OVERVIEW OF RECENT AERO-OPTICS FLIGHT TESTS

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The final expression of any flight related investigation is actual flight data. Historically, this only occurs after exhaustive ground testing. Aero-optics did not follow this trend. Indeed it was early flight testing (circa late 1950s-early 1960s) that indicated the presence of a near-field aero-optics problem. Aero-optics flight testing had the advantage of advancing with the state of the art in aero-optics ground testing--this by virtue of "non-interference" testing during the ALL Cycle II Program. The flight testing portion of the aero-optics culminated in a series of dedicated tests commonly called Cycle II.5. This paper will trace these flight tests in a summary manner while highlighting the objectives and conclusions from the tests.

Figure 1 shows a chronological listing of the relevant aero-optics flight testing along with the objectives of each flight. Flights before project PRESS have not been included. We will now summarize each of these test series.

The first credible flight aero-optics data were collected during the Lincoln Laboratory project "PRESS" flights. "PRESS" flights were reentry observation missions using optical trackers looking through slightly recessed optical quality windows on an Air Force NC-135A. While tracking fixed sources, i.e., stars, an unusual amount of blurring was observed during flight as compared to ground tracking. The obvious losses in seeing were attributed to the aircraft boundary layer, the small shear layer over the recessed viewing ports, and heat transfer through the aircraft skin. Optical losses were estimated at 5 to 20 μrad using a shearing interferometer.[1] The boundary layer thickness at the point of measurement was approximately 30 cm, with a small (1.5 cm) shear layer next to the fuselage. In addition to documenting the observed optical losses of the PRESS flights, the effects of turbulent supression techniques were investigated.[2] These attempts were in general unsuccessful.[1,2] The PRESS flights represented the first documented aero-optics flight data. These data were limited in scope and tended to serve the PRESS mission. The data did give rise to a variety of explanations of the source of degradation and provided the stimulator for further study.

The next significant aero-optics flights were a dedicated series performed on NASA AMES' Lear 23 in January 1975. The Lear tests were designed to unravel some of the mysteries surrounding the existing flight and wind tunnel data. Specifically, the applicable aerodynamic scaling laws were sought as was the characteristic scale size of the near field turbulence. Toward these objectives additional data were provided, but firm conclusion were not to be found due to limited diagnostics. Ten dedicated missions were flown over a Mach range of 0.3 to 0.8 and from $1.5\text{X}10^3$m to $12.2\text{X}10^3$m altitude. Constant dynamic pressure and constant Mach profiles were flown. Optical instrumentation consisted of Kelsall's fast shearing interferometer[3] and an AFWL line spread function measurement (LSF).[4,5] The experimental set up is shown in Figure 2 and Figure 3.

Both turbulent boundary layers and fence generated shear flows were observed using integrated path optical techniques (Figure 4). These flight tests showed the expected aperture scaling (Figure 5a) and indicated that shear flows were optically less desirable (Figure 5b).[4] Unfortunately, the flights did not show the expected dependence on free-stream density and Mach number and the expected correlation between the MTF and LSF was not always present.[4] Scaling of the observed HeNe wavelength data to 10.6μ did provide a timely indication that near field distortions were not an issue for long wavelengths. Most important, these tests represented the first dedicated aero-optics flight tests and underscored the need for a more thorough investigation. The flights also provided an airborne checkout of equipment designated for the ALL Cycle II tests.

Chronologically, the next flight aero-optics data were obtained as part of the ALL Cycle II tests. The ALL Cycle II program was a linear propagation and tracking demonstration of the ALL flight hardware. The flights afforded the opportunity to look at both the mechanical and optical properties of the ALL tracker which had recently been investigated in a series of wind-tunnel tests (Ref 6, 7, 8, 9, 10). One of the Cycle II objectives was "to isolate and measure beam degradation due to near field aircraft induced effects and natural turbulence effects."[11,12] Two classes of measurements were used in these optical tests - an overall ALL optical train degradation examination using a 10.6μ Fast Shearing Interferometer (FSI) with an angle of arrival (AOA) detector and a boundary-layer/free-stream turbulence examination from a pointer independent platform using a visible FSI (the same one used in the Lear Jet work) and a scintillometer (Figures 6 and 7). Alignment between the two aircraft was obtained through two ALPE computer driver trackers using HeNe sources (Figure 8). The ALL tracker provided its own track capability. Additionally, atmospheric turbulence data were obtained using a fine hot wire mounted on a T-39 which measured C_T^2 from which C_N^2 was inferred (Figure 9). Twenty-one flights over an eight-month period were used to collect the Cycle II propagation data. The T-39 data were generated over a two-year span.

As apparent in Figures 6, 7, and 8, the Cycle II tests were fairly complex, involving multiple simultaneous measurement and several aircraft. The FSI proved to be a significant improvement over the slow shearing predecessor. Its high speed (an MTF every 3 msec) froze the atmospheric turbulence and allowed statistically meaningful samples to be processed. Even more so than the slow shearing interferometer, the FSI was vibrationally insensitive (vibration data being collected with the AOA). Additional data included pointer system performance obtained from the tracker error signals and a large number of accelerometers and pressure transducer to document the aero-dynamic parameters.

Some interesting conclusions were drawn from the Cycle II aero-optics flights. Both the FSI and AOA data indicated that, for 10.6μ, atmospheric turbulence and near field turbulence are not major factors in total system performance, a result forecasted from the Lear Jet tests. Platform jitter was the largest contributor to system degradation. As in previous aero-optics flight tests, correlation to aircraft flight parameters were not readily obvious (Figure 10). AOA and MTF data were sensitive to flight configuration with the non-full forward fairing having the highest jitter and largest distortion (Figure 11). Turret/ fairing aerodynamic performing was gratifying in that it matched predictions (Figures 12 and 13).

Observed natural turbulence data (C_N^2) obtained from the T-39 was roughly in keeping with other observations but with a significant discrepancy being observed in the measured frequency spectra data versus theoretical spectra (Figures 14 and 15a, b). These data were collected under a variety of conditions (0.5 to 12.5 km) with data being analyzable from 1 Hz to 200 Hz. An operational consideration was the problems encountered with the survivability of the probe with frequent probe breakage occurring. In these measurements, C_T^2 was measured using temperature fluctuations only, with Mach number and velocity (i.e. compressibility) not being accounted for, an assumption which later tests showed to be generally reasonable.

In general, the Cycle II flight data contributed significantly to the aero-optic program by delegating 10.6μ atmospheric and near field turbulence to second order effects while highlighting the importance of airframe aerodynamic buffet. The flights did not, however, quantify the entire airborne aero-optics problem and continued undersettled the aerodynamic scaling laws and correlation between optical data inferred by using aerodynamic measurements.

Cycle II.5 was a dedicated aero-optics program conducted in the Summer of 1977 using an NKC-135A. This aircraft was modified to incorporate an aft aero-optics data station. Diagnostics, finally, included a serious aerodynamic effort using the advances in aero-optical tunnel testing techniques (ref. 13, 14, 15). Multiple hot wires (constant current and constant temperature) mounted to two independently movable probes (a total of 4 wires), an LDV using an argon laser, and a visible FSI were installed. The starboard side of the aircraft was smoothed forward of the measurement station and incorporated a noninterference FSI return mirror and LDV directing assembly (Figure 16a, b). An optical quality ($< \lambda/10$) window was flush-mounted at the measurement station to transmit the HeNe FSI signal. Provisions were made to mount a series of porous fences at various positions upstream of the measurement station to allow investigation of shear flows as well as boundary layers. The extended displacement of the measurement station from the nose of the aircraft produced actual Reynolds Number $> 10^7/m$, values impossible to achieve for transonic speeds by wind-tunnel simulation.

The prime objective of the Cycle II.5 flights was to demonstrate the scalability of aero-optics data. In essence, the NASA Ames 6 x 6 aero-optics wind-tunnel experiments were repeated at flight Reynolds numbers allowing a direct scaling comparison. Additionally, the contribution of heat transfer through the the aircraft skin on the optical quality of the near field flow was quantified as was the feasibility of using aero measurements to infer optical phenomena. The flight tests encompassed about 50 hours of flight test time and covered the entire aircraft flight envelope ($0.20 \leq M_{\infty} < 0.88$, $0.1km \leq altitude \leq 15.24$ km)

Conclusions from the Cycle II.5 tests were encouraging. Scaling of wind tunnel data was demonstrated and non-dimensional quantities were verified.[16,17,18] Correlation between direct FSI measurements of near field optical losses to inferred losses using aerodynamic parameters (i.e. density magnitude and scale sizes) was very high--a much sought after result since aero-inferred measurements, which are integrated point data, are generally easier to quantify and obtain. Aircraft thermal gradients were shown to have insignificant effects on near field optical seeing[19] for the observed flight conditions ($0.2 < M < 0.9$). The comparison of shear layer data to boundary layer data showed all the optical losses occurring in the small shear layer region with losses being not too different from turbulent boundary of corresponding intensity (an observation leading to a "conservation of fluctuating index of refraction theory"). As an unforecasted bonus, the anemometers, which accounted for Mach effects, were shown to have promise in measuring a broad spectrum of free-stream turbulence. Resolution of turbulence scales from several mm to several km was shown to be feasible at least to heights of 4.7 km. This last observation encouraged the development of an atmospheric turbulence probe for use during the ALL Cycle III tests.

Cycle II.5 was the last aero-optics flight test. Because of the Cycle II.5 results, ground testing of near-field losses was shown to be clearly feasible for any specific flight configuration--with subscale results being accurately scalable. Current aero-optics flight investigations are limited to an atmospheric turbulence probe installed on the nose of the ALL diagnostic aircraft. The probes (Figure 17) carries constant current and constant temperature fine wires and are free from engine induced broad band noise (they do, however, see turbine compressor noise). Recent work with this probe have shown it capable of resolving atmospheric turbulence up to 17 km altitude over scale sizes of 5mm to 0.5km.[20] The probe is presently being used to quantify atmospheric turbulent sources (thunderstorms, topographic, etc) and to contribute to the atmospheric turbulence data base.

It is apparent that aero-optics flight testing has reached its apex and further extensive flight measurements are not required. Such is the hallmark of a developed discipline. The papers to follow will cover in detail the more relevant of the forementioned tests.

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SYMBOLS

I/I_0	Strehl ratio
I_F/I_{NF}	Ratio of peak intensities for a fence to a non-fence
δ_b	Boundary-layer thickness
δ_F	Fence height
λ	Probe laser wavelength
M_∞	Free-stream Mach number
MTF	Modulated transfer function
L_0	Characteristic turbulence scale size
ℓ_0	Characteristic turbulence scale size
$\emptyset(K)$	Power spectral density function of the fluctuating temperature
K	Frequency
$C_N{}^2$	Index of refraction coefficient
$C_T{}^2$	Temperature coefficient
$\emptyset$	Characteristic value of $\emptyset(K)$
CP_{rms}	Root mean square of the fluctuating static pressure
f	Frequency
Φ	Normalized power spectral density function of the fluctuating static pressure
U_∞	Free-stream velocity
q_∞	Free-stream dynamic pressure
D	Characteristic length (turret diameter)

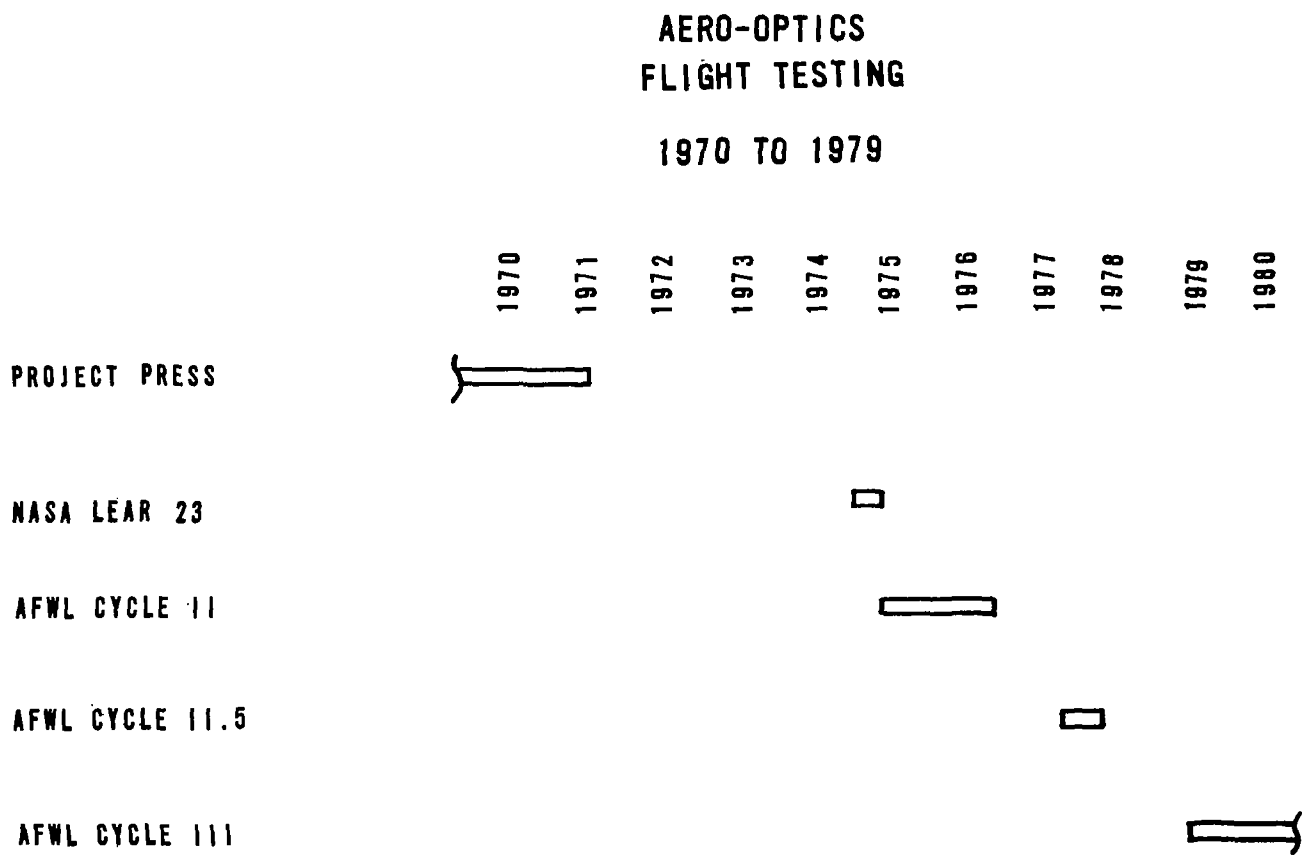

Figure 1. Chronological listing of aero-optics flight tests 1970-1979.

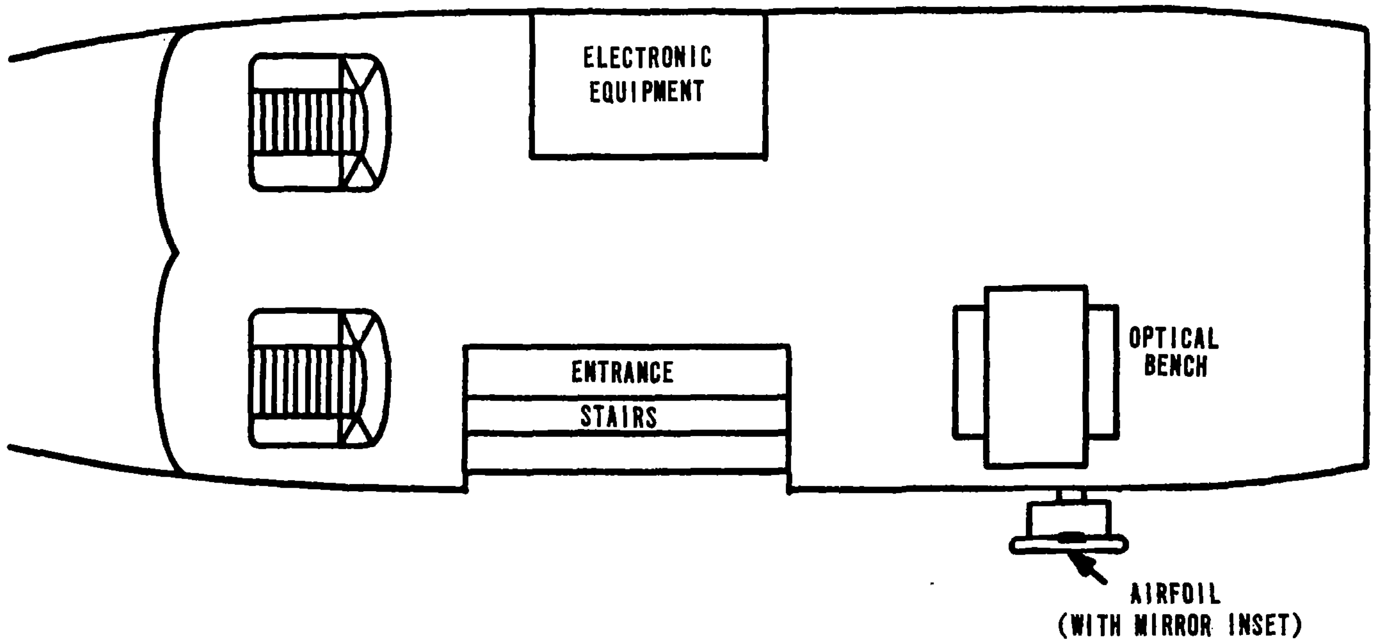

Figure 2. Lear Jet experimental layout: top view.

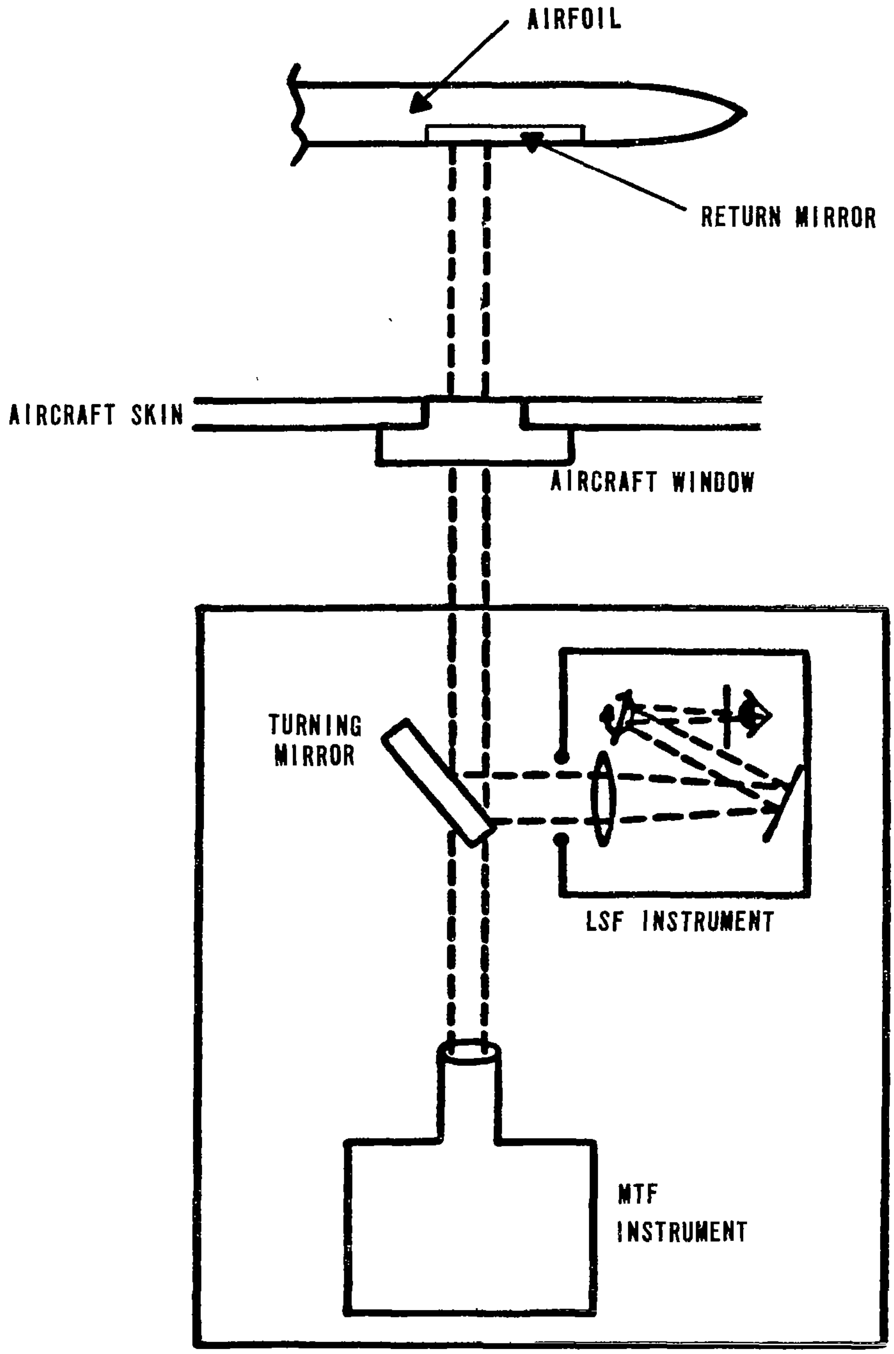

Figure 3. Lear Jet optical bench.

LEAR JET: TBL/SHEAR LAYER

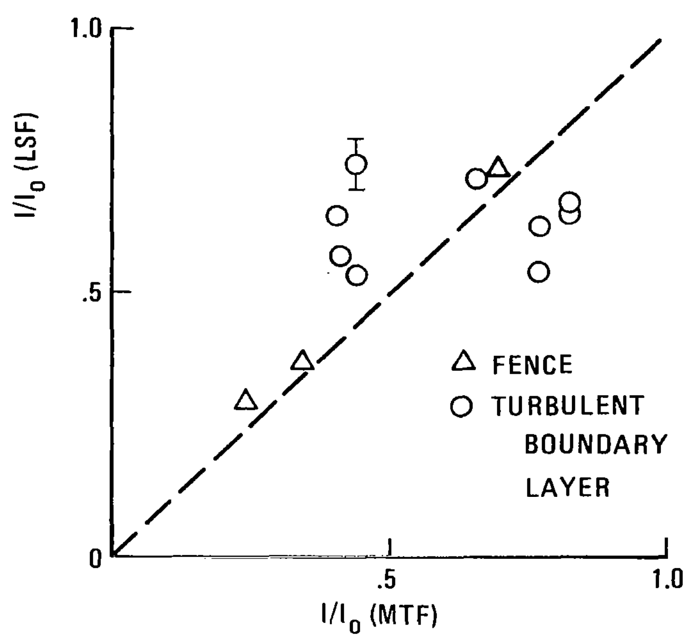

Figure 4. Comparison of LSF and MTF data for fence and turbulent boundary layers.

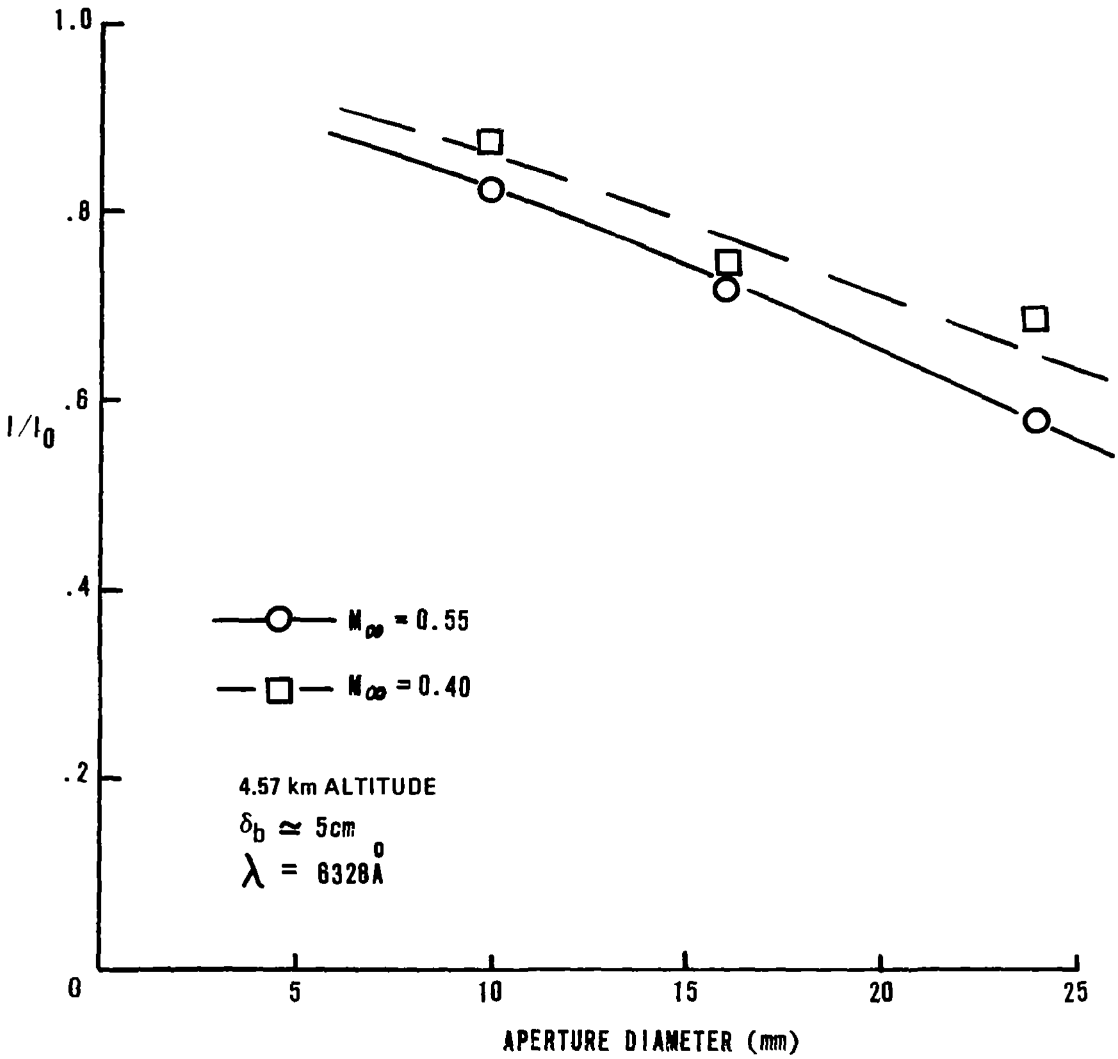

Figure 5a. Effect of aperture diameter on I/I_o for a turbulent boundary layer.

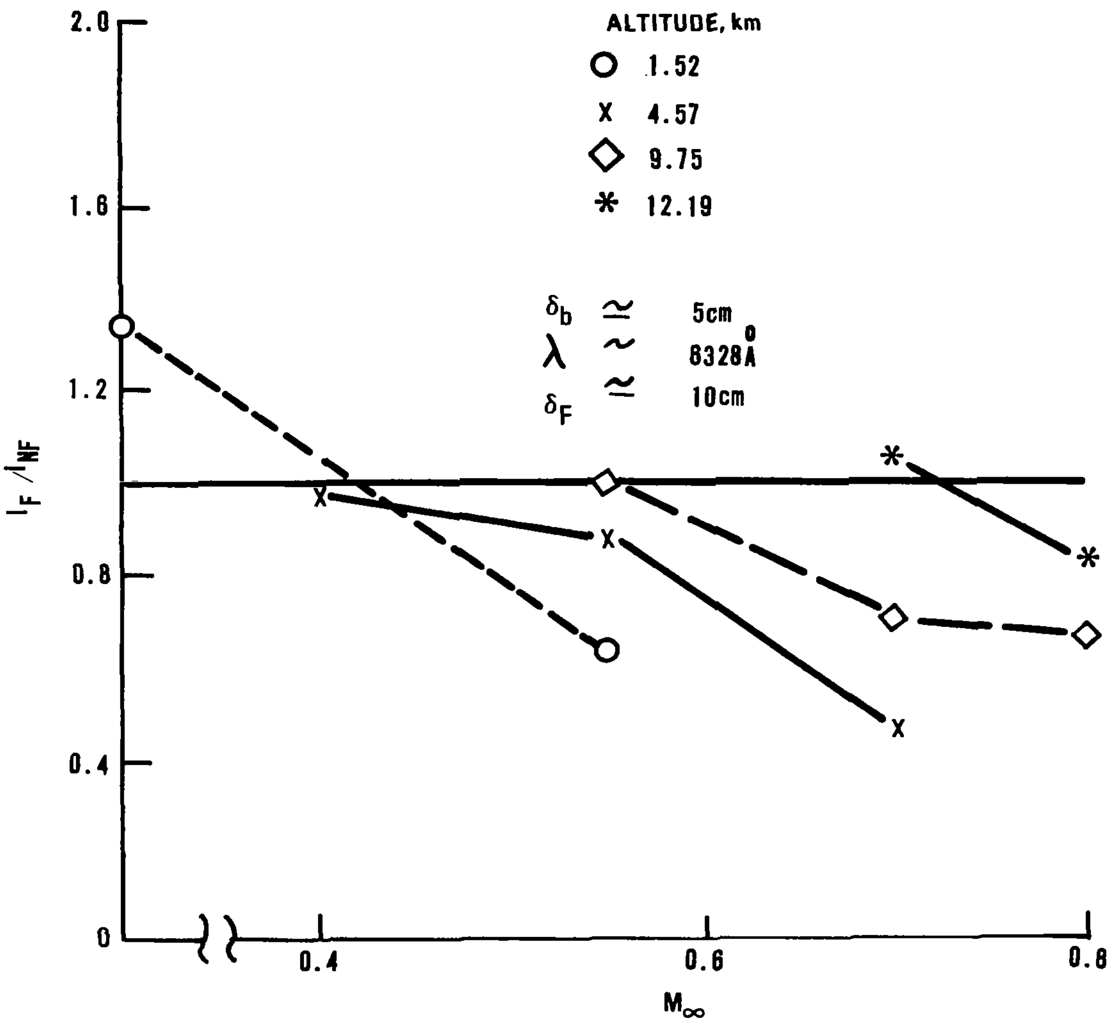

Figure 5b. Relative effect of fences as a function of Mach number for a 24mm aperture.

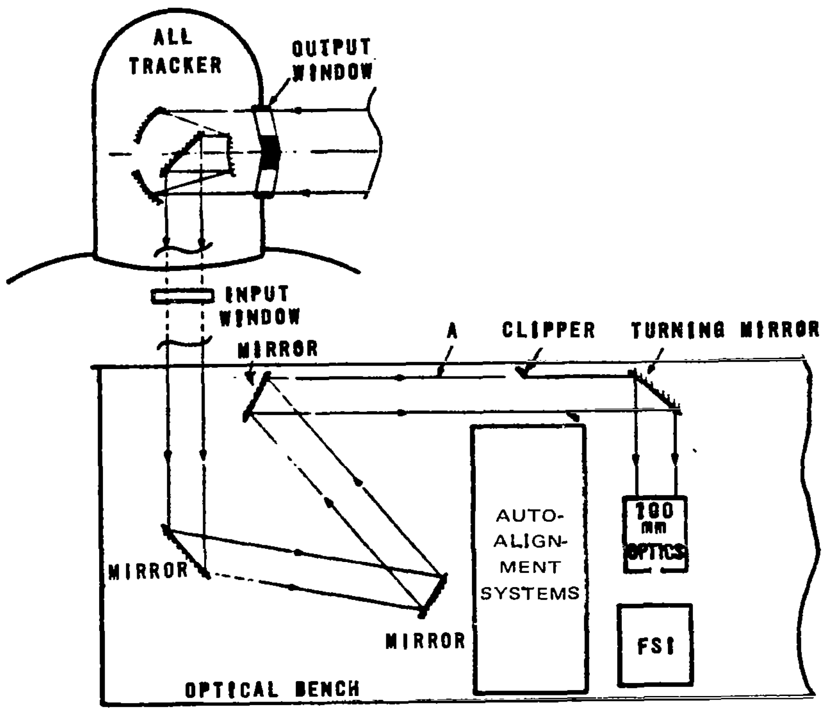

Figure 6. Cycle II optical diagnostic layout.

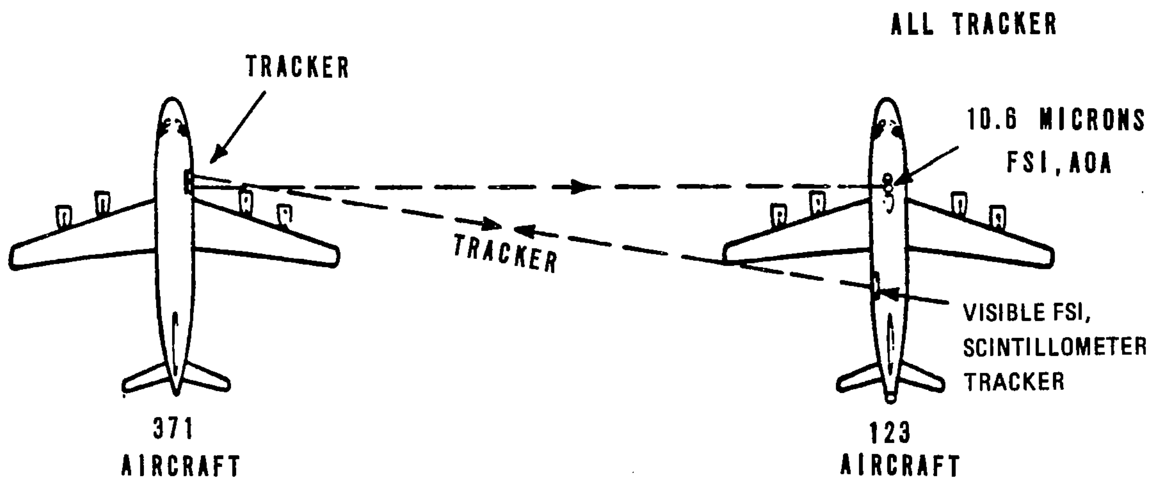

Figure 7. Cycle II experimental setup.

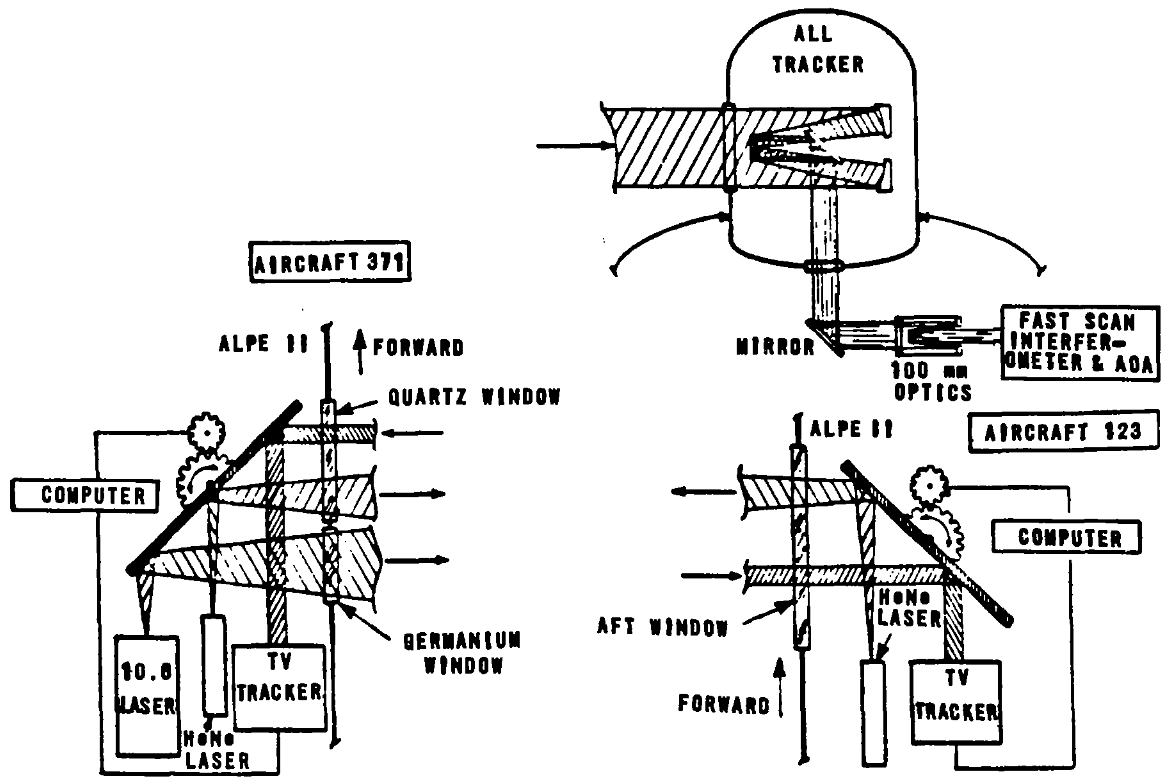

Figure 8. Cycle II tracker system for propagation measurement.

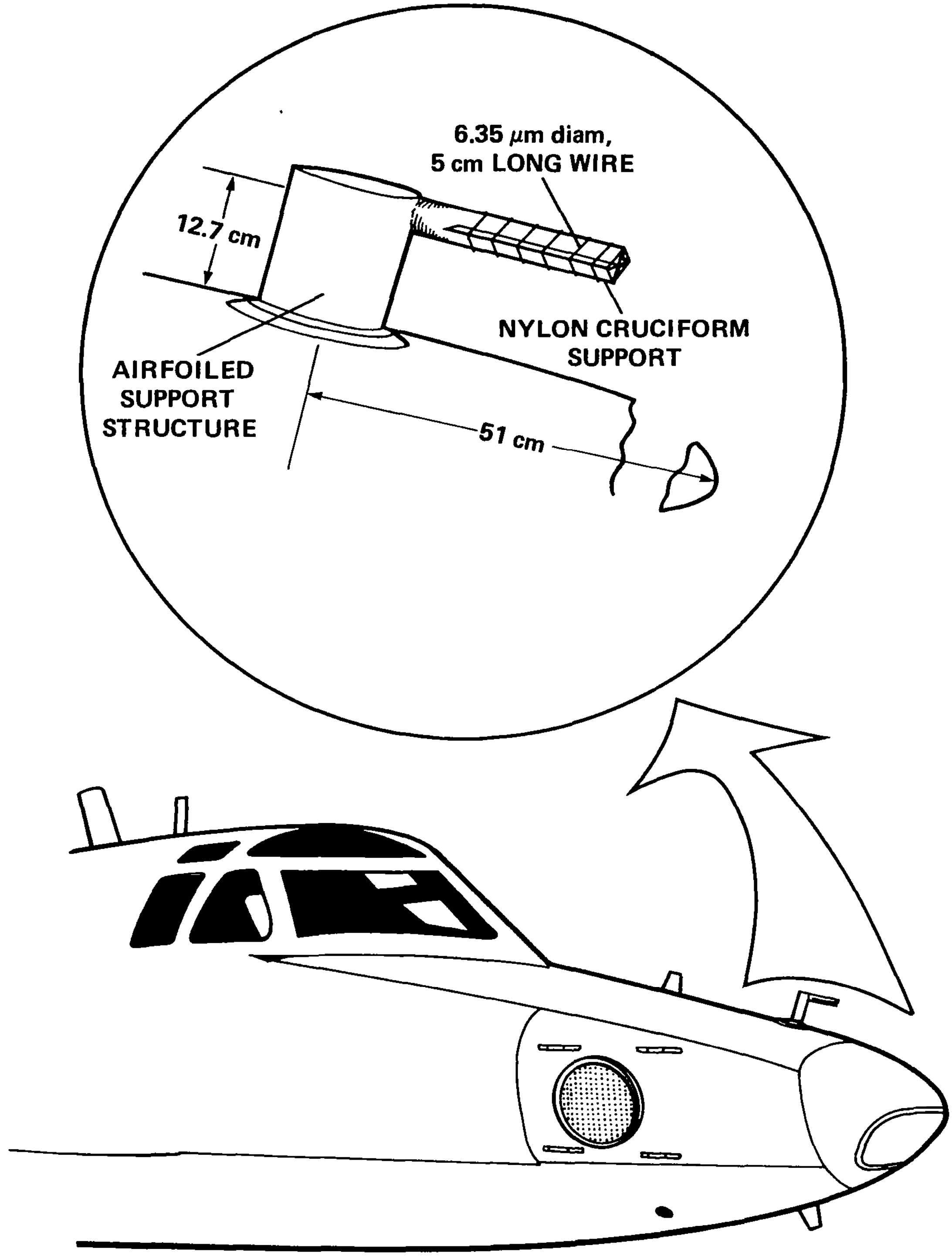

Figure 9. Fine wire mounted on a T-39.

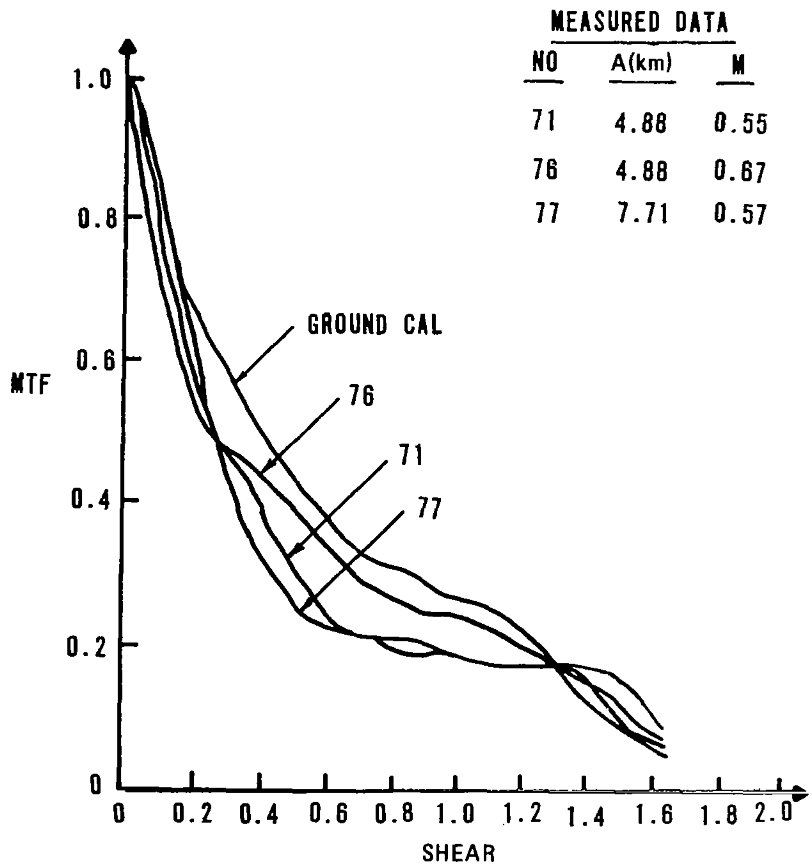

Figure 10. Sample Cycle II data showing the effect of altitude and Mach number on optical degradation.

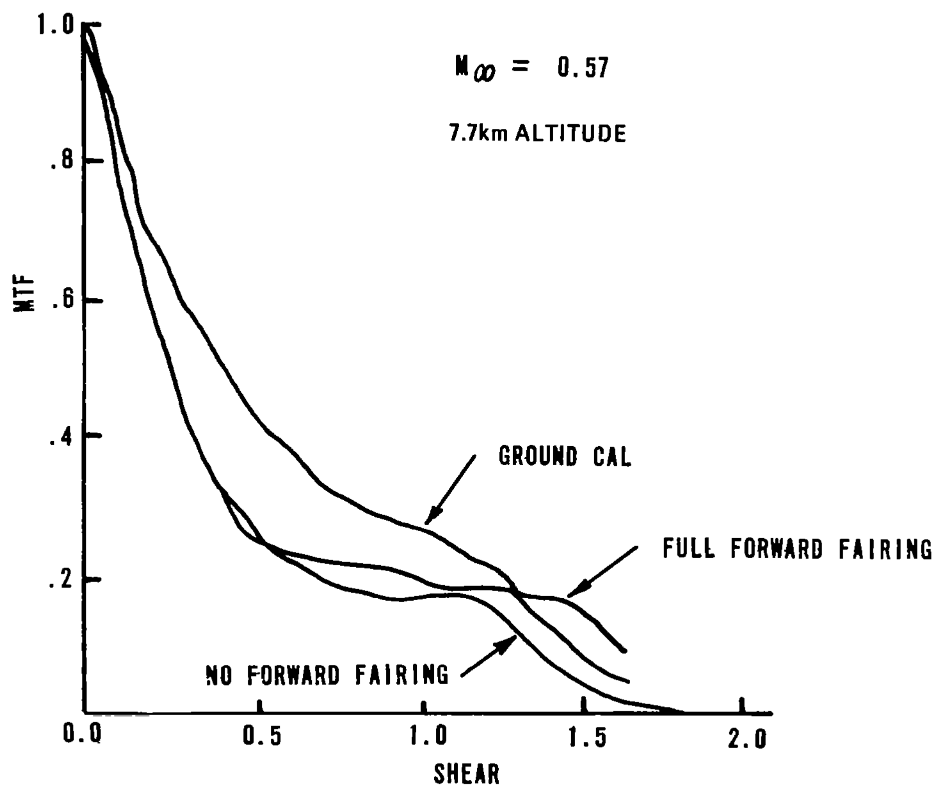

Figure 11. Effect of aircraft configuration on optical degradation.

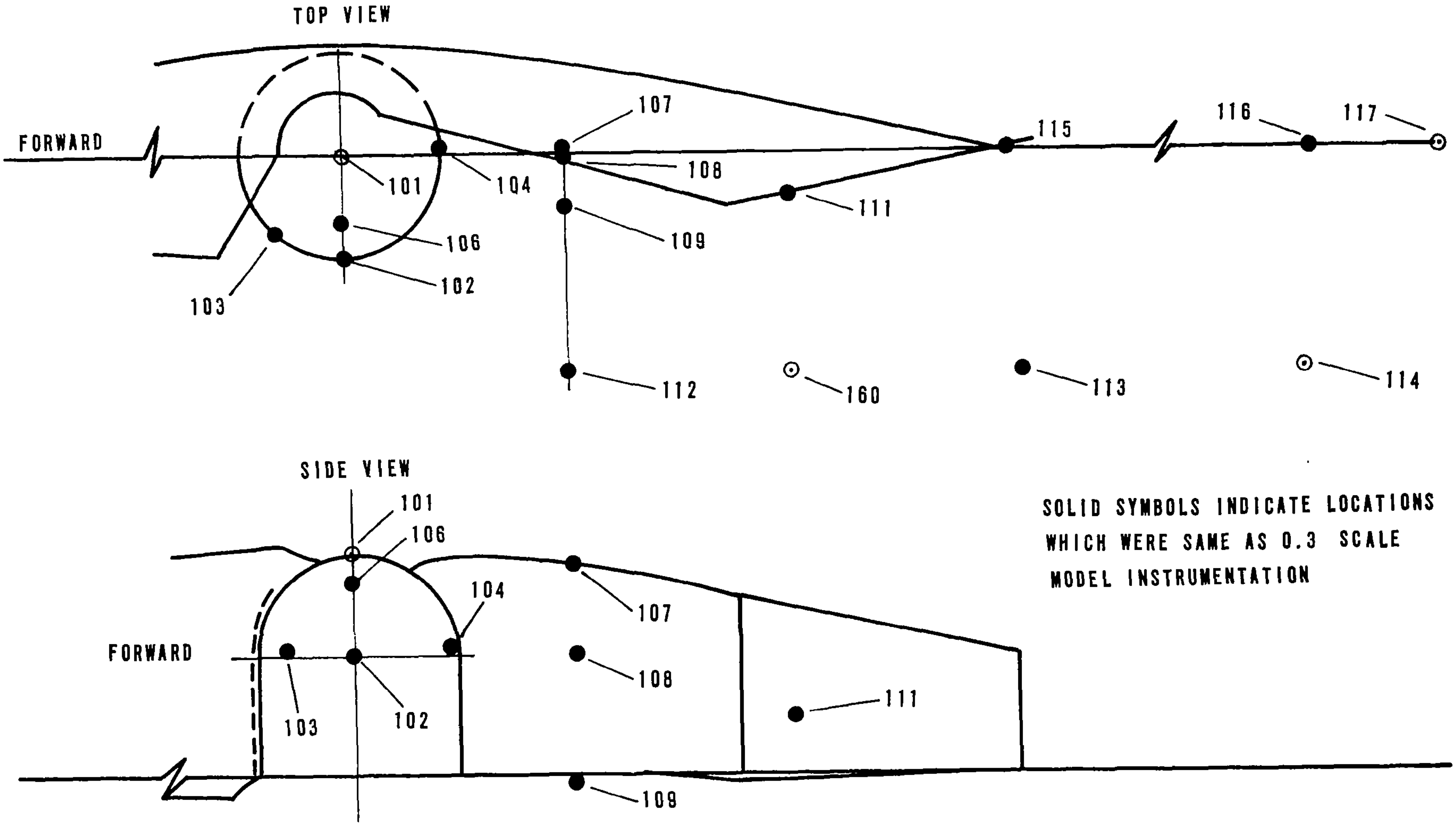

Figure 12a. Location of transducers used in flight to ground simulation comparison.

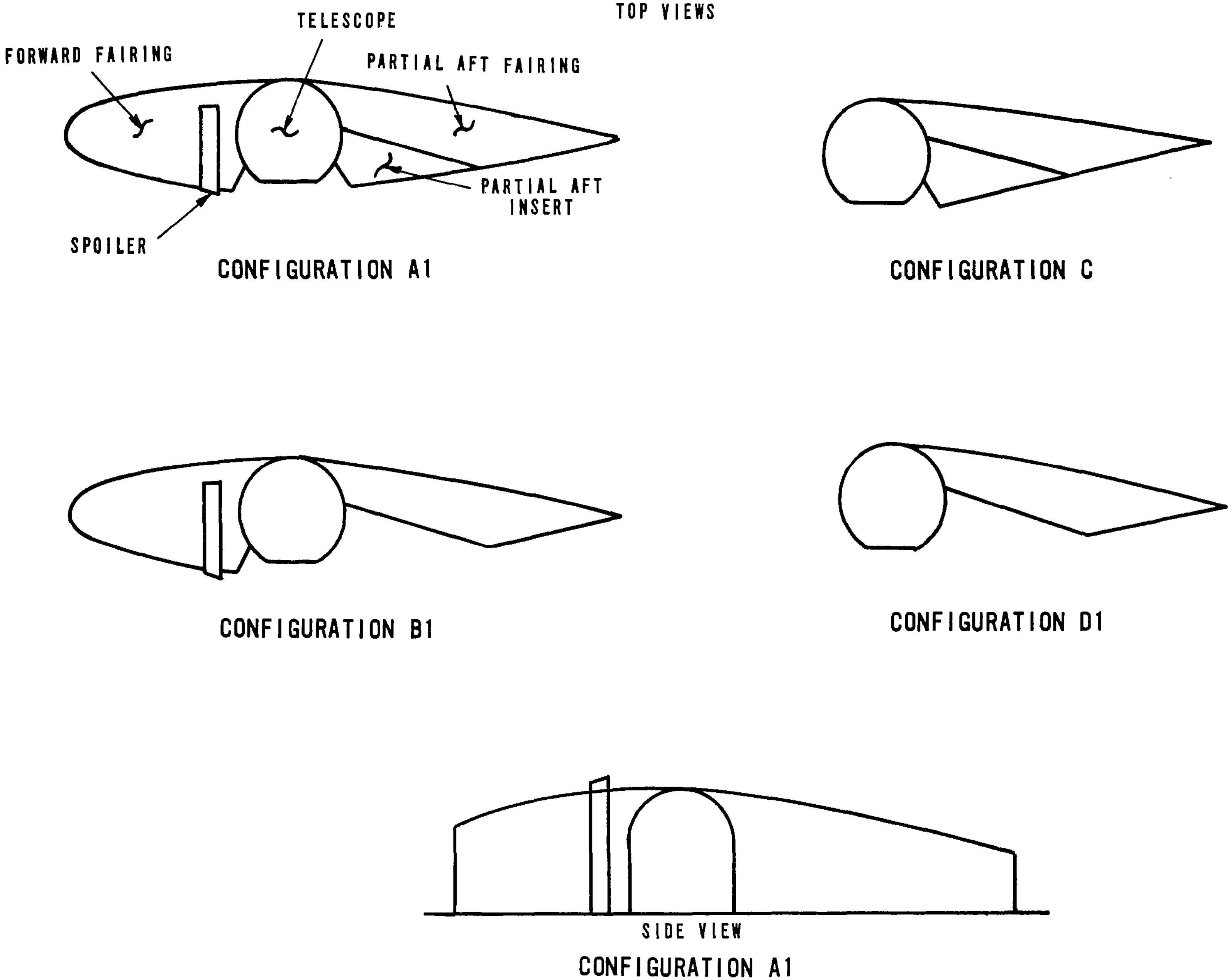

Figure 12b. Fairing configurations.

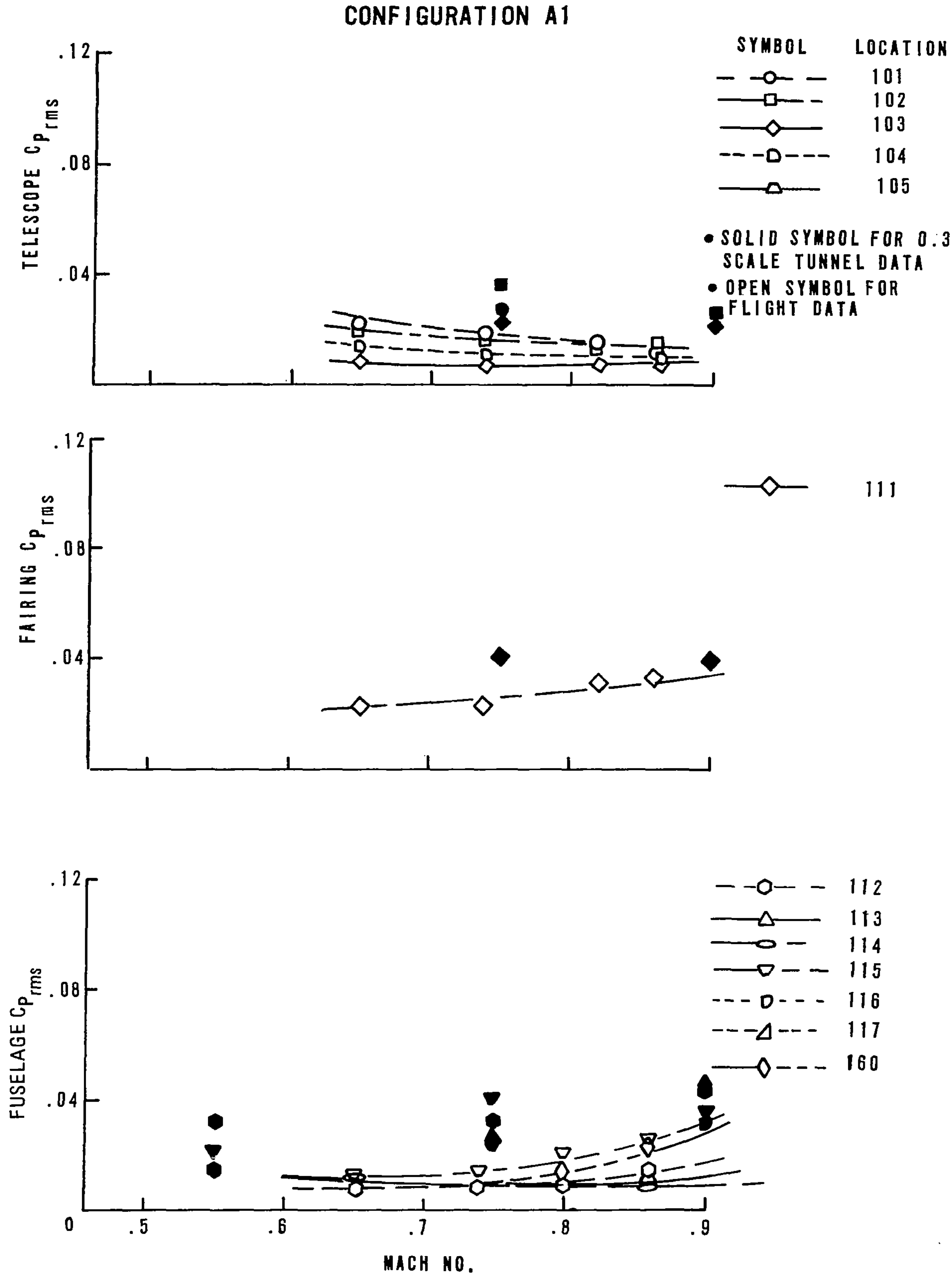

Figure 13a. Sample of flight and ground pressure spectral data.

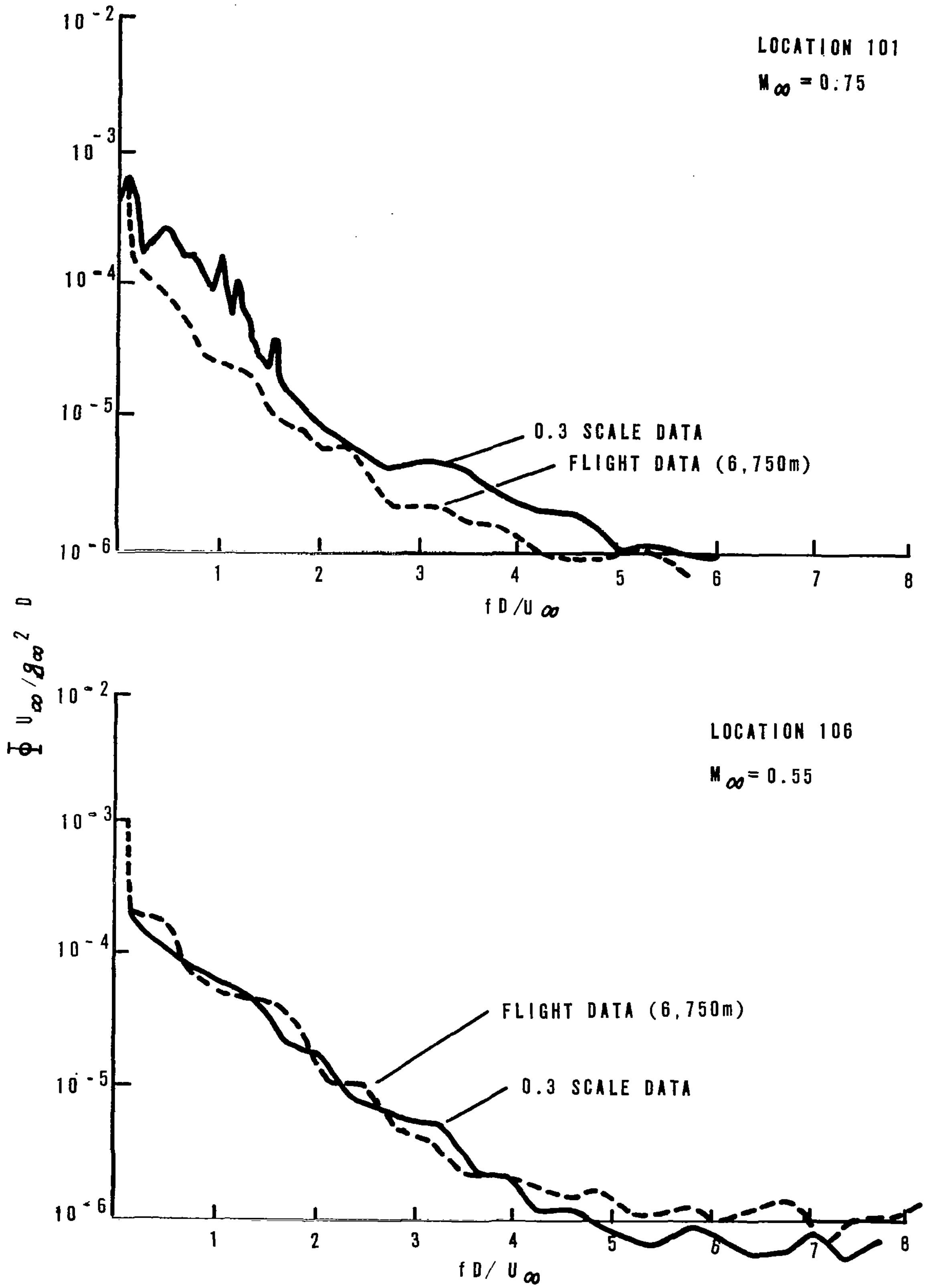

Figure 13b. Sample of flight and ground pressure spectral data.

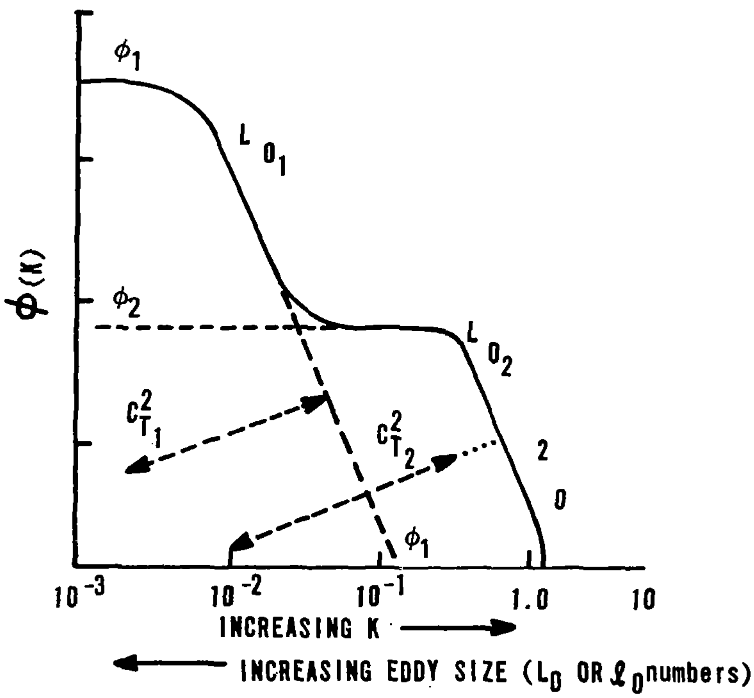

Figure 14. Typical Cycle II hot wire spectrum from the T-39.

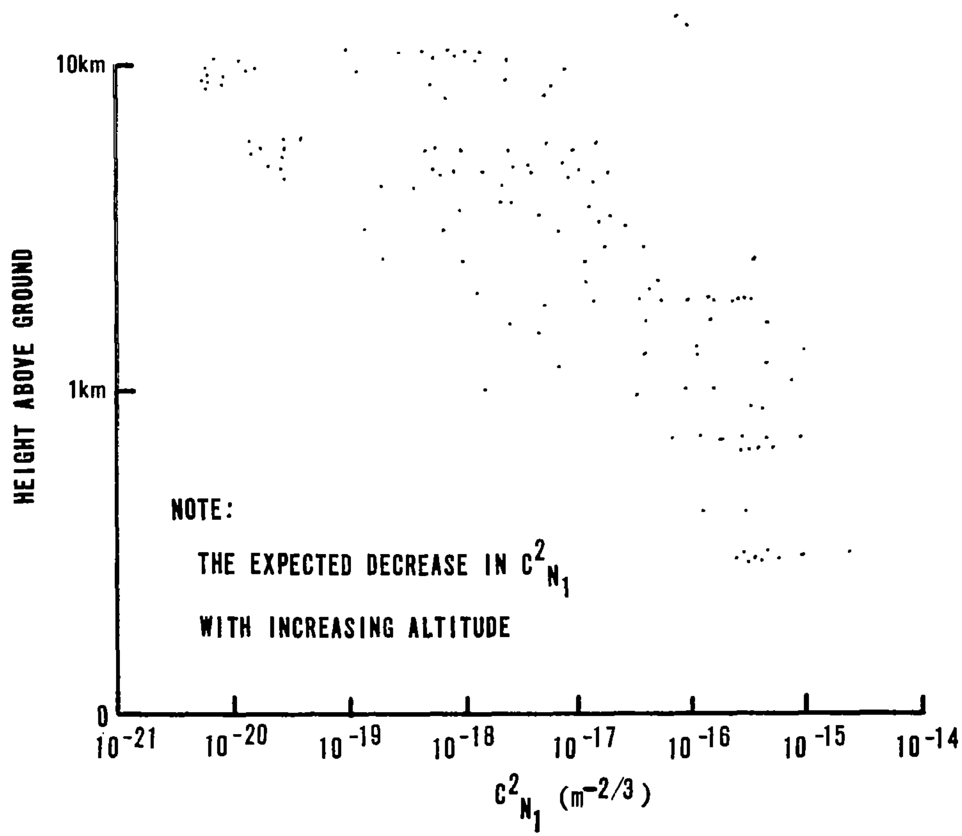

Figure 15a. Correlations of C_N^2 with altitude. From Cycle II T-39 data.

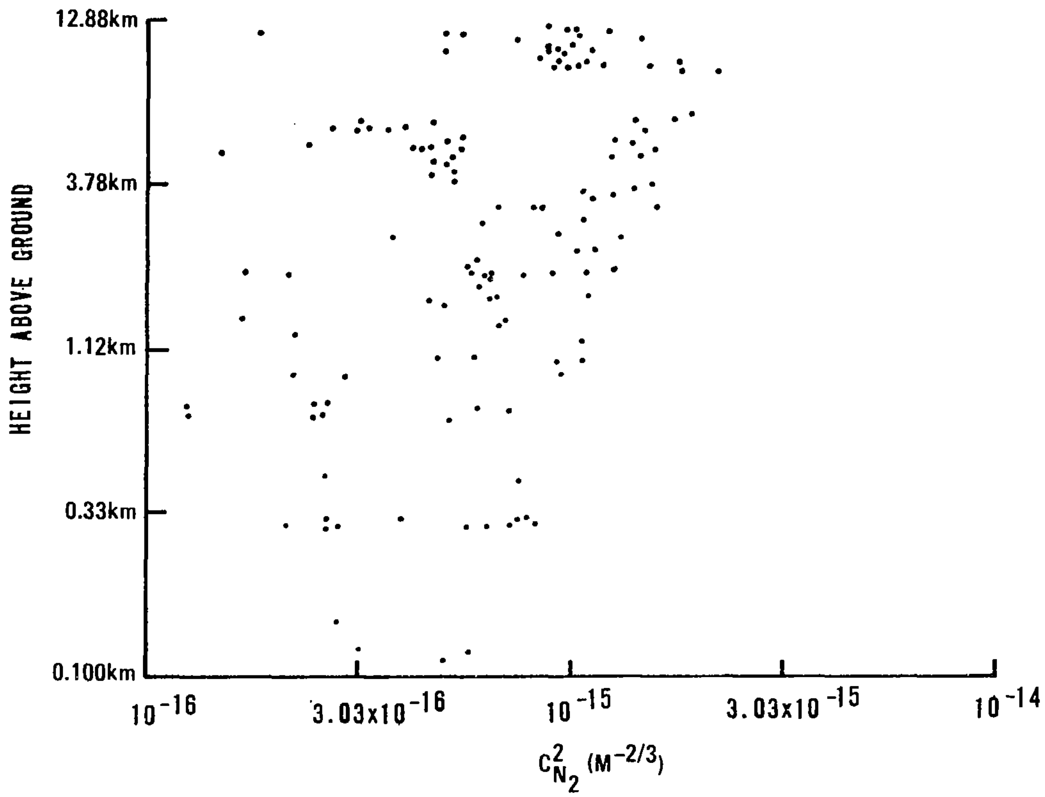

Figure 15b. Correlation of $C_N^{\ 2}$ with altitude. From Cycle II T-39 data.

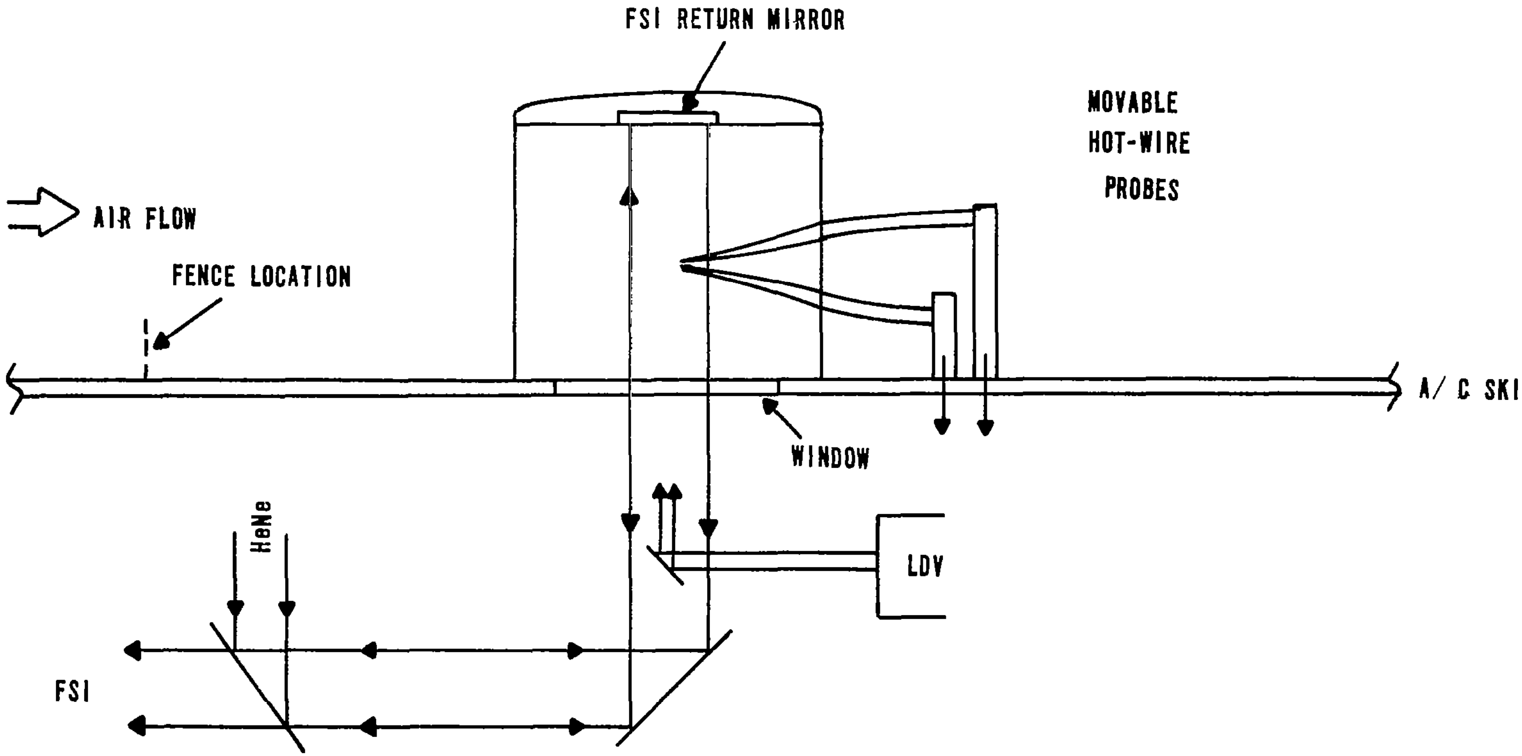

Figure 16a. Cycle II.5 experimental setup.

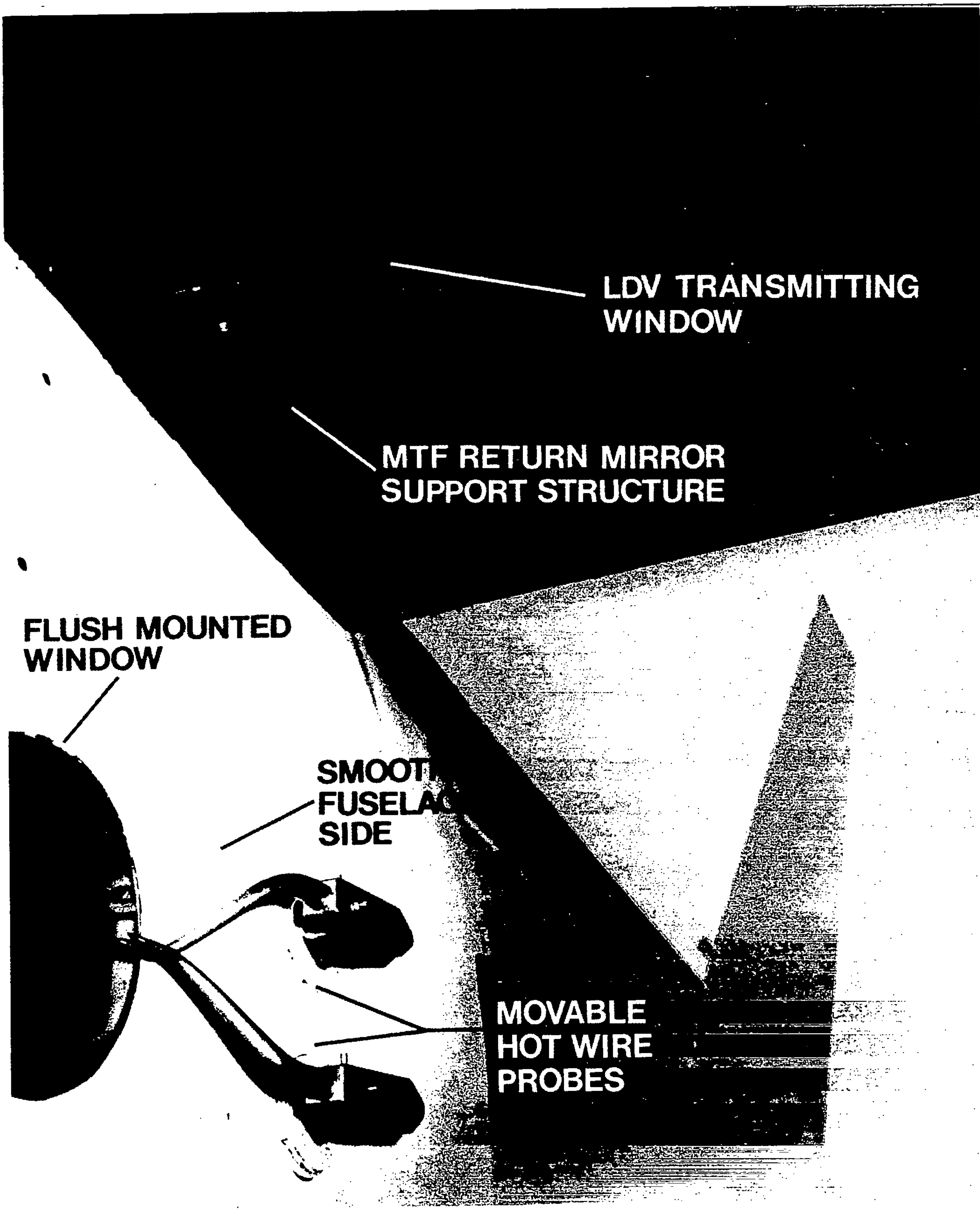

Figure 16b. Cycle II.5 experiment station.

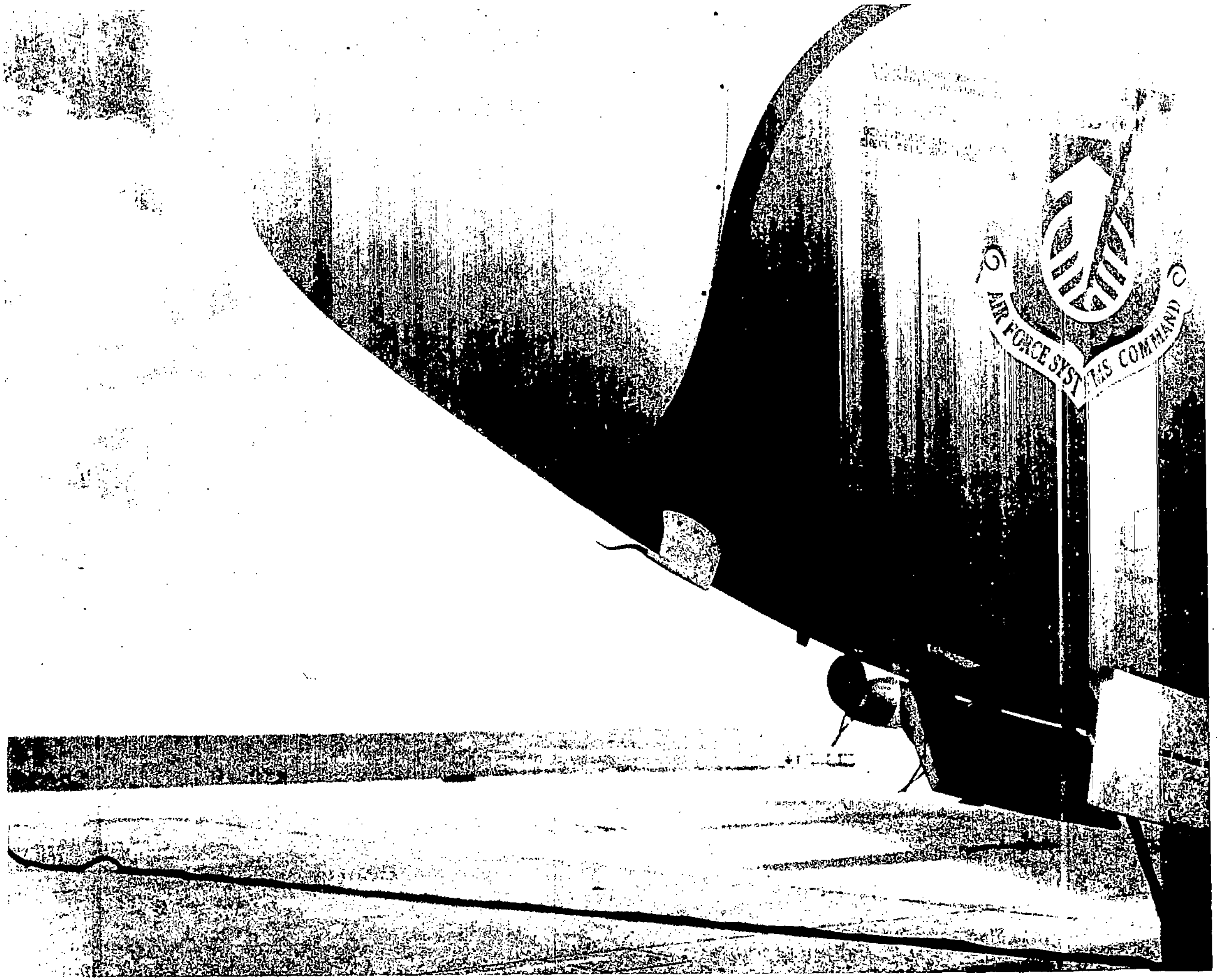

Figure 17. Atmospheric turbulence probe mounted to the nose of an Air Force NC135A.