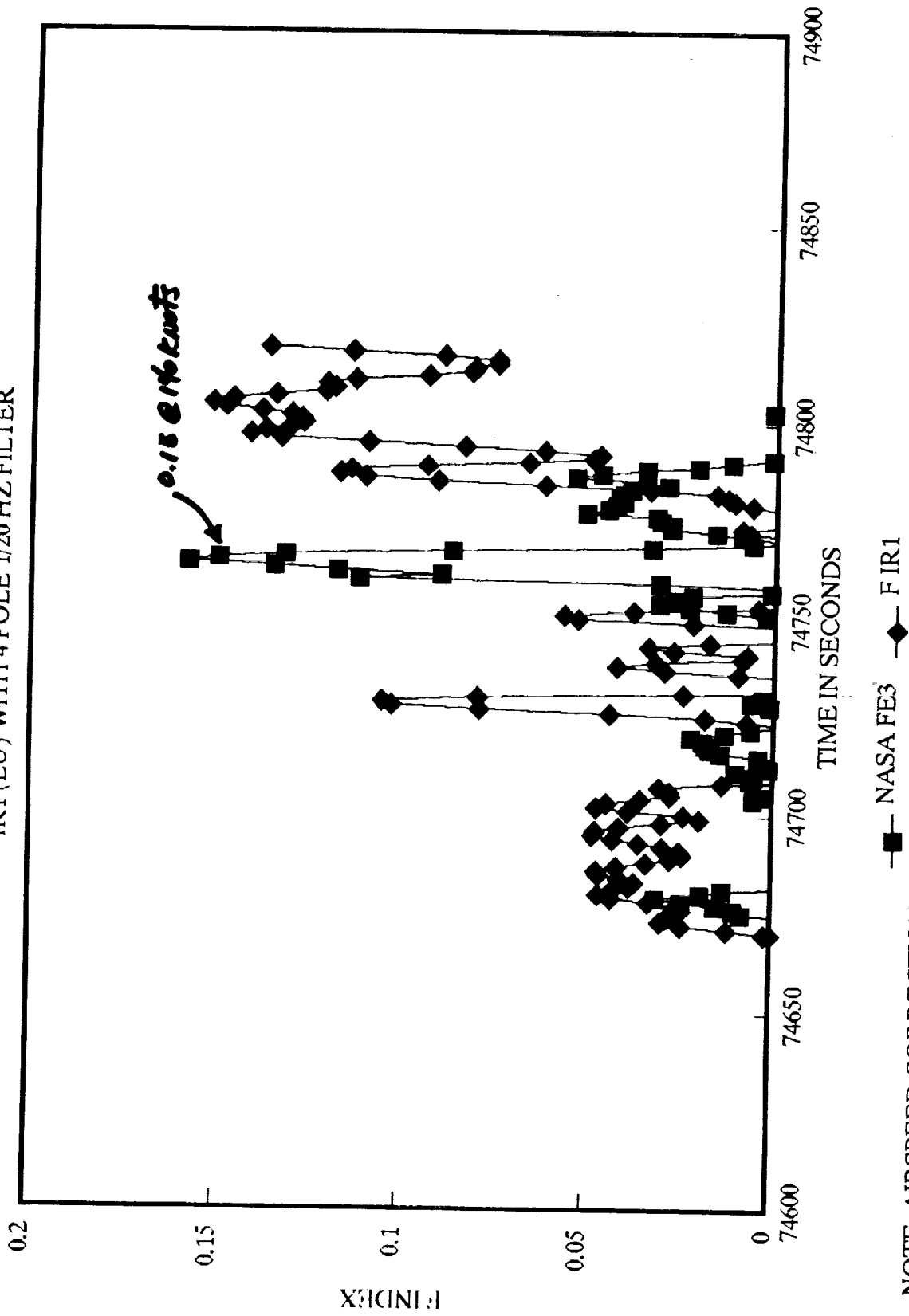
Several post-flight tests were performed by computer on the data from this NASA test run. One was the use of a 4 pole 1/20 Hz filter on the raw data before entering it in the TPS algorithm. In addition, the NASA algorithm output was adjusted to 140 knots, even though the actual airspeed was about 235 knots average. This data is shown for the AWAS IR detector that looks up (LU) from the aircraft waterline by approximately 3 degrees. The predictive F indication from AWAS was considerably lower in magnitude than the inertial NASA F indication, which could be a result of the window still not being very clear. However, since the IR sensed the event about 34 seconds ahead of the inertial response, it appears that the IR was able to perform from a considerable distance in this case.

HAZARD INDEX – NASA EVENT B143
IR2 (LF) WITH 4 POLE 1/20 HZ FILTER

0.15 @ 146 knots

H INDEX

TIME IN SECONDS

NASA FE3   F IR2

NOTE: AIRSPEED CORRECTION APPLIED

750
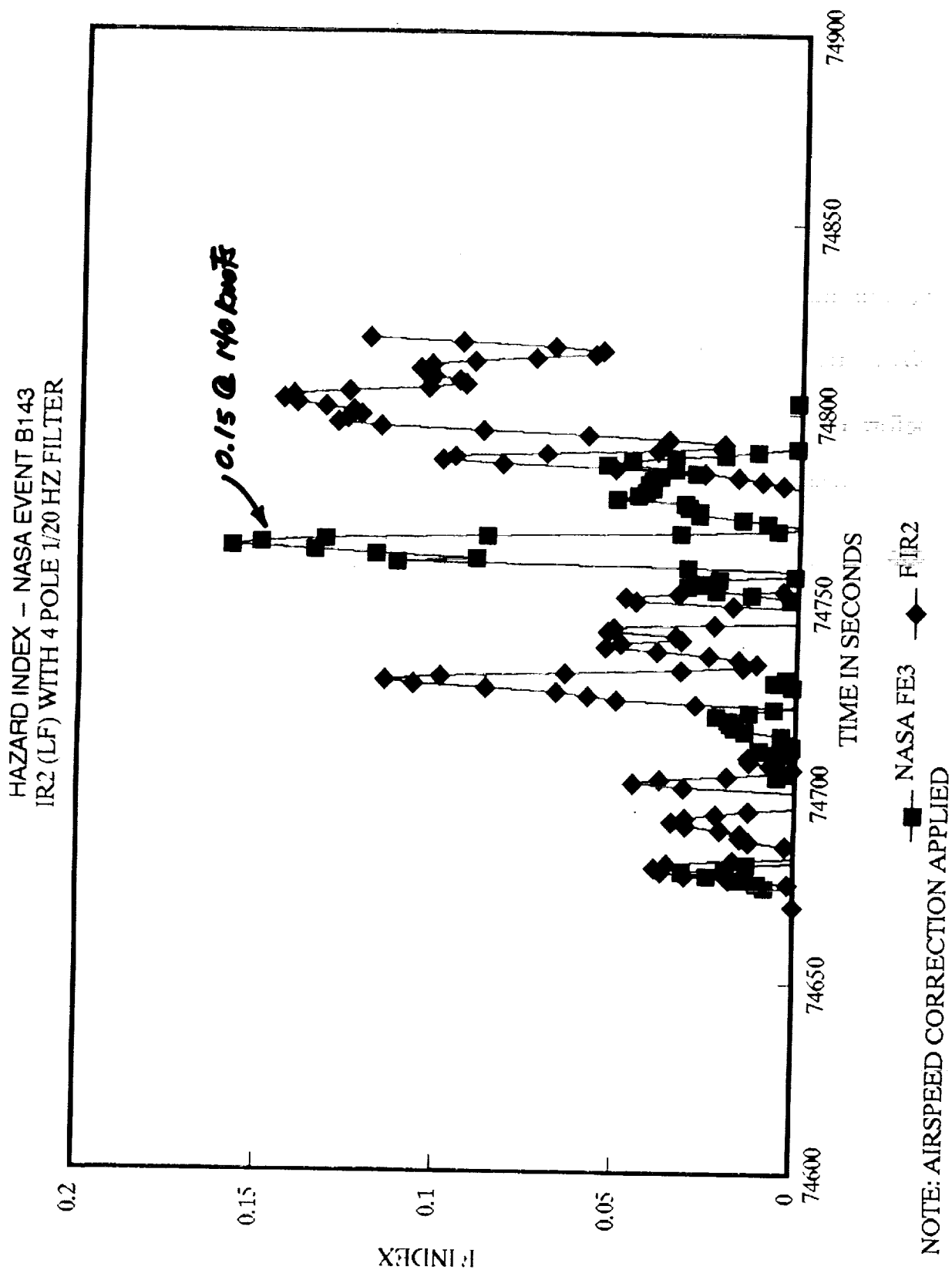
An identical treatment was given to the AWAS IR detector that was looking up from the waterline by only about 1 degree (LF). In this case the AWAS provided an F value of almost 0.12, and the airspeed corrected NASA algorithm provided a little over 0.15 for its F factor. The peak provided by the AWAS system preceded the NASA peak by about 34 seconds.

HAZARD INDEX – NASA EVENT B143
THERMAL INDEX WITH 4 POLE 1/20 HZ FILTER

0.15 @ 146 knots

F INDEX

TIME IN SECONDS

74600   74650   74700   74750   74800   74850   74900

0   0.05   0.1   0.15   0.2

NASA FE3   F THERM

NOTE: AIRSPEED CORRECTION APPLIED

752
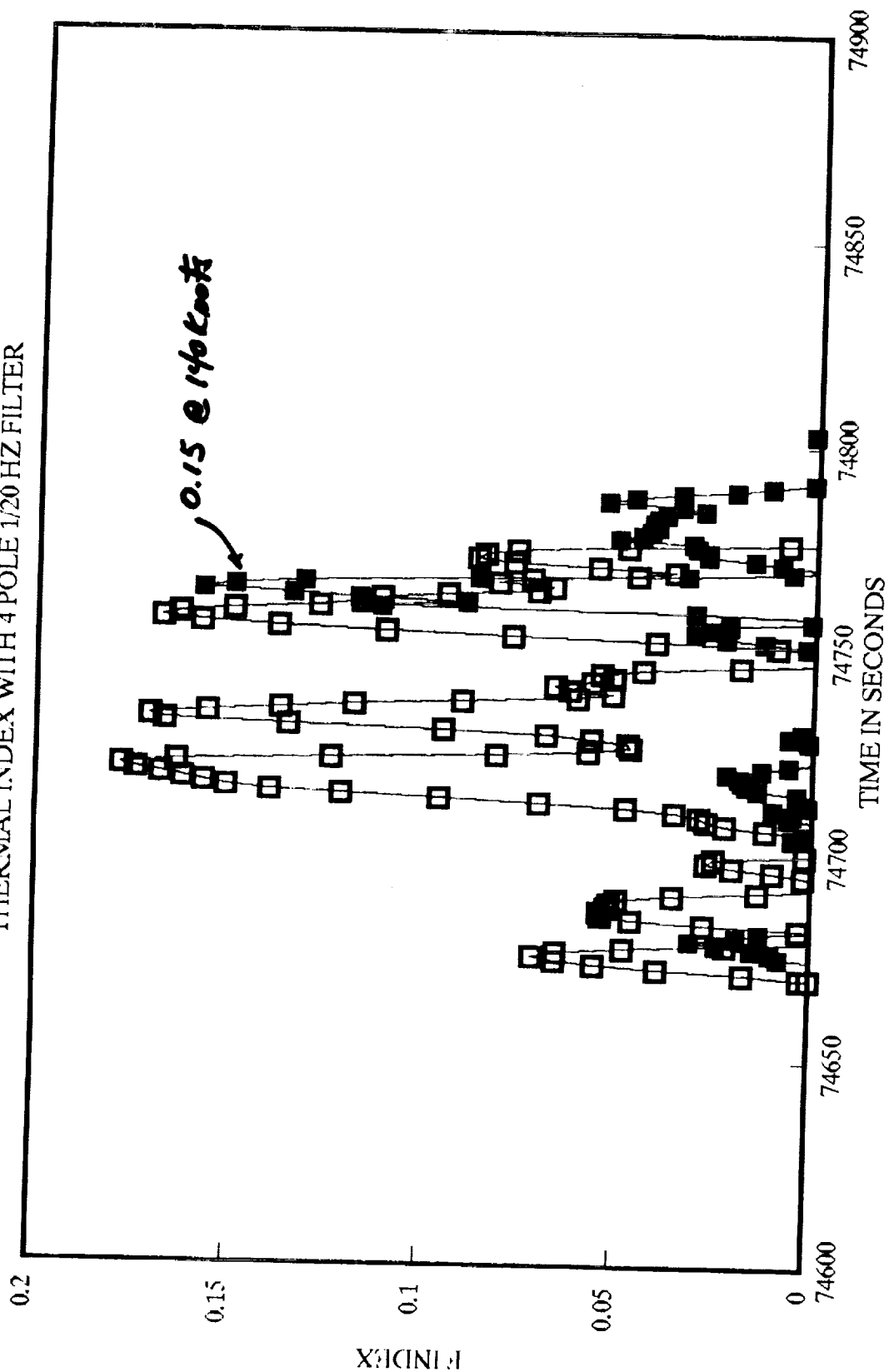
The OAT based AWAS signal was also run through the 4 pole 1/20 Hz filter. This provided an F value of 0.18, and procceeded the NASA algorithm to the trigger point of 0.15 by 48 seconds. This F value for the thermal system was larger than anticipated, and responded sooner than would normally have been anticipated. Both of these effects could well have resulted from high airspeed through rain on the approach to the event. The smaller AWAS IR F values than the NASA values were in good agreement with the TDWR measurements.

TDWR PLOTS

REFLECTIVITY

2 MILES IN 1" / HR RAIN

754

The TDWR reflectivity data indicate 2 miles of flight in 1"/hour rain prior to contact with the event. This could account for the OAT response that was very early and large at this 235 knot airspeed. This would provide a signal that was about 26 seconds early.

NASA / TPS SUMMER PROGRAM 92

AWAS III

SW 2.1.2.1 = 3.2 NWA

756

If the AWAS is flown in the 1992 summer NASA B737 test program, the

AWAS software will be upgraded to that presently being flown by Northwest

Air Lines.

TECHNICAL ISSUES

LOOK DISTANCE

AIRSPEED CORRECTIONS

MODE SELECTION OVERRIDE

There are a number of technical, as well as flight profile issues that must be resolved before further test flights into microbursts for the purpose of evaluating the AWAS in comparison with the NASA systems can be conducted. These are:

1. Change in the mirror/window installation.

2. Adjustment of airspeed effects in excess of the normal landing and take off airspeeds.

3. Overriding the AWAS automatic modes by NASA personnel.

RULES FOR SUCCESS / FAILURE

TPS PERSONNEL ON EVERY FLIGHT

PREAGREED WRITTEN PROCEDURE

RECENT FAA DIRECTION (AWAS IV)

AWAS IV PREDICTIVE w/REACTIVE

The most recent FAA direction with respect to certification of AWAS is the development of AWAS-IV. This would combine the present predictive IR and OAT features with a reactive inertial system utilizing the NASA algorithm. The new combined system will provide prediction with the 100% detection (not protection) that is presently required.

AWAS IV PREDICTIVE WITH REACTIVE

```
   IR SENSOR          OAT          INERTIAL        A/C
     DATA                                          DATA
```

- CAT TPS ALGO
- IR LLWS ALGO
- THERMAL ALGO
- LLWS NASA ALGO

AWAS IV
COMPUTER/CONTROLLER

COCKPIT INTERFACE

LAMPS
- LLWS
- CAT

INOP

VOICE
"WINDSHEAR AHEAD"
OR
"WINDSHEAR"
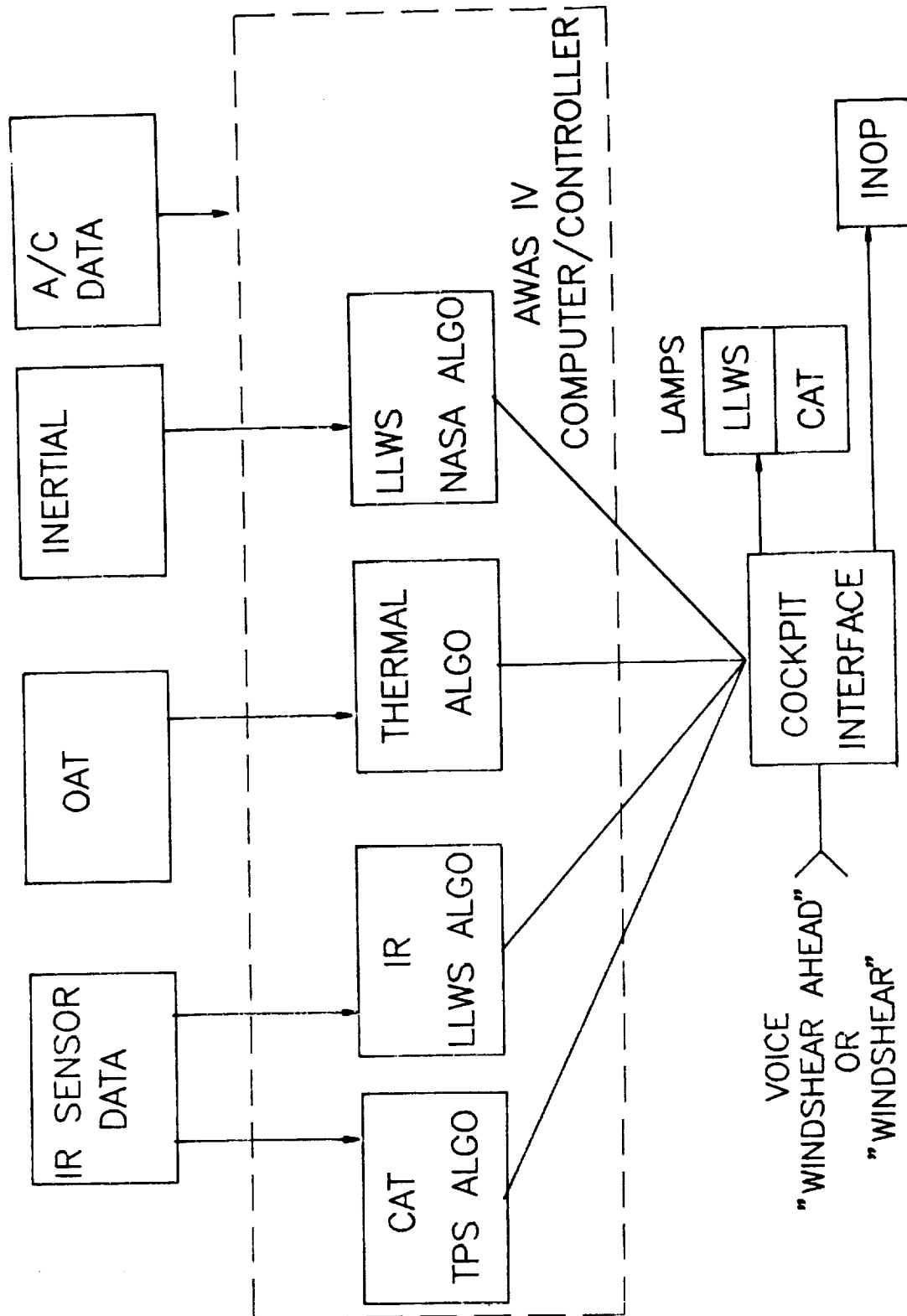
10APR92

630275 REV X

763

The block diagram for AWAS-IV shows the added inertial data input to the

NASA algorithm for LLWS. It also shows the IR sensor input at altitudes of

15,000 feet, and above, being used for the prediction of CAT (Clear Air

Turbulence) events. The cockpit interface provides for aural warnings and

lamps. The lamps would provide LLWS and CAT warnings. In addition,

there would be a lamp to warn of inoperation of the AWAS system. It is

critical for safety purposes that the pilot know if the AWAS is not operating.

IR FEATURE

THERMAL FEATURE

REACTIVE FEATURE
NASA ALGORITHM

CLEAR AIR TURBULENCE FEATURE

DISPLAY SECTION

LAMPS

INOP-ALERTS-CAUTIONS

Another aspect of the communication with the pilot is the providing of "cautions" when there is high probability of danger due to atmospheric conditions, but no specific event has been detected.

AURAL ALERTS

PREDICTIVE
2X "WINDSHEAR AHEAD"

THERMAL OR REACTIVE
3X "WINDSHEAR"

768

CERTIFICATION PLAN

STC PROCESS

NATIONAL WINDSHEAR TEAM
EQUIVALENT SAFETY FINDING

AWAS with REACTIVE
= REACTIVE + GUIDANCE

770

PREDICTIVE CERTIFICATION

USE FLIGHT DATA UND / NASA

USE FLIGHT DATA AA / NWA

The predictive certification will use flight data from the UND and NASA flights to determine the ability of the AWAS to predict events. The flight data from American and Northwest Air Lines flights will be used to determine the level of nuisance alerts.

COMPUTER MODELLING

TASS / DROEGEMEIER MODELS

GENERIC REACTIVE SECTION

FOLLOW AC 25-12

CONCLUSIONS

AWAS MODELLED FOR CONFIDENCE

AWAS FLOWN THROUGH EVENTS

AWAS FLOWN ON REVENUE
SERVICE (>5000 FLTS)

CERTIFICATION END OF 1992

AWAS IV
AVAILABLE
IN
1993

Development of the Advance Warning Airborne System (AWAS)
Questions and Answers

Q: Roland Bowles (NASA Langley) - You talked about designing to a 140 knot target airspeed. That means you have a design methodology because in fact you designed it for 140. Why can't we repeat that methodology and design it for 210?

A: Pat Adamson (Turbulence Prediction Systems) - I think it could be done. I don't think it could be done in time for this deployment. I also have a problem with spending a lot of energy designing something that we are not intended to use. Airplanes don't operate in that regime.

Q: Roland Bowles (NASA Langley) - We are showing on charts that we are taking data measured under one set of conditions and as you point out scaling it back to another. So it seems to me that you must have your own scaling relationship. I think it would be important to this audience for you to discuss what you think is the technical basis for relating an IR measurement to an airplane energy change?

A: Pat Adamson (Turbulence Prediction Systems) - I think it comes down to the forcing function of the event. A downdraft is cold air falling. If you look at the accident/incident data you see a sustained temperature drop over about thirty seconds as the aircraft penetrates the encounter. Now we don't use the actual aircraft temperature data, but we use the temperature gradient data as the forcing function for our algorithm. That is really the basis for it.

Q: John Hansman (MIT) - I was a little confused by your nuisance alert chart. On the American Airlines data, was that 20% of all the flight hours or flights you received some sort of nuisance alert?

A: Pat Adamson (Turbulence Prediction Systems) - That is correct.

John Hansman (MIT) - I am a little concerned from a display and human factors standpoint. If you have nuisance alerts at any significant level and you alert with a simple light in the cockpit, then you are going to run into fidelity or trust problems with the crew. Do you want to comment on that?

Pat Adamson (Turbulence Prediction Systems) - I totally agree with you. I think that it is an unacceptable alerting ratio. We decided to get at least 3,000 flights in our database before we made any significant software revision. So that we could look at the data. Right now on 3-2 we have one alert in 135 flights. We do not anticipate an alert any more often than the recommended nuisance alerting in the reactive systems. We have to get down to nuisance alerts of less than one per 2,500 flights or so, and that is where we think we are going.

Q: Jim Evans (MIT) - How do you discriminate between gust fronts, which are going to produce a gain in energy state, versus microbursts? They both have pools of cool air.

A: Pat Adamson (Turbulence Prediction Systems) - What we are looking at is a temperature gradient and a specific signature. I guess that is the best answer that I can give you.

Q: Jim Evans (MIT) - Have you attempted to fly through a lot of gust fronts and demonstrate that you are not generating an incorrect alert or do you view it as a correct alert?

A: Pat Adamson (Turbulence Prediction Systems) - I guess if the shear is high enough, even if it is a negative shear, I would be considering it a dangerous event.

Jim Evans (MIT) - When you go into a gust front you usually get a headwind increase but you do not have a tailwind, so you actually have an increase in energy state. It maybe a controllability issue, or a long landing, but it is not like the plane is going to get smashed out of the sky.

Pat Adamson (Turbulence Prediction Systems) - That's true. Looking at the work that Marilyn Wolfson did in your organization, her concern was that the dangerous events were associated with pre-existing gust fronts or thunderstorm outflows. Several of the gust front data show very high turbulence or vorticity associated with them. As it is right now, what we are trying to do is to use the temperature gradient and the signature to discriminate between severe events and non-severe events.

Q: Gerry Aubrey (United Airlines) - Do you have a threshold for what is the significant clear air turbulence you want to indicate?

A: Pat Adamson (Turbulence Prediction Systems) - We are working on that. The data that we are using for indication of severity is the vertical acceleration of the aircraft. We have been using 0.2 G or greater. But, the airlines do not seem to be interested in this small of a threat. They are much more interested in the larger one. We do not have much data where there is a severe event, even in some 5,000 flights.

Q: Kim Elmore (NCAR) - I would like to follow up on something that Jim Evans was talking about, and that is discrimination between a gust front event and a microburst event. Specifically in the Denver area, because that is where I have most of my experience, we find that the gust fronts tend to be colder events generally than the microburst. As I understand it, that would set off even a louder bell?

A: Pat Adamson (Turbulence Prediction Systems) - It depends, we look at not only the temperature drop but the signature that as we would encounter that event at 140 knots. If the temperature gradient is too high or too short in time it would discriminate against it.

Q: Kim Elmore (NCAR) - O.K. so if it is too high or too short or too big a gradient then you tend to throw that out?

A: Pat Adamson (Turbulence Prediction Systems) - That is correct.

Q: Pete Sinclair (Colorado State University) - I think the answer to that question is going to end up in the scanning procedure that will come out later on. We will be able to scan across the gust front and see quite a different configuration than a small microburst. My question is how do you keep the system clean and abrasion free? How do you keep it clean without a sealed system where the mirror and the whole system is internally sealed?

A: Pat Adamson (Turbulence Prediction Systems) - Actually, that has been sort of a revelation. When we first put this on we were worried about that. The mirror is heated. It has 120 watts of heat, with heavy gold plate on it, and the window is flush against the skin. The natural cleansing action of the rain and the warm mirror seems to be very effective. On American Airlines we have a coated window, we went to material that was supplied to us by Ball Brothers Aerospace and we now have five months on that installation without having to clean it or touch it. So, the natural cleaning action and the rain with the warm mirror seems to be very effective. We have been very surprised at how well that has worked.

Q: Paul Robinson (Lockheed) - You say an IR measurement is based on the detection of cold air in descent and this terminal effect is the driver of the microburst. However, the structure of the microburst requires the presence of the ground causing added divergence. This is an inertial effect. How can a purely thermal measurement detect this danger?

A: Pat Adamson (Turbulence Prediction Systems) - Essentially what we do is we assume that a sustained cold air downdraft, as sensed by an aircraft platform, is going to do one of two things: first, if it is above the outflow it is going to detect the core of the event. When I say sustained, I am expecting that temperature change that I derived to exist over about thirty seconds. I am not looking for a single little pulse of cold air, I am looking for a sustained temperature drop that I calculate as I traverse say a mile and a half at normal aircraft speed. That cold air is going to hit the ground and diverge. The second condition is if in fact I am in the outflow, I expected the outflow as I move through this mile and a half spatial realm is cold. That is basically how I do it.

Q: Paul Robinson (Lockheed) - By inferring the wind from the temperature you can possibly detect a microburst type hazardous shear. Can you ever get a hazardous shear without that temperature change?

A: Pat Adamson (Turbulence Prediction Systems) - Can you ever? Probably.

Q: Paul Robinson (Lockheed) - It is the shear that is going to effect the aircraft, so if your instrument won't pick up the temperature change, but the shear is still there, then it would not work as a predictive system.

A: Pat Adamson (Turbulence Prediction Systems) - The way I went at that, Paul, was I actually took aircraft incident data and I used the algorithm that I have against each and every event that I could get my hands on. I got the data from the NTSB. For example, yesterday I looked at the data from event 143, Fred Proctor was good enough to share his model as well as the actual aircraft data. In every case that I have found so far, and that is probably about sixty cases including the JAWS actual airborne penetrations, if I use the algorithm I could calculate the shear from the temperature drop. I assume that the cold air that is falling is going to flow out in the outflow over a sustained time, not a single little pulse, but over time. That is how I do it.

Q: Paul Robinson (Lockheed) - Using NASA's In Situ algorithm do you alter the systems properties based on the output of this algorithm?

A: Pat Adamson (Turbulence Prediction Systems) - We are certainly looking at that. I think there is some real benefit in taking advantage of a combined system. If you are going to have a reactive algorithm on board with a predictive system, I think you should look at the system as a combined system. We have not really sorted out all the details on that. When you look at the operational aspects, and that is a lot of what we have been trying to do with the airlines, the nuisance issue is equally as important as being able to predict the event. If you have high nuisance obviously it is useless to be able to predict the event, because the pilot won't believe it. We do not want to repeat that particular lesson. So yes we are trying to best understand how to combine these systems and make it a better system between the two.

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A Millimeter-Wave Radiometer for Detecting Microbursts
Dr. Robert McMillan, Georgia Tech Research Institute

A MILLIMETER-WAVE RADIOMETER FOR THE DETECTION OF MICROBURSTS

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ABSTRACT

This paper describes a millimeter-wave radiometer for the detection of wind shear from airborne platforms or at airport terminals. This proposed instrument will operate near the group of atmospheric oxygen absorptions centered near 60 GHz, which it will use to sense temperature from a distance. The instrument will use two channels to provide two different temperature measurements, providing the basis for solution of two equations in two unknowns, which are range to the wind shear plume and its temperature. A third channel will measure ambient atmospheric temperature. Depending on the temperature difference between the wind-shear plume and ambient, the standard deviation of range measurement accuracy is expected to be about 1 km at 5 km range, while the temperature measurement standard deviation will be about one-fourth the temperature difference between plume and ambient at this range. The instrument is expected to perform usefully at ranges up to 10 km, giving adequate warning of the presence of wind shear even for high performance jet aircraft. Other atmospheric hazards which might be detected by this radiometer include aircraft wakes and vortices, clear-air turbulence, and wind rotors, although the latter two phenomena would be detected by an airborne version of the instrument. A separate radiometer channel will be provided in the proposed instrument to detect aircraft wakes and vortices based on perturbation of the spectrum of microscopic atmospheric temperature fluctuations caused by the passage of large aircraft.

A MILLIMETER-WAVE RADIOMETER
FOR DETECTING MICROBURSTS

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A MILLIMETER-WAVE RADIOMETER FOR THE DETECTION OF MICROBURSTS

1. Introduction

It has been estimated that one-half of all aircraft fatalities are caused by inclement weather. One of the most significant manifestations of severe weather, and one which is of great concern with regard to aviation safety, is the phenomenon of wind shear, which is a severe downdraft associated with thunderstorms or other atmospheric instabilities. Since wind shear apparently originates at high altitudes, it is characterized by temperatures lower than the surrounding atmosphere, which provides some basis for building devices for its detection. A strong correlation has been established between the temperature of a wind-shear event and its severity. As an example, Figure 1 [1] shows the measured velocity of a downdraft as a function of its temperature difference compared to the surrounding air. Figure 2 shows the actual measured temperature profile of a wind-shear event which was severe enough to pose danger to aircraft [2].

This proposal describes a device for remote detection of wind shear based on a millimeter-wave (MMW) radiometer which operates on a frequency located on the low-frequency skirt of the group of oxygen absorptions broadly centered at 60 GHz. Such a radiometer was originally described by Haroules and Brown [3] in 1969, but the availability of much better and more sophisticated components since the publication of Reference [3] makes the MMW approach much more attractive. Furthermore, careful measurements of the oxygen absorption coefficient as a function of frequency have been made by Liebe and his coworkers [4], and provide the basis for accurate determination of both the range to the event and its temperature differential, which is a measure of its severity. Range and Temperature measurements are discussed in Section 2.

To detect a temperature change in the atmosphere with a radiometer, it is necessary that the frequency of operation be chosen to lie in an absorption band; otherwise the area of affected atmosphere will be invisible to the radiometer. It is also important that the absorption coefficient not be too large, since the radiometer must be able to see through the atmosphere between itself and the region of modified temperature. For these reasons, the frequency of operation must be chosen to lie in a mildly absorbing region of the atmosphere. The band of oxygen absorptions located near 60 GHz is a good choice for this application because it is broad enough so that the absorption does not change rapidly with frequency and low enough in frequency that excellent components are available for radiometer construction. It will be shown in Section 2 that it is possible to measure both the range to the microburst plume and the difference in temperature between it and the surrounding atmosphere. This paper gives details on the design and construction of a microburst detection radiometer operating in this absorption band.
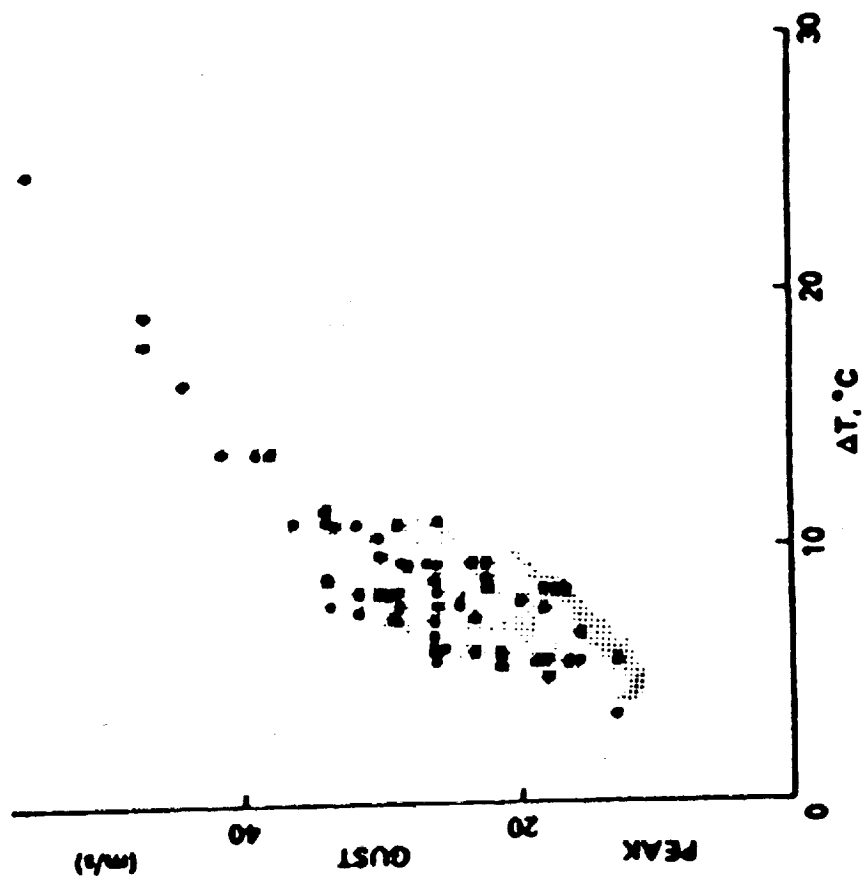
784

Figure 1. Scatter plot of downdraft velocity as a function of its temperature difference compared to the surrounding air.
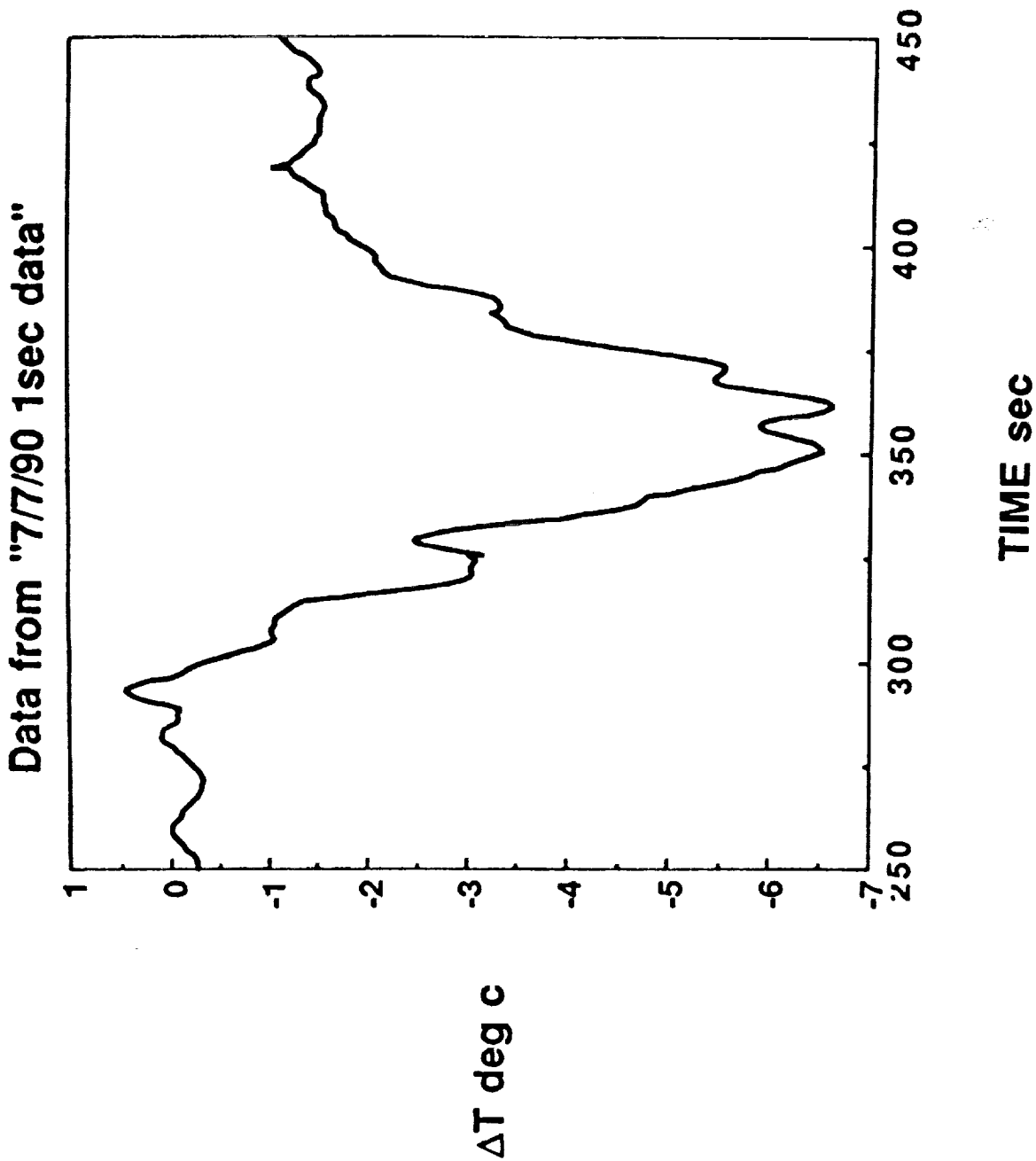
Figure 2. Measured temperature profile of an actual wind shear event.

2. Theory of Operation
2.1 Measurements of Range and Temperature of Wind Shear Event

The radiometer equation gives the temperature observed by a radiometer located at position $z = 0$ looking through a volume of the atmosphere characterized by temperature $T(z)$ and absorption coefficient $\alpha(z)$ as

$$T_A = \int_0^\infty \alpha(z)T(z)\exp[-\int_z^\infty \alpha(z')dz']dz, \quad (1)$$

where T_A is the antenna temperature measured by the radiometer. This equation is simply the sum of the temperature contributions of all elements of length dz in the path attenuated by the atmosphere between the radiometer and the length element. If a horizontal path and homogeneity of the individual regions of the atmosphere are assumed, the integration is trivial, and interesting and useful results are obtained.

In this section, the antenna temperature which one would expect to observe with a radiometer pointing at a wind shear plume through a region of absorbing atmosphere will be calculated. In this analysis, it is assumed that the temperatures and absorption coefficients are reasonably constant in each of the volumes of the atmosphere considered. This requirement will be met if the paths are fairly nearly horizontal, although it is expected that this concept will still be viable for slant-path geometry, although the integrations will be more complex. Consider the geometry shown in Figure 3 in which a radiometer antenna at location h is embedded in a region of temperature T_1 and absorption coefficient α_1 extending to h. The radiometer looks through this medium at a second region extending to infinity which has a temperature T_2 and absorption coefficient α_2. This geometry will be recognized as that which occurs in the atmosphere when a wind shear event which is totally absorbing occurs. If the plume is not totally absorbing, i.e. if it is possible to see through it to the other side, range and temperature measurements will not be accurate, but the presence of the wind-shear event will still be detected. This case will be discussed briefly later, but it is likely that most wind shear events are characterized by total absorption, which is certainly the case for wet microbursts. For dry microbursts of limited horizontal extent, the radiometer will not work as well, but the addition of other channels would provide better detection of these types of events. The number of radiometer channels and their frequencies must be the subject of further study.
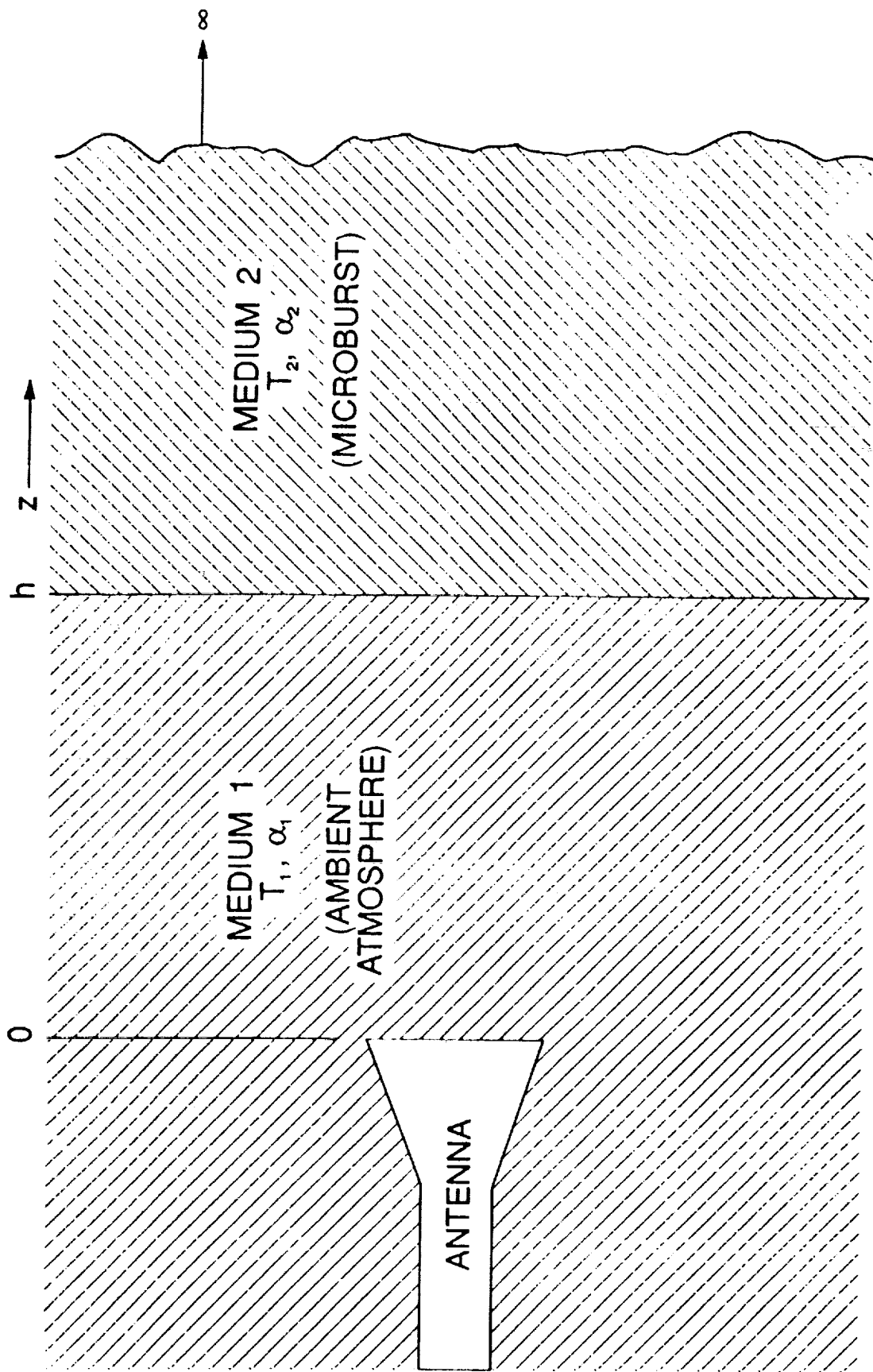
Figure 3. Atmospheric temperature geometry used for calculation of range and temperature of a wind shear event.

Now assume that the radiometer has three channels, one of which lies in a strongly absorbing region of the atmosphere. This channel, since its range is limited by absorption, will simply measure the ambient air temperature T_1. The other two channels, denoted by A and B, are chosen to lie in low and moderately absorbing regions, respectively. If it is assumed that these two regions are homogeneous in temperature and absorption coefficient, it is not difficult to show that the antenna temperatures observed by these two channels are:

$$T_A = T_1 + (T_2 - T_1)e^{-\alpha_A h}, \qquad (2)$$

$$T_B = T_1 + (T_2 - T_1)e^{-\alpha_B h}, \qquad (3)$$

Where α_A and α_B are the absorption coefficients of the atmosphere in region 1 in the low and moderately absorbing bands, respectively. Note that the absorption coefficient of region 2 does not appear in these equations because region 2 is considered to be infinite in extent. These two equations can be solved for the range h to the plume and the temperature difference between it and the surrounding air. These calculations give:

$$h = \frac{1}{\alpha_B - \alpha_A} \ln\left(\frac{T_1 - T_A}{T_1 - T_B}\right), \qquad (4)$$

$$T_1 - T_2 = (T_1 - T_A)^{\frac{\alpha_B}{\alpha_B - \alpha_A}}(T_1 - T_B)^{-\frac{\alpha_A}{\alpha_B - \alpha_A}}. \qquad (5)$$

The parameters of interest to the detection of wind-shear plumes can thus be determined by a radiometer operating in an absorption band of the atmosphere. Section 3 describes the design and construction of such a three-channel radiometer operating on and near the absorption band due to oxygen, which lies near 60 GHz.

2.2 Detection of Other Atmospheric Hazards

To the extent that other atmospheric hazards are characterized by changes in temperature, or by changes in the spectrum of microscopic temperature fluctuations, the proposed radiometer would also be able to detect them. It is possible that detection of clear-air turbulence (CAT), wind rotors, and aircraft wakes and vortices could be made using the proposed instrument, although detections of CAT and wind rotors are primarily airborne applications. The original proposal for this type radiometer by Haroules and Brown [3] addressed specifically the detection of CAT, which causes dozens of injuries every year. Several people were injured recently when a Delta Airlines flight encountered CAT over North Georgia. Since this problem was caused by a

severe downdraft, it is likely that the temperature of the air mass in front of the aircraft was lower than ambient, and could therefore be detected by the proposed instrument. Updrafts could also be detected because of temperature differences between them and ambient.

Wind rotors have been observed primarily in the Western U.S. where they result from winds descending mountain slopes, resulting in a "horizontal tornado" effect. A wind rotor has been cited as a possible cause of the crash of a commercial airliner in Colorado Springs in 1990 [5], with resultant heavy loss of life. Since the air masses resulting in wind rotors originate at high altitudes, it is very likely that their temperature differences from ambient are significant, and might therefore be a basis for detection of these events by a millimeter-wave radiometer. Apparently little is known about the temperature profiles of these phenomena, since they have heretofore been considered rather benign, but if an airborne radiometer were to sense a sharp temperature difference between the air mass ahead and ambient, it would be wise for a pilot to take evasive action.

Wakes and wing-tip vortices have long been recognized as hazards during takeoff and landing operations, especially when smaller aircraft follow larger. To avoid problems with this type of turbulence, it is necessary to space takeoffs and landings at fairly large time intervals so that the disturbances have time to dissipate. If a means could be found to detect these disturbances, it is possible that the frequencies of takeoffs and landings could be increased significantly.

It is possible that the proposed instrument could detect wakes and vortices by one of two methods. The first involves sensing the average ambient temperature in the wake of an aircraft. Since the passage of a large aircraft will mix warmer air from the boundary layer with cooler air from higher altitudes, the average ambient temperature of the air behind an airplane will increase. By using a radiometer with an integration time of 1 second, it is possible to detect a temperature difference of about 0.1 degrees Kelvin. Assuming a temperature lapse rate in the atmosphere of 6 degrees per kilometer, the temperature at an altitude of 100 m would be about 0.6 degrees lower than that on the surface. If after the passage of an aircraft the temperature is observed to be higher than that observed before passage, the presence of a disturbance might be indicated. When the observed temperature returns to its nominal value, the disturbance will have passed. Although this method might work, an approach based on sensing the temperature spectrum of the disturbance is considered more viable, and is discussed in the following paragraphs.

The atmosphere is very dynamic, even under apparently stable conditions of light winds, moderate temperatures, and no precipitation. Its parameters are constantly changing on a microscopic scale, and these changes affect many observables, for example the propagation of electromagnetic radiation. A commonly cited example of the effects of these microscopic changes is the twinkling of stars and the shimmering of images when viewed through long atmospheric paths. One of the parameters which changes on a

790

microscopic scale is temperature. The instantaneous temperature of the atmosphere at a given location may be expressed as the sum of an average value and a fluctuating component:

$$T = T_{avg} + T_{fluc} \qquad (6).$$

The radiometer channel with the long integration time mentioned above measures T_{avg}, and the channel to be discussed below measures T_{fluc}.

The fluctuating component of the atmospheric temperature has a power spectrum that has been studied extensively [6,7,8], and is well understood, provided there are no disturbances in the atmosphere to perturb it. Measurements of the spectrum of temperature fluctuations are usually made under controlled conditions in open areas far from natural features which would cause perturbation. Since carefully controlled conditions are required for precise measurements of the temperature fluctuation spectrum, it is reasonable to expect that the passage of a large body, such as an airplane, through the atmosphere would significantly perturb this spectrum. It is suggested that this perturbation of the fluctuation spectrum be studied as a possible basis for the detection of wake and vortex turbulence. One of the channels of the three-channel radiometer designed to detect wind shear would be used for this purpose. It would not even be necessary to add another channel, since a separate integrator could be added to an existing channel. The output of this integrator, which would have a very short time constant for detection of fast fluctuations, would be fed into a computer which would calculate the fourier transform of the amplitude fluctuations, thus giving the power spectrum. This process would be continuous, so that any short-term change in the spectrum could be detected in a very short time. The dissipation time of the turbulence would then be the time required for the spectrum to return to normal within prescribed limits. As mentioned above, this characteristic of the atmosphere might also be used to detect wind rotors, or might serve as a method complementary to that involving average temperature changes. The next section discusses in detail the design of a radiometer for detection of wind shear and other atmospheric anomalies.

3. Approach

Figure 4 is a block diagram of the radiometer. Radiation is collected by the horn/lens antenna and fed into a full waveguide band mixer covering the 40 - 60 GHz band This mixer is pumped by a Gunn local oscillator operating at a frequency of 43 GHz. The signal input from the antenna is through a waveguide section with dimensions chosen to cut off all radiation at frequencies lower than about 45 GHz, so that the superheterodyne image frequencies are effectively eliminated, making this instrument a single-sideband radiometer. The output of this mixer feeds an intermediate frequency amplifier covering the range 6 - 18 GHz. The output of this amplifier is split into three channels of 6 - 8, 9
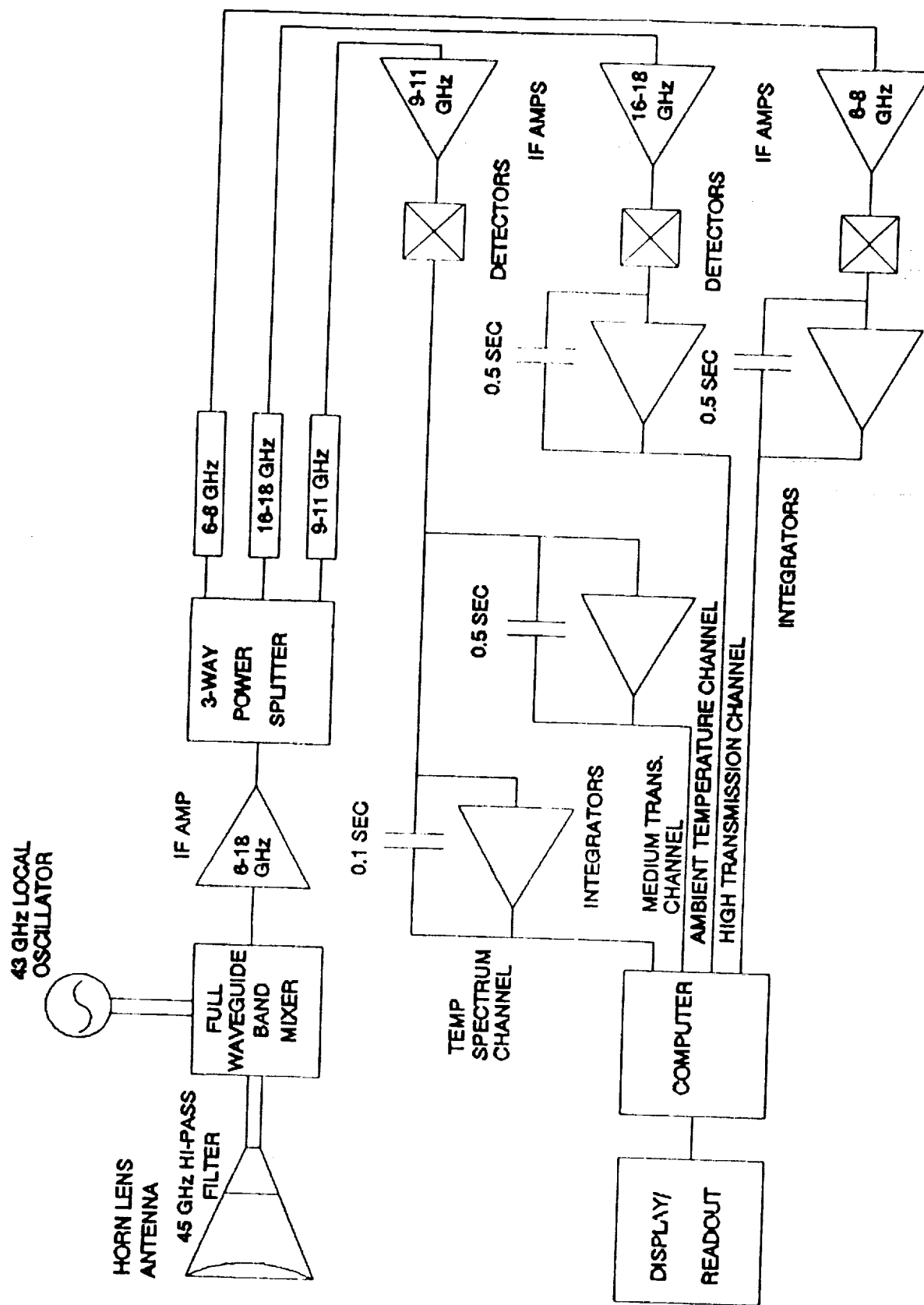
Figure 4. Block diagram of the three-channel radiometer for detecting microbursts.

- 11, and 16 - 18 GHz by a power splitter followed by bandpass filters. These three bands correspond to the signal frequency bands of 49 - 51, 52 - 54, and 59 - 61 GHz, with the images of these frequencies cut off by the input waveguide filter. The receiver will then see the atmospheric temperature in each of the above three channels without the necessity for averaging with image channels. Each of these IFs is fed into an amplifier, whose output is detected and passed into the data processing system. Figure 5 shows the relationship of the three radiometer channels to the 60 GHz oxygen absorption band, calculated using the method devised by Liebe and Layton.

Measurements of the temperature fluctuation spectrum are made by providing a separate integrator with a short time constant for the 52-54 GHz channel. Figure 4 shows that this channel may be added by simply coupling the 9-11 GHz detector output into two separate integrators. The time constant of this spectrum channel must be short enough to resolve the highest frequency fluctuations of interest, but not so short that system noise becomes comparable to temperature fluctuations. Some experimentation will be required to determine the optimum time constant for this channel, although Figure 4 shows a value of 0.1 sec. The output of this spectrum channel is input to the computer, which calculates a fourier transform to arrive at the temperature fluctuation spectrum. This process is done continuously, so that changes in the fluctuation spectrum caused by the passage of aircraft can be easily observed by comparing these spectra before and after.

The existing 9-11 GHz radiometer channel, which has a time constant of 0.5 sec, will be used to measure the average temperature of the air mass behind the aircraft to look for changes due to turbulence. It is possible that a separate integrator will also be used for this purpose, since one might prefer a slightly longer time constant for better resolution.

The radiometer is calibrated by periodically using the input to the antenna to look alternatively at hot and cold loads of known temperatures. Calibration is necessary to negate the effects of changes in gain of the mixer and IF amplifiers. In the future, if these components can be made more stable and housed in a temperature controlled enclosure, it may be possible to build a radiometer requiring calibration only at the beginning of a measurement cycle, so that the wind-shear radiometer could be built with no moving parts.

In the data processing system, the range to the plume and its temperature are calculated using Equations (4) and (5). If no microburst is present, all of the channels will read the same temperature, and the result of calculating range and temperature difference will just be random fluctuations whose amplitude will be a function of system noise. It will be possible to devise algorithms which will recognize a given threshold temperature change and be able to determine whether the change is consistent over some given number of samples. If so, the data processor will calculate a range and give a warning based on the measured

OXYGEN ATTENUATION NEAR 60 GHz

T=15C, P=1013mb, RH=60, 100%

OXYGEN ATTENUATION PROFILES

AMBIENT TEMPERATURE CHANNEL

INTERMEDIATE CHANNEL

HIGH TRANSMISSION CHANNEL

HIGH-PASS FILTER CUTOFF

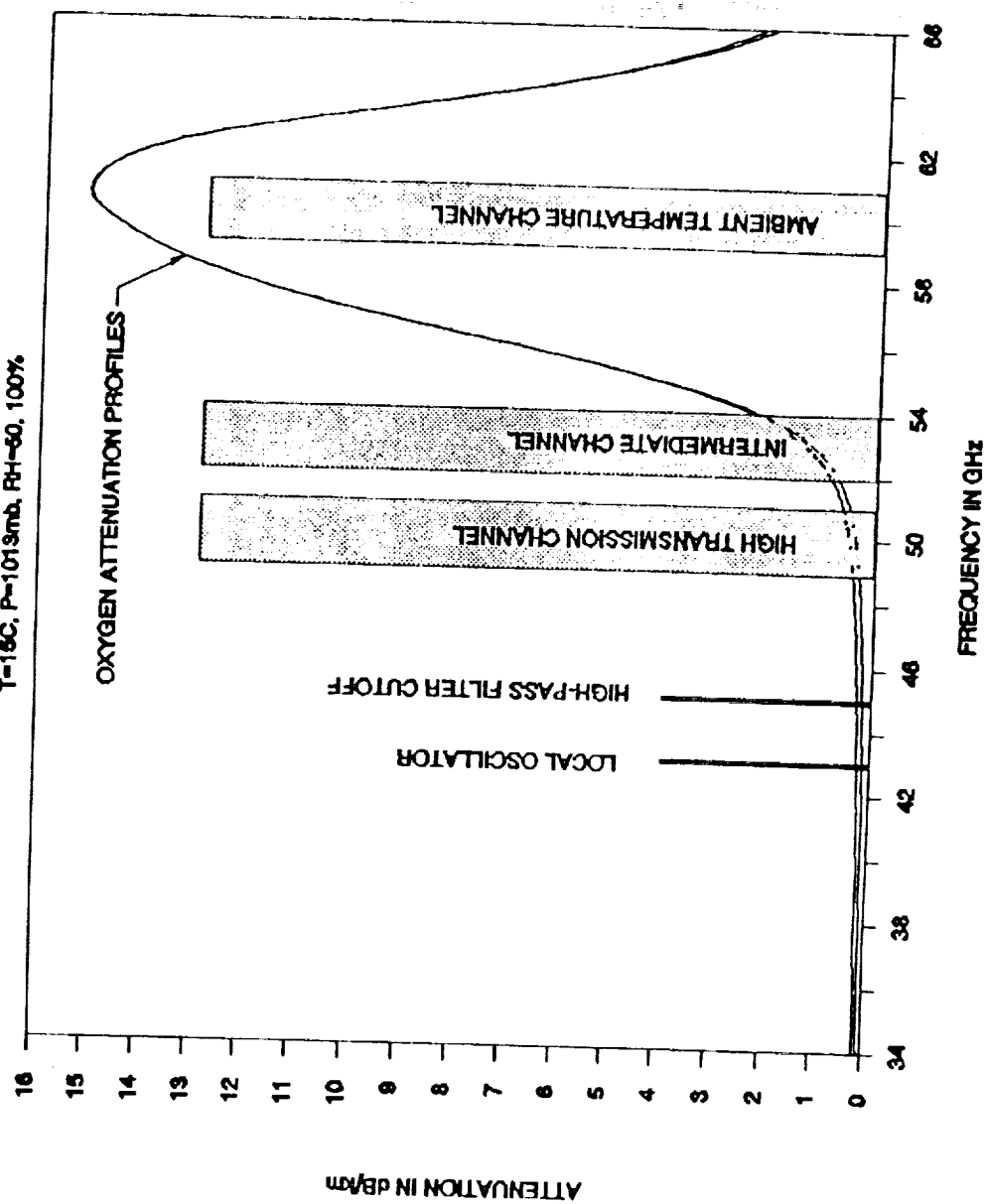LOCAL OSCILLATOR

ATTENUATION IN dB/km

FREQUENCY IN GHz

Figure 5. Relationship of the three radiometer channels to the 60 GHz oxygen absorption.

ΔT. As the wind shear comes closer to the radiometer, the range and temperature measurements will become more accurate, and false alarms will happen less often.

The absorption band of oxygen lying near 60 GHz is the ideal range of frequencies in which to operate a temperature sensing radiometer. Unlike water vapor, another possibility, which varies widely in concentration from one location to another, the mixing ratio of oxygen is constant throughout the world. Furthermore, due to the careful work of H. J. Liebe and coworkers [4] at the National Telecommunications Information Agency, the absorption coefficients of oxygen are known to an accuracy of 0.1 dB/km over the range of atmospheric conditions likely to be encountered under microburst conditions. These measurements include the effects of water vapor, rain, snow, and fog. Liebe is currently engaged in a project which has the goal of increasing this accuracy to the order of 0.01 dB/km, which will improve the performance of the wind-shear radiometer, as will be discussed in Section 4.

The fact that the three radiometer channels respond to regions of the atmosphere at different ranges is accounted for by the concept of the weighting function, which is defined as the coefficient of temperature in the antenna temperature integral Equation (1). For horizontal propagation, where α and T vary little with range, the weighting function is just $\alpha(z)\exp[-\alpha(z)]$ where z is range. Since α varies little with range for a horizontal path, it is taken to be constant for the case of interest. It will be recognized that equations (1) and (2) result from solving this integral for constant α and T for the two regions considered. The weighting functions for the three radiometer channels defined by Figure 3 are shown in Figure 6. Note that the weighting for the 59-61 GHz channel is heavily biased to short ranges, while that for the 49-51 GHz channel shows nearly uniform weighting independent of range. This result is in contrast to the downlooking weighting functions normally shown for the oxygen absorption, which show well-defined peaks because of decreasing attenuation as frequency deviates from the center of the oxygen absorptions.

The concept of the weighting function provides a means for measuring the horizontal temperature profile of the atmosphere. By choosing several radiometer channels centered at different frequencies on the low-frequency skirt of the oxygen absorption, it would be possible to sense the temperature at as many different ranges in front of the radiometer, giving the desired profile, assuming the various regions have sharply defined boundaries. Since these weighting functions are not peaked as are those used for downlooking radiometry, the measurements would not be as accurate as for the downlooking case, but the possibility exists for probing fairly complex temperature profiles within wind shear events, such as that shown in Figure 2. However, for general aviation use, the three-channel radiometer described above is considered adequate.
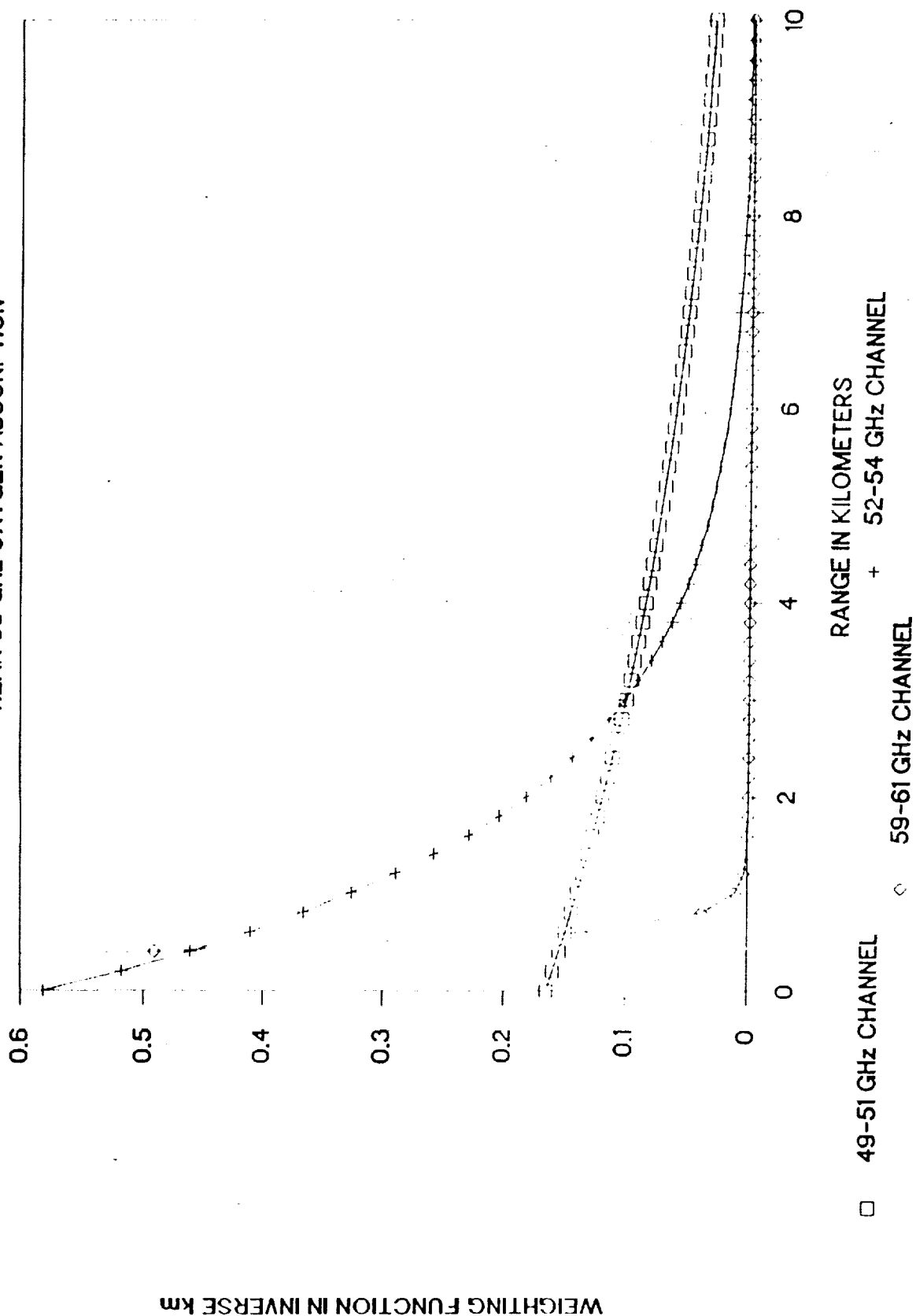
Figure 6. Weighting functions for the three radiometer channels shown in Figure 5.

4. Range and Temperature Error Calculations

Using the above equations for range and temperature difference, the known accuracies in the determination of oxygen attenuation coefficients, and the expected noise performance of the three radiometer channels, it is possible to calculate the rms error in the measurement of these important parameters. For any function of n variables $f(x_1, x_2, \ldots x_n)$, the variance is given by

$$\sigma_f^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma_i^2. \qquad (6)$$

Since we have closed-form expressions for h and $T_1 - T_2$, it is not difficult to calculate these errors, but first it is necessary to determine the errors for the variables x_i. We assume that we know the oxygen absorption to an rms accuracy of 0.1 dB/km. The accuracies with which we know the temperatures are determined by the radiometer equation for minimum detectable temperature

$$\Delta T_{min} = \frac{K(T_{sys} + T_{ant})}{\sqrt{B \tau}}, \qquad (7)$$

where K is a constant (taken to be 1.5 which accounts for gain fluctuations), T_{sys} is system noise temperature, T_{ant} is antenna temperature, B is system bandwidth, and τ is integration time. The typical single-sideband noise figure of the mixer-amplifier combination proposed for use in this application is 10 dB over the range 49-61 GHz. Using Equation (7), the minimum detectable temperature of the three channels is then 0.14 degrees, assuming an integration time of 0.5 s and a bandwidth of 2 GHz for all channels. These values then become the standard deviations of the errors in measuring T_1, T_A, and T_B which are substituted into Equation (6) for calculation of the range and temperature measurement errors. The other errors used in this calculation are the errors in the determination of the O_2 attenuation, which have a standard deviation of 0.1 dB/km = 0.04 km^{-1} as mentioned above.

Using the equations for range and temperature difference derived above, the error Equation (6), and the standard deviations discussed in the last paragraph, it is possible to calculate the errors in determination of range and temperature difference for a radiometer with the given noise performance. The results of the range measurement error calculations are given in Figure 7 as a function of range for ΔTs of 5, 10, 20, and 30 degrees. Note that range measurement is more accurate for the larger temperature differences, as expected. The temperature measurement errors are shown in Figure 8, using the same parameters. At a range of 5 km, the range measurement error has a standard deviation of about 2 km, and the temperature

RANGE MEASUREMENT ERROR

ALPHA A = 0.1 km–1, ALPHA B = 0.5 km–1

RANGE TO MICROBURST IN KILOMETERS

STD DEV OF RANGE MEAS ERROR IN km–1

□ DELTA T = 5 DEG

+ DELTA T = 10 DEG   ◇ DELTA T = 20 DEG

△ DELTA T = 30 DEG   × ALPHA ONLY
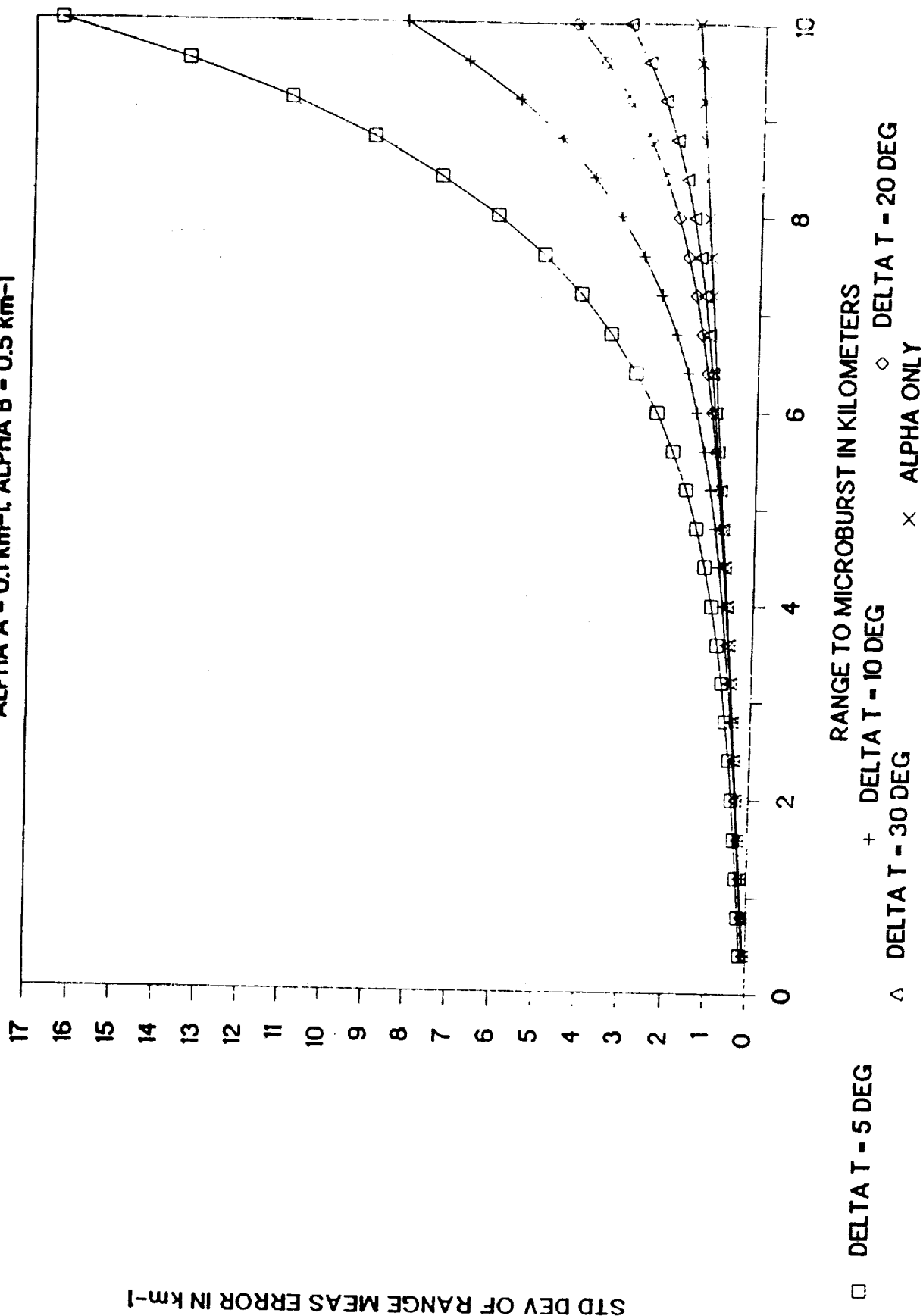
Figure 7. Range measurement errors for the wind shear radiometer
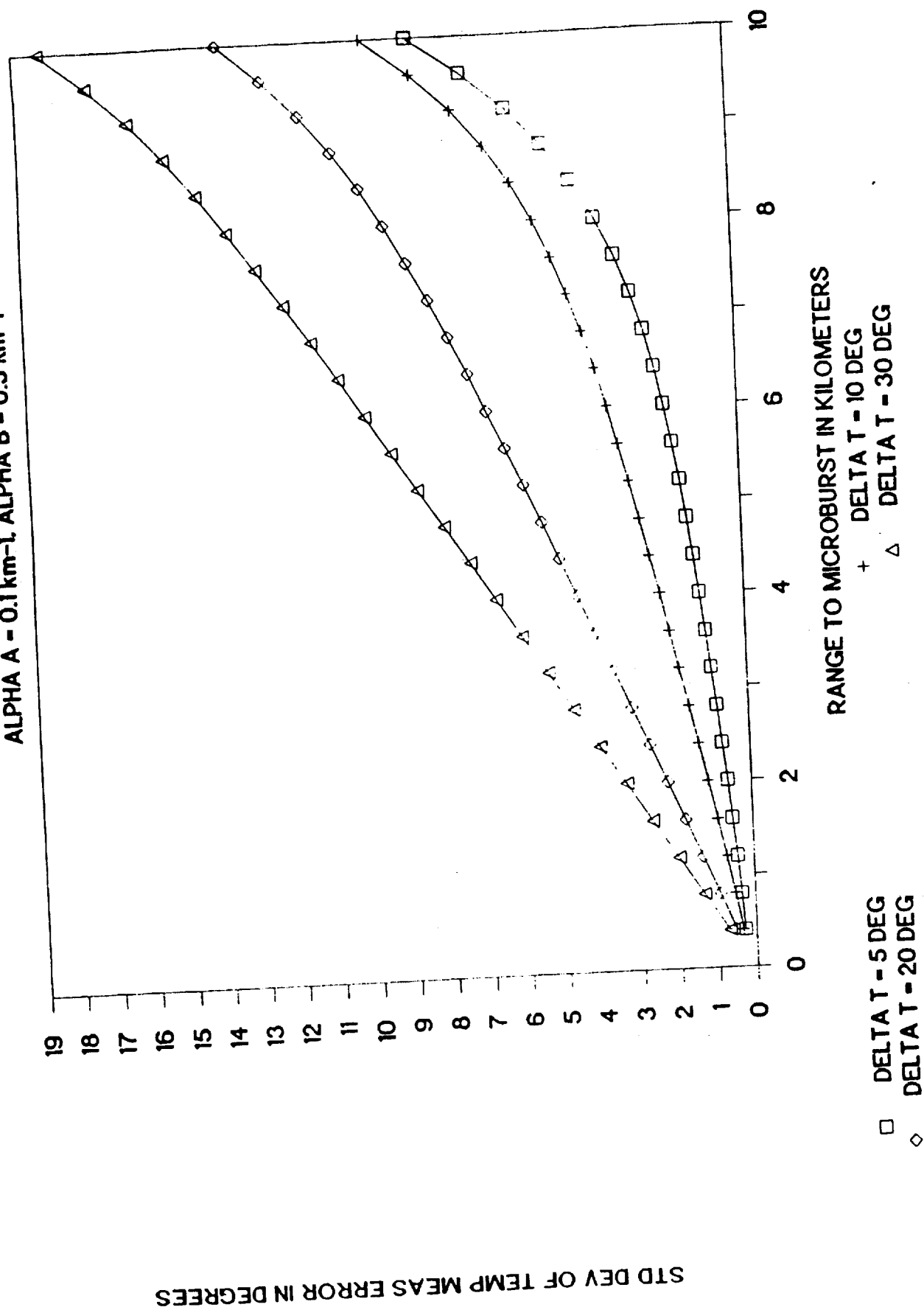as a function of range.

Figure 8. Temperature measurement errors for the wind shear radiometer as a function of range.

measurement error standard deviation is about one-third the temperature difference between the microburst plume and ambient for all cases.

It is possible to show that more than half these errors at 5 km is due to uncertainty in our knowledge of the oxygen absorption coefficient. If the work being done by Liebe [4], in which the accuracy of these absorptions can be known to 0.01 dB/km, can be applied to this radiometer, its range and temperature measurement accuracy can be improved considerably. This feature of the millimeter-wave system emphasizes a significant advantage over the infrared system, which operates at a wavelength of about 16 microns. Absorptions in the infrared are not known to great accuracy, and even if they were, the presence of literally thousands of water vapor absorptions in this region would make the determination of absorption nearly impossible because of the great variation in water vapor concentration from place to place. Because of these limitations, it would probably be impossible to measure accurately the range and temperature of a microburst using an infrared system, although detection of its presence is certainly possible.

5. Evaluation of Wind-Shear Radiometer Performance

Although wind-shear events are very hazardous to aircraft, they still occur very rarely. Because of this rarity in occurrence, adequate testing of the radiometer will be a problem. For proper testing of this instrument, it is necessary for it to view a region of the atmosphere that is at ambient temperature for distances near the point of the test and colder than ambient for regions further away. Fortunately, these requirements are met by the vertical temperature profile of the atmosphere, which will be near ambient temperature near the surface, but will decrease in temperature at an approximate lapse rate of -6 degrees centigrade per kilometer above the surface. The temperature of the atmosphere as viewed by an uplooking radiometer is given by Equation (1), with the addition of a small correction due to the cosmic background temperature attenuated by the atmosphere, which is negligible at these frequencies of interest. By looking upward into the clear sky, the radiometer will see different temperatures in each of its three channels, in a manner similar to what it would see by looking horizontally through the atmosphere at a wind-shear plume. The 59-61 GHz channel would measure the ambient temperature, while the 52-54 and the 49-51 GHz channels would see progressively lower temperatures, since they would see higher into the atmosphere where the temperatures are lower. In this way, the data processing system associated with this instrument would "think" that it is seeing a wind shear plume at a given range. By solving Equation (1) numerically for the temperatures in the three channels corresponding to the prevailing atmospheric conditions, it will be possible to arrive at the range and temperature of the microburst which the radiometer "thinks" it sees. In this way the accuracy of the instrument and its associated data processing algorithms can be assessed. Of course, the instrument will also be used to look horizontally at inclement weather to determine its capability for detecting wind shear if

it does occur, but the vertical-looking, clear-sky tests described above will probably yield a more accurate measure of system performance.

For evaluating the ability of the radiometer to detect aircraft wakes and vortices, it will be necessary to place the instrument near an airport so that these phenomena occur with some regularity. The radiometer would simply be pointed at the runway glide path and the observed temperature spectra would be processed as described above.

9. Summary

We have described a three-channel radiometer based on off-the-shelf parts which we expect to be able to detect the difference in temperature between a microburst plume and ambient air with good accuracy. This instrument, which uses the family of oxygen absorptions centered near 60 GHz as an emitter to measure temperature, would have no moving parts (assuming that calibration issues can be resolved) and would not require a cooled detector. This instrument will be capable of measuring both the range to a wind-shear event and its temperature, which is a measure of its severity. A separate radiometer channel senses the atmospheric temperature fluctuation spectrum for detection of aircraft wakes and vortices. Furthermore, it would have a significant advantage over infrared instruments based on the same principle in propagation through atmospheric aerosols such as clouds and dust, and a marginal advantage in propagation through rain. Another advantage of the millimeter wave instrument over the infrared instrument is based on our knowledge of atmospheric attenuation near 60 GHz. This attenuation is known to high accuracy for a wide variety of atmospheric conditions, including fog, rain, high humidity, and even snow. The large number of atmospheric species with transitions in the infrared bands and our lack of knowledge about them means that it is difficult to know the attenuation coefficients at these wavelengths. This problem is made especially severe by the presence of water vapor, which has literally thousands of transitions in the IR bands and whose concentration varies widely from place to place. Because of the careful work of H. J. Liebe and his coworkers, this problem does not exist for the proposed millimeter-wave instrument, since atmospheric absorption coefficients in the oxygen bands are known to an accuracy of 0.1 dB/km, with the promise of even better accuracy based on later work.

The proposed instrument would probably be used most effectively on board aircraft, where it might also be able to detect clear air turbulence and wind rotors. For ground-based applications, it would supplement the existing terminal doppler weather radar systems at large airports and would serve as a stand alone wind shear detector for smaller airports. In ground-based applications, the radiometer might also be able to detect wingtip vortices.

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3. G. G. Haroules and W. E. Brown, "A 60 GHz Multi-Frequency Radiometric Sensor for Detecting Clear Air Turbulence in the Troposphere", IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-5, No. 5, Sept. 1969, pp. 712-723.

4. H. J. Liebe and D. H. Layton, NTIA Report 87-224, National Telecommunications and Information Association, Boulder, CO, (1987).

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A Millimeter-Wave Radiometer for Detecting of Microbursts
Questions and Answers

Q: Phil Brockman (NASA Langley) - I used to do a lot of measurements with passive infrared, and it seemed like the signal would depend on the temperature difference and also a difference in the absorption or emissivity. If you are looking downward you should see a change in water vapor concentration. What happens if you go into rain, where you are coming out of clear air and then you hit some rain? The emissivity and absorption will probably change. Sometime along the line I would like to hear some of the infrared people address this issue.

A: Bob McMillan (Georgia Tech) - Well rain is a problem of course. At any frequency above 30 or 40 gigahertz the attenuation is almost constant because you are in the knee of the absorption/scattering region. I think that this instrument would probably perform very similarly to the infrared instrument in rain. I do not think there is very much difference in absorption or scattering.

Q: Phil Brockman (NASA Langley) - If you are coming out of clear air and then you hit rain, there is a sudden change. Do you have a problem when that happens?

A: Bob McMillan (Georgia Tech) - Some of the pictures that I have seen in the last couple of days have shown a microburst cell imbedded in a huge rainstorm. I think this instrument would have trouble seeing through the rain to that cell. If the rain were maybe less than four millimeters per hour, then it might would be able to detect it. But in Florida for example, I know you get 60 or 100 millimeter per hour rains. I think most of us have trouble with that kind of weather.

Q: Kim Elmore (NCAR) - Aside from this instruments potential to see wing tip vorticies and perhaps clear air turbulence. What do you see as its ability to tell us things that the TDWR could not tell us in a microburst type of environment.

A: Bob McMillan (Georgia Tech) - I don't think there is anything that this instrument can tell us that the TDWR couldn't. Maybe I should address your question from the point of view of the airborne radars. This instrument and the infrared instrument should be able to detect stuff that is associated with clear air and with no scatters, because it depends on temperature and not back scatter. I guess the TDWR has so much power that it sees these things even in clear air.

Pete Sinclair (Colorado State University) - You might consider including the third layer behind the microburst into the model that you have. We have found with the infrared that this is an area that will leak through the back of the microburst, especially in Denver where the precipitation is light. That field of radiance is an important factor and if you do not take that into account the microburst looks a lot better than it really is.

Bob McMillan (Georgia Tech) - That is an excellent point. I think what we would do in the case of clear air is to increase the absorption coefficients so the instrument does not see through. We would move those RF channels up on the oxygen line so it does not see as far. In that case there would be less leakage. We have actually done that. We have looked at the effect of having that.

Session VIII. Passive Infrared Technology

Colorado State University Research
Dr. Pete Sinclair, Colorado State University

Presentation not available

806

Colorado State University Research
Questions and Answers

Q: Roland Bowles (NASA Langley) - Now that you have done these experiments, how would you relate the measurables, the observables of the IR instrument, to aircraft hazard?

A: Pete Sinclair (Colorado State University) - That is our summer program. Looking at this last example, with the detached or displaced vortex, it is a very weak microburst in terms of temperature difference. But, it is a great hazard, depending on what altitude you are at and what orientation you are flying with respect to the microburst. It is not really clear to us that we should make a forecast from the temperature difference directly without knowing what the trajectory of the aircraft is in relation to the microburst structure. I can't answer how we do that right now, but I think that is the bottom line in this whole thing.

Roland Bowles (NASA Langley) - So I would interpret your comment to mean, that is an unsolved problem in your mind.

Pete Sinclair (Colorado State University) - Well, it is unsolved. We have a lot of data that we could put a model together with and give you a forecast. But, I would be worried right now that with a slightly different approach or departure mode we would have some false alarms. I think more study needs to be made on that.

Roland Bowles (NASA Langley) - Based on our discussion and some of the questions you have asked, you seem to have a very strong opinion about probing these things under five hundred feet, and I think that is good from a scientific point of view. But, the whole idea of the airborne systems technology work, and what operators need, is to avoid getting there based on measurements down there. We are not trying to quantify how strong they can be. We are sitting outside pinging on them, and we are not going to go in there if those measurements show a hazard.

Pete Sinclair (Colorado State University) - If you are going to make a model or a prediction, you have to know what is there, for those critical cases when the measurements that we are making, like you are with the radar, are slightly higher.

Roland Bowles (NASA Langley) - All of the radar data you saw yesterday was two degrees below the horizon. The measurements were being made right down into the ground.

Pete Sinclair (Colorado State University) - That is right. We are trying to verify from the flight measurements, what those radar values really mean, and what our radiometer measurements really mean.

Roland Bowles (NASA Langley) - I can understand the desire to scale the radiometer observable to an expected hazard, but the pulse Doppler systems make a direct measurement.

Pete Sinclair (Colorado State University) - They do. But if you average over a kilometer, I think for some aircraft you miss important parts of the velocity spectrum that can affect them, even for the heavies that get very close to the ground. We have a different hazard factor. In the

hazard factor that you developed we have added a height term. When you get down to 50 meters we are jumping that hazard factor way up. Any moderate hazard factor at 50 meters is a lot different than at say 500 meters.

Roland Bowles (NASA Langley) - Obviously, but that is the whole idea of remote sensing. You are sitting outside pinging on it, and making a decision before you go there. The other thing is the scaling on your balsa vanes and picking a 250 meter averaging length, you are looking at scales of motion that just absolutely don't effect airplanes to any great extent. You are seeing small scale, you are not talking about long term effects. With the thrust to weight you have in that airplane, if you encountered a 0.3 hazard you would not be here today, if they were sustained. Those spurious peaks are not of significant interest.

Pete Sinclair (Colorado State University) - No, I disagree with you Roland. They are not spurious peaks, they are continuous values that are building up. We are not looking at, for example, turbulence inside a thunderstorm where we have giant peaks. We are looking at a field that is coherent, that is either downward or upward. It has peak values, but the field is coherent and in the average it is not affected by the spurious peak. It is very strong. The unusual point about this and that concerned us a lot is that once you get close to the ground we are worried about the turbulence because in our airplane turbulence is a big factor. These things are flowing relatively smoothly, not like a thunderstorm or a convective situation. We do not get the G loading and the vane response from turbulence that we would normally. These are definite build ups and definite shear layers.

Roland Bowles (NASA Langley) - We will discuss this some more, but 0.25 and 0.3's in vertical motion, you are talking five to six thousand feet per minute of downdraft. Clearly that Cessna could not handle that for any length of time.

Pete Sinclair (Colorado State University) - Our true airspeeds are about 55 to 60 meters per second. I am talking 10 to 15 meters per second of downdraft. That is going to give you a 0.2 value. You have to remember we are traveling less than half the airspeed of what you guys are.

Roland Bowles (NASA Langley) - But that makes the effect on the airplane flight-path-angle depression even worse, because it is scaled as one over the airspeed. You just would not be here if that were true, for any significant amount of time.

Session IX. Terminal Doppler Weather Radar

Session IX. Terminal Doppler Weather Radar

The Orlando TDWR Testbed and Airborne Wind Shear Data Comparison Results

Dr. Steven Campbell, MIT Lincoln Laboratory
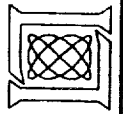Anthony Berke, MIT Lincoln Laboratory
Michael Matthews, MIT Lincoln Laboratory

ORLANDO TDWR TESTBED AND AIRBORNE WIND SHEAR DATA COMPARISON RESULTS

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SDC 4/16/92

Fourth Combined Manufacturers' and Technologists'
Airborne Wind Shear Review Meeting
April 14-16, 1992
Williamsburg, Virginia

"Orlando TDWR Testbed and Airborne Wind Shear Data Comparison Results"

Steven D. Campbell, Anthony J. Berke and Michael P. Matthews

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The focus of this talk is on comparing Terminal Doppler Weather Radar (TDWR) and airborne wind shear data in computing a microburst hazard index called the F factor. The TDWR is a ground-based system for detecting wind shear hazards to aviation in the terminal area. The Federal Aviation Administration will begin deploying TDWR units near 45 airports in late 1992. As part of this development effort, M.I.T. Lincoln Laboratory operates under F.A.A. support a TDWR testbed radar in Orlando, Fl..

During the past two years, a series of flight tests has been conducted with instrumented aircraft penetrating microburst events while under testbed radar surveillance. These tests were carried out with a Cessna Citation II aircraft operated by the University of North Dakota (UND) Center for Aerospace Sciences in 1990, and a Boeing 737 operated by NASA Langley Research Center in 1991. A large data base of approximately 60 instrumented microburst penetrations has been obtained from these flights.

The test flights in 1990 included the first-ever demonstration of real-time transmission of TDWR microburst graphical warnings to an aircraft for cockpit display. A similar demonstration was carried out in 1991, with the TDWR microburst alerts being used to direct the NASA aircraft in making microburst penetrations.

Post-flight analysis was performed under NASA funding to compare the F factor (Bowles & Targ, 1988) as measured by aircraft in situ sensors and estimated from TDWR microburst alarms. It was found that improvements are needed in the

TDWR microburst alarm generation process to allow the aircraft F factor to be estimated accurately. These improvements include: shear-based outflow detection, physical model-based alarm representation, and compensation for the dependence of outflow intensity on altitude. The rationale for these improvements will now be discussed.

The aircraft F factor can be estimated from TDWR microburst alarms using a formula proposed by Bowles (1988):

$$F_{TDWR} = K' (\Delta V/\Delta R) [GS/g + 2h/TAS] = F_x + F_z \qquad (1)$$

where $\Delta V/\Delta R$ is the TDWR-measured shear, GS is the aircraft ground speed, g is gravitational acceleration, h is the radar beam height and TAS is the aircraft true airspeed. K' is a factor which attempts to relate the average shear in the microburst, $\Delta V/\Delta R$, to the peak shear in the microburst over a 1 km distance. The GS/g term corresponds to the horizontal component of F (F_x) and the 2h/TAS term is an estimate of the vertical (downdraft) component of F (F_z). It should be noted that the equation assumes that the aircraft penetrates through the center of the microburst.

It was found that applying Equation 1 to current TDWR microburst alarms often overestimates the aircraft F factor. Examination of TDWR radar data shows that strong microbursts often contain small regions of intense shear inside a larger region of less intense shear. These intense shear regions are not identified by the current microburst detection algorithm, which attempts to identify the peak-to-peak velocity loss, rather than shear. Because of this, the shear associated with a microburst alarm is underestimated for strong microbursts. Applying the K' factor to this underestimated shear leads to the correct F factor estimate for strong microbursts, but overestimates the F factor for weak microbursts.

In order to better quantify the shear for use in Equation 1, a least-squares shear estimator was developed. The base polar radar data was first smoothed using a 0.5 km x 0.5 km median filter. The least-squares estimator was then applied over a seven-gate window of TDWR velocity data for an effective distance of 0.9 km (i.e., 6 gates center-to-center x 150 m per gate). The corresponding shear values were then applied to the following equation:

$$F_{SHEAR} = (dV/dR)|_h [GS/g + 2h/TAS] \qquad (2)$$

where $(dV/dR)|_h$ is the least-squares shear at the radar beam height.

It was found that Equation 2 was an improvement but still often overestimated the aircraft F factor. Further examination of the radar data showed that there was a strong dependence of the outflow strength on altitude. Work by Mark Isaminger and Paul Biron of Lincoln showed that the outflow strength decreases linearly with height above the surface. This result was consistent with an analytical model of microburst outflows developed by Vicroy of NASA Langley (1991); this model is a modification

of an earlier model developed by Oseguera and Bowles (1988). In the Vicroy and Oseguera & Bowles models, the horizontal shear is described by a shaping function, $p(z)$, which is zero at the surface, reaches a peak at height h_m and then drops off with increasing altitude.

Using the altitude shaping function, $p(z)$, the horizontal shear at the aircraft altitude, a, can be estimated:

$$(dV/dR)|_a = (dV/dR)|_h \mid p(a)/p(h) \mid \qquad (3)$$

and the revised F factor estimate can be written as:

$$F_{ALT.CORR.} = (dV/dR)|_a \mid GS/g + 2a/TAS \mid \qquad (4)$$

where we now use the aircraft altitude, a, in the downdraft estimation term, $2a/TAS$. This formula reflects the concept that as the aircraft altitude increases, the horizontal shear will decrease but the downdraft component will increase.

Equation 4 was found to estimate the F_x component quite accurately, but still tends to overestimate the F_z component. Further reflection shows that the $2a/TAS$ term leads to an overestimate of the vertical component, since it is assumed that the aircraft flies directly through the center of the microburst. In fact, many of the penetrations were made at the edge of the outflow where the Vicroy model predicts an updraft, rather than a downdraft.

Accordingly, a final modification was tested which divided the aircraft data into center and edge penetrations. For center penetrations, the unmodified Equation 4 was used; for edge penetrations, the vertical component estimator was changed to $-a/TAS$ (i.e., an updraft at the edge equal to half the center downdraft):

$$F_{HOR.CORR.} = (dV/dR)|_a \mid GS/g + 2a/TAS \mid, \text{ center} \qquad (5a)$$
$$= (dV/dR)|_a \mid GS/g - a/TAS \mid, \text{ edge} \qquad (5b)$$

Applying Equation 5 yielded an improvement in the mean F_z component, however, the data points were clustered as either too high or too low. A further refinement would be to scale the vertical compensation according to distance from the outflow center.

These results lead to the notion that several improvements could be made to the existing TDWR microburst recognition algorithm to allow accurate F factor estimation. First, shear-based outflow detection at multiple thresholds would allow regions of intense shear to be identified inside of larger outflow regions. Second, these shear regions could be used to create a microburst representation based on a physical model consisting of an outflow center and an outflow edge. Third, an analytic microburst model or other technique could be used to compensate for the dependence of outflow intensity on altitude. Fourth, the improved microburst representation could

be used to estimate the vertical component of the microburst based on distance from the outflow center.

A key goal for operations during the summer of 1992 will be to more accurately characterize the altitude dependence of microburst outflows. It is planned to accomplish this goal by carrying out rapid, low-altitude scans of microburst outflows by three radars during aircraft penetrations. The three radars will be the TDWR testbed plus two C-band radars operated under F.A.A. funding by the University of North Dakota and Massachusetts Institute of Technology. These radars are situated in such a fashion to allow triple-Doppler reconstruction of the three-dimensional wind fields at the Orlando airport. These triple-Doppler wind field reconstructions will allow both the horizontal and vertical components measured by airborne and ground-based sensors to be compared.

In summary, a large data base of instrumented microburst penetrations while under TDWR testbed radar surveillance has been obtained over the past two years at Orlando. These tests also marked the first-ever demonstration of real-time data link transmission of TDWR microburst alerts to aircraft for graphical display in the cockpit. Additional flight tests will be performed in 1992, including penetrations with rapid update, low-altitude triple-Doppler radar scans.

Sixty microburst penetrations have been examined to determine how well the aircraft F factor can be estimated from TDWR data. Analysis of the data shows that several improvements to the current microburst recognition algorithm would be needed to allow the aircraft F factor to be accurately estimated. These improvements would improve the quality of the microburst alerts currently supplied to ATC personnel and, in the future, supplied to pilots directly via Mode S Data Link.
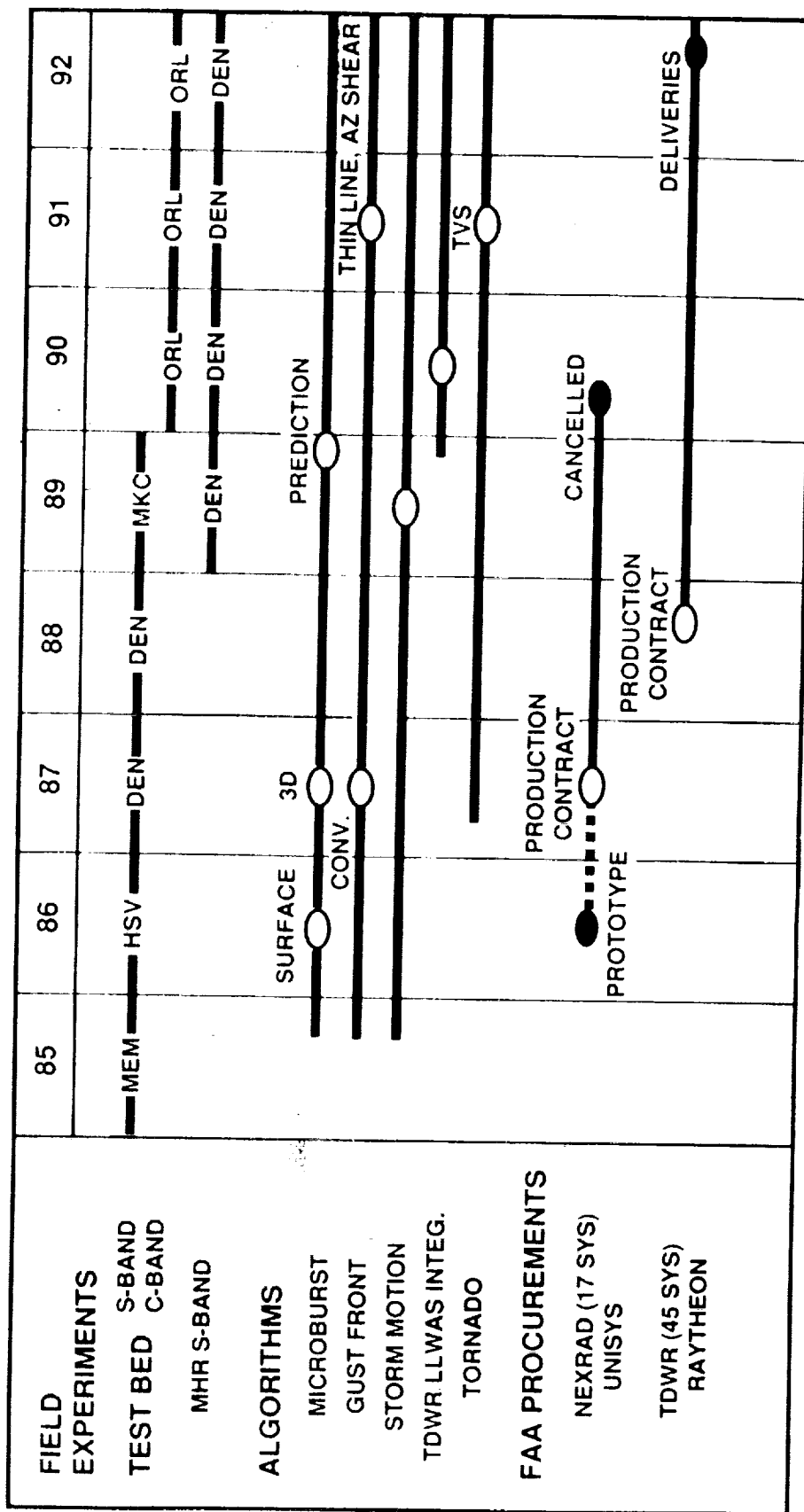
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1. Bowles, R.L. and R. Targ: Wind Shear Detection and Avoidance: Airborne Systems Perspective, International Congress of Aeronautical Sciences, Jerusalem, Israel, August-September, 1988.

2. Vicroy, D.D.: A Simple, Analytical, Axisymmetric Microburst Model for Downdraft Estimation, NASA Technical Memorandum 104053, NASA Langley Research Center, Hampton, VA, February, 1991.

3. Oseguera, R.M., and R.L. Bowles: A Simple, Analytic 3-Dimensional Downburst Model Based on Boundary Layer Stagnation Flow, NASA Technical Memorandum 100632, NASA Langley Research Center, July, 1988.

OUTLINE

- TERMINAL DOPPLER WEATHER RADAR (TDWR) PROGRAM

- ORLANDO FLIGHT TEST & DATA LINK ACTIVITIES

- TDWR F FACTOR ESTIMATION ISSUES:

  - HORIZONTAL SHEAR COMPUTATION

  - MICROBURST ALARM REPRESENTATION

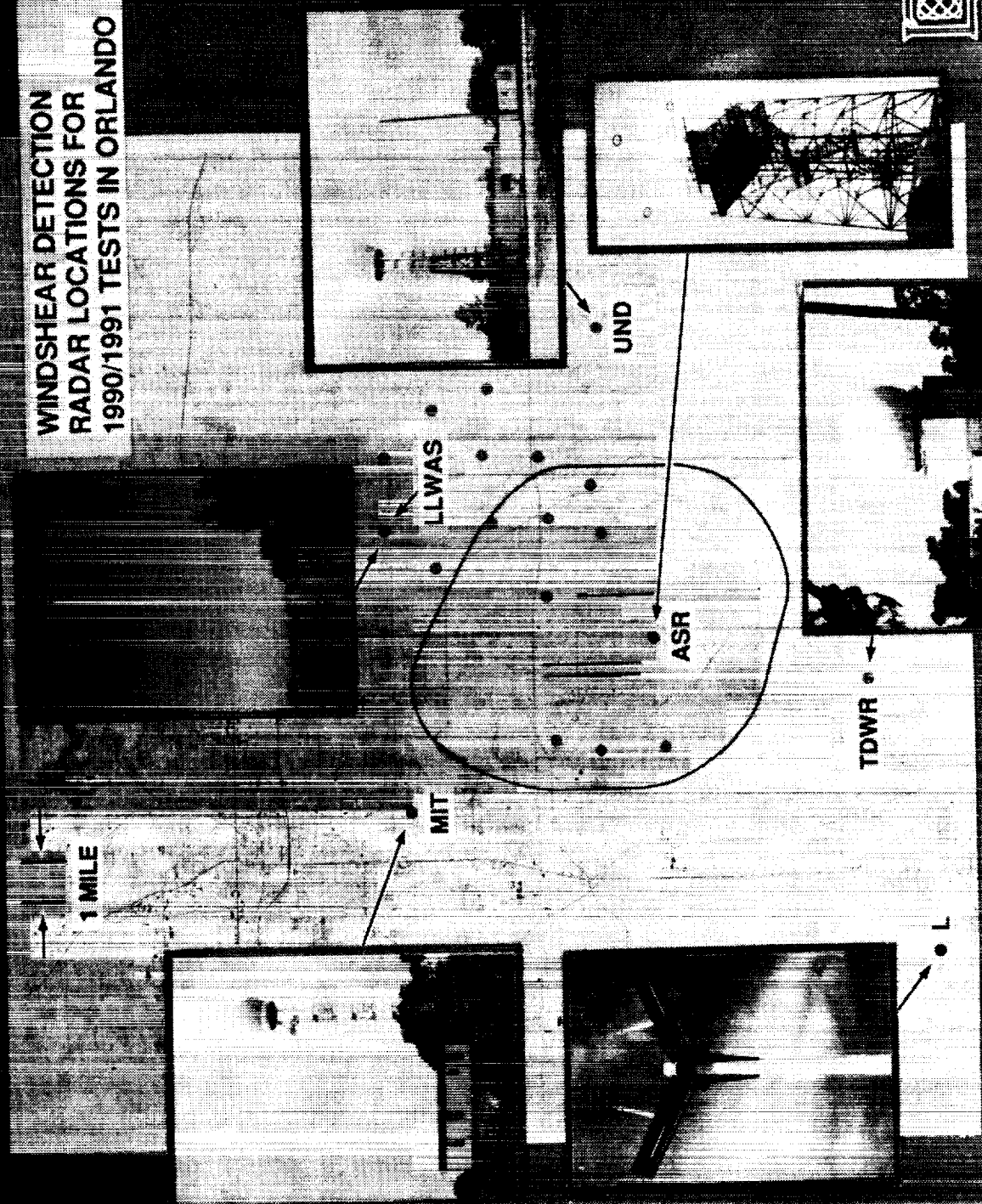 - ALTITUDE DEPENDENCE

  - DOWNDRAFT ESTIMATION

- SUMMARY

TERMINAL DOPPLER WEATHER RADAR PROGRAM

	85	86	87	88	89	90	91	92
FIELD EXPERIMENTS								
TEST BED S-BAND	MEM	HSV	DEN	DEN	MKC			
C-BAND						ORL	ORL	ORL
MHR S-BAND				DEN	DEN		DEN	DEN
ALGORITHMS								
MICROBURST	SURFACE		3D			PREDICTION		
GUST FRONT		CONV.					THIN LINE, AZ SHEAR	
STORM MOTION								
TDWR LLWAS INTEG.								
TORNADO							TVS	
FAA PROCUREMENTS								
NEXRAD (17 SYS) UNISYS		PROTOTYPE	PRODUCTION CONTRACT			CANCELLED		
TDWR (45 SYS) RAYTHEON				PRODUCTION CONTRACT				DELIVERIES

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818

WINDSHEAR DETECTION
RADAR LOCATIONS FOR
1990/1991 TESTS IN ORLANDO

UND

LLWAS

ASR

TDWR

MIT

1 MILE

L

819

TDWR MICROBURST DETECTION PERFORMANCE

	PROBABILITY OF DETECTION		PROBABILITY OF FALSE ALARM
HUNTSVILLE '86	$\Delta V > 30$ kt	1.0	.05
	$\Delta V > 20$ kt	.89	
DENVER '87 – '88	$\Delta V > 30$ kt	.98	.04
	$\Delta V > 20$ kt	.86	
KANSAS CITY '89	$\Delta V > 30$ kt	.97	.09
	$\Delta V > 20$ kt	.94	
ORLANDO '90	$\Delta V > 30$ kt	1.0	.02
	$\Delta V > 20$ kt	.93	

820

179850-1

ORLANDO '91 TDWR TESTBED ACTIVITIES

- FLIGHT PATH SHEAR INTEGRATION

  - SIGNIFICANTLY REDUCED OVERWARNING PROBLEMS
    NOTED IN PRIOR YEAR DEMONSTRATIONS

- TDWR/ELLWAS INTEGRATION

  - PERFORMS MESSAGE LEVEL INTEGRATION OF TDWR
    AND ENHANCED LLWAS WIND SHEAR WARNINGS

- OPERATIONAL DEMONSTRATION

  - TESTBED RADAR IS FUNCTIONALLY IDENTICAL TO
    TDWR SYSTEMS TO BE DEPLOYED BY F.A.A.

  - WIND SHEAR WARNING PROVIDED OPERATIONALLY
    TO ORLANDO ATC DURING 6 WEEK PERIOD
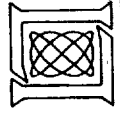
FLIGHT TEST ACTIVITY AT ORLANDO

- **SUMMER '90:**

  - UNIVERSITY OF NORTH DAKOTA (UND)
    CESSNA CITATION II RESEARCH AIRCRAFT

  - FIRST DEMONSTRATION OF DATA LINKING TDWR
    MICROBURST ALERTS TO AIRCRAFT IN REAL–TIME

  - 40 MICROBURST PENETRATIONS WITH TDWR
    SURVEILLANCE

- **SUMMER '91:**

  - NASA LANGLEY RESEARCH CENTER B737 AIRCRAFT

  - DATA LINKED TDWR MB ALERTS USED TO GUIDE
    MICROBURST PENETRATIONS

  - 20 MICROBURST PENETRATIONS WITH TDWR SURV.

SDC 4/16/92

DATA LINK TO NASA B737

Test Aircraft

NASA
737

Packet Radio

NASA Hangar

Packet
Radio

Modem
Link

TDWR Testbed

Sun
Workstation

NASA
Cockpit
Server

MB
Shapes

Waypoint
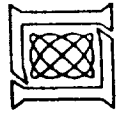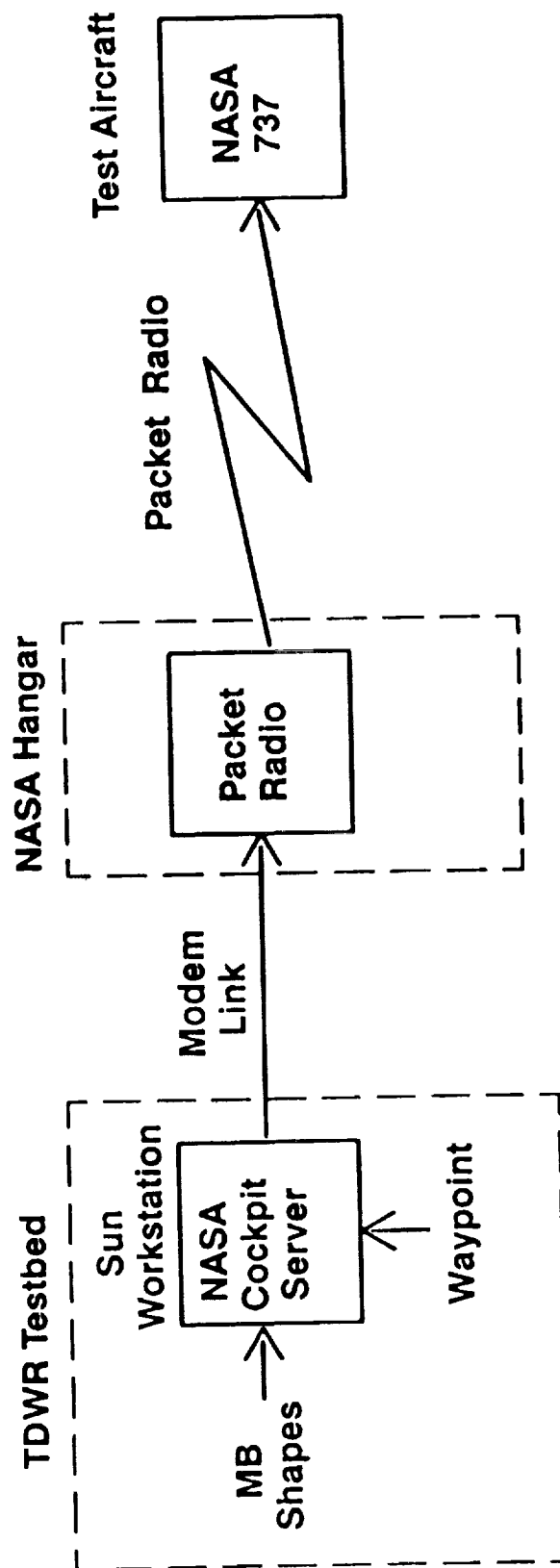
NASA COCKPIT DISPLAY

220 KT 1000FT
20:45:00

IN SITU F 0.017
DATA AGE 00:55
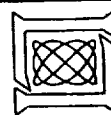
025

03

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00

22

33

TDWR ALERT

44
0.14

824
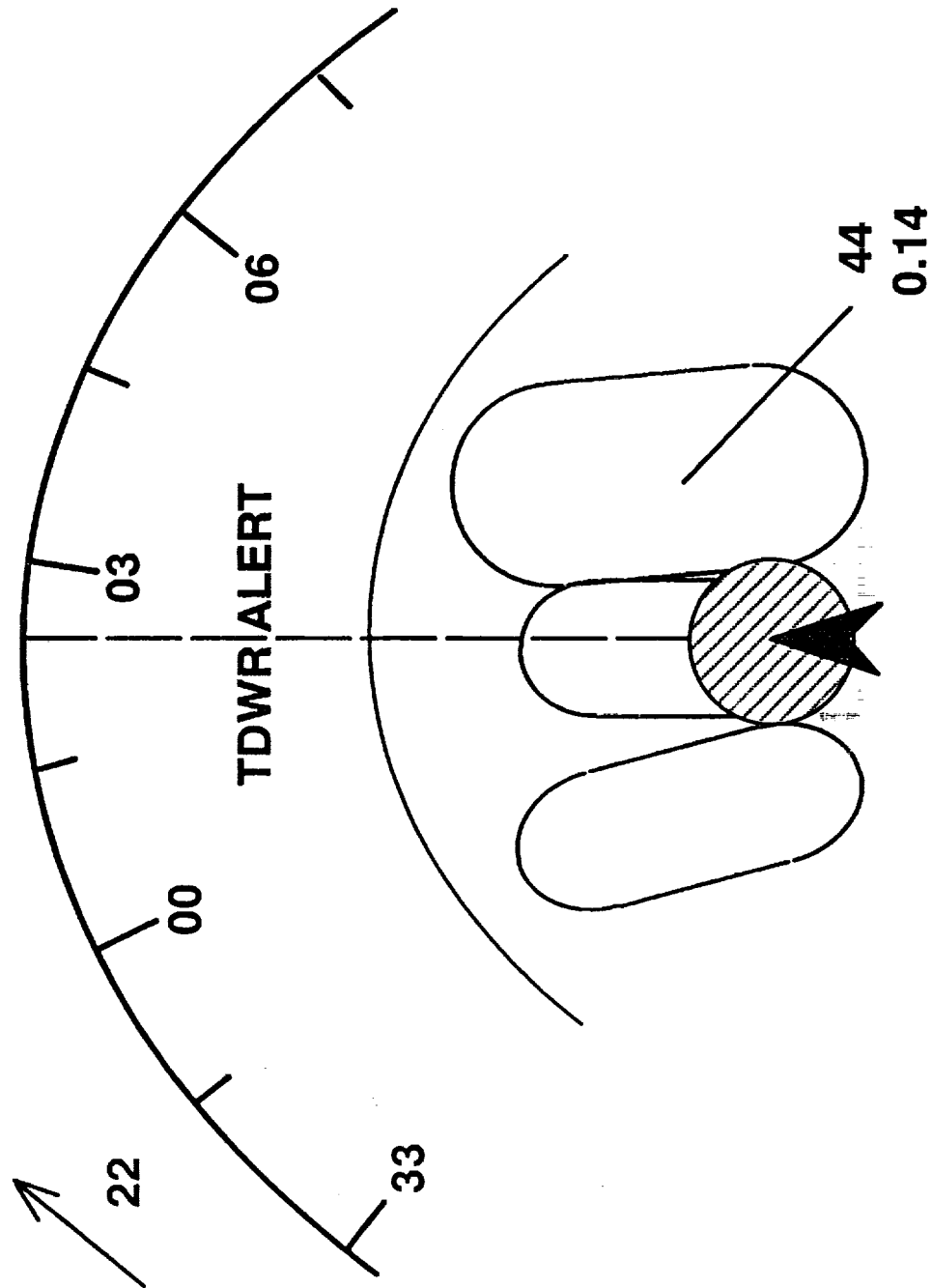
TDWR F FACTOR ESTIMATE

$$F = \frac{\dot{W}_x}{g} - \frac{W_z}{TAS} = F_x + F_z$$

ASSUME:

$$\dot{W}_x = \frac{\Delta V}{\Delta R} \, GS$$

$$W_z = -2h \, \frac{\Delta V}{\Delta R}$$

$$\hat{F}_{TDWR} = K' \frac{\Delta V}{\Delta R} \left(\frac{GS}{g} + \frac{2h}{TAS} \right)$$
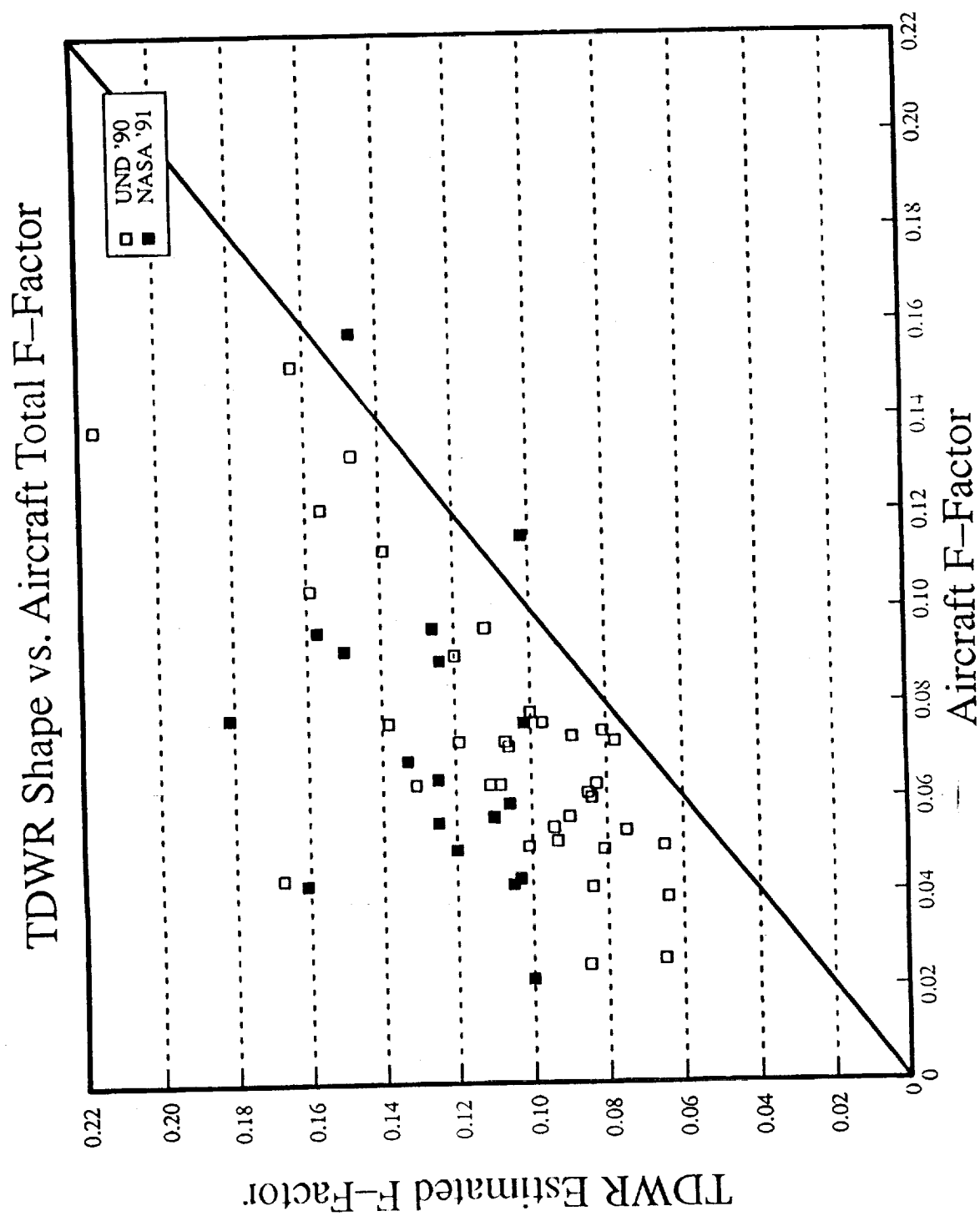
CONTINUITY

Radar beam height

W_z Downdraft

h

$\frac{\Delta R}{2}$ Radius

$\frac{\Delta V}{2} = W_x$ Outflow

$$W_z \, \pi \left(\frac{\Delta R}{2}\right)^2 = \frac{\Delta V}{2} \, 2\pi \, \frac{\Delta R}{2} \, h$$
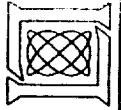
$$W_z = -2h \, \frac{\Delta V}{\Delta R}$$

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TDWR Shape vs. Aircraft Total F-Factor

TDWR Estimated F-Factor

Aircraft F-Factor

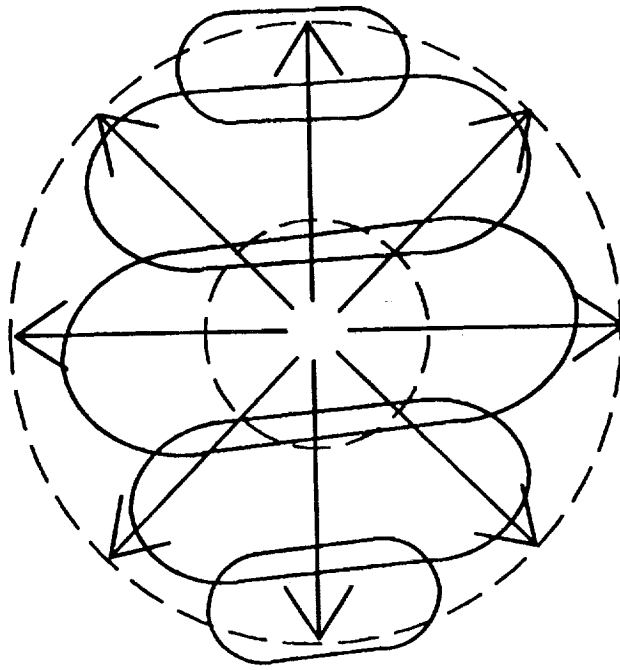UND '90
NASA '91
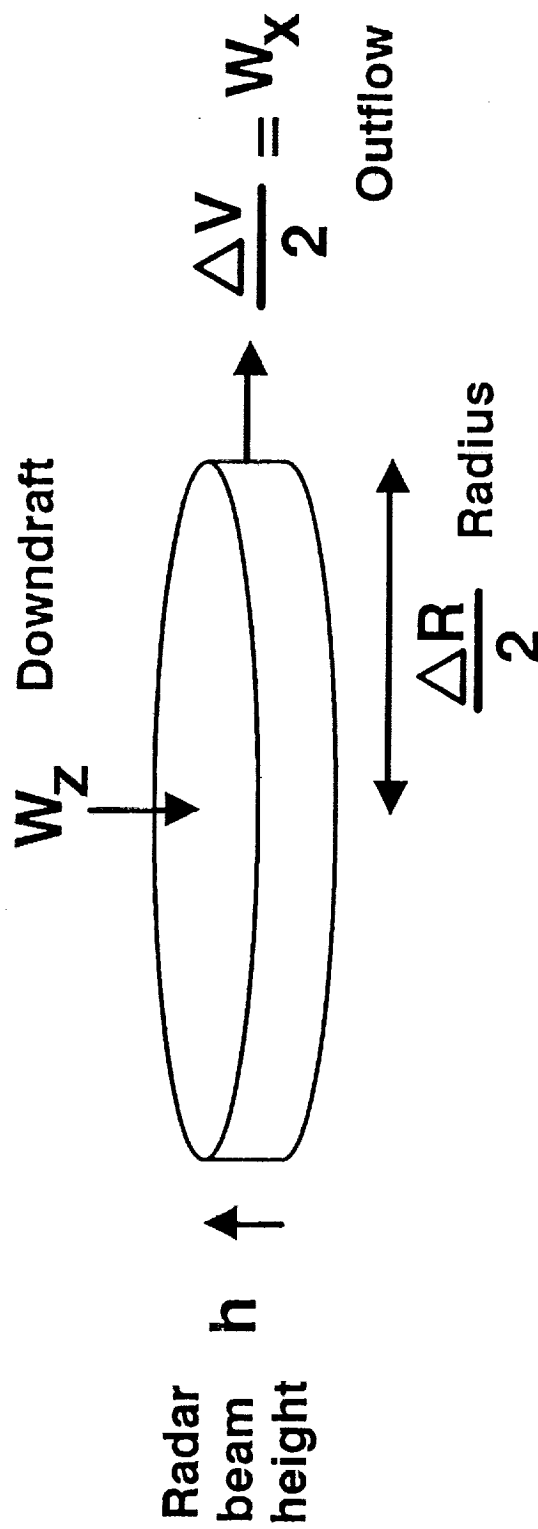
MICROBURST REPRESENTATION
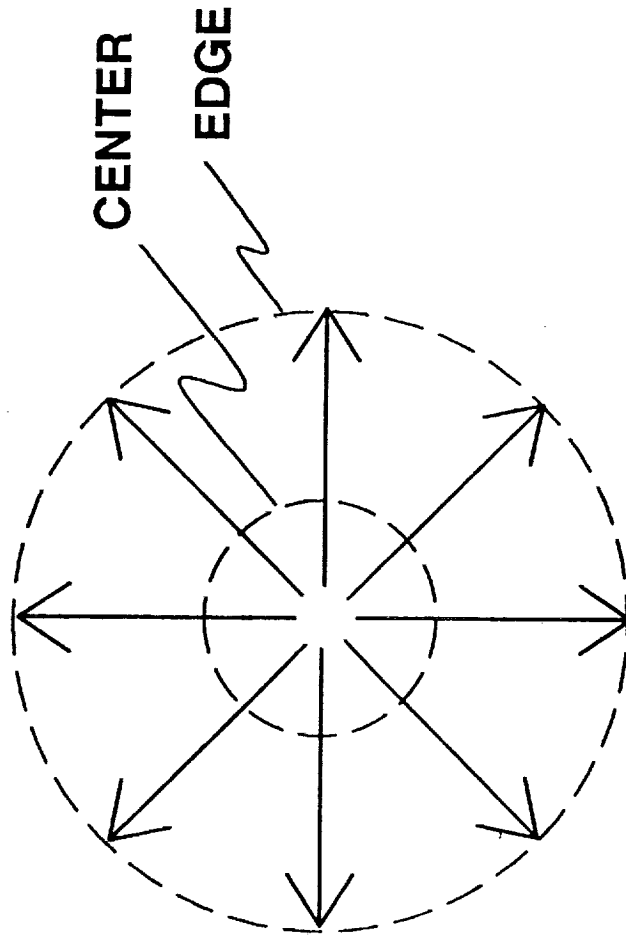
CENTER

EDGE

PHYSICAL MODEL:

- STRONG SHEAR & DOWNDRAFT AT CENTER

- WEAKER SHEAR & UPDRAFT AT EDGE
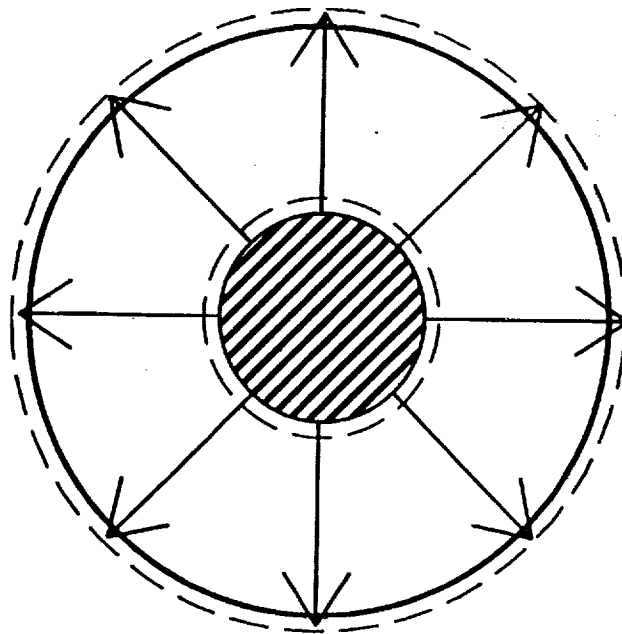
- ALTITUDE DEPENDENT

MICROBURST REPRESENTATION

CURRENT MICROBURST SHAPES:

- CENTER NOT WELL LOCALIZED
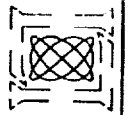
- EDGE EXTENT UNDERESTIMATED
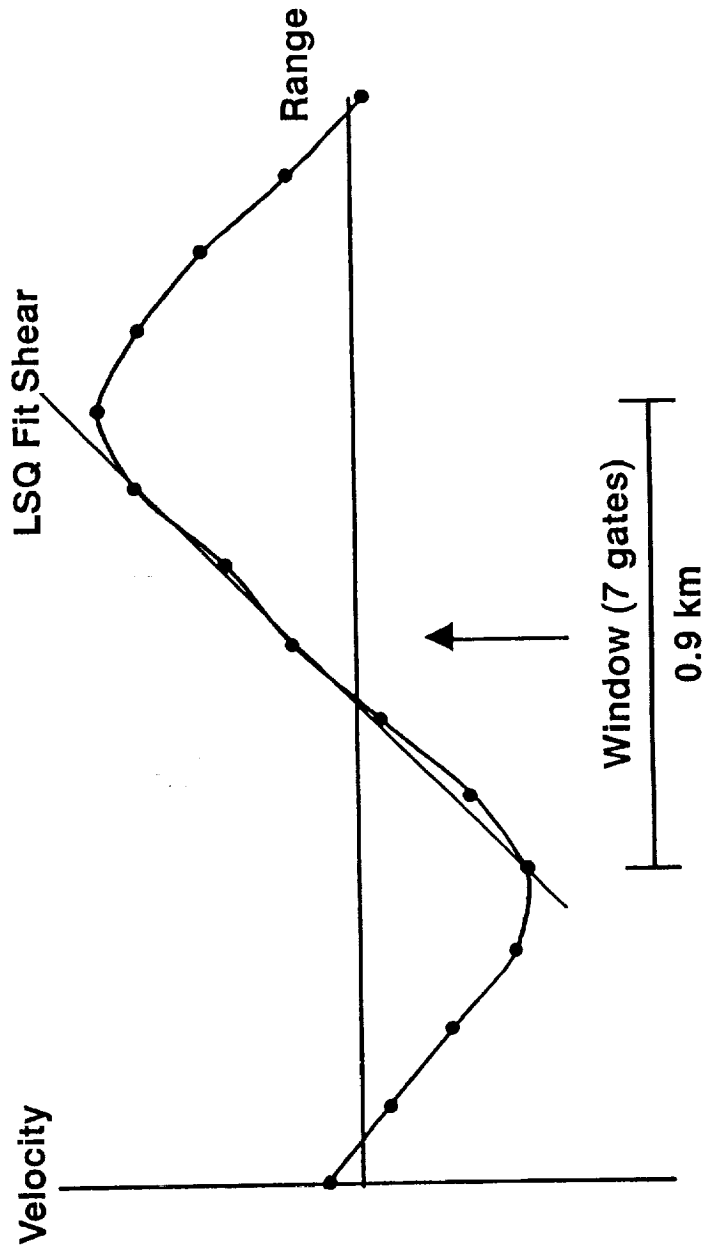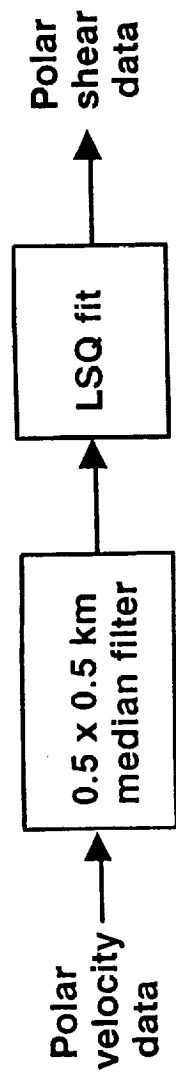
- NO ALTITUDE DEPENDENCE

MICROBURST REPRESENTATION

PROPOSED SHAPE IMPROVEMENTS:

    – SHEAR–BASED OUTFLOW DETECTION

    – LOCALIZE CENTER AND EDGE

    – ALTITUDE COMPENSATION

SHEAR COMPUTATION

Polar velocity data → [0.5 x 0.5 km median filter] → [LSQ fit] → Polar shear data

LSQ Fit Shear

Range
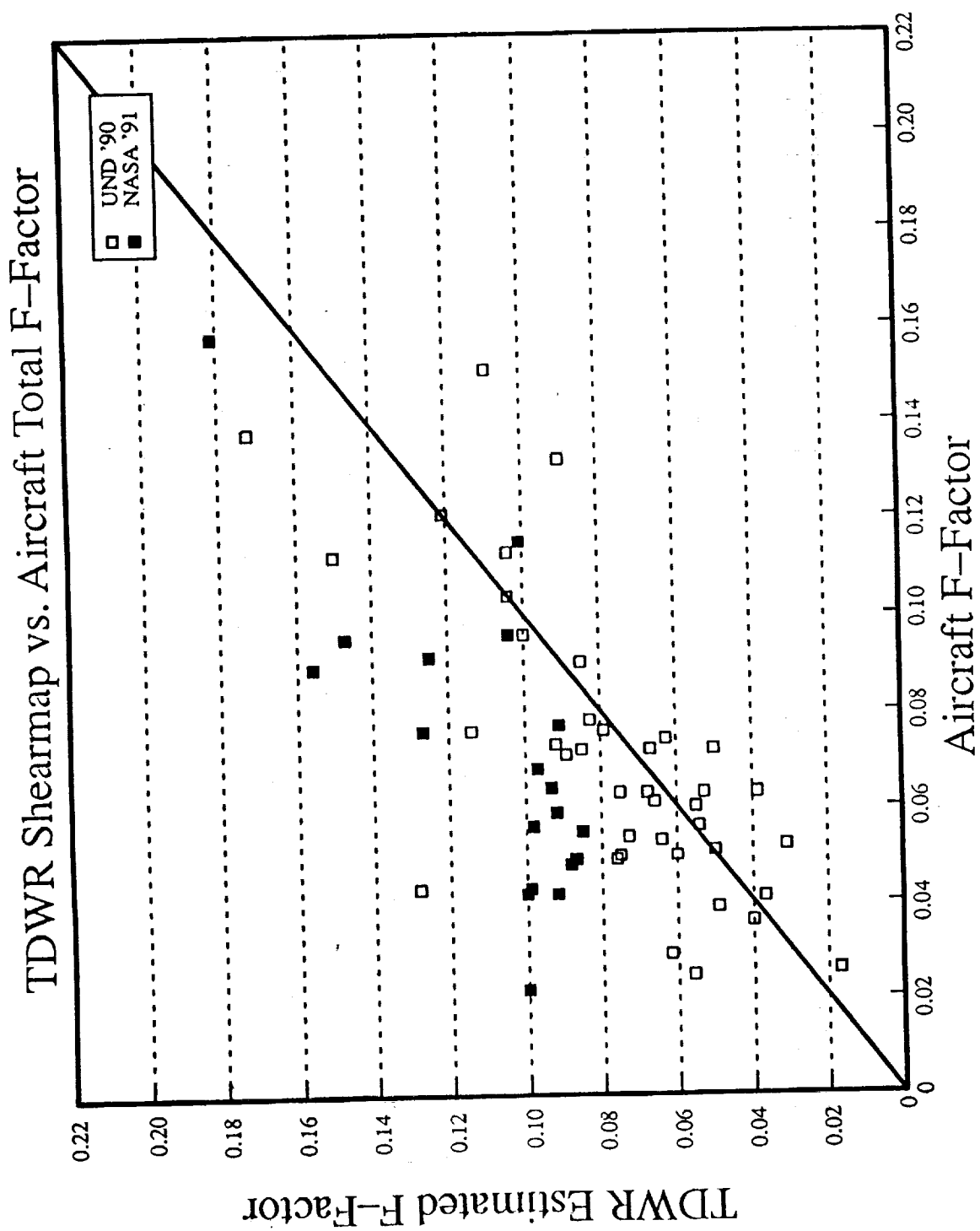
Velocity

Window (7 gates)

0.9 km

SUBSTITUTE LSQ SHEAR

$$\hat{F}_{SHEAR} = \left(\frac{dV}{dR} \right)_{h_r} \left(\frac{GS}{g} + \frac{2h_r}{TAS} \right)$$

WHERE:

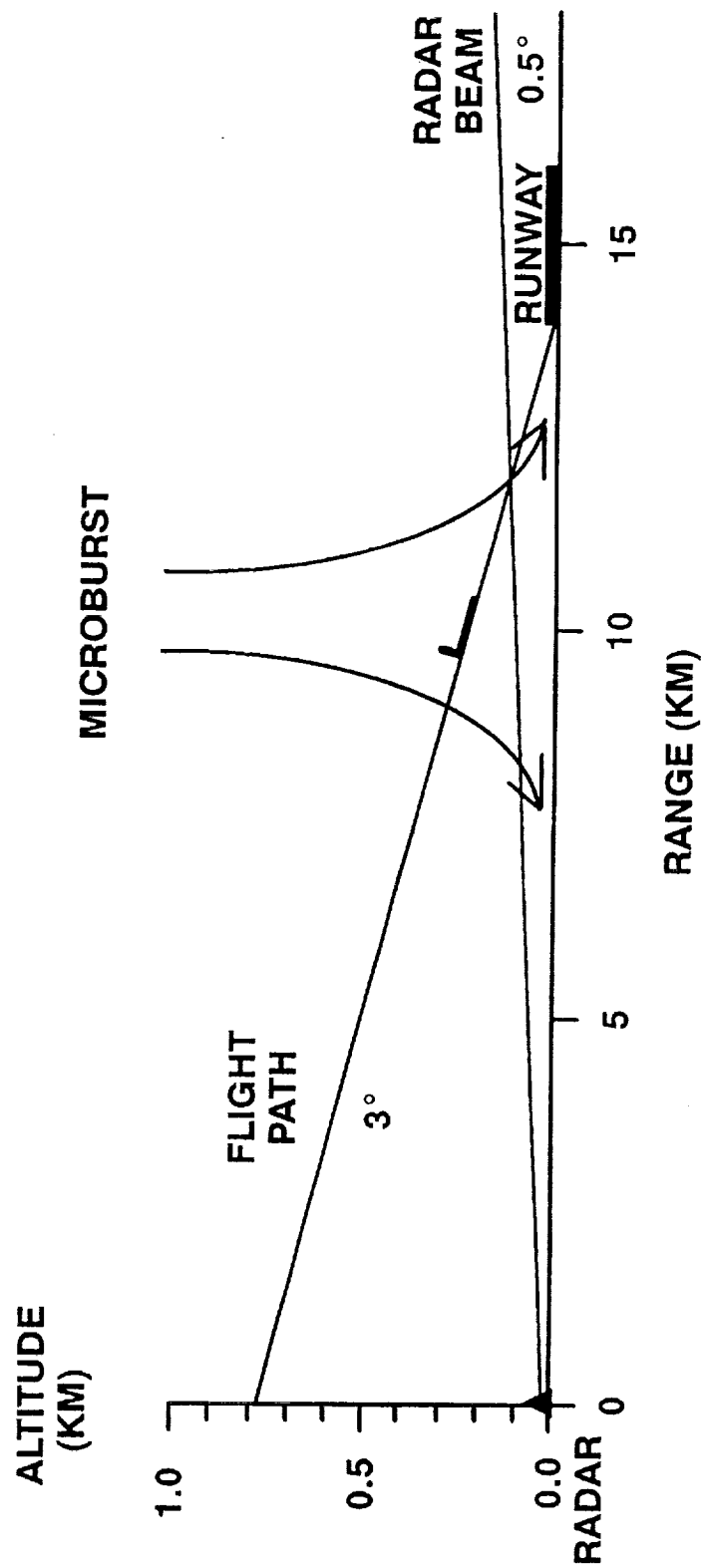h_r = RADAR BEAM HEIGHT

$\left(\dfrac{dV}{dR} \right)_{h_r}$ = COMPUTED LSQ SHEAR

832

TDWR Shearmap vs. Aircraft Total F-Factor

UND '90
NASA '91

TDWR Estimated F-Factor

Aircraft F-Factor

MICROBURST OUTFLOW ALTITUDE DEPENDENCE

SDC 4/16/92

834

Mean Vertical Velocity Structure of Orlando Microburst
DeltaV Max = 22m/s

Legend:
— Viceroy Shaping Function
■ FL-2 High Resolution Measurements

X-axis: DeltaV (m/s)
Y-axis: Height (meters)
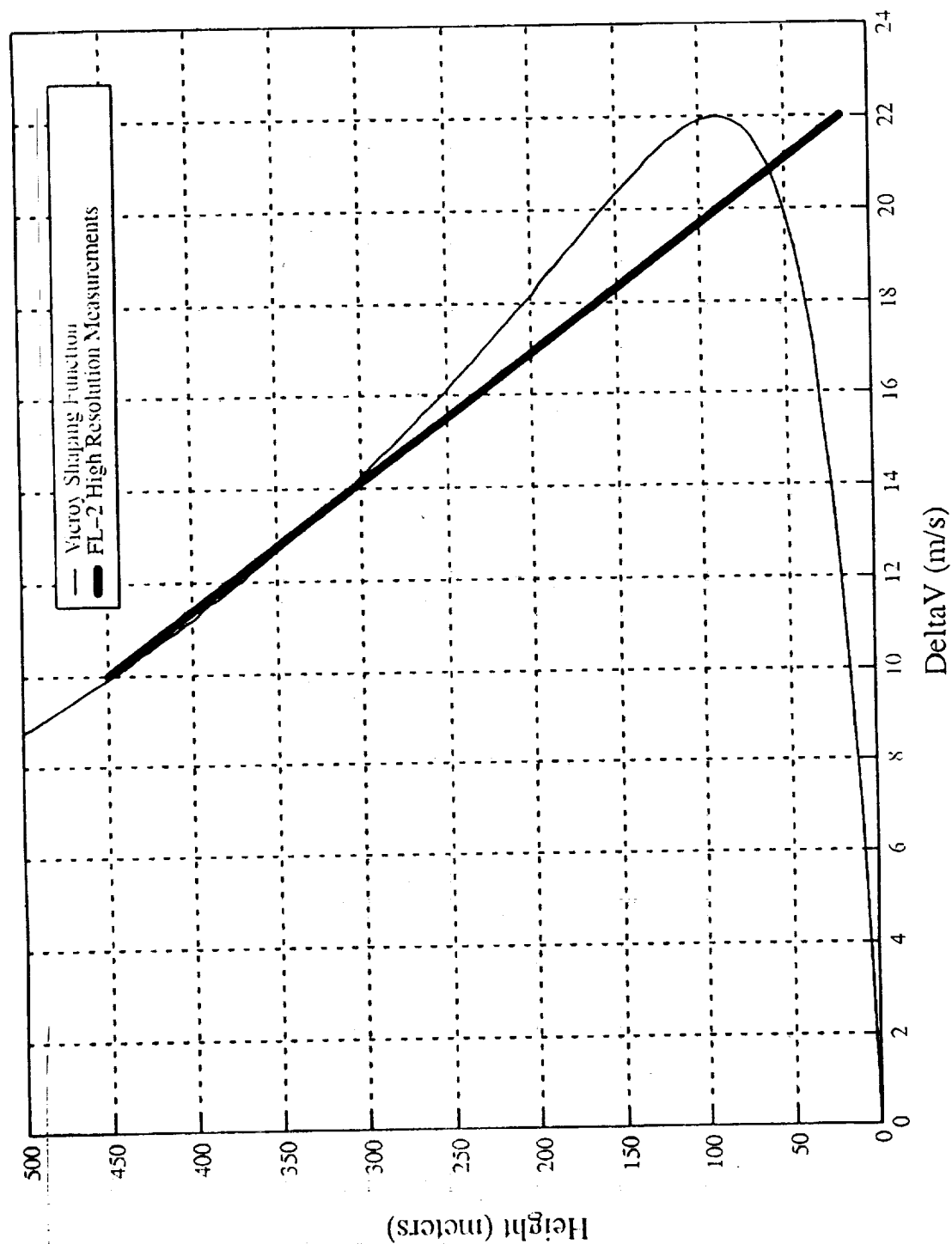
Vertical Shear Structure of Orlando Microburst
6/20/91 21:24

836
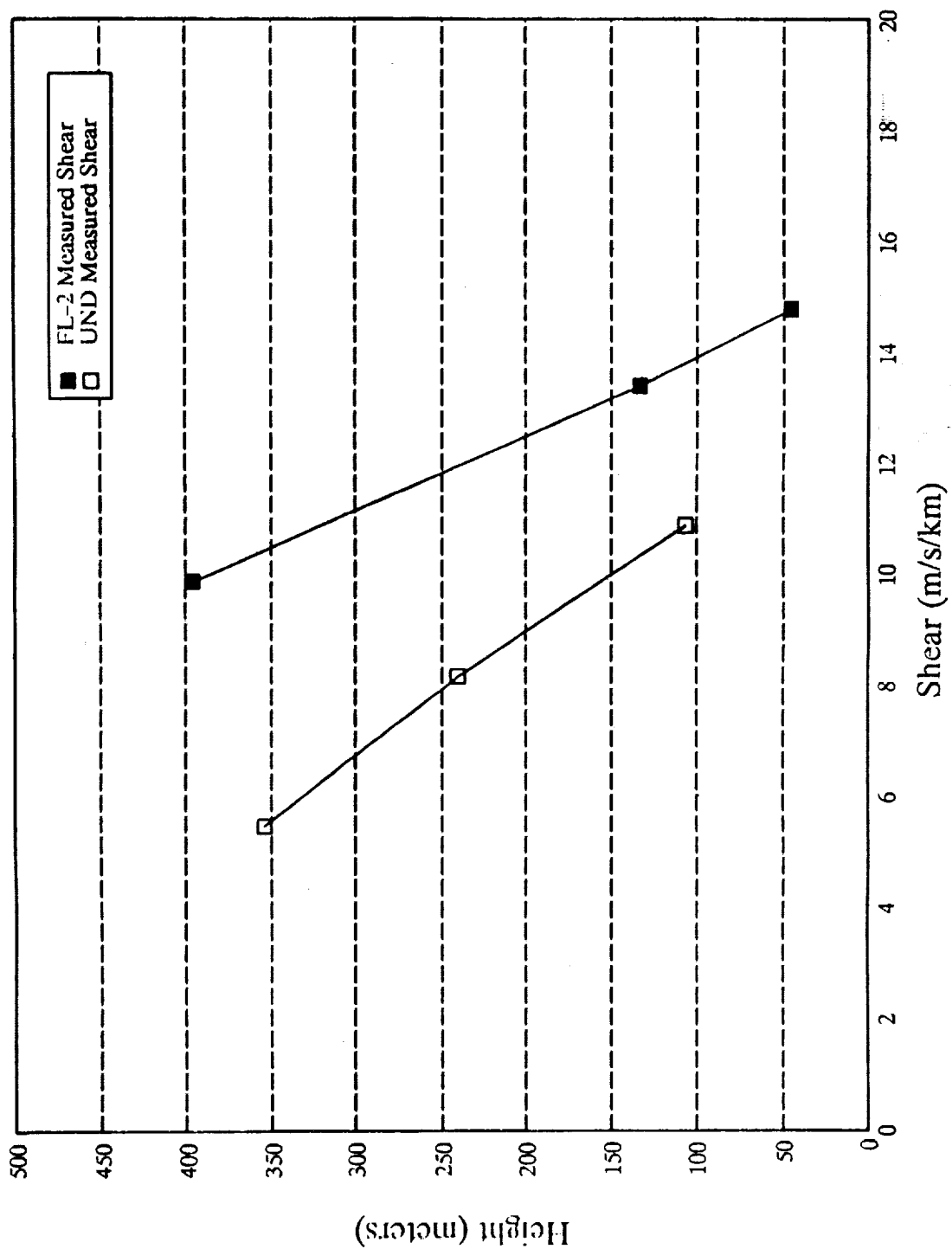
CORRECT FOR ALTITUDE DEPENDENCE

$$\hat{F}_{\substack{\text{ALT.}\\\text{CORR.}}} = \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} + \frac{2\,h_a}{TAS}\right)$$

WHERE:

$$\left(\frac{dV}{dR}\right)_{h_a} = \left(\frac{dV}{dR}\right)_{h_r} \left(\frac{p(h_a)}{p(h_r)}\right)$$
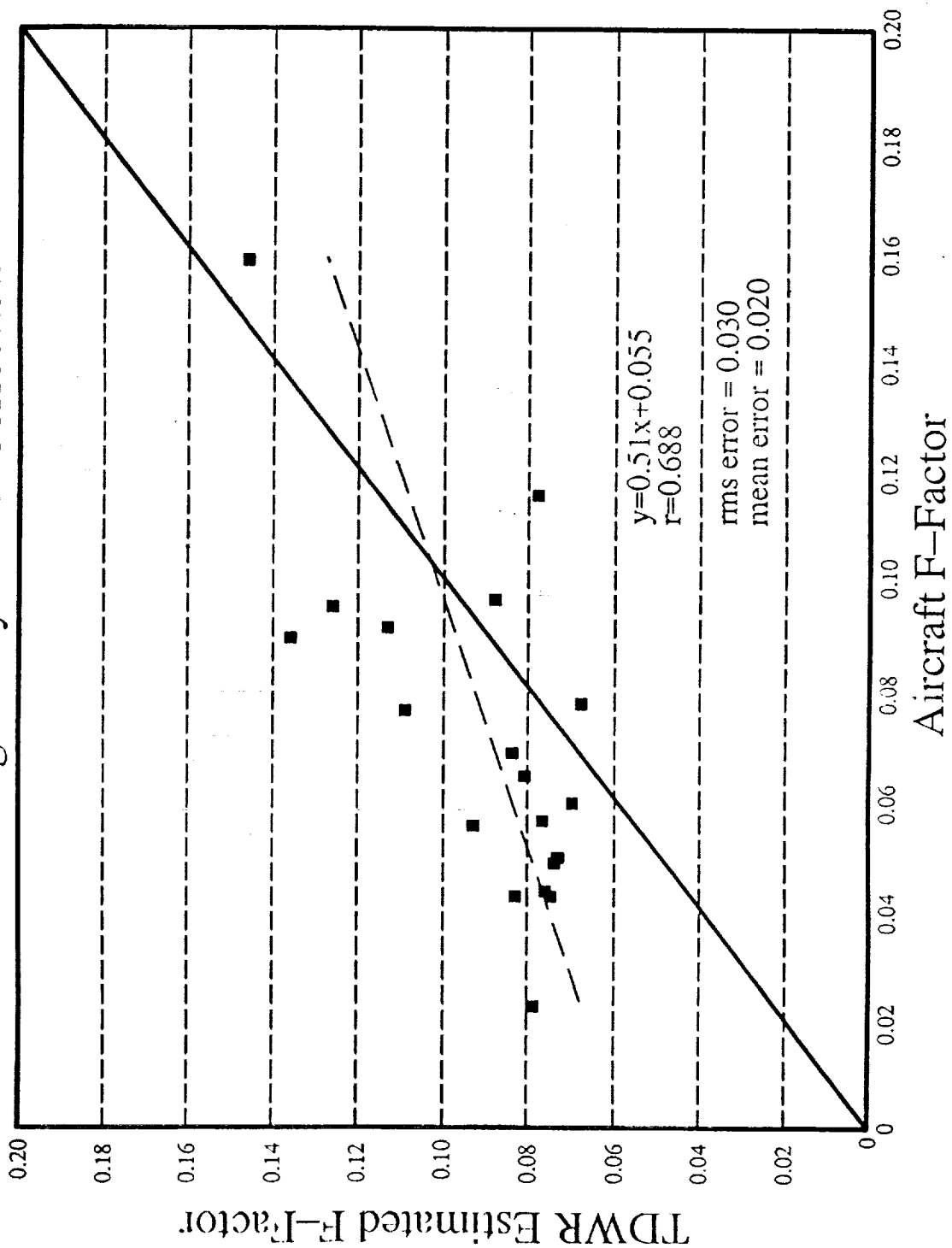
h_a = AIRCRAFT ALTITUDE

$p(z)$ = HORIZONTAL SHEAR VS. ALTITUDE (VICROY/O&B MODEL)

TDWR Shearmap vs. Aircraft Total F-Factor using Vicroy Model Correction

$y=0.51x+0.055$
$r=0.688$

rms error = 0.030
mean error = 0.020

TDWR Estimated F-Factor

Aircraft F-Factor

Plotting Time => 04/07/1992 18:16:16

TDWR Shearmap vs. Aircraft Horizontal F-Factor
@ Ftotal Peak Time using Vicroy Model Correction

y=0.60x+0.030
r=0.729

rms = 0.016
mean error = 0.007

Aircraft F-Factor

TDWR Estimated F-Factor
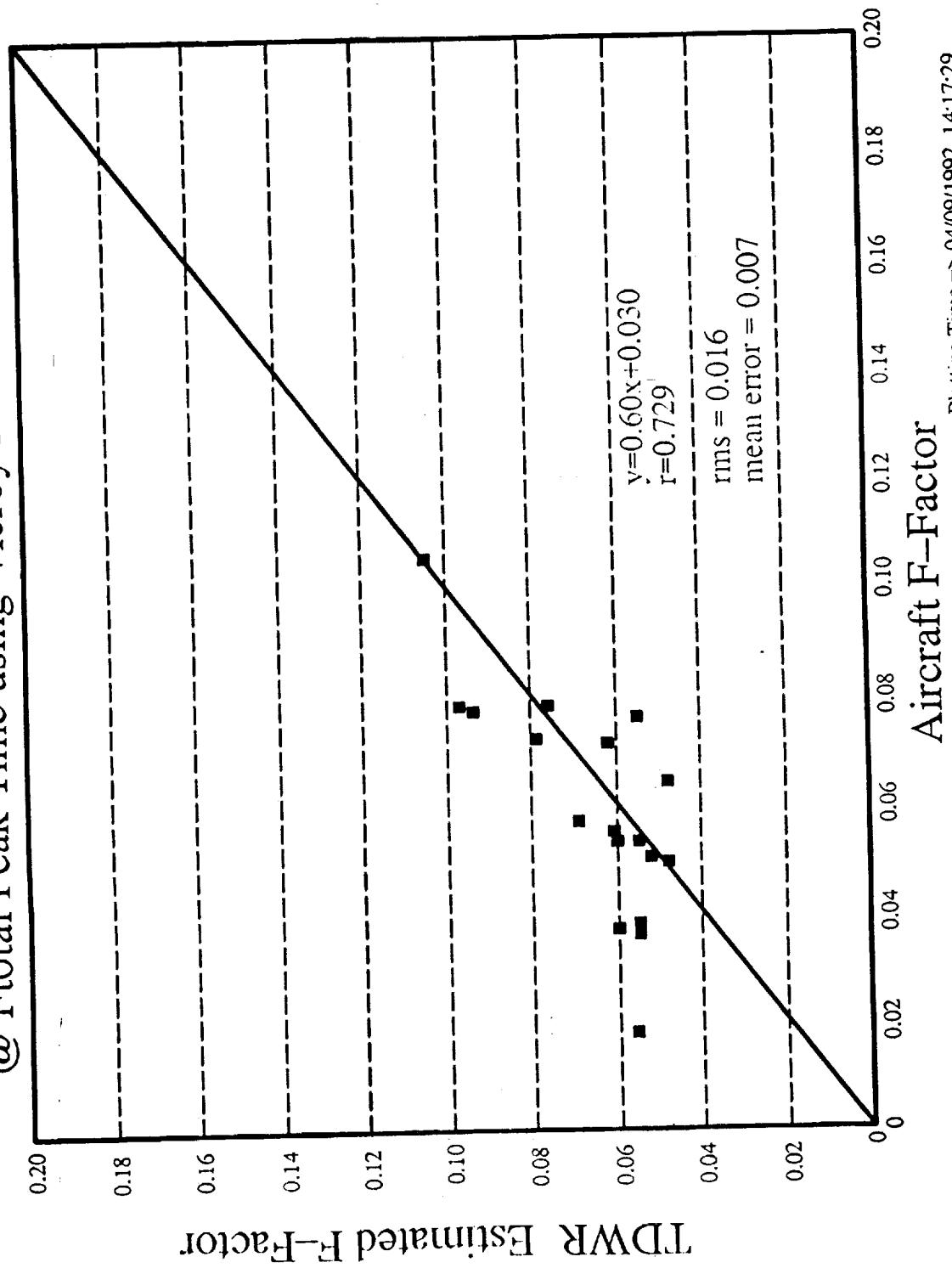
Plotting Time => 04/09/1992 14:17:29

839

TDWR Shearmap vs. Aircraft Vertical F-Factor
@ Ftotal Peak Time using Vicroy Model Correction

TDWR Estimated F-Factor

Aircraft F-Factor

Plotting Time => 04/10/1992 11:37:51

840

HORIZONTAL OFFSET COMPENSATION
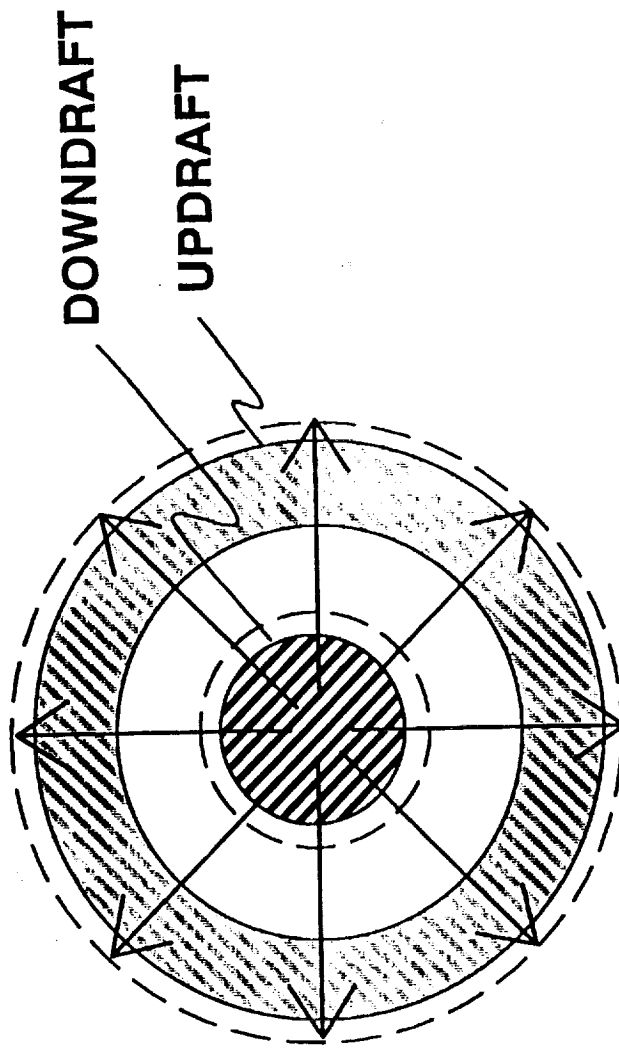
DOWNDRAFT
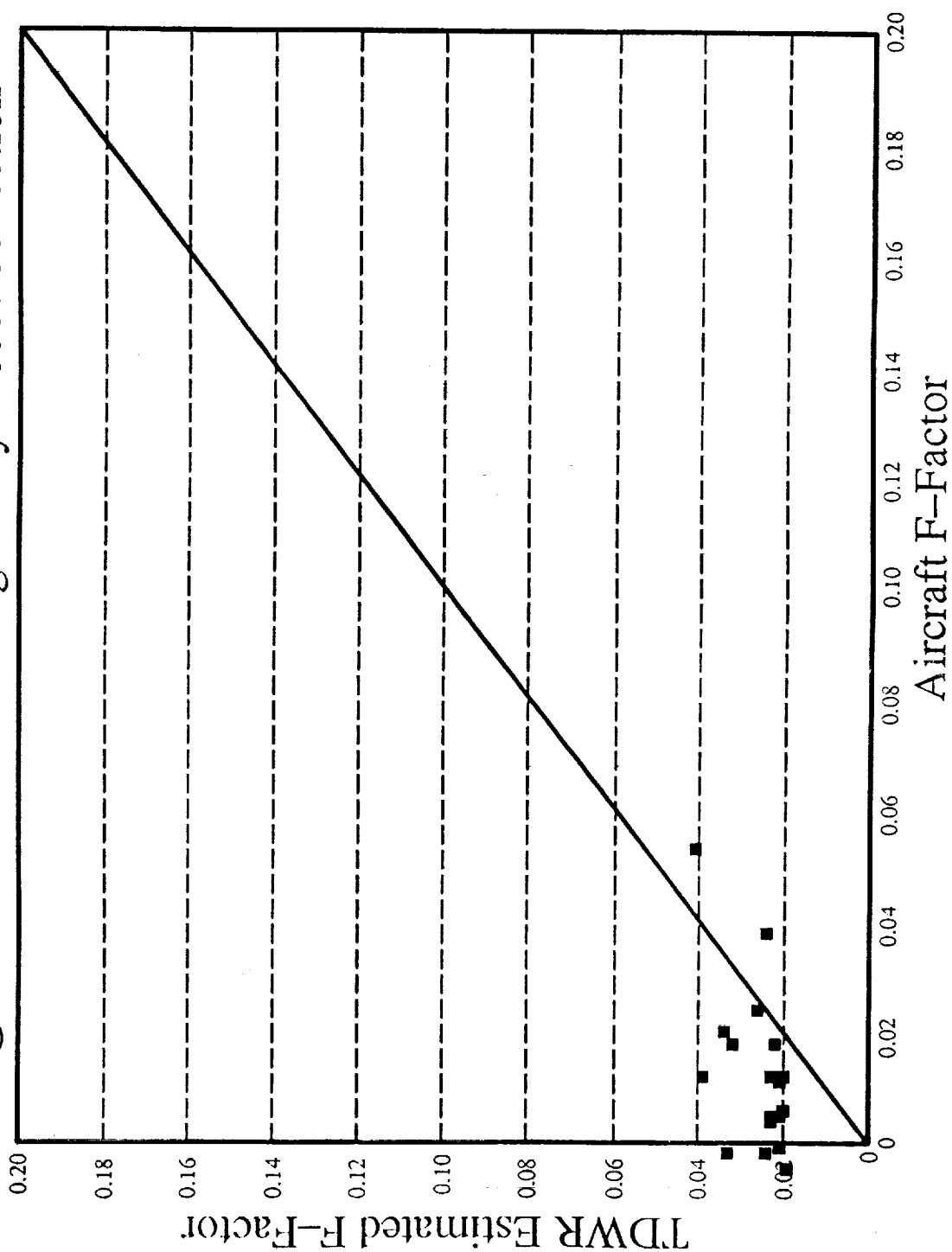
UPDRAFT

VERTICAL COMPONENT:

- POSITIVE 2a/TAS FOR CENTER

- NEGATIVE a/TAS FOR EDGE

- NEED TO LOCALIZE OUTFLOW CENTER & EDGE

CORRECT FOR HORIZONTAL OFFSET

$$\hat{F}_{\substack{\text{HORIZ.}\\ \text{CORR.}}} = \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} + \frac{2h_a}{TAS}\right) \text{, CENTER PENETRATION (DOWNDRAFT)}$$

$$= \left(\frac{dV}{dR}\right)_{h_a} \left(\frac{GS}{g} - \frac{h_a}{TAS}\right) \text{, EDGE PENETRATION (UPDRAFT)}$$

TDWR Shearmap vs. Aircraft Total F-Factor
using Horizontal Offset Correction

$y=0.56x+0.044$
$r=0.684$

rms error = 0.026
mean error = 0.013

Aircraft F-Factor

TDWR Estimated F-Factor
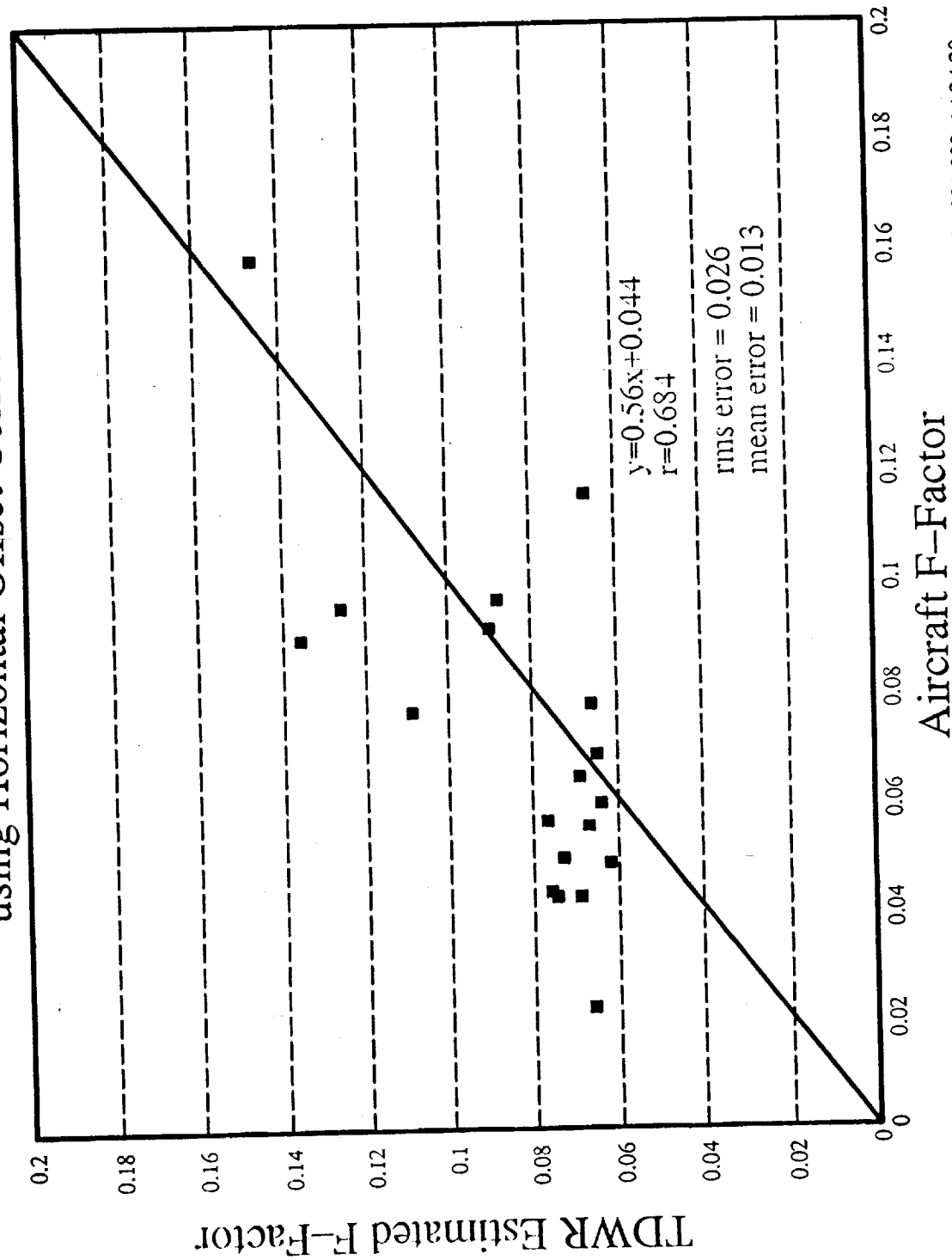
Plotting Time => 04/09/1992 14:24:20

843

OPTIONS FOR MODIFYING TDWR SOFTWARE

- **TERMINAL DOPPLER WEATHER RADAR PROGRAM:**

  - TDWR CONTRACTOR (RAYTHEON)

    - CURRENTLY IN PROGRESS FOR FLIGHT PATH SHEAR INTEGRATION AND TDWR/ELLWAS INTEGRATION

  - PROGRAM SUPPORT FACILITY (F.A.A.)

    - CURRENTLY BEING ESTABLISHED AT OK CITY

- **INTEGRATED TERMINAL WEATHER SYSTEM (ITWS):**

  - WILL INVOLVE ADDITIONAL ALGORITHMS OPERATING ON TDWR REFLECTIVITY AND VELOCITY DATA

  - INTEGRATES DATA FROM GROUND–BASED AND AIRBORNE SENSORS (E.G., ACARS DATA)

  - OPERATIONAL TESTS IN 1993–1994, FOLLOWED BY INITIAL OPERATIONAL CAPABILITY (IOC) IN 1996
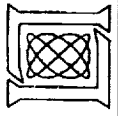
SUMMARY

- FLIGHT TEST ACTIVITY AT ORLANDO TDWR TESTBED:

  - SIXTY INSTRUMENTED MB PENETRATIONS

  - DATA LINK DEMONSTRATIONS

- IMPROVING TDWR F FACTOR ESTIMATES:

  - SHEAR–BASED OUTFLOW DETECTION

  - PHYSICAL MODEL–BASED MICROBURST SHAPES

  - COMPENSATION FOR ALTITUDE DEPENDENCE

- FUTURE PLANS

  - NASA FLIGHTS IN '92 (PLUS OTHER AIRCRAFT)

  - RAPID TRIPLE–DOPPLER LOW–ALTITUDE SCANS

SDC 4/16/92

845
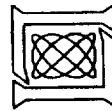
The Orlando TDWR Testbed and Airborne Wind Shear
Data Comparison Results
Questions and Answers

Q: Dan Vicroy (NASA Langley) - You pointed out some improvements or possible improvements to the TDWR algorithms. Can you comment on the implementation issues and what kind of time line you are looking at for implementing these improvements?

A: Steve Campbell (MIT Lincoln Lab.) - The TDWR was implemented as a very fast track program. We knew that there would be some refinements. When the TDWR was designed, the idea was that all you needed to do was detect the change in velocity. I think we now understand that it is not true. There are really two avenues through which we could make improvements. One is that the FAA expects to upgrade the TDWR algorithms over a period of time. The other is that there is another program which is starting up called the Integrated Terminal Weather System Program in which we will be incorporating data from a number of sources, TDWR, surface observations and aircraft data. That may also be an avenue for making these improvements. As far as how long that is going to take, well it is going to take some years. I think we are at least plugged into that process.

TDWR 1991 Program Review

Kim Elmore, National Center for Atmospheric Research

TDWR 1991 PROGRAM REVIEW

HISTORY OF WIND SHEAR STUDIES
AT STAPLETON INTERNATIONAL AIRPORT

1982: JAWS

1984: CLAWS

1987: Network Expansion LLWAS Operational Demonstration
TDWR Off-Line Test

1988: TDWR Operational Demonstration

1989: TNEXRAD Operational Demonstration
LLWAS Runway Extension Evaluation
Rudimentary TDWR/LLWAS Integration

1990: Enhanced TDWR/LLWAS Algorithm Demonstration

1991: TDWR/LLWAS Integration
Advanced Algorithm Development (off-line)

TDWR DEMONSTRATIONS
NOTABLE RESULTS/EVENTS

1988

SUCCESSFUL OPERATIONAL DEMONSTRATION OF TDWR

JULY 11 ENCOUNTER

JULY 16 SHUTDOWN DUE TO OVERWARNING

AUGUST 12 VERIFIER INSERT

CHANGE IN MICROBURST ALERT FORMAT

MICROBURST "COAST" FEATURE IMPLEMENTED

1989

FIRST USE OF MILE HIGH RADAR

FIRST INTEGRATION OF TDWR/LLWAS ALARMS

JULY 8 ENCOUNTER

SEPTEMBER 2 ENCOUNTER

849

NOTABLE RESULTS/EVENTS CONT'D

1990

ENHANCED TDWR/LLWAS INTEGRATION TEST

TDWR/LLWAS INTEGRATION TEST

TDWR/LLWAS SYSTEM RUN BY FAA PERSONNEL

1991

CONTINUE TDWR/LLWAS INTEGRATION DEMO

INTEGRATION SPECIFICATION COMPLETED

850

TDWR DEMONSTRATION
DENVER CHRONOLOGY

PRODUCTS	1988	1989	1990	1991
MICROBURST	X	X	X	X
GUST FRONT	X	X	X	X
WIND SHIFT	X	X	X	X
PRECIPITATION	X	X	X	X
LLWAS WINDS	X	X	X	X
NOWCAST		X	X	
STORM MOTION		X	X	X
WIND SHEAR POTENTIAL				X (OFF LINE)
TORNADO VORTEX SIGNATURE				X (OFF LINE)

851

11 JULY '88

EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = (0.00, 0.00)   TIME = 88 7 11 22 9 0

UND = (-2.74, 20.55)   REMOVED VECT. = (5.52, -5.72)
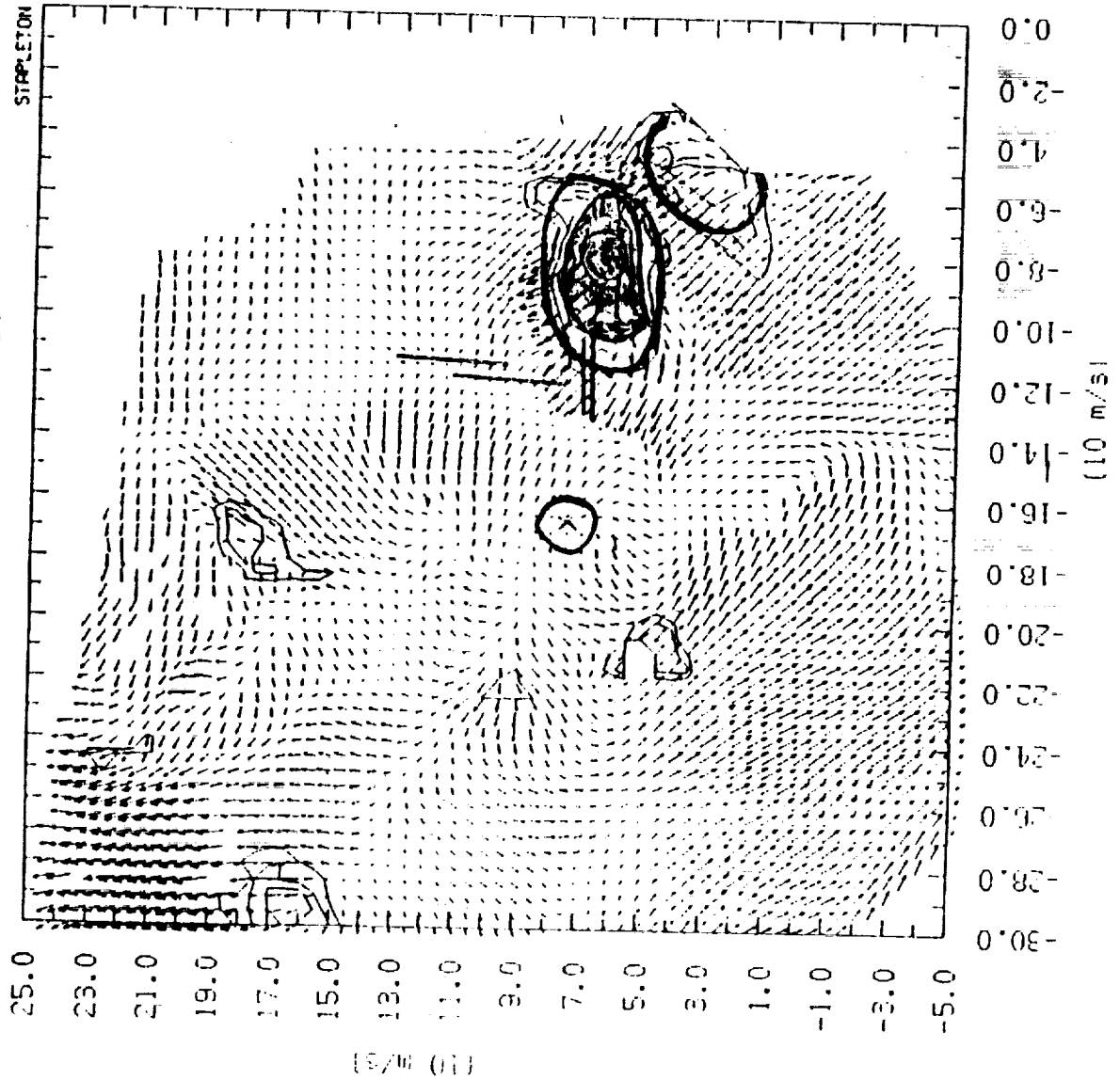
H = 25.24

STAPLETON

(10 m/s)

25.0 23.0 21.0 19.0 17.0 15.0 13.0 11.0 9.0 7.0 5.0 3.0 1.0 -1.0 -3.0 -5.0

(10 m/s)

0.0 -2.0 -4.0 -6.0 -8.0 -10.0 -12.0 -14.0 -16.0 -18.0 -20.0 -22.0 -24.0 -26.0 -28.0 -30.0

16 JULY '88 "TRUTH"

EDDY FIELD(WITH VELOCITY DIFFERENCE BY SEARCH OVERLAY)

FL2 = (0.00, 0.00)   TIME = 88 7 16 22 23 34

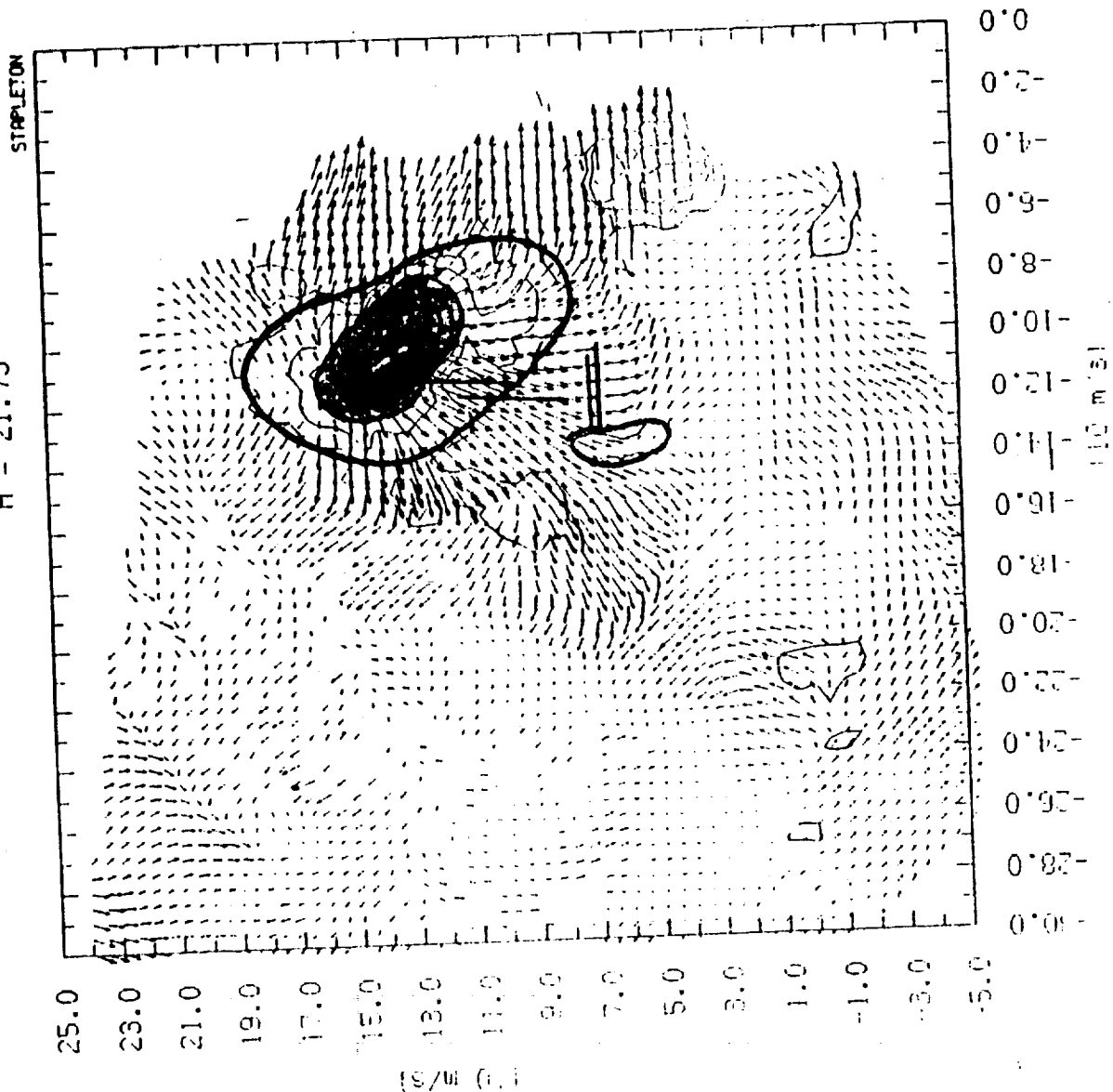UND = (-2.74, 20.55)   REMOVED VECT. = (2.80, -2.82)

H = 21.73

STAPLETON

GEOGRAPHIC EVENT DISPLAY
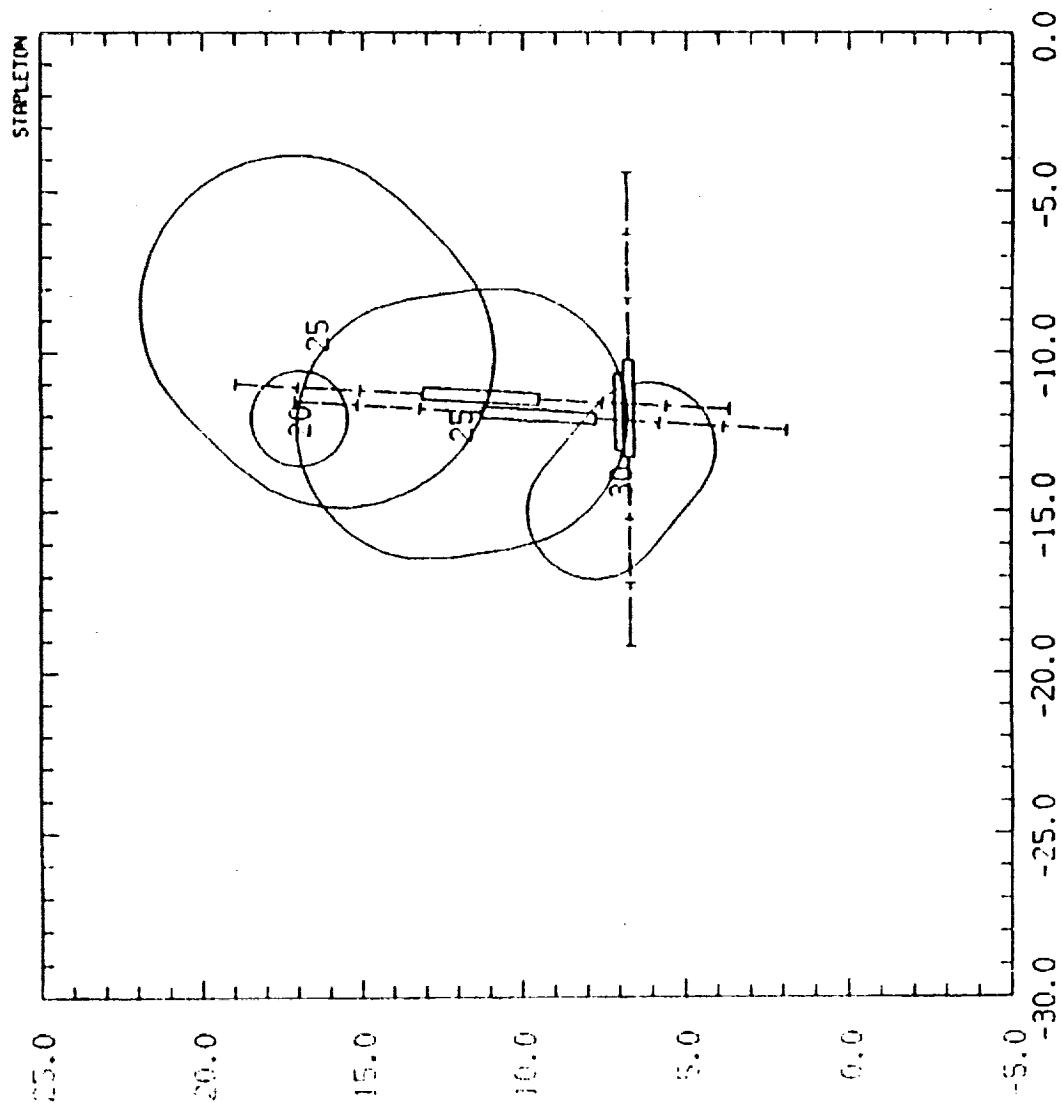
TIME = 88 7 16 22 23 34

SHAPES

16 JULY '88
ALARMS

8 JULY '89

89 7 8 23:20:41

44
36
8
10
42
8
10
3
11

9
15
11
8
10
12

KNOTS

855
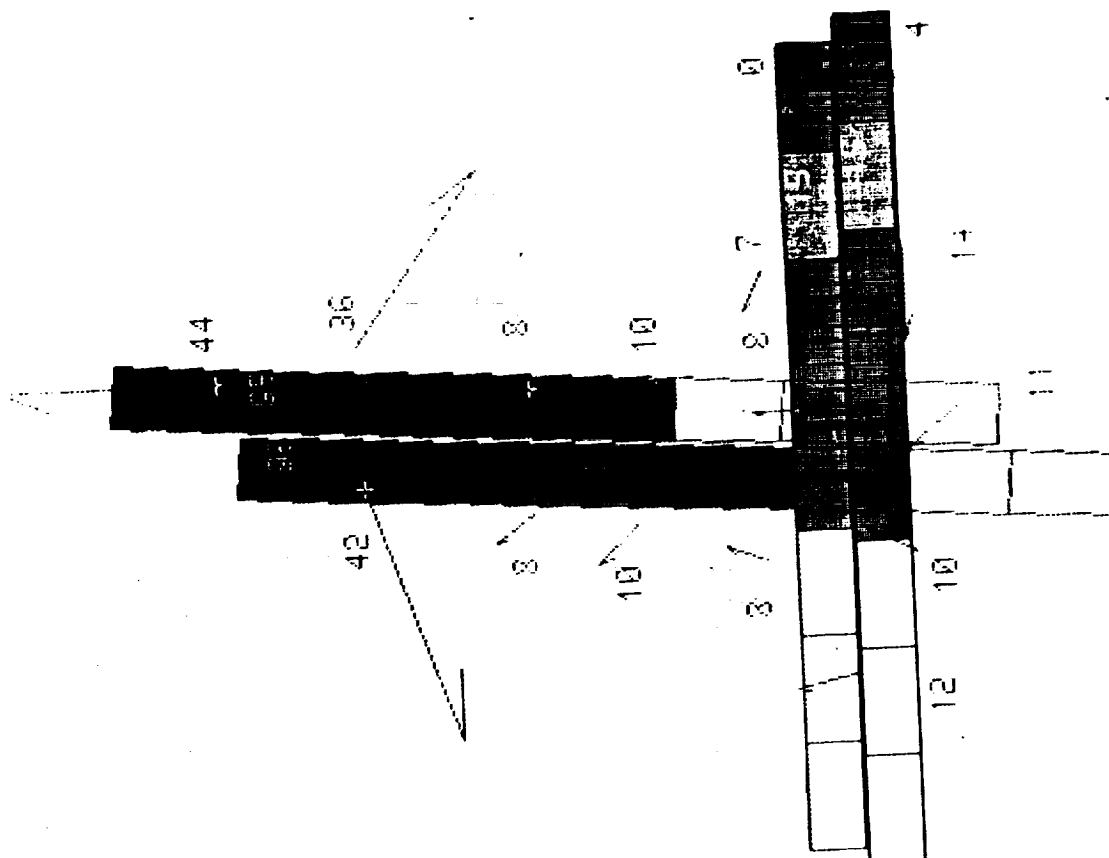
OVERVIEW OF GENERIC INTEGRATION CONCEPTS

- Exploit Strengths of Stand-Alone Systems

- Limit Impact of Weaknesses of Stand-Alone Systems

- User-End Products (Graphic and Alphanumeric) Should Be Transparent as to Source

OVERVIEW OF GENERIC INTEGRATION CONCEPTS
(continued)

Three Possible Techniques:

1. Alphanumeric-Level
   - Generate consensus of runway alerts by taking "worst case" alphanumeric alerts from stand-alones.

2. Data-Level, "Bottom-Up"
   - Synthesize raw data to then generate end-products.

3. Product-Level, "Top-Down"
   - Utilize intermediate products to generate end-products. "Expert-system".

Denver Operations 1991:

Operational 1 June - 31 August

Noon to 7 pm daily

Total Days - 92

Terminal Doppler Weather Radar (TDWR)
Project Setting

Edge of
Foothills

Longmont
ARTCC/CWSU

56 Kb

TDWR Operations
Center

Boulder

T1

56 Kb

New
Airport

Mile High
Radar

10 km

Future
NEXRAD
Site

17 km

Stapleton

Denver
Metro
Area

Height of MHR
.5° beam over
Stapleton is
148 m (480 ft)
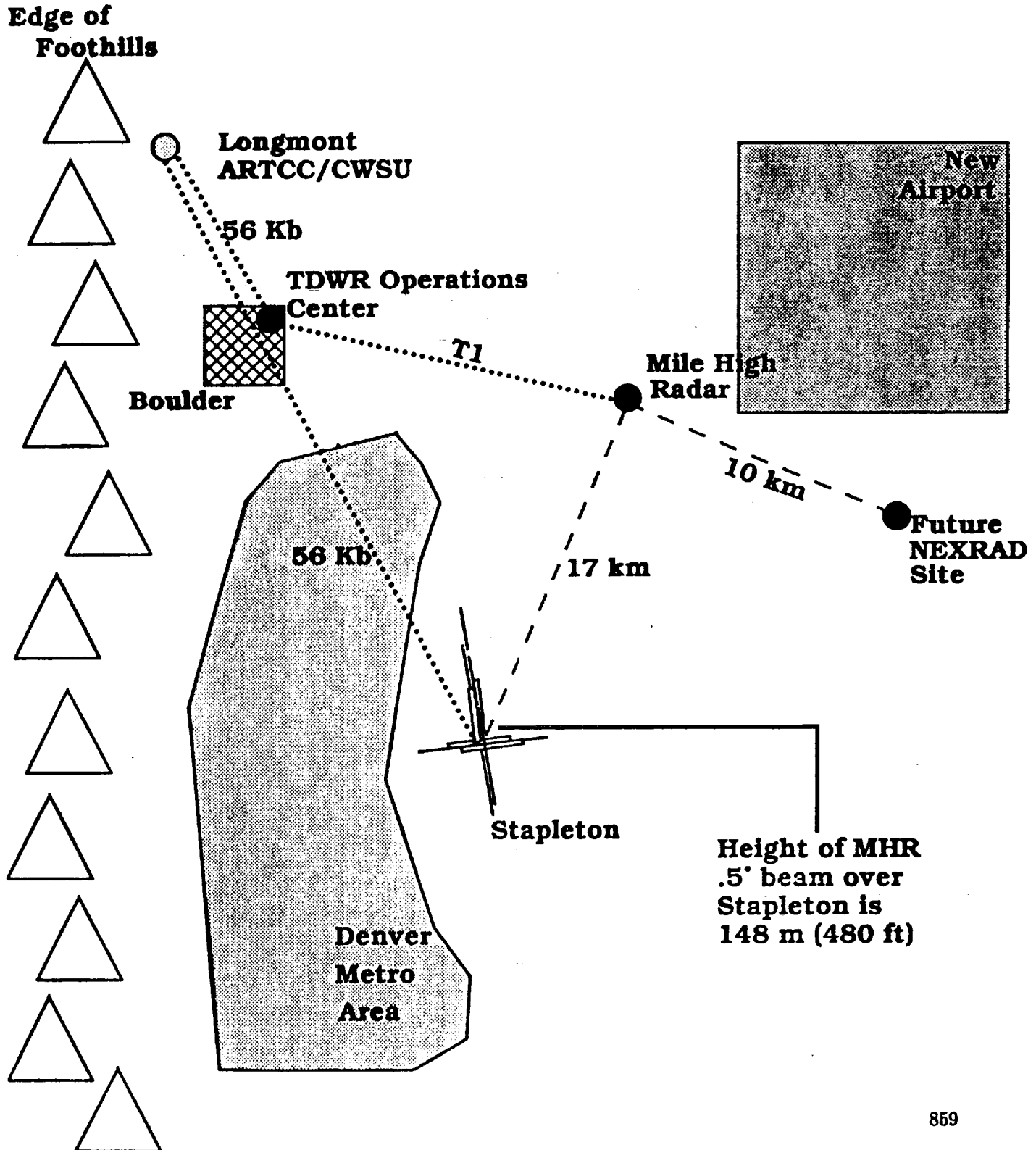
TDWR 1991 PROGRAM REVIEW

1991 OBJECTIVES:

a) Protect Stapleton from wind shear

b) Evaluate TDWR & LLWAS stand-alone systems

c) Test & demonstrate the TDWR/LLWAS integration algorithm

d) Evaluate TDWR algorithm performance during winter conditions

e) Test & evaluate (off-line) "new" algorithms

f) Provide a reliable, stable system

Denver Operations 1991:

Algorithms:

Microburst Detection
Gust Front Detection
Windshift Prediction
Precipitation
Storm Motion
TDWR/LLWAS Integration
TVS (Tornado) (Offline)
Windshear Potential (offline)

861

Denver Operations 1991:

Facility Demonstration:

ATCT
TRACON
CWSU(ARTCC)
United Airlines

Denver Operations 1991:

Events: Microbursts - 69 (within 5nm of airport)

Strongest Microburst - 55kts (July 12th and 30th)

Gust Fronts - 57

Strongest Gust Front - 45 kts (1 June)

Total Alarm Time (Integrated LLWAS/TDWR) - 35.7 hours

Total Alarm Time - 6.6% of total operational time

863

LLWAS DEMONSTRATIONS
DENVER MICROBURST SCORING

	1988	1989	1990	1991
POD*	X	90%	95%	96%
FAR	X	14%	3%	1%

* For Events Within LLWAS Network Only!

TDWR DEMONSTRATIONS
DENVER MICROBURST SCORING

	1988	1989	1990	1991
POD*	98%	94%	92%	91%
FAR	2%	**12%	3%	2%

TDWR/LLWAS INTEGRATION

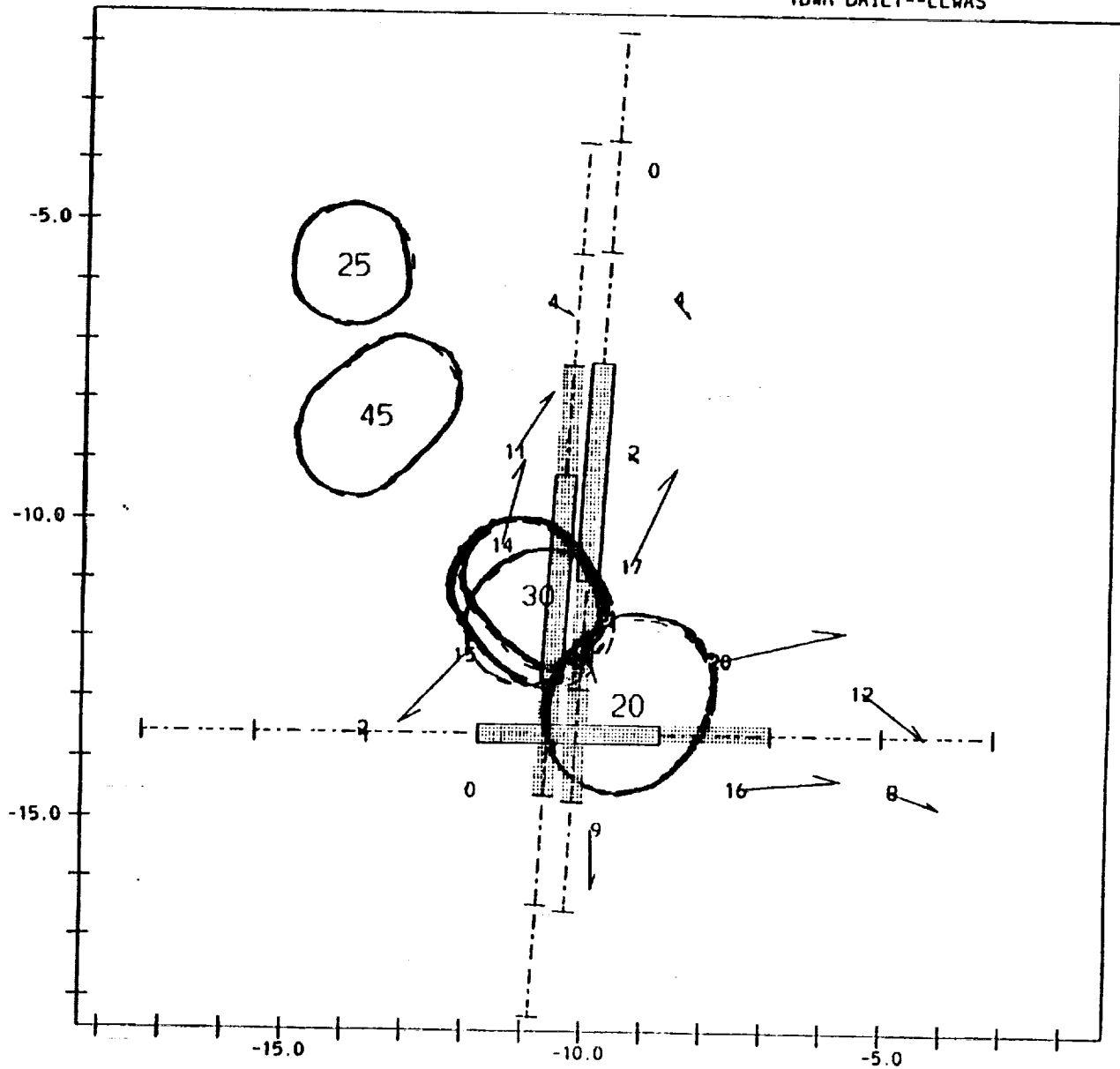|				
POD				93%
FAR				2%

* For Events With Losses ≥30 kts

** High FAR due to new radar (Mile High Radar)

865

29 - JUN - 91   22.59.39

TOWR DAILY--LLWAS

BLUE = TO...
RED = LLW
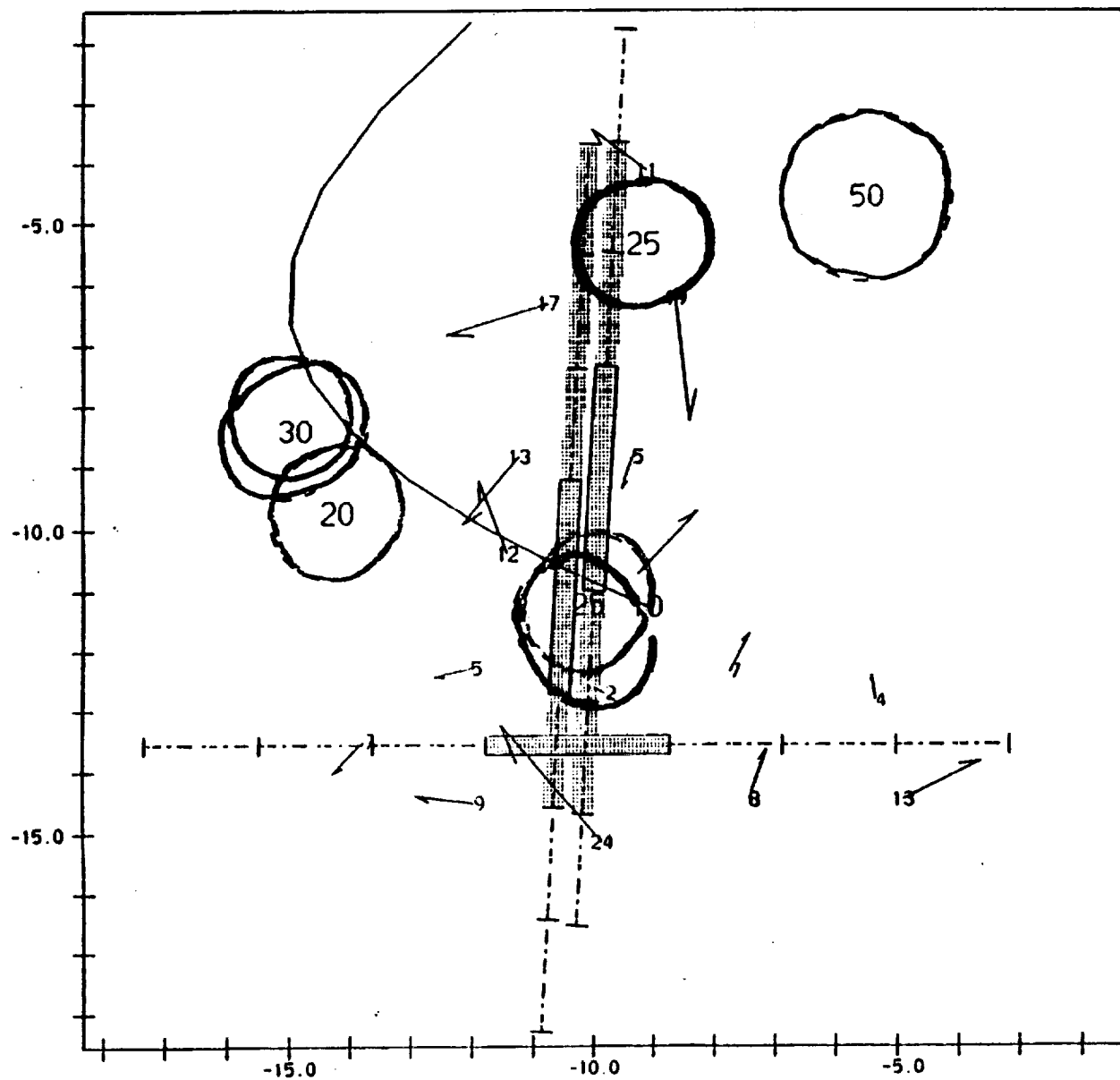
12 - JUL - 91   21.59. 0

TOWR DAILY--LLWAS

30

40

-5.0

-10.0

-15.0

-15.0

-10.0

-5.0

20

30

869
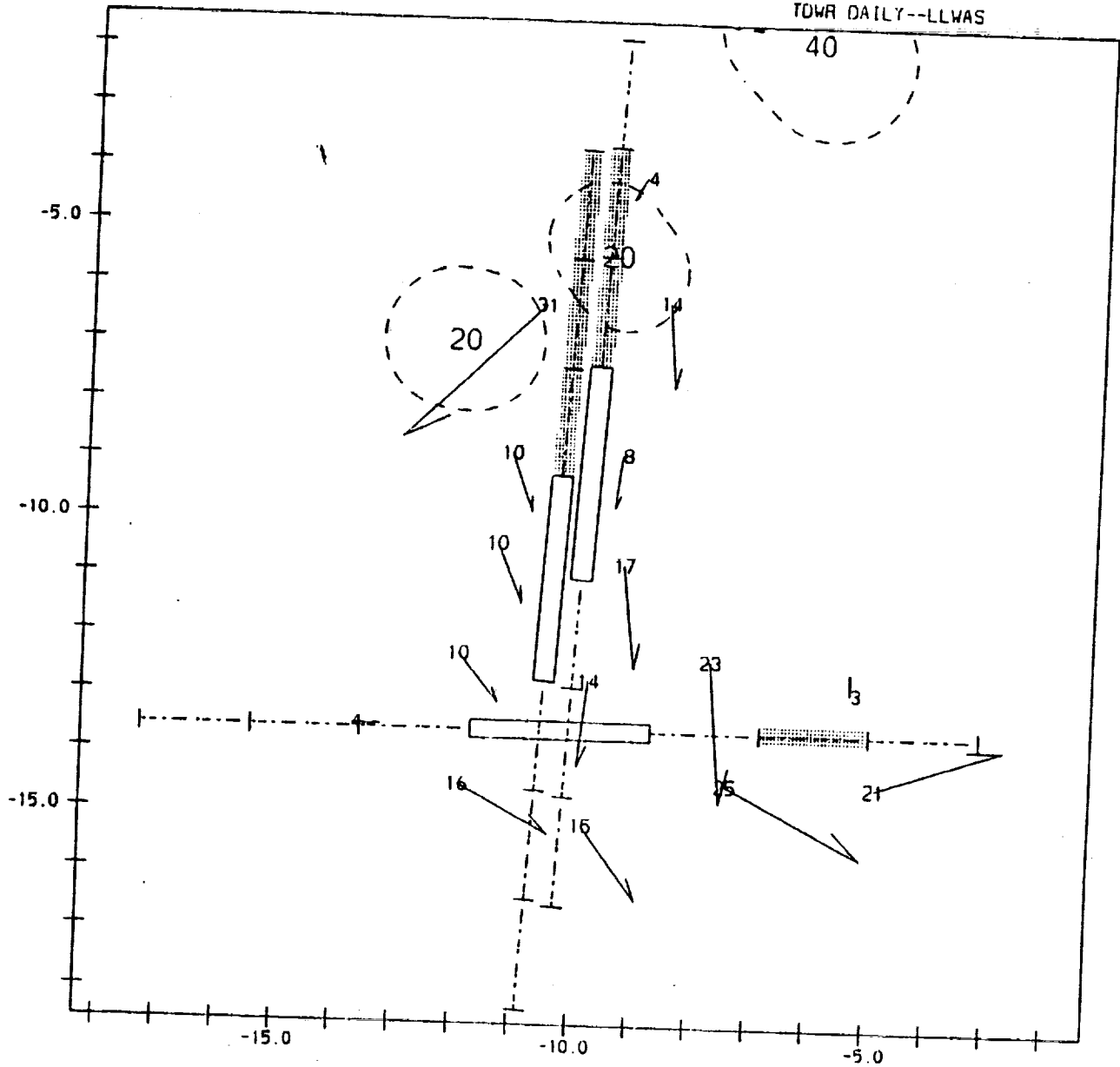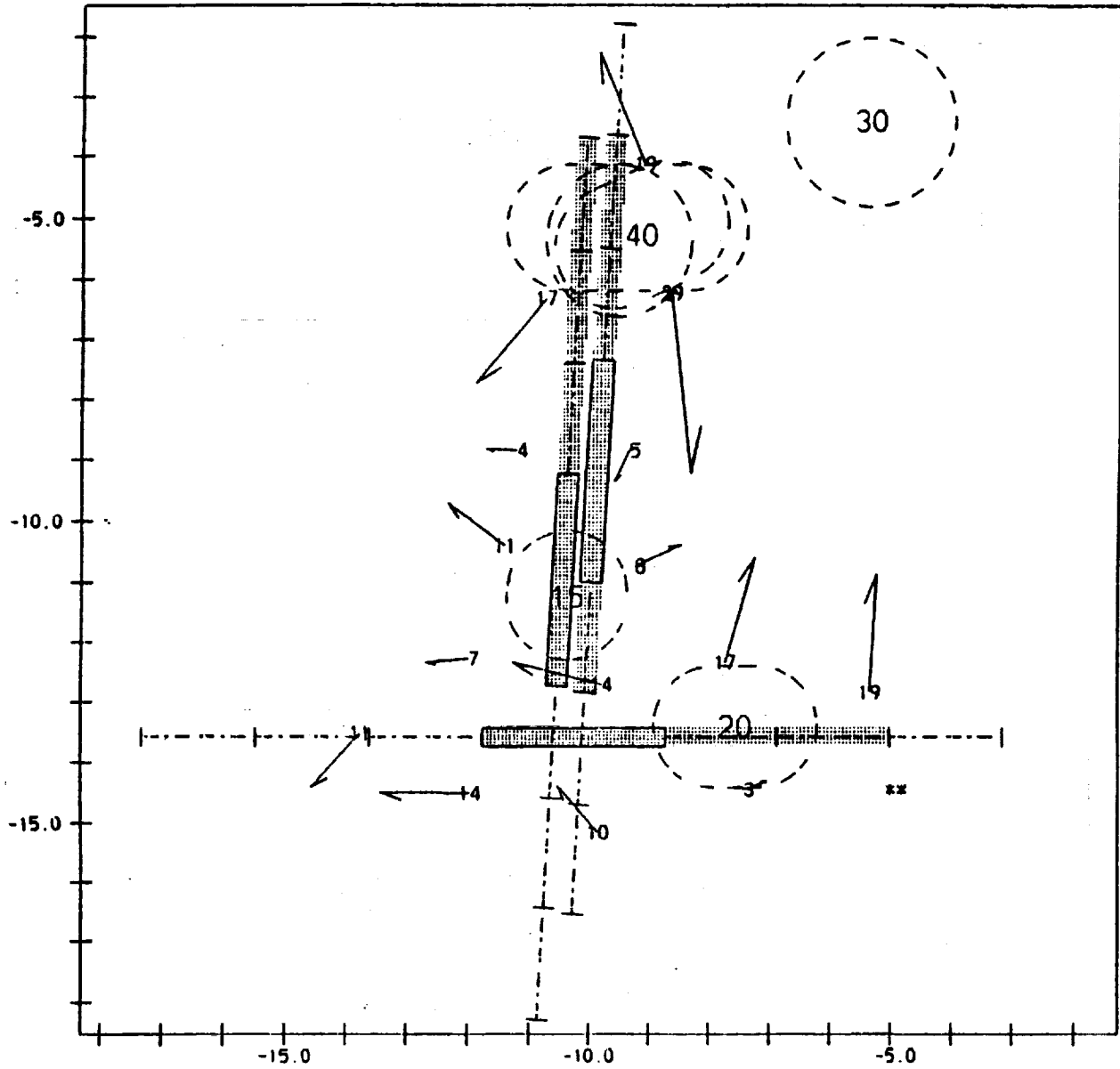
FY-92 Plans

Summer Operations (1 June - 31 August)

Operational Time - noon to 19:00 LT, daily

Products: Microburst Detection
Gust Front Detection
Windshift Prediction
Storm Motion
Precipitation
TDWR/LLWAS Integration (Spec Compliant)
TVS (Tornado)
Windshear Potential
Shear-Based MB - offline
Shear-Based GF - offline
Shear-based Tornado - offline
New Storm Track/Prediction - offline

FY-92 TDWR Plans - Denver

Winter Operations (20 January - 15 March)

Operational Times - 10:00 to 17:00 Daily

During Storms - extended hours

Products: Microburst Detection
Gust Front Detection
Windshift Prediction
TDWR/LLWAS Integration
Precipitation
Storm Motion
Snowfall Rate (new)
TVS (tornado) (offline)
Windshear Potential (offline)

NASA-NCAR '92

Dates: 6 July - 21 July

Changes for '92:

Waypoints with shear (2-D, 1 km)

Markers (up to 10)

Real-Time Reflectivity uplink
(4 levels)

Downlink A/C Position

Downlink A/C alarm status

"Quick look" data (48 hr turnaround)

Polarimetric radar data for
hail avoidance

NASA-NCAR '92

Dates: 6 July - 21 July

Changes for '92:

- Waypoints with shear (2-D, 1 km)
- Markers (up to 10)
- Real-Time Reflectivity uplink
  (4 levels)
- Downlink A/C Position
- Downlink A/C alarm status
- "Quick look" data (48 hr turnaround)
- Polarimetric radar data for
  hail avoidance

Q: Branimir Dulic (Transport Canada) - Could you elaborate on that polarometric radar. What kind of radar is it?

A: Kim Elmore (NCAR) - Well, it is a 10 centimeter radar, it is the NCAR CP2 radar. We can look at all kinds of things. We can look at KDP, PDP, linear depolarization ratios, ZDR, plus we actually have dual band radar capability, we have X band and S band. It is linear polarization. NOAA operates a circular polarization radar, but we operate linear polarization, horizontal, and vertical. We have a polarization switch so we can change from one to the other. Typically with polarometric radars, because you interlace pulses, you cut your Nyquist interval in half. We are going to install a processor where we can retain the Nyquist interval because we will use phase information from both polarizations instead of just horizontal.

Q: Joe Youssefi (Honeywell) - The false alert rates that you quoted, one or two percent, what are the units for that?

A: Jim Evans (MIT) - They are not false alert rates. They are probabilities that when you issue an alert that it is false. There is an important difference between this and the way people are talking about false alert rates with respect to the airborne systems. In the ground based systems, we have been convinced that from a pilot's belief view point you should have a high probability that when we present you alert that it actually is a valid alert. If you take false alert rates, it turns out most of the time there is no weather. If you actually had a false alert rate as low as one a week, it might mean that the probability when you hear an alert that it is false could be 90%.

Q: Joe Youssefi (Honeywell) - Let me see if I understand. If you give a hundred alerts the probability would be that there is one out of the hundred that is false?

A: Kim Elmore (NCAR) - That is correct.

Q: Joe Youssefi (Honeywell) - I had a second question relating to the issue of the dry microburst season in Denver.

A: Kim Elmore (NCAR) - I knew that was going to come up. Pete Sinclair and us seem to be somewhat at odds. NASA will be in Denver for basically the month of July, which was the month that Dr. Sinclair suggested they avoid. Our studies have found that while June is a great month for microbursts, they tend to also be associated with hail. So, if you just want to study microburst that is fine, but if want to fly airplanes through them that is not fine. So we counseled them to avoid June. Our experience has been that sometime in August we usually lose the Southwest monsoon over the Denver area which gives us the mid level moisture that we need for the dry low reflectivity microburst. Now it is absolutely true that we could have microbursts into October, certainly. But, our work has found that the highest frequency of them tends to be sometime in July. Those of you that did not know that Denver had a monsoon season it does.

Q: Pat Adamson (Turbulence Prediction Systems) - Are you doing a calculation of the F-factor? If so, are you using a similar formula or has work been done in that area?

A: Kim Elmore (NCAR) - From our shear base stuff we will be calculating F this season. We will be doing it essentially the same way that Steve and NASA do it.

Q: Pat Adamson (Turbulence Prediction Systems) - So the formula for a vertical computation is the same for wet or dry microburst?

A: Kim Elmore (NCAR) - Yes.

Session X. Flight Management Research

N 9 3 - 1 4 8 5 3

Experimental Evaluation of Candidate Graphical Microburst Alert Displays

Craig Wanke, Massachusetts Institute of Technology
Dr. R. John Hansman, Massachusetts Institute of Technology

Experimental Evaluation of Candidate Graphical Microburst Alert Displays

ASL

Craig Wanke and Dr. R. John Hansman
Department of Aeronautics and Astronautics
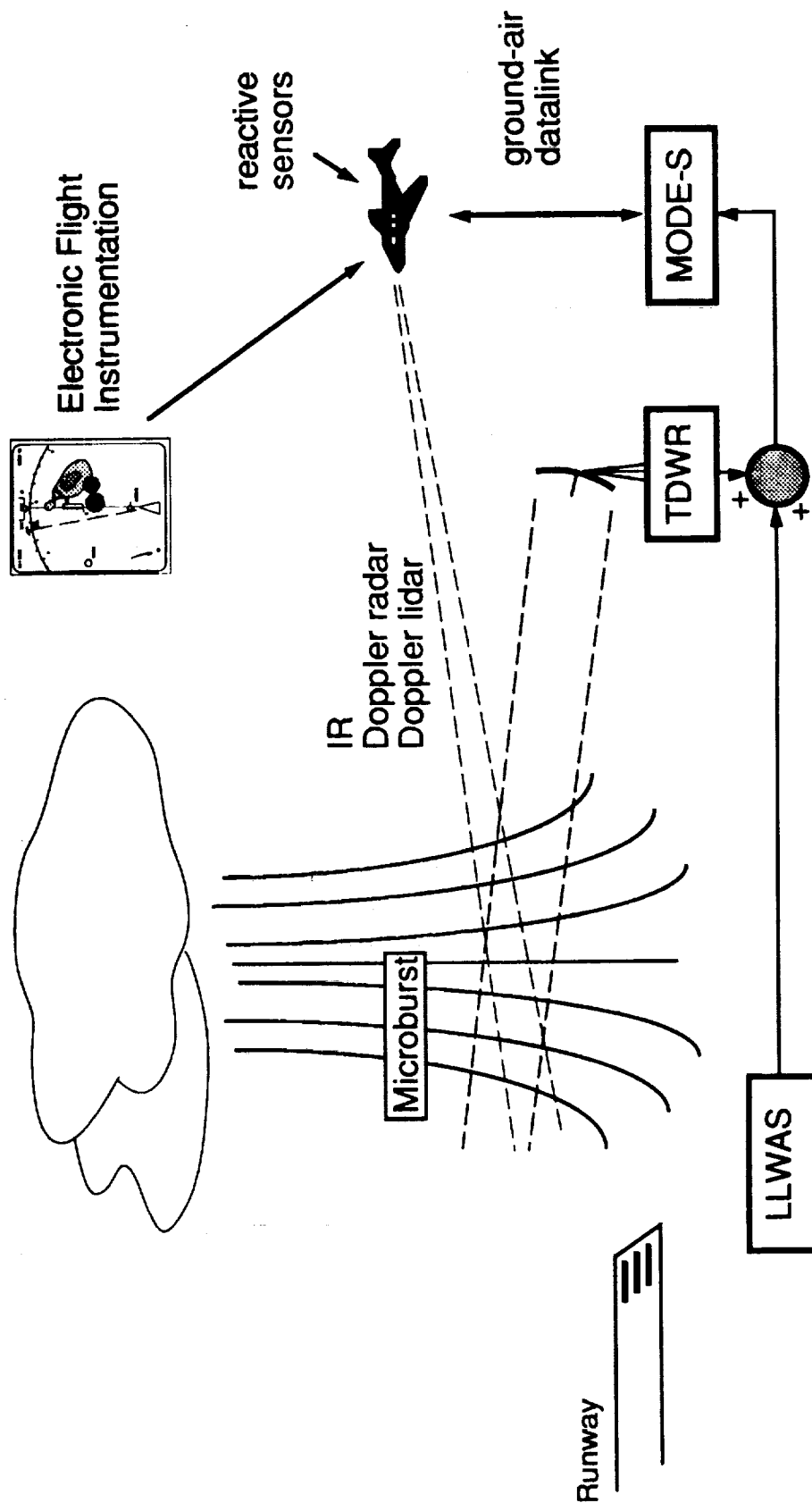Massachusetts Institute of Technology
Cambridge, Massachusetts USA

Fourth Combined Manufacturers' and Technologists'
Airborne Wind Shear Review Meeting

April 14-16, 1992   Williamsburg, VA

MICROBURST DETECTION AND ALERTING

reactive sensors

Electronic Flight
Instrumentation

ground-air
datalink

MODE-S

IR
Doppler radar
Doppler lidar

TDWR

Microburst

Runway

LLWAS

PREVIOUS PART-TASK SIMULATOR EXPERIMENT: COMPARISON OF PRESENTATION MODES (6/89)

- Designed to compare verbal, textual, and graphical modes of cockpit presentation

- Evaluated microburst alert presentation and ATC clearance amendment delivery

- July-August 1989: 8 total subjects participated, active airline pilots qualified on 757-767 aircraft

- 9 scenarios flown by each subject:

    Descent and Approach into DEN
    3 scenarios in each presentation mode

    Descent: 3 ATC clearance amendments
    Approach: Microburst alerts

- Sidetask, NASA subjective workload evaluation

- Post-session debriefing

PRESENTATION MODE COMPARISON: RESULTS
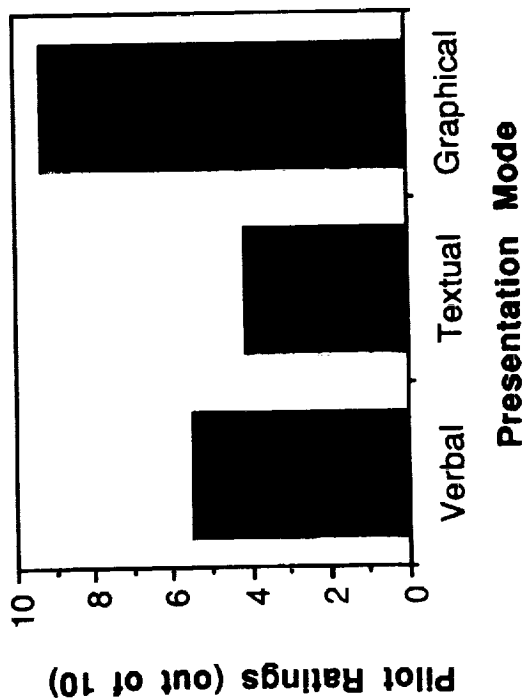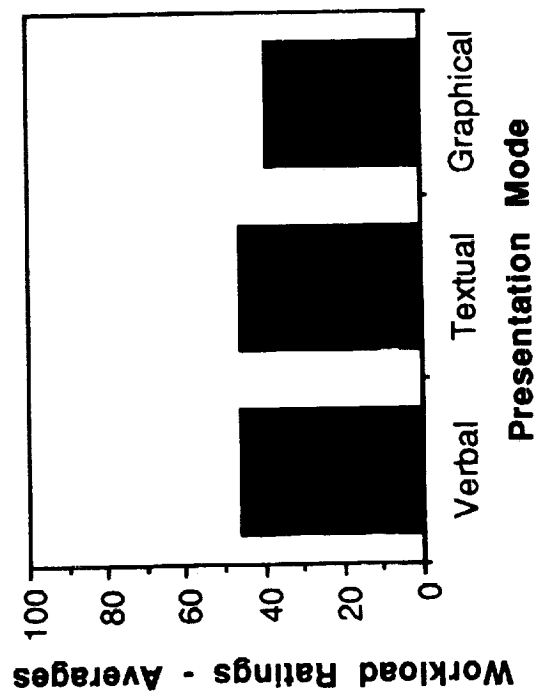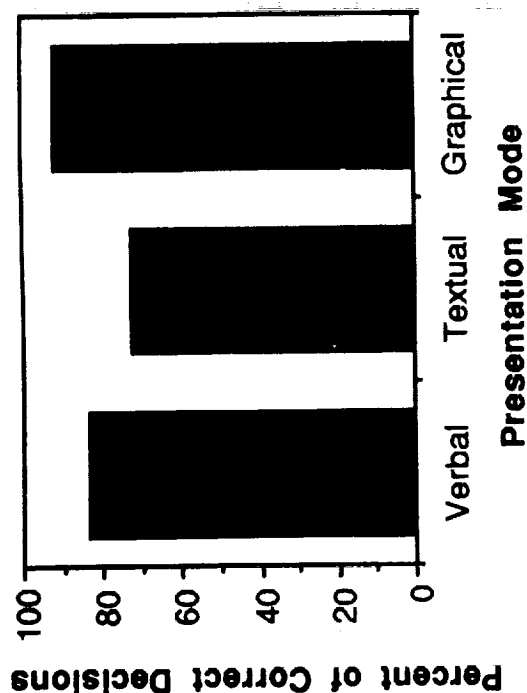
ADVANTAGES OF GRAPHICAL MODE OF PRESENTATION

- Very positive pilot response, preferred strongly over other modes

- Decreased workload with respect to other modes

- Decision-making accuracy and speed better than other modes

- Allowed pilots to plan and request non-standard missed approaches

- Graphical display is consistent with human cognitive mapping:
  Speeds comprehension, improves situational awareness

GRAPHICAL MICROBURST ALERT EXPERIMENT: OBJECTIVES

Overall Goal:

To recommend an effective graphical alert format for use in a multi-sensor environment

Effective = clear, easily understood, aids crew situational awareness

Issues:

- Is presentation on the EHSI clear, effective?

- Should microbursts be displayed with multiple intensity levels, or only as a single-level "hazardous" alert?

- Should data from separate sensors be "fused" into a single alert, or displayed as "discrete" alerts?

- What are the procedural implications of using graphical microburst alerts?

  --> Positional information is now present

GRAPHICAL MICROBURST ALERT EXPERIMENT: OVERVIEW

- Used MIT Advanced Cockpit Simulator

- Three prototype display formats were tested

- 12 simulated approaches to fictional airports were flown by each subject

- Exit Questionnaire given

- June, 1991: Nine active line EFIS/FMC-qualified pilots participated

  Subjects averaged 5890 hours of total flight experience, 1130 hours of flight experience on EFIS/FMC aircraft

- Combined with graphical terrain avoidance display experiment

CONTROL DISPLAY UNIT

CAGER	036 / 16.9	35000 / 350
WENNY	060 / 23.5	30000 / 300
WATKI		25000 / 250
EKR	076 / 17.4	20000 / 250

IBM PC
& Keyboard

IRIS 4D Display

MCP Status

ALT	V/S	HDG	SPD
5000		016	180

Clock
0619 6z

Windscreen

GPWS
PULL UP
GND
PROX

ADI
GS 193
2470
A/T IDLE
CMD
LNAV
VNAV

Vertical Speed
Altitude Speed
5300
-200

185
Speed

Terrain Display
8.9 NM   0623.7z
TRK [030] M
36   3   6
WENNY
CAGER
GS 5
4
4

Marker Beacons
OUTER
MID
INNER

Gear Status
NOSE
LEFT RIGHT

Flap Status
1 5 15 20 25 30
UP

EHSI
8.9 NM   0623.7z
TRK [030] M
36   3   6
WENNY
FCS
CAGER
FLOTS
KCOS
17
10

EHSI Display Controls
20 40 80 160 320
10
APP
MAP APT VOR WPT WXR

Landing Gear/Flap Controls
5 15 20 25 30
1
UP
FLAPS
UP O GEAR
DOWN

Mode Control Panel (MCP)
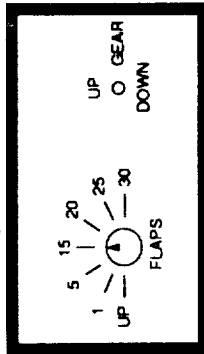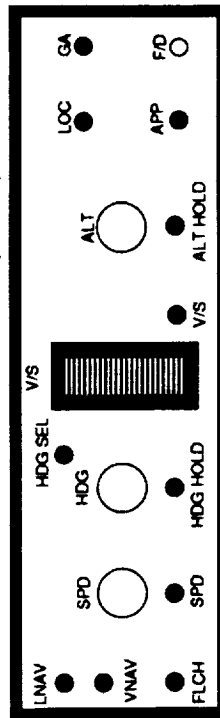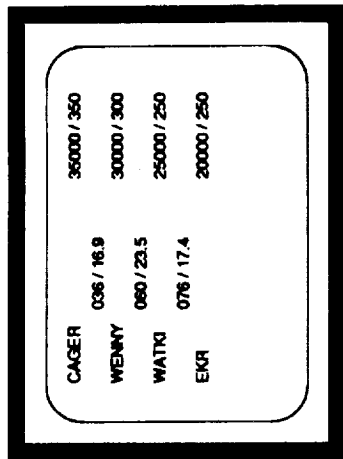
LNAV
VNAV
FLCH
SPD
HDG
HDG SEL
V/S
ALT
SPD
HDG HOLD
ALT HOLD
V/S
LOC
APP
GA
F/D
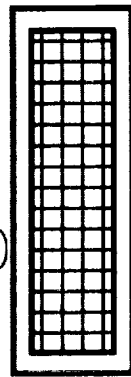
EHSI = Electronic Horizontal Situation Indicator
ADI = Attitude Direction Indicator

CANDIDATE DISPLAY DESIGN

- Three display formats designed to resolve two important issues in graphical alert design:

  - "Fused" vs. "Discrete" information display

  - Should intensity information be displayed?

- Nominal display "A" used "fused" information to display only those microbursts which exceed a hazard threshold

- Display "B" used three different hazard levels with different graphical symbols

- Display "C" used different icons for airborne look-ahead and ground-generated alerts

- Hazard Criterion: Average F-factor over one-half nm

DISPLAY A: "FUSED" ALERTS

10.1 DME

0835.4z

TRK | 057 | M

9
6
6R
5
3

DEN

KAPA

ALTUR

18

Solid red shape "hazardous" microburst
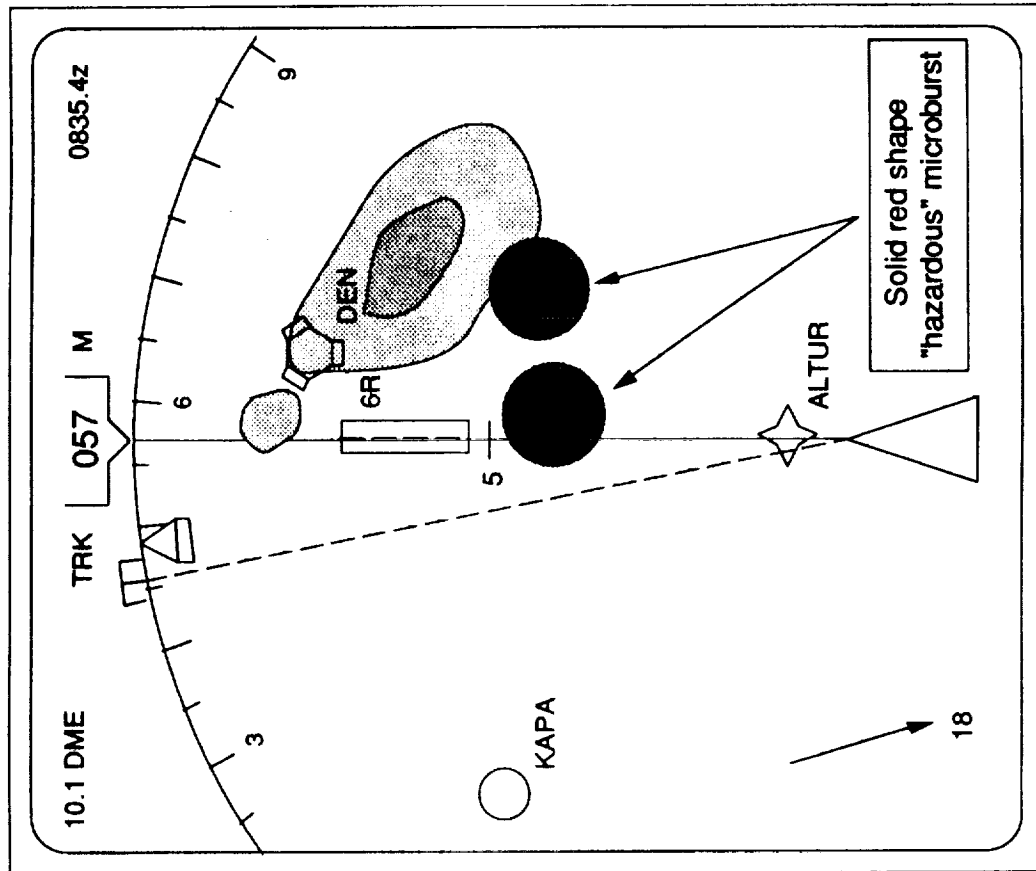
DISPLAY B: "FUSED" ALERTS + INTENSITY

890
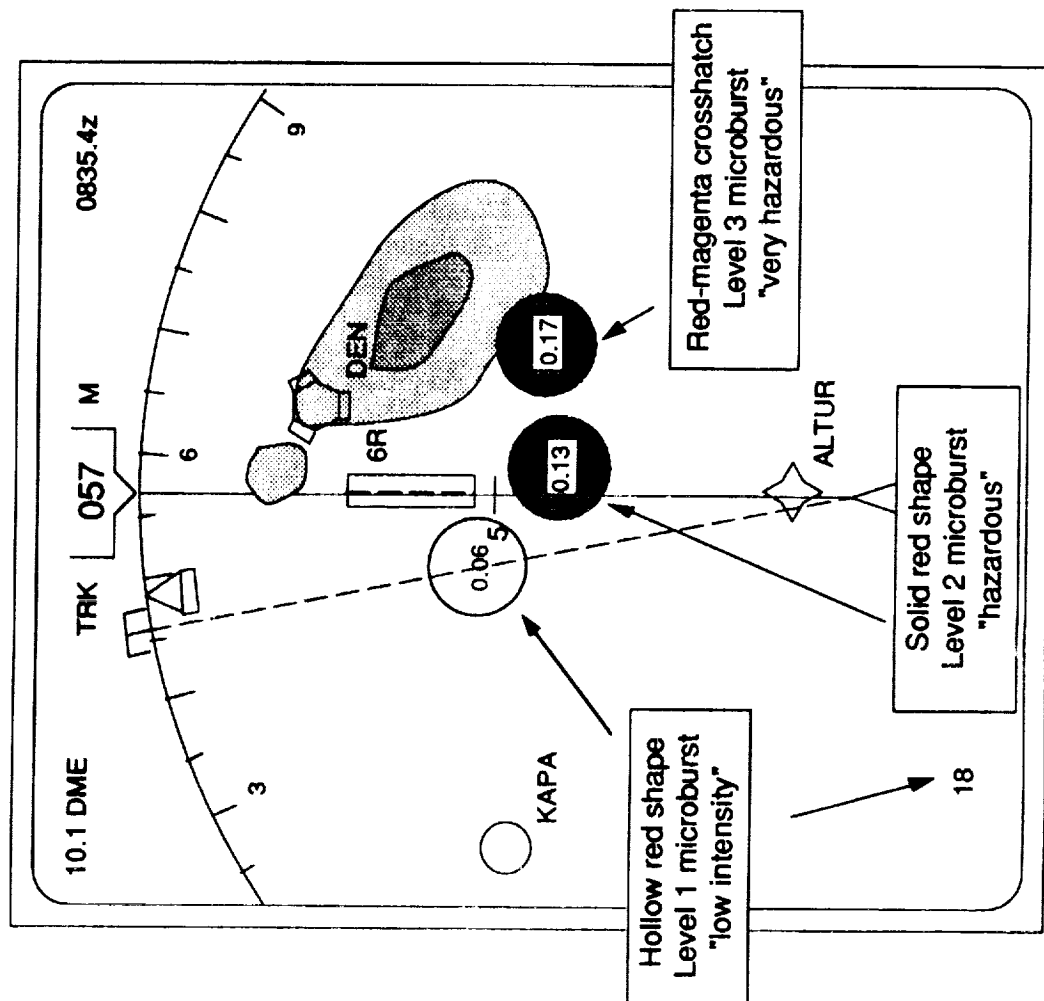
EXPLANATION OF F-FACTOR CRITERION TO PILOTS

- Needed to explain F-factor to pilots clearly, relevant to their experience:

  Loss in available climb capability, due to both head wind loss and downdraft in microburst core

- Three intensity levels displayed, based on highest F-factor averaged over one-half nautical mile (3000 feet):

  $0.05 < F < 0.1$:   "Low Intensity" alert
  Aircraft will lose <u>one-third to two-thirds</u> of available climb capability

  $0.1 < F < 0.15$:   "Hazardous" alert
  Aircraft will lose <u>two-thirds to all</u> of available climb capability

  $F > 0.15$ "Very Hazardous" alert
  Aircraft will be <u>forced to descend</u>

- These conditions will occur if the aircraft is flown through the center of the microburst (icon).

- Pilots were receptive to this explanation

891

DISPLAY C: "DISCRETE" ALERTS

10.1 DME   TRK | 057 | M   0835.4z

3

9

6

5

DEN

6R

KAPA

ALTUR

18

Solid red shape
"hazardous" microburst,
ground-based sensor

Red-yellow crosshatch region
"hazardous" microburst,
airborne forward-look sensor
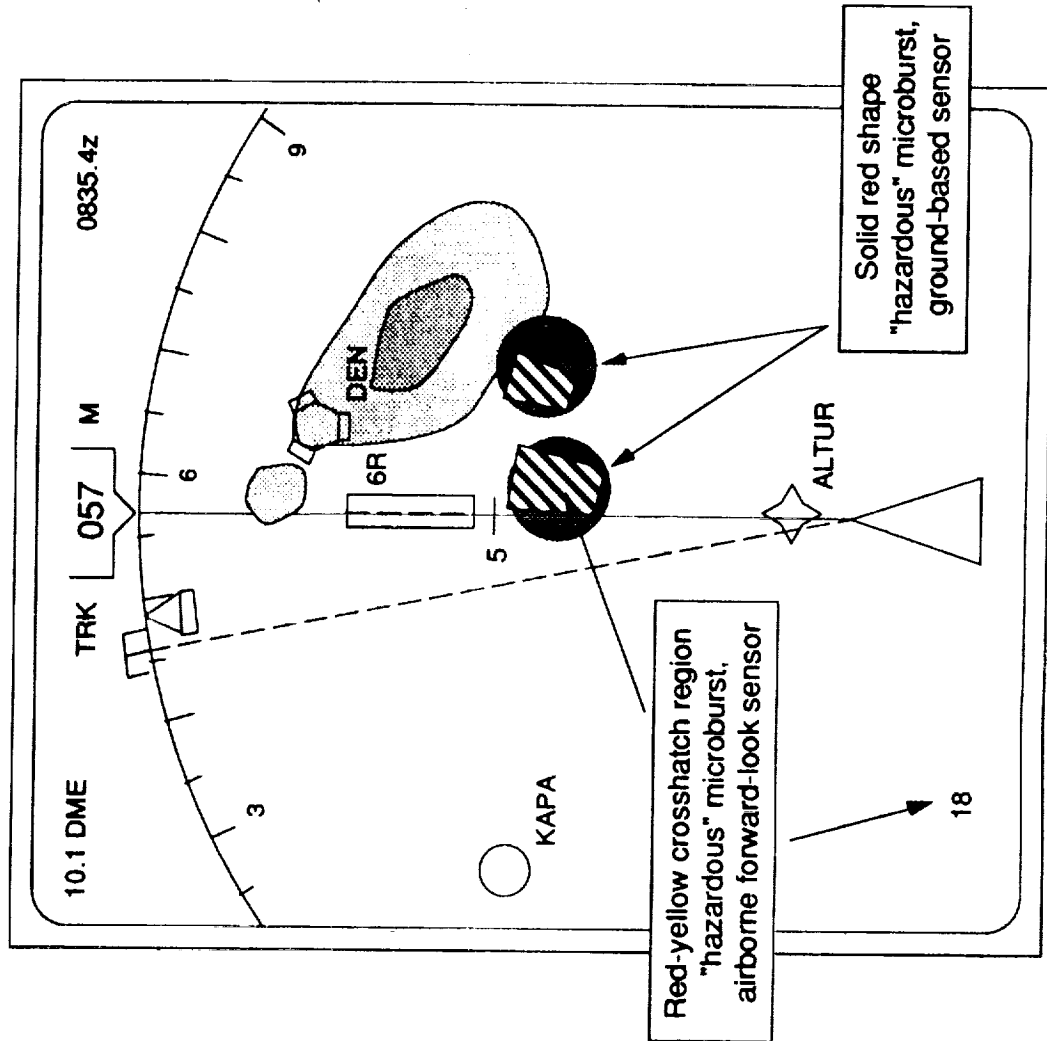
SCENARIO DESIGN

- 12 approach scenarios to fictional airports

- Test matrix variables

  Three display types

  "Wet" and "dry" weather conditions

  "Threat", "non-threat", "no microburst" scenarios

- Designed to evaluate performance differences between displays, "wet" and "dry" situations

- How far from a hazardous microburst is the go/no-go decision made?

- Provide enough situations to get useful commentary from pilots, useful observations of pilot reactions

893

RESULTS: VISUAL CLARITY OF ALERTS ON EHSI

- Pilots were asked to rate visual clarity on a scale of 1 to 4:

  1 = "very difficult to read"   4 = "very easy to read"
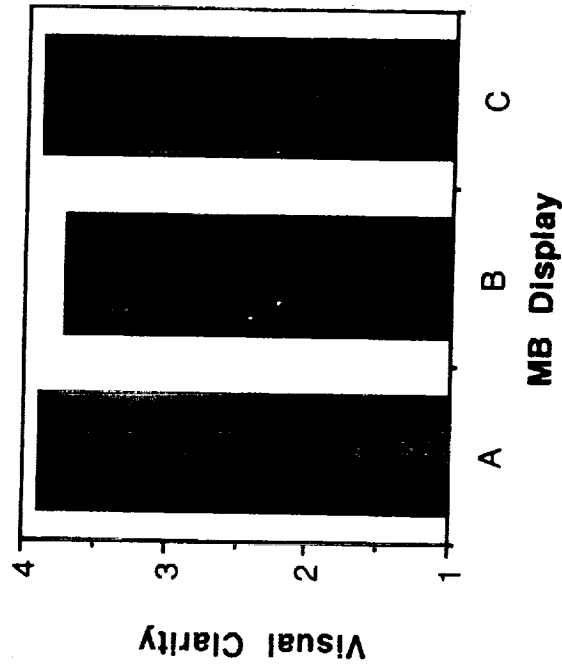
Visual Clarity (y-axis): 4, 3, 2, 1

MB Display (x-axis): A   B   C

Display A: "Fused" data, single intensity level
Display B: "Fused" data, three levels of intensity
Display C: "Discrete" data, single intensity level

894

RESULTS: OVERALL RANKINGS

- Pilots were asked to rank the displays in order of preference
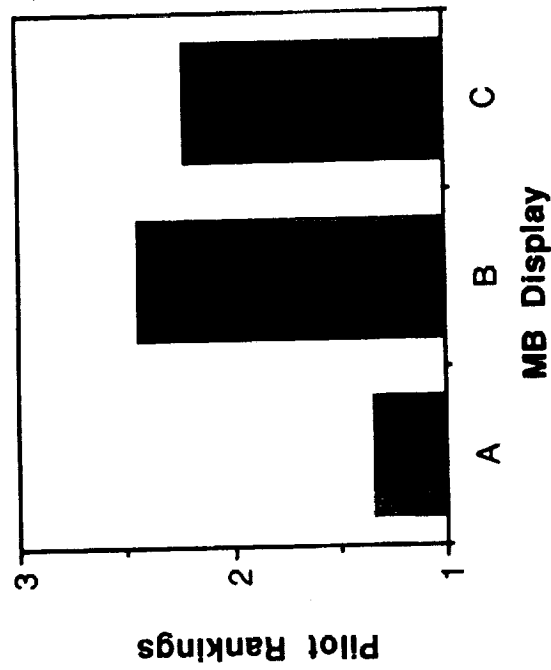
Display A: "Fused" data, single intensity level
Display B: "Fused" data, three levels of intensity
Display C: "Discrete" data, single intensity level

RESULTS: USEFULNESS

- Pilots were asked to individually rate the three displays in terms of how useful they were to understanding the weather situation

  1 = "not at all useful"   4 = "very useful"

Display A: "Fused" data, single intensity level
Display B: "Fused" data, three levels of intensity
Display C: "Discrete" data, single intensity level

RESULTS: NEED RANKINGS OF DISPLAY FEATURES

- Pilots were asked to rate the need for individual display features

1 = "unnecessary"   4 = "essential"
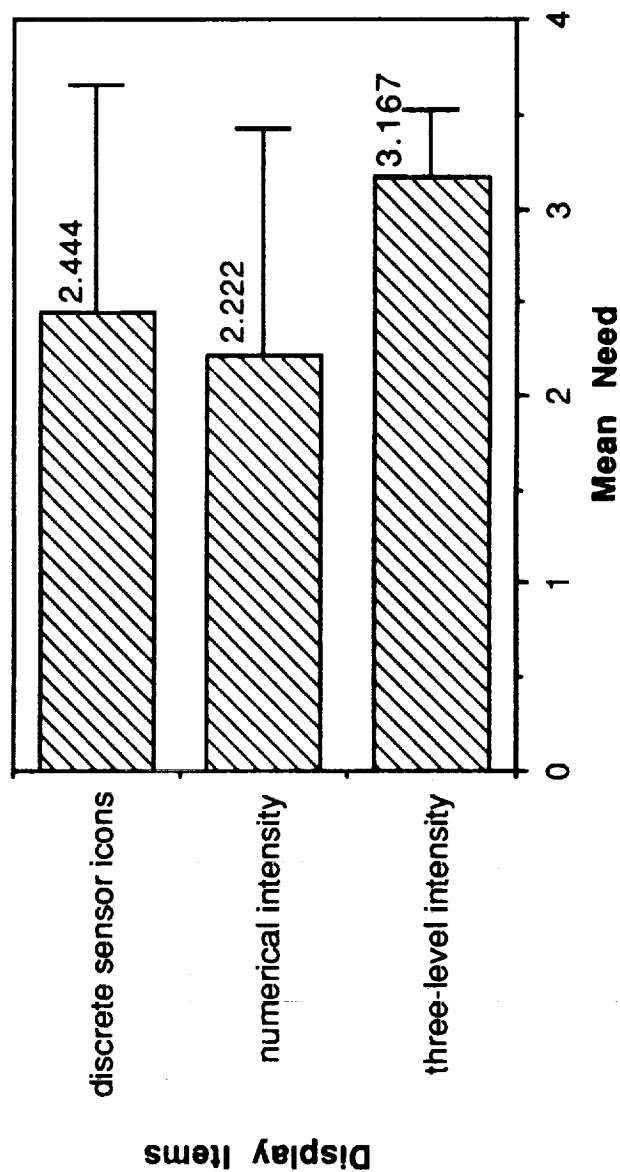
PROCEDURAL IMPLICATIONS OF GRAPHICAL ALERTS
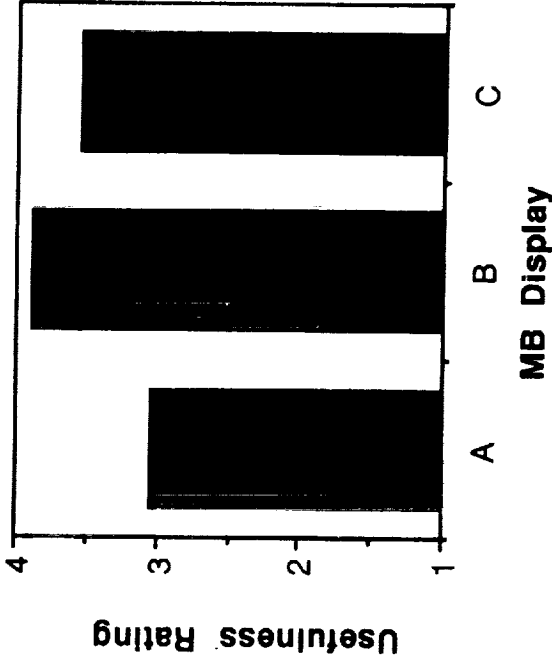
- "Decision distance" to make go/no-go decision

  Mean response: 4.26 nm   Std Dev = 1.15 nm

  At limit range of airborne lookahead systems under development

- Missed approach planning

  Can negotiate a turn with ATC prior to declaring missed approach

  Potential difficulty with emergency deviations

- "Secondary" alerts carry significant weight due to visual impact of graphical display -- lowest alert threshold is critical

  It is likely that pilots will not fly through <u>any</u> icon on the approach

  Compare with current TDWR "wind shear with loss" alerts

898

PROCEDURAL IMPLICATIONS OF GRAPHICAL ALERTS

- Lateral safety margin: "How close can a hazardous microburst icon be to the approach track where you will still continue the approach?"

  Responses from 2 to 15 nm

- Compare with TDWR alert methodology:

Departure	Runway	Approach
2	1	1	2	40	3

2 nm 3 nm
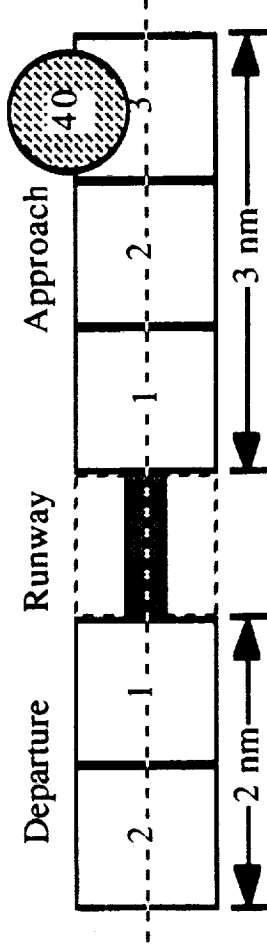
Microburst shapes which fall more than one-half mile from approach track do not generate an alert

...But an overwarning problem is perceived by pilots anyway

- Presenting the information graphically would explain to the pilot the "nuisance alerts" generated when microburst is off the flight path!

CONCLUSIONS AND RECOMMENDATIONS

- Multiple intensity levels should be used

  More visually compelling, intensity trend information, can maintain greater distance from very intense events

  F-factor hazard criterion was understood, accepted by pilots

- Issue of "fused" vs. "discrete" alerts was not resolved

  Possible solution: display "fused" icons to gain accuracy advantages of data fusion, and use separate indicators to show when airborne sensors detect a microburst

- Additional training is necessary

  Straight-ahead missed approach is an option

  Microbursts are localized, low-altitude events

- Can take the form of recommended crew procedures for use with automated graphical microburst alerts

900

C-7

CURRENT WORK: MULTI-SENSOR DATA FUSION

- Desirable parameters for crew alerting have been determined

  Location & Extent
  Intensity Level

- Multiple sensors may be available:

  Platforms: Airborne, Ground-Based
  Type: Remote, *in-situ*

  Large differences in measurement type and update rate

  No single sensor has "ideal" geometry

- <u>Multi-sensor data fusion could have significant benefits.</u>

  Improved accuracy

  Resolve conflicting measurements

- Can occur on "product level" or "data level"

- <u>Current work</u>: development of a data-level algorithm for multi-sensor microburst hazard assessment

901

OVERVIEW OF ALGORITHM

- **Basic Concept:** Use our knowledge of microburst fluid mechanics and measured microburst statistics to estimate microburst hazard.

- Assumes that microburst can be represented by a simple analytical model

    Modified Vicroy-Oseguera-Bowles microburst model

- Estimate the "best" parameters of that model given all of the available wind measurements

    TDWR, LLWAS, inertial data, airborne radar, airborne lidar

- Intensity, Location, and Extent can then be determined from the current list of parameters

- Based on an Extended Kalman Filter: Allows use of measured historical microburst characteristics to aid estimation process

- Can be used with multiple microbursts

- Currently testing with simulated microburst winds: will be tested on real data in the future

Experimental Evaluation of Candidate Graphical Microburst Alert Displays
Questions and Answers

Q: Unknown - Did you look at the cases where perhaps where there was a disagreement between ground based information or airborne sensor data?

A: Craig Wanke (MIT) - We did not. That is actually one of the major points. For the data fusion cases we showed two icons that were essentially overlaid. Clearly there is a significant problem if those do not line up. If you have a computer algorithm that attempts to interpret that in a realizable way, that is probably more effective than showing the pilot the two non agreeing icons on a three mile final and asking him to figure out what is really going on. That is really one of the biggest arguments for data fusion. But, that is something that we could not really test in our experiment.

Bob Hall (Airline Pilots Association) - I don't have a question, but I wanted to find the appropriate time to make a comment to the group here. This looked like it might be a good time to do that. I wanted to offer a few words of encouragement and motivation to the industry from the ultimate end user, which are the pilots. As you are probably aware, ALPA has been very active in this whole wind shear endeavor for probably over ten years, even before some of the major accidents occurred. We would like to think that we were instrumental in getting some of the FAR changes which mandated the reactive devices that are going into our cockpits now. We are very thankful to be getting these reactive devices into our cockpits. As nice as the reactive device is, we kind of view it as a nice back up. What we would really like to have is a predictive systems, which is what we are talking about in this conference today. A few years ago we were very concerned that even though we had gotten the reactive devices mandated, we were concerned that the industry would drop all the research and development on the predictive devices. We were concerned that in endorsing those changes we might lose out in what we really wanted. I am just here to emphasize and motivate you to keep up the good work. We are very glad to see the progress that is being made, especially in the Doppler radar. I was a little discouraged several years ago about the clutter problems. It looks like those have been really overcome and now we are pressing on to talking about how do we get the information to the cockpit. So please keep up the good work, and be assured that pilots do want accurate, reliable, predictive systems that will help us to avoid the wind shear hazards.

Q: Howard Williams (Gulfstream Aerospace) - I believe we can echo what has just been stated. Relative to your pilot evaluation, did you have any FAA pilots as part of the team?

A: Craig Wanke (MIT) - No, we did not. These were all airline pilots.

Q: Howard Williams (Gulfstream Aerospace) - Do you feel that these types of displays are certifiable or have you reached that stage yet?

A: Craig Wanke (MIT) - We haven't really reached that stage yet. We haven't thought seriously about the certifiability issues.

John Hansman (MIT) - We see what we are doing more as baseline work. We are not trying to certify a specific display, but provide baseline data on the utility of these type of display concepts. As you go into a particular display configuration there will be certifiability issues. These were not designed to be certified displays.

Q: Sam Shirck (Continental Airlines) - Did you make any studies that involved TCAS on your displays?

A: Craig Wanke (MIT) - No we did not.

Sam Shirck (Continental Airlines) - I would encourage you, if your marching orders permit, to look at an independent display for hazards such as TCAS and wind shear. As much as I like to see wind shear on a moving map, I don't think we can put much more on an EHSI than we have right now. If you have ever ridden in the cockpit going into the Denver area, and watch what happens on the TCAS system on an EFIS, it is very exciting. Although the engineering is capable of putting all this stuff on there, I am not sure that we as pilots can get it off and use it. TCAS is a very important part of this whole display issue. I would encourage you to investigate a dedicated display for hazards and to involve the TCAS scenarios in that.

A: Craig Wanke (MIT) - That is certainly a consideration and that is something that probably should be worked on, but I don't know that we have any plans to do TCAS studies. We are doing some similar stuff with terrain alerting displays.

John Hansman (MIT) - That is a very valid point. The whole issue of display clutter and display priority is a critical issue for this, for data link, for a whole bunch of areas. What do you do when you have two high priority messages that over write? Craig alluded to the fact that we are doing a second experiment which was a terrain alerting experiment with a separate dedicated terrain alerting display. As you are aware there is a display space availability problem in the cockpit. There is also a second problem, which is if you have a short term critical alert you do not want the crew to go heads down to evaluate the threat and resolve it. So you go into this trade off of where do you want the crew looking. We understand the issue. We didn't include TCAS because of experimental difficulties, not because we do not think it is a problem.

Pat Adamson (Turbulence Prediction Systems) - I encourage everybody to look at the S7 ARP wind shear document. There is a lot of work going on with that committee on displays with regard to short look and longer look predictive systems. In fact, there is a draft out of a display concept. I think that the entire community should be looking at that as well as studies of such displays. Clearly there are several types of wind shear systems being considered from short look to longer look. I guess I would encourage you to take a look at that document as part of your studies.

N 93-14854

Wind Shear Related Research at Princeton University

Dr. Robert Stengel, Princeton University

Wind Shear-Related Research at Princeton University

Robert F. Stengel

Department of Mechanical and Aerospace Engineering

April 1992

Real-Time Decision Aiding:
Aircraft Guidance for Wind Shear Avoidance

Target Pitch Angle and Optimal Recovery
from Wind Shear Encounter

Dynamic Behavior of an Aircraft Encountering a Wind Vortex

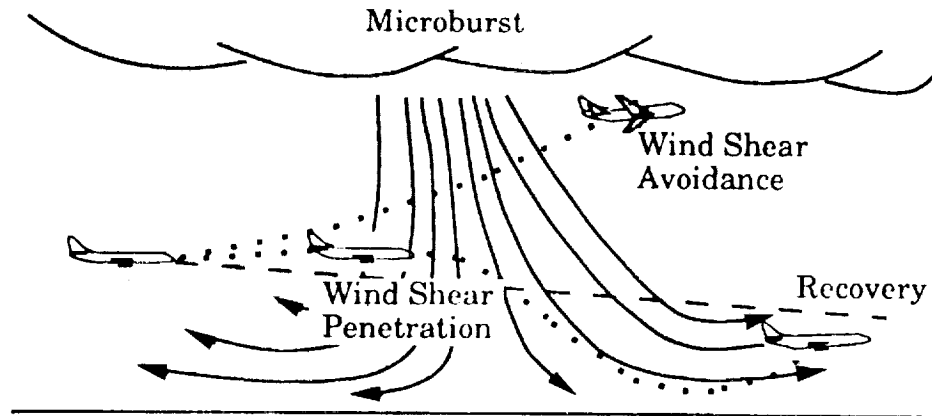# Real-Time Decision Aiding: Aircraft Guidance for Wind Shear Avoidance

D. Alexander Stratton and Robert F. Stengel
Princeton University

Presentation Outline
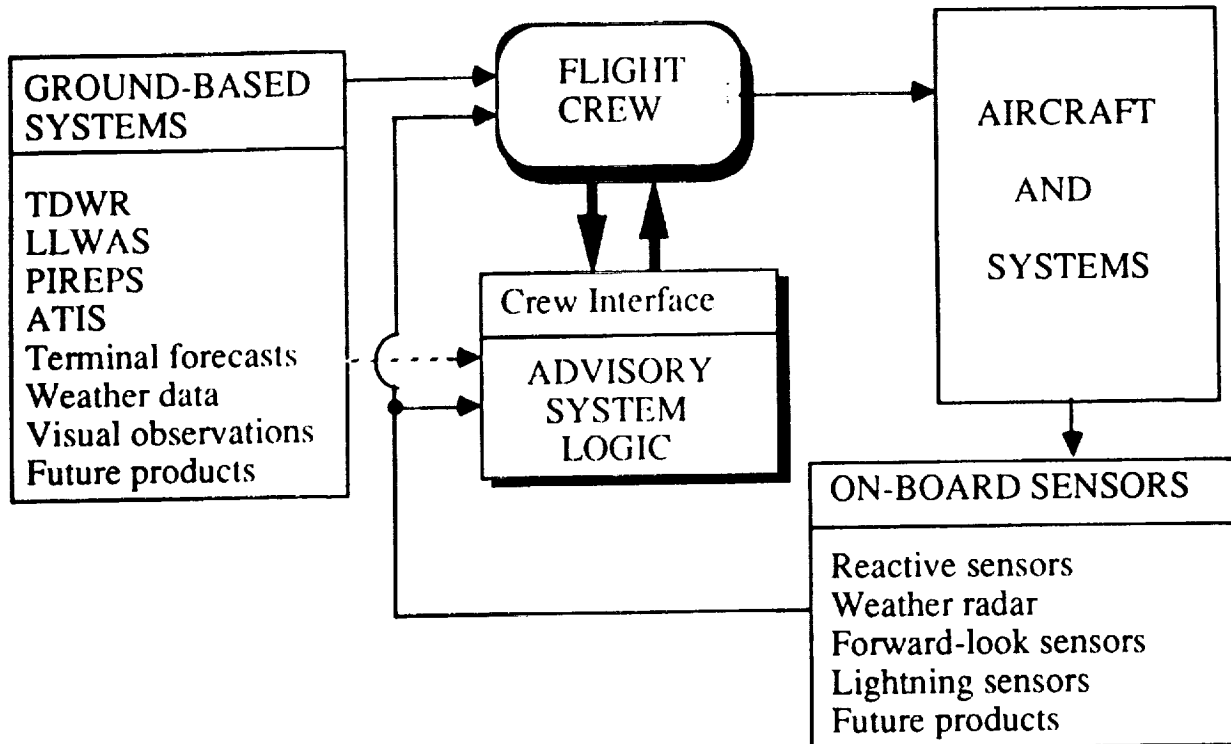
- The Microburst Hazard to Aviation

- Processes of a Wind Shear Advisory System

- Simulated Microburst Encounters

# The Low-Altitude Wind Shear Threat

- Microburst phenomenon
    - Short-lived, powerful outflow
    - Aircraft performance, control
- Microburst research
    - Wet, dry environments classified
    - Frequency, characteristics determined
    - Guidance and control strategies

An Advisory System for Wind Shear Avoidance

GROUND-BASED SYSTEMS

TDWR
LLWAS
PIREPS
ATIS
Terminal forecasts
Weather data
Visual observations
Future products

FLIGHT CREW

AIRCRAFT AND SYSTEMS

Crew Interface

ADVISORY SYSTEM LOGIC

ON-BOARD SENSORS

Reactive sensors
Weather radar
Forward-look sensors
Lightning sensors
Future products

- Support crew decision reliability
  - Monitoring and estimation, data link
  - Risk assessment
  - Provide decision alternatives
  - Recovery procedures

- Define computational structure
  - Summarize relevant information
  - Incorporate meteorological data
  - Declarative structure, convert to real-time

Princeton University

909

Reducing the Wind Shear Threat
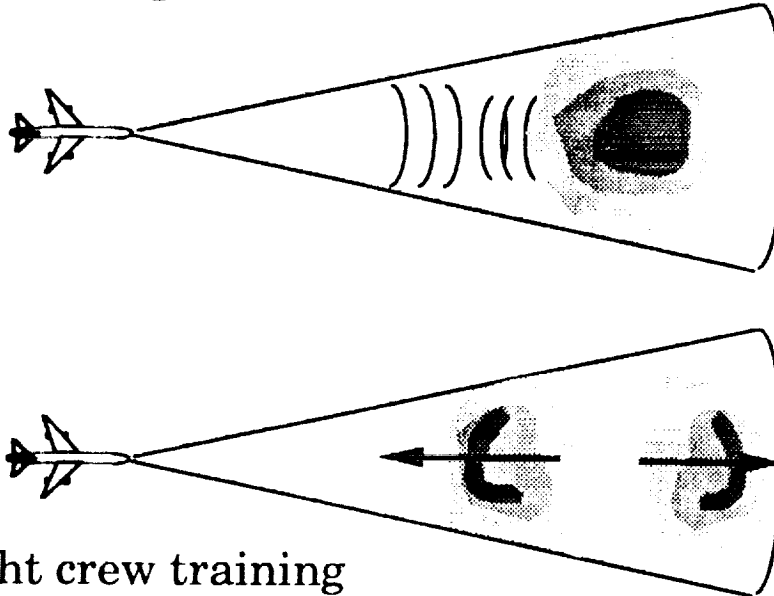
- Flight crew training
    FAA Windshear Training Aid

- Ground-based detection systems
    LLWAS, TDWR
    Weather services, forecasting

- Airborne detection technology
    Doppler radar, lidar, infra-red
    Radar reflectivity, lightning

- Integration, information transfer

Princeton University

Energy-Based Hazard Model

One-dimensional energy model:

$$E_s(t) = \left(\frac{1}{2g}\right)V_a^2 + h$$

$$\frac{dE_s}{dt}(t) = P_s - \mathcal{F}(t)V_a$$

- $\mathcal{F}$ - "F-factor" (Bowles)

$$\mathcal{F}(t) = \left(\frac{1}{g}\right)\frac{dw_x}{dt}(t) - \frac{w_h(t)}{V_a}$$
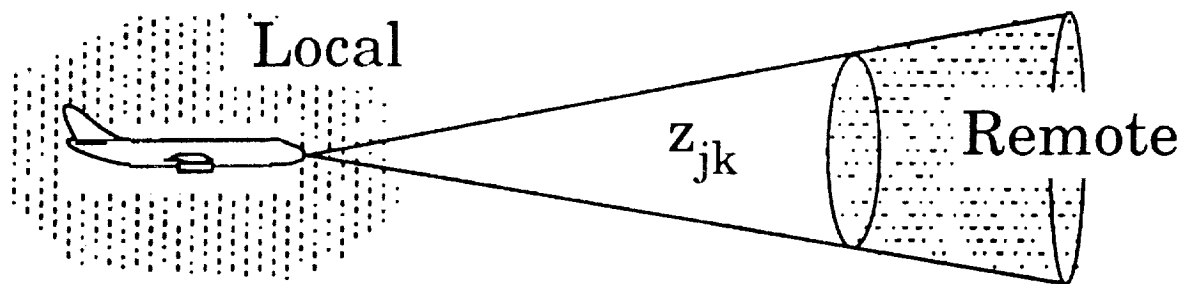
Specific excess power (P_s) variation

Airspeed variation

NASA Langley – 0.1 average $\mathcal{F}$ over 1 km

- Energy deviation across shear

$$\Delta E_s = -\mathcal{F}_{ave}\Delta x = -\frac{V_{an}}{g}\Delta w_x + \frac{w_{h_{ave}}}{V_{an}}\Delta x$$

Princeton University

911

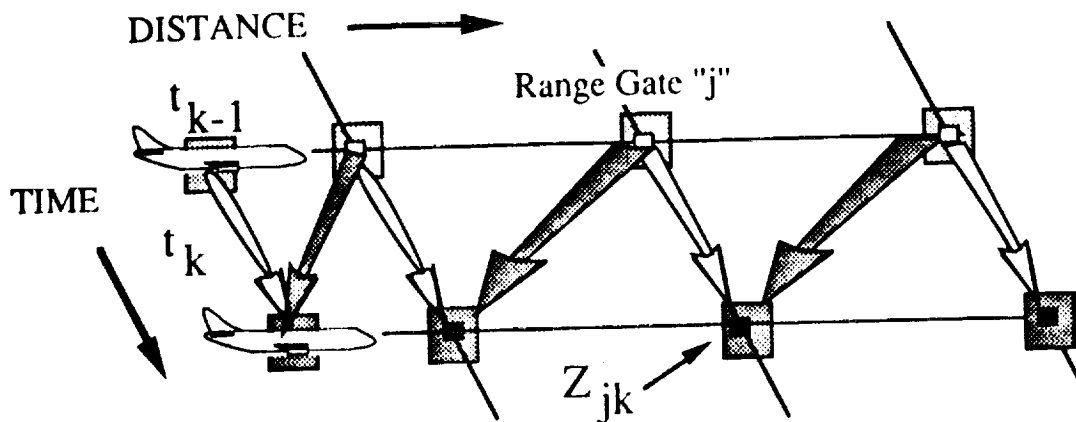# Forward-Look Sensor Measurement of Wind Shear

Local

z_{jk} Remote

| Relative Speed of the Air Masses | = | Remote Wind Speed with respect to Aircraft | − | Aircraft Speed with respect to Local Air Mass |

$$\Delta w_{jk} = z_{jk} - V_a$$

- Aircraft Specific Energy Loss

$$\Delta E_S = -\mathcal{F}_{ave}\Delta x = -\frac{V_{an}}{g}\Delta w_x + \frac{wh_{ave}}{V_{an}}\Delta x$$

Stochastic Prediction Algorithm

DISTANCE →

Range Gate "j"

t_{k-1}

TIME

t_k

Z_{jk}

- Coupled Kalman filters

    "Random walk" stochastic model

    Sensor platform motion - state propagation

    Parallel processing

    Optimize design gain parameter

- Coupled predictive-reactive detection

- Positive detection - threshold exceedence

Probability-Based Decision Strategy
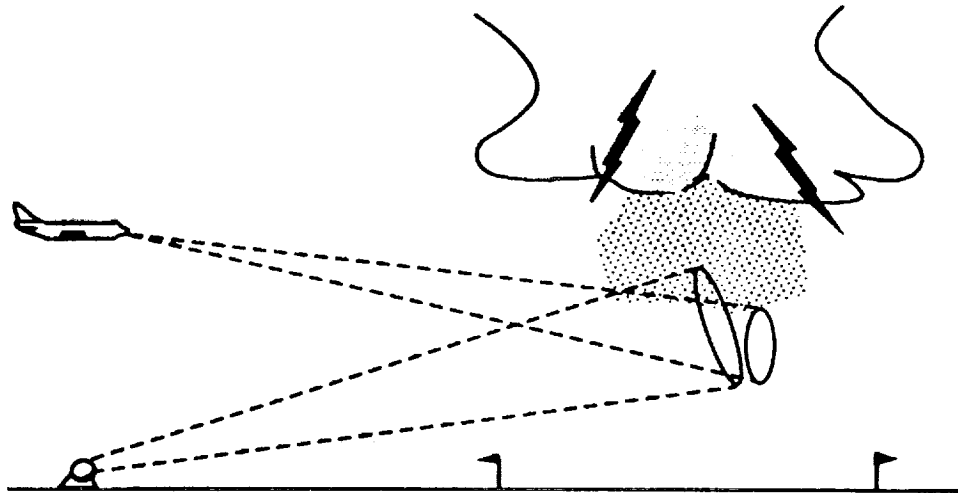
- Predictive measurements $\mathbf{z_p}(t)$

- Probability-based decision-making

$$\Pr\{\exists t_i \in [t, t_f]: \mathbf{w}(t_i) \in \mathcal{U} \mid \mathbf{z_p}(t), u_d(t) = u_{d_1}\} < T \Rightarrow u_d(t) = u_{d_1}$$

- Bayesian inference

$$\Pr\{H \mid \mathbf{z_p}(t)\} = \frac{\Pr\{\mathbf{z_p}(t) \mid H\}}{\Pr\{\mathbf{z_p}(t)\}} \Pr\{H\}$$

- Joint probability computation

Princeton University

Computational Processes for Decision Aiding

- Identify Knowledge, Structure
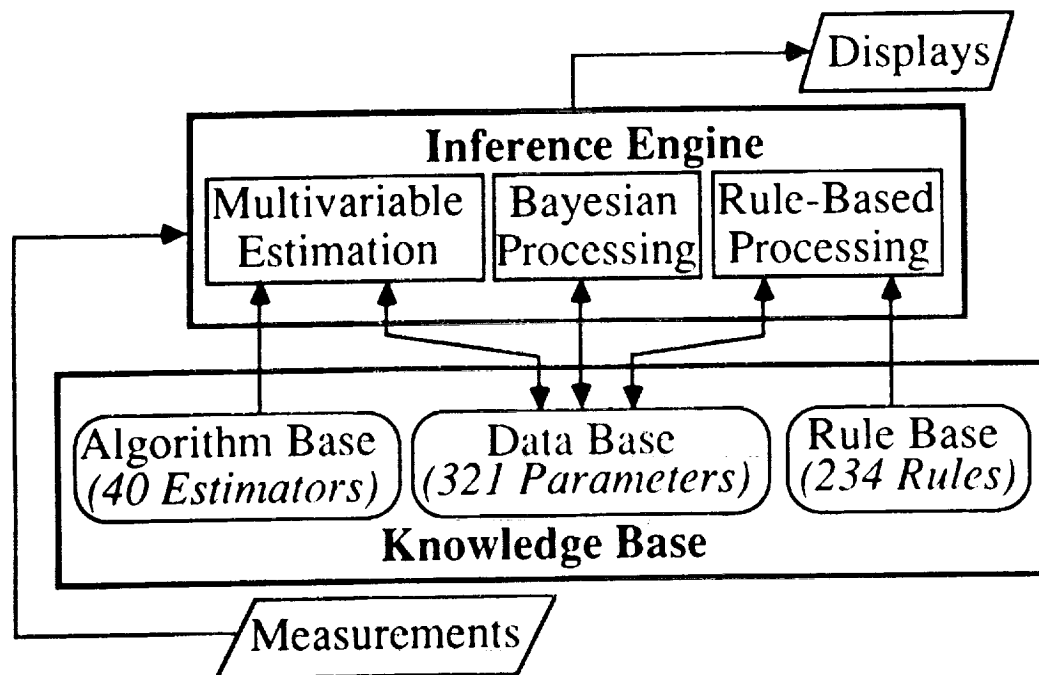
- Rule-Based Logic

    Declarative, back-chaining inference

    Top-level monitoring, assessment, planning, guidance functions

- Bayesian Logic

    Statistical model, data-driven inference

- Multivariable Estimation

    Stochastic model

Bayesian Network Risk Assessment

Geographical Location
Pr{Arid Region} = 1.0
Pr{Non-Arid} = 0.0

Time-of-Day
Pr{Morning} = 0.0
Pr{Afternoon} = 1.0
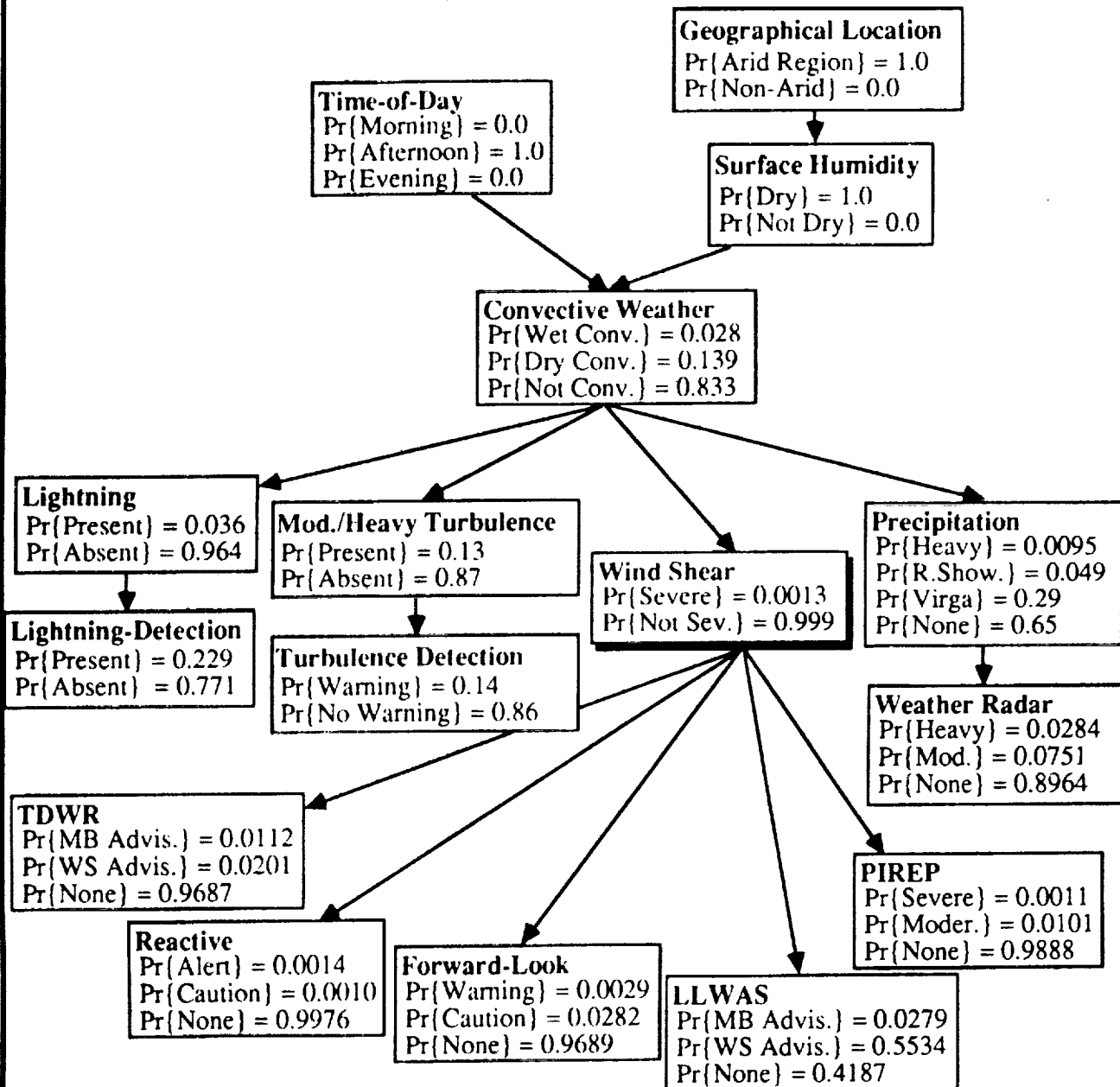Pr{Evening} = 0.0

Surface Humidity
Pr{Dry} = 1.0
Pr{Not Dry} = 0.0

Convective Weather
Pr{Wet Conv.} = 0.028
Pr{Dry Conv.} = 0.139
Pr{Not Conv.} = 0.833

Lightning
Pr{Present} = 0.036
Pr{Absent} = 0.964

Mod./Heavy Turbulence
Pr{Present} = 0.13
Pr{Absent} = 0.87

Wind Shear
Pr{Severe} = 0.0013
Pr{Not Sev.} = 0.999

Precipitation
Pr{Heavy} = 0.0095
Pr{R.Show.} = 0.049
Pr{Virga} = 0.29
Pr{None} = 0.65

Lightning-Detection
Pr{Present} = 0.229
Pr{Absent} = 0.771

Turbulence Detection
Pr{Warning} = 0.14
Pr{No Warning} = 0.86

Weather Radar
Pr{Heavy} = 0.0284
Pr{Mod.} = 0.0751
Pr{None} = 0.8964

TDWR
Pr{MB Advis.} = 0.0112
Pr{WS Advis.} = 0.0201
Pr{None} = 0.9687

Reactive
Pr{Alert} = 0.0014
Pr{Caution} = 0.0010
Pr{None} = 0.9976

Forward-Look
Pr{Warning} = 0.0029
Pr{Caution} = 0.0282
Pr{None} = 0.9689

LLWAS
Pr{MB Advis.} = 0.0279
Pr{WS Advis.} = 0.5534
Pr{None} = 0.4187

PIREP
Pr{Severe} = 0.0011
Pr{Moder.} = 0.0101
Pr{None} = 0.9888

- Assign link probabilities, priors
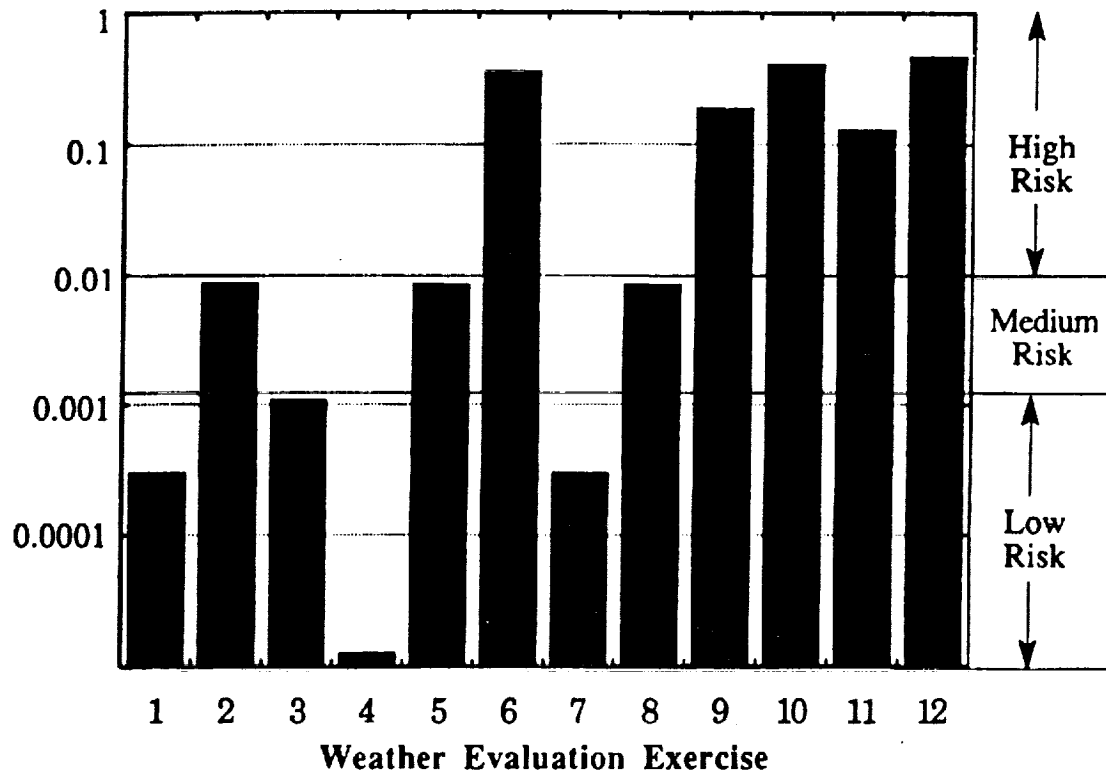- Probabilities updates, Bayes's theorem

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Spatial and Temporal Factors

- Likelihoods weigh timeliness, nearness
  - Dual-doppler data (Hjelmfelt, 1988)
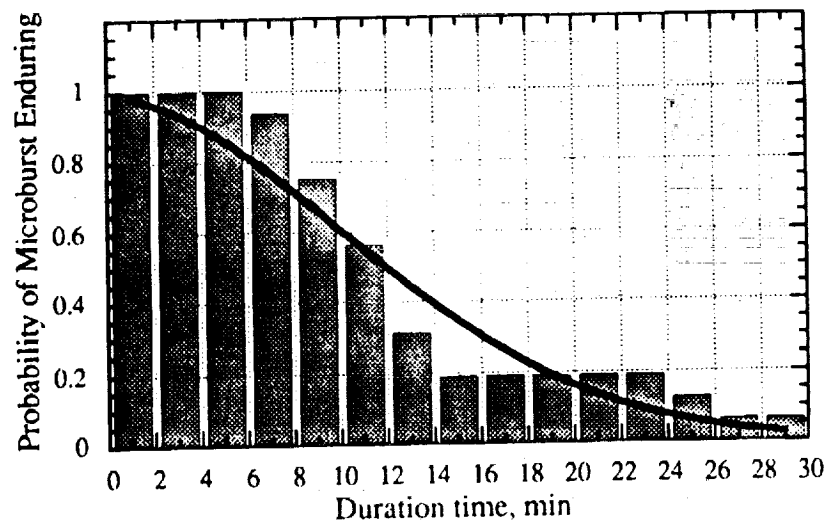
- Network time-dependant, re-initialize

- Repeated evidence, downgrade relevance

Risk Assessment Benchmarks

- Windshear Training Aid Guidelines

    - 12 Weather Evaluation Exercises

    - Risk Assessed by WTA authors

        Example: moderate convection
        results in Medium risk

- Bayesian Network Calculations

    - Monotonic relationship

    - Subjective levels assigned

Robustness of Predictive Wind Shear Detection

- Robustness issues

  Variation in microburst structure

  Vertical winds unmeasured

  Bandwidth limitations

- Detection robustness metrics

  Probability of Correct Warning, Pr{A | WS}

  False Warning Probability, Pr{A | ¬ WS}

$$Pr\{WS \mid A\} = \frac{Pr\{A \mid WS\}}{Pr\{A\}} Pr\{WS\}$$

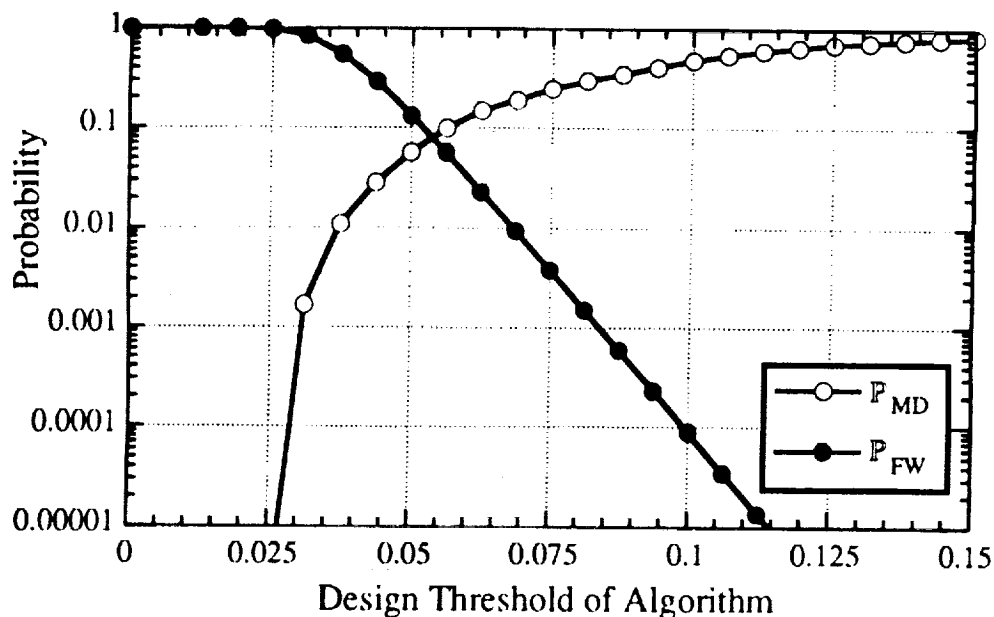$$Pr\{A\} = Pr\{A \mid WS\}Pr\{WS\} + Pr\{A \mid \neg WS\}[1 - Pr\{WS\}]$$

- Accuracy metrics

  Mean-Square Prediction Error

  Mean Advance Warning Time

Prediction Algorithm Refinement

- Probability of Correct, Missed Detection
  Monte Carlo analysis

- Design parameter optimization
  Mean-Square Hazard Prediction Error

- False Warning Probability

$$N(T_d) = \frac{\sigma_{\dot{y}}}{2\pi\sigma_y} e^{-\left(\frac{T_d{}^2}{2\sigma_y{}^2}\right)}$$

- Benchmark Statistics for Bayesian Network
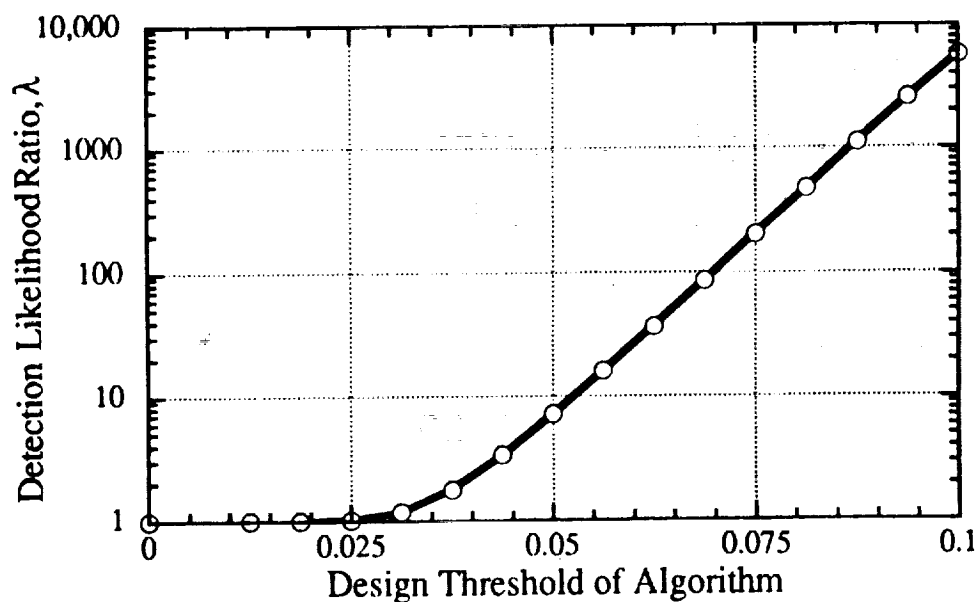
Selection of Design Threshold

- Fixed design threshold

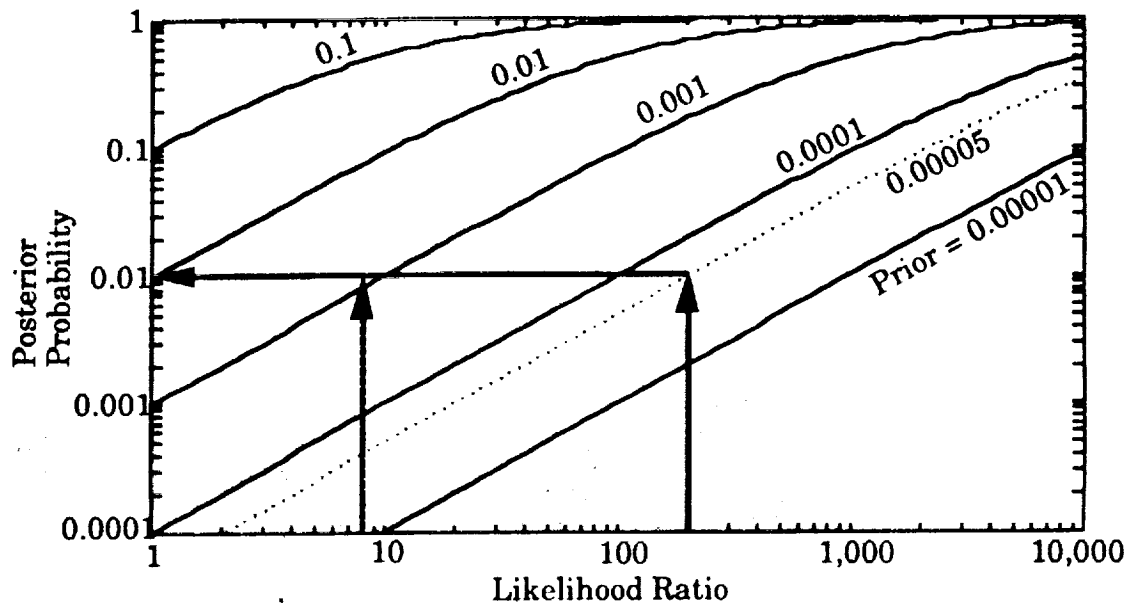 Tolerance for false warning rate

  Tolerance for wind shear encounter

$$\lambda = \frac{\mathbb{P}_{CW}}{\mathbb{P}_{FW}}$$

$$\lambda = \frac{Pr\{WS \mid A\}}{[1 - Pr\{WS \mid A\}]} \frac{[1 - Pr\{WS\}]}{Pr\{WS\}}$$

- Variable or multiple threshold

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Benefit of Integrated Warning

- CASE 1

    Prior Pr{H} = 1/20,000

    Likelihood ratio = 200 (0.075 radial F)

    Posterior = 1/100

- CASE 2

    Prior Pr{H | E} = 1/1000

    Likelihood ratio = 8 (0.05 radial F)

    Posterior = 1/100

Wind Shear Safety Advisor Determines "High" Risk

Princeton Wind Shear Safety Advisor	
Clear Define Scenario Presets Reset Parameters Run System Tutorial	
Guidance Information and User Interaction Window	**Rule Monitoring Window**

Guidance Information and User Interaction Window	Rule Monitoring Window
●●● **WINDSHEAR ADVISORY ALERT** ●● • RISK OF WIND SHEAR ENCOUNTER DURING • TAKEOFF AT DENVER IS HIGH, DUE TO: • DRY-SURFACE • VIRGA • TDWR, WS-ADVISORY • AVOIDANCE STRATEGY: DELAY OPERATIONS ●● Will the next flight phase be delayed?	so the hazard is now displayed PLANNING: A hazard is to be displayed to the flight crew, so the hazard is now displayed. PLANNING: An avoidance strategy is required for the next flight phase, so the recommended avoidance strategy is to delay YES NO

Sensor Information Window	**Status Information Window**
●●● **WEATHER ADVISORY INFORMATION** ●● • • A report has been received from data link. • • A TDWR WS-ADVISORY was reported near the • TAKEOFF path at DENVER • 0.2 minutes ago. • ●●	●● WEATHER ADVISORY INFORMATION ●● • • Awaiting takeoff from DENVER. • Takeoff scheduled to begin • in 0.7 MINUTES. • • Risk of Wind Shear Encounter is MEDIUM. • Risk of Heavy Precipitation is LOW. • ●●

Conclusions

- Diverse information aids hazard avoidance

- Explicit models easier to refine, validate
    - explicit conditions
    - statistical data, analysis

- Architecture for strategic decision-making
    - Mission planning, vehicle guidance
    - Failure detection, reconfiguration

- WSSA logic applications
    - Pilot training aid
    - Automated detection, recovery guidance

Reducing the Threat: Manual Recovery Strategies

- After liftoff/on approach technique
  - Aggressive application of thrust
  - Pitch toward 15° attitude
  - "Respect Stick Shaker"
  - Higher attitude, thrust if necessary

- On the runway
  - Aggressive application of thrust
  - Below V1, abort takeoff
  - Above Vr, rotate toward 15°
  - With less than 2000 ft runway, rotate toward 15° (possible tail scrape)

- Pilot Report

L C A
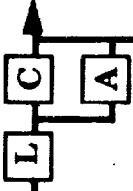
Target Pitch Angle for the Microburst Escape Maneuver
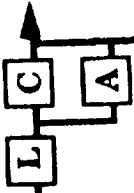
Sandeep S. Mulgund and Robert F. Stengel

Overview

- The Wind Shear Problem

- Previous research

- Effect of wind shear on airplane performance

- Recovery strategies for inadvertent encounters with wind shear

- Present Research

    Recovery technique for commuter-class aircraft

    Trajectory Optimization

- Conclusions

# Recovery Technique for Inadvertent Encounter

FAA Wind Shear Training Aid

- Apply maximum thrust and rotate aircraft toward initial pitch target of 15˚, while respecting "stick shaker"

- Maintain aircraft configuration

Why Constant Pitch?

- Attitude indicator is one of few major aircraft instruments not affected by microburst environment

- Easily recalled in emergency

Why 15˚ as the target?

- Easily recalled in emergency

- 15˚ mark on attitude indicator can be targeted even in heavy turbulence

- Provides good recovery performance for *jet transports* in a wide spectrum of shear encounters

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927

L C A
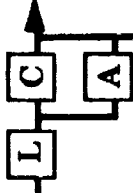
Application to Commuter/General Aviation Aircraft

Issues
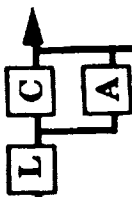
- Lower takeoff and approach speeds than jet transports
- Lower wing loading
- Lower specific excess power

Objective

- Apply FAA recovery strategy to this class of aircraft
- Methodology for identification of Target Pitch Angle (TPA)

Commuter Aircraft Model

- Simulation model representative of light twin prop - 6300 lb g.w.
- Point Mass dynamics

Princeton University

Maximum Climb Capability in Wind Shear

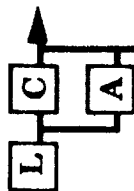- Rate of Climb:

$$\dot{h} = V\sin\gamma + w_h$$

- Maximize steady-state rate of climb under an imposed F-Factor

$$F = \frac{\dot{w}_x}{g} - \frac{w_h}{V}$$

$$\text{(a)}\ F = \frac{\dot{w}_x}{g}$$

$$\text{(b)}\ F = -\frac{w_h}{V}$$

- Aircraft in initial approach configuration: 45° flaps, gear retracted

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929

Laboratory for Control and Automation

Effect of Wind Shear on Maximum Rate of Climb

Downdraft

Horizontal Shear

Rate of Climb (ft/min)

2000

1500

1000

500

0

-500

0   0.05   0.1   0.15   0.2   0.25
F-Factor

Horizontal Shear

Downdraft

Airspeed (knots)

75

70

65

60

55

0   0.05   0.1   0.15   0.2   0.25
F-Factor

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930
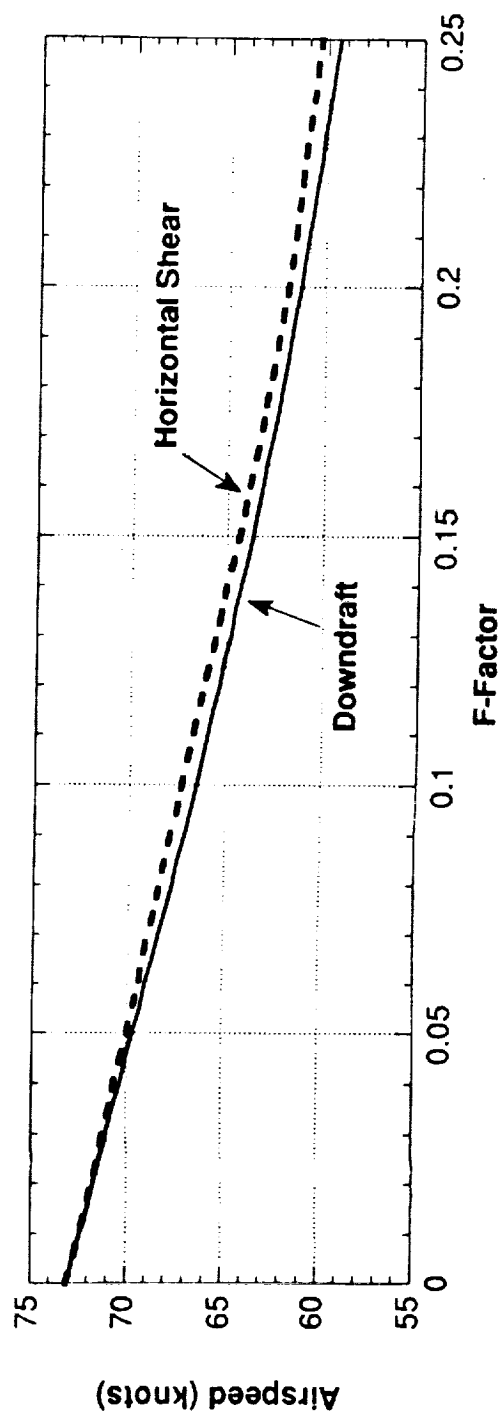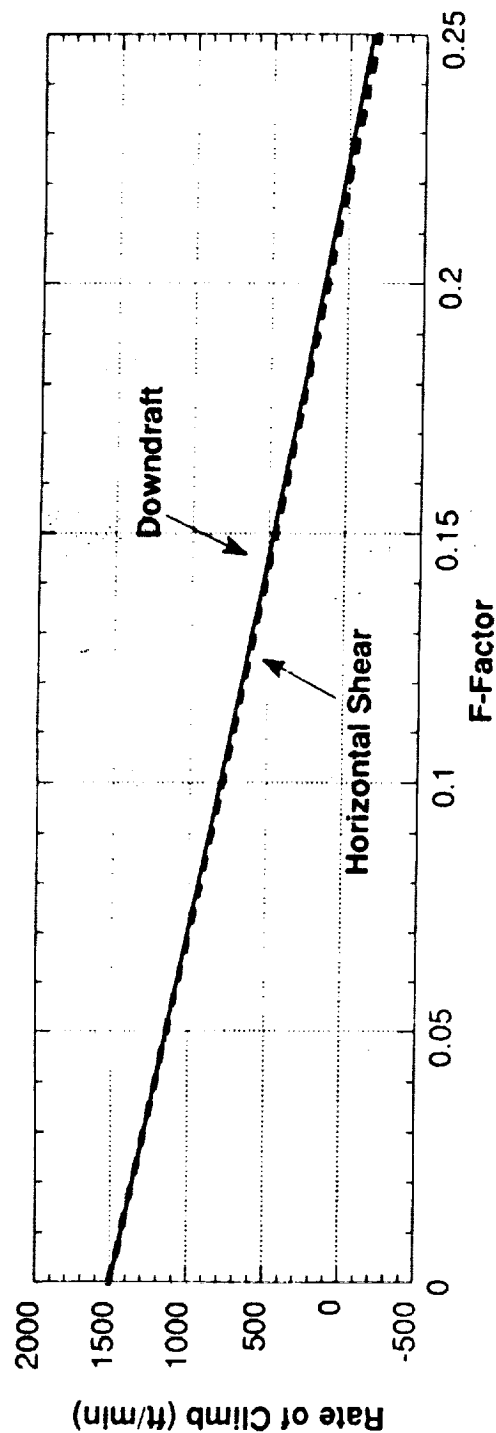
Angle of Attack and Pitch Attitude for Best Climb in Wind Shear

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Princeton University
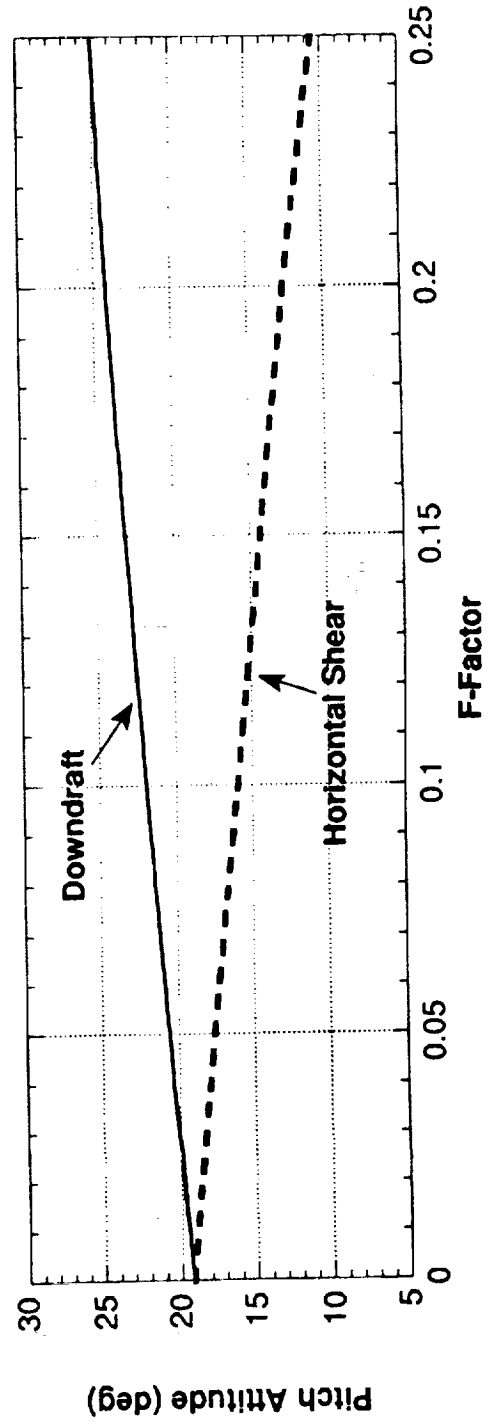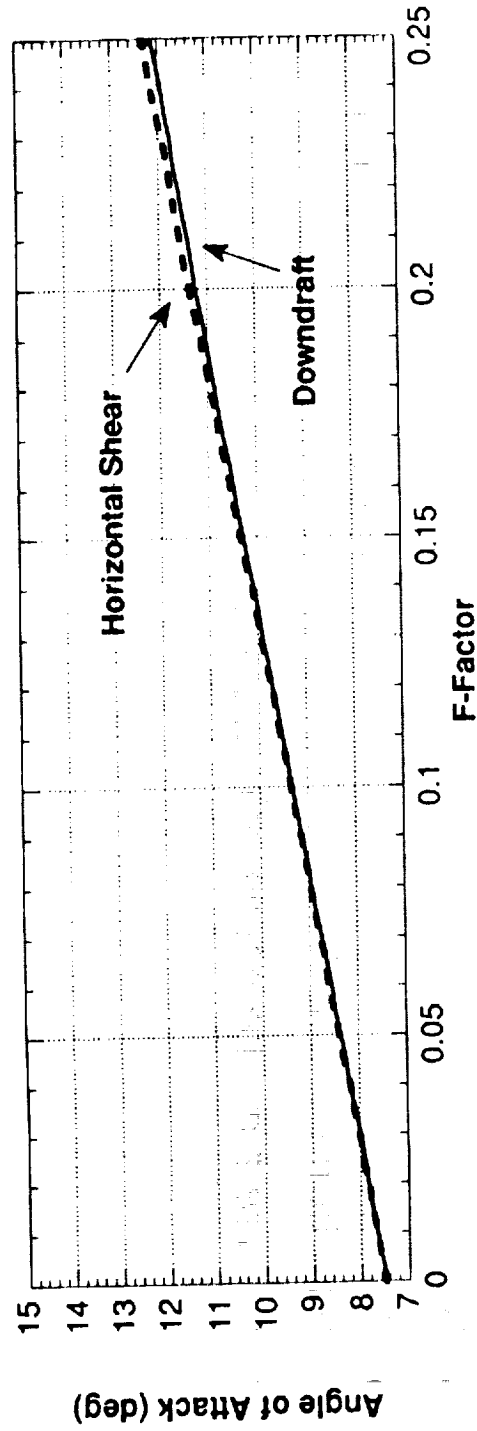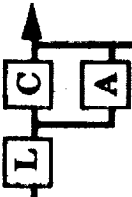
Implications

- Pitch attitude for climb rate depends on source of threat

- Actual environment contains regions of both downdraft and horizontal shear

- Single target pitch angle is a compromise

- Nature of trade-off may be ascertained through simulation of microburst encounters

- Require a mathematical microburst model

Princeton University

Simulation of Encounter During Final Approach

Initiate Recovery
if F exceeds 0.1

x_o

h_o
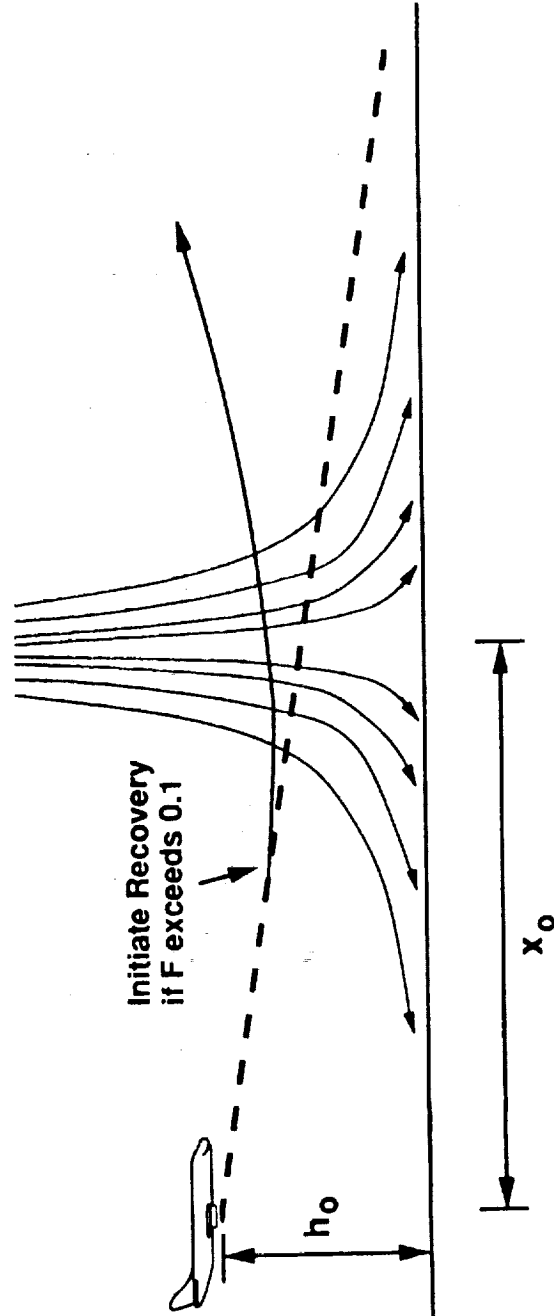
- Microburst core placed directly along flight path
- Aircraft tracks glide slope prior to shear entry

Laboratory for Control and Automation
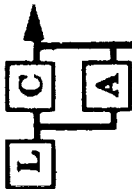
Effect of Initial Altitude on Minimum Recovery Altitude

V_o = 95 knots
δF = 45°

Shear Parameters:

R = 3000 ft
U_{max} = 80 ft/s
Z_{max} = 150 ft

Initial Distance
from Core: 10,000 ft

h_o = 1400 ft

1200 ft

1000 ft

800 ft

600 ft

Minimum Recovery Altitude (ft)

450 400 350 300 250 200 150 100 50

6 8 10 12 14 16 18 20

Target Pitch Angle (degrees)

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934
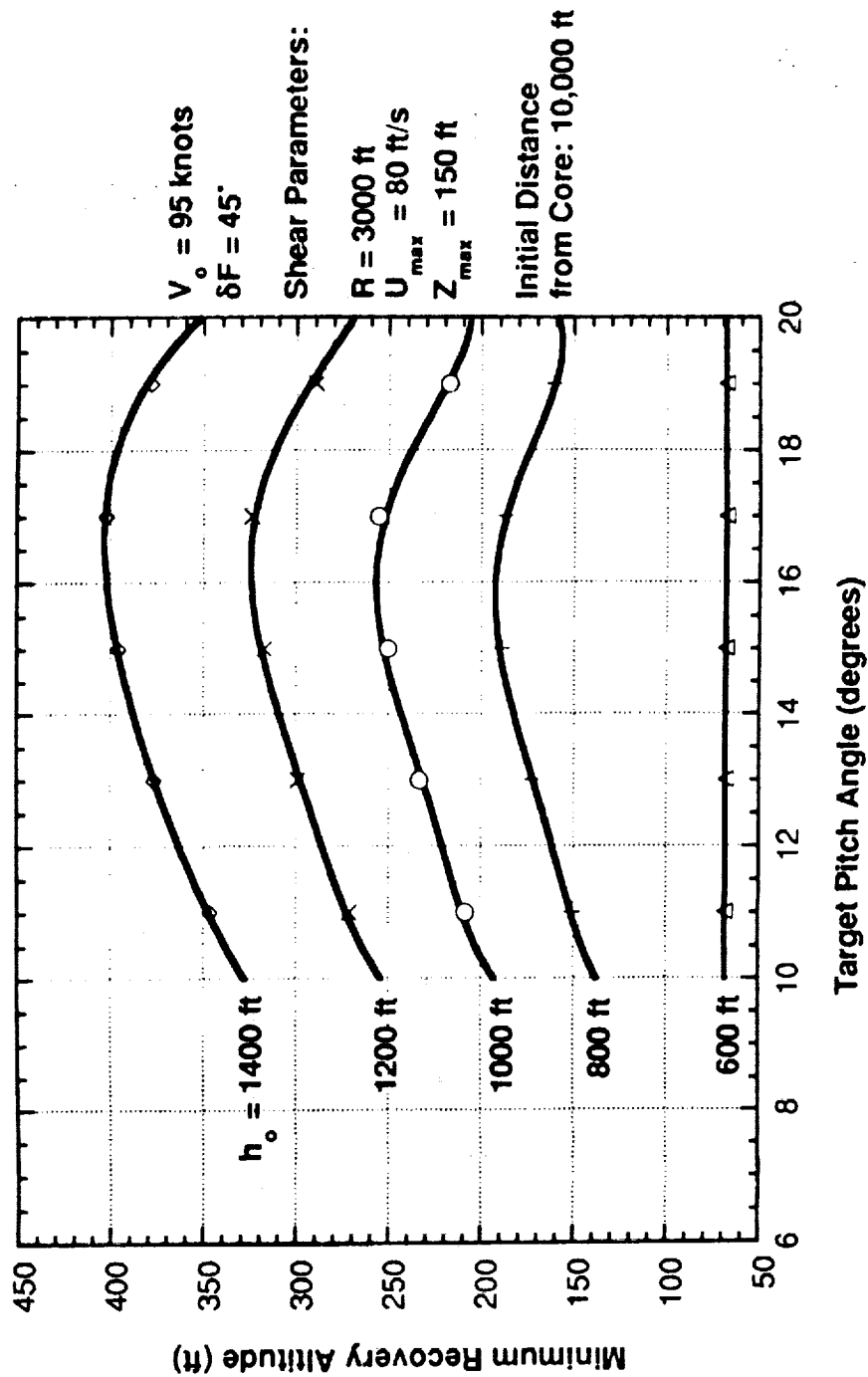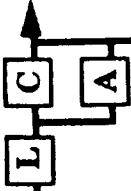
Effect of Shear Strength on Minimum Recovery Altitude
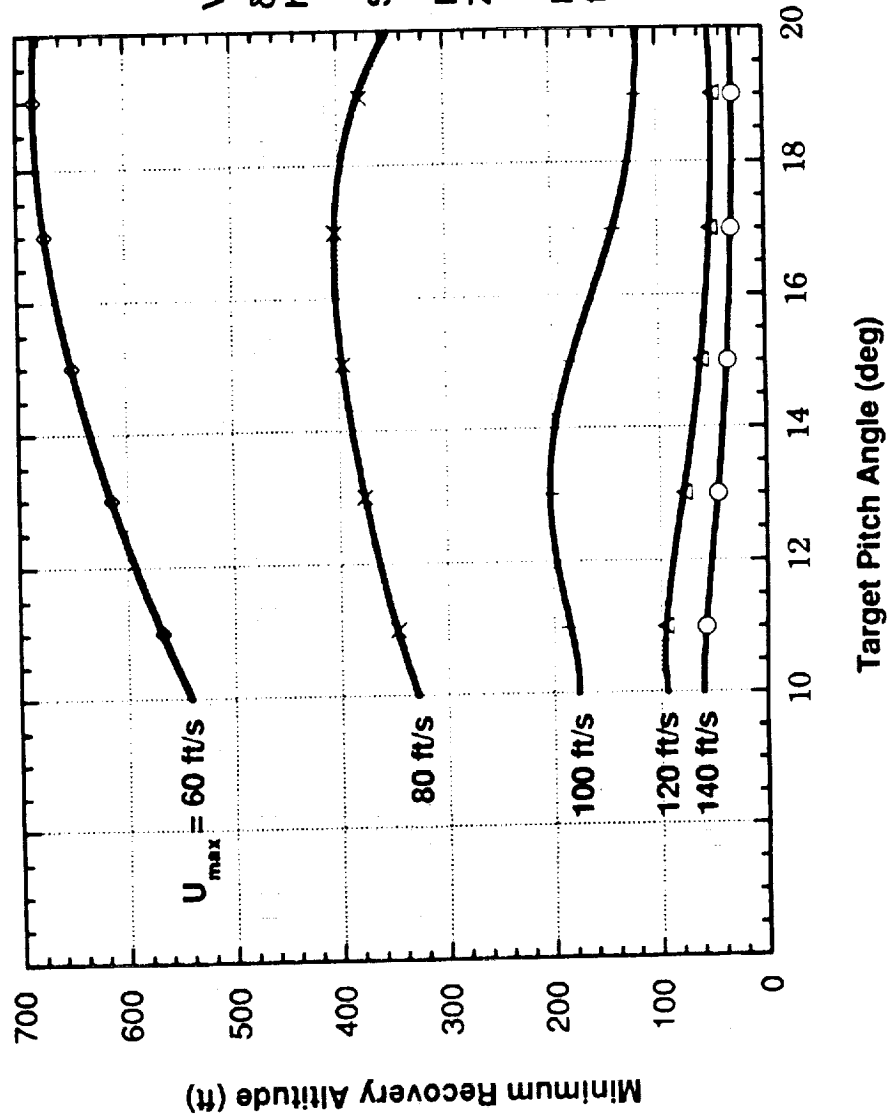
V_o = 95 knots
δF = 45°
h_o = 1400 ft

Shear Parameters:

R = 3000 ft
Z_{max} = 150 ft

Initial Distance
from Core: 10,000 ft

U_{max} = 60 ft/s

80 ft/s

100 ft/s

120 ft/s
140 ft/s

Minimum Recovery Altitude (ft)

700
600
500
400
300
200
100
0

Target Pitch Angle (deg)

10   12   14   16   18   20
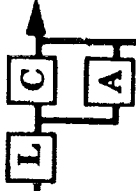
Trajectory Optimization in Wind Shear

- Find **x**(*t*), **u**(*t*) to minimize

$$J = \phi[\mathbf{x}(t_f), t_f] + \int_{t_o}^{t_f} L[\mathbf{x}(t), \mathbf{u}(t), t] dt$$

- What is optimal?

- Successful recovery ⇒ Avoiding ground impact

- Maximize minimum altitude ⇒ Minimize maximum deviation from a high reference altitude: [Miele]

$$I = \max_{t}(h_{ref} - h(t)) \qquad t_o \leq t \leq t_f$$

- Equivalent Lagrangian problem:

$$J = \int_{t_o}^{t_f}(h_{ref} - h(t))^q dt \qquad q >> 2 \text{ and even}$$
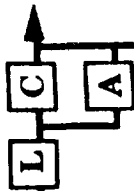
Altitude and Angle of Attack vs. Time for TPA and Optimal Recovery
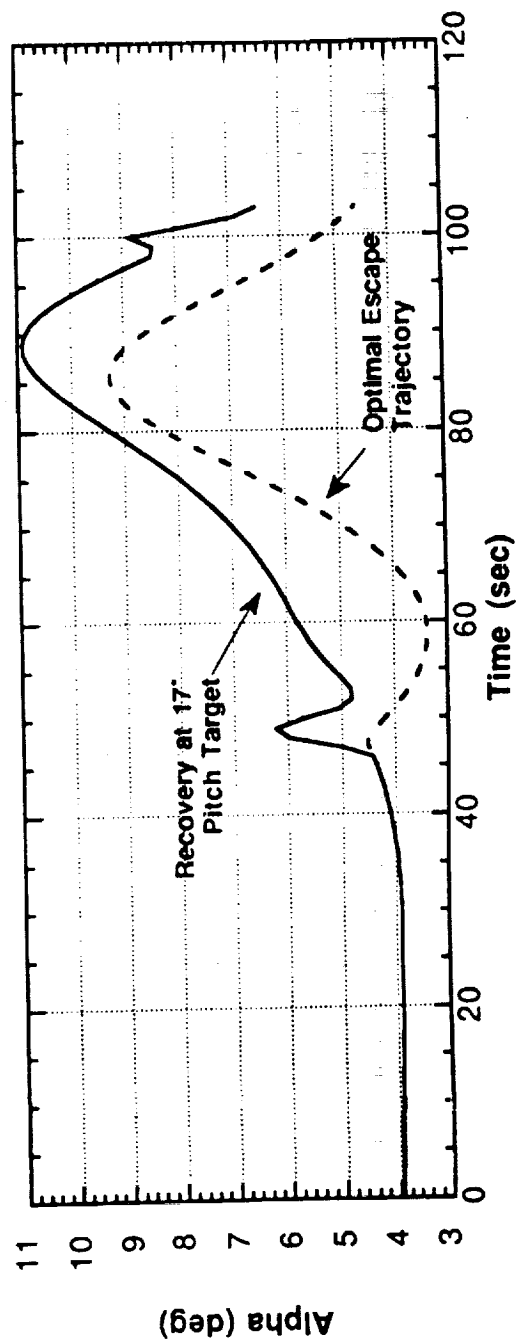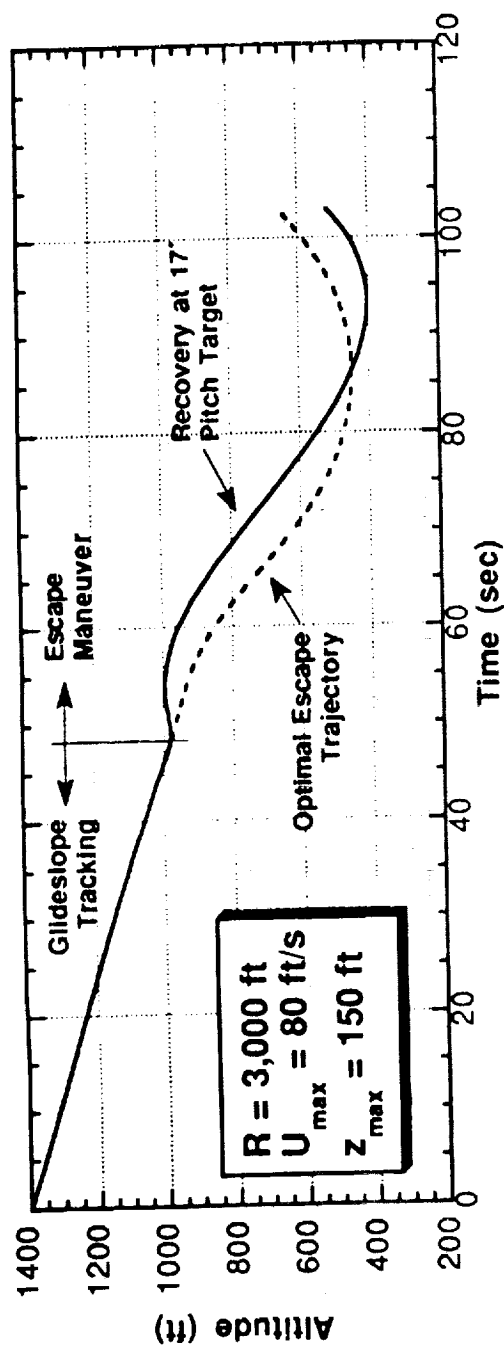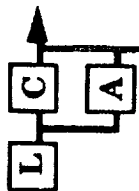
Pitch Attitude and Airspeed vs. Time for TPA and Optimal Recovery
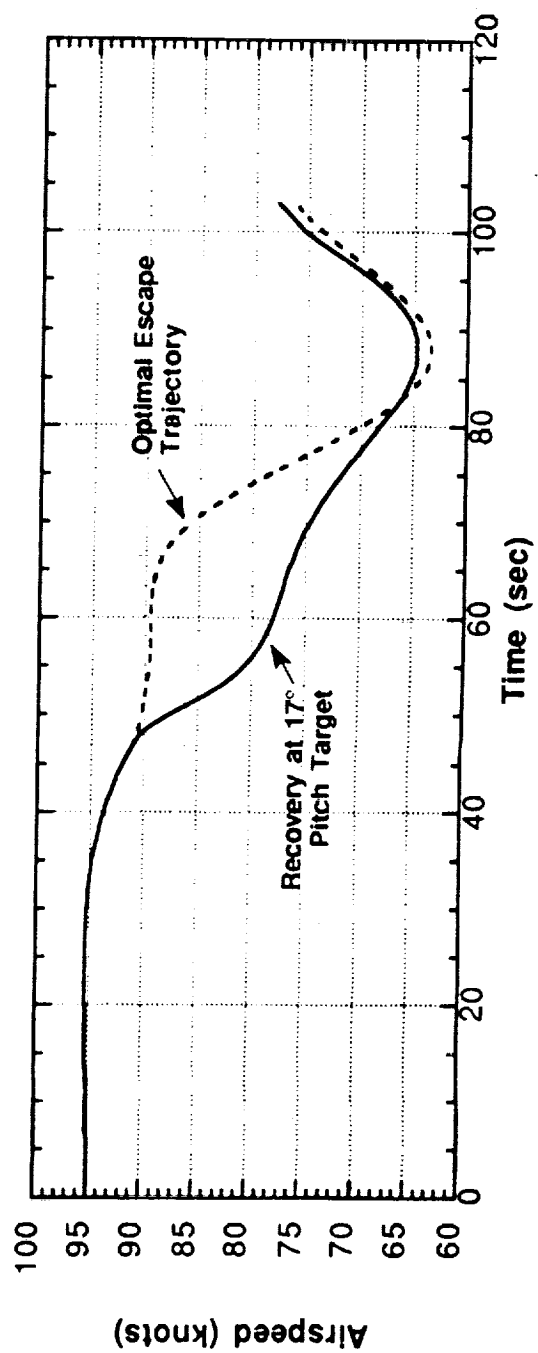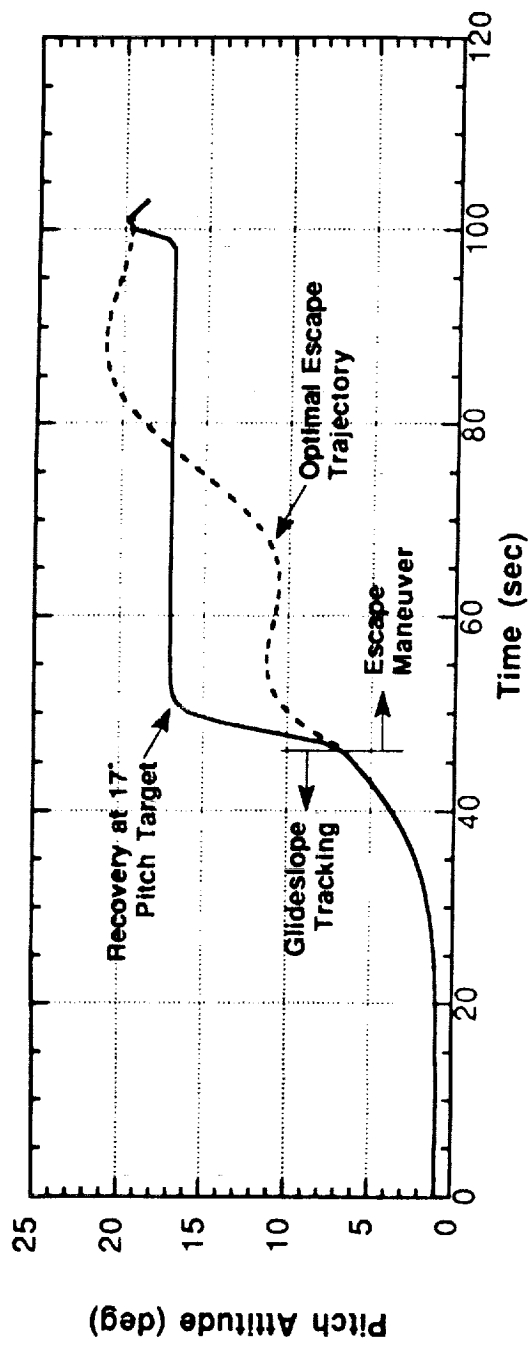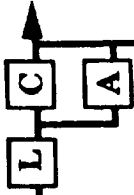
Comparison of Trajectories

- Performance

	TPA Recovery	Optimal Recovery
Min. Altitude (ft)	403	455
Min. E_s (ft)	596	630
Min. Airspeed (kts)	65	63
Max. Alpha (deg)	11.0	9.3

- Qualitative features

  Optimal trajectory involves initial reduction in pitch attitude

  Positive climb rate established earlier in optimal recovery
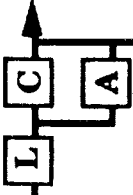
Conclusions

- Aircraft attitude for best climb rate depends on source of threat

- TPA simulation results - no single attitude stands out

- Optimal trajectory analysis - TPA not optimal, but reasonable
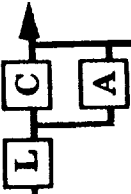
Computation of Optimal Trajectories

- Aircraft subject to two constraints:

$$-20° \leq \delta_E \leq 20°$$

$$V \geq 125 \text{ knots}$$

- Airspeed constraint imposed using a penalty function:

$$L(\boldsymbol{x}, \boldsymbol{u}) = L(\boldsymbol{x}, \boldsymbol{u}) + L_V(V)$$

where

$$L_V(V) = \begin{cases} 0 & V > V_{min} \\ K_V[V - V_{min}]^2 & V \leq V_{min} \end{cases}$$

- Contribution of L_V to cost grows quadratically with magnitude of constraint violation

Altitude vs. Time for Optimal Paths through 4 Different Downbursts

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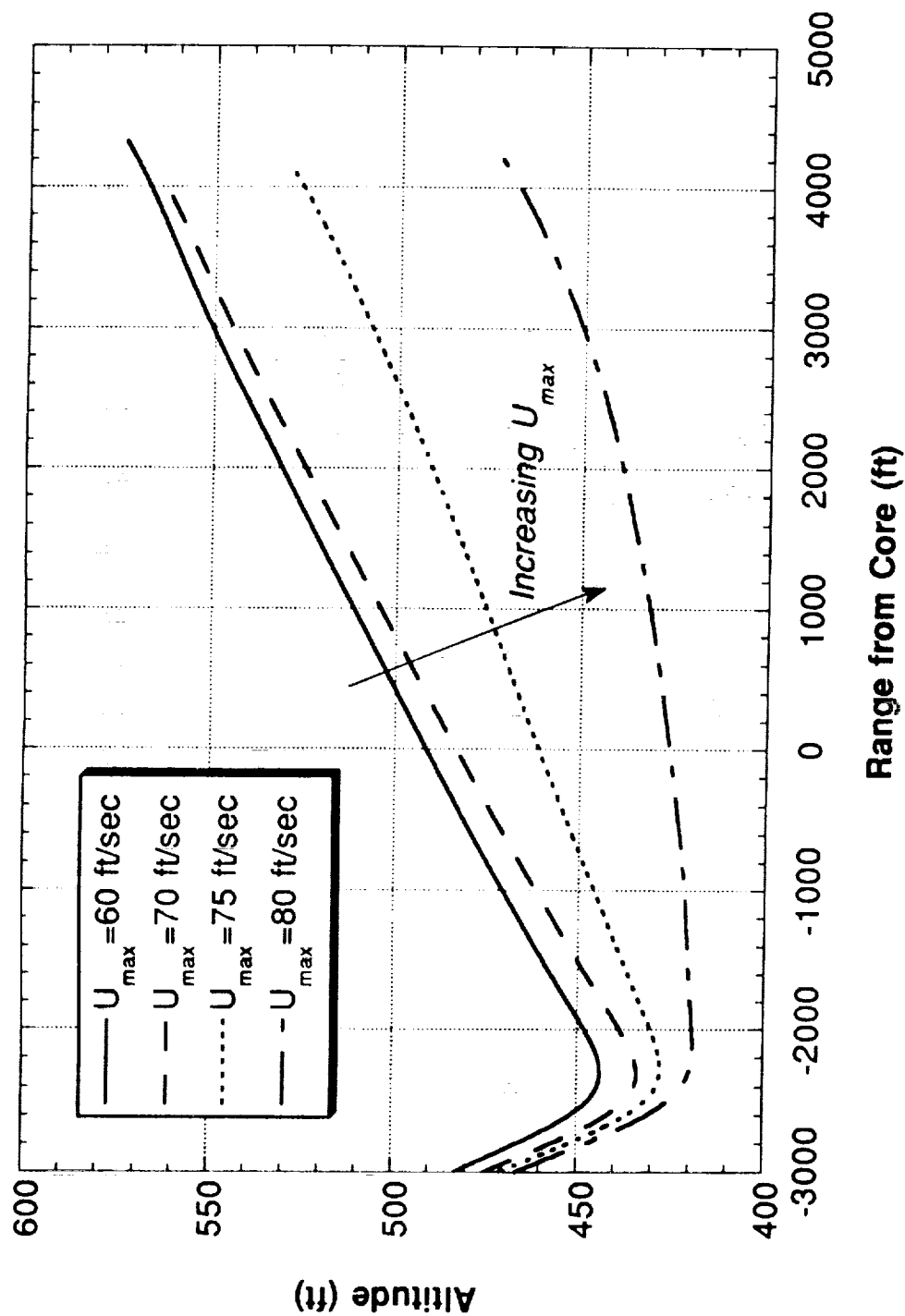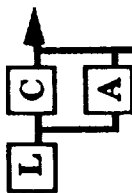
Rate of Climb vs. Time for Optimal Paths through 4 different Downbursts
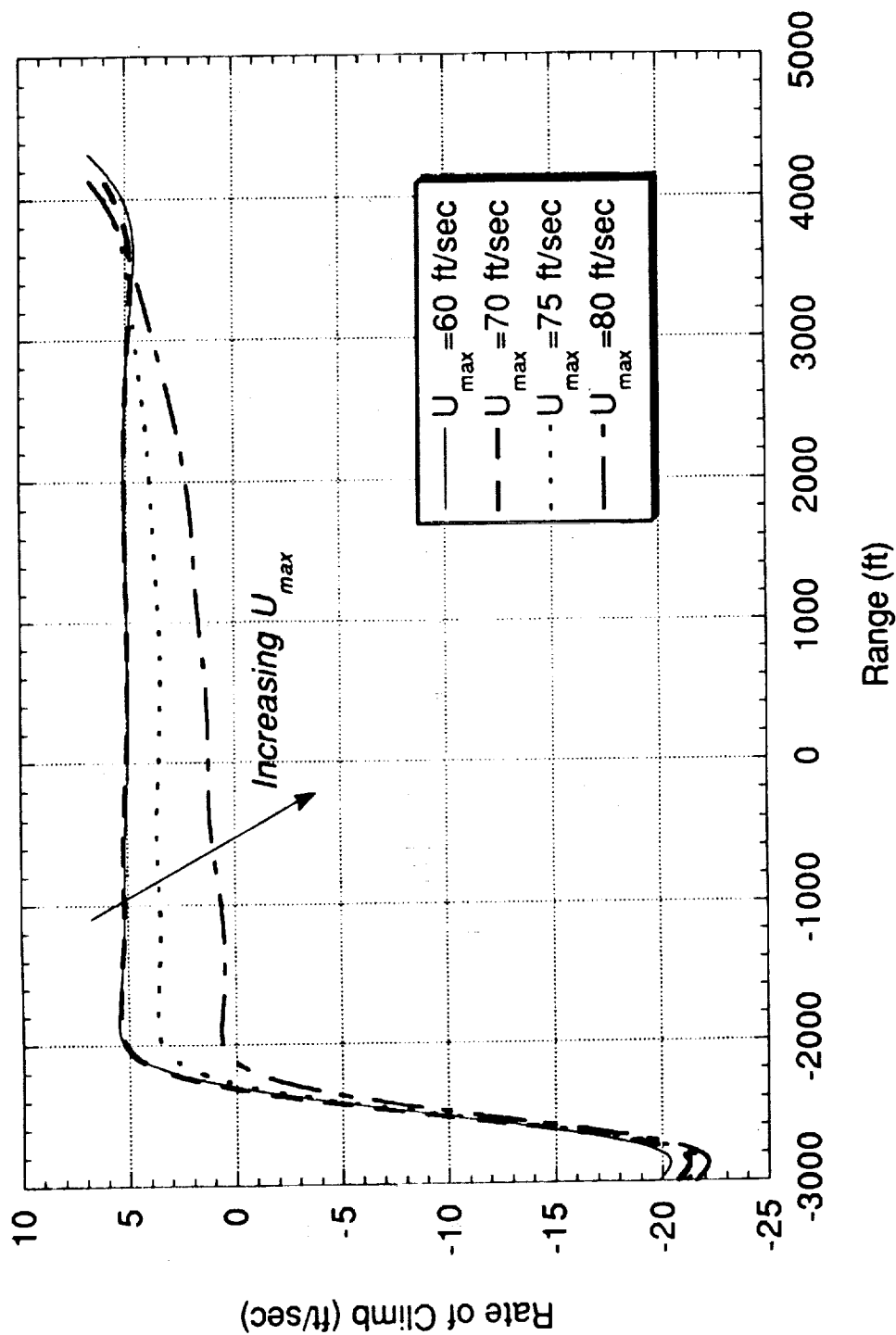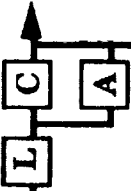
Airspeed vs. Time for Optimal Paths through 4 different Downbursts

Legend:
- $U_{max} = 60$ ft/sec
- $U_{max} = 70$ ft/sec
- $U_{max} = 75$ ft/sec
- $U_{max} = 80$ ft/sec

Increasing U_{max}

Penalty Function Threshold

Airspeed (ft/sec)

Range (ft)

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Princeton University

944
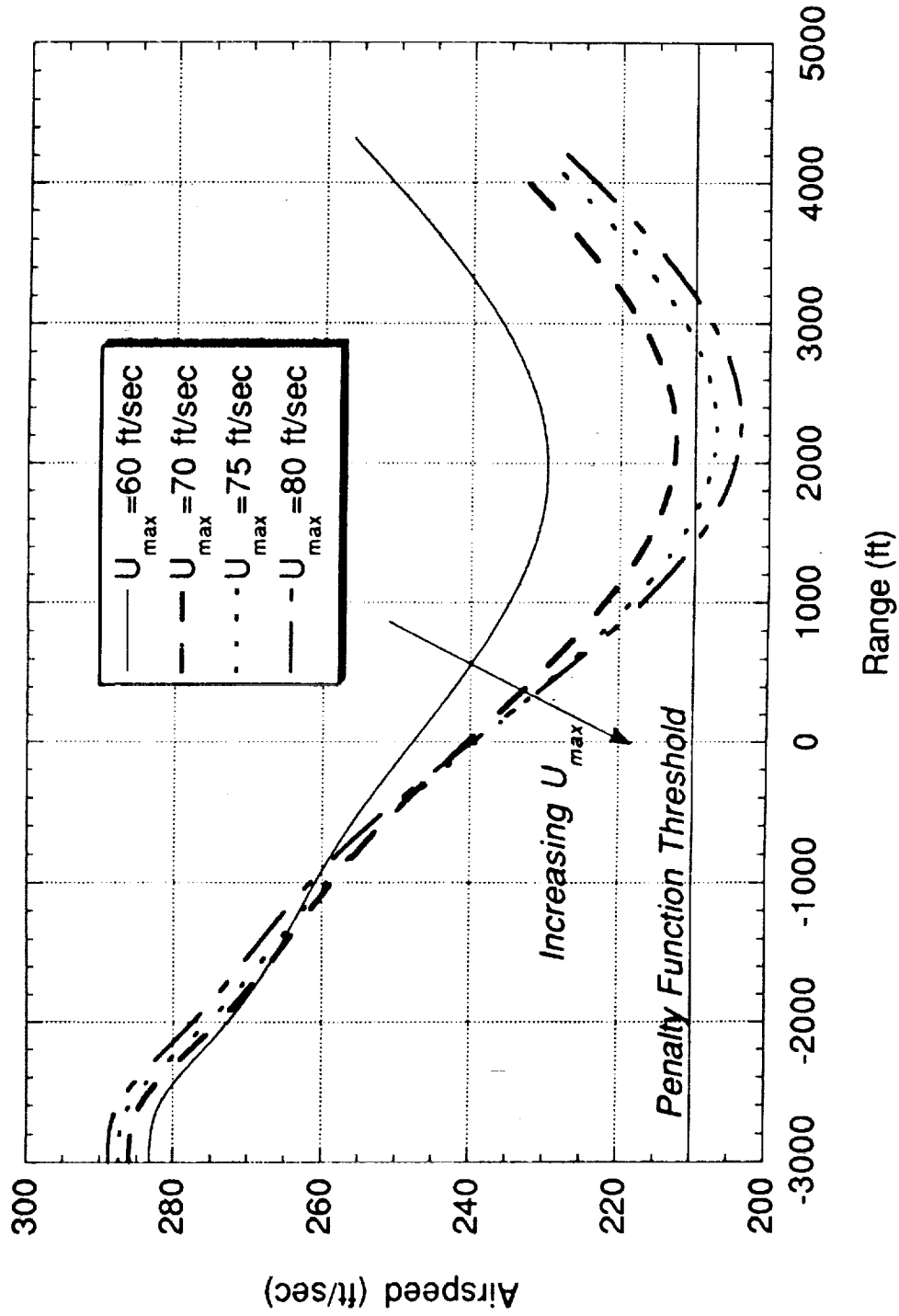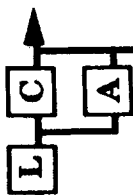
Qualitative Features of the Optimal Flight Paths

- Rapid transition from descending to level or ascending flight

- Targeted rate of climb during escape depends on wind shear severity

  Weak to moderate $\Rightarrow$ Aircraft reaches 5 ft/sec climb rate

  Severe to very severe $\Rightarrow$ Aircraft reaches a lower climb rate

- Lower climb rate in severe microbursts results in reduced violation of minimum airspeed constraint

OK, but...

- Global knowledge of flowfield required for optimization

- Results not immediately applicable to real-time feedback control

945

Future Work:
Neural Networks for Real-Time Flight Guidance

- Train neural network with results of trajectory optimization

- Can parametrize microbursts according to size and severity

- Network generates flight path angle commands according to position within flow field

- Availability of forward-look information could assist in flight-path planning

Princeton University
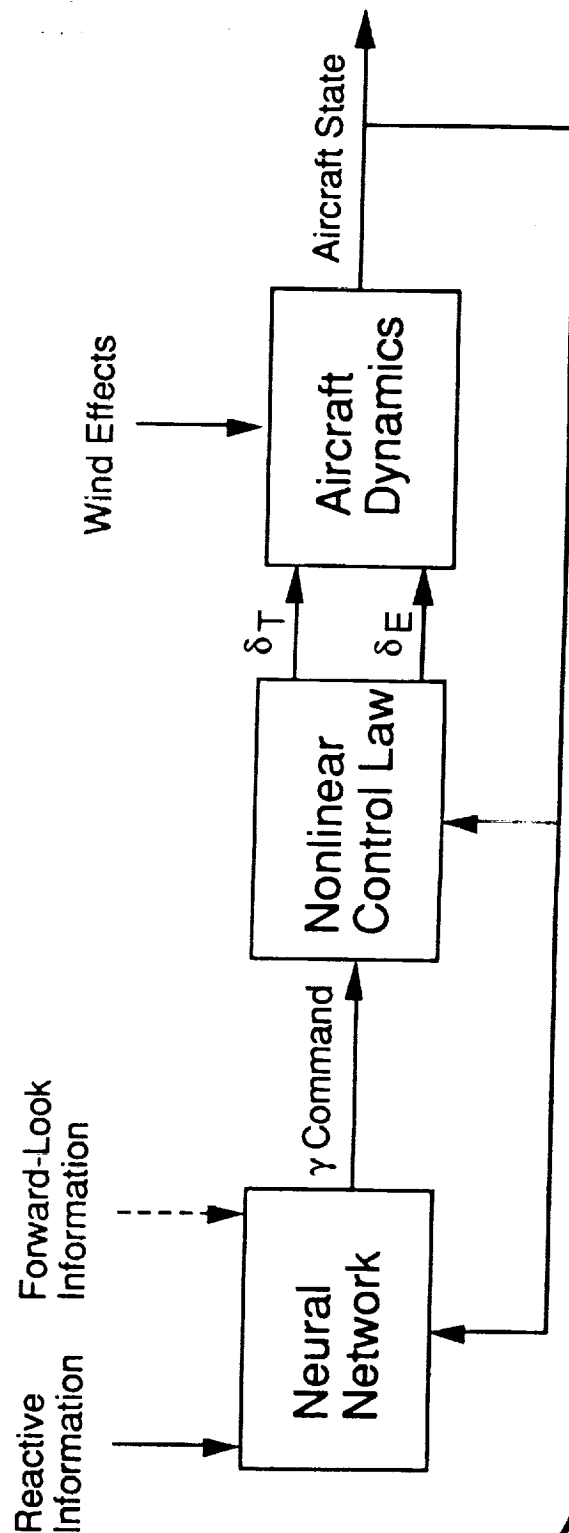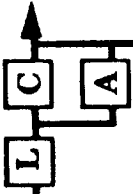
Neural Networks for Aircraft Control

Benefits and Limitations of Trajectory Optimization

- Provides insight into the nature of control action required to most effectively achieve a specified goal

- Require global knowledge of microburst

- Optimal performance can only be approximated in real-time

Enter Neural Networks!

- Objective: Teach a neural network to fly an airplane through windshear using the results of trajectory optimization as training data

- Families of optimal trajectories through a broad spectrum of microbursts must be developed

- Robust optimization technique needed - cost functions weights themselves need to be optimized

Laboratory for Control and Automation
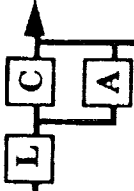
DYNAMIC BEHAVIOUR OF AN AIRCRAFT ENCOUNTERING A SINGLE AXIS VORTEX

Darin R. Spilman

Princeton University

FLIGHT PATH

intended flight path

roll, yaw right

pitch attitude
near vertical

xr

yr

z

Xr

Yr

WIND ROTOR FORMATION

MOUNTAIN

Laboratory for Control and Automation

Princeton University

L C A

WIND ROTOR MODEL

Vt : tangential velocity
Vc : core velocity
rc : core radius

ideal vortex

linear approximation

measured 747 vortex

Vt/Vc

2.0

1.0

0.5

-0.5

-1.0

-2.0

r/rc

-8.0 -6.0 -2.0 2.0 4.0 6.0 8.0

$0 < r/rc < 1$:	$Vt/Vc = r/rc$
$1 < r/rc < 3$:	$Vt/Vc = 1.15 - .15(r/rc)$
$3 < r/rc < 7$:	$Vt/Vc = .88 - .06(r/rc)$

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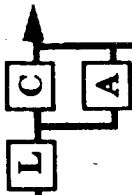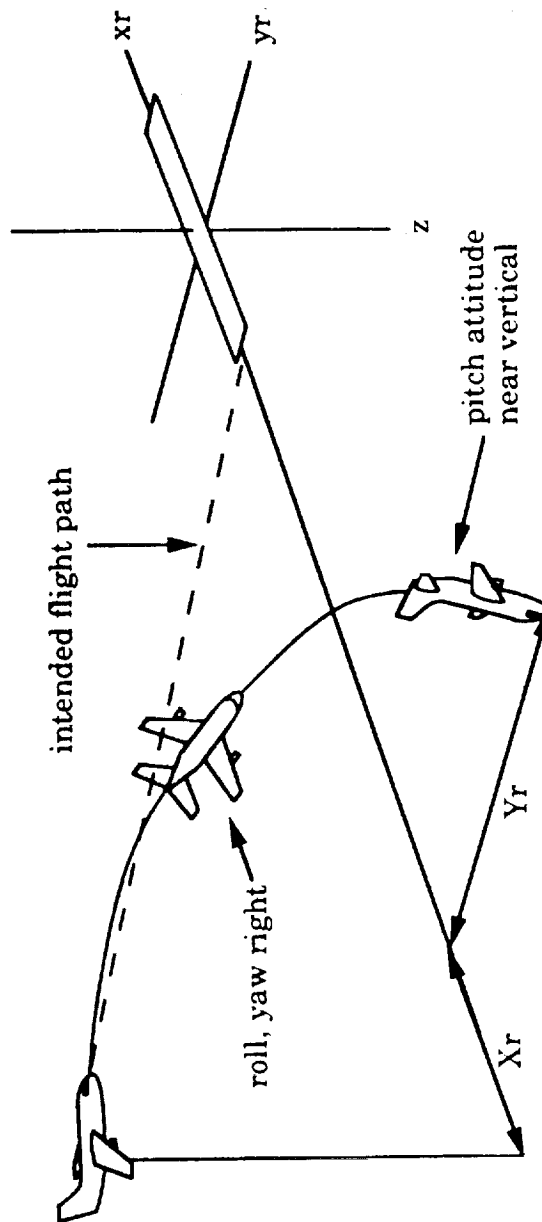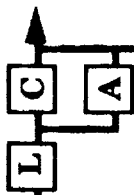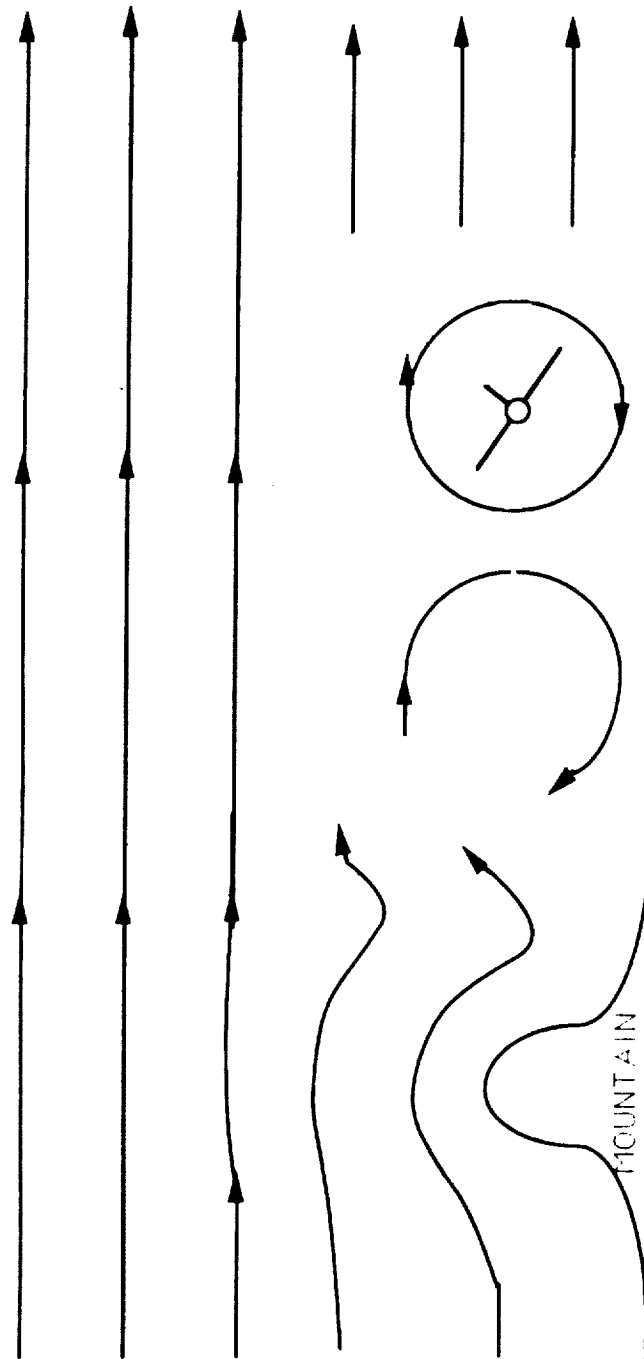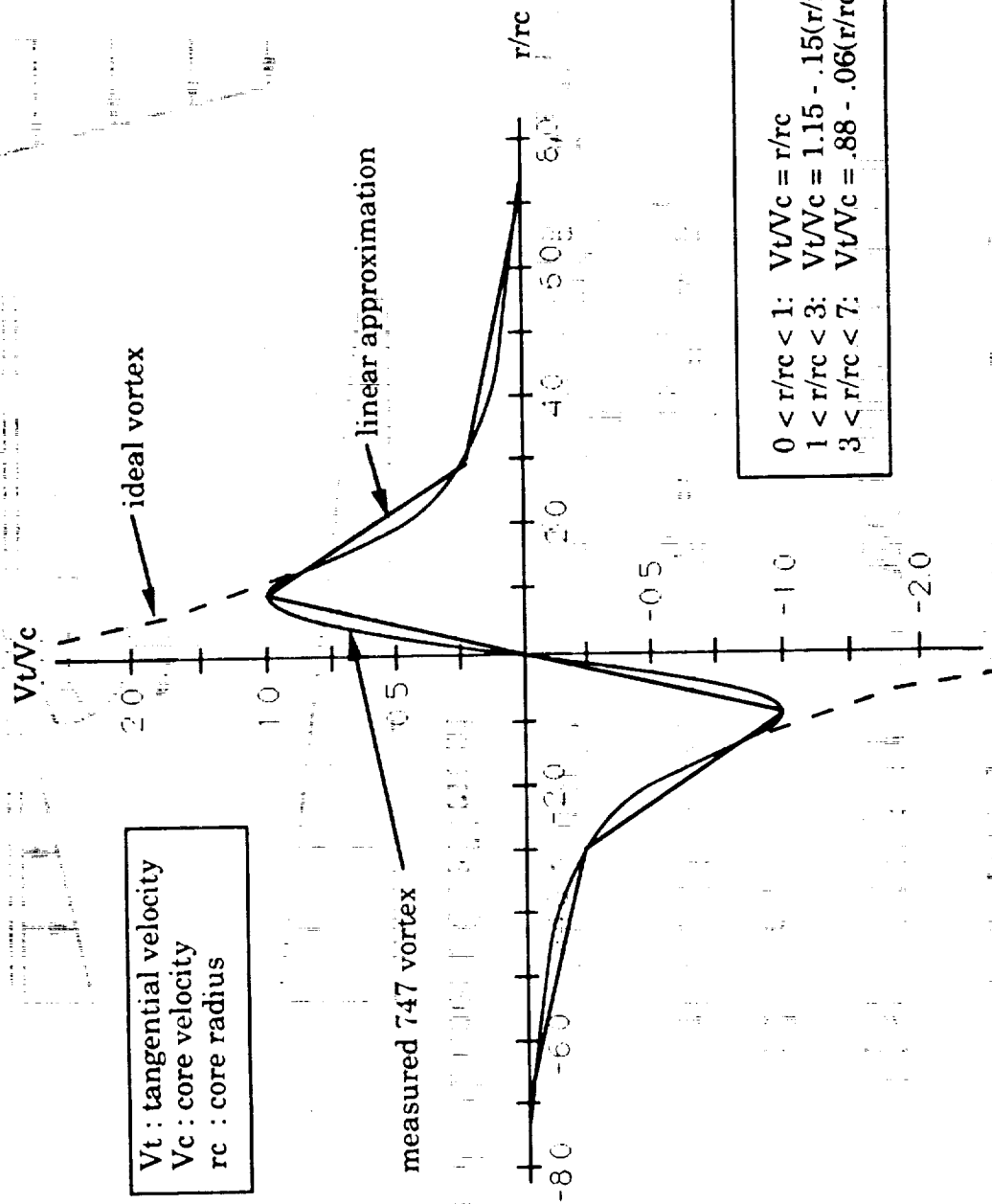
WIND EFFECTS ON AIRCRAFT

1. Equations of Motion

   Translational kinematics $\qquad \dot{\vec{r}}_E = L_{EB}\,\vec{v}_B + \vec{w}_E$

   Translational dynamics $\qquad \dot{\vec{v}}_E = \dfrac{F_B}{m} - H_I^B g - \tilde{w}_B\,v_B - \dot{\tilde{w}}_B$

2. Force & Moment Coefficients

w_Y

p

v_Z
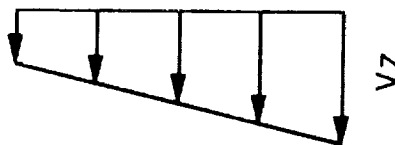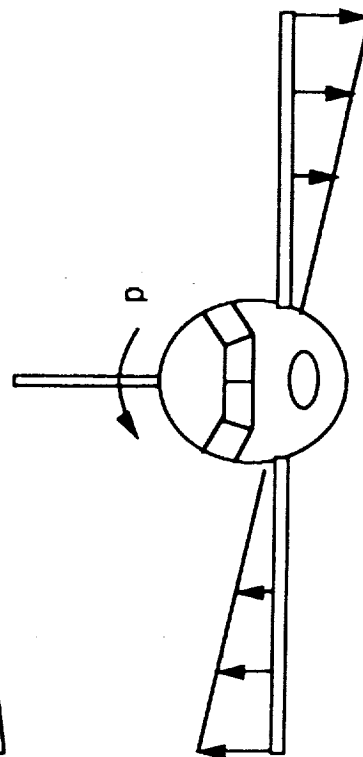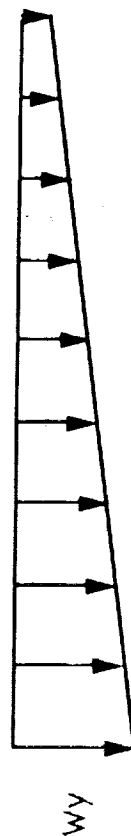
$(C_{RL})_{ROLL} = (C_{RLp})p - (C_{RLp_{wing}} + C_{RLp_{htail}})w_Y + (C_{RLp_{vtail}})v_Z$
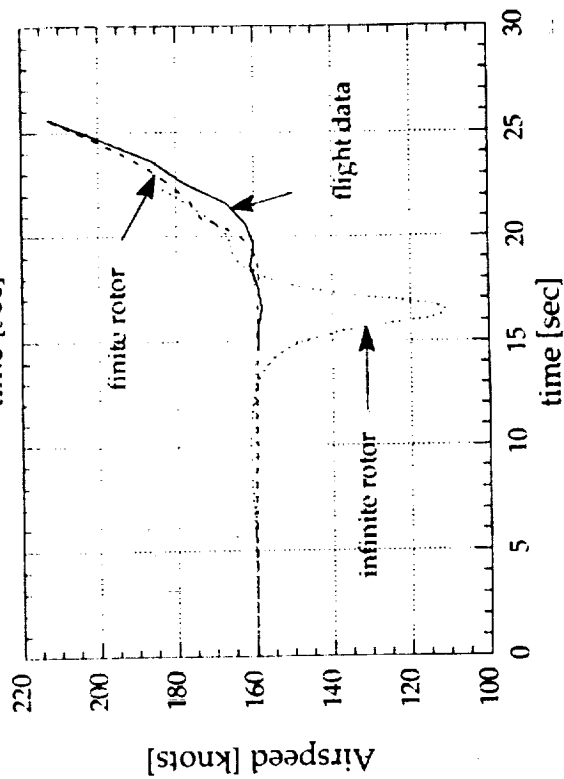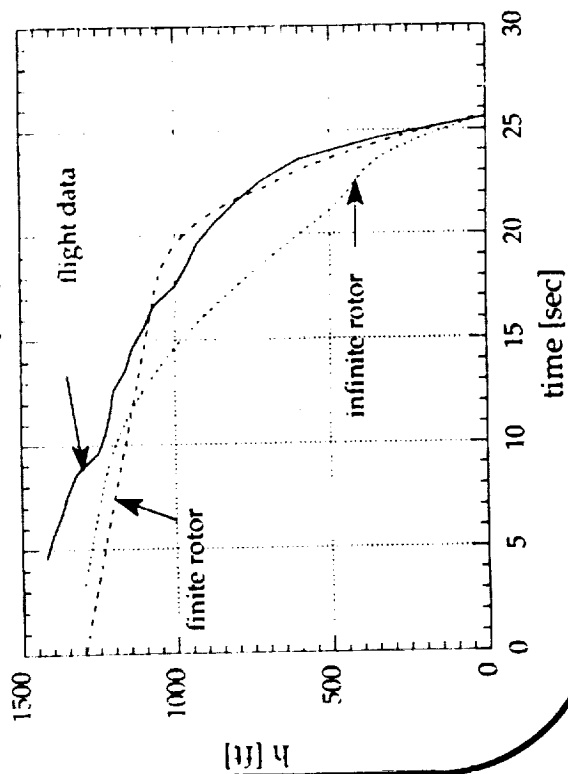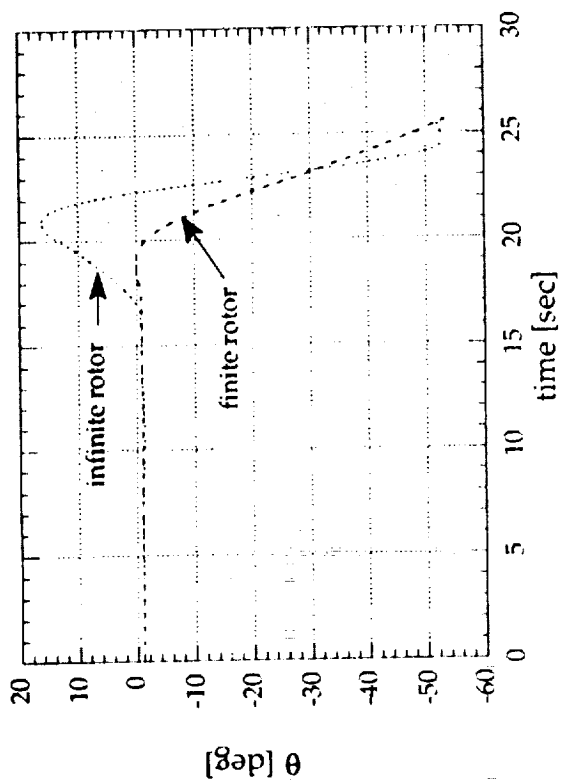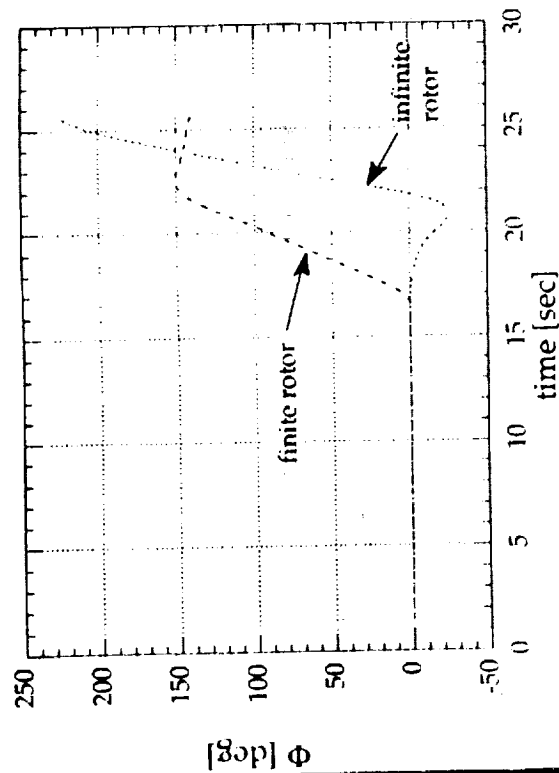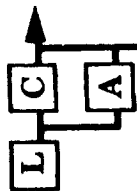
CONCLUSIONS?

TBD

Wind Shear Related Research at Princeton University
Questions and Answers

Unknown - I would like to comment that Rob's work is independent of the accident investigation on the Colorado Springs accident which is still far from complete. We appreciate the efforts that they are doing, but you should not leave here with any conclusions based on it.

Rob Stengel (Princeton University) - No certainly and we have not made any conclusions either.

Session XI. Regulation, Certification and System Standards

958

Session XI. Regulation, Certification and System Standards

Systems Issues in Airborne Doppler Radar/LIDAR Certification

Dr. James Evans, MIT Lincoln Laboratory

SYSTEMS ISSUES IN AIRBORNE DOPPLER RADAR/LIDAR CERTIFICATION

JAMES E. EVANS

MIT LINCOLN LABORATORY

APRIL 16, 1992
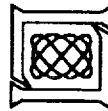
OUTLINE

- **THESIS**

- **GROUND CLUTTER CHALLENGE**

  - ANTENNA POINTING / MICROBURST OUTLFOW HEIGHTS
  - CLUTTER FILTERING / TRANSMITTER STABILITY
  - RANGE SIDELOBES

- **MOVING SCATTERERS (BIRDS, BUGS)**

- **RANGE AMBIGUITIES**

  - WEATHER CLUTTER
  - GROUND CLUTTER

- **RAIN ATTENUATION**

- **SUMMARY**

961

THESIS

- DESIGN OF COST/EFFECTIVE DOPPLER RADAR/LIDAR SENSOR REQUIRES TRADEOFFS BETWEEN:

    - ENVIRONMENTAL RESILIENCE

    - HARDWARE COST/COMPLEXITY

- ASSUMPTIONS ABOUT ENVIRONMENT ARE UNCLEAR AND, MAY DIFFER AMONGST SYSTEMS

- EXPERIMENTAL TESTING SHOULD BE CONSISTENT WITH VERIFYING ENVIRONMENTAL RESILIENCE

- DETAILED SYSTEM ANALYSIS SHOULD BE A PART OF CERTIFICATION PACKAGE

GROUND CLUTTER CHALLENGE

RANGE SIDELOBES

CLUTTER LEVEL

ANTENNA
BEAMWIDTH
SIDELOBES

ANTENNA TILT

WEATHER LEVELS,
SPATIAL DISTRIBUTION

INPUT
SIGNAL TO → FILTER
CLUTTER LEVEL

TRANSMITTER
STABILITY

FILTER
CHARACTERISTICS

EFFECTIVE
SIGNAL TO
CLUTTER
LEVEL
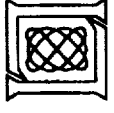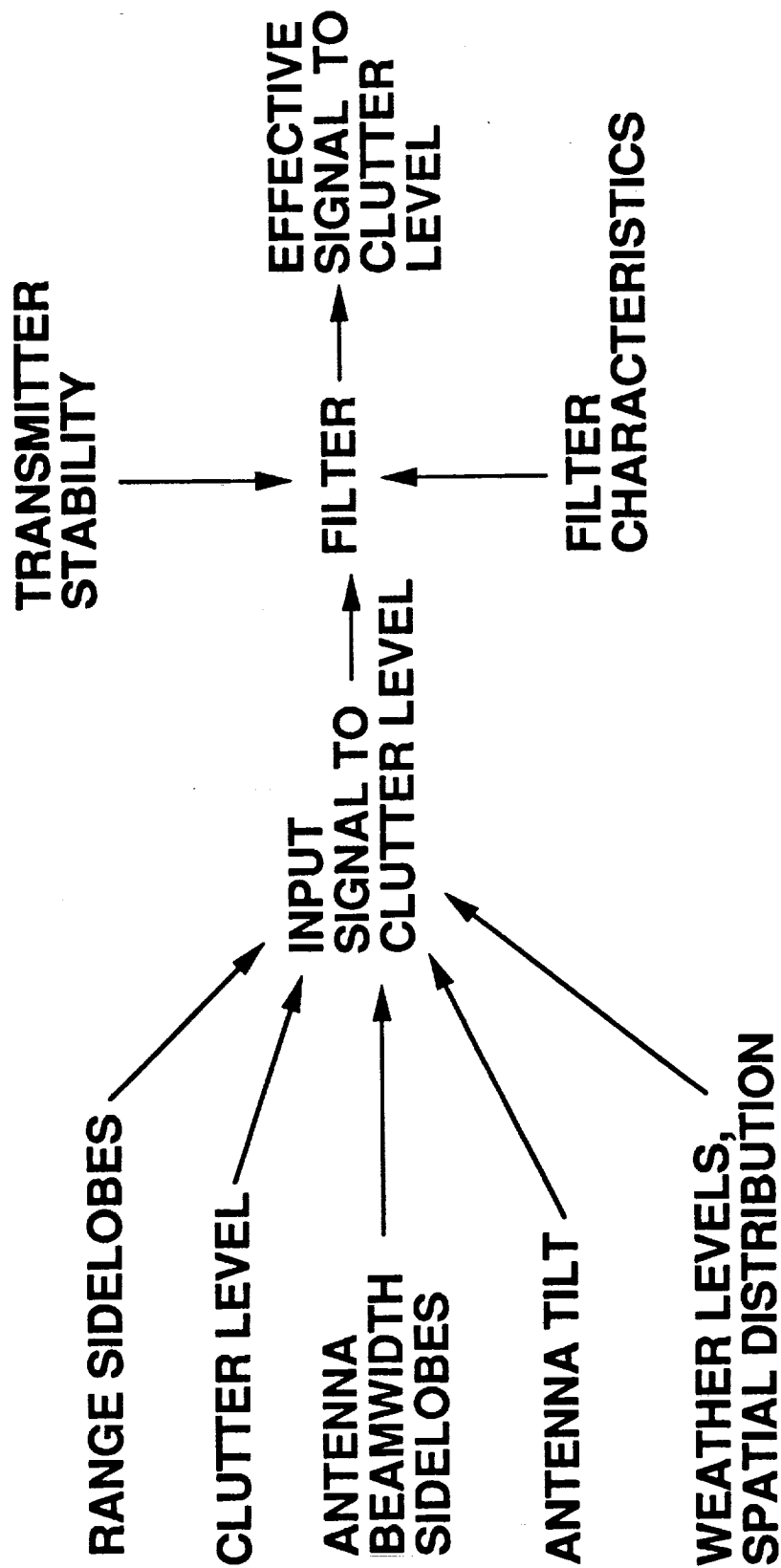
GROUND CLUTTER CHALLENGE

NOMINAL WARNING TIME (SEC)	RANGE (km)	URBAN CLUTTER ($\sigma_0 = -40$ dB) EXPRESSED AS dBZ	3° BEAMWIDTH HEIGHT (m)
7.5	0.5	42	25
15	1	39	50
30	2	36	100
60	4	33	200

CONCLUSION:
SOME COMBINATION OF ANTENNA TILTING AND GROUND CLUTTER SUPPRESSION WILL BE REQUIRED
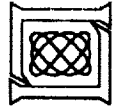
MOVING CLUTTER CHALLENGE

NOMINAL WARNING TIME (SEC)	RANGE (km)	SEAGULL ($\sigma = 10^{-2}$ m^2) IN dBZ	HOUSEFLY ($\sigma = 10^{-5}$ m^2) IN dBZ
7.5	0.5	50	20
15	1.0	44	14
30	2.0	38	8
60	4.0	32	2

X - BAND ANTENNA BEAMWIDTH = 3°

CONCLUSION:
MANY SMALL SCALE PERTURBATIONS WILL
BE FOUND IN DOPPLER VELOCITY FIELDS

OBSCURATION BY DISTANT STORMS
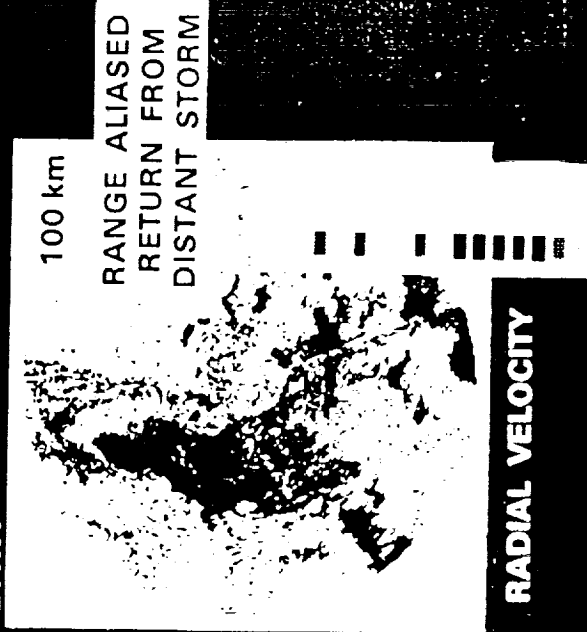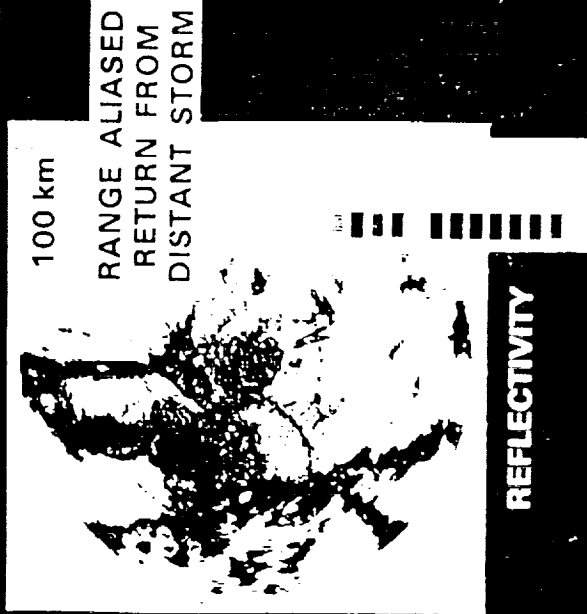
RANGE AMBIGUOUS WEATHER CHALLENGE

NOMINAL WARNING TIME (SEC)	RANGE (KM)	EFFECTIVE dBZ OF 50 dBZ SECOND TRIP ECHO
7.5	0.5	8
1.5	1	14
30	2	20
60	4	26

X BAND   PRF = 2000 Hz

CONCLUSION:
RANGE AMBIGUOUS WEATHER ECHOS ARE
OF CONCERN FOR LONGER WARNING TIMES

967

SUMMARY

- MANY TRADEOFFS EXIST BETWEEN

  - ENVIRONMENTAL RESILIENCE

  - SYSTEM COST / COMPLEXITY

- DEVELOPERS NEED GUIDANCE ON "NOMINAL WORST CASE" ENVIRONMENT FOR SYSTEM DESIGN

- SOME ISSUES (E.G., MOVING SCATTERERS) ARE MOST CONVENIENTLY ADDRESSED EXPERIMENTALLY

- NEED SYSTEM DESIGN ORIENTED APPROACH TO CERTIFICATION DATA PACKAGES

968

Systems Issues in Airborne Doppler Radar/LIDAR Certification
Questions and Answers

Bruce Mathews (Westinghouse) - I would like to state that Westinghouse wishes to distinguish that its antenna beam is in no way pointed in an arbitrary fashion. The hazard factor that we produce and are detecting is for the expected trajectory of the aircraft. We expect that to be accurate, to some degree, no matter what altitude. I think you have raised many valid points. I especially like the point that you made about the limitations of simulation for certifying an airborne radar. Many of the points that you have made about radar cross sections, and the detection of other small targets in the presence of those kinds of radar cross sections are very valid. Thirdly, I would like to say, there are other forms besides this wind shear review meeting where these kinds of systems development issues have been raised including the AIRINC Tag meetings and the RTCA. To some extent I think what NASA has been doing is trying to shape or form a skeleton that we can move along, in sort of a road map fashion, toward certification. In summary though, I think you have made some very good points about certification of airborne radar.

Session XI. Regulation, Certification and System Standards

FAA Regulatory / System Standards / Certification Status
Frank Rock, Federal Aviation Administration

Presentation not available

972

Dave Gollings (FAA) - I would like to put in a little pitch for the pilots. I think we are in pretty good shape in terms of defining the threat. We are in pretty good shape as far as modeling and what kind of simulation needs to be done to certify. We are way behind the eight ball in terms of defining and standardizing the symbology for the display. I don't think the FAA wants to be in the position of legislating that. We are looking to industry to tell us what kind of symbology they would like, and will work with you on standardizing it.

Frank Rock (FAA) - That is a very important point that was just made. Standardization of displays and symbology, we have that problem almost every time we get a new product coming on board the airplane. We have gone through it with TCAS and we are looking at it again here for predictive wind shear.

Randy Avera (FAA) - I would like to encourage everybody to feel free to give us calls at the FAA when you submit for a supplemental type certificate. A lot of people are intimidated and I would like to remind you that we are not the IRS. We are people who's job is to help you get your project approved, and like has been said here the fewer requirements the better. Some of our applicants will send in a STC application and that is the last you will ever here from them until they call up one day and say "hey where is my STC" and we say "where is your data." Submission of the application, the data, and trips to the ACO's to discuss it face to face has a lot of credit. People working together solve a lot of problems and you understand things clearer. We would like to encourage you at your separate ACO's that you are dealing with, to maintain a good continuous working relationship there. That is going to cut down on the time that it ultimately takes to get the product in the aircraft and approved.

Frank Rock (FAA) - That reminds me of the guy that came to the ACO and said, "I want my aircraft certified." And the guy says "where is your data package." He says, "I don't need one I have the airplane outside." And the guy says "well you have got to have the data so that we know that it complies with all the regulations." And he said "I don't see why you need to do that, come on out I will take you for a ride and show you that it does all those nice things."

Q: Roland Bowles (NASA Langley) - Is it possible to start a certification procedure without the RTCA having completed its business?

A: Frank Rock (FAA) - Tony Broderick reminds us constantly that an applicant has a right to certify his equipment with whatever data he presents. It does not have to be from any recognized group or organization. The RTCA is a committee that has been recognized by us and other agencies as an advisory group, and is made up of all the interested parties in the aviation community. We take their input as being one that at least identifies what needs to be done to equipment onboard the airplane. That is the whole purpose for these men to get together and donate their time, and the manufacturers pay their salaries. We could walk off and do as we please, that could happen. At times I have done it, where I disagreed with the SAE or the RTCA committee. I don't like to do that and I don't think that any of the other FAA types like to do it if at all possible.

Q: Roland Bowles (NASA Langley) - But any manufacturer could bring his own technology, his own methodology and means and that could be accepted?

A: Frank Rock (FAA) - He has a right to do that yes.

Roland Bowles (NASA Langley) - I guess my message is that perhaps somebody ought to be thinking about RTCA's for some of these other technologies. Right now the only one that has made any real headway, and we are supporting it, is the radar.

Frank Rock (FAA) - The procedure to generate an RTCA committee is that any interested party could submit a request to what used to be the old executive committee, to consider a technology to be looked at or form a committee to examine and develop the standards for it. That can be done by most industry people. The FAA can do it as well.

Q: Jim Evans (MIT) - It was stated that the threat environment specification is largely complete and in good shape. How has the threat specification for the wind shear phenomena and the clutter environment been established and where can one obtain a copy of the specification?

A: Kirk Baker (FAA) - The FAA right now is developing a systems requirements document, and part of that document includes wind modeling that we are working with NASA to develop. Those models right now are largely being developed for the wind shear phenomenon itself. One of those includes a gust front, but largely is focused on microburst. Part of what we have seen these last two days obviously is going to effect probably some of the ways that we start to look at those. For example, the flight paths that we have the applicant demonstrate through these different events. The clutter environment is something that we are probably going to look to NASA to help us develop. The vendors themselves have been doing quite a lot of work in clutter mapping and we would expect that they would provide those maps and environments to us and those would be overlaid in the simulations. There is probably going to be some flight testing involved also. I think Roland stated earlier that it is going to be a combined mixture of different types of demonstrations. I encourage the applicants to step forward and make an effort to start putting together their ideas in how they plan to demonstrate the intended functions of their systems. We in the FAA can't provide you with a cookbook answer right now and we do not intend to. We are going to give you some minimum requirements that we think are applicable, and you are going to have to demonstrate those minimum requirements. We are in the process of developing those. This is an on going thing so to say we are in good shape, I think we are. I think we have got some things down in writing and we are continually working to improve those and it will continue through the summer I am sure.

Q: Unknown - Will the FAA be willing to certify a non-universal wind shear detector to meet the rule mandate? Should this question be answered prior to the vendors producing their technology?

Roland Bowles (NASA Langley) - As you know, in the airborne side there has been a lot of focus on the convective microburst kinds of environments as hazardous. In fact you can even see in the algorithms, features that depend on some sort of stagnation flow with outflows and estimates of certain mechanical properties in the wind field to help support the alerting structure. The question is, from the certification point of view, are you willing to certify microburst

detectors or are you going to certify wind shear detectors for whatever the atmospheric phenomenon is that gives rise to some level of agreed upon energy change that could be hazardous to the airplane? That is kind of the question.

A: Kirk Baker (FAA) - We are going to do wind shear detection that gives rise to hazardous energy changes to airplanes.

Q: Roland Bowles (NASA Langley) - How does the industry feel about that? Whose ox does that gore? Nobodies oxen got gored, so it must be all right. I think that has significant ramifications with regard to certification.

Jim Evans (MIT) - It seems to me that when you start talking about whether you build physical understanding about the phenomenon that may cause it versus not, you may adopt a slightly different principle. That is, if you have an event that possibly looks marginal, if we can decide what marginal is, that you insist that it have more meteorological characteristics, to rule out the marginal cases. Let me give an example of that. This came up with the LLWAS system. There were a lot of problems with the enhanced LLWAS system creating false alerts in gusty Chinook winds. The problem was, there might be a shear but it was very momentary. In fact, it would not even be there seven seconds later. There was something there, but it wasn't clear it deserved to be called a microburst in the sense that it was a very transient phenomenon. The same issue arises here. You go out and you make a measurement fifteen seconds or thirty seconds in advance and if the thing goes away under some kind of very transient environmental condition then there is a question about creating nuisance alerts. So, when you look at something and it looks like a serious shear, it is a high level shear and it even seems to have some persistence, then maybe I don't demand that it meet a convective storms criteria. If I have something that just popped up and it looks kind of marginal, maybe I insist that it at least look like something that is going to stick around for a while.

Roland Bowles (NASA Langley) - A good example of that is a report floating around the country concerning the Cafe Pacific 747-400 that got two wind shear alerts going into Singapore. About 300 miles off shore there was a tropical depression. Reasonable people can look at that data and question, was that just abnormal structure and turbulent flows being produced by that off shore depression, or was that a hazardous wind environment? I suspect you could give to five different competent analyst and get maybe two and a half different answers. The point is that there are many things in the atmosphere that can give rise to energy change, but the ones that we clearly must protect from are the microburst convective downdraft kinds of things. I think the answer that we heard from Kirk was that you must protect against all atmospheric phenomenon that will give rise to hazardous energy change to the airplane. Whatever it's atmospheric source, character or origin. I really thought some of you radar guys out there would say something about this.

Jim Evans (MIT) - I think we are beginning to repeal rationality. One thing I always hate about meteorologists is they always talk about extreme events, the most dry, the coldest, the wettest or whatever. If we are going to talk about all possible atmospheric conditions, I don't understand what the test program is going to be to deal with all the possible combinations of atmospheric phenomenon we could ever imagine. You will never test against all that. It is bizarre. In fact it doesn't make practical sense. If you are willing to accept that adequate protection is provided by

a reactive system that doesn't provide any reactive output on takeoff until you have gotten to at least 50 feet in altitude, I would argue that there is a fraction of events that are potentially hazardous that it is not going to protect you against. And, if you are willing to buy that, why do you then want to turn around and require protection against everything when you have already stated it is safe below 50 feet. I think you are repealing rationality. You have to make some value judgments and stick by them.

Roland Bowles (NASA Langley) - Don't accuse me of being a meteorologist. I think this is a fairly important question. One of these days somebody is going to walk into an ACO office and say, "Look what I got. This microburst detector is the best thing since sliced bread." and they are going to say, "So what. What about the other nine or ten test cases that you must protect the airplane against." It gets at the heart of the certification procedure. Are we going to do it? Are we going to have the target generator concept that the RTCA is looking at? Are we going to have gust fronts in there, off shore strong sea breezes, Chinook winds, thunder storms and all those embedded. I do not think the industry can afford that target generator to plug your radar into to show a minimum operating performance standard. Are we going to do it in simulation? Who in the country is building the database which will be qualified to subject the various instrumentation capabilities to, for detection performance, rejection of certain characteristics that are not considered hazardous, etc. This is where we are on the airborne side. How do you test the adequacy of a system? By what means do we do this? Who says that these databases are qualified for these uses? Or, do you get some good old boys from the industry together and they write a MOP because they all think they can meet it? I think some of you understand that problem.

Results of In-service Evaluation of Wind Shear Systems

Todd Murr, Northwest Airlines

RESULTS OF IN-SERVICE EVALUATION OF WINDSHEAR SYSTEMS

Todd E. Murr

Northwest Airlines

Fourth Combined Manufacturers' and Technologists'

Airborne Windshear Review Meeting

Williamsburg, VA

April 14-16, 1992

INTRODUCTION

- Objective of the evaluation

- Preliminary results

- Conclusions

OBJECTIVE

Collect data in the operational environment to determine the capability of windshear systems and their effectiveness.

COMPONENTS OF THE OBJECTIVE

- Collect operational data

- Determine system capability

- Evaluate system effectiveness

DATA COLLECTION

- Aircraft state parameters

- System parameters

- Weather Information

- All phases of flight

- Collection focused on windshears

SYSTEM CAPABILITY

- Will NOT intentionally fly into a windshear

- Work with NASA and FAA to determine system capability criteria

- Must rely on outside sources for "proof of concept"

983

SYSTEM EFFECTIVENESS

- "ready for service"

- Data reviewed and published on a monthly basis

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┌──────┐      ┌─────────────────┐      ┌─────────┐
│ Data │ ───→ │ Success Criteria│ ───→ │ Report  │
│      │      │     Board       │      │         │
└──────┘      └─────────────────┘      └─────────┘
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984
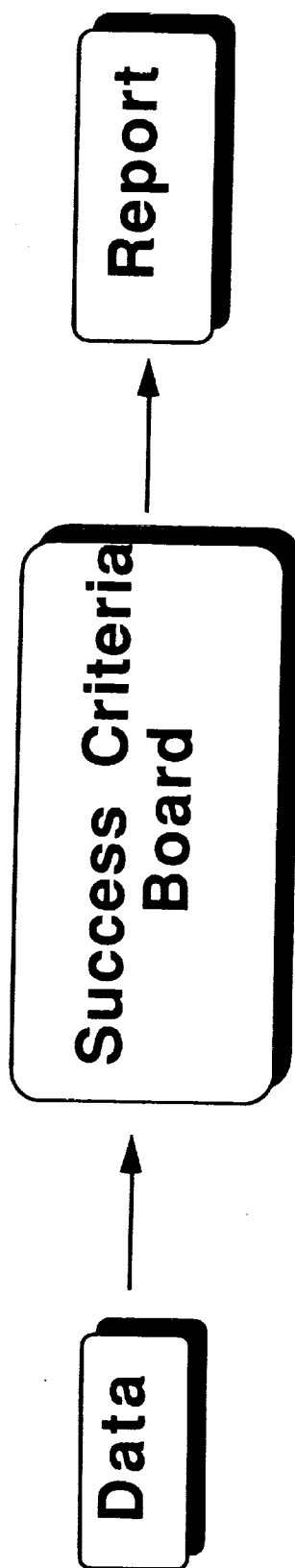
PROGRAM DESCRIPTION

- Two windshear systems
  - TPS AWAS III (Predictive)
  - Honeywell WSC (Reactive)

- Installed on three DC-9-30

- Data collected on revenue flights

PROGRAM TIMELINE

Debug

System
Upgrade

Final
Configuration

Dec '91

Mar '92
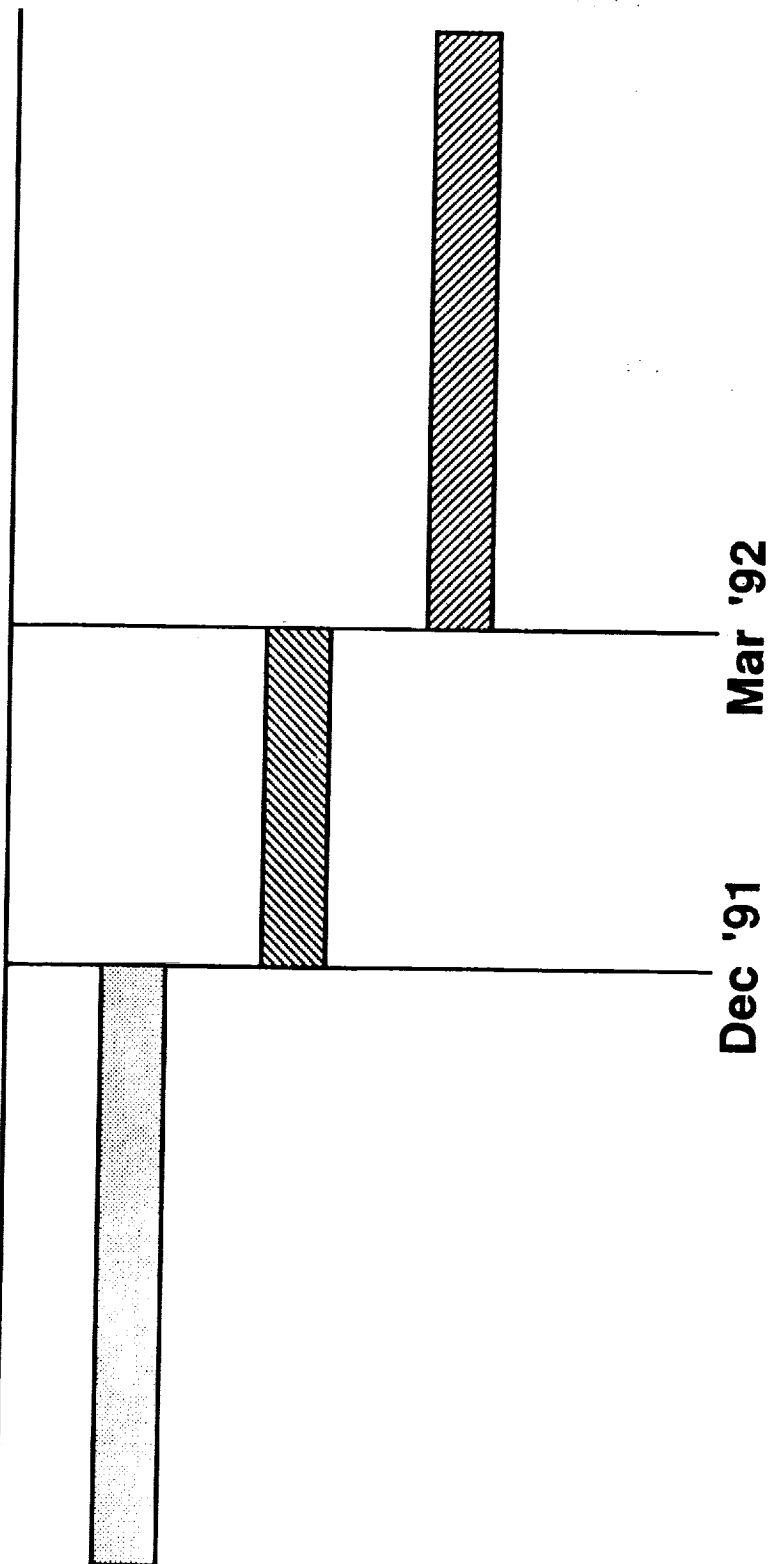
RESULTS OF DEBUG

- Defined "Normal" operations

- Interfacing with analog aircraft
  - Power supply
  - Sensor signals

- Better understanding how the systems operate

987

RESULTS OF SYSTEM UPGRADE

- Both systems operated at least 95% of the time

- AWAS III required a software upgrade

- Most aircraft induced nuisances and failures were eliminated

RESULTS OF FINAL CONFIGURATION

- Evaluation started in March

- Completion in June '92

- Both Systems Operating favorable

989

AWAS III PERFORMANCE

Operating Performance

990
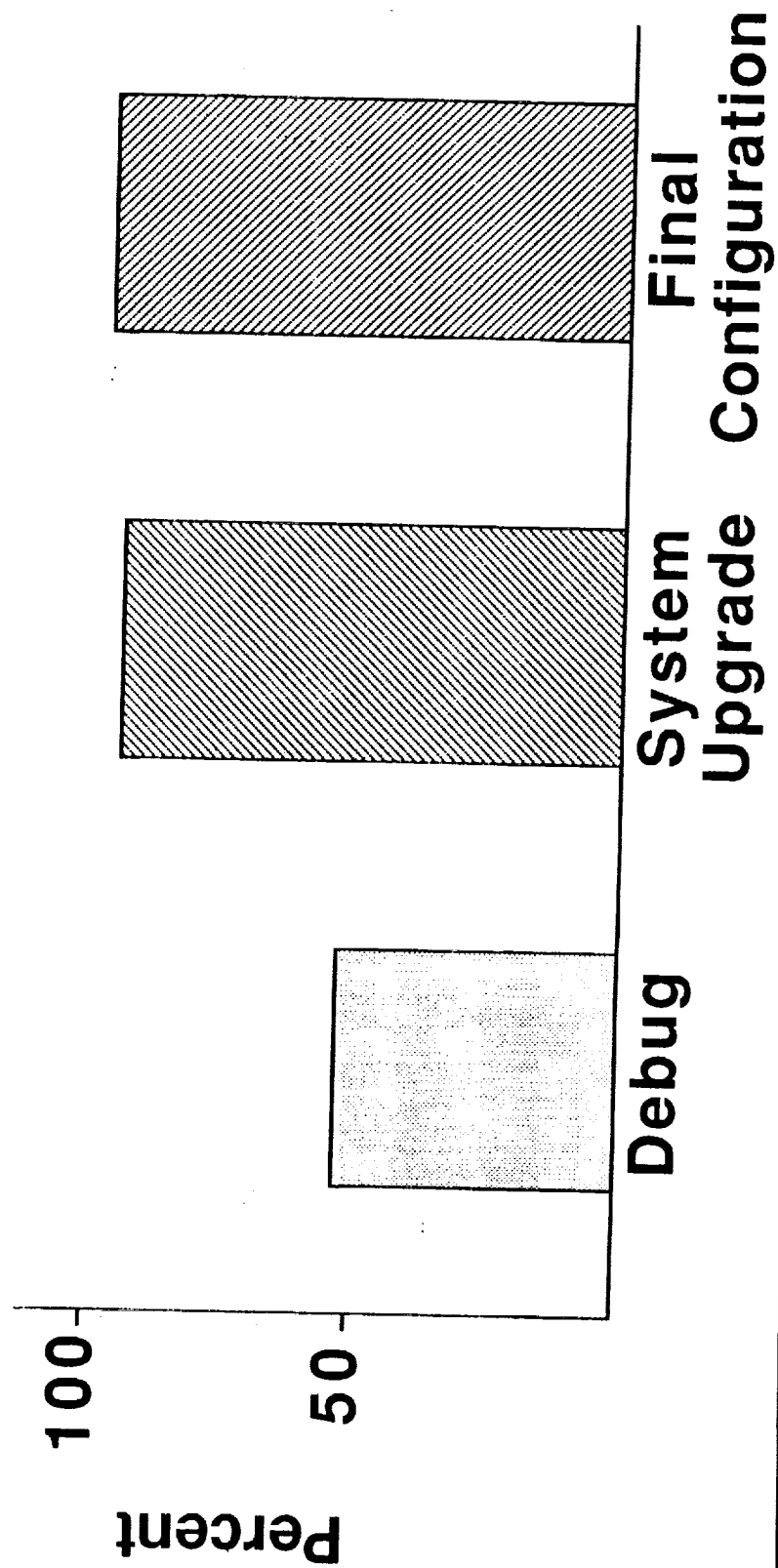
WSC PERFORMANCE

Operating Performance

991
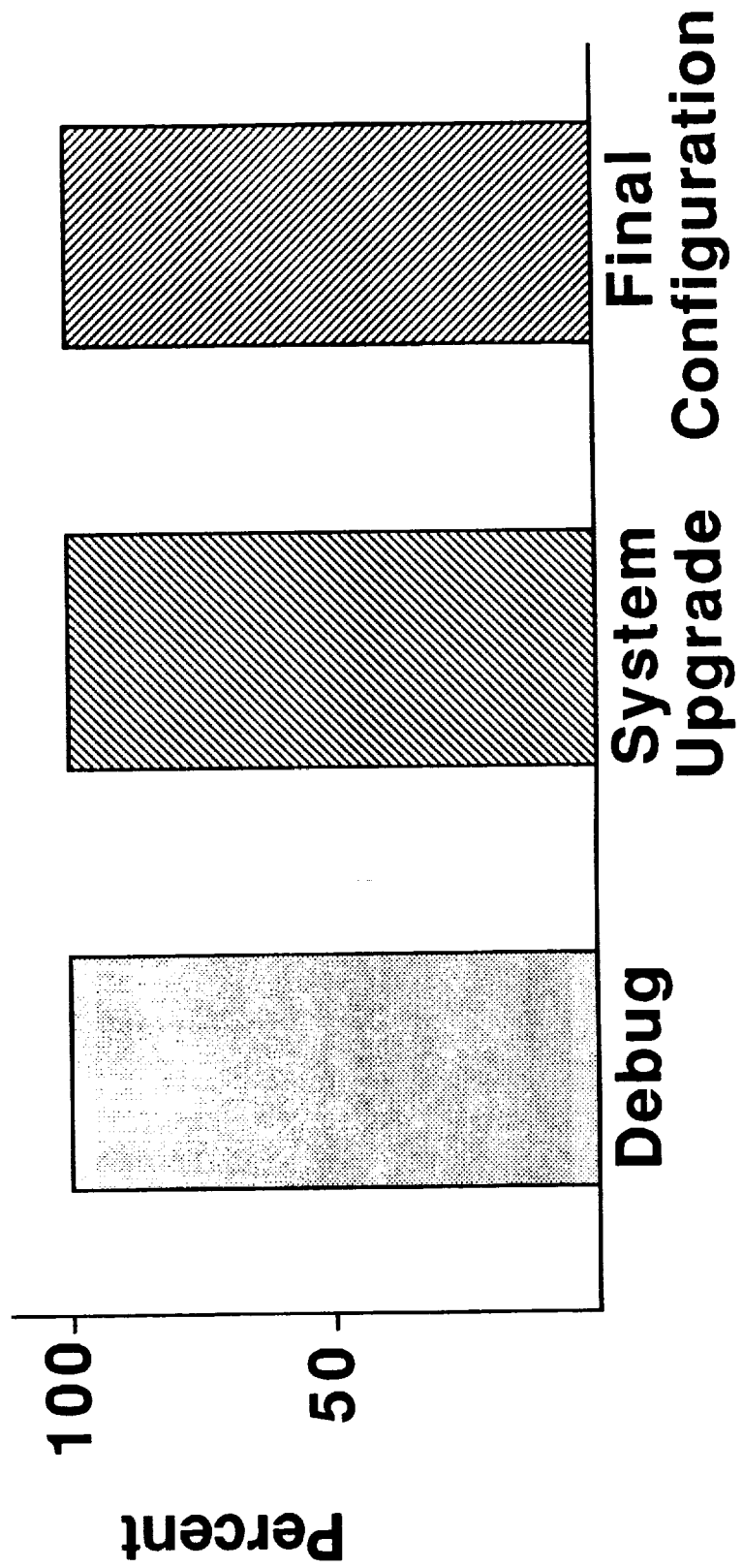
AWAS III NUISANCE RATE

Nuisances per 1000 Flight Hours

	Debug	System Upgrade	Final Configuration
Number of Nuisance	138	145	0

WSC NUISANCE RATE

Nuisances per 1000 Flight Hours

Number of Nuisance

1	0	0
Debug	System Upgrade	Final Configuration

993
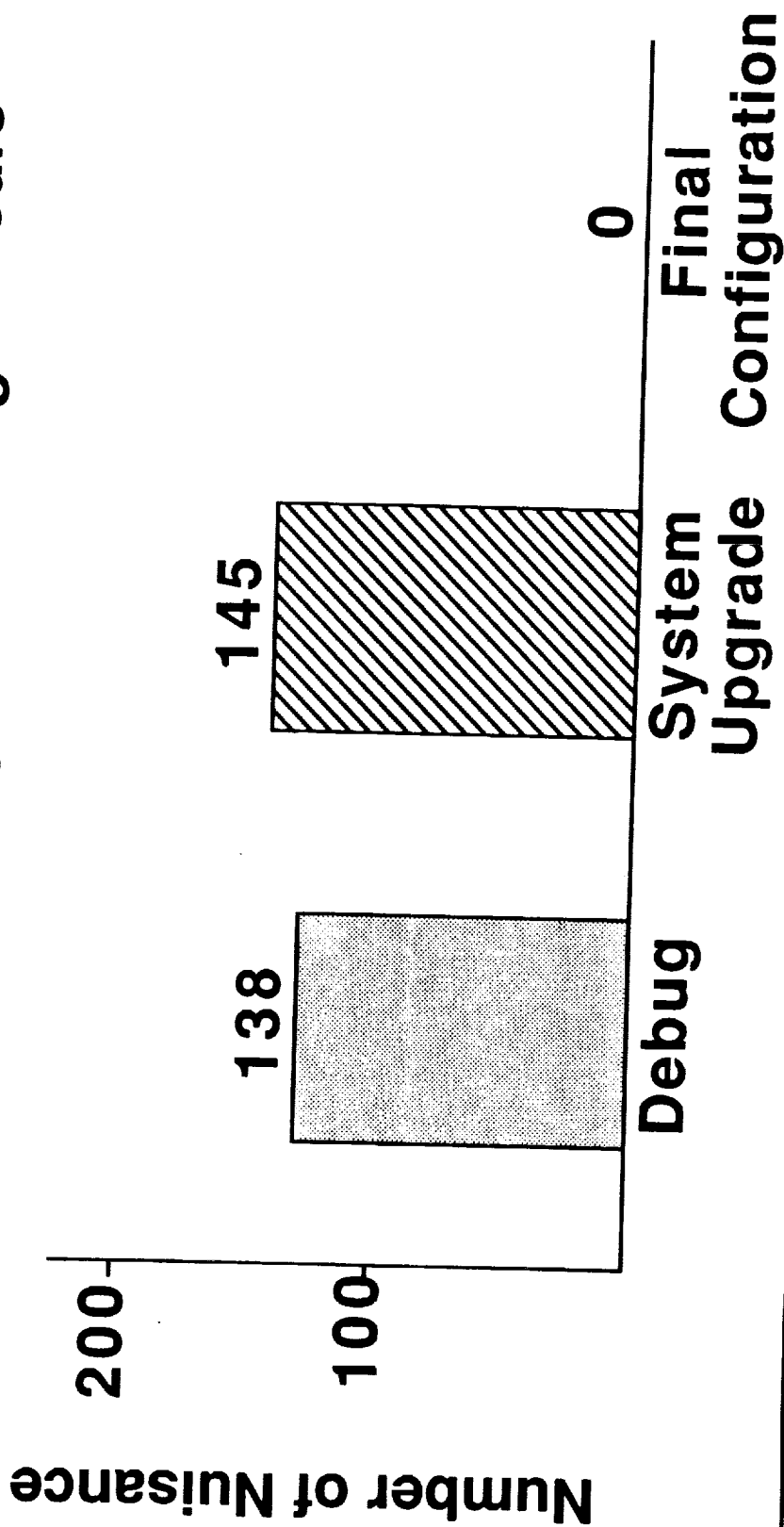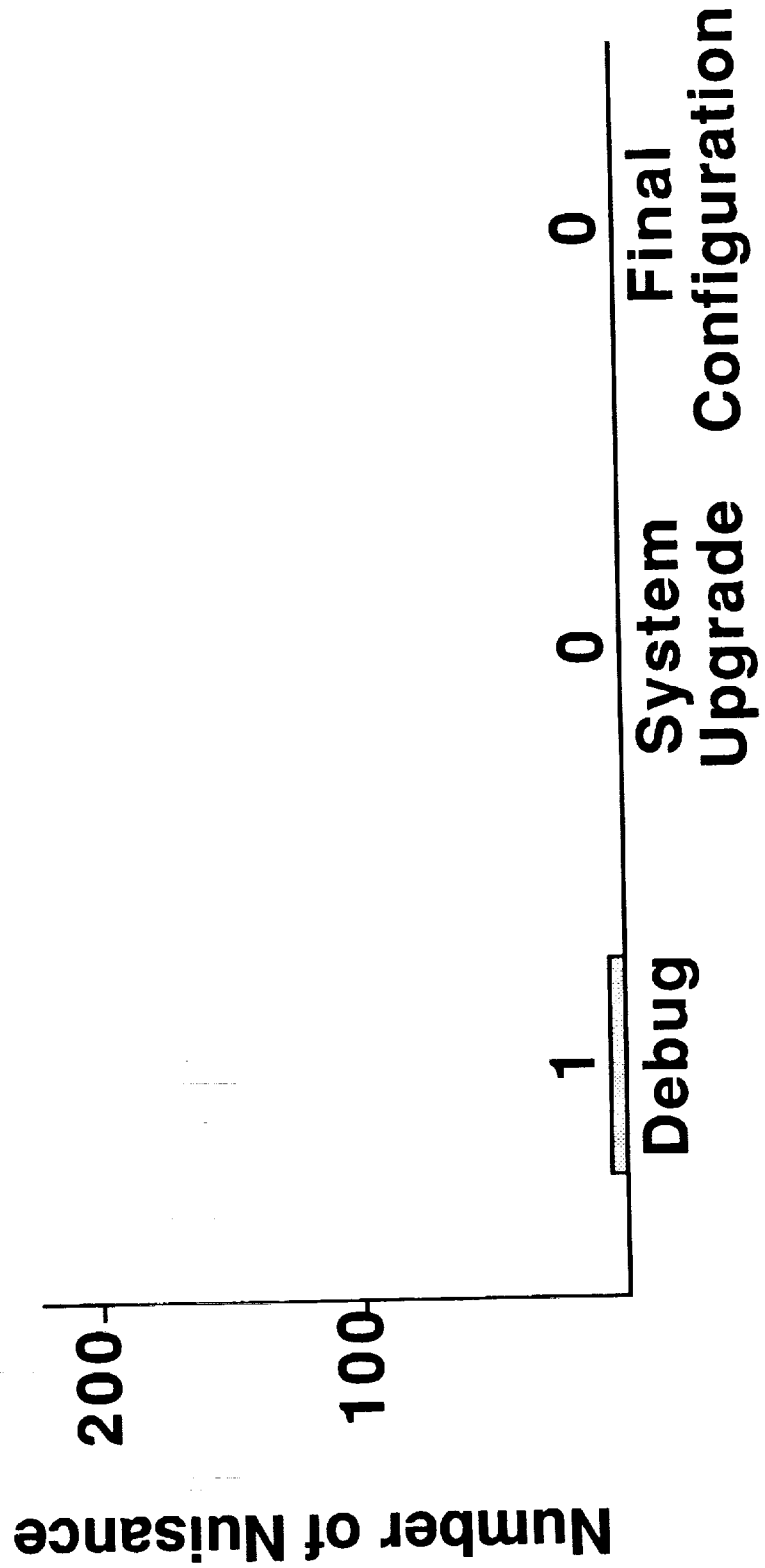
CONCLUSION

- WSC performance is exceptional

- AWAS III performance has improved

- Northwest is addressing issues raised by predictive systems

- Knowledge gained will be used to determine best solution

994

Results of In-service Evaluation of Wind Shear Systems
Questions and Answers

Q: Larry Gordan (MITRE) - Could you just take a minute and talk about some of the issues that predictor systems raise to pilots from your point of view?

A: Todd Murr (Northwest Airlines) - A lot of the concern that Northwest is having deals with pilot confidence and nuisance rate. If you detect an event thirty seconds ahead, by the time they penetrate this event there may not be an event or they will be at a lot higher altitude so they won't be getting the outflow. Also, if you are familiar with Northwest we are doing a lot of the curve path approaches. If you have a system that constantly looks three nautical miles out in front of you as you are doing a curve path approach, this might raise some interesting issues that we haven't addressed yet or we don't know how to address.

Q: Jim Evans (MIT) - When you talk about the performance being exceptional. How many wind shears do you reckon the systems have detected?

A: Todd Murr (Northwest Airlines) - I would say that we haven't seen any wind shears at all. We do not expect to see any wind shears and hope not to in this evaluation program.

N93-14857

In-service Evaluation of Wind Shear Systems
Capt. Sam Shirck, Continental Airlines

C-5

*Picture of N88777

Good Afternoon Ladies and Gentlemen

This was our first bite of the windshear apple! A Continental Flight from Denver to Houston , August 7, 1975. Fortunately in this accident there was no loss of life, others have been far less so.

Following this occurrence, a comprehensive study was undertaken by Continental Airlines Flight Operations to establish procedures to prevent a re-occurrence of this type of accident. Text and simulator training were developed and employed shortly thereafter.

FAA mandated windshear training is now required, low level windshear alerting systems have been installed at some airports, terminal doppler weather reporting systems have been installed at two airports with 40 or more coming soon, since this accident.

Reactive windshear systems , the best answer industry had at the time, have been installed on many aircraft and are now required on all aircraft being delivered.

N88777 encountered a strong microburst tailwind component of over 60 knots just at rotation. In our mind, the present reactive windshear systems, by themselves, will not prevent this type of accident. TDWR and LLWAS will not be installed at all airports that are subject to these microburst phenomena. Therefore, an advanced warning system, predictive, if you will, is required for the safety of our passengers.

We have worked over the past two years with Bendix, Collins, Westinghouse, and Dr. Pete Sinclair of CSU to find a solution to the windshear problem that is cost effective and provides the margin of safety required. With the able assistance of the FAA aircraft certification office in Long Beach we have modified three aircraft in our fleet, 1 737-300 and 2 A-300's, to assist the vendors in data collection. The 737 was delivered from Boeing with a Sunstrand Mk V GPWS/WS system; it has been modified by adding another Sunstrand Mk V. Dr. Sinclair's IR unit, a modified Collins WXR-700 weather radar system, and an optical disk recording system. The A-300 aircraft have similar modifications, one featuring a modified Bendix RDR-4A radar and the other a Westinghouse MODAR 3000 system. Each aircraft has the Sunstrand reactive system installed to furnish a base line for windshear correlation. All windshear information is transparent to the flight deck and normal operating procedures are unaffected. Because of comprehensive windshear avoidance procedures developed by the FAA and NASA, and employed by our airline, no significant shears have been encountered. However, an enormous amount of data has been collected to aid in ground clutter reduction and moving target discrimination in the approach and departure areas.

Recent meetings with the FAA, NASA Langley, and the vendors make us feel that the windshear solution is at hand. We intend to proceed under the 5256 exemption and feel certification of a predictive windshear system will be possible in the mid 1993 time frame.

We would now like to present some display and alerting scenarios that the predictive systems will provide.

1) Landing- windshear detected 1.5 miles or more from aircraft.

2) Landing- windshear detected 1.5 miles or less from aircraft.

3) Takeoff- windshear detected prior to V1 within 5 miles.

4) Takeoff- windshear detected after V1 within 1.5 miles.

5) Takeoff- windshear detected after V1 1.5 to 5 miles

These efforts have been possible because of a true and abiding commitment to safety by Bendix, Collins, Sunstrand, Westinghouse and Dr. Sinclair.

We would like to express our appreciation for the advice, assistance and encouragement we've received from Dr. Bowle's group at NASA Langley. When it's dark in the tunnel it's nice to have someone not only have a candle, but to light it to show the way.

Thank you for your attendance

Continental Airlines

—CONDITIONS—
- AIRCRAFT — BELOW 1500 FT. ON FINAL
- WX — WINDSHEAR WITHIN 5NM

—ALERTS—
- LAMP

FLASH 3 TIMES THEN STEADY–CANCELABLE–REARMED

> WINDSHEAR
> AHEAD

- AURAL — ATTESON/CHIME
- DISPLAY — WINDSHEAR ICON YELLOW/BLACK
  POP UP IS OFF TO WX/WS MODE

—PILOT ACTION—
- AS REQUIRED POTENTIAL TO MANUEVER AND AVOID
- REPORTS WS TO ATC
- NEGOTIATE AVOIDANCE AND/OR MANUEVER
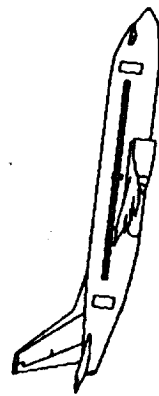
1500 FT.
AGL
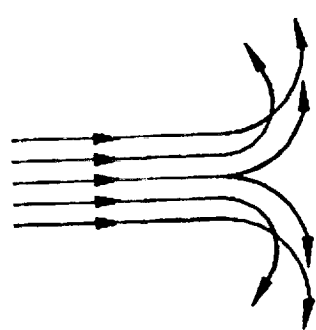
1.5NM

5NM

Continental Airlines

—CONDITIONS—
- AIRCRAFT – BELOW 1500 FT. ON FINAL
- WX   – WINDSHEAR WITHIN 1.5NM

—ALERTS—
- LAMP
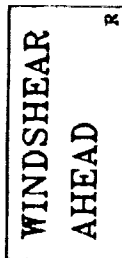
  | WINDSHEAR |
  | AHEAD | ®

- AURAL   "WINDSHEAR AHEAD" 1 REPEAT
- DISPLAY WINDSHEAR ICON RED/BLACK
           POP UP IS OFF TO WS MODE

—PILOT ACTION—
- GO AROUND
- REPORTS WS TO ATC
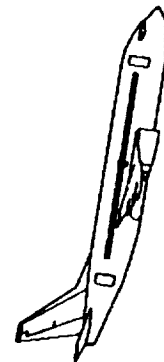
1500 FT.
AGL
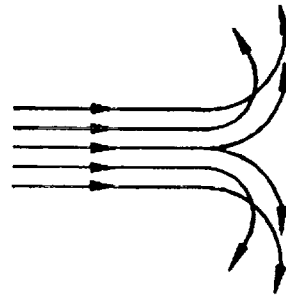
1.5NM   5NM

Continental Airlines

—CONDITIONS—

- AIRCRAFT — END OF RUNWAY TO V₁
- WX — WINDSHEAR WITHIN 5NM

—ALERTS—

- LAMP · REPORT AHEAD TO ATC

WINDSHEAR AHEAD

- AURAL "WINDSHEAR AHEAD" 1 REPEAT
- DISPLAY WINDSHEAR ICON RED/BLACK POP UP IS OFF TO WS MODE

—PILOT ACTION—

- RTO
- REPORTS WS TO ATC

"WINDSHEAR AHEAD" 2 REPEATS

WINDSHEAR

- W · ENCOUNTER WINDSHEAR
- A/C · T/O — BEYOND

—S R S—

—AL T A—

A/C

5NM

1.5NM

DO NOT DISPLAY ROTATION

TKO-2
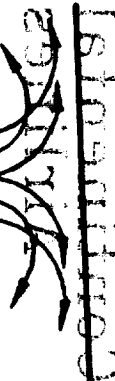
—CONDITIONS—
· AIRCRAFT – BEYOND V₁
· WX   – ENCOUNTERED WINDSHEAR

—ALERTS—
· LAMP
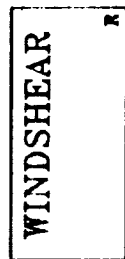
| WINDSHEAR | ᴿ |

· AURAL*   "WINDSHEAR AHEAD" 2 REPEATS *
· DISPLAY   NONE

—PILOT ACTION—
· WTARP
· REPORTS WS TO ATC

* AURAL INHIBITED
  100 KNOTS TO ROTATION

V₂   1.5NM   5NM

1004
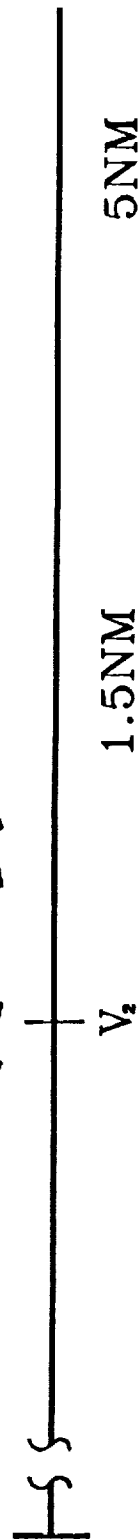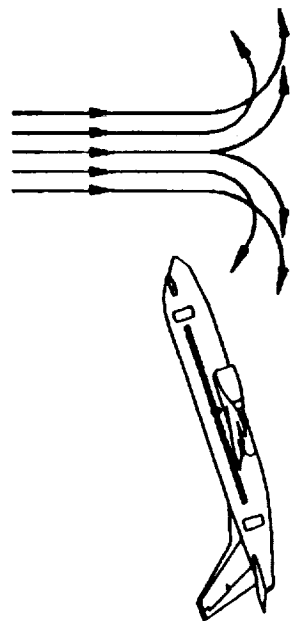
Continental Airlines

—CONDITIONS—
- AIRCRAFT – TAKEOFF ROLL BEYOND V
- WX – WINDSHEAR BETWEEN 1.5NM AND 5NM

—ALERTS—
- LAMP

| WINDSHEAR |
| AHEAD ▲ |

- AURAL* "WINDSHEAR AHEAD" 1 REPEAT
- DISPLAY WINDSHEAR ICON YELLOW/BLACK
  WINDSHEAR POP UP IS OFF TO WX/WS MODE

—PILOT ACTION—
- TO MAX POWER
- NOTIFY ATC
- AVOID WS
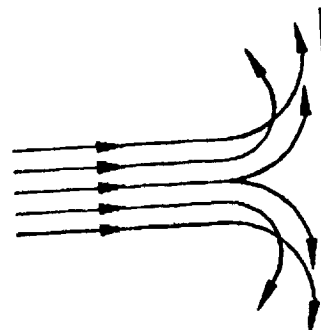
* AURAL INHIBITED 100 KNOTS TO ROTATION

V_R V_2 1.5NM   5NM

1005

Session XI. Regulation, Certification and System Standards

Advanced Technology Wind Shear Prediction System Evaluation

Capt. Greg Gering, American Airlines

AMERICAN AIRLINES

ADVANCED TECHNOLOGY WINDSHEAR PREDICTION SYSTEM EVALUATION

(GMG 1 4/16/92)

PROGRAM OVERVIEW

O AA/Turbulence Prediction Systems have installed Forward Looking Infrared Predictive Windshear System on 3 MD-80 aircraft.

O AA/TPS AWAS III evaluation is a joint effort.

O The AWAS III is installed in the NLG area and a data recorder is installed in the E/E compartment.

(GMG 2 4/16/92)

MIRROR

AWAS

MARKER EVENT

MECHANICS CALL BUTTON
(COCKPIT)

DATA
RECORDER

RS232

28 VDC AIRCRAFT POWER

VIA GROUND
SWITCH &
PITOT
HEATER
SWITCH

28 VDC AIRCRAFT POWER

ARINC 429 HSDB

#2 DIGITAL
FLIGHT
GUIDANCE
COMPUTER

15 VDC

POWER
SUPPLY

115 VAC
AIRCRAFT POWER
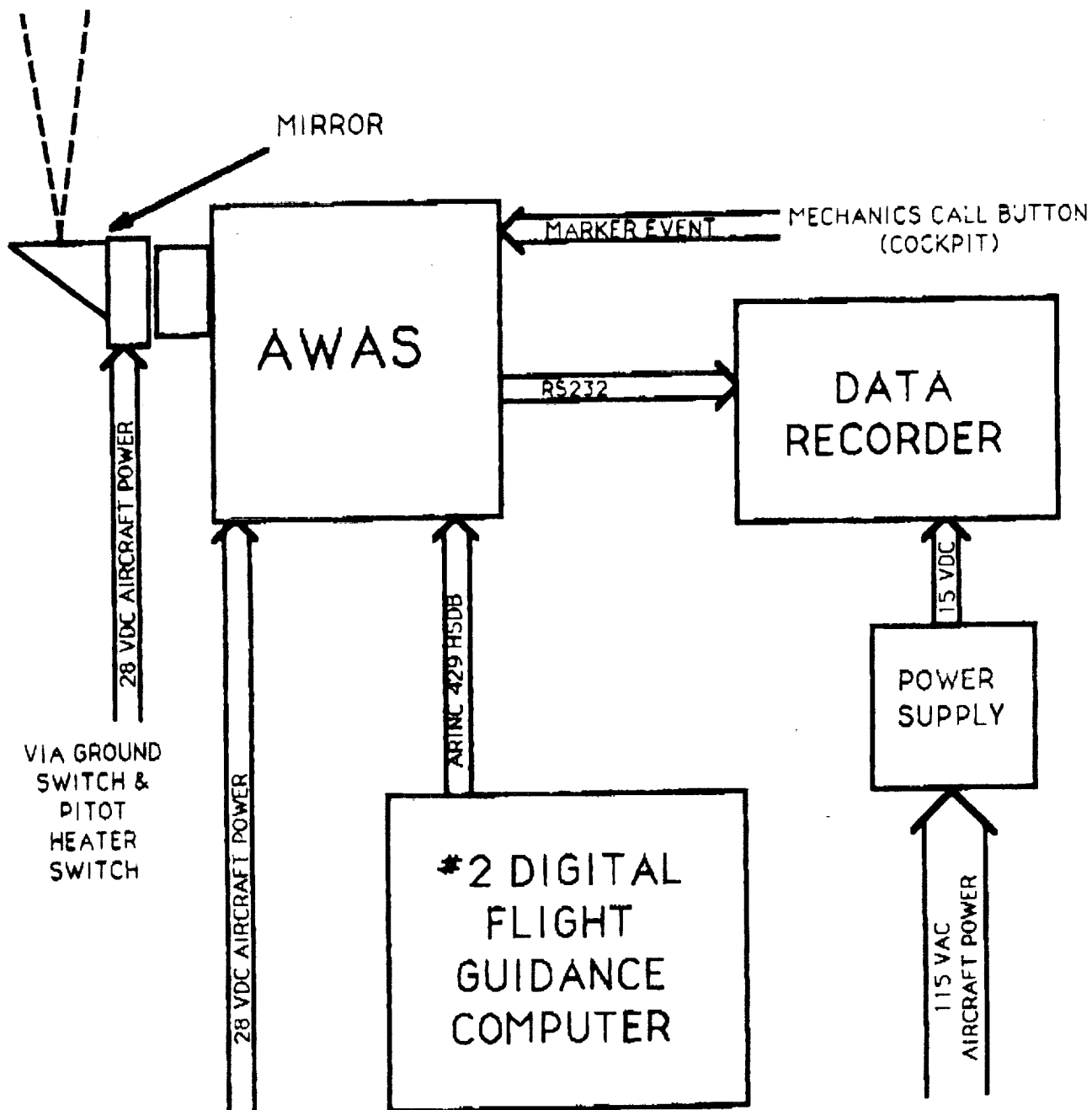
AA/TPS AWAS INSTALLATION BLOCK
DIAGRAM

SYSTEM RELIABILITY

O The AWAS has not been removed due to a hardware failure since the debugging cycle ended.

O When required for S/W update, removal time is approximately 10 minutes.

O Mirrors have been durable. No replacement during the testing.

O Windows cleaned monthly. One window replaced in December by one with a protective epoxy coating.

(GMG 4 4/16/92)

SYSTEM EVALUATION

O 3700 cycles of data have been collected.

O All aircraft are flying with the latest S/W (ver 2.1.1.4).

O S/W has new data labels that match the NASA algorithm.

O S/W frozen in October 1992. 1000 cycles with latest S/W.

(GMG 5 4/16/92)

TECHNICAL ISSUES

O The lens with the diamond like coating is still not available.

O The NASA algorithm and appropriate flight data, for double checking the AWAS system was only recently implemented.

(GMG 6 4/16/92)

1013

Results of American In-service Evaluations
Questions and Answers

Roland Bowles (NASA Langley) - I feel I have to defend your comment about the In Situ algorithm. As you know there was a formal request that we required for that. It went out to four manufacturers. You saw the results from Collins, they used it. I don't know to what degree Westinghouse has used it, but never the less that information was clearly in your vendors hands. We saw no reasonable attempt to use that algorithm at all. In fact I think it was fairly confusing for people to use because of the distribution of accelerometers located around the airplane. You have got some in the tail, some in the nose, but nothing near the CG. I think it have been in your vendors hands, but there have been no will to work with it.

Greg Gering (American Airlines) - I really was not trying to put blame in any one spot. We started our flight testing before you did your summer flight tests. Some of the decisions that we made were made before the things were available. It was just one of those things where we were trying to meet the time line for a 1995 installation. We ended up going into the flight test before we had all the data and we are trying to back in stuff later. I am not saying that you did not provide it on time or anything else. We were collecting data before we had it and we tried to back it in later.

Q: Roland Bowles (NASA Langley) - What has prevented backing it in? Is it that American has lost interest in the whole program, or is it that your vendor can't work with it?

A: Greg Gering (American Airlines) - We are collecting the data and we have 1,000 cycles since last October of data that we can use for it.

Q: Russel Targ (Lockheed) - As a technologist I am a little puzzled about what seems to be a systems evaluation in which nothing happens. We have three airlines very pleased that they have mounted a brick in the cargo bay. There have been no false alarms, no nuisance alerts, no alerts of any kind, and they all conclude that it looks good to them. I am puzzled as to how this amounts to an enthusiastic systems evaluation of a system that hasn't apparently done anything. Certainly in the NASA flights where your going through microbursts, you have some successes and some failures, but above all there is data. That is of course what anybody would want to evaluate the system. So, I am puzzled as to the criteria that the airlines are applying for these enthusiastic reports that we have heard?

A: Greg Gering (American Airlines) - I won't say that we are enthusiastic about how the system has been totaling working. Our part of the evaluation was not to find a microburst or a wind shear. The basic part that all three airlines went into flight testing for was to provide the high number of cycles and high number of hours in normal operation, and look for some of the base line noise.

Unknown - I was going to add a little bit to that. I have flown for twenty years in all types of environments and in over 12,000 hours I have never flown through a microburst. I think you will find that most pilots, military or air carrier don't. Especially today with the amount of education we have had in the area. If you see one or you think you are about to encounter the conditions

where you might find an event like that you tend to avoid them. A test program on an air transport category aircraft is certainly not going to take any precedence over normal procedures.

Sam Shirck (Continental Airlines) - We have collected a tremendous amount of data that we are not processing ourselves. We do not build systems, we do not build radars, we just use them and break them and buy more of them. They keep us out of the mud and the trees and things like that. We are not to interested in the data. We are interested in what is going to be developed. My gut reaction as a pilot to what I am hearing from Bendix, Collins and Westinghouse is that they are damn close, and we are really happy with that. We think by the middle of next year we will possibly have a certified system, at least by the end of 1993. I sit in the back of the airplane once in a while and I am happy that we have got something that is going to keep it from wallowing around like triple seven did, where you don't have a chance on take off. That accident happened on an 82 degree day on a balanced field. The airplane definitely loves the ground at Denver. There is not enough oxygen up there. The type of system we are looking for will prevent this type of an accident, or of it even coming close to happening. So I think we are very optimistic, from all three vendors. We are disappointed that the IR is not showing the results that we had hoped. We are proud of what NASA is doing. We are proud of the support that the FAA has given us and the opportunity that Tony gave us for the two year extension. So we are elated. We are a lot better off than we were before.

GENERAL QUESTIONS AND ANSWERS

Q: Unknown - When you discuss gust rejection, I understand the physics of ignoring short time scale things along the flight path in the horizontal dimension. However, during the real crashes, aren't there some substantial controllability issues. Why is that is never discussed? Is it just because it is to hard to model and measure, or is it really not an issue?

A: Dave Hinton (NASA Langley) - Well, I am not going to say it is not an issue. Obviously in the Dallas/Fort Worth crash there were a few significant control problems associated with coming out the back side of that microburst. However, I do not know of any other cases where that has been true. That turbulence or upset was not a problem to the airplane until a very significant amount of energy had been taken out of the aircraft by the wind shear it had just flown through. By far the predominant effect from a microburst or a wind shear is the performance impact on the airplane. There are control problems. As a matter of fact there was an incident in Japan concerning an L-1011 I believe that made a very severe landing and it popped rivets out of the wings because of turbulence close to the ground. Terrain induced turbulence; that is a problem. But it is not the problem we are studying. You can cite Dallas/Fort Worth, but generally that is not the problem that caused the loss of life in microburst wind shear accidents.

Dan Vicroy (NASA Langley) - Just as a side note, I did a study about three years ago that looked at the handling the qualities effect rather than the performance effect. What is the effect on the handling qualities when you fly through a microburst? I looked at pitching and rolling moments and some of the asymmetrical aerodynamic loading, and so on. There is an effect there, but again it is a second order effect when compared to performance degradation that the airplane sees.

Q: Jim Evans (MIT) - I have a question I guess for the FAA. What is the FAA's decision process going to be apropos this rule making for reactive versus forward looking systems. It would appear from the results that Joe Gibson supplied that there is some concern about preventing accidents with reactive systems. Now it can be claimed that they have prevented a lot of accidents, but I will also note that only 15% of the air fleet was equipped, and they are not having accidents either. So it doesn't follow that reactive systems have prevented accidents. If we come to a point two or three years down the line and the look ahead system, which certainly have a desirable factor of being able to do avoidance, aren't yet certified, will the FAA require people to install the reactive systems or instead would it take the attitude that the potential advantages are great enough that people would be able to defer installing the reactive systems to see the look ahead can be brought to a suitable level of maturity?

A: Frank Rock (FAA) - It is a regulation; you have it, it is on the books; it has been mandated and you have a compliance date. I believe this one was mandated by Congress as well, which means you are going to have to get special dispensation to get around that. The regulation in the situation that we had with the predictive systems was one in which the petitioners petitioned the administrator for an extension and they were given two years for an extension. Those people who have not done that will have to comply with the rule. Now when we get to that point of course, other things may happen. There may be petitions by a large group of people such as the ATA or someone like that, who petition the rule to be extended. This is all possible, but right now there is nothing in the works that would indicate that it would go beyond the 1993 date. That is the date

that the TCAS as well as the reactive system requirement ends.

Q: Myron Clark (FAA) - There has been extensive discussion on calculating F-factors. I do not believe I have heard any discussion of the error ranges in the calculations.

A: Roland Bowles (NASA Langley) - We have done those, and here is a simple way to look at it. For remote sensors, the way we calculate it is basically the scalar groundspeed divided by acceleration of gravity times a measured estimate of the gradient. That whole term is actually much more complicated, but at the risk of being run out of here I am not going to show you what it is. It actually is a rank two tensor taken with a suitable inner product. It depends on all nine elements of the wind field gradient; three winds shearing in three dimensions. For purposes of this calculation the simple form is O.K. From this we subtract the vertical wind divided by the airspeed. One way to look at this is to let there be a nominal value of the things that can have errors. Groundspeed measurement can have error, that is coming right off of the airplane or an estimate from the ground radar. The gradient estimate, the partial of horizontal wind with distance, can have errors. The vertical wind estimate can have error and airspeed can have an error, because that is a measurement off the airplane state variables. But, the airspeed errors are very small and trivial so we won't bother it. So, the change in F depends upon taking the appropriate derivatives of the things that have errors. You evaluate it around a nominal value. Take the RMS and throw in reasonable errors in groundspeed measurement, gradient measurement and vertical wind measurements, and you find that the error is on the order of 10% of the threshold value. In fact, that was one of our instrument requirements that we try to hold the error to 10% of the threshold value. I did not bring the curve with me, Myron, but the problem is under control.

Myron Clark (FAA) - A little follow up on that, if I may Roland. I know that test pilots want to know the F-factor because they are out there flying in it. But, what I am concerned about and I don't think there is anybody in my organization that is to enthralled with, is the idea of letting pilots know what the F-factor is and what the aircraft performance is so they can play one against the other. So, as long as we are not thinking along those lines.

Roland Bowles (NASA Langley) - No, this is the variable by which one thresholds to enunciate through excepted caution warning protocol in the flight deck, a level 3 alert. No, we don't say it is .09, tell me whether you got that performance at your configuration and weight and if is O.K. No, absolutely not. No sensible person would propose that.

Q: Gerry Aubrey (United Airlines) - We have heard a lot the past couple of days about forward looking wind shear on the glide slope. How about on the takeoff?

A: Brac Bracalente (NASA Langley) - From NASA's standpoint, we are using it during takeoff. We usually tilt it up at about three degrees on takeoff. I did show one event where we landed with a small microburst at the departure end of the runway. We were in an auto-tilt mode, and as we came down the antenna was tilted up. After landing it was at about plus one and a half degrees and as we taxied down the runway we were still detecting it at the other end. We feel the radar can be very useful for takeoff and work there as well as it does in the landing case. In fact, we think the landing case is more difficult than takeoff. So, we feel that if we can solve that, then we can probably handle the takeoff.

Bruce Mathews (Westinghouse) - We have collected data on the Continental from weight on wheels to 2500 feet, landing or takeoff. When we were in Orlando we did see wind shear during one of our takeoffs and we could show you a tape of that if you are interested. We operate the mode the same way whether it is landing or takeoff. We point the beam as a function of altitude, so it does not matter. The prediction is made a little different on takeoff because you are trying to project where the takeoff path is going to be. That would be the only difference, the expected path of the aircraft.

Q: Mike Lewis (NASA Langley) - We have heard throughout the conference fairly open discussion about the IR system and its performance from the other airlines; false alarm rates, nuisance alert rates and things like that. We have not heard the equivalent sort of information about the radar performance on Continental. I think from what you said you aren't looking at the data and that the radar manufacturers are taking it all home, and they say it works great. That is perhaps not the same sort of treatment we have been giving to the IR box. The question is either for Continental or the particular radar vendors who are operating on Continental. Can you provide that same sort of information that we have been hearing about the IR box as to the radar performance on false alarm rate?

A: Steve Grasley (Allied-Signal) - At this point and time the data gathering effort from our perspective at least at Bendix is fairly new. We are analyzing data I don't think we can convincingly say to ourselves that it is performing at X level. We don't know that yet. But you can be assured that we have dialogue with all potential customers about that and we share that data with them rather closely. I would say that there is probably a chance that we can talk about those things more in detail at the next conference or in the future.

Q: Mike Lewis (NASA Langley) - From the data that you have looked at so far have you seen any false or nuisance alarms in the radar results?

A: Steve Grasley (Allied-Signal) - We haven't but we are not processing in that nature yet. We are still looking primarily at raw data and raw calculations as opposed to calculated F-factor and how that may be interpreted. We are not to that stage.

Roland Bowles (NASA Langley) - There was a well defined basis on which airlines were given the exemption option. The real question is has there been sufficient data collected to warrant continuing the exemption process? And if so, where is it? And who has seen it? Fair question, Frank? I don't think we saw any data this morning from the airlines. I think we saw some good stuff from the manufacturers, but we didn't see a hell of a lot of data from the airlines. I guess your point Sam is that you are letting the manufacturers do it for you. Maybe each manufacturer that is in the exemption process could comment on whether he is meeting his plan as approved by the FAA to move forward in the exemption process?

Bruce Mathews (Westinghouse) - In response to Mike's question if I can still remember it. We reached our final configuration about April 3rd. We do not have a lot of data. We have one tape and we were glad we got it. Continental helped us get it by pulling that tape fast for us. We do not have a lot of data to show for what I would say is a final configuration. We will be able to start collecting that though and we will show it to people as we get it. I think our plans are to move into a different phase of development. We are going to get ready to go fly our BAC 111

again with our equipment to gather data on microbursts. It's very difficult to put a qualifying hazardous microburst minimal detectable features into a qualifying urban airport clutter environment and I think that is what we want to do in some sense for certification. I do not know how you can do that with a realistic small number of flights. We have got to get the mountain and Mohammed and super impose them on each other. This is the way we are going to proceed with our development. We are flying for false alarm performance now, and we will fly for microburst but we will have to do these things separately because they don't seem to happen a lot together. To demonstrate a hundred thousand hour false alarm time is going to take a long time. I heard people begging me to turn off that false alarm tape that I was running. If you want to look at it you can look at it. These things are not exciting to look at, and grown men let alone women and children don't want to look at urban clutter as you are landing in it, it is just not neat stuff to look at.

Q: Roland Bowles (NASA Langley) - Where did you get one hundred thousand hour false alarm rate? Where did you get that number from?

A: Bruce Mathews (Westinghouse) - Well, I think that is flight hours, one hundred thousand flight hours of false alarm data.

Roland Bowles (NASA Langley) - It is two hundred and fifty flight hours.

Bruce Mathews (Westinghouse) - Is that what it is? OK, good.

Q: Dan Stack (ALPA) - Regarding in flight detection and prediction of hazards. We have seen presentations that indicate the real risk can exist not only in the immediate vicinity of a microburst but at a considerable distance away. It appears that some testing and evaluation is necessary tangential from the core, prior to the certification process. What plans are in place to insure that these items are adequately addressed? When this area is thoroughly mixed it will probably lose its temperature difference from surrounding air mass

A: Dave Hinton (NASA Langley) - From a performance stand point it is part of our plans when we go into pilot simulations to look into an issue of how close to a microburst icon might you want to come, or how far should you stay away from one of those given various icon shaping algorithms. I see John Hansmen has left, but at MIT they have done some parametric studies looking at the effect of being off center in a microburst and have found the threat drops considerably at very short distances away from the core and it is a very localized event. With respect to other phenomenon that may exist some distance from a microburst such as a gust front, somebody may want to raise the issue. I do not know of anybody looking at gust front detection as generated by microburst that may be some distance away.

Q: Unknown - There were two things that seemed to me to be coming out as somewhat of a standard during the discussion the last few days. One of those was the comparison of different sensors against the In Situ algorithm results. Is there going to be some requirement to make that comparison somewhere? Is that going to be something that we are going to have to consider? Also, we talked a lot in the last couple of days about averaging the F-factor calculation across one kilometer. Is that becoming the standard? You hear a lot of consideration that in some aircraft it is not right, maybe in some others it is? I don't know if there is a real answer at this point and

time, but those two things seem to be coming out as kind of a standard. I am not so sure that it is exactly right.

A: Kirk Baker (FAA) - If you are flight testing a radar there is a couple of ways you can validate what you are seeing, and NASA has shown that. One is by TDWR and the other is by an In Situ F measurement. I don't see us deviating from that method of demonstrating the truth of your system. I think that is the technique that is around and I think we will be using it. It is something that we are going to have to negotiate, depending on what you propose to do in your certification plans to demonstrate that your system performs its intended function. Something that we have also asked NASA to help us with is defining the threat. The one kilometer averaged F seems to be something that is coming out as a viable way to probably take care of some of the wind shears that people keep trying to get us to say you don't have to protect against. One kilometer seems to weed those out. It is a sustained F over one kilometer. I think that the real threat to an airplane is a sustained F, so that is a standard that we will probably be starting out with?

Mike Lewis (NASA Langley) - What we have tried to do and was summarized in the curves that I showed a couple of days ago, is to postulate a certain set of assumptions and show what an aircraft can withstand given that set of assumptions. I think it is NASA's feeling that it is the FAA's job to decide whether those are in fact FAA agreed upon assumptions, or whether they want to change those. That may or may not have an effect on whether that simple one kilometer test is adequate. From what we have seen, and I showed in the last curve of my presentation, that simple test seemed to do a very adequate job of protecting against even the close call incidents by a wide margin and certainly against the accident cases.

Mary Jo Hoffman (Honeywell) - I have a comment on this F-factor issue. This is my first wind shear conference. I think I can help you guys see the forest for the trees. I came in here and everyone was talking about F values of 0.15 and it is kind of an assumed thing now that it is a standard. It is the same as this one kilometer sustained F-factor issue. Perhaps we should consider a ranking of the performance of the vehicle as something like a percentage of the thrust minus the drag over the weight, the energy capability of the aircraft. For example, in a 727 I might want my red alert to go off at a F of 0.1 but if I am in a 747-400 I do not want it to go off unless it is a 0.2. It is just an issue that I am throwing out for discussion.

Sam Shirk (Continental Airlines) - I think you are going to find a lot of comments from the airlines on that. A lot of the newer two engine aircraft have tremendous performance capabilities. I know discussions at American, Northwest and we at Continental are hoping that the FAA can see fit to certify a system where aircraft performance will be factored in, I hate to say that because I know they are here to help us and it is the other FAA, but there are some good reasons to have a relaxed F-factor if you will on the airplanes that have great performance. I think it is an issue that we as airlines I know hope that the FAA does address and hopefully in a manner that we would like to see it addressed.

Q: Roland Bowles (NASA Langley) - Why Sam?

A: Sam Shirk (Continental Airlines) - What we are really talking about here is a true performance factor. I think operationally the airlines really need this latitude. I can see it

plugging our system up. Our ATC system is overloaded right now. I think there is good reason to be able to depart with a 737-300, a 767 or a 757 series airplane, when a 747-400 or a 727 might sit on the ground because it doesn't have the performance margin. I think it is something that we have to look at, at least from the ATC side of the equation. As to whether that same microburst that we have decided now that we are going to fly through is going to grow, that is a touchy situation. Maybe it will get smaller too. I am not suggesting that on takeoff if we have got a microburst inside of a mile and a half we say "Hey this airplane has got a lot of go to it, that is no problem, I'll press on." I am not saying that at all. I am saying for that stuff that is perhaps outside a three miles, that might be a consideration that we would have. It also might be a consideration on final whether to abort the landing or to continue. I think it is something that we have to look at.

Q: Roland Bowles (NASA Langley) - When you look at the one kilometer criteria, what you are saying is that it is O.K. to go ahead and take something on the order of a three knot per second hit, for something on the order of ten seconds. Or equivalently, almost 2,000 foot per minute induced sink rate. That is what 0.105 will do for you. Now you may have a lot of performance left, but I am not so sure you would necessarily want to use it. You would like not to expose yourself, because it can get worse. Kurt, do you ever envision a situation where you will make thresholding aircraft specific?

A: Kirk Baker (FAA) - Maybe some of you old dinosaurs can help me that were around when the TSO was written. I think this subject was heavily debated, varying the threshold for the performance of the airplane. The situation that you ran into with the reactive system was you could have a 737 on the runway in front of your 747 takeoff and fly right through something that you probably would not want the 747 to fly through. I think that was one of the reasons that we felt that we would stick with just one threshold. For predictive systems, where you have the ability to look ahead, in my opinion you are going to run into the same type of operational concerns. You are going to have guys going through and some guys going around, and they are all going to be wondering why did that guy go through it and I did not have an alert, or why did that guy go around I don't see anything out there. I think it is something we can entertain, but I am not sure much is going to be gained out of it. These events are not that common and they are short lived. I would like to see the thresholds stay at the same standard that we have it now for reactive. If someone can come up with a scheme that seems to make sense both technically and operationally I am sure we would consider it for the forward looking system.

Jim Evans (MIT) - I would like to make some comments on what we have learned from TDWR experience. TDWR and LLWAS have both gone through a mode which for example there are a distinction between microburst alerts and wind shear alerts with loss. The guidance by the airlines has been by and large when they get a microburst alert the people should not operate and when they get wind shear alert with loss they in fact have a pilot decision that takes into account how loaded the plane is, the density altitude, a bunch of things can be worked in. When we look at our statistics we see far greater numbers, by factors of four or five, of the wind shear alerts with loss than microburst alerts. I can certainly say that in places like Orlando, based on some of our experiences between 1990-1991, it made a big difference whether we were calling some alerts a microburst alert versus a wind shear alert with loss. I think that at least in Orlando where you get a lot of minutes a year of alerts it does make a difference. Now you can say it doesn't make a difference so much to one pilot, but I can tell you that the air traffic down there was getting pretty

annoyed after a while in 1990 when we were very conservative. I think that right now in the ground based systems there is some reason for latitude. One of the other elements about some of the look ahead systems is if I have gone over an F of some number for one kilometer, I would also ask what about the next kilometer, and the next kilometer beyond that. If I have a thing that sticks up like a thumb nail and it is one kilometer I may feel differently than if it is a little longer than that. That is another thing that you would know from the look ahead system, presumably in some cases at least, it would know how big it is. John Hansmen showed some examples of a pilot presentation that in a sense had some form of gradation that allowed a pilot to take into consideration these other factors that get lost when you go to a fixed red-green threshold.

Q: Roland Bowles (NASA Langley) - In effect we are doing some of that today. It is my understanding that in some of the certified reactive systems today we will gain schedule before the threshold test as a function of altitude. For example, we might be computing the energy loss parameter, but down gaining it to 80% value before testing threshold. Then, let the gain go through one, as you go through 750 feet, therefore increasing the sensitivity of the system. So in effect, depending on what airplane that is on, we may be doing some aircraft specific stuff right now. I believe there are systems out there that gain schedule with altitude. Kurt, do you know of any such systems?

A: Kirk Baker (FAA) - Sundstrand does do some gain scheduling. I am not that familiar with their systems so I don't really feel I can get into the technical side of it. It is usually not the varying of the threshold, it is the timing of the gain itself.

Roland Bowles (NASA Langley) - I do not know how many airplanes we have out there, but a reasonably significant number were equipped prior to the TSO locking up 0.105 as the threshold. So, I know we have some planes out there that the thresholds are set at 0.12 right now. There is a 20% variation right there between some early variance and what the threshold calls for right now.

Dave Hinton (NASA Langley) - I guess I also would like to add one thing to that. Think about what we are trying to do with these systems. We are trying to prevent the airplane from being exposed to a hazardous situation, perhaps very close to the ground. If you park one of these microbursts at the middle marker and you throw 767 with a lot of performance into that, but you throw in a little pilot recognition delay, you may be digging up approach lights before you get all that thrust turned around and going the other direction. It is possible. Also, we have an existing training package out in the fleet that has played a major role in preventing any accidents since 1985. It gives the pilot certain guidelines as to when the atmosphere is doing something very unnatural and you shouldn't be there and you should go around. Now if we start talking about bumping thresholds up to perhaps 0.15 when you are back at the outer marker, and there is a 0.13 microburst sitting inside, you are going to deny that pilot an alert yet expose the airplane to a situation where the wind shear training is going to kick in, and the crew is going to say I shouldn't be here. So you are going to go around anyway, but you have exposed the airplane to the threat at low altitude. That is something that has to be considered I think if you want to start bumping up thresholds as a function of airplane performance.

Mike Lewis (NASA Langley) - I would agree, and the same case holds on rotation. You can postulate the special case of the microburst right at rotation for which all the extra power in the

world isn't doing you much good. At that point all the air planes are essentially equal as far as there margins and so forth.

Terry Zweifel (Honeywell) - If you vary these things with altitude, in essence what you are doing is sucking the guy in to go lower. The lower he goes the worse it gets, and you just delay and lose valuable time. Those who have been in simulators with reactive systems and flown out of a wind shear know that one, two or three seconds can make a big difference on whether you survive the accident. That is why I personally do not like the idea of scheduling. In our system we don't actually use 0.105. We use an energy loss threshold which is kind of the equivalent of what Roland has been talking about. 0.105 is really an energy rate of the airplane. So if you take it over 1,000 meters, in essence you are integrating that rate. Whenever you establish the distance you are saying that is how much energy I will let the airplane lose before I turn on the light. We do the same thing except it is a time based type of thing.

Roland Bowles (NASA Langley) - It seems to me that any kind of tinkering with that kind of mechanics inside the boxes is no substitute for good design. A lot of the reasons for raising thresholds is to get rid of other undesirable features. There may be better ways to design those features out, and maintain the integrity of the protection system.

Terry Zweifel (Honeywell) - Obviously if you could do it somehow you would like to set the threshold much lower than that. The reason for raising it is to get some gust rejection out of it. There is always a compromise over where that level is going to be. I think that is going to be true of some of these predictive systems as well as the reactive systems. I think the 0.105 establishes a base line for commercial airplanes and is probably valid for the whole fleet that we see out there now. I think Roland has probably looked into that and in fact proven that to himself.

Frank Rock (FAA) - I wasn't getting up to say anything, I was getting up to leave, but let me just throw a little bit into there. After forty years of working in this business, I haven's seen a system that hasn't been improved for some reason or other over a period of time. I have never seen a system go out on the market and stay static. It always improves, so we can always expect that there is somebody coming behind us that is smarter than we are and do it better.

Q: Terry Zweifel (Honeywell) - I do not want this to appear as a biased comment coming from someone who works on reactive shears, but over the past three days we saw the Doppler radar, the infrared and the LIDAR results, and while I can't say that it is true, it looks like there is a possibility there may be shears that they won't detect. It was stated that maybe the Doppler radar would have to go down to minus 15 dBZ. I am not a radar guy, I don't even know if that is feasible, but it doesn't sound real good. My question is, would the FAA certify a system for which there were known cases where it would not detect a shear?

A: Kirk Baker (FAA) - One of the things that you have heard talked about, is what is the real intent behind a system like a wind shear detection system? Is it to detect a wind shear, or to prevent an accident as a result of a wind shear? That question has come up, it is not the first time we have been asked, and it is going to keep coming up. It is part of establishing a probability of a missed event. In our requirements document we have something called a missed event and that is what you just described. How are we going to decide what is an acceptable rating? I am not sure yet. TDWR has a 90% probability miss, and we have heard discussions on what that really

means. When you put something on an airplane and it is classified as an essential system, it has to have a probability of missing of 10^{-5}. Now there is also a lot of conjecture about whether a radar system can meet a requirement like that. Somewhere along the line we are going to have to sit down and grind through some safety tradeoffs. If we can only detect 98% with a forward looking system, we have to make sure that for the 2% that we miss we can justify why we accepted that. I have a feeling it is going to be based on some great improvement on safety. That is the only way I can see it. From what I have seen right now I don't think the radars can meet 10^{-5}, maybe they can. That is going to come out in the certification work that we do. We are going to see what the extremes are, and we are going to test the extremes. The models that we create are going to be in high clutter, embedded rain, dry microburst on the other side scenarios. We are going to have to test the bounds to see if we can come up with what is the probability of a missed event for a system like this. I think it is kind of early to say that we won't certify a system that can't detect that 2%. We are going to have to look at it. We want to be careful not to stifle some real promising technology.

Roland Bowles (NASA Langley) - This is one that I really get sort of excited about because if I look at the TSO there is no such specification in there for reactive manufacturers. They state a probability of nuisance alert. All these alerts are carefully defined as per the SAE document, very carefully defined. I think that is one of rigorous things that has come up on the airborne side. When we talk about alerts for ground base systems is not a rigorously defined alert. Some people would argue that is advisory information. I don't think there is a missed alert specification in the TSO. What you do is you take 7 or 8 or 10 accident reconstructions and show that you could have detected those. Now we are coming in with other industries and we are going to generate a new number and hold them accountable for some ten to the minus whatever. I don't see that it is necessary. The point is that you can be so rigorous here that you lock out some growth in marketplace and competitive issues involving this nation's avionics and civil transport. You could do that real easy.

Q: Terry Zweifel (Honeywell) - Does that mean that the LIDAR would have its own value and the Doppler radar would have a different percentage that you allow it to miss and the infrared another, or how would you do that?

A: Roland Bowles (NASA Langley) - No, I would hope not. I would hope that a careful analysis from an aviation safety perspective would be done. Someday there will be a hole in the ground resulting from an airplane crash involving a reactive box. If we could have prevented that with a forward look system that had a detection probability of 0.7 it may have been worth it. We don't want to rule out the technology based on an arbitrary set of numbers unless it is based on really careful analysis. I think the issue on the analog airplane is a good one, I was in the room when that one was set up and I know where it came from?

Terry Zweifel (Honeywell) - Well, obviously one of the things you could do is something like TPS did. You can incorporate a backup In Situ algorithm, that is a possibility. That makes the system cost more because now it has to have accelerometers and air data inputs that perhaps weren't needed in the first place. I was just curious to know what the thinking of the FAA was on all of this. ·

Jim Evans (MIT) - You really haven't responded in a fair way to the challenge that was put forth by Joe Gibson. What we are trying to do is to prevent accidents. Now we have already heard about the Continental Flight, there was also an Air Cubana flight which crashed in Havana, and there was a takeoff accident. You wouldn't even argue that they would have been prevented by and In Situ system. It seems to me that if we are going to run around arguing about accidents and which accidents would or would not have been prevented, you would lump those two incidents in and you would be down to an 80% system. The challenge that was put forth by Gibson was, as you go to more and more severe sheared events you come to events for which a reactive system does not react fast enough, and what is the probability of that? I don't know how you could prove that it was 10^{-5} of all microburst events. I don't think you could hold that for one minute. It seems to me that what you are talking about is the probability of preventing accidents. I think Joe Gibson put forth a structured approach for dealing with the analysis. I have never seen the details of the simulations that proved on all the accidents which occurred that you surely could have prevented them and I don't think we would know that. The reason we don't know that is all we know is what the winds were like on the path that the plane flew. We have no way of knowing what the winds were had the plane been responding and tried to fly a slightly different path. I think there is a lot of elements to it that we just don't know. I would argue that you want to go back and start worrying about probabilities of preventing accidents and we will start talking about where the accidents would occur and why they might occur.

Terry Zweifel (Honeywell) - But then you run into the same problem. How can you prove the infrared would have prevented an accident? That is the difficulty that you can get into when you try that tack. How do you prove any of them would have prevented it?

Jim Evans (MIT) - My only point would be that if you are willing to acknowledge that the reactive systems don't really provide effective protection from a microburst on the runway when you are about to takeoff. It seems that we can argue from there.

Terry Zweifel (Honeywell) - Actually what you are saying isn't quite true, some of the systems do detect wind shears on takeoff.

Q: Sam Shirk (Continental Airlines) - Do they detect them effectively?

A: Terry Zweifel (Honeywell) - Well, define effectively?

Q: Sam Shirk (Continental Airlines) - Do they work?

A: Terry Zweifel (Honeywell) - Yes, they are certified to do it. I hope that the FAA would not certify a system that flat out did not work. I mean I think we can give them a lot more credit than that. We have run it on simulations of the accidents, including the one you had the picture of, and it did detect it.

Roland Bowles (NASA Langley) - I don't how many valid alerts we have got out there right now in the reactive system. But I know one thing, NASA 515 got more real confirmed microburst penetrations than you have probably got in the civil fleet right now. We know how our reactive box works. I have not seen any evidence of how the boxes that are already out there work.

Q: Terry Zweifel (Honeywell) - It sounds like you think I am pushing a cause here. I wasn't trying to say take your radars and go home, the reactive has solved the problem. That is not what I am trying to do. I am trying to say, suppose you get to the point where these technologies simply can not do it, you simply can not design, for example, a Doppler radar that can go down to minus 15 dBZ and detect a shear. What do you do then? You say well lets stop and go look at some other technology or how do you define where this is?

A: Roland Bowles (NASA Langley) - Well, I think there is very adequate precedence in the air worthiness flight standard side of FAA. We know there is a gust load that will not keep a wing on an airplane and we design to some maximum gust load, but there is one out there that is going to tear it apart.

Q: Terry Zweifel (Honeywell) - But the probability there is a lot higher than 10^{-5}. Either that or I am going to take the bus back to Phoenix. Obviously airplanes are not totally bullet proof. I was just bringing up the point of what do you do. I would hate to see everybody go down these different technology roads and it very well could be that no one of these technologies can detect all of these shears - dry microbursts, wet microburst all of that stuff. Then where are you and how do you define what is acceptable?

A: Roland Bowles (NASA Langley) - It is going to be settled in policy I think, with some degree of analysis to support that. As Jim pointed out there is no doubt some out there that will bite anybody regardless of how good your reactive system is. If you could save one accident per ten years would that be justifiable for forward look, even though its detection probability may be 0.8?

Terry Zweifel (Honeywell) - But then we can take that to the extreme. Lets assume it can only detect 0.05 and it saves one airplane. Where is the line?

Roland Bowles (NASA Langley) - I think the engineering integrity has to be good enough to prevent something like that getting through.

Terry Zweifel (Honeywell) - That is the point, the whole area seems to be fuzzy to me. I was just wondering how the FAA and the industry were addressing that or if any real thought had been given to it. You have got some pretty gung-ho programs going here and 1995 isn't that far away. It seems like some of these things have got to be settled fairly soon.

Kirk Baker (FAA) - I don't think we can answer that question right now. I haven't seen the vendors step up and say this is as good as my system can do. I don't know how the FAA can make a judgment until we know exactly what you can do. Right now the position that I have taken is to go to the regulations. It says in AC1309 an essential system to performance intended function must meet 10^{-5}. That is where I am at right now. I have not seen any of the vendors step up and say, well, I can only see a 2 dBZ dry microburst in a certain clutter environment. We are going to take the hard line.

Q: Unknown - You made the statement earlier on that the criteria was one of preventing accidents and things bumping into the ground. That is not necessarily the same as detecting a dry microburst because there are category dry microburst that may not be detected, but they also may not be hazardous? We as manufacturers and designers do have a set of design criteria. We

depend upon Roland Bowles and his team to define a target. I think it is Byron and Lee that provided statistics on probabilities of various microbursts occurring. We look at designing air system to detect those. What is missing from those statistics is how many of those remaining are hazardous. We do need that information from the scientific community if we are going to answer the 10^{-5} question. Depending upon how you chose to define that. Is it the detection of the microburst that is important or is it prevention of the accident that is important?

A: Kirk Baker (FAA) - That is the obvious question. That is why I stated earlier that I think we need to sit down and come up with a logical and scientifically validated, as well as it can be, description of what "intended function" really means. That is what you are trying to describe. Is it to detect any microburst or wind shear phenomenon or is it to prevent accidents? We are going to have to sit down and develop that, and I am not going to give you the answer right now because I do not know what it is.

Roland Bowles (NASA Langley) - I would like to challenge the other side of the industry, Joe and Boeing and all of you guys, lets build a reactive system for 10^{-5} that we can slip into some of this technology, and all march forward. Lets hybridize! That gets a lot of people off the hook doesn't it.

Kirk Baker (FAA) - Sure does and it makes my job easier.

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13. ABSTRACT (Maximum 200 words)

The Fourth Combined Manufacturers' and Technologists' Conference was hosted jointly by NASA Langley Research Center (LaRC) and the Federal Aviation Administration (FAA) in Williamsburg, Virginia, on April 14-16, 1992. The meeting was co-chaired by Dr. Roland Bowles of LaRC and Bob Passman of the FAA. The purpose of the meeting was to transfer significant ongoing results of the NASA/FAA joint Airborne Wind Shear Program to the technical industry and to pose problems of current concern to the combined group. It also provided a forum for manufacturers to review forward-look technology concepts and for technologists to gain an understanding of the problems encountered by the manufacturers during the development of airborne equipment and the FAA certification requirements. The present document has been compiled to record the essence of the technology updates and discussions which follow each.

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