LEAR JET BOUNDARY LAYER/SHEAR LAYER
LASER PROPAGATION EXPERIMENTS

ABSTRACT

In early 1975 the Air Force Weapons Laboratory, in concert with NASA Ames and Lincoln Laboratory, conducted aircraft turbulent boundary layer and shear layer experiments using a Lear jet. Test objectives included these:

1. Compare optical degradations of aircraft turbulent boundary layers with shear layers generated by aerodynamic fences for a range of altitudes and Mach numbers;

2. Compare Modulation Transfer Function (MTF) and Line Spread Function (LSF) measurements for the same flight conditions.

A collimated 2.5 cm diameter helium-neon laser (0.63μ) traversed the approximate 5 cm thick natural aircraft boundary layer in double pass via a reflective airfoil located 25 cm from the fuselage. In addition, several flights examined shear layer-induced optical degradations produced by an aerodynamic fence located 20 cm upstream of the optical axis. Flight altitudes ranged from 1.5 to 12 km, while Mach numbers were varied from 0.3 to 0.8. Average Line Spread Function (LSF) and Modulation Transfer Function (MTF) data were obtained by averaging a large number of tilt-removed curves. Fourier transforming the resulting average MTF yields an LSF, thus affording a direct comparison of the two optical measurements. Agreement was good for the aerodynamic fence arrangement, but only fair in the case of a turbulent

boundary layer. Values of phase variance inferred from the LSF instrument for a single pass through the random flow and corrected for a large aperture ranged from 0.08 to 0.11 waves (λ = .63μ) for the boundary layer. Corresponding values for the fence vary from 0.08 to 0.16 waves. Extrapolation of these values to 10.6μ suggests negligible degradation for a CO_2 laser transmitted through a 5 cm thick, subsonic turbulent boundary layer.

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Introduction

The AFWL, together with NASA Ames and Lincoln Laboratory, have con-
ducted aircraft boundary layer and shear layer laser measurements using
a NASA Lear jet. These experiments were designed to:

1. Compare optical degradations of aircraft turbulent boundary layers
with shear layers generated by aerodynamic fences;

2. Compare Modulation Transfer Function (MTF) and Line Spread Function
(LSF) measurements for the same flight conditions. These are Fourier Trans-
form pairs.

Experiments were conducted at Moffett Field, California, during January
1975. A collimated helium-neon laser (6328Å) was the source. The aperture
diameter was 25 millimeters. A 7 cm fused quartz window and a reflective
airfoil located 25 cm from the fuselage permitted a double pass of the laser
beam through the approximate 5 cm thick aircraft boundary layer. The equip-
ment was arrayed on an optical bench in the Lear jet. A beam splitter per-
mitted simultaneous MTF and LSF measurements. However, because of limited
space for experimenters, each flight was dedicated to one of the two measure-
ments.

Aircraft missions were flown at altitudes ranging from 1.6 to 12 kilo-
meters. Mach numbers were varied from 0.3 to 0.8. Typical flight durations

were 2.5 hours. A total of seven data missions were flown in this series. Three flights studied the effects of an aerodynamic fence located just upstream of the optical axis. The remaining four missions examined fundamental aircraft boundary layers (i.e., fence removed).

All data were recorded on magnetic tape. A storage oscilloscope and camera provided inflight "quick look" capability. Oscillograms were generated between flights for additional experimental guidance.

Description of Experiment

Figure 1 shows an experimental overview. The airfoil is 25 cm from the aircraft fuselage skin. A 4.3 cm diameter mirror was flush mounted on the airfoil, and served to direct the laser beam back into the aircraft. An internal mirror was used to provide an inflight reference beam. In addition, both pre-and post-flight calibrations were performed.

Figure 2 depicts the aerodynamic fence arrangement. The fence is 7.5 cm high and 45 cm long. Hole diameters are 6 mm, while the overall porosity of this fence is about 50 percent. The distance from the fence to the center of the laser optical axis is 20 cm.

Figure 3 shows the internal optical table, on which are mounted the MTF and LSF instruments.

Line Spread Function Measurements

The LSF instrumentation consists of a 30 centimeter focal length lens; a variable iris of 24 mm, 16 mm, and 10 mm; a silicon photodetector; and a dual-slit aperture. An additional reference detector and a divider circuit were included in order to remove any fluctuations introduced by variations in the laser output intensity. The lens was used to focus the laser beam

onto the dual-slit aperture located in front of the detector. The parallel slits are 2 microns wide and separated by 100 microns, thus, providing a reference on the oscilloscope display for accurately measuring the width of each LSF curve. The scanning mirror was driven by a 60 Hz triangular waveform to dither the focused spot back and forth across the slits. Total excursion at the detector was about 2 mm. As the focused spot traverses each slit, the detector response traces out a waveform on the oscilloscope that corresponds to the LSF. The experimental procedure will be discussed next.

LSF Data Processing

The LSF data was recorded on a Sangamo Sabre III analog tape recorder. Some photos were taken while the data were being recorded, but it proved to be much simpler to take postflight photos from the tape recorder playback. At AFWL, preliminary estimates were extracted from visicorder records of the taped data. These estimates were later compared with computer results and found to be in good agreement.

This program locates the peak of each LSF curve, centers each curve about its peak value, then overlays about 1000 randomly selected curves in order to obtain the average LSF for any particular experimental condition. Figures 4 and 5 are examples of average LSF curves obtained for a calibration and an in-flight condition, respectively.

Modulation Transfer Function Device

The Modulation Transfer Function (MTF) of these random flows was measured via a fast shearing interferometer. The MTF is the modulus of the Optical Transfer Function (OTF) which is in turn defined as the Fourier transform of the point spread function of the optical system. The OTF is also the autocorrelation of the system's pupil function. The pupil function

describes not only the shape of the system's limiting aperture, but also the phase of the optical wave across it. Phase perturbations induced on a beam by the turbulent boundary layer are included in the system pupil function, and therefore in the OTF. It can be argued that for a random phenomenon such as turbulence, the phase of the OTF averages to zero, and so OTF and the MTF of the turbulent layer are identical.

The measurement of the boundary layer MTF was done with a fast scanning, shearing interferometer (FSI) designed by Kelsall. A thorough description of the principle and operation of the FSI can be found in references 1 and 2 and we mention only the pertinent points here.

This common path interferometer contains a beam splitter, mirrors, a rotating glass plate called the shear plate, light collecting optics, and a detector. The incoming beam is split into two beams, which pass through the shear plate and are eventually recombined and pass to the detector. The rotating shear plate displaces one beam laterally with respect to the other and introduces a time varying path difference between the beams. After recombination, the beams constructively and destructively interfere, depending on the phase distribution across the beam and the path difference. The resulting signal at the detector is, neglecting terms of no importance in this experiment,

$$F(S) = 1 + |\tau(S)| \cos k\delta(t) \qquad (1)$$

where $\delta(t)$ is a linear function of time describing the path difference between the beams, and S is a normalized displacement, called shear value, and is directly related to the spatial frequency, k. Thus, the output of the interferometer is (apart from a d-c term) a sinusoidal whose envelope is the system MTF, $\tau(S)$. The shear plate rotates at 3600 rpm, resulting in the

measurement of an MTF in about 1.5 milliseconds, with successive MTF's measured every 8 milliseconds.

Finally, note that the output of the FSI is

$$\tau(S) \atop FSI = \tau_0(S) \ \tau_{BL}(S) \tag{2}$$

That is, the measured MTF is the product of the optical system MTF without turbulence and the MTF of the turbulent boundary layer. The unperturbed system MTF is measured before flight and thus can be removed from the flight measurements. MTF-interred intensity degradation I/I_0 was obtained by first averaging 53 randomly selected curves for a particular flight event. The Fourier transform of this average was then taken. Finally, dividing this transform by the calibration transform yields the predicted line spread functions. Because LSF and MTF are a transform pair, this affords a direct comparison of I/I_0 via independent measuring techniques.

Figure 6 shows a correlation plot of the average I/I_0 value directly measured by the LSF with the corresponding MTF-inferred value of I/I_0. Agreement is only fair for the boundary layer measurements, yet quite good in the case of the aerodynamic fence.

Table 1 is an expanded view of the data base. Column 1 contains the altitude, Mach number and experimental configuration - "TBL" denotes turbulent boundary layer, and "F" aerodynamic fence. The double pass line spread functions shown in Figure 6 appear in columns 2 and 3. Column 4 contains the predicted Strehl ratio for a single pass of the 2.4 cm diameter beam through the random flow. In Appendix A this is shown to be the square root of the LSF in double pass. Column 5 shows the estimated Strehl value for an infinite aperture, that is, one large compared with correlation lengths within the random flow. The final column depicts phase variances associated with the large aperture Strehl values in units of helium-neon

laser wavelength $(\lambda = 0.69\mu)$.

Table 1

COMPARISON OF (I/I_o)MTF AND (I/I_o)LSF

Altitude-Mach No.-Configuration			I/I_0MTF	I/I_0LSF	I/I_0PS	I/I_0 $_\infty$	σ
40K	0.8	TBL	0.77	0.63	.79	.70	.10
32K	0.8	TBL	0.41	0.65	.81	.73	.09
32K	0.8	TBL	0.82	0.65	.81	.73	.09
32K	0.7	TBL	0.44	0.74	.86	.80	.08
32K	0.55	TBL	0.44	0.54	.73	.62	.11
15K	0.7	TBL	0.82	0.67	.82	.73	.09
15K	0.55	TBL	0.41	0.57	.75	.63	.11
5K	0.4	TBL	0.77	0.54	.73	.62	.11
15K	0.7	F	0.24	0.30	.55	.39	.16
5K	0.55	F	0.34	0.37	.61	.46	.14
5K	0.4	F	0.69	0.73	.85	.80	.08

Experimental Error

Pre-and Post-flight Line Spread Function (LSF) calibrations were performed for each aircraft mission. In all cases these two calibration peak intensity values agreed to within 5%. An average of these two numbers was then used as the reference intensity, I_0, for that flight.

The use of operational amplifiers, precision resistors and components, and mercury batteries insured short-term stability within 5%. The reference detector and divider circuit, designed to null out laser source amplitude fluctuations, contributed less than 1% error. Likewise, digitization of the magnetic tape data with subsequent analysis resulted in a comparably negligible error.

The primary source of error lay in the non-uniform response of the LSF detector for laser spots small compared with the sensing surface - this was indeed the case for the nominal 30 micron diameter spots scanning across the two micron slits. During system checkout, it was found that vertical beam motion of 1 millimeter up and down a slit resulted in detector response vari-

ations of ±5%. This would correspond to a beam angle of arrival fluctuation of ±1.5 milliradians. Observed in flight angle-of-arrival fluctuations were small compared with this value. Therefore, total experimental error for the LSF measurement is within ±10%.

Conclusions

Laser propagation experiments through the boundary layer of a Lear jet have been accomplished. Measurement techniques consisted of a Modulation Transfer Function (MTF) device and a Line Spread Function (LSF) instrument. Both techniques measure the decrease in focal plane beam intensity after a collimated laser beam has made a double pass through the aircraft disturbance. Aperture diameter for the helium-neon laser ($6328\overset{\circ}{A}$) was 2.5 cm. Aircraft altitudes ranged from 1.6 to 12 km, with Mach numbers covering the 0.3 to 0.8 domain. Major conclusions from this series are as follows:

(1) Aerodynamic fences are optically noisier than free turbulent boundary layers. Ironically, fences are generally placed in the vicinity of an open port to aerodynamically quiesce flows in that cavity;

(2) MTF and LSF measurements correlated very well for the fence (F); less well for no fence (NF). These two measurements are Fourier Transform pairs;

(3) Values of phase variance inferred from the LSF instrument and corrected for a single pass through the random disturbance and an infinite aperture (i.e., beam diameter much larger than flow correlation lengths) range from 0.08 to 0.11 waves ($\lambda = 0.63\mu$) and 0.08 to 0.16 waves for the boundary layers and shear layers, respectively.

REFERENCES

1. Kelsall, D. "Rapid Interferometric Technique for MTF Measurements in the Visible or Infrared Region", Appl. Opt. 12, 1398, (1973).

2. Kelsall, D., "Optical 'Seeing' Through the Atmosphere by an Interferometric Technique", J. Opt. Soc. Amer. 63, 1472, (1973).

APPENDIX A

THEORY OF LINE SCAN DEVICE

In the line scan device the point spread function associated with a certain aperture and phase aberration is scanned across a thin slit, and the power passing through the slit is recorded as a function of time. If $i(x,y)$ is the point spread function then time dependent irradiance in the focal plane for a point spread function moving with velocity V along the x axis is $J(x,y,t) = i(x + Vt, y)$ and the power passing through a slit of width ε parallel to the y axis is

$$I(t) = \int_{-\infty}^{\infty} \int_{-\varepsilon/2}^{\varepsilon/2} J(x,y,t)dxdy \qquad (A1)$$

If the slit is narrow compared with the diameter of the point spread function and if the slit is centered about $x = 0$ equation A1 becomes

$$I(t) = \sum_{-\infty}^{\infty} \int J(o,y,t)dy$$
$$= \sum_{-\infty}^{\infty} \int i(Vt,y)dy \qquad (A2)$$

the quantity $I(t)$ is the quantity directly measured in the experiment.

The degradation produced by a random phase aberration is usually expressed in terms of the Strehl ratio

$$S = \frac{i(o)}{i_0(o)} \qquad (A3)$$

This is the ratio of the peak value $i(o)$ of the point spread function with aberration to the peak value $i_0(o)$ of the point spread function without aberration. For small rms phase aberration or when the scale size of the

phase aberration is much smaller than the aperture size of the instrument, the Strehl ratio is given by the expression

$$\frac{i}{i_o} = \exp\{-k^2\sigma^2\} \tag{A4}$$

where $k = 2\pi/\lambda$ is the wave number and σ^2 is the variance of the aberration function (i.e., it is the variance of the optical path length through the aberrating medium, where the average is taken over the aperture of the instrument).

To obtain the point spread function $i(x,y)$ from the line scan function $I(t)$ one must in general solve the integral in equation A2. However, if the degradation of the point spread function is represented by a simple spreading then it can be shown that the relation between the Strehl ratio and the ratio of the peak values of the line scan function, with and without phase aberration is given by

$$\left(\frac{I}{I_o}\right)^2 = \frac{i}{i_o} = \exp\{-k^2\sigma^2\} \tag{A5}$$

For this preliminary analysis we shall use this simple relation to estimate the Strehl ratio.

Now in the experiment the beam passes through the aircraft boundary layer twice. In applications, on the other hand, one is interested in the decrease of peak irradiance for one pass through a boundary layer. If σ_1^2 is the variance of the optical path length for one pass through the boundary layer the Strehl ratio for one pass would be

$$\left(\frac{i}{i_o}\right)_1 = \exp(-k^2\sigma_1^2) \tag{A6}$$

For two passes through the boundary layer the variance is $\sigma^2 = 4\sigma_1^2$.

It follows that if in the experiment one observes a line scan peak ratio I/I_o then for a beam making one pass through the boundary layer the estimated Strehl ratio is just

$$\frac{i}{i_0} = \sqrt{\frac{I}{I_0}}$$

ELECTRONIC
EQUIPMENT

OPTICAL
BENCH

AIR SHIELD
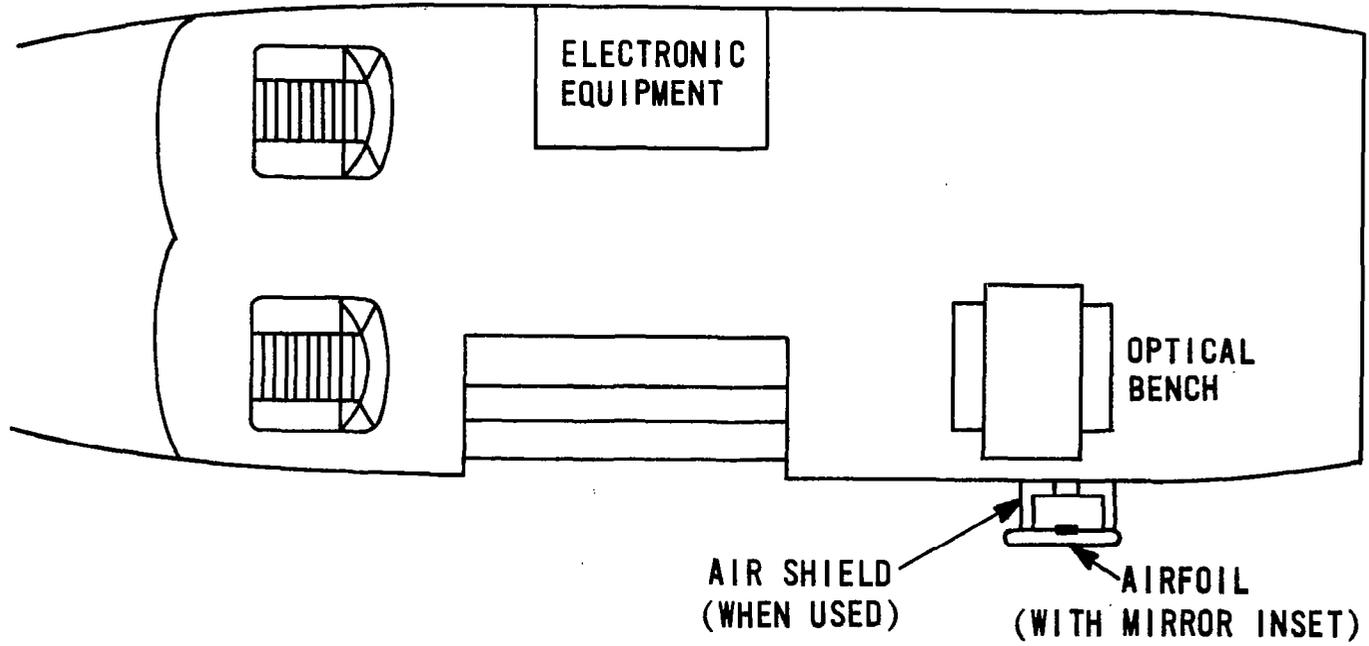(WHEN USED)

AIRFOIL
(WITH MIRROR INSET)

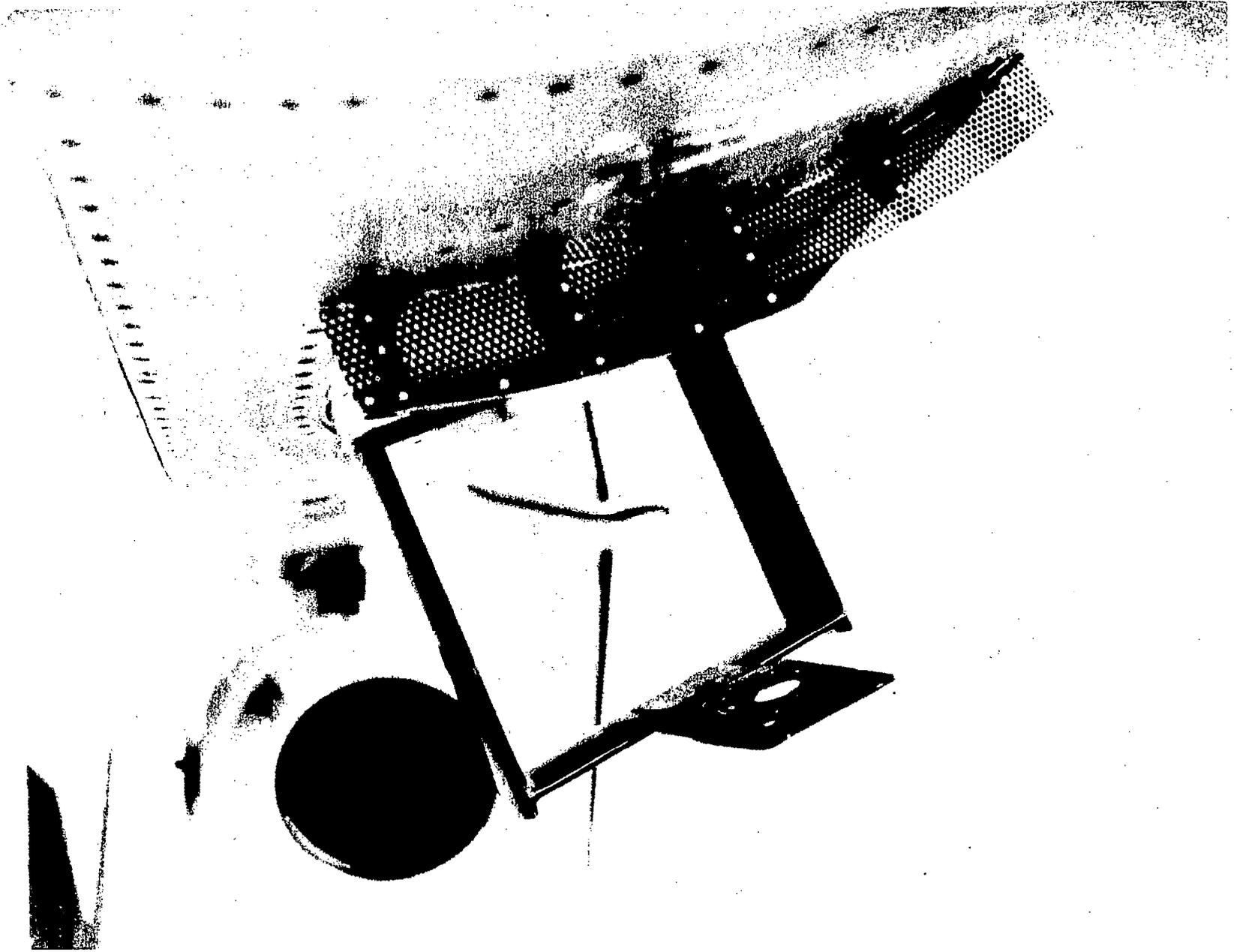Figure 1.- Lear Jet experimental overview.

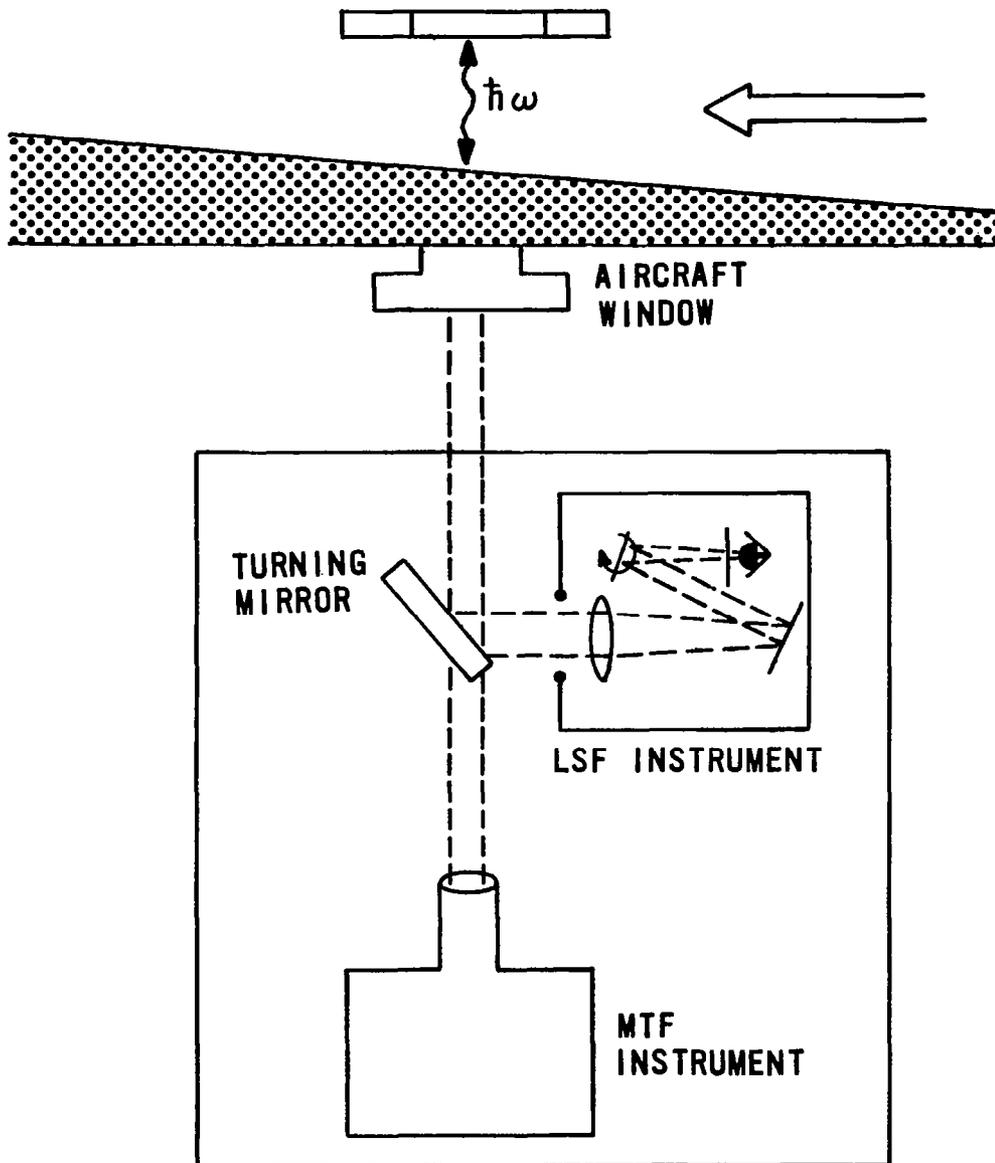Figure 2 - Aerodynamic fence arrangement.
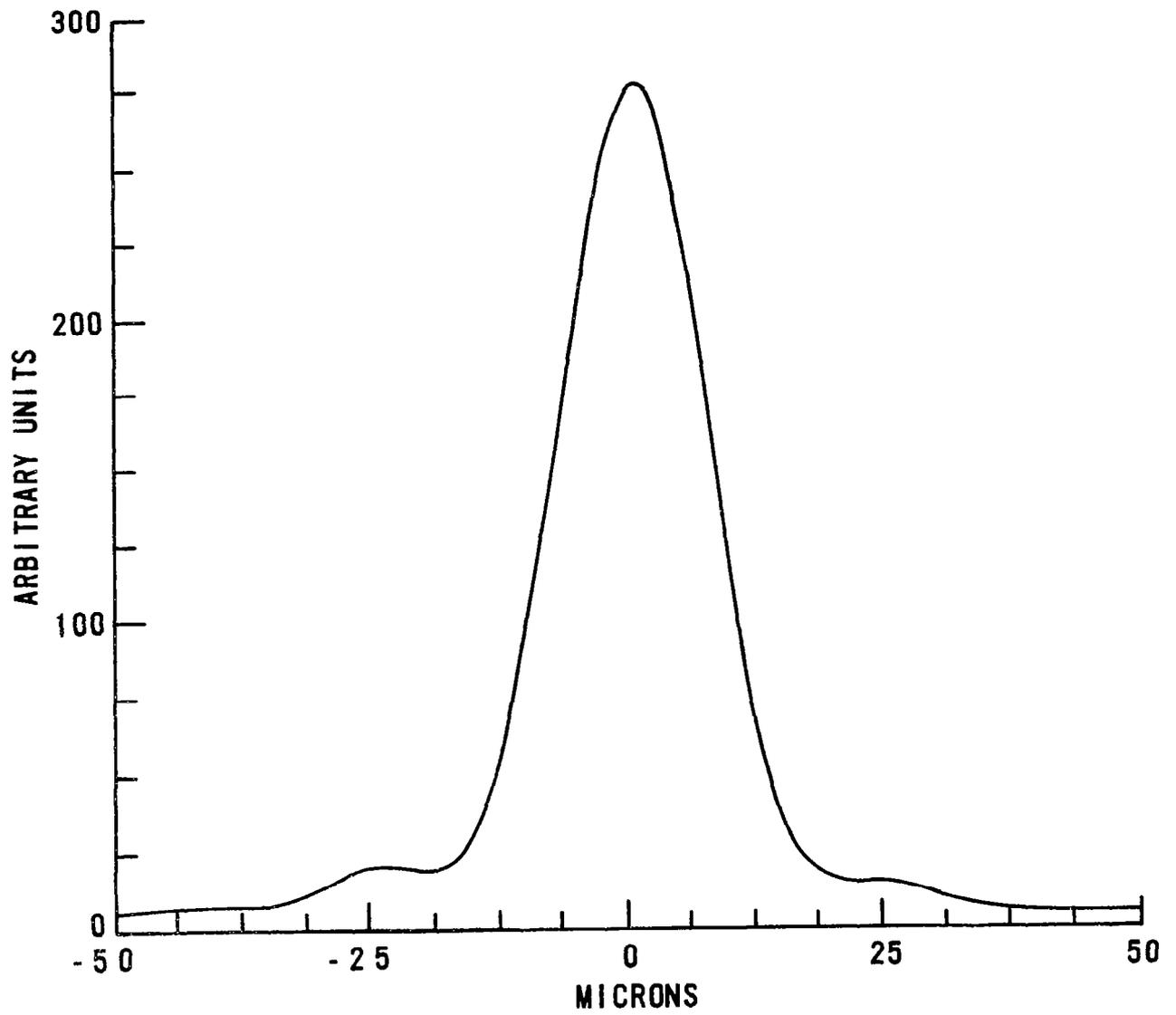
Figure 3.- Instrumentation setup.
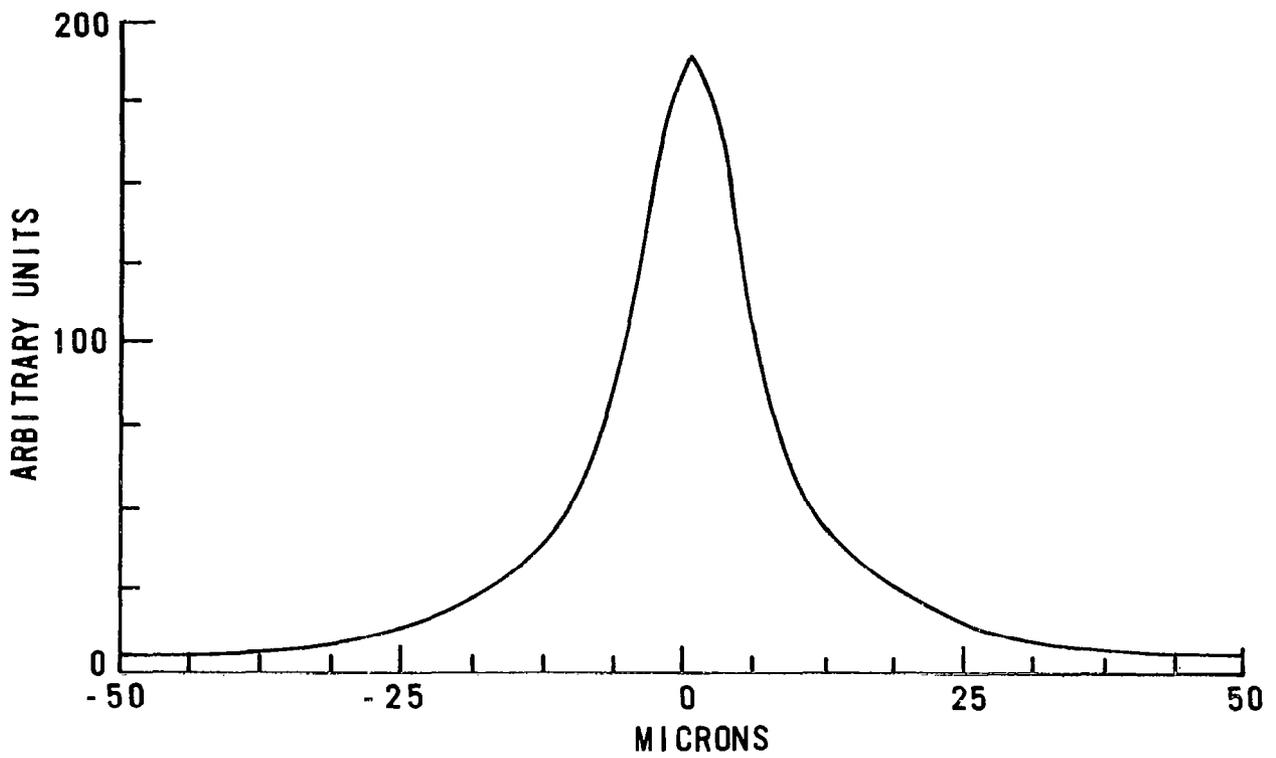
Figure 4.- Typical LSF calibration curve.
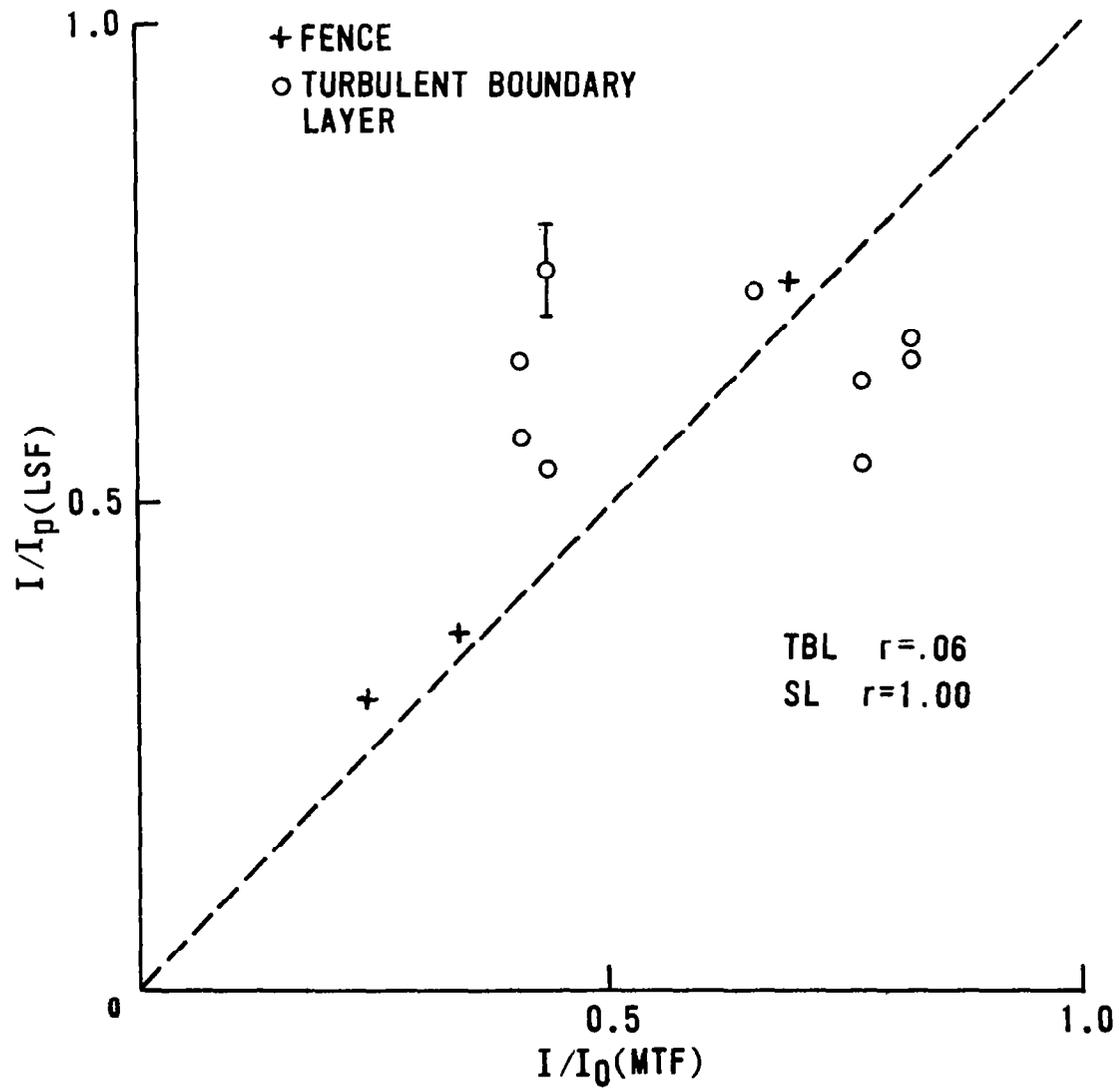
Figure 5.- Typical LSF in flight data curve.

Figure 6.- Correlation plot of line spread functions inferred from LSF
and MTF measurements.