

**An experimental assessment of the use of ground-level
microphones to measure the fly-over noise of
jet-engined aircraft**

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ABSTRACT

During a series of aircraft flight trials to measure the noise levels of six different military jet aircraft types in low-altitude high-speed operations, noise measurements were made using microphones at ground level and at a height of 1.2 m. The programme provided the opportunity to obtain reliable data on the difference between sound pressure levels from the two microphone arrangements, for sound incident over a range of angles, from 0° (aircraft overhead) to approximately 80°.

Substantial differences from ground level to 1.2 m were observed in measurements of maximum perceived noise level, effective perceived noise level and maximum A-weighted sound pressure level. When considering sound incident to the ground at angles less than approximately 60° from vertical, these differences were found to be independent of angle of incidence for all the six aircraft and all flight procedures. Within this range of sound incidence angles the ground-plane arrangement produced data that closely approximated pressure-doubled values, and the conventional 1.2 m-high microphone gave rise to noise levels approximately 4 dB lower. For sound incident at angles greater than 60° from vertical, the difference between noise levels measured using the two microphone configurations was found to depend on angle of incidence, reducing to zero at approximately 75°. This dependence on angle of sound incidence is probably caused by acoustic shadowing of the ground-plane arrangement, resulting from temperature and wind speed gradients in the atmosphere.

It is concluded that when noise measurements are made using the ground-plane arrangement, the effects of meteorological conditions must be considered in relation to sound incident at angles greater than approximately 60°.

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1 INTRODUCTION

In previous NPL Reports¹⁻⁶, the differences between noise levels obtained using microphones close to the ground plane and at a height of 1.2 m, from over-flying propeller-powered and jet-engined aircraft, have been examined. In all these studies, noise levels were measured over a range of angles of sound incidence from normal (0°) up to approximately 50° , encompassing the angles at which maximum noise levels occur at locations under the aircraft flight path. From the data presented in the reports, a ground-plane microphone arrangement has been shown to provide noise data that closely approximate pressure-doubled values for the sound incidence angles covered. The ground-plane arrangement consisted throughout of a half-inch free-field microphone, inverted over a 0.4 m-diameter, hard, rigid baffle placed flush with the surrounding ground, the microphone off-set from the centre by three-quarters of the baffle radius and mounted such that a line drawn from it to the centre of the baffle was perpendicular to the projected line of aircraft flight. The use of this arrangement is now a requirement in the noise certification procedures for propeller-driven light aircraft⁷, in which the maximum A-weighted sound pressure level under the flight path has to be determined. The noise certification procedures for commercial jet-powered aircraft⁷, on the other hand, require effective perceived noise levels (EPNL) to be determined, both under the flight path and along a sideline. Contributions to EPNL are received at all locations of interest from a range of sound incidence angles extending beyond 50° , and so it is of interest to study the performance of ground plane microphone arrangements at greater angles.

In this report the performance of the ground-plane arrangement is assessed for angles of sound incidence up to approximately 80° . Noise data are presented from the overflight of several military jet aircraft types, namely the Panavia Tornado GR1, Sepecat Jaguar, British Aerospace Harrier GR5, British Aerospace Hawk T1A, McDonnell Douglas F-15 and General Dynamics F-16. Results are presented for a range of aircraft heights, speeds and engine power settings. The flight test programme, named "Exercise Luce Belle", was carried out jointly with the RAF Institute of Community and Occupational Medicine (ICOM), and was carried out to examine the noise from high-speed, low-altitude operations^{8,9}. As military aircraft, the six types considered in this report are not subject to noise certification, but having source noise characteristics similar to commercial jet-powered aircraft, they provide noise data suitable for inferring the performance of the ground-plane microphone.

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2 EXPERIMENTAL ARRANGEMENTS AND PROCEDURES

2.1 TEST SITE

Flight tests were carried out at the Royal Aeronautical Establishment, West Freugh, Scotland. Noise measurements were made at two locations at the South end of the hard target area, see Figure 1.

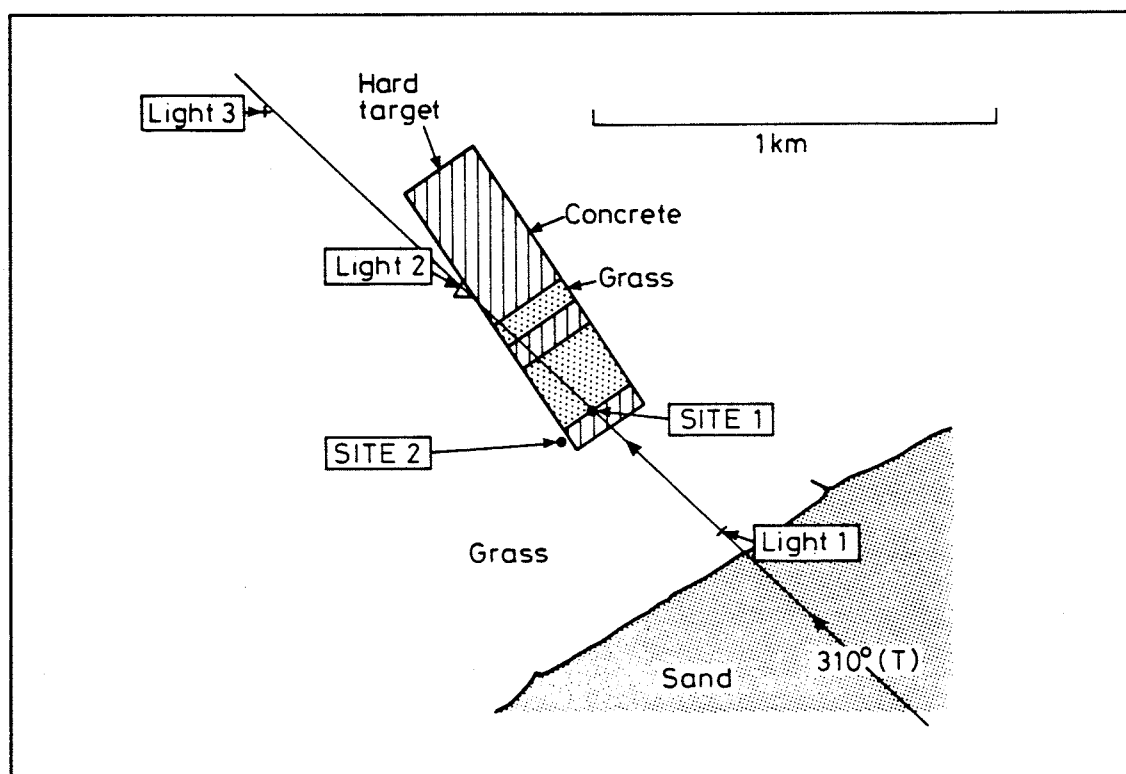


Figure 1 Plan of test site

Site 1 was directly on the aircraft ground track close to a grass/concrete border, and microphones were positioned on both the grass and concrete surfaces. Site 2 was approximately 100 m to the side of site 1 and microphones were positioned on a grass surface. Further details of microphone deployment are given in Section 2.2. All aircraft followed the track shown at a bearing of 310 degrees. The acoustic properties of the concrete and grass surfaces were not measured, but may be assumed to be similar to surfaces examined as part of a previous study¹⁰ where a specific flow resistance of a grass surface was estimated to be 800 kPa.s.m^{-2} and that for a concrete area was 20 MPa.s.m^{-2} .

2.2 MICROPHONE DEPLOYMENT

Six microphone systems were used, each employing a Brüel and Kjaer type 4165 half-inch condenser microphone and type 2619 pre-amplifier. Four microphones were located at site 1 and two at site 2. Detailed positional data are shown in Figure 2.

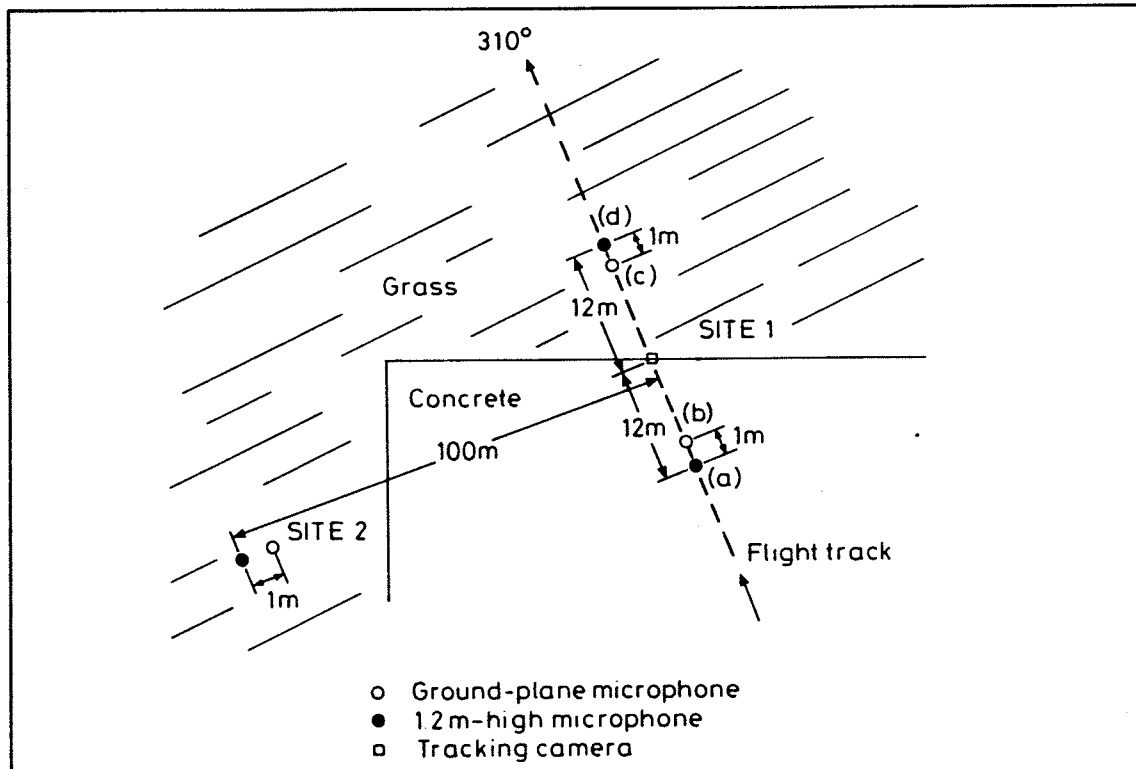


Figure 2 Microphone positions

The four microphones positioned at site 1 were arranged as follows:

- (a) 1.2 m above the concrete ground surface with the plane of the microphone diaphragm perpendicular to the ground surface and parallel with the expected line of aircraft flight,
- (b) inverted, with the microphone diaphragm 7 mm above and parallel to the concrete ground surface, the body of the microphone being supported by a small tripod.
- (c) inverted as (b) above, but over a 0.4 m diameter steel baffle having its upper surface flush with the ground surface (by removing a 0.4 m diameter circle of turf),
- (d) as microphone (a) above,

The two microphones positioned at site 2 were arranged as follows:

- (e) as microphone (c) above,
- (f) as microphone (d) above.

2.3 AIRCRAFT MANOEUVRES

Each aircraft operated under a range of engine power settings with several combinations of speed and altitude, each with at least two replications. The nominal flight conditions, which were selected as being representative of those encountered in low-level flying, are listed in Table 1.

The actual measured conditions are shown for each of the six aircraft types in Figures 3 to 8. The data in all six figures are displayed using identical axes, thus permitting a ready evaluation of the differences within and between individual aircraft flight conditions, and groups of data points for repeated nominal flight conditions are circled and annotated. These groups are used in the statistical analysis described in Section 3.3. Pilots were instructed to adjust engine power at the start of each run to achieve the required speed when over site 1. For each run the aircraft was directed on to the correct line from the South East of the measurement area and all tracking and noise measurement instrumentation electronically "marked" with a dead zero time (DZT), then the pilot used three lights, shown in Figure 1, to line up for the overflight. Each aircraft was required to maintain, as near as possible, a constant set of flight conditions over a distance from 8 km on approach to the measurement area to 4 km on departure.

Table 1 Nominal flight conditions

AIRCRAFT	HEIGHT (feet)	SPEED (knots)	ENGINE POWER
Tornado	250	420	90%
	250	480	93%
	250	550	96%
	100	420	90%
	100	480	93%
	100	550	96%
Harrier	250	420	90%
	250	480	Max. dry
	100	420	90%
	100	480	Max. dry
Jaguar	250	420	97%
	250	480	Max. dry
	250	550	Max. dry
	100	420	97%
	100	480	Max. dry
	100	550	Max. dry
Hawk	250	420	93% - 94%
	250	480	Max. dry
	150	420	93% - 94%
	150	480	Max. dry
F-15	300	420	85%
	300	480	89%
	300	550	97%
	200	420	85%
	200	480	89%
	200	550	97%
F-16	300	420	85%
	300	480	89%
	300	550	95%
	200	420	85%
	200	480	89%
	200	550	95%

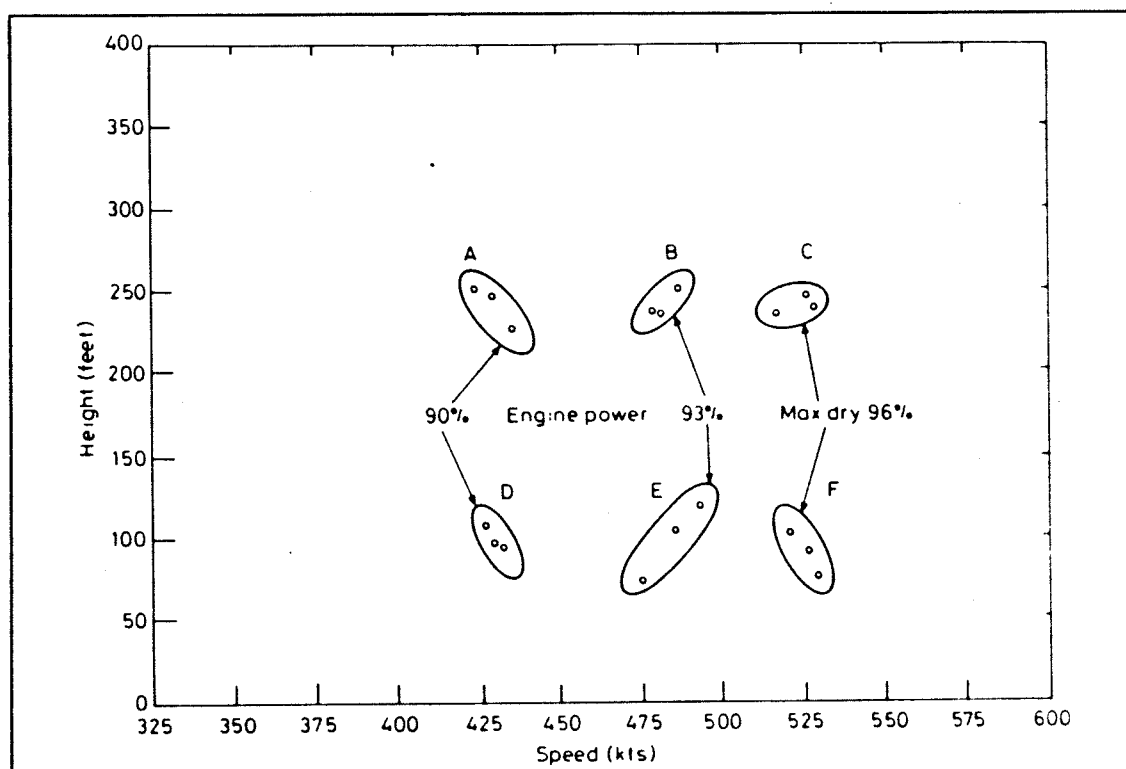


Figure 3 Flight parameters for the Tornado

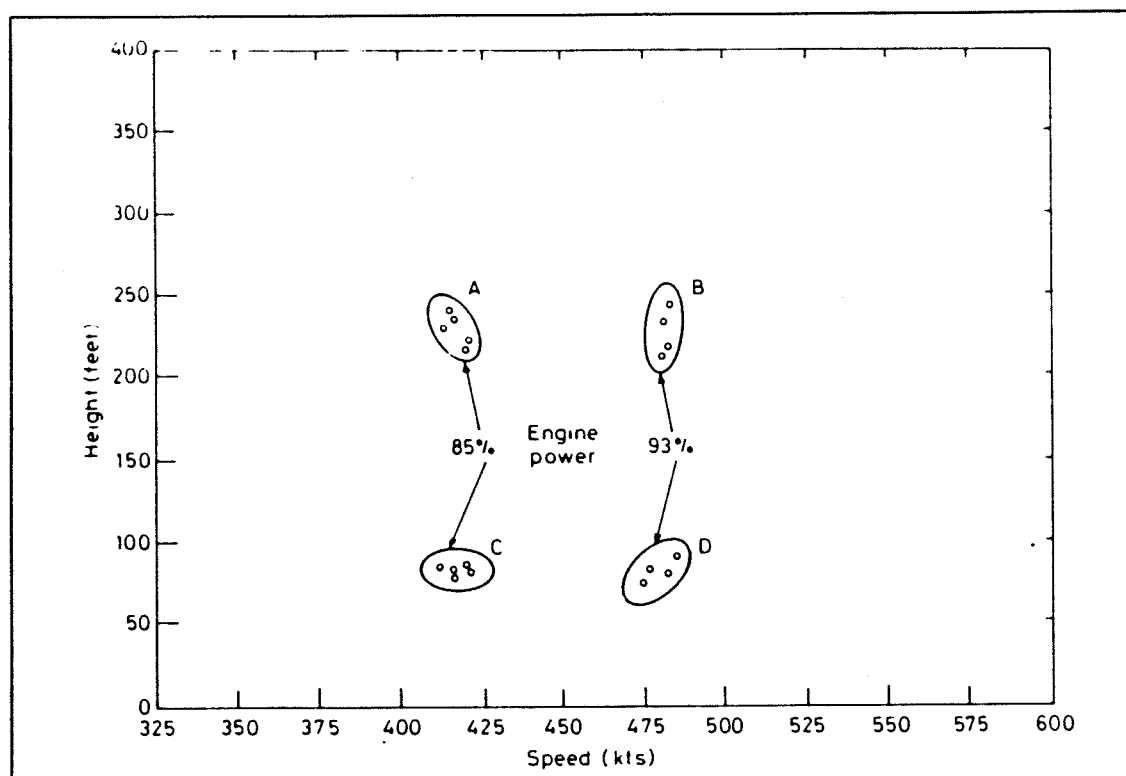


Figure 4 Flight parameters for the Harrier

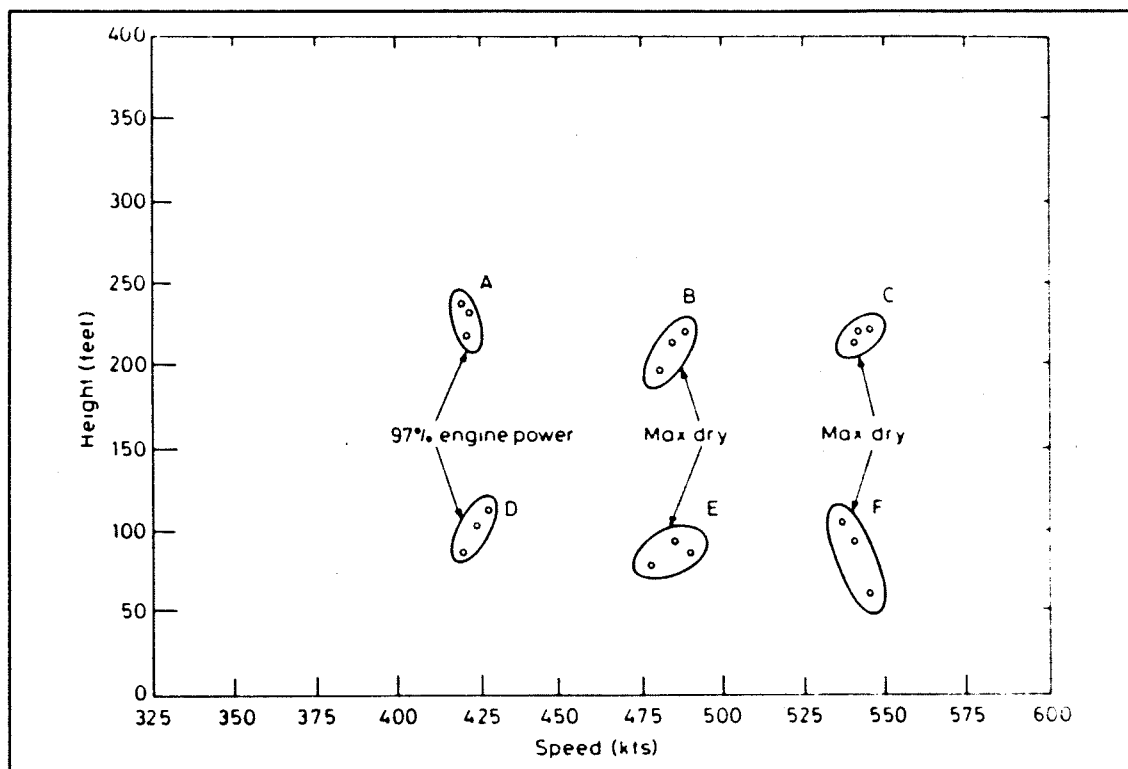


Figure 5 Flight parameters for the Jaguar

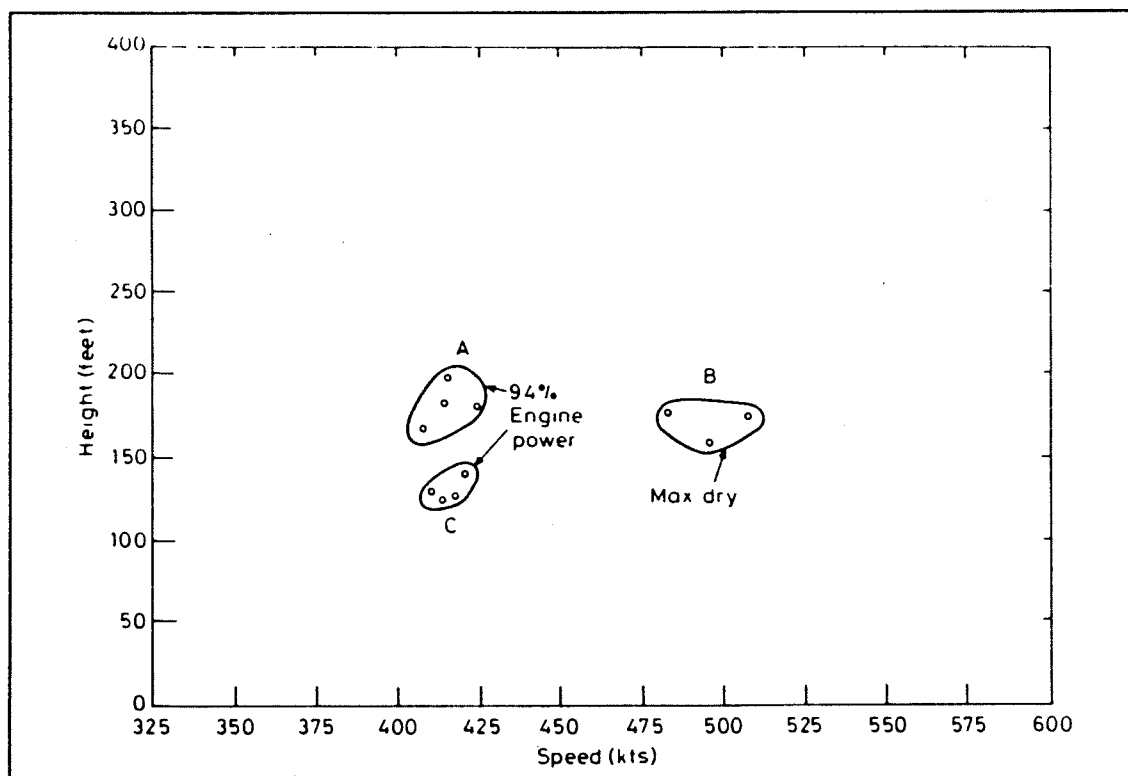


Figure 6 Flight parameters for the Hawk

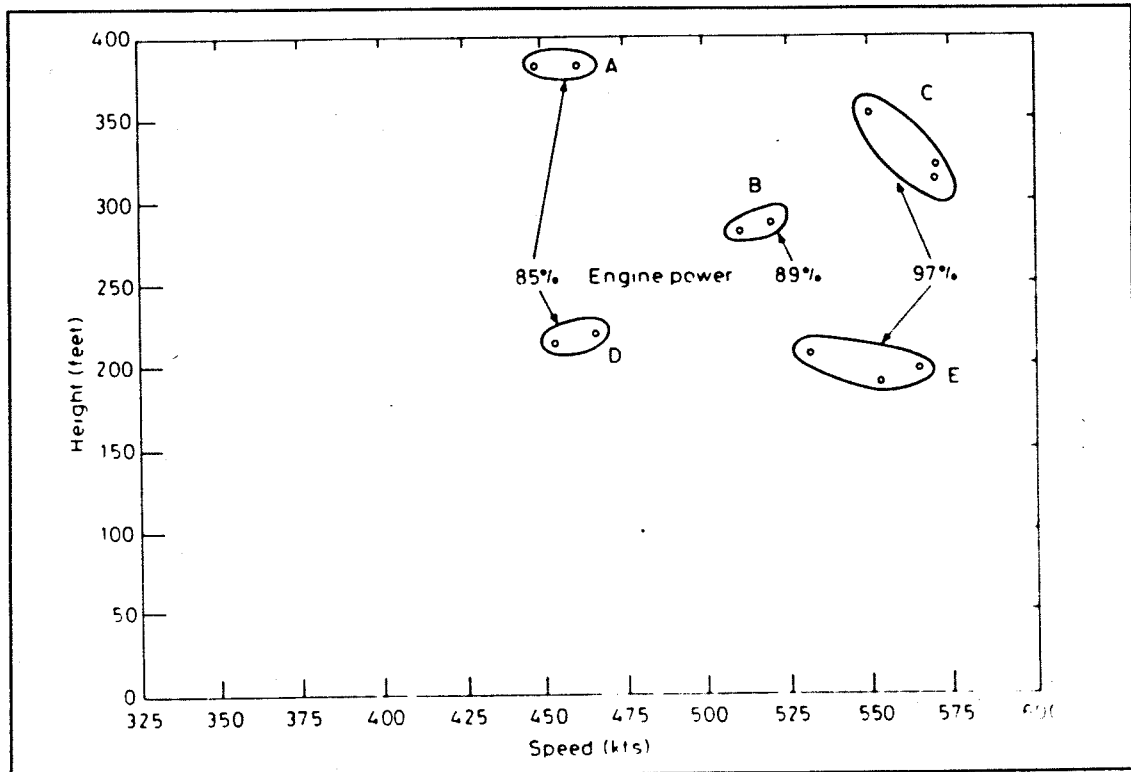


Figure 7 Flight parameters for the F-15

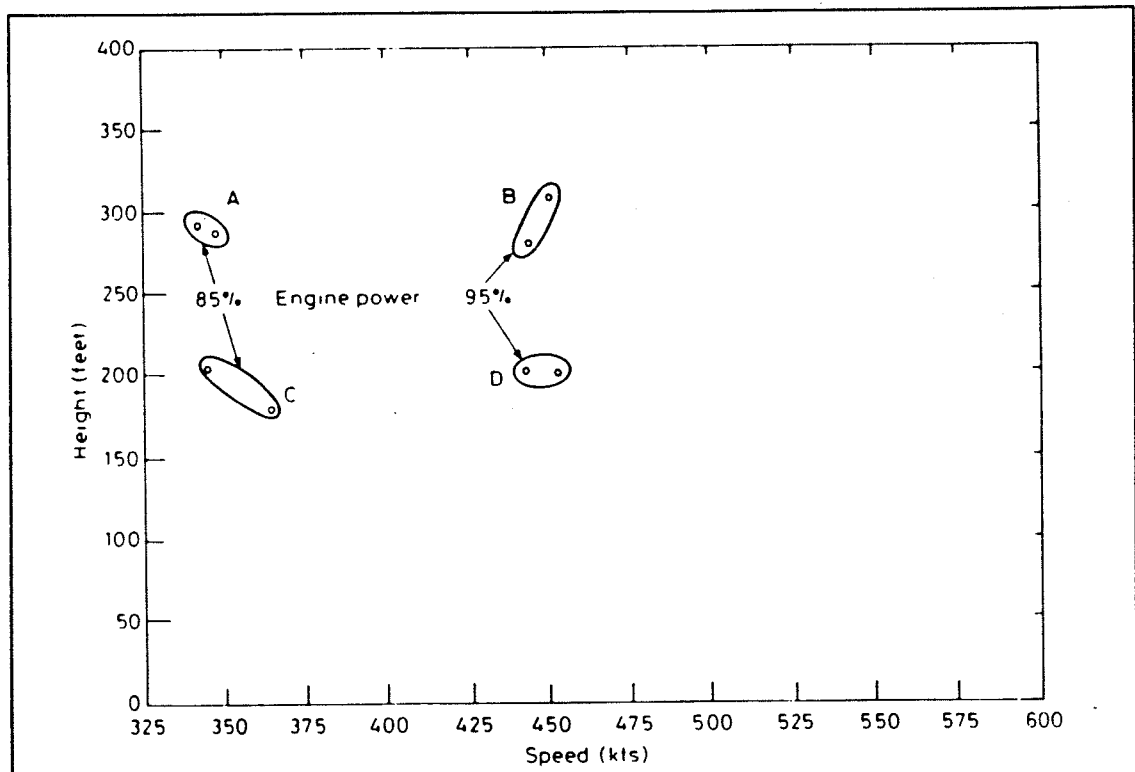


Figure 8 Flight parameters for the F-16

2.4 AIRCRAFT TRACKING

Each overflight was tracked by RAE West Freugh personnel using optical kine-theodolites and radar. The data, supplied in the form of a computer print out and on magnetic tape, gave aircraft height, polar coordinates and distance from site 1 as a function of time. The data were interrogated by computer and the change from -ve distance (aircraft approach) to +ve distance (aircraft departure) noted. A linear interpolation procedure was used to estimate aircraft position and time when over site 1 (ie zero distance). In addition, positional data were obtained using a video technique developed at NPL¹¹, using a single camera directed vertically upwards in order to obtain the aircraft height and off-track distance as it passed through the camera field of view. The camera was positioned on the grass/runway border at site 1 and the aircraft position relative to all microphone locations was calculated using the geometric data in Figure 2. Data from the NPL video system were used during periods of poor visibility, when the kine-theodolite data were unreliable.

2.5 METEOROLOGICAL MEASUREMENTS

Meteorological data were measured at the beginning of each sortie using an instrumented untethered balloon. Before launch, from the SE end of the hard target area, temperature, atmospheric pressure, relative humidity and wind speed and direction were measured. On release, the balloon was tracked by kine theodolite and wind speed and direction at altitude were estimated from the trajectory. Values of temperature, relative humidity and atmospheric pressure were transmitted to a ground-based receiver at one-second intervals throughout the visible duration of the flight. These data were interpolated by computer and printed out as a function of altitude, starting at 50 feet and then at intervals of 50 feet. In addition, data were obtained at a height of 15 feet from the control tower immediately prior to each overflight.

2.6 METHOD OF DATA RECORDING AND ANALYSIS

The microphones were grouped in pairs (a/b, c/d, e/f), see Figure 2, and the signals from each pair were recorded digitally on separate tracks of a Sony PCM 2000 DAT recorder, together with an IRIG B time code signal. Recordings were made to cover at least the duration of the straight and level flight. Each recorded microphone signal was replayed through a Brüel and Kjaer digital frequency analyzer type 2131 controlled by a Tektronix 4052A microcomputer. The signal was sampled at 0.1 s intervals throughout the flyover and the resulting 1/3-octave

spectra were stored in digital form on disc together with the associated time code data. Typically this resulted in storing 55 spectra from each microphone for each flyover. The time code for each measured spectrum was compared with the RAE (or NPL) tracking data and aircraft positional co-ordinates were estimated, and from these an aircraft angular bearing was calculated and stored on computer disc with the corresponding noise spectrum.

In estimating the aircraft position, due allowance was made for the exact location of each microphone in relation to the position of the single tracking camera system at the centre of the microphone array. Because the aircraft speed was not negligible compared with the speed of sound, the angle of incidence of sound at a given time was not necessarily equal to the aircraft bearing angle. So, using data describing aircraft speed, the aircraft bearing angle was converted to angle of sound incidence and also stored on disc.

Aircraft noise certification procedures⁷ require that noise levels during an aircraft flyover are described in terms of the perceived noise level (PNL) and overall in terms of EPNL. In this report, differences between noise levels obtained using the six different microphone systems are therefore examined primarily in terms of PNL and EPNL, and additionally in terms of the A-weighted sound pressure levels (L_{Amax}).

The principal objective was to examine the differences between noise levels measured using a 1.2 m-high microphone and a ground-plane microphone arrangement, and to determine their cause. To achieve this objective it is convenient to compare the performance of the systems under test by making reference to an undistorted datum, either of free-field or pressure-doubled levels. Because of the close proximity of the ground surface, measurement of a free-field value was impractical. A true pressure-doubled sound-field, however, would have been detected by a microphone located with its diaphragm flush with an infinite perfectly-reflecting surface. Such an arrangement was not included in the microphone deployment (see Section 2.2). So, results are presented as differences between the 1.2 m-high microphone data and the corresponding ground-plane data. However, previous reports¹⁻⁶ have shown that the difference between noise levels measured using the ground-plane arrangement and pressure-doubled values is small, and so the results discussed in this Report may be assumed to closely approximate differences from pressure-doubled levels.

3. RESULTS AND DISCUSSION

3.1 TRACKING DATA

Data from the RAE kinetheodolites and from the NPL video system were processed using a microcomputer and a flight profile for each aircraft overflight obtained. The profiles were in the form of a plot of off-track and altitude against horizontal distance (or time) along the aircraft track. Aircraft speed and altitude when the aircraft was directly above the NPL camera position at measurement site 1 are shown in Figures 3 to 8. The corresponding values of off-track for each aircraft type are shown in Table 2 as mean values together with the associated standard deviation. A positive value of off-track represents the aircraft passing to the West of site 1.

Table 2 Off-track distances

AIRCRAFT	MEAN (OFF-TRACK)	STANDARD DEVIATION
	metres	metres
Tornado	2.6	6.1
Harrier	-0.9	3.9
Jaguar	0.7	6.2
Hawk	0.7	4.0
F-15	0	5.8
F-16	3.0	3.2

The data shown in Table 2 are calculated using results from all flights of each aircraft (ie a combination of all altitudes, speeds and power settings). The standard deviations for each group of replicated conditions (see Figures 3 to 8) are generally less than those in Table 2. The tracking results discussed above describe the aircraft location at zero horizontal distance (the position of the NPL video camera). However, these results are representative of aircraft location over a range of approximately ± 3 km about this "zero distance". Outside these limits, aircraft altitude and off-track were observed to depart from the precise flight track requirements (see Section 2.3). Generally altitude increased (ie the aircraft reduced height on approach to the measurement site and then increased on departure) and the aircraft turned off

the required track on departure, the direction (east or west) alternating between successive overflights. The noise data discussed in this Report (either PNL or A-weighted) are mainly confined to the instant of maximum noise level, which occurs within this region of stable flight condition, and so the departure from straight and level flight will have no effect on the reported data.

3.2 NOISE LEVELS

In previous NPL Reports¹⁻⁶ a comparison was made between as-measured acoustic data and those after correction for the effects of interference (1.2 m-high microphone) or diffraction (ground-plane arrangement). These corrections depended on angle of sound incidence and frequency, and were applied to individual spectra sampled during the aircraft overflight. To obtain sufficient accuracy in individual one-third-octave band levels the corrections were usually obtained by interpolating data arrays describing the variation of noise levels as a function of angle of incidence in intervals of 1°. The aircraft flight procedures described in this Report were all high-speed low-altitude overflights with typical "10 dB down" separations of between 1 s and 3 s. The change in aircraft location (and hence angle of incidence) with time were such that interference corrections (which are highly dependent on angle of incidence) are unreliable. Hence, differences between data obtained using the ground-plane arrangement and a 1.2 m-high microphone are examined primarily in their as-measured form.

The differences in maximum PNL, ΔL , calculated as ground-plane data minus 1.2 m-high data, for all overflights at both measurement sites, are shown in Figures 9 to 14. ΔL is presented as a function of the angle of sound incidence at which the maximum PNL occurred, the angles having been calculated as described in Section 2.6. The measurement sites from which the data points were derived and the corresponding altitudes of the aircraft are indicated on the figures.

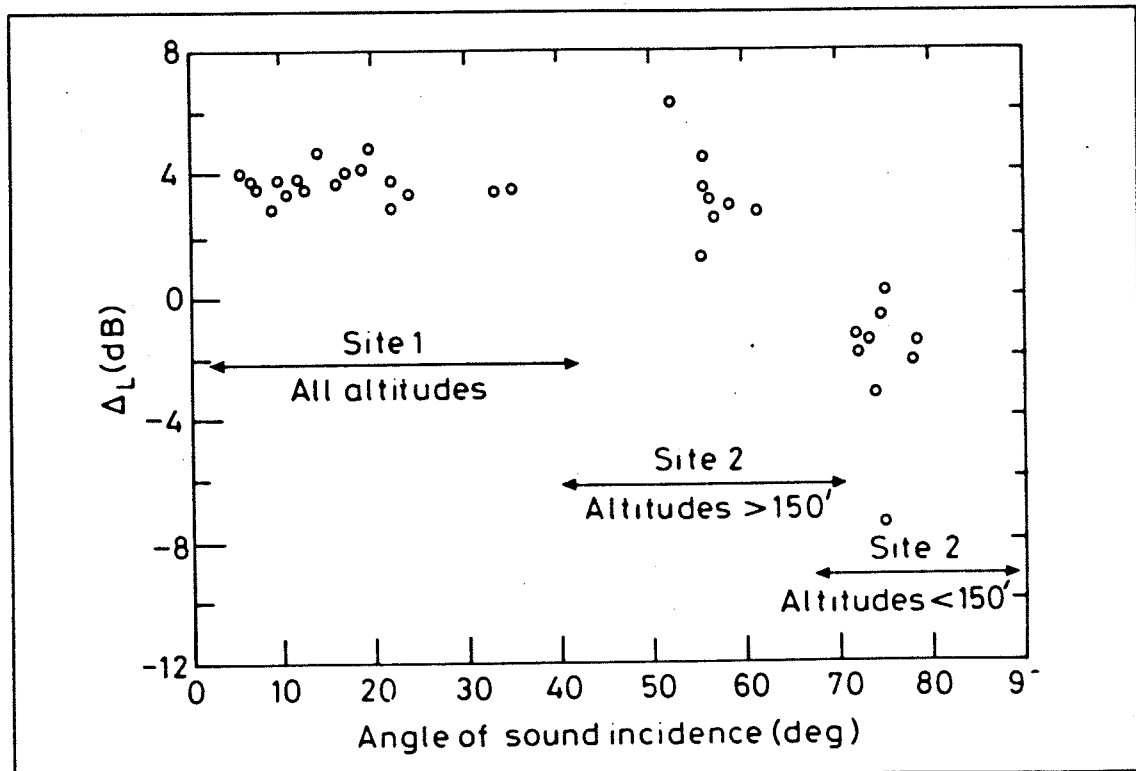


Figure 9 Variation of Δ_L (PNL) with angle of incidence for the Tornado

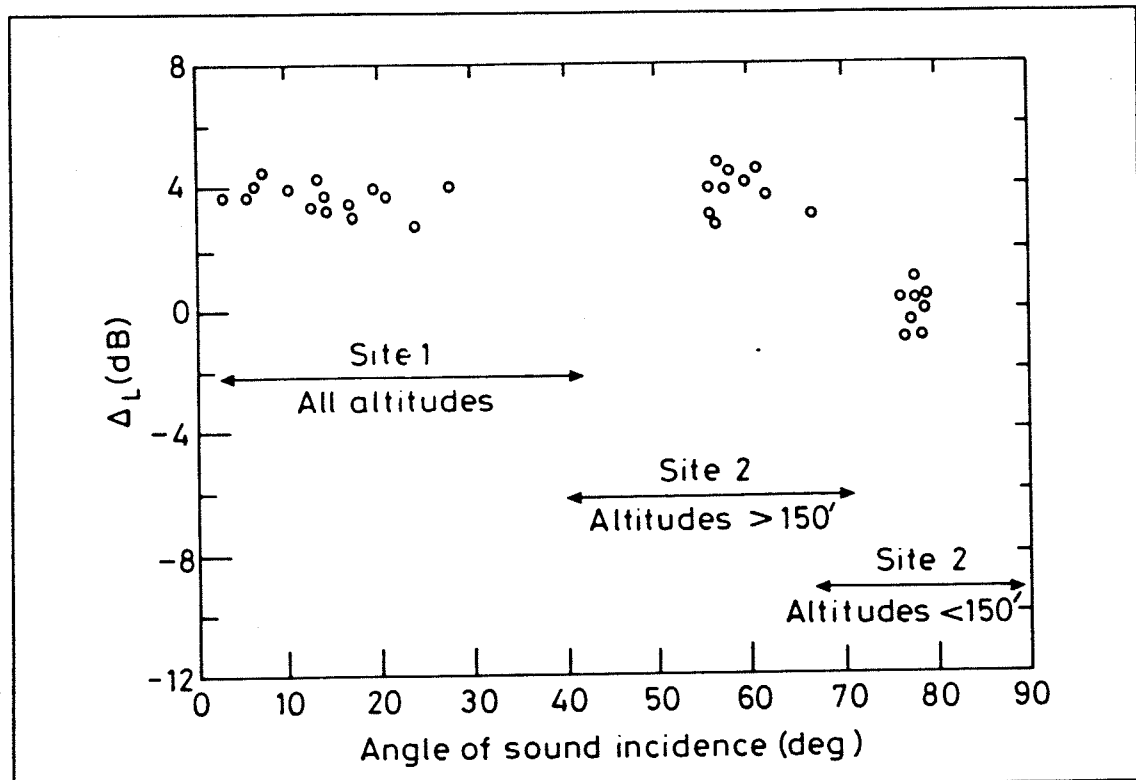


Figure 10 Variation of Δ_L (PNL) with angle of incidence for the Harrier

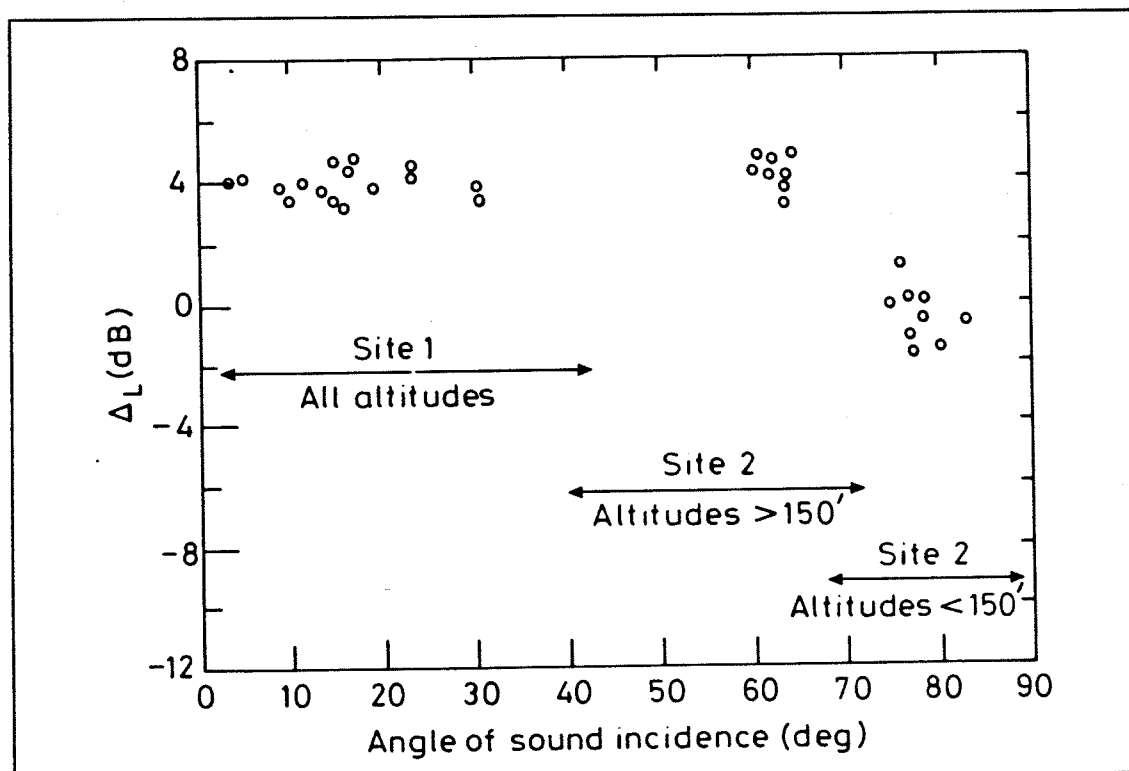


Figure 11 Variation of Δ_L (PNL) with angle of incidence for the Jaguar

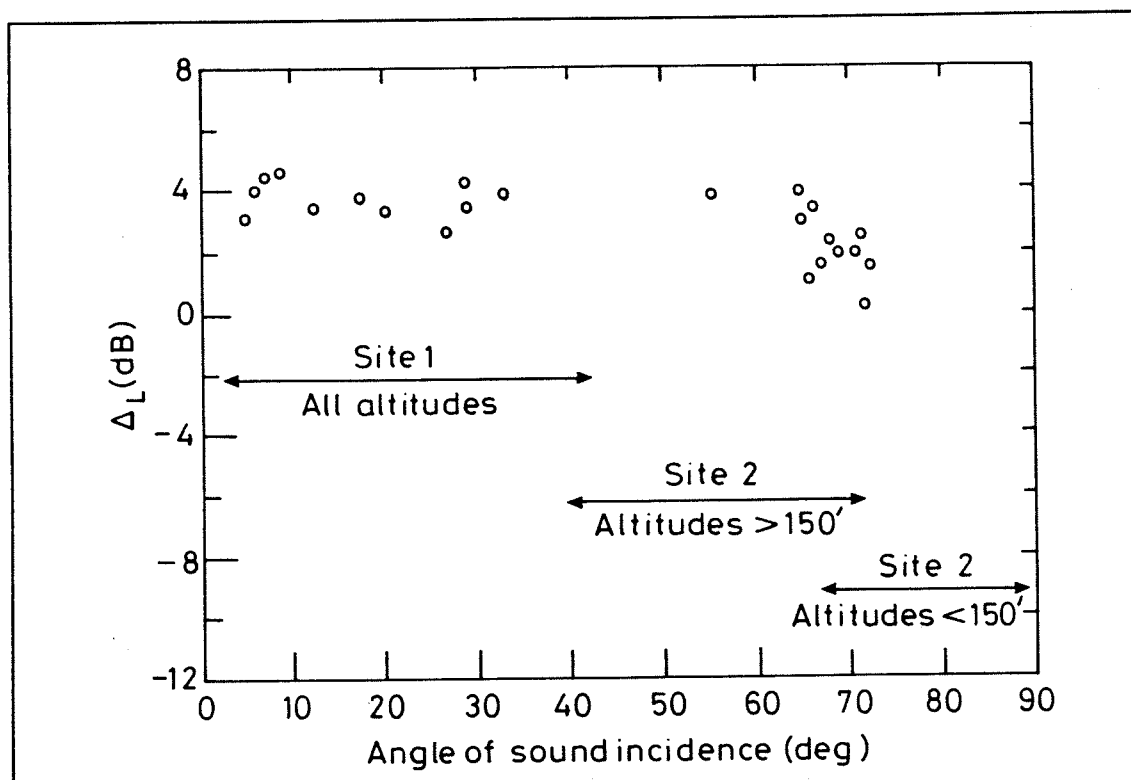


Figure 12 Variation of Δ_L (PNL) with angle of incidence for the Hawk

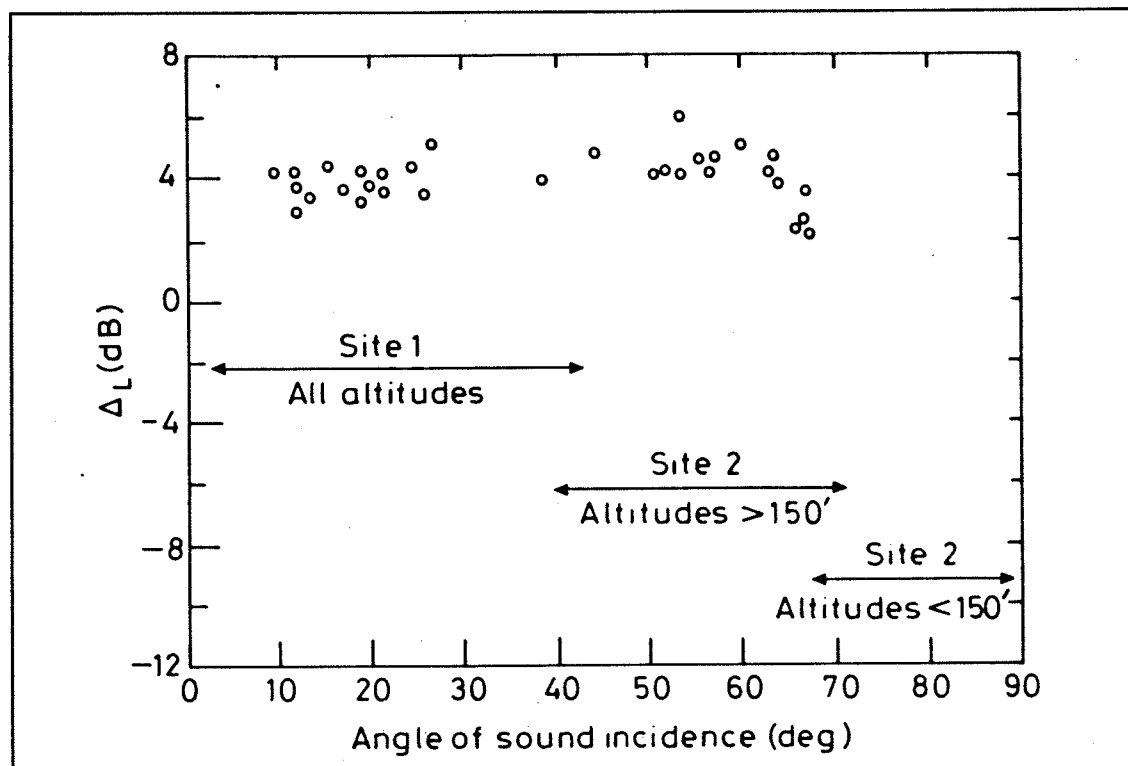


Figure 13 Variation of Δ_L (PNL) with angle of incidence for the F-15

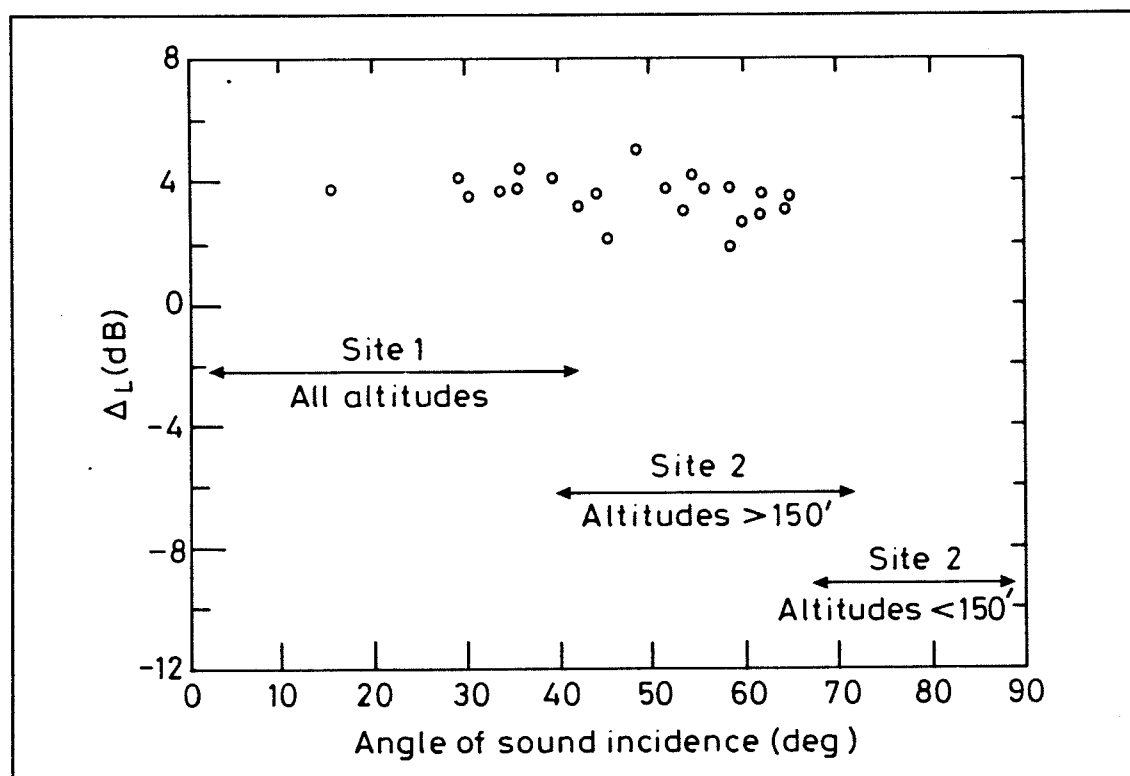


Figure 14 Variation of Δ_L (PNL) with angle of incidence for the F-16

Figures 9 to 14 show that for all six aircraft types the magnitude of ΔL is essentially constant over an angular range from practically 0° to 60° . Values of ΔL were similarly determined with respect to EPNL and L_{Amax} and averages for all three noise measures within this range of sound incidence angles are presented for the six aircraft types in Table 3. The statistical significance of the small variations in these average values between aircraft type (a range of only 0.29 dB for PNL) and variations between individual overflights within each aircraft type is discussed in detail in Section 3.3.

Table 3 Mean values of ΔL at Site 1

AIRCRAFT	MEAN ΔL (dB)		
	PNL	EPNL	L_{Amax}
Tornado	3.91	3.85	3.85
Harrier	3.72	3.64	3.72
Jaguar	3.97	3.91	4.06
Hawk	3.78	3.6	3.62
F-15	3.91	3.71	3.67
F-16	3.68	3.77	3.84
MEAN VALUE	3.83	3.75	3.79

Because of the similarity of data shown for each aircraft in Figures 9 to 14, all those for PNL have been combined and are shown on the same axes in Figure 15. Similarly, results are presented in Figures 16 and 17 in terms of EPNL and maximum A-weighted levels (L_{Amax}) respectively.

In all three cases, at angles of incidence for the maximum noise levels greater than approximately 60° , the values of ΔL reduce, approaching zero at about 75° . It is not clear whether this reduction is the result of changes in the output of the 1.2 m-high microphone, the ground-plane microphone or both; this question is addressed in Section 3.5.

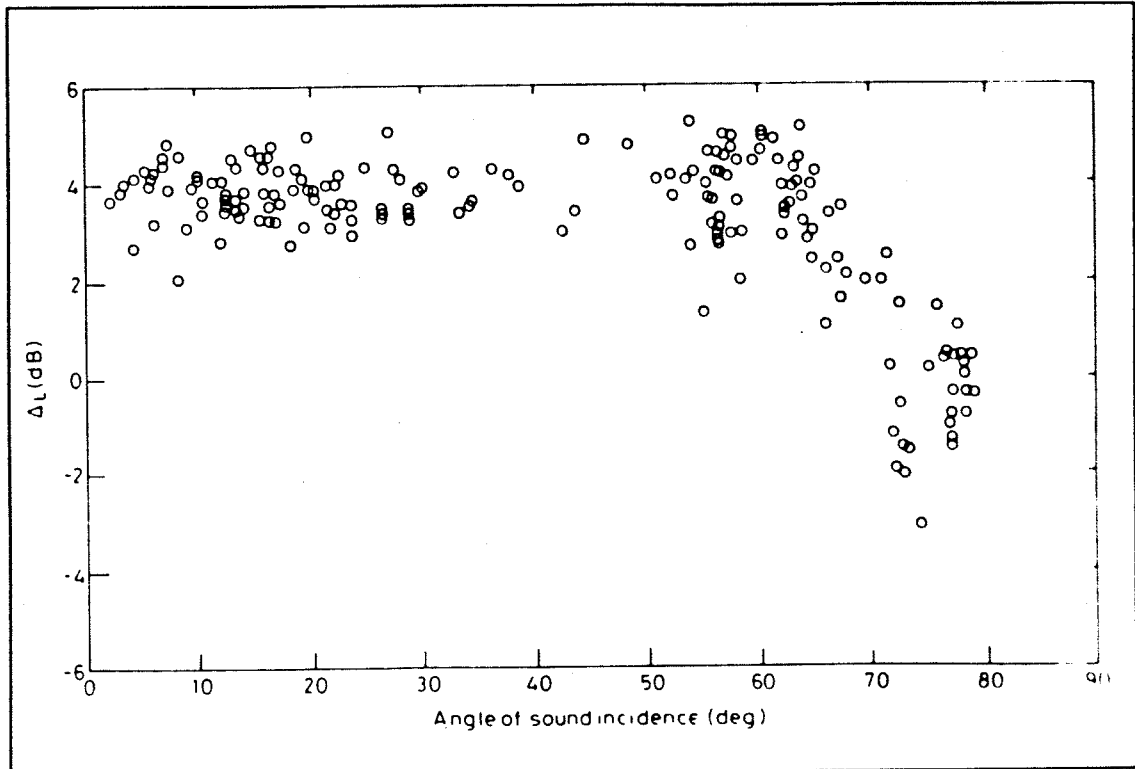


Figure 15 Variation of ΔL (PNL) with angle of incidence for all aircraft

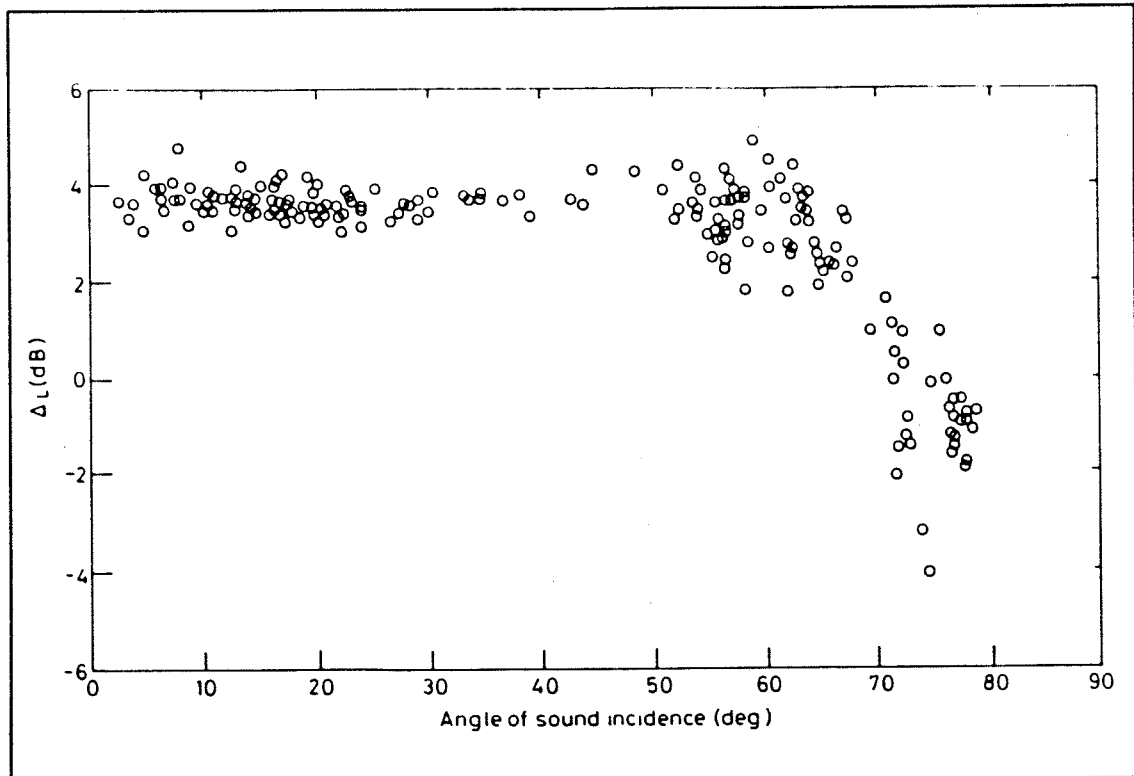


Figure 16 Variation of ΔL (EPNL) with angle of incidence for all aircraft

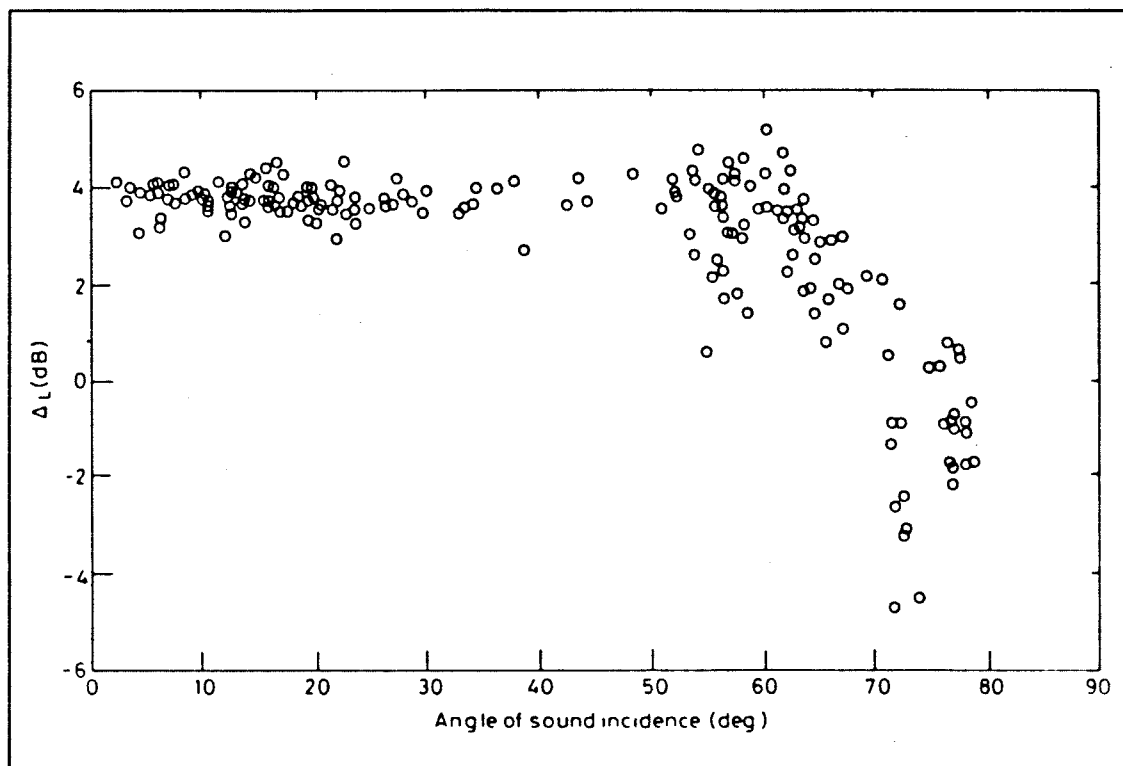


Figure 17 Variation of ΔL (L_{Amax}) with angle of incidence for all aircraft

3.3 STATISTICAL ANALYSIS OF SITE 1 DATA

At measurement site 1, the angles of sound incidence for maximum perceived noise levels and maximum A-weighted sound pressure levels extended to just over 40°. It can be seen from Figures 15, 16 and 17 that ΔL was essentially constant over this range of angles and therefore it was possible to establish mean values of ΔL for PNL, EPNL and L_{Amax} , from the repeated flights of the aircraft in the nominal flight conditions identified in Table 1 of Section 2.3. So, for instance, the Tornado data were examined in six groups obtained for flight conditions annotated A to F in Figure 3, each group comprising measurements made during three runs at the same nominal conditions. The mean ΔL for the three noise measures are shown in Tables 4, 5 and 6.

Table 4 Mean values of ΔL (PNL) for Site 1

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	3.6	4.3	4.1	3.5	4.2	3.7
Harrier	3.6	3.7	3.9	3.7		
Jaguar	4.3	3.8	4.1	4.5	3.7	3.5
Hawk	4.0	3.3	4.0			
F-15	3.3	4.4	4.1	4.0	3.6	
F-16	3.6	3.4	3.4	4.3		

Table 5 Mean values of ΔL (EPNL) for Site 1

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	3.7	3.9	4.1	3.8	4.2	3.7
Harrier	3.5	3.6	3.7	3.9	-	-
Jaguar	3.9	3.8	4.0	4.4	3.7	3.7
Hawk	3.6	3.3	3.8	-	-	-
F-15	3.4	3.9	3.7	3.7	3.8	-
F-16	3.8	3.6	3.8	4.0	-	-

Table 6 Mean values of ΔL (L_{Amax}) for Site 1

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	3.9	3.9	3.9	4.0	3.8	3.6
Harrier	3.9	3.6	3.6	3.7	-	-
Jaguar	4.1	4.0	4.3	4.1	4.0	3.8
Hawk	3.9	3.5	3.5	-	-	-
F-15	3.5	3.7	3.8	3.7	3.5	-
F-16	3.9	3.8	3.6	3.9	-	-

An analysis of variance was performed on the data from microphone systems (c) and (d) to test whether the variations in mean ΔL between nominal flight conditions differed significantly from the variations between individual runs. The significance levels of the differences would be 0.05 or less at the generally accepted 95% confidence interval if ΔL depended upon the aircraft speed, height and power setting. The values found are shown in Table 7, and are in fact greater than 0.05 (indicating no significant dependence upon flight conditions) in all cases except that of EPNL for the Jaguar aircraft.

Table 7 Analysis of variance of data from Site 1 related to aircraft flight conditions

AIRCRAFT	SIGNIFICANCE LEVEL		
	NOISE MEASURE		
	PNL	EPNL	L_{Amax}
Tornado	0.30	0.54	0.72
Harrier	0.79	0.11	0.15
Jaguar	0.15	0.00	0.2
Hawk	0.23	0.06	0.09
F-15	0.09	0.31	0.15
F-16	0.38	0.07	0.41

The significant result for EPNL of the Jaguar is due to the exceptionally large ΔL for flight condition D (low altitude, low speed). The reason for that anomaly is not clear, but it arose in only one out of a total of 28 flight conditions across the six aircraft types, and it seems safe to conclude that at Site 1 the difference between noise levels measured using microphones 1.2 m high and near the ground is independent of the aircraft flight parameters.

Having established that ΔL at this site was not connected to aircraft speed, height and power setting, the values in Tables 4, 5 and 6 were averaged across flight conditions, and those averages were tested for aircraft type dependence. The significance levels of the differences between the variations of these averages and those from individual over-flights, with respect to PNL, EPNL and L_{Amax} , are 0.67, 0.21 and 0.07. Thus, at the 95% confidence interval, ΔL was independent also of aircraft type. Finally, the average ΔL from flight condition and aircraft type were averaged across each of the three noise measures, and the variations tested for dependence in this respect. The significance level of the differences from variations between individual flights turned out to be 0.46, indicating the absence of a connection with the noise measure.

3.4 STATISTICAL ANALYSIS OF SITE 2 DATA

The angles of sound incidence of interest at measurement Site 2 extended from 40° to more than 80° . The mean ΔL found for the three noise measures, from the six aircraft types in the previously-identified flight conditions, are shown in Tables 8, 9 and 10.

Table 8 Mean values of ΔL (PNL) for Site 2

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	3.8	3.3	2.3	-1.4	-1.7	-1.4
Harrier	3.8	4.5	0	0.1		
Jaguar	4.6	5.2	4.1	0.4	-0.7	-0.5
Hawk	1.6	3.5	1.9			
F-15	4.1	5.6	4.8	4.2	2.8	
F-16	3.1	4.3	3.0	3.6		

Table 9 Mean values of ΔL (EPNL) for Site 2

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	3.1	2.9	3.4	-1.9	-1.3	-0.5
Harrier	2.8	3.3	-1.5	-1.0		
Jaguar	3.9	4.0	3.8	0	-0.9	-0.6
Hawk	2.1	2.6	1.5			
F-15	4.2	4.8	4.1	3.7	3.1	
F-16	3.7	3.7	3.1	2.5		

Table 10 Mean values of ΔL (L_{Amax}) for Site 2

AIRCRAFT	MEAN ΔL (dB)					
	FLIGHT CONDITION					
	A	B	C	D	E	F
Tornado	2.2	1.9	1.6	-3.5	-2.7	-2.0
Harrier	3.9	4.2	-0.7	0.3		
Jaguar	4.8	3.9	3.1	-0.1	-1.4	-1.6
Hawk	1.1	3.2	1.6			
F-15	3.7	3.8	3.5	3.3	2.3	
F-16	2.9	4.3	1.9	2.9		

The data for Site 2 in Tables 8, 9 and 10 show some substantial differences from those for Site 1 in Tables 4, 5 and 6, with ΔL decreasing to zero and even becoming negative in some cases. An analysis of variance was again performed to test for the significance of the variations with aircraft flight conditions, and the significance levels are shown in Table 11. These show a strong dependence for all noise measures with the single exception of PNL for the F-16 aircraft.

Table 11 Analysis of variance of data from Site 2 related to aircraft flight conditions

AIRCRAFT	SIGNIFICANCE LEVEL		
	NOISE MEASURE		
	PNL	EPNL	L_{Amax}
Tornado	0.00	0.00	0.00
Harrier	0.00	0.00	0.00
Jaguar	0.00	0.00	0.00
Hawk	0.00	0.00	0.00
F-15	0.02	0.01	0.05
F-16	0.14	0.01	0.01

The three flight parameters grouped together for the purpose of this analysis were the aircraft speed, engine power setting and altitude. That associated with the gross changes of ΔL in Tables 8, 9 and 10 was the altitude, changing from nominally 250 feet for conditions A, B and C of the Tornado and Jaguar to nominally 100 feet for conditions D, E and F, and again from 250 feet for conditions A and B of the Harrier and Hawk to 100 feet for conditions C and D. These aircraft altitudes gave rise to angles of sound incidence at the measurement microphones of approximately 50° and 75° respectively. It therefore appears, taking these results for the sideline position together with those from site 1 where the aircraft were more nearly overhead, that the difference (ΔL) between aircraft noise levels measured using microphones at a height of 1.2 m and close to the ground is strongly affected by the angle of sound incidence above some angle within this range. The reasons for this dependence emerge from further analysis described below in Section 3.5. They are associated with local topography and atmospheric conditions, but while the angle at which they start to have an effect is probably around 65° , the range of conditions encountered during these measurements was too limited for it to be identified closely.

3.5 FREQUENCY ANALYSIS AND PROPAGATION CALCULATIONS

In attempting to find an explanation of the angular dependence of ΔL at high sound incidence angles, data at the instant of maximum PNL from both Site 1 and Site 2 were analysed in one-third-octave frequency bands over the range 50 Hz to 10 kHz. The results from this analysis have been divided into two groups: one containing data obtained when the angle of sound incidence was greater than 65° (nominal altitude 100-200 feet) and another containing data when the angle was less than 65° (nominal altitude 250-300 feet). The basis for this grouping is discussed in Section 3.4. Mean ΔL (for one-third-octave sound pressure levels) for each of the six aircraft types flying at nominal altitudes of 250-300 feet are shown in Figure 18, and those for flights at nominal altitudes of 100-200 feet are shown in Figure 19.

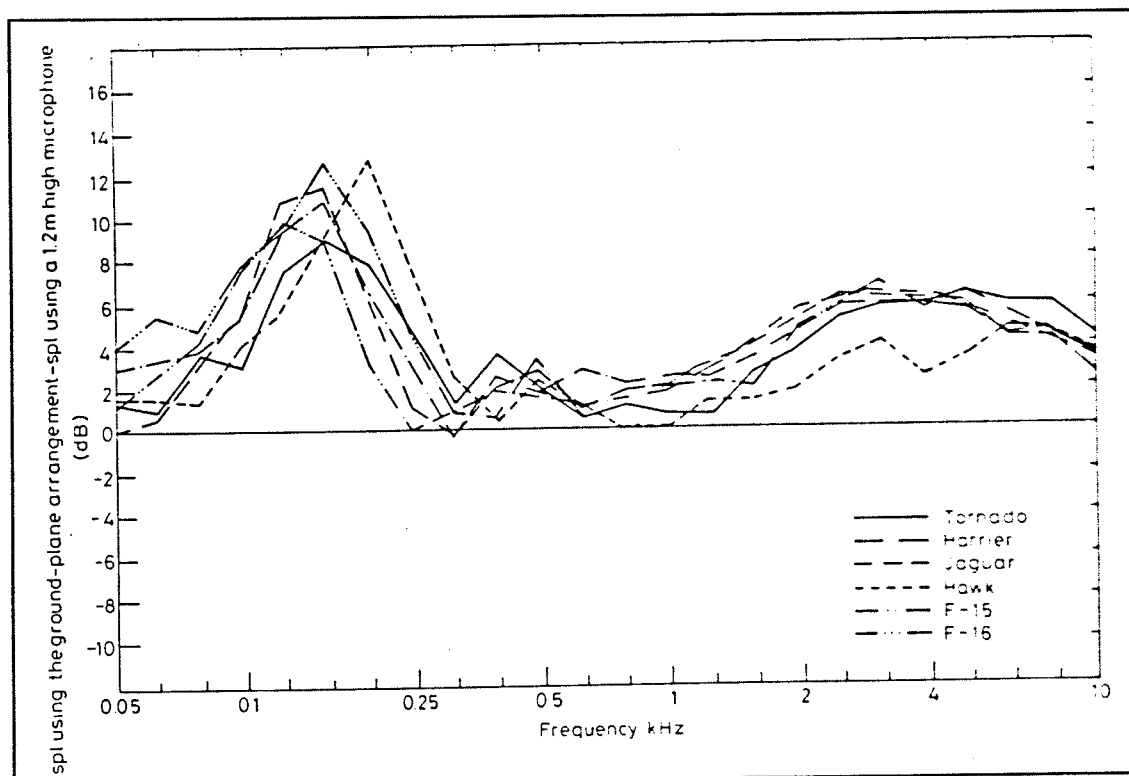


Figure 18 Spectra of mean ΔL (1/3-octave sound pressure level) at the instant of maximum PNL at Site 2 from aircraft flying at nominally 250-300 feet.

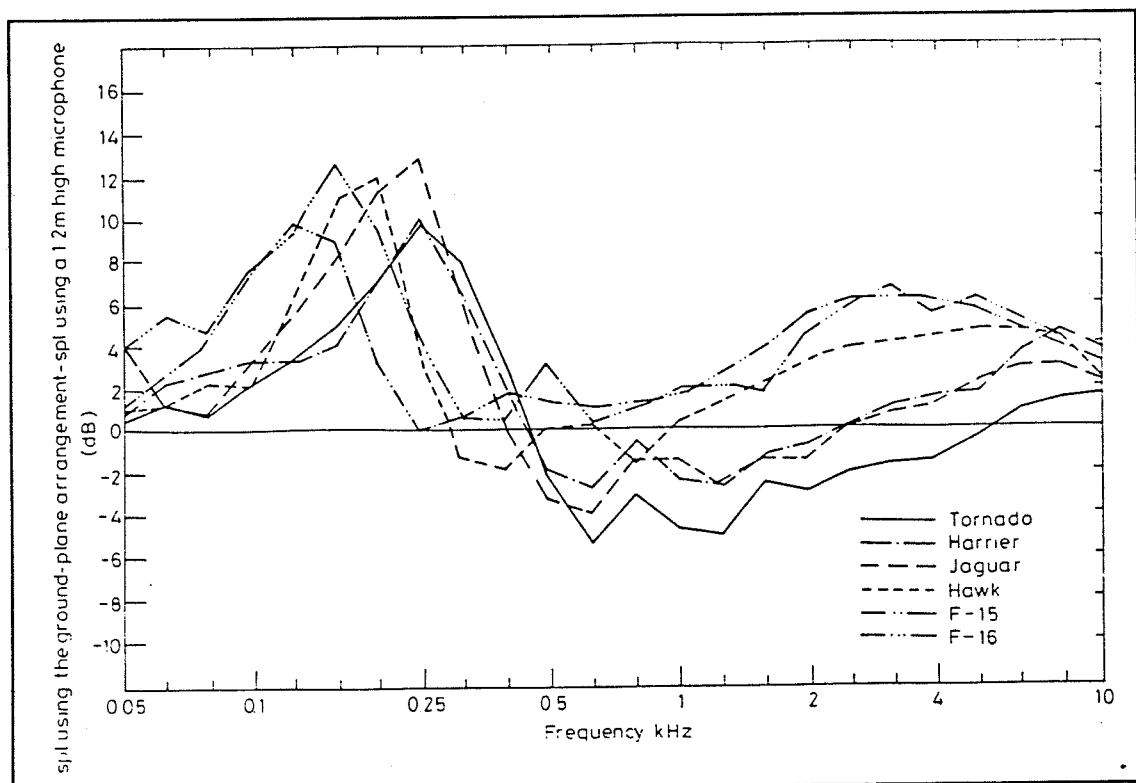


Figure 19 Spectra of mean ΔL (1/3-octave sound pressure level) at the instant of maximum PNL at Site 2 from aircraft flying at nominally 100-200 feet.

In Figure 18, ΔL is generally positive, as would be expected if the ground-level microphone registers a pressure-doubled sound pressure level. The large peak occurring between 125 and 160 Hz is due to the interference cancellation between the direct and ground-reflected sound waves at the 1.2 m-high microphone. Values of ΔL for the Hawk, F-15 and F-16 aircraft are similar in Figures 18 and 19. In the case of the Hawk, the flights which were supposed to be at nominally 250 feet were in fact made in the range 160-200 feet, and those supposed to be at nominally 150 feet in fact took place in the range 130-140 feet, so the total range of actual altitudes was restricted. In the cases of the F-15 and F-16, none of the flights were at less than 170 feet (ie angles of sound incidence at the microphones were in no case greater than 63°), despite the nominal altitudes specified. So for these two aircraft the values of ΔL shown in Figures 18 and 19 would be expected to be similar as they both correspond to data obtained when the angle of sound incidence was less than approximately 65° .

By contrast, the values of ΔL in Figure 19 for the Tornado, Harrier and Jaguar aircraft show a shift of the peak resulting from the interference cancellation at the 1.2 m-high microphone to 250 Hz, and magnitudes of ΔL substantially lower than in Figure 18 (even assuming negative values) over a wide range of frequencies. The change in frequency of the interference cancellation in the latter three cases is directly attributable to the differences in aircraft altitudes, and in particular to the different angles of sound incidence. However, it can be seen from Figures 18 and 19 that the value of ΔL when expressed in PNL (see Figure 15) is controlled by sound energy at the higher frequencies (above approximately 1 kHz) and the effects of interference are negligible. At these higher frequencies the range of mean ΔL between aircraft type (actually a result of variations in angle of sound incidence) is greater for the data in Figure 19 than in Figure 18. For instance at 3.15 kHz (approximately the peak of the NOY contours) the ΔL range is 8.4 dB in Figure 19 and 2.5 dB in Figure 18 (only 0.9 dB neglecting the Hawk data). This difference in range is an indication of the dependence of ΔL on angle of sound incidence. A closer examination reveals a correlation between ΔL and aircraft altitude (angle of incidence), and, therefore, it may be concluded that the anomalous values of ΔL are directly attributable to problems at higher frequencies. However, this analysis gives no indication of whether the changes in magnitude of ΔL are due to an amplification of the noise levels at the 1.2 m-high microphone or to an attenuation of the levels near the ground.

The next step was to examine the differences between one-third-octave sound pressure levels at Sites 1 and 2, and to compare these with simple sound propagation calculations allowing

only for air attenuation¹⁵ and spherical wave spreading. In this simple procedure it is assumed that the frequency distribution of the noise signal at Site 1 is similar to that at Site 2 (ie the aircraft is essentially an omni-directional noise source). While this is patently not the case, the effects of directivity will be similar for both microphone arrangements and as here it is the differences between the two systems that are under investigation, directivity effects will be largely eliminated. The measured differences have been examined for all overflights for all aircraft but for the purposes of this investigation only the Tornado results are reproduced; this aircraft exhibited the most marked variation in ΔL values with altitude. Mean differences between levels from the 1.2 m-high microphones and between those from the ground-level microphones at the two sites for the Tornado aircraft at a nominal altitude of 250 feet are shown in Figure 20, and those for the same aircraft at a nominal altitude of 100 feet are shown in Figure 21, in both cases compared with predicted differences from elementary sound propagation theory.

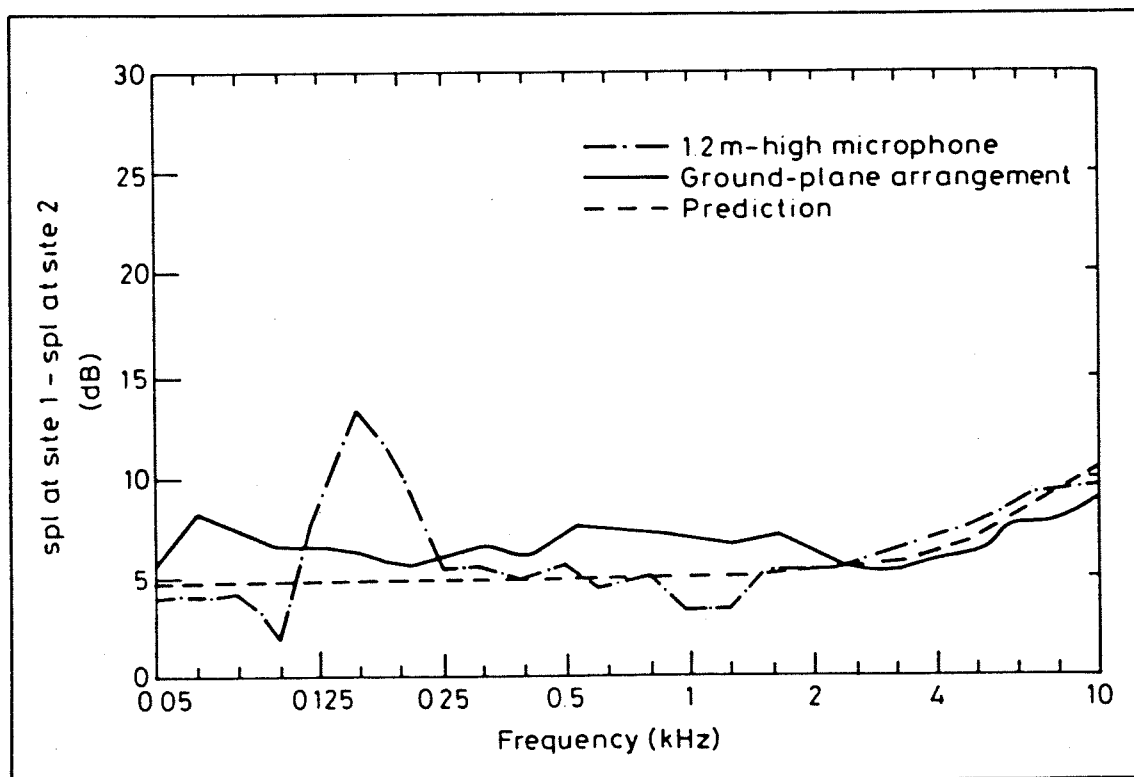


Figure 20 Measured and predicted differences between 1/3-octave sound pressure levels at Sites 1 and 2, for the Tornado aircraft flying at nominally 250 feet.

It can be seen from Figure 20, with the aircraft at around 250 feet (ie with angles of sound incidence nowhere any greater than about 50°) that, while there is a tendency for the data from the ground-plane arrangement to show larger difference at middle frequencies, both microphone systems have similar results and are reasonably close to the (simple) predicted

values. The peak at lower frequencies in the 1.2 m-high microphone data is the result of differences in interference cancellation frequency between the two 1.2 m-high microphone systems.

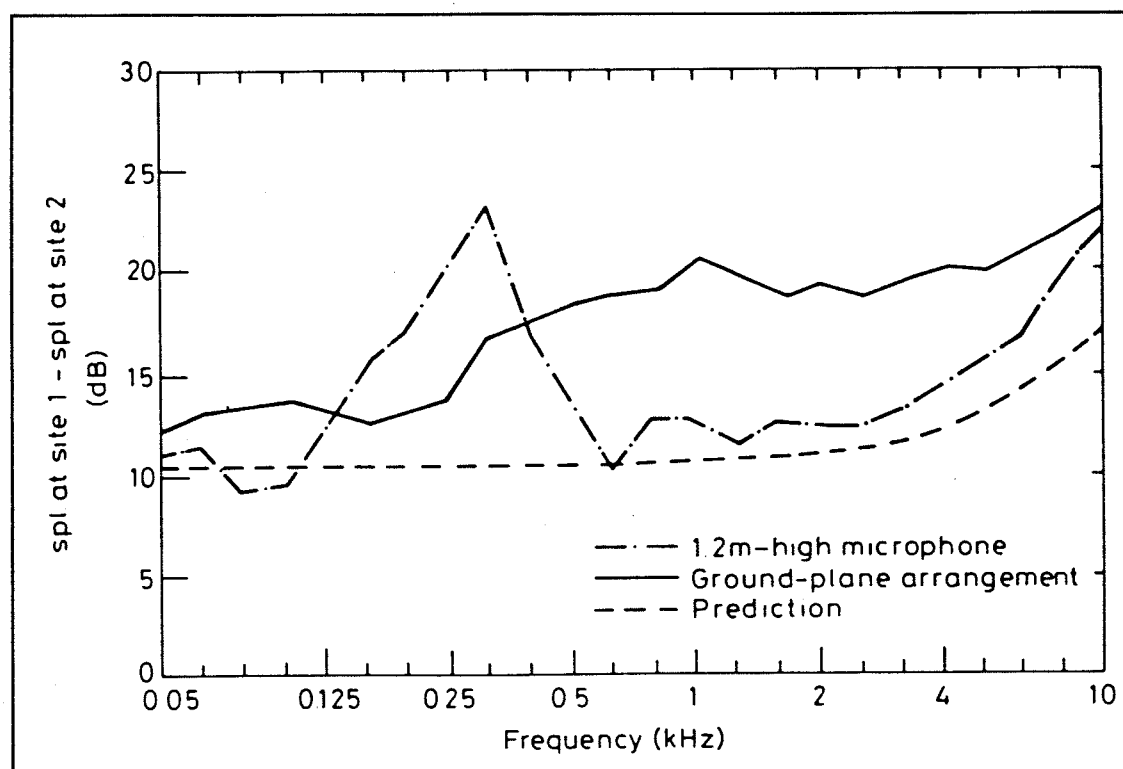


Figure 21 Measured and predicted differences between 1/3-octave sound pressure levels at Sites 1 and 2, for the Tornado aircraft flying at nominally 100 feet.

In Figure 21, on the other hand, with the aircraft at around 100 feet (and angles of sound incidence at the sideline Site 2 of about 75°) the differences from the 1.2 m-high microphones agreed reasonably with the predictions at frequencies above those influenced by interference effects at approximately 250 Hz, but the differences from the ground-level microphones were much greater than predicted over the whole frequency range. This means that it was the sound pressure levels at the ground microphones at Site 2 which were attenuated, leading to the fall-off in magnitude of ΔL noted above.

A study was made of the scientific literature on sound propagation to find an explanation for the extra attenuation of sound pressure levels near the ground surface from a distant source at a low angle of elevation. The most likely cause was upward diffraction of sound waves travelling through the atmosphere near the ground surface, in other words acoustic shadowing, due to the effects of negative vertical temperature and wind gradients. The literature reviewed by Embleton¹³ is extensive. One method to estimate the effects of wind and temperature

gradients¹⁴ makes use of work by Rasmussen¹⁵, but it requires knowledge of the two parameters in greater detail than was available here (meteorological data were only available above a height of 15 feet, see Section 2.5) and in any case, with the source/receiver geometry used, it is restricted to source heights of no more than 25 feet.

A theoretical approach developed by Tooms¹⁶ in principle allows for consideration of a range of source/receiver geometry. Unfortunately, it does not allow for changing ground conditions along the propagation path, and so cannot model directly the arrangement used here for the ground-level microphone mounted above a reflecting disc. However Attenborough¹⁷ has used this approach and, in private correspondence, has concluded that with a combination of absorbent ground cover and steep upward refraction near the ground a substantial part of the sound energy travelling near grazing incidence can be subject to excess attenuation.

Support for this conclusion comes from some experimental data showing the effects of shadowing¹⁸, with sound propagating in the presence of wind and temperature gradients and also turbulence over a grass-covered surface with the source in the grass/air boundary and at a separation from the receiver of 230 m. One-third-octave sound pressure levels at heights between 0.25 m and 7 m above the ground surface are presented. A curve was fitted to these data and extrapolated to yield differences due to shadowing between sound pressure levels at ground level and a height of 1.2 m, at frequencies of 500 Hz, 1 kHz, 2 kHz and 4 kHz, amounting respectively to 4 dB, 6 dB, 8 dB and 3 dB. The comparable values drawn from the ΔL data of Figure 19, for the Tornado aircraft, after allowing for the effects of pressure doubling at the ground-level microphone and energy addition of direct and ground-reflected sound at the 1.2 m-high microphone, are respectively 5 dB, 8 dB, 6 dB and 4 dB. The source location for the acoustic shadowing study is quite different from that of the aircraft in flight which are the subject of the present investigation, yet the results serve to illustrate how sound pressure levels measured near the ground can be affected when the aircraft is at a very low angle of elevation above the ground plane.

4 CONCLUSIONS

In measuring the noise of jet-engined aircraft in flight, the relationship between noise levels measured close to the ground plane using a microphone inverted over a hard disc and those measured at a height of 1.2 m is well defined at sound incidence angles within the range 0° to approximately 60° from the vertical. At these angles, the ground-level microphone yields data that closely approximate pressure-doubled values, and gives rise to maximum perceived noise levels, effective perceived noise levels and maximum A-weighted sound pressure levels that are almost 4 dB above those from a 1.2 m-high microphone, irrespective of aircraft type, flight speed, engine power setting and altitude.

For sound incident at angles greater than 60° from the vertical, the difference between noise levels measured near the ground surface and at a height of 1.2 m appears from the results obtained here to depend strongly upon the angle of incidence. The measured difference fell to zero at an angle of around 75° , and at greater angles the 1.2 m-high microphone yielded higher noise levels. The changes in the magnitude of the difference came about through attenuation of the output of the ground-level microphone at large angles of incidence. This in turn was probably caused by upward diffraction of the sound waves travelling at low angles of elevation above the ground, under the action of temperature and wind gradients in the atmosphere, so causing acoustic shadowing at ground level. The effect might itself depend upon local meteorological conditions, and the extent of the angular dependence might vary in different conditions, but the range of conditions encountered during these measurements was not great enough to allow conclusions to be drawn on this.

In view of the above, it must be advised that with present knowledge, ground-level microphones should not be used for noise measurements where angles of sound incidence exceed 60° . More experimental data and theoretical analysis are required to define further the angular dependence of noise levels measured at ground level, and so possibly to develop corrections which could be applied at angles between 60° and 90° . Empirical data are needed at smaller angular increments and in a wider range of weather conditions than were attainable in this investigation, and sound propagation theory needs to be extended to enable sound transmission to be modelled from a sound source at elevations of up to 30° through realistic atmospheric conditions to a receiver at a point on the ground.

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