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Session VII. Airborne LIDAR Technology

NASA/LMSC Instrument Design & Fabrication

Dr. Russel Targ, Lockheed Missiles and Space

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CLASS

COHERENT LIDAR AIRBORNE SHEAR SENSOR

WINDSHEAR AVOIDANCE

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CLASS-10 FLIGHT TEST PROGRAM

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- 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

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- 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)

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.

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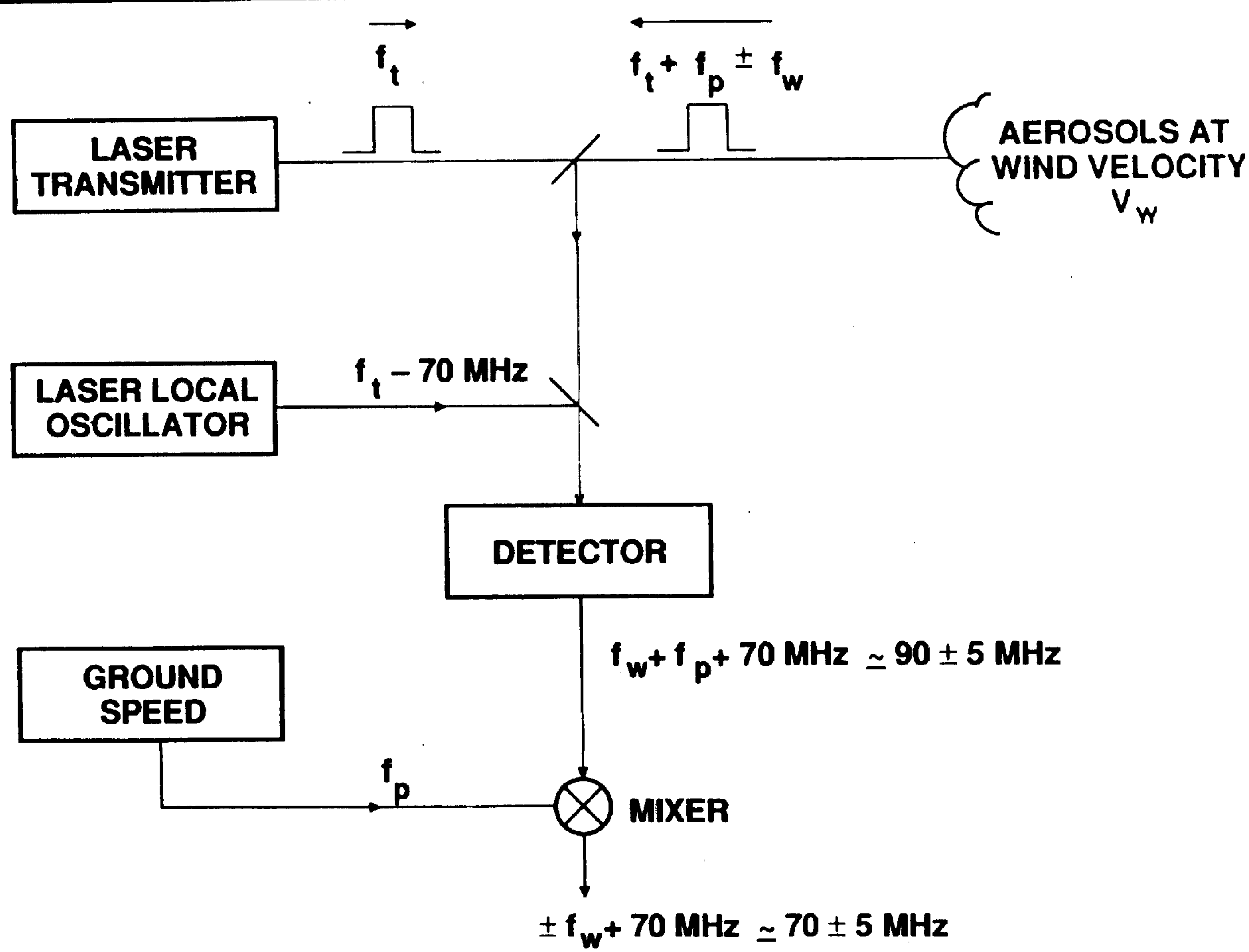
DOPPLER WIND VELOCITY MEASUREMENT



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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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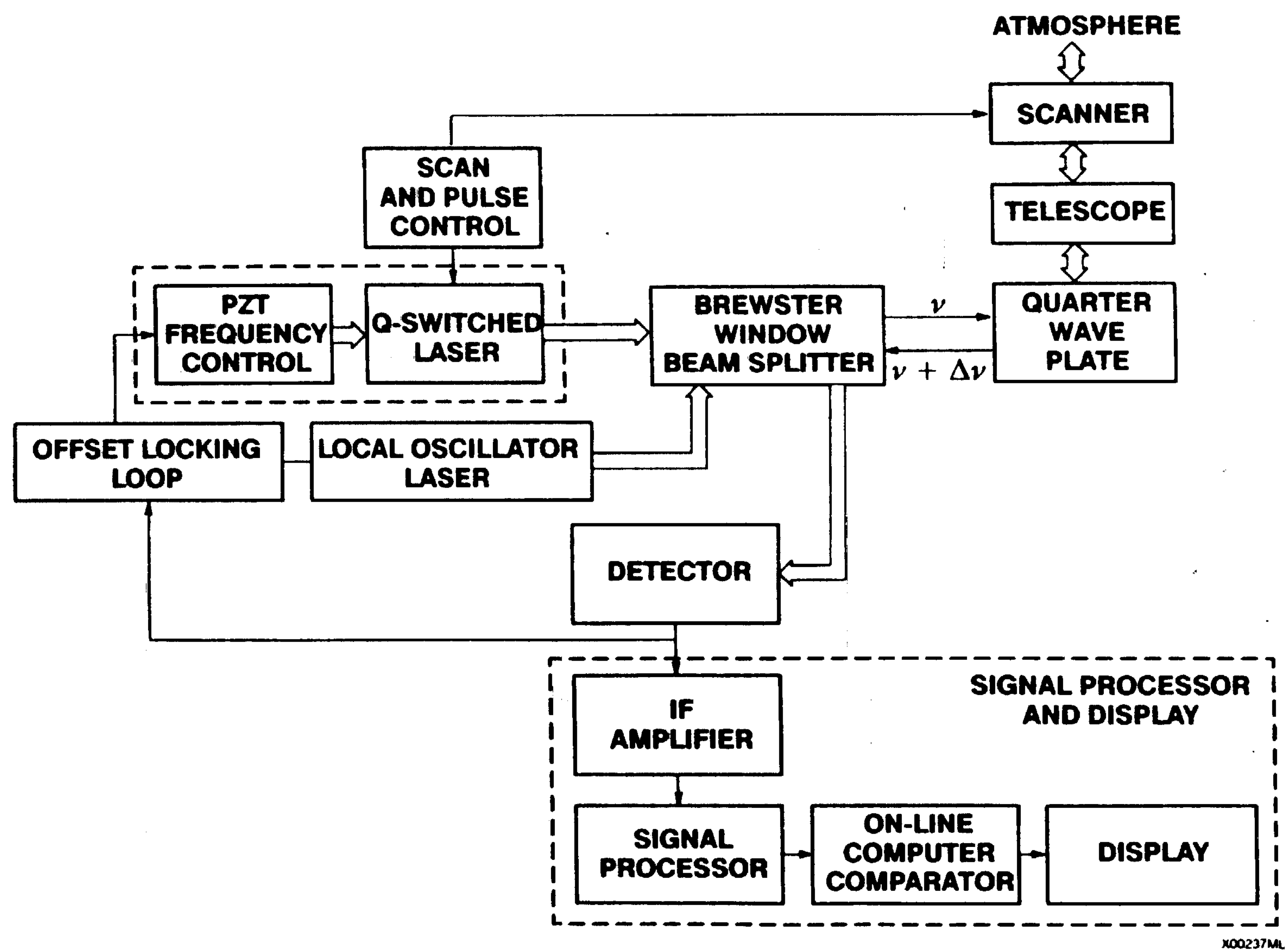
BLOCK DIAGRAM USING PULSED LASER



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SYSTEMS SPECIFICATIONS RATIONALE

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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

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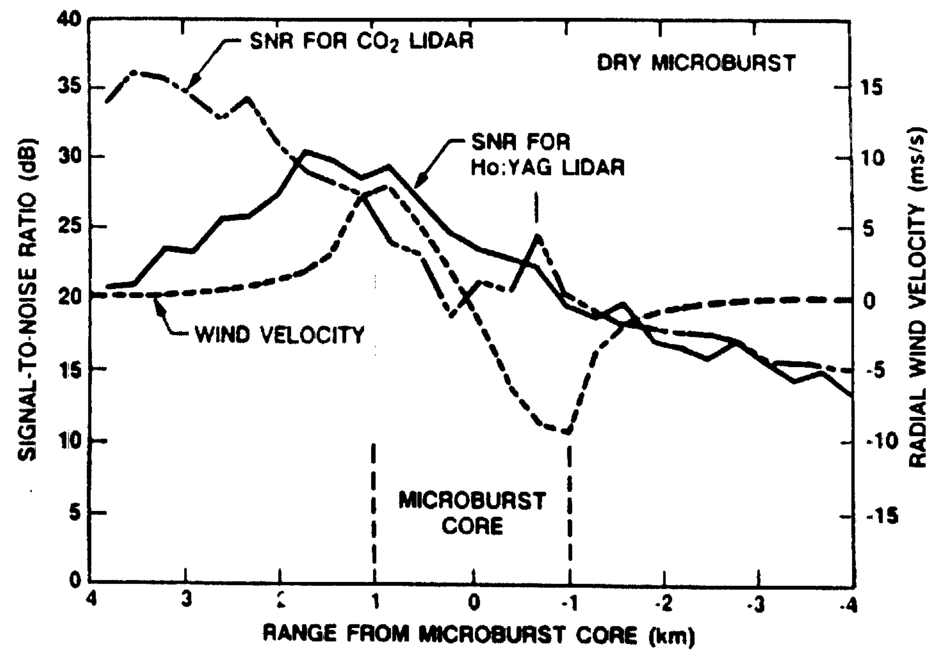
VARIATION OF SIGNAL-TO-NOISE RATIOS AND TRUE WIND VELOCITY WITH DISTANCE



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VELOCITY ERROR AS A FUNCTION OF SIGNAL-TO-NOISE RATIO, WITH TURBULENCE

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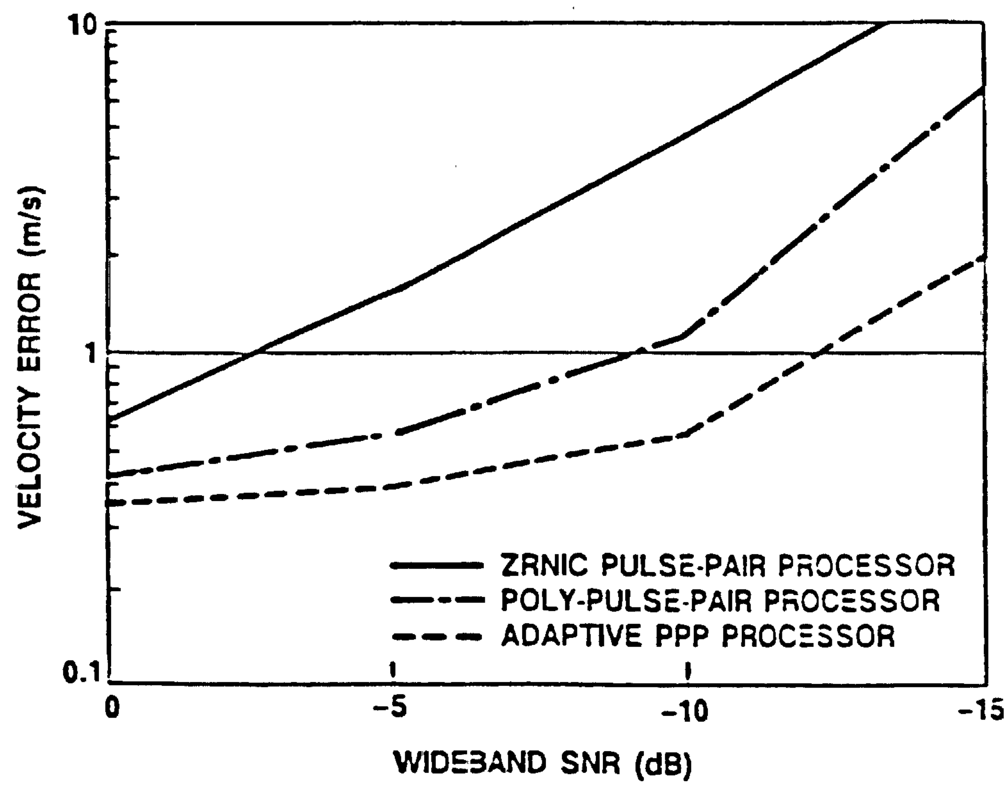

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FINAL CLASS OPTOMECHANICAL DESIGN ON NASA B/737

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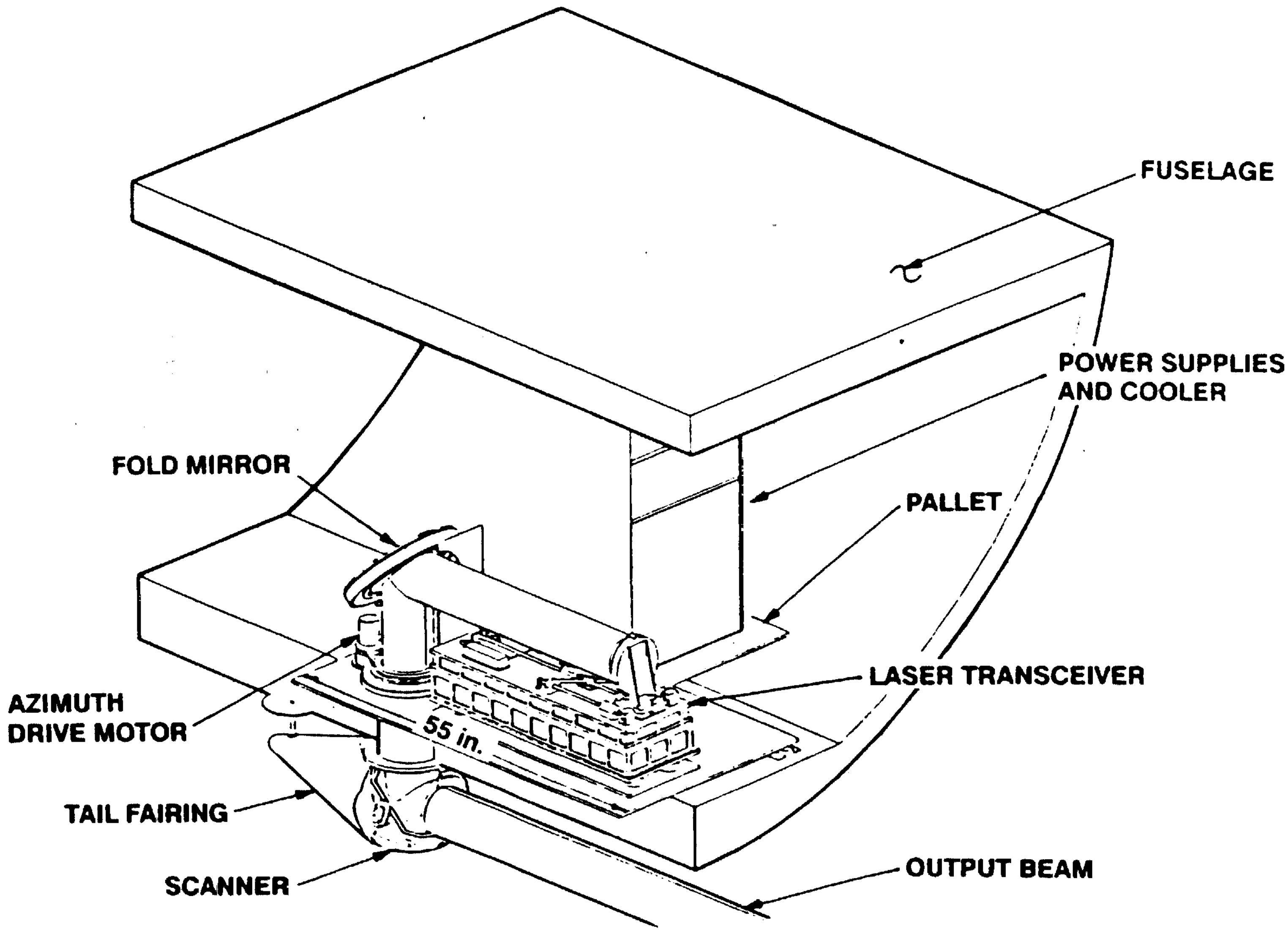

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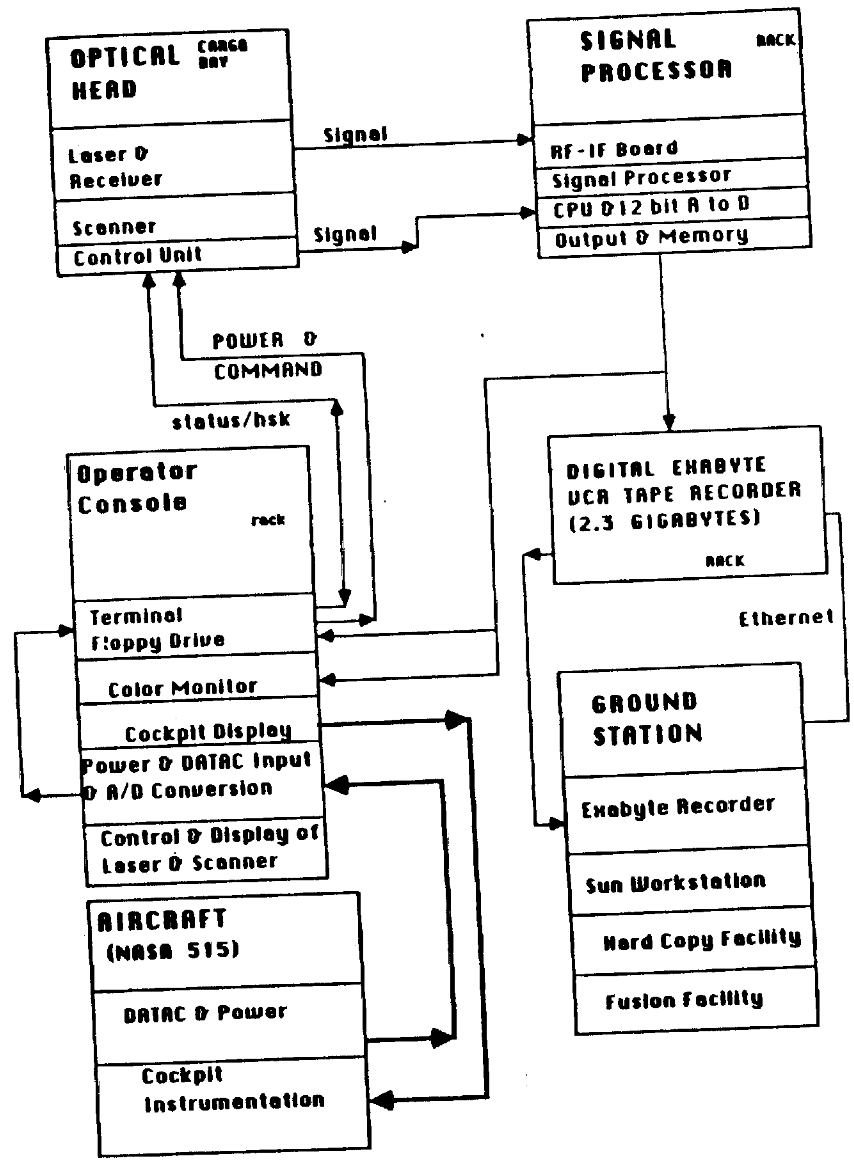
CLASS LASER WINDSHEAR DETECTOR BLOCK DIAGRAM



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 ±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.

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

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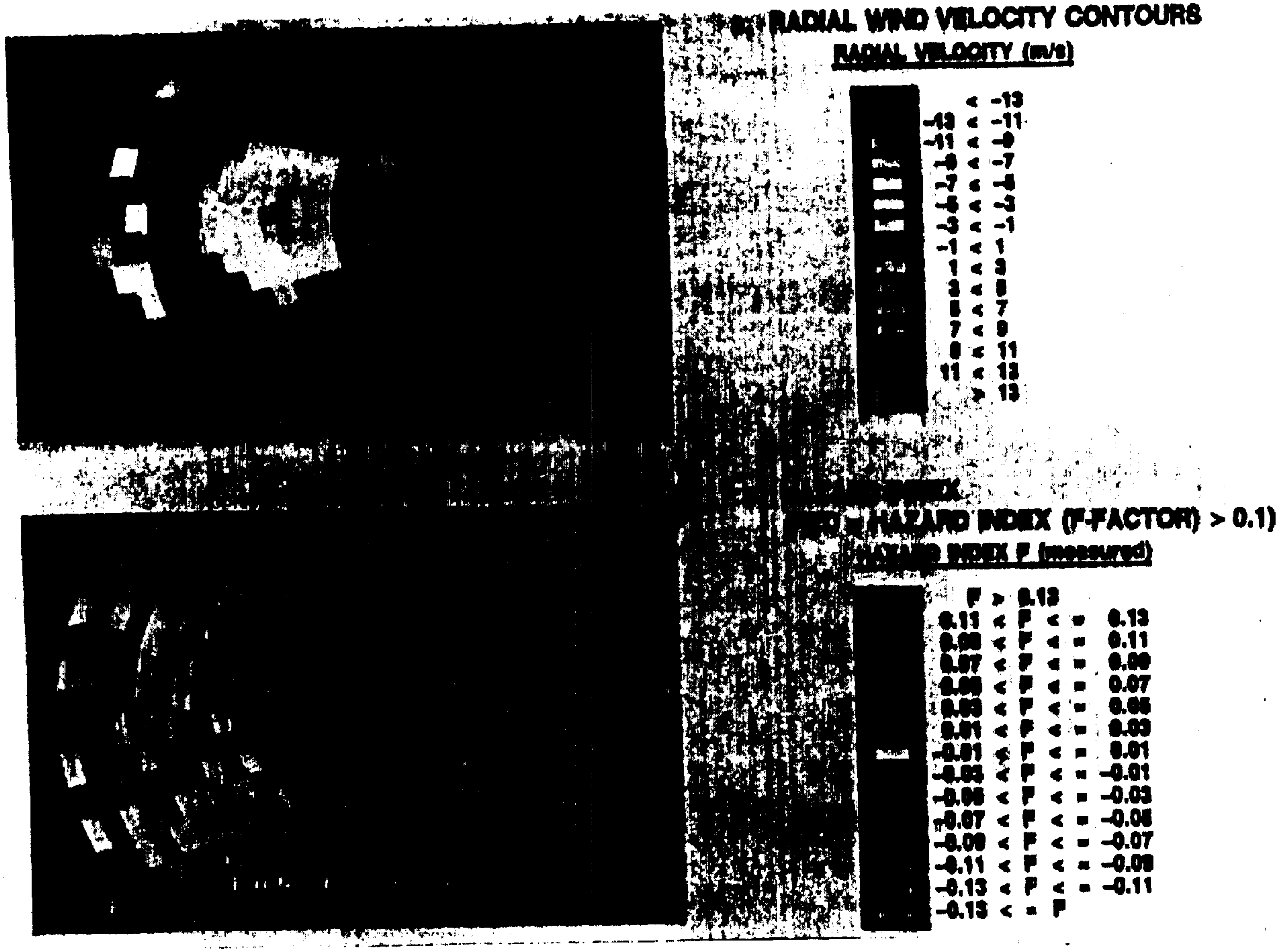

ORIGINAL PAGE IS OF POOR QUALITY

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COHERENT LIDAR AIRBORNE SHEAR SENSOR (CLASS) SNR VS. RANGE: 10.6 μm, 8.5 mJ, 10 km AEROSOL RETURNS AT NASA, HAMPTON, VA

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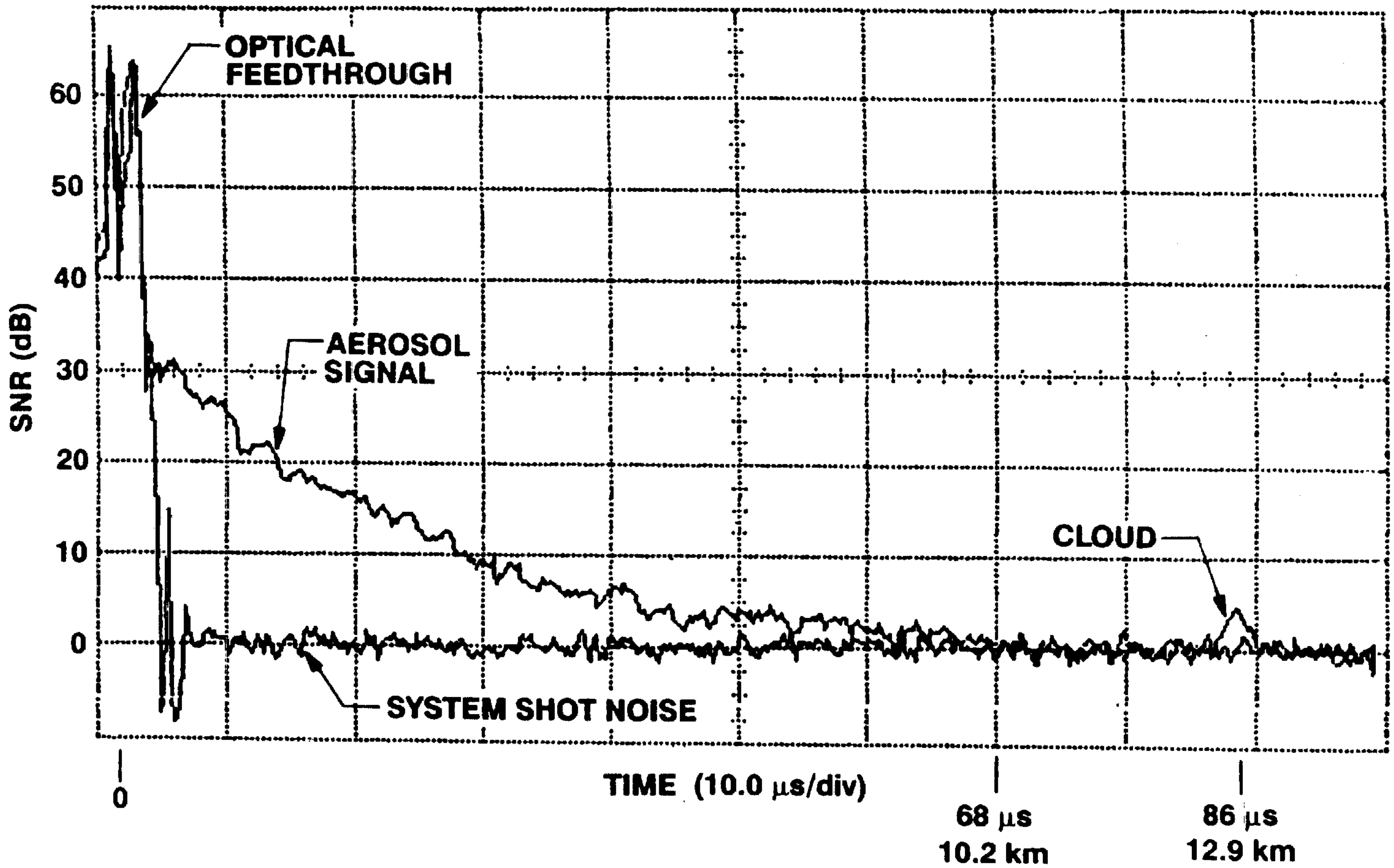

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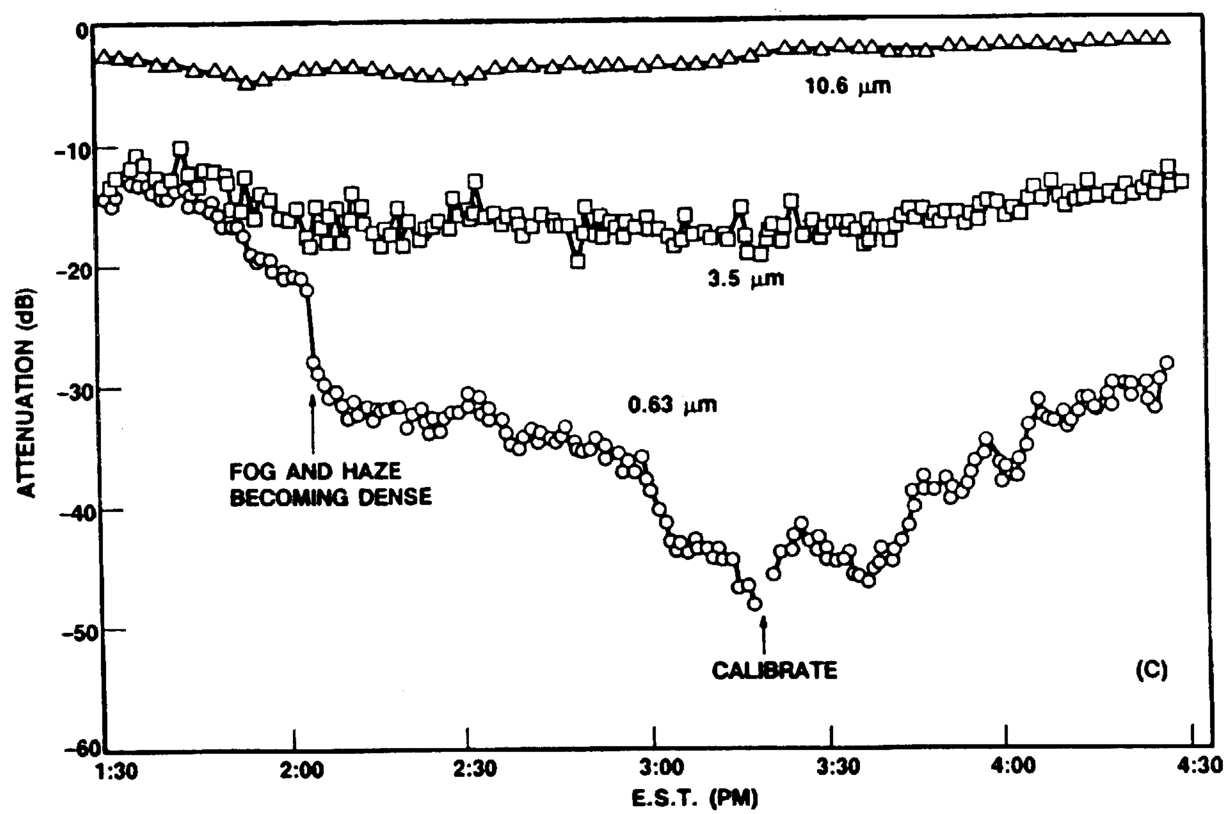
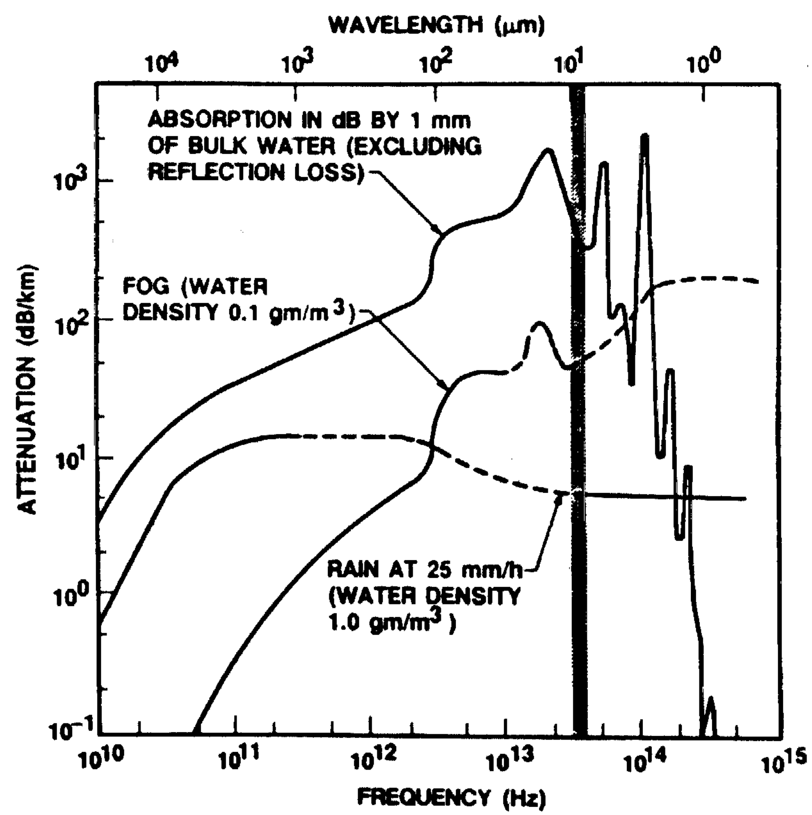
ATTENUATION DUE TO FOG

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

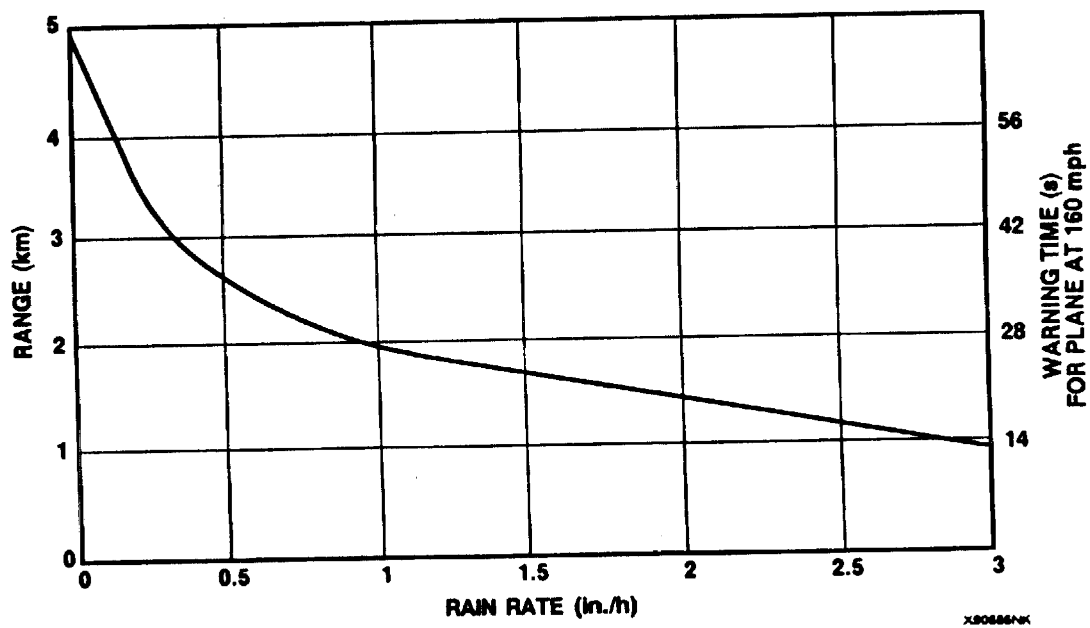
The data in this figure show the attenuation due to rain and fog for signals across the electromagnetic spectrum. Of particular interest is the attenuation for infrared radiation at 10.6 μm. At this wavelength, and a rain rate of 1 in. per hour, the attenuation is approximately 8 decibels per kilometer.



From T. S. Chu and D. C. Hogg, BSTJ, May 1988

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.



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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.