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The CAA Aircraft Noise Contour Model: ANCON Version 1

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SUMMARY

This document describes the basis of the computer model currently used by the CAA to generate contour maps of aircraft noise exposure level around airports. Developed from the earlier Noise and Number Index (NNI) model, this now produces contours of Equivalent Sound Level (Leq) in dB(A). The main difference between the procedures used to compute these two noise indices lies in the algorithms for calculating single-event levels. A detailed comparison of these accompanies a general description of the method by which index values are computed and turned into contours. The sources of input data and likely future developments are also considered.

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GLOSSARY OF TERMS

Frequently used terms and symbols are defined below: others which are only used locally in the text are defined where they first occur.

Ambient noise	The total noise at a location - from all sources.
AIR	Aerospace Information Report (SAE document).
ANIS	Aircraft Noise Index Study (Ref 8).
ATCEU	Air Traffic Control Evaluation Unit (UK)
b	Half-length of flight path segment.
Background noise	That component of ambient noise which is not generated by aircraft.
CAA	Civil Aviation Authority (UK)
d	Distance from field point to ground track.
$D(\psi)$	Function describing directional pattern of aircraft noise behind start-of-roll.
d_p	Perpendicular distance from field point to ground track or its extension.
dB	Decibel units describing sound level L or changes of sound level.
dB(A)	Units of sound level on the A-weighted scale.
dB/dd	The rate at which sound level falls with distance from the aircraft flight path is expressed in decibels per distance-doubling.
Dipole	A directional sound source comprising a pair of adjacent but out-of-phase monopoles. Due to interaction effects its sound radiation pattern resembles a figure-of-eight; ie maximum along the line joining the constituent monoples and zero in the plane dividing them. The dipole is a fundamental concept in aerodynamic noise theory; here it is used as a basis of an expression for the Noise Fraction F.
DOT	Department of Transport (UK)
ECAC	European Civil Aviation Conference
Emission level	An expression used to describe the amount of sound emitted by an aircraft in decibel terms. In the noise models described here, this is specifically defined as L_{ref}.
F	Noise Fraction - the ratio of the noise energy received from an aircraft traversing a flight path segment of finite length to that which would result if the segment were extended indefinitely in each direction.
Field point	A point on the ground at which noise exposure variables are to be determined.
Ground track	The vertical projection of an aircraft flight path onto level ground.

h	Minimum source height used in calculation of lateral attenuation from initial climb segment.
ICAO	International Civil Aviation Organisation.
INM	Integrated Noise Model: aircraft noise contour model used by the USA Federal Aviation Administration.
L	Sound level. The magnitude of sound expressed on conventional logarithmic scales of sound energy. All levels, in dB, are expressible as 10 times the log of an acoustic energy ratio. With one exception (L_{PN}), all sound levels in this report are expressed on the A-scale with values in dB(A). Although levels on the A-scale are usually abbreviated L_A, for simplicity herein, the subscript A is generally omitted. Thus, for example, Equivalent Sound Level is abbreviated L_{eq} rather than L_{Aeq}.
L(t)	The sound level (instantaneous or short-term average value) at any particular time t.
L_{eq}	Equivalent Sound Level of aircraft noise in dB(A) (often called equivalent continuous sound level). The sound level averaged over a specific period of time, eg 16 hours, 24 hours etc. It is sound *energy* that is averaged, not the decibel level - whence the expression 'energy-averaging'. An accurate value can normally be estimated by averaging sound energy during those restricted periods of time when the aircraft noise exceeds the background noise.
L_{eq}(16-hr)	L_{eq} averaged over a 16-hour period, specifically 0700 - 2300 local time.
L'_{eq}	Equivalent sound level of total, ambient noise which combines aircraft and non-aircraft background noise. It is obtained by time-averaging the continuous record of sound energy.
L_{max}	The maximum value of L(t) recorded at a field point during an aircraft fly-by.
L'_{max}	The maximum value of L(t) generated by an aircraft on a particular flight path segment - extended as necessary in either direction. Used in the calculation of L_{SE}, its value is hypothetical unless the field point is alongside the segment (i.e. ψ_0 and ψ_1 are both acute angles).
L_{ref}	Reference noise level which defines the amount of noise emitted by an aircraft. It is a nominal sound level in dB(A) at a distance of 152.5m (500 feet) from the aircraft.
L_{PN}	Perceived Noise Level. As defined rigorously, L_{PN} is calculated from a short-term band level spectrum (octave or one-third octave) of the noise. In CAA noise contour work, it has usually been defined by the numerical approximation $L_{PN} \approx L_A + 13$ recommended by ICAO (Ref 16).
L_{SE}	The sound exposure level generated by a single aircraft fly-by, in dB(A). This accounts for the duration of the sound as well as its intensity; it is equal to the sound level of that 1-second burst of steady sound which contains the same (A-weighted) acoustic energy as the aircraft sound. This abbreviation is more consistent with the subscript convention than the commonly used alternative, SEL.

L_{max}, L_{SE}, L_{PN}	The italics denote *average* levels, ie of all N aircraft sound events. Like L_{eq}, these are 'energy averages'.
Log	Logarithm: all logarithms are to a base of 10.
Monopole	A technical term used to describe a simple non-directional sound source, ie a source which radiates uniformly in all directions.
N	The number of sounds 'heard' during the specific time period of interest; ie those whose maximum levels exceed a specified threshold ('cutoff').
NATS	National Air Traffic Services (UK)
NNI	Noise and Number Index
OPCS	Office of Population Censuses and Surveys
PNdB	'Perceived Noise' decibels; values on the L_{PN} scale.
r	Distance from field point to mid-point of flight path segment.
s	Shortest distance from field point to flight path segment.
s_0, s_1	Distances from field point to ends of flight path segment.
s_p	Perpendicular distance from field point to flight path or its extension.
SAE	Society of Automotive Engineers (USA)
t	Time, seconds.
t_0	Time at start of noise measurement, seconds.
T	Duration of sound event, seconds.
V	Aircraft speed, m/s.
β	Elevation angle in calculation of lateral attenuation.
δ	Angle used to define preferred sound radiation direction in calculation of Noise Fraction, F.
ΔL_{∞}	An empirical sound level correction to allow for effects of source directivity on sound exposure level.
ΔL_{SE}	Sound exposure level contribution from single finite flight path segment.
$\Delta L_{SE\infty}$	Sound exposure level contribution from single infinite flight path segment - with no lateral attenuation.
φ	Angle between flight direction and the line joining segment mid-point and field point.

Λ	Lateral attenuation, dB.
ψ_0, ψ_1	Angles between flight path segment and lines joining ends of segment to field point.
Ψ	Angle between forward runway centreline and the line joining the start-of-roll and observer positions.
θ	Elevation angle used to determine ground attenuation in NNI model.

Subscripts:	i	event number
	j	flight path segment number
	p	perpendicular

1 INTRODUCTION

1.1 For the purposes of assessing the impact of aircraft noise on people living near airports, a means is required of quantifying the noise in terms which indicate its likely adverse effects upon people. These effects are numerous and complicated and, in practice, it is necessary to simplify the problem by averaging both noise and human response variables. Average annoyance is commonly used as an index of public response to noise intrusion; the magnitude of the noise is defined in terms of average sound levels and numbers of aircraft noise events during specified periods of time. The relationships between noise and annoyance are determined by social survey studies and related research and these, to a large extent, guide the choice of indices used to define noise exposure.

1.2 The expression 'noise exposure' covers the physical dimensions of the noise experienced over a period of time by people at a particular location. For aircraft noise, important among these are the numbers and timings of the events, their maximum sound levels and their durations. Also relevant to problems of measurement and analysis is the presence of noise from other sources, often referred to as 'background noise'. Together, aircraft noise and background noise comprise the total or ambient noise.

1.3 In the vicinity of airports, aircraft noise is generally very much more intense than that of other common noise sources. Thus the sounds of aircraft flying to or from a nearby airport are easily identified as such and tend to exceed the levels of other background sounds (often dominated by road traffic noise) by margins of 20dB or more. For this reason it has become normal practice to quantify aircraft noise exposure using event-based indices rather than the distribution statistics employed for the noise of road traffic and other more continuous sounds.

1.4 The characteristics of any particular aircraft noise event are controlled by aircraft type (especially its engines and propulsion system), weight at the time, mode of operation (ie flight configuration, especially whether it is taking off or landing), its power settings, flight path, speed, atmospheric conditions (temperature, humidity, wind speed and direction and turbulence), the surrounding terrain and ground cover, including the presence of obstacles (natural and/or man-made, particularly if these are close to the receiver position). To avoid the difficulties of considering the latter, it is usual to confine attention to 'free-field' sound, ie a few feet above the ground away from obstructions which affect sound propagation.

1.5 The magnitude and extent of aircraft noise exposure around airports are depicted on a map by *contours* of constant aircraft noise index values (Figure 1) which are analogous to the isobars on weather maps. Although, in principle, the position of the contours could be established by measurement alone, this would require near continuous monitoring at a large number of positions over a long period of time. This would be extremely expensive as well as difficult to arrange. Instead, the contours are determined by mathematical modelling using computer programs which simulate the emissions and propagation of noise from air traffic. Such models do however use data based on very large numbers of field measurements, ie they are largely empirically based.

1.6 In the UK, the Department of Transport (DOT), which has responsibility for determining government policy on aircraft noise, uses aircraft noise contours both to record the changes of aircraft noise which occur from year to year (contours for the London airports are published annually) and to forecast the likely environmental effects of proposed future changes in aircraft and airport operations. They are also used by the Department of the Environment and local government agencies for the purposes of development control (Ref 1). They are often presented in evidence at Public Inquiries into airport developments.

1.7 Until 1990, the official index of aircraft noise exposure in the UK was the Noise and Number Index (NNI). The origins, applications and method of calculation of NNI are described in References 2 and 3. Contour maps of NNI were generated by the CAA using a special computer model developed and maintained for this pupose.

1.8 NNI was devised by the Wilson Committee (Ref 4) from the results of a social survey performed in the vicinity of London (Heathrow) Airport in 1961. Although some subsequent studies (eg see Refs 5-7) tended to support continued use of the index, the Aircraft Noise Index Study (ANIS) carried out in 1982 indicated that Equivalent Sound Level (L_{eq}), used for general-purpose measurement of environmental noise exposure in the UK and many other countries, might be preferable in the future (Ref 8). In order to establish a system for the adoption of the L_{eq} measure, the DOT conducted a public consultation on the question, the results of which are described in Ref 9 (see paragraphs 2.9 and 2.16 for further details). This revealed substantial majority support for the change and an official announcement of the replacement of NNI by L_{eq} was made in September 1990 (Ref 10). In support of this change, the CAA computer model has been revised and extended to generate aircraft noise contours in L_{eq} and this report outlines the underlying methodology.

1.9 The general principles of aircraft noise modelling and the background to the DOT's adoption of L_{eq} are outlined in Section 2. The basic difference between the modelling of NNI and L_{eq} lies in the method used to quantify the sound levels associated with individual aircraft movements, the L_{eq} version being much more complex. The composition of the NNI model is thus reviewed in Section 3 as an introduction to the more advanced L_{eq} model derived from it which is described in Section 4. Section 5 explains how event levels are summed to generate a matrix of noise-index values from which the contours are plotted. It then outlines how the model is maintained and used in practice and points out requirements for its further development.

1.10 It must be stressed that this report is concerned with the methods by which the CAA noise model has been extended to generate contours of L_{eq} rather than NNI. At present the L_{eq} model, ANCON, is at an early development stage; like those of its predecessors, its accuracy will be subject to repeated testing and refinement through an ongoing programme of data collection, analysis and comparisons of theory and measurement. This validation process will be described in future reports.

2 AIRCRAFT NOISE MODELLING

General Principles

2.1 It will be clear from the foregoing that totally accurate, detailed simulation of ground-level noise exposure due to air traffic, taking all known factors into account, would require a complex mathematical model, the data input requirements for which would make it impractical for general use. Any practical model has to involve considerable simplification but, to be worthwhile, it must take into account the tracks followed by arriving and departing aircraft, the numbers and types of aircraft, their height and noise emission profiles, and the effects of the air and the ground surface upon the propagation of sound. There is inherent variability in all of these factors, much of which is large, and the practical modelling process is therefore statistical in the sense that this variation has to be 'averaged out'. The aim is to achieve a high level of accuracy in the estimation of *average* values of aircraft noise exposure.

2.2 A common simplification is to disregard the existence of several additional minor influences, including local topography and ground cover, buildings and other obstacles, natural or man-made, and weather conditions, especially wind speed and direction. These naturally vary from place to place - in the case of weather, from time to time - and it is usually impractical to account for them in any systematic way in the generation of contours. It is of course important to avoid or compensate for them when gathering input data; noise measuring microphones must, as far as possible, be positioned to avoid extraneous effects. In turn, computer models usually ignore local detail; the contour calculations assume flat, uniform ground surface and a homogeneous atmosphere (although some approximate topographical adjustments have sometimes been made in the case of airports located in hilly terrain).

2.3 A major use of ANCON is in the preparation of (retrospective) annual noise contours for airports. A foundation of the methodology, which distinguishes it from many procedures used elsewhere, is that the computations are based on actual measurements and reflect the actual operation of the airports over a specified period. Each year, large numbers of noise levels and, in alternate years flight paths, are recorded near the London Airports and added to the data bank. Updating the database in this way ensures that the model properly reflects ongoing improvements in aircraft performance, noise emissions and air traffic control practice. Key requirements of the new L_{eq} model were that: (i) the calculation procedures should be directly comparable with those used for NNI (if possible it should utilise the same database) and (ii) the methodology should retain a firm empirical base.

2.4 The NNI took account of a daily average number of aircraft sounds heard and their average maximum sound level, L_{max}. The L_{max} associated with any particular movement was determined as a simple function of the shortest distance to the aircraft flight path. An essential advance of the L_{eq} scale over NNI is the inclusion of sound duration effects. To construct L_{eq} in a similar way to NNI, it is necessary to define noise events on the Sound Exposure Level (L_{SE}) scale which takes account of their duration. For any aircraft flyover, L_{SE} is rather more difficult to estimate than L_{max} because it depends on the flight profile of the aircraft as well as its nearest distance. The L_{eq} model therefore requires more complicated logic than the NNI model.

2.5 Many countries have developed their own procedures for describing and assessing aircraft noise impact and, although these differ little in general concept, their details vary markedly. There have thus been some international moves to introduce a degree of uniformity into aircraft noise contouring methodology, which are embodied in various procedures suggested, for example, in References 11, 12 and 13. These are largely based on Aerospace Information Report AIR 1845 (Ref 11) developed by the Society of Automotive Engineers (SAE) Aircraft Noise Committee A21, which, for more than 30 years, has played an important rôle in the development of international measurement standards for aircraft noise. The ICAO and ECAC draft standards (Refs 12 and 13) incorporate substantial elements of the AIR but clarify and simplify the method leaving as much flexibility as possible so that users can adapt the procedures to special local or national needs. In particular, different countries employ different indices of noise exposure; the intention is to standardise the modelling methodology.

2.6 The main features of the SAE proposals and related ones are as follows:

(i) Extensive databases are required which can only be generated using information supplied by aircraft manufacturers. They include, for different aircraft types, flight profiles, engine power settings and relationships between noise level and distance for a range of power settings.

(ii) The basic noise calculation framework including grid patterns, noise radiation geometry and modelling are very similar. It is normally expected that an array of noise levels will be calculated and then converted into a contour map using a suitable computer graphics package.

(iii) Although the sources of aircraft data in (i) are not specified in detail, a procedure is included for calculating excess 'lateral' sound attenuation, attributable to the effects of engine installations and ground absorption.

(iv) The effects of turning flight (curved flight paths) on L_{eq} are recognised but no specific procedures to simulate them are recommended (some possible approaches to account for the effect of turns on the duration of an aircraft noise event are suggested - that adopted here is described in paragraph 4.6 *et seq*).

2.7 Although CAA staff contributed to the development of the SAE and ECAC recommendations, it was recognised at the outset that whilst it was necessary for the new L_{eq} computer model to reflect the international proposals, such an approach would require comprehensive tabulations of aircraft noise and performance data (including standardised aircraft flight profiles and noise-distance curves for different engine power settings) which could not be obtained from the well established NNI-type field measurements. Although such a change was not ruled out for the longer term, it was considered that it would not be prudent to change from the existing framework: in particular, the established methodology offers some assurance of validity and accuracy, whereas the SAE schemes have not been tested in this regard. To ensure that the method of calculating L_{eq} would be totally consistent with that used to generate NNI contours, it was decided that, initially, the L_{eq} model should retain the same basic structure and the same database as the NNI model.

Department of Transport practice

2.8 The main conclusions which emerged from an analysis of the DOT's consultation on changing the aircraft noise index from NNI to L_{eq} are summarised here; the full details may be found in Reference 9.

2.9 Technical support for the change of index came from the UK Aircraft Noise Index Study (ANIS) (Ref 8). While L_{eq} (which, it should be stressed, was determined in that study by measurement rather than computer modelling) was shown to be better correlated with peoples' annoyance reactions than NNI, no particular values of L_{eq} separated significantly different reactions, although there was some evidence of a step increase in annoyance at about 57dB(A) L_{eq}(24-hr) (58dB(A) L_{eq}(16-hr)). Regression lines relating measurements of NNI and L_{eq} were presented but these were specific to the conditions in 1982. In any event there is no unique physical relationship between L_{eq} and NNI.

2.10 The ANIS research revealed no 'better' predictor of annoyance than 24-hour L_{eq}. However, the adoption of a 24-hour index would have been rather a substantial change from the previous 12-hour one and in any event it would not have permitted a recognition of the somewhat different considerations applying to the evaluation of noise by day and by night. Also, numerous concerns about the the 24-hour index were raised during the DOT consultation (Ref 9). Two studies of the effects of aircraft noise upon sleep (Refs 14 and 15) showed L_{eq} for the period 2300 - 0700 hrs (local) to be a relevant measure of night noise and this is logically complemented by a 16-hour day value. The great majority of all aircraft movements at UK airports occur between the hours of 0700 and 2300 and, furthermore, as a predictor of annoyance, L_{eq}(16-hr) was actually found to be statistically little different from L_{eq}(24-hr). The 8-hour night, which *is* the night noise monitoring period for Heathrow and Gatwick, covers the typical hours of sleep and includes that part of the night during which night restrictions on aircraft operations are imposed at the London airports. Contours of L_{eq}(8-hr) are already used by the DOT for evaluating the effectiveness of these restrictions. With regard to longer term averaging, there appeared to be no reason to change the NNI practice of computing noise exposures for the average summer day (between mid-June and mid-September) for day or night values.

2.11 It was recognised that, ideally, the use of L_{eq} as an index of aircraft noise impact should meet four basic requirements:

1) Published daytime contours should be broadly indicative of the same levels of noise impact, ie average annoyance levels, as the long established 35, 45 and 55 NNI contours (irrespective of any intermediate values which could be included).

2) Published contours should have values which are convenient and logical, eg they should be integers at equal intervals which are related to key properties of decibel and/or decimal scales. For example, steps of 3dB or 5dB would meet this requirement.

3) The number and spacing of L_{eq} contours should not differ markedly from customary NNI practice.

4) At the time of change, equivalent L_{eq} and NNI contours should be reasonably matched in shape and size.

It was impossible to meet all these requirements exactly so some trade-offs were unavoidable.

2.12 For busier airports, 3dB intervals of L_{eq} are roughly equivalent to 5-unit intervals of NNI and it was therefore concluded that suitable daytime L_{eq}values, covering the range equivalent to 35-55 NNI, span the interval from 57 to 69 dB(A) L_{eq}(16-hr) in steps of 3 or 6dB. The values marking average annoyance levels of 'low', 'moderate' and 'high' (corresponding to the previously used 35, 45 and 55 NNI) were consequently taken to be 57, 63 and 69 dB(A) L_{eq}(16-hr).

3 THE NNI MODEL (calculation of NNI at a single point)

3.1 The Noise and Number Index is defined as

$$\text{NNI} = \mathit{L_{PN}} + 15 \log \text{N} - 80 \qquad \text{... (1)}$$

where N is the number of events exceeding or equal to 80 PNdB between 0700 and 1900 hrs local time on an average summer day (specifically averaged over the 92-day period between 16 June and 15 September inclusive) and $\mathit{L_{PN}}$ is the energy-average maximum perceived noise level of these N events calculated as follows:

$$\mathit{L_{PN}} = 10 \log \left\{ \frac{1}{\text{N}} \sum_{i=1}^{\text{N}} 10^{\text{L}_{\text{PNi}}/10} \right\} \qquad \text{... (2)}$$

where L_{PN_i} is the perceived noise level of an individual event.

3.2 Since the input data are actually measured in dB(A) and converted to PNdB by the ICAO recommended approximation (Ref 16), $L_{PN} = L + 13$, Equation (1) could be written in the equivalent form:-

$$\text{NNI} = \mathit{L_{max}} + 15 \log \text{N} - 67 \qquad \text{... (3)}$$

where $\mathit{L_{max}}$ is the energy average of the N individual values of L_{max}. It is calculated by summing contributions from all relevant aircraft traffic on nearby flight paths.

L_{max} algorithm

3.3 A basic assumption of the NNI model is that, at any point on the ground, the maximum level L_{max} generated by any particular aircraft movement is determined by the 'closest point of approach' or 'minimum slant distance' of the aircraft as it flies by. Specifically, the level L_{max} is determined from the aircraft noise emission level defined by a *reference noise level* L_{ref} at a distance of 152.5m (500 ft) from the aircraft and its minimum slant distance s (Figure 2). L_{max} is computed on the assumption that, when the elevation θ (in the vertical plane) of the line-of-sight to the aircraft is more than 14.2° above the horizon, the level decreases by 8dB with every doubling of distance (dd) from the aircraft.

NNI Attenuation

3.4 At smaller angles, the attenuation rate rises progressively to 10dB/dd as the elevation falls to zero according to the following expression which is plotted in Figure 3:

$$\text{Attenuation rate (dB/dd)} = 8 + 555(0.06 - \sin^2 \theta)^2 \qquad \text{... (4)}$$

The combined attenuation function (4), referred to herein as *NNI attenuation,* is central to the NNI concept. It was based on data available when the model was first developed and remained unchanged thereafter. The 8dB figure is firmly linked to the L_{ref} values which are in turn derived empirically by applying that attenuation rate to measurements made at various distances from the aircraft flight paths. Since non-dissipative 'spherical spreading' accounts for 6dB/dd, these rules effectively attribute 2dB/dd each to the effects of *atmospheric attenuation* and *ground absorption* (Figure 4). This is an approximation to what is really a very complex process but it has generally been considered adequate for quantifying relative noise impact.

4 THE L_{eq} MODEL (calculation of L_{eq} at a single point)

Definition of aircraft noise L_{eq}

4.1 In general, the equivalent sound level, L'_{eq}, of *any* continuous noise, steady or variable, during some time interval T, is described by the integral

$$L'_{eq} = 10 \log \left\{ \frac{1}{T} \int_{t_0}^{t_0+T} 10^{L(t)/10} \, dt \right\} \qquad \text{... (5)}$$

where L(t) is the instantaneous sound level at time t, and t_0 is the start of the measurement period. The quantity in the brackets is, effectively, the average sound energy - the total energy divided by the time. Thus L'_{eq} can also be defined as the 'energy average' sound level during the period T.

4.2 At places near airports, the total (ambient) noise is a combination of aircraft noise and background (ie non-aircraft) noise. The equivalent sound level of the aircraft noise component only, L_{eq}, is the level of that part of the total noise which is generated by aircraft. In the absence of background noise, aircraft noise L_{eq} would be defined exactly by Equation 5, i.e. with the continuous integral. In practice, provided the sound levels of the aircraft noise event levels exceed the background level by a substantial margin (say more than 10 dB) - which within the confines of published aircraft noise contours they usually do - aircraft L_{eq} may be accurately estimated by limiting the integration in Equation 5 to those periods during which the aircraft noise exceeds the backgound, i.e. during the aircraft noise events themselves.

4.3 For any single event, the sound exposure level is given by

$$L_{SE} = 10 \log \left\{ \frac{1}{T_{ref}} \int_{t_1}^{t_2} 10^{L(t)/10} \, dt \right\} \qquad \text{... (6)}$$

where t_1 and t_2 define the start and end of the event and T_{ref} is a reference time of 1 second (included to non-dimensionalise the right-hand side of the equation). To obtain a 'true' result, the interval $t_2 - t_1$ should be long enough to ensure that lengthening the interval would cause a negligible rise in L_{SE}. Provided the integration period encompasses all sound energy within 10dB of L_{max} (generally at least 90% of the total associated with the event), the resultant estimate of L_{SE} lies within about 0.5 dB of the 'true' value (the usual aim). With this proviso, L_{eq} can then be defined by the simple approximation

$$L_{eq} \approx \mathit{L_{SE}} + 10 \log N + \text{constant} \qquad \dots (7)$$

which has a similar form to the NNI Equation 3. Here, N is the total number of aircraft noise events, the constant is equal to - 10 log (measurement period) and $\mathit{L_{SE}}$ is the log-average sound exposure level of the N events:-

$$\mathit{L_{SE}} = 10 \log \left\{ \frac{1}{N} \sum_{i=1}^{N} 10^{L_{SEi}/10} \right\} \qquad \dots (8a)$$

L_{SE} algorithm

4.4 At each specified field point, L_{eq} is calculated using Equations 7 and 8a where, to reiterate, N is the total number of aircraft noise events 'heard' during the period of interest and $\mathit{L_{SE}}$ is the energy-average sound exposure level of those N events. These events are the relevant sounds of all *movements* of each different aircraft *type* on each different flight *path* to and from the airport; ie, mathematically

$$\mathit{L_{SE}} = 10 \log \left\{ \frac{1}{N} \sum_{\text{paths}} \sum_{\text{types}} \sum_{\text{movements}} 10^{L_{SE}/10} \right\} \qquad \dots (8b)$$

where L_{SE} pertains to a particular type on a particular route.

4.5 In principle, L_{SE} could be calculated for each aircraft type as an explicit function of noise emission level, minimum slant distance and elevation; as was L_{max} in the NNI Model. For air-to-ground propagation from a uniform, straight, flight path, a fall of 5-6 dB per doubling of slant distance would broadly be consistent with the 8dB/dd figure used for L_{max} in the NNI algorithm. (Other, more elaborate functions of distance, derived by empirical or other means, could be tabulated if desired.) The straight-path values of L_{SE} could be adjusted in some way to account for the effects of any changes of heading and engine power which occur along the flight path.

4.6 However, this would not meet the requirement to use the existing NNI database and, therefore, L_{SE} is instead determined by effective time-integration of L(t) at the receiver point. As illustrated in Figure 5, this has been done by retaining the basic structure of the NNI model, which approximates actual flight paths by series of straight line segments, and summing the contributions from all *noise-significant segments* of each path to obtain the L_{SE} for each aircraft type on that path; ie

$$L_{SE} = 10 \log \left\{ \sum_{j} 10^{\Delta L_{SEj}/10} \right\} \qquad \dots (9)$$

where ΔL_{SEj}, calculated via L_{max} values, is the contributions to L_{SE} of the jth segment of the path. Sufficient segments would need to be defined such that speed and L_{ref} can be assumed uniform on each, and to provide realistic simulations of curved paths where necessary.

4.7 The procedure for calculating ΔL_{SE}, the segment sound exposure level, is the core of the L_{eq} model. The calculation for any particular segment involves a number of steps:-

- The first is to establish whether or not the segment is noise-significant; those which do not make a significant contribution to the total sound energy at the field point because their levels do not exceed a specified *threshold* or cutoff level, are disregarded.
- If the segment is noise-significant a hypothetical *'base' sound exposure level* $\Delta L_{SE\infty}$ is determined initially assuming the segment to be infinitely long. This is the sound exposure level the aircraft would generate if it flew along a coincident but infinite path at uniform speed, emitting constant noise.
- Its finite length restricts the actual noise energy from the segment to a fraction F of the infinite line value. This is termed the *noise fraction* of the segment and it is calculated as a function of the angles subtended by the ends of the segment.
- Except at high angles of elevation, the modified value is further reduced by the effects of *lateral attenuation*, which is calculated by a more elaborate procedure than that used in the NNI model.
- Further factors affect noise radiated from the aircraft when they are on or near the runway (a) during *initial climb* and (b) during *start-of-roll and runway acceleration.* These have to be accounted for at field points which are strongly influenced by these phases of operation.

The remainder of this section describes each of these steps in turn.

Sound level threshold (cutoff)

4.8 A practical requirement of any contour model is a fixed sound level threshold or cutoff below which minor aircraft noise energy contributions can be neglected. Without one, N, the number of events 'heard' at any location is calculated to be at least equal to the number of aircraft movements at the airport . Average L_{SE} values, especially lower ones, are also sensitive to the choice of cutoff; so too is the subsequent computation time which is roughly proportional to the total number of flight path segments included.

4.9 Figure 6a shows an idealised time-history of aircraft noise exposure; a sequence of events superimposed on a uniform background noise. The NNI incorporates a 'cutoff' level of 80 PNdB/67dB(A) below which aircraft noise events are disregarded - but the L_{max} value of every event which equals or exceeds the threshold is incorporated into the index value.

4.10 In order to determine the L_{SE} values of the events counted into the NNI, a lower threshold is required. Figure 6b illustrates how L_{eq}, L_{SE} and N change as the cutoff level λ is altered. As λ decreases, more sound energy is admitted and L_{eq} increases asymptotically to a stable value because most of the sound energy is contained in the higher peaks. However, this stability of L_{eq} obscures a changing balance between L_{SE}, which continues to decrease and N, which continues to increase, as λ goes down. If L_{eq} only is of interest, then the choice of λ is immaterial provided the noisier events are not excluded. However, the choice is more critical if L_{SE} and/or N are also required.

4.11 Reasonably accurate estimation of a true event L_{SE} (see paragraph 4.3) requires integration over at least the highest 10 dB of its time-history. Thus, to define L_{SE} accurately for all the sounds which would be included in NNI, the L_{eq} cutoff should be at or below 57dB(A). But use of this lower threshold automatically adds into L_{eq} the sound energy of other events whose maxima lie between 57 and 67 dB(A) - which would be excluded from NNI. Because the time-histories of these additional events are truncated less than 10dB below their peaks; their 'measured' L_{SE} values (based only on energy above the threshold) underestimate their true values.

4.12 Nevertheless, use of a single cutoff is quite consistent with the concept of an audibility threshold; the practical aim of the noise modelling process should be to take into account, as realistically as possible, numbers of aircraft events actually heard. It is expected that for most major airport applications a threshold in the range 55-60 dB(A) will provide valid estimates of L_{eq}, L_{SE} and N. At present, (55dB(A) is used). But any threshold can be specified in the L_{eq} model and for special applications, for example in the case of lightly used aerodromes in areas of low background noise, the use of lower values could be considered.

Base sound exposure level (due to hypothetical, infinite flight path segment)

4.13 The geometry of noise radiation from a single flight path segment to a field point is shown in Figure 7. A flight path segment is considered to be noise significant if it causes L(t) to exceed λ. If so, the first step in the calculation of ΔL_{SE} is to determine an uncorrected base sound exposure level, $\Delta L_{SE\infty}$, the (hypothetical) sound exposure level which would result, in the absence of lateral attenuation, if the flight path segment extended indefinitely in both directions. Appendix A shows that a simple monopole source travelling at constant (low) speed V along a continuous straight line generates a sound exposure level L_{SE} at any point distance s from the path given by:-

$$L_{SE} = L_{max} + 10 \log \left(\frac{s_p}{V}\right) + \text{constant}$$

where the constant depends upon the sound propagation exponent. Although this result is obtained from very simple theory, it points to the following empirical relationship for $\Delta L_{SE\infty}$:-

$$\Delta L_{SE\infty} = L'_{max}(L_{ref}, s_p) + 10 \log \left(\frac{s_p}{V}\right) + \Delta L_{\infty} \qquad \text{... (10)}$$

where L'_{max} is computed by the NNI algorithm (paragraph 3.3). The slant distance s_p is the shortest (ie perpendicular) distance from the field point P to the extended (infinite) segment, V is the aircraft speed and ΔL_{∞} is an adjustment to account for the effects of source directivity. As shown in Appendix A, this latter term can be defined analytically for idealised sound sources such as a simple monopole, but it is determined from measured data for real aircraft sounds (paragraphs 5.10 and 5.11). The second and third terms on the right hand side of Equation 10 together comprise the 'duration correction' for the sound of a uniform source, steadily traversing an 'infinitely long' straight path. It should be noted that, in the case of a finite path segment, L'_{max} is a hypothetical value unless the field point lies alongside the segment (where both ψ_0 and ψ_1 are acute), ie L(t) does not actually reach L'_{max} whilst the aircraft is on the segment.

Segment Noise Fraction (effect of finite segment length)

4.14 Because of its finite length, the sound energy radiated to the field point from the segment is only a fraction F of that radiated from the hypothetical infinite segment. This, taken together with the additional effects of lateral attenuation, Λ, which accounts for both ground absorption and lateral directionality of aircraft noise (paragraph 4.19 et seq), means that the contribution of this one segment to the event L_{SE} is

$$\Delta L_{SE} = \Delta L_{SE\infty} + 10 \log F - \Lambda \qquad \dots (11)$$

4.15 A basic 'Noise Fraction' F is calculated as a mathematical function of the angles ψ_0 and ψ_1 subtended by the beginning and end of the flight path segment (Figure 7). The function is adapted from one developed in the USA for the Federal Aviation Administration's Integrated Noise Model, INM (Ref 17). This incorporates an 'idealised' value (Ref 18) given by:

$$F = \frac{\cos \psi_0 + \cos \psi_1}{2} \qquad \dots (12)$$

It is shown in Appendix B that, at increasingly large distances r from a segment of half-length b,

$$F(r,\varphi) \rightarrow \frac{b}{r} \sin^2 \varphi \qquad \dots (13)$$

where, at these large distances, $\varphi \approx \psi_0 \approx -\psi_1$. In this 'far field' expression, the angular variation $\sin^2 \varphi$ is the figure-of-eight directivity pattern of the sound radiated by a lateral dipole source which, in the INM logic, is considered to provide a reasonable simulation of the directionality of aircraft noise radiation.

4.16 The function in equation (12) has been tested in simulations involving a variety of flight profiles, by comparing the calculated L_{SE} values with ones generated using a representative directional source model to compute and integrate, step-by-step, the time history of sound level at the receiver point. The source directionality used, illustrated in Figure 8, is based on an analysis of a number of measured flyover noise time-histories. In general, for flight profiles in which L_{ref}, speed and/or direction, change relatively slowly from segment to segment, the simple Noise Fraction given by Equation 12 gives accurate approximations. However, if large changes of sound level occur (for example after an engine power change), deficiencies can arise in the vicinity of the junction between segments. These are caused by neglect of the longitudinal asymmetry of real aircraft noise which reaches a maximum in the rear quadrant (Figure 8). Thus, for example, after a power increase, L_{SE} values calculated alongside the quieter segment can be too low at positions which would, in reality, be influenced by sound radiated backwards from the noisier segment.

4.17 Thus, for departing jet aircraft only (propeller driven aircraft and all arrivals are excluded), this under-estimation has been alleviated by a modification to the Noise Fraction term which effectively causes the dipole lobes to lean backwards. This is achieved by the simple expedient of computing a modified or 'skewed' noise fraction F', not at the specified field point P, but at a position P' displaced forward by an amount which is a function of the 'directivity angle', δ (Figure 9), currently set at the typical value of 45°. (The lateral distance from the segment remains unchanged.) Appendix B shows that with this simple modification, the far-field directivity becomes

$$F'(r,\varphi) = F(r,\varphi) . \left\{ \frac{\tan^2 \varphi + 1}{\tan^2 \varphi + (1 + \tan \varphi \tan \delta)^2} \right\}^{3/2} \qquad \dots (14)$$

which is plotted, together with Equation 13, in Figure 10. (Note that F' does not have to be generated using Equation 14 in the computer model; the equation is given here solely to illustrate the effects of displacing the field point in the computations).

4.18 In most L_{eq} calculations, the effect of this Noise Fraction modification on L_{SE} is very small. Alongside a long uniform segment, for example, where ψ_0 and ψ_1 are both small, the field point displacement has no effect on ΔL_{SE} because it is negligible by comparison with the segment length. (The pattern of L(t) at the displaced point is identical - it merely occurs at a different time.) Similarly, it has small effects on L_{SE} in the case of a sequence of flight path segments involving relatively small changes of L_{ref} and/or direction because their combined geometry and sound radiation differ little from those of a single long, straight segment. It is for this reason that the directivity correction is **not** applied to the noise of aircraft on final approach segments as, at standard noise contour positions, these are effectively very long with uniform L_{ref} values. Overall, because L_{eq} is generally dominated by the noise radiated laterally from the nearest and noisiest flight path segments, it is relatively insensitive to the precise details of the function F'. This is especially true of its values at small angles to the flight direction. Only at positions immediately behind the start of the aircraft take-off run does 'small-angle' noise sometimes predominate - and this is treated as a special case (see paragraphs 4.28 *et seq*).

4.19 To summarise, the Noise Fraction, which accounts for the finite length of a flight path segment, is calculated in all cases using Equation 12. However, to reflect the pronounced directional characteristics associated with departing jet aircraft, a displaced field point is used as illustrated in Figure 9.

Lateral attenuation

4.20 The excess attenuation at low elevation angles, approximated in the NNI model by the second term on the right hand side of Equation (4), in effect includes both source directivity and ground absorption effects. The combination of these is now referred to as *lateral attenuation.* A comprehensive study performed by the SAE (Ref 19) provides a more elaborate formulation of lateral attenuation and this has been incorporated into the L_{eq} model. Mainly because of engine installation effects (eg acoustic shielding by aircraft structure, mixing of exhaust streams etc) jet aircraft tend to radiate less noise to the side than downwards, and this adds to the apparent attenuation of sound propagated in directions at lower angles to the horizontal. Although the NNI model (cautiously) neglects such effects at elevations greater than 14.2°, the SAE work indicated that they actually remain significant at angles up to 60°, ie the NNI model is over-cautious. Ref 19 provides an empirical relationship for the variation of lateral attenuation with distance to the side of a long (infinite) flight path.

4.21 Figure 11 shows the geometry of the SAE lateral attenuation algorithm: s_p and d_p are the perpendicular (ie shortest) distances, in metres, from the receiver point P to, respectively, the flight path and the ground track. (The ground track is the vertical projection of the flight path onto level ground.) The point S is the effective source position on the flight path. The elevation angle, β, in degrees, between the two shortest lines is therefore measured in a plane normal to the flight path (ie $\beta = \cos^{-1}(d_p/s_p)$ and is thus defined slightly differently to the elevation θ used in the NNI model which is measured in the vertical plane - see Figure 2).

4.22 Putting $d_p = d$, SAE lateral attenuation, in dB, is given by the empirical equation[*]

$$\Lambda(d,\beta) = \frac{G(d).A(\beta)}{13.86} \qquad \text{... (15)}$$

where

$$G(d) = 15.09\,[1 - e^{-0.00274d}] \quad \text{for } 0 \le d \le 914\text{m} \qquad \text{... (16)}$$

$$= 13.86 \quad \text{for } d > 914\text{m} \qquad \text{... (17)}$$

and

$$A(\beta) = 3.96 - 0.066\beta + 9.9\,e^{-0.13\beta} \quad \text{for } 0° \le \beta \le 60° \qquad \text{... (18)}$$

$$= 0 \quad \text{for } 60° < \beta \le 90° \qquad \text{... (19)}$$

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[*] For consistency, the notation and arrangement used here differs slightly from that given in the SAE document (Reference 19).

4.23 These relationships, which are plotted as functions of distance and elevation in Figure 12, implicitly apply to 'long' flight path segments; ie they are appropriate to situations where the aircraft passes by in a steady operating configuration and the shortest line to the segment is a perpendicular which meets it at significant distances from either end. In such circumstances, L_{SE} is dominated by the noise from that single segment and, more specifically, by that part of the segment noise which travels over shorter distances and from higher elevation angles. Application of the SAE rules to propagation from distant, finite segments, where there is no perpendicular from the field point, thus requires an adaptation of the SAE model. This follows the approach used in the INM in which d and β in Equations 15 through 19 are defined by the shortest lines from the field point to the segment flight path and ground track, regardless of whether they meet the segment at one or the other of its ends, or between them. The various geometries which arise for different field point positions are illustrated in Figure 13.

4.24 Ref 11 points out that the SAE procedure was developed for jet aircraft only and that lateral attenuation effects should be ignored for propeller-driven aircraft. In the absence of any specific recommendation, it remains the practice at present to retain the simple NNI attenuation function (4) for the noise of propeller aircraft.

Initial climb

4.25 Comparisons of its output with the more detailed step-by-step computations indicated that this simple segment model exaggerates the lateral attenuation for 'terminal flight segments', ie the initial climb illustrated in Figure 14. This is because, in certain cases, the elevation β of the nearest segment point is too small to provide a realistic value of Λ. For example, when the shortest line joins the field point P' to the end of the segment which touches the ground at S' (on the runway), the calculated segment attenuation $\Lambda(d,\beta)$ is maximal, ie it is calculated for $\beta = 0$. Sound from that segment actually emanates from its entire length, the upper portion of which may be much less affected by ground absorption, ie the effective 'mean' elevation for the segment may be rather greater than zero and the real attenuation rather less than the $\beta = 0$ value. Similar overestimates of Λ may arise for non-zero but small values of β.

4.26 So as not to underestimate the ΔL_{SE} contributions from the initial climb segment, a minimum value is imposed on the effective source height used to calculate the lateral attenuation $\Lambda(d,\beta)$. If S, the nearest point on the flight path to P, is less than some minimum height, h, above the ground, an effective source position S_e is substituted - at the point where the height *is* equal to h. Values of d and β appropriate to that point are then used in the calculation of $\Lambda(d,\beta)$.

4.27 This initial climb segment adjustment is a provisional device which will be refined during further model development. Currently h is set equal to the mean height of the path segment.

Start-of-roll and runway accelerations

4.28 The procedure for calculating the segment noise level ΔL_{SE} is based on constant aircraft speed. Consequently, at present, the take-off run, which involves large accelerations, is simulated by a set of contiguous sub-segments, each with a constant speed. The ability to adjust the number, lengths, speeds and reference noise levels of these segments allows any stipulated ground-roll noise emission characteristics to be modelled in some detail. Up to the present, noise generated during the landing run, ie during deceleration after touch-down, has been disregarded (but see paragraph 6.3).

4.29 Special considerations apply to the noise exposure behind the aircraft at start-of-roll where L_{eq} may be dominated by noise radiated at small angles to the longitudinal axis of the aircraft. In the NNI model, noise behind the take-off start-of-roll is calculated rather cautiously as a simple non-directional function of L_{ref} and distance. Thus, behind the runway, the calculated contour of the take-off noise is semicircular (Figure 15). However, it has long been known that due to the highly directional characteristics of aircraft noise, the contour actually exhibits pronounced lobes at acute angles to the extended runway centreline.

4.30 By consolidating data from many sources, including measurements made at Heathrow Airport, the SAE (Ref 11) devised an empirical description of a 'fleet average' directivity pattern, $D(\Psi)$. Illustrated in Figure 15, this is given by the following cubic equations in Ψ, the angle between the aircraft direction of movement and the line joining the start-of-roll and the field point:

For $90° \leq \Psi \leq 148.4°$:-

$$D(\Psi) = 51.468 - 1.553\,\Psi + 0.015147\,\Psi^2 - 0.000047173\,\Psi^3 \qquad \ldots (20)$$

For $148.4° \leq \Psi \leq 180°$:-

$$D(\Psi) = 339.18 - 2.5802\,\Psi - 0.0045545\,\Psi^2 + 0.000044193\,\Psi^3 \qquad \ldots .(21)$$

The take-off roll contribution to the sound exposure level at any point behind the start-of-roll is then given by

$$\Delta L_{tor}(d,\Psi) = \Delta L_{SE_{gr}}(d,90°) + D(\Psi) \qquad \ldots (22)$$

where d is the radial distance from the start-of-roll and $\Delta L_{SE_{gr}}(d,90°)$ is the level generated at the same distance d to the side of the start-of-roll ($\Psi = 90°$) by *all* ground-roll segments. Equations 20 and 21 define only the shape of the directivity pattern; the absolute sound levels behind start-of-roll are determined by the lateral value $\Delta L_{SE_{gr}}(d,90°)$.

5 GENERATION OF NOISE INDEX CONTOURS

Calculation of the noise index array

5.1 The process by which the noise contours are generated from input information describing

a) the approach and departure *routes* or *flight tracks*,
b) the *traffic* upon them in terms of the numbers of different aircraft types,
c) the *dispersion* of individual flight tracks, and
d) the average *flight profiles* (of height, noise emission and speed) of the different types

is essentially common to both NNI and L_{eq} models. It involves the calculation of a spacial array of index values from which the contours are subsequently calculated and plotted.

5.2 At any field location, the index value, NNI or L_{eq}, is determined by summing all significant event levels (ie those which exceed the cutoff criterion) received there during the specified time period. Since it is assumed that all aircraft of the same type generate identical single event levels, the summation only has to be carried out over aircraft types and routes, taking account of the numbers of movements of each type on each route (including each of the dispersed tracks; see paragraph 5.9).

5.3 For airports with many routes, aircraft types and movements, noise contour modelling can involve a very large number of calculations. However, computer time can be minimised by avoiding unnecessary ones, the main objective being to avoid calculating negligible elemental contributions to the noise level. ANCON includes logic to exclude from the calculations (a) those type/segment combinations whose levels will lie below the cutoff threshold and (b) grid points which lie outside the largest contour of interest.

5.4 At present, noise contours are generated from the noise index array using a commercially available graphics package (GINO). Although this performs satisfactorily, the use of a uniform rectangular grid (to which it is restricted) is a serious limitation because a finer mesh is necessary to define the shape of the inner, smaller (ie higher level) contours with the same resolution as the larger, outer contours. Thus a future aim is to incorporate a variable grid spacing. Until this is available, the present practice will be continued which is to select the single rectangular grid spacing which best compromises the conflicting constraints of resolution and computer capacity/time.

Input data

5.5 For the purposes of generating retrospective noise exposure contours for the London Airports, data bases for ANCON are generated and maintained by an ongoing programme of measurement around those airports.

5.6 When contours are required for planning purposes, ie to indicate the likely situation at some future date, input data are usually compiled from information provided by NATS and the traffic forecasting agencies (eg BAA, CAA Economic Regulation Group), taking account of past experience (eg in the case of flight path dispersions). Inevitably the process involves numerous assumptions about future developments and the uncertainties associated with these have to be considered when evaluating the results. The model is, of course, structured so that suitable data from any source may be utilised.

Aircraft types

5.7 In the present context, an aircraft 'type' is defined by one of a number of noise/performance categories, which represents its unique contibution to the airport noise climate. At present, a total of 29 categories are used to generate annual contours for Heathrow, Gatwick and Stansted Airports; these are listed in Appendix C. In the main, one category covers one particular aircraft type/model from a particular manufacturer, eg a Boeing 757 or an Airbus A310. However, some categories include more than one type/model because they have very similar noise characteristics (eg BAC1-11/Tupolev Tu134). Smaller, quieter, types of general aviation aircraft, although having differing individual characteristics, have a relatively small total influence on the noise contours of larger airports and it is appropriate to classify them into very few categories. These include business jets, and single and twin propeller aircraft. In some cases, one type is divided between more than one category. Thus, for example, it is necessary to distinguish between Chapter 2 and Chapter 3 versions[*] of the Boeing 737 such as the -200 and -300 models, but not between different Chapter 3 versions, ie the -300, -400 and -500 models which use very similar engines.

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[*] These designations refer to Chapters of Annex 16 to the ICAO Chicago Convention (Ref 16) which defines aircraft noise certification standards. Most civil jet transport aircraft operating at present conform to either Chapter 2 or Chapter 3, the latter being the current and more stringent standard.

Nominal flight tracks

5.8 The nominal route may be a Standard Instrument Departure track or, in the case of historical contour modelling, the mean of a sample of radar-measured flight tracks. The ground-track of each nominal departure or arrival route is represented mathematically by a sequence of contiguous straight segments. The radar data from which the route geometries are calculated are obtained from coordinated measurements carried out by the NATS' Air Traffic Control Evaluation Unit (ATCEU).

Flight track dispersion

5.9 Accurate noise exposure estimation requires a realistic simulation of the lateral scatter of flight tracks actually observed in operational practice. Thus most routes are represented by a set of dispersed tracks in addition to the central one. The positions of these side-tracks are usually defined in relation to the standard deviations of the dispersion at various distances along the route. In most standard NNI calculations, two side-tracks were added at distances of 1.36 and 2.86 standard deviations on either side of the centreline track. Of the total route traffic, 55% was concentrated on the centre track with 22% and 1% respectively assigned to each of the first and second side-tracks. This representation has been retained in L_{eq} calculations performed to date. For retrospective work, the standard deviations are determined from an analysis of radar data; for forecasts, estimates are based upon past experience with similar route patterns. In some cases, especially for arrival routes involving a wide range of procedures for joining the glide-slope, this simplified approach is inadequate. In such cases suitable sets of 'sub-tracks' are defined to provide more realistic simulation of the swathes of measured tracks.

Flight profiles (height, speed and noise)

5.10 A single departure climb profile is defined for each aircraft type. This also divides the flight path into straight segments, which, being governed by changes in climb angle, speed and/or reference noise level, are independent of ground track segments. Each profile segment is defined by six values: the track distances to its beginning and end, the heights of its ends above ground level, the aircraft speed along the segment and the reference noise level, L_{ref}. Ultimately, a separate directivity term, ΔL_{∞}, may also be defined for each aircraft type; at present common values are used, one each for takeoff and landing.

5.11 The flight profiles for the different aircraft types are estimated from analyses of noise and radar data. Noise measurements are made at various points and for various periods around the airports. The readings are subsequently correlated with radar measured flight paths and flight information and classified by aircraft type. From this data are calculated the L_{ref} values and mean flight profiles. The directivity terms have been determined initially by matching the measured and computed relationships between L_{max} and L_{SE}.

Traffic

5.12 Total L_{eq}-relevant aircraft movements during the appropriate summer period (mid-June to mid-September) are derived from the airport runway controller's logs. In some instances, eg where a significant number of non-recorded training movements occur, the runway logs have to be supplemented by data from other sources.

5.13 Future-date contours are based on a combination of forecast routes, aircraft types and traffic distributions together with aircraft performance data, measured for existing types or estimated for projected future types.

6 FURTHER MODEL DEVELOPMENTS

6.1 The CAA noise model has been used for many years in support of the Department of Transport's administration of Government noise policy at Heathrow, Gatwick and Stansted Airports. For this purpose, it has been used and developed to meet the main requirement of portraying, as accurately as possible, actual noise exposures experienced around those airports. Deficiencies have been remedied as and when they have been found; for the most part these have involved changes to the the way in which measured data are analysed and input to the model rather than to the mathematical model itself. Following the switch from NNI to L_{eq}, the intention is to continue this process of data collection and analysis, model testing and refinement although, due to the increased complexity of the model, the requirements are now somewhat more demanding. The results of ongoing validation work will be the subject of future reports.

6.2 The introduction of the L_{eq} model ANCON represents a significant advance on the previous NNI practice through the inclusion of sound duration effects and the introduction of the SAE algorithms for lateral attenuation and start-of-roll noise. These involve methodologies which are well-established elsewhere but their full validation will be a major aim of future field studies as will be general improvements in accuracy as verified by experimental checking.

6.3 Currently under consideration is the question of noise generated by the use of reverse thrust to retard aircraft immediately after landing. Because this represents a relatively small component of total aircraft noise energy emissions, and actually occurs during the ground-roll of the aircraft, it has not in the past been included as part of the 'air-noise' modelling process. A new study is now under way to investigate its magnitude and means for modelling it.

6.4 For the immediate future, further studies are expected to concentrate on sound duration effects which are embodied in the Noise Fraction and source directivity functions. Initially, the algorithms have been calibrated by matching the measured and computed relationships between L_{max} and L_{SE} using data averaged over many aircraft types. For aircraft in flight, particular attention is needed to differences between aircraft types and to the effects of turns and power changes. For aircraft on the runway, this includes the effects of aircraft acceleration.

6.5 Also a subject for scrutiny is the accuracy of the lateral attenuation calculations which requires data measured at a wide range of locations. A number of possible refinements to the model may be considered. A particular question concerns the air-to-ground propagation rules. Standardised procedures for the estimation of atmospheric absorption (Refs 8-10) indicate that, while an attenuation rate of 8dB/dd may be a good average figure for aircraft peak levels over distances up to about 1000m (from within which most data has been obtained), the average rate is different at greater distances. Alternative algorithms to take account of this need to be evaluated against new experimental data. Furthermore, the latter may have to take account of weather variations which has not been necessary for the shorter range measurements. The lateral attenuation procedure, which was based on data obtained from aircraft operations involving a high percentage of Chapter 2 aircraft also requires re-examination as the mix of aircraft types in airline fleets continues to change. The present use of the simple NNI attenuation for propeller aircraft also needs to be re-examined as does the manner in which the lateral attenuation is modelled for initial climb flight segments.

6.6 The natural spread of flight paths about any nominal route is presently simulated by using five laterally dispersed tracks to define a flight corridor. Although this has proved to be quite satisfactory in the majority of applications, it can be fairly wasteful of computer time in some and too coarse an approximation in others. A possible solution is to allocate a number of tracks which varies with distance along various routes.

6.7 An outstanding matter for attention in the longer term, referred to in paragraph 5.4, concerns the optimisation of the geometry of the grid matrix of noise index values. At present this sometimes creates a need for separate computer runs for large and small contours of the same case. A graded grid spacing would allow more efficient and/or more accurate calculations.

6.8 The ANCON model, as described in this document, is Version 1.0. The model will continue to be further developed in the light of new measured data and in response to constructive comments from those involved in the assessment of aircraft noise impact. Following major revisions to the theory or to the mathematical algorithms, further versions of this report will be issued.

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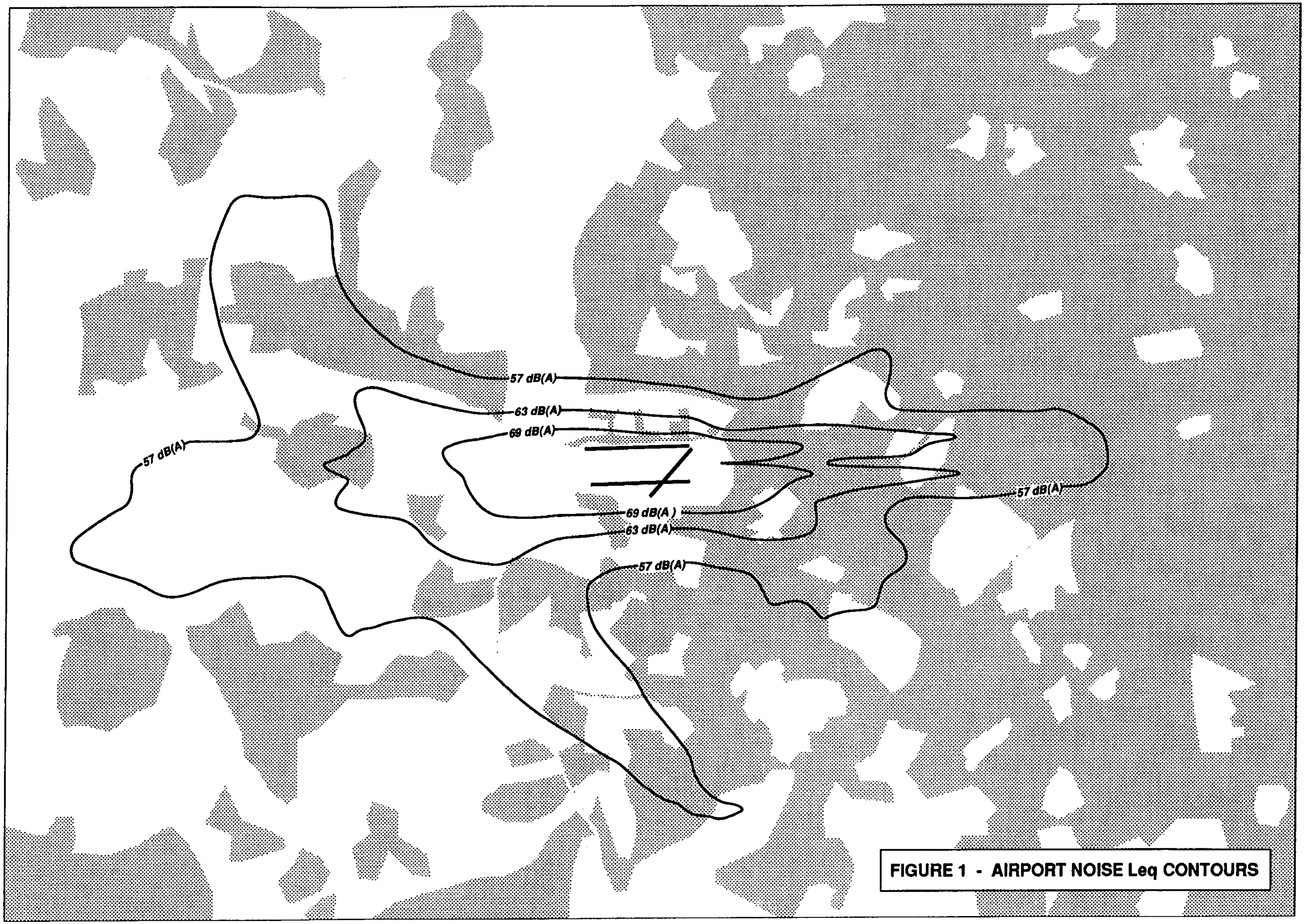


FIGURE 1 - AIRPORT NOISE Leq CONTOURS

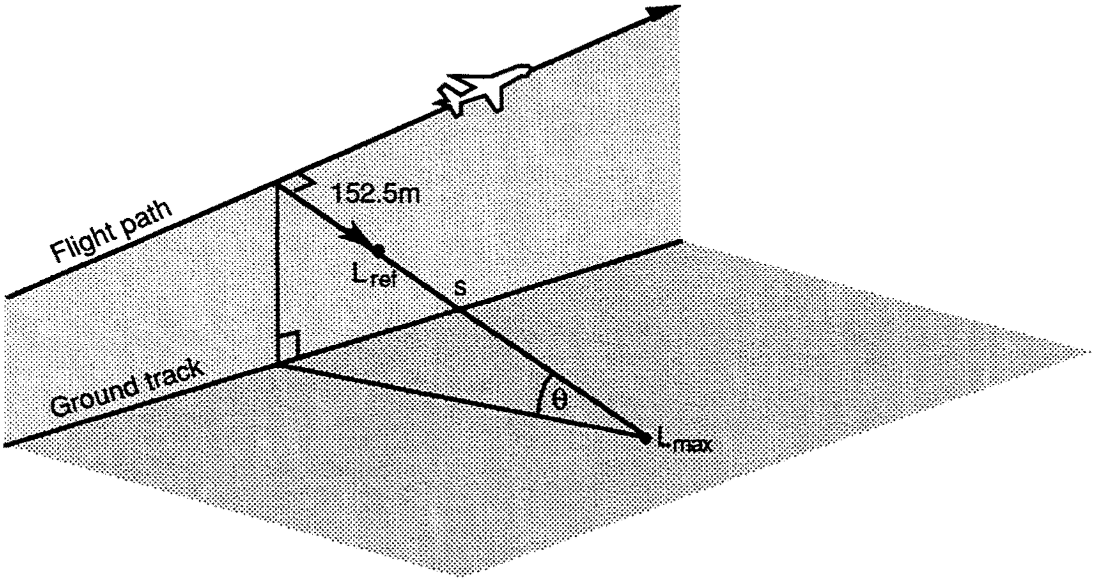


FIGURE 2 - VARIABLES IN THE CALCULATION OF L_{max}

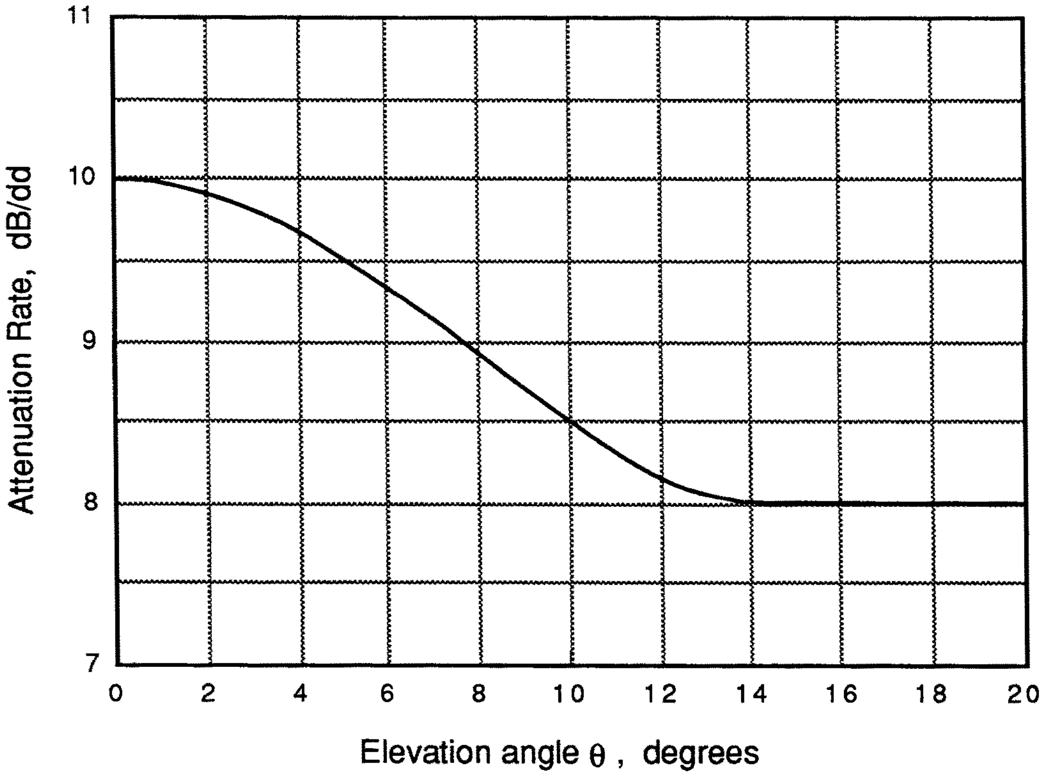


FIGURE 3 - NNI MODEL: VARIATION OF ATTENUATION RATE WITH ELEVATION ANGLE (Equation 4)

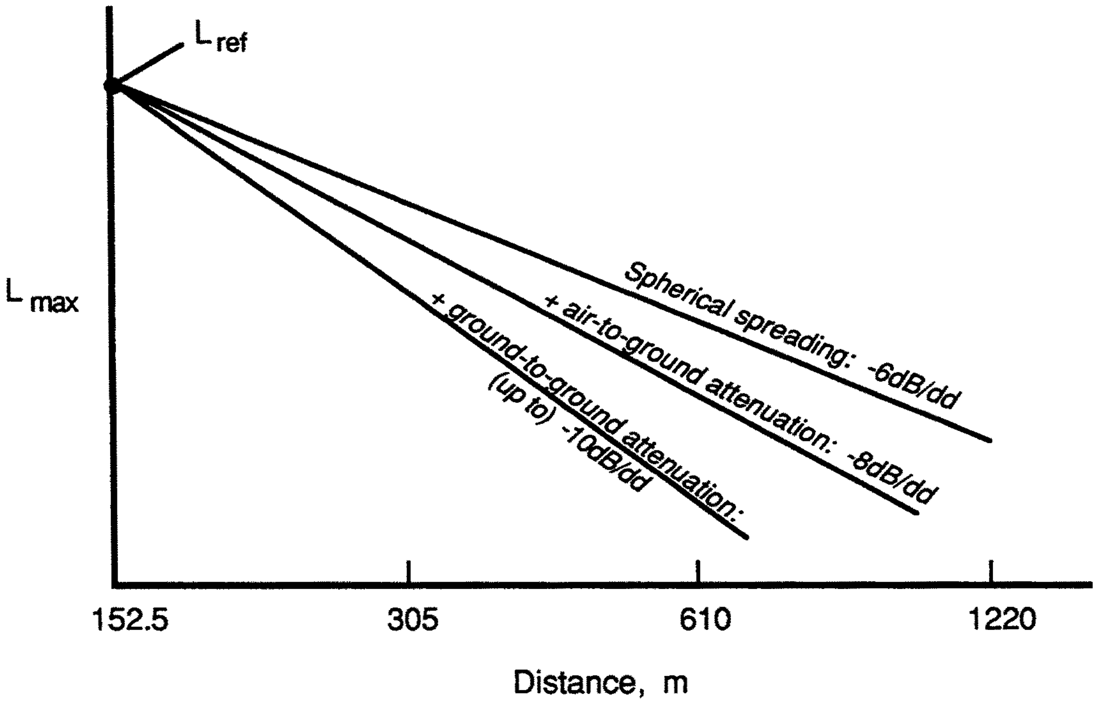


FIGURE 4 - COMPOSITION OF NNI ATTENUATION

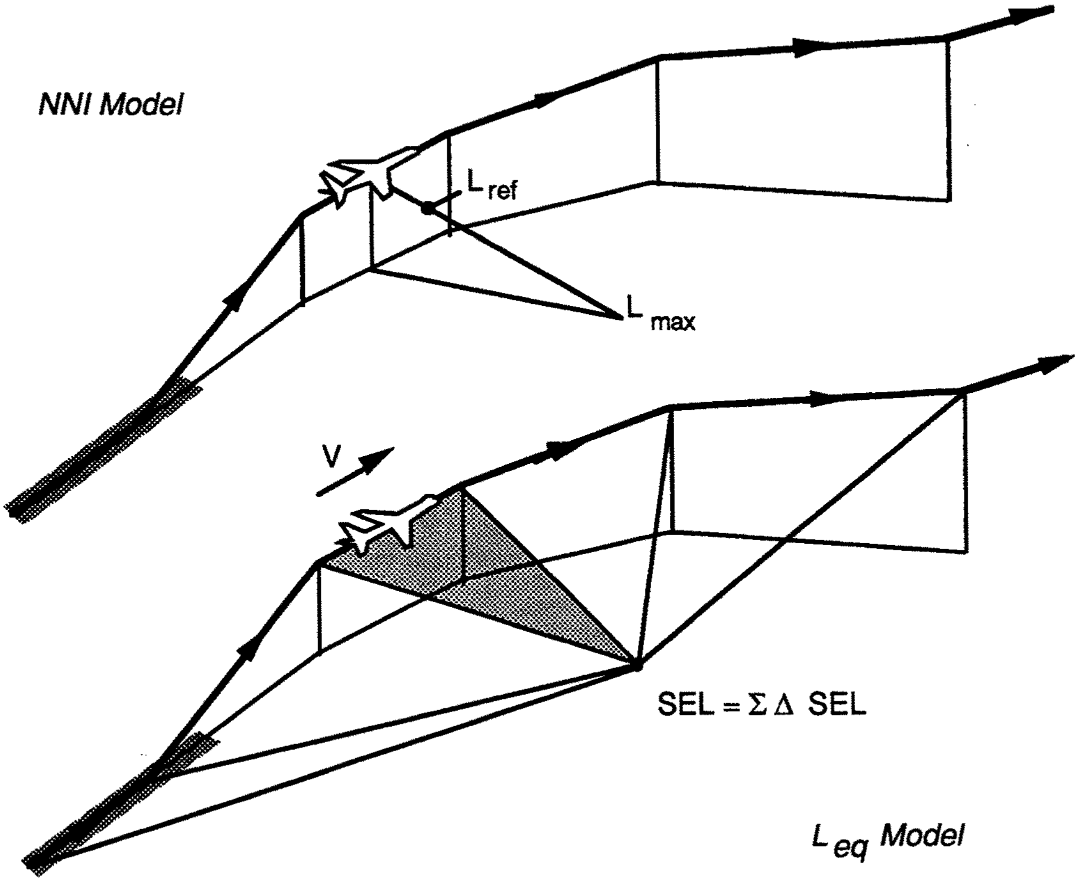


FIGURE 5 - FLIGHT PATH STRUCTURE IN NOISE MODELS

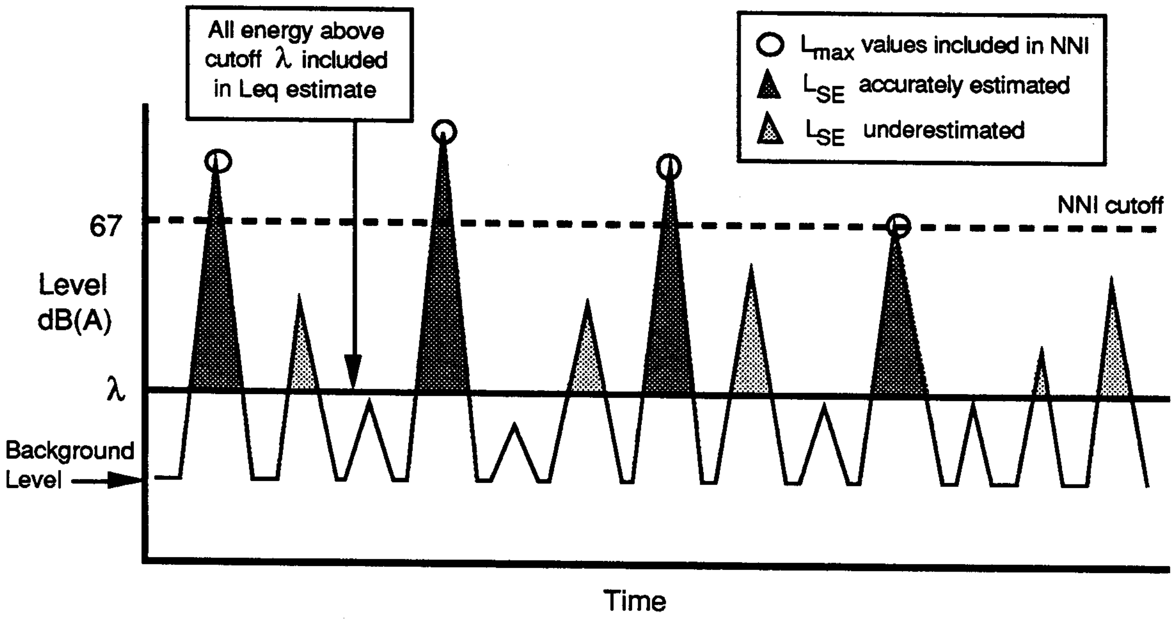


FIGURE 6a - IDEALISED TIME HISTORY OF AIR TRAFFIC NOISE INDICATING EFFECT OF CUTOFF LEVEL λ

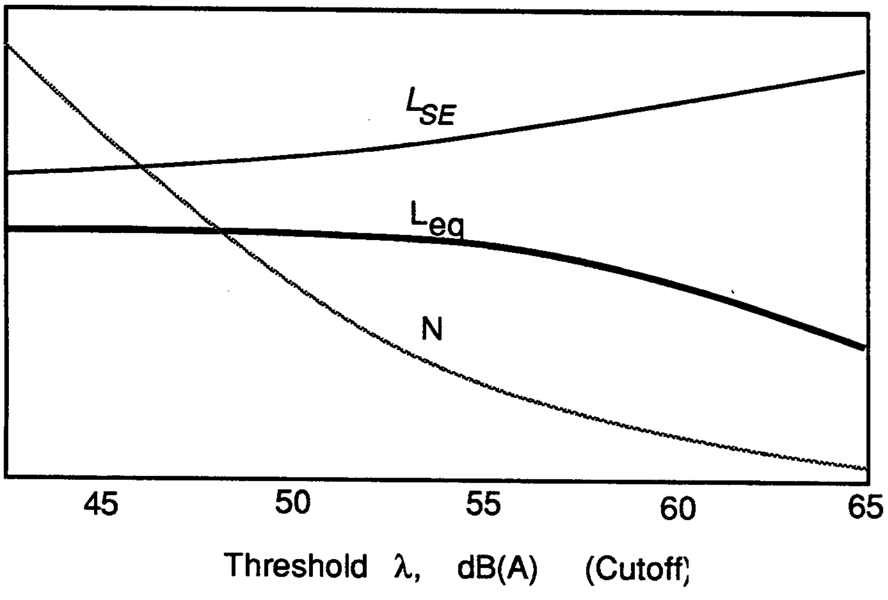


FIGURE 6b - ILLUSTRATION OF EFFECT OF CUTOFF LEVEL λ ON L_{eq}, L_{SE} AND N

(showing how lowering λ increases the number of events N but lowers their average level L_{SE} such that L_{eq} tends towards a stable value.)

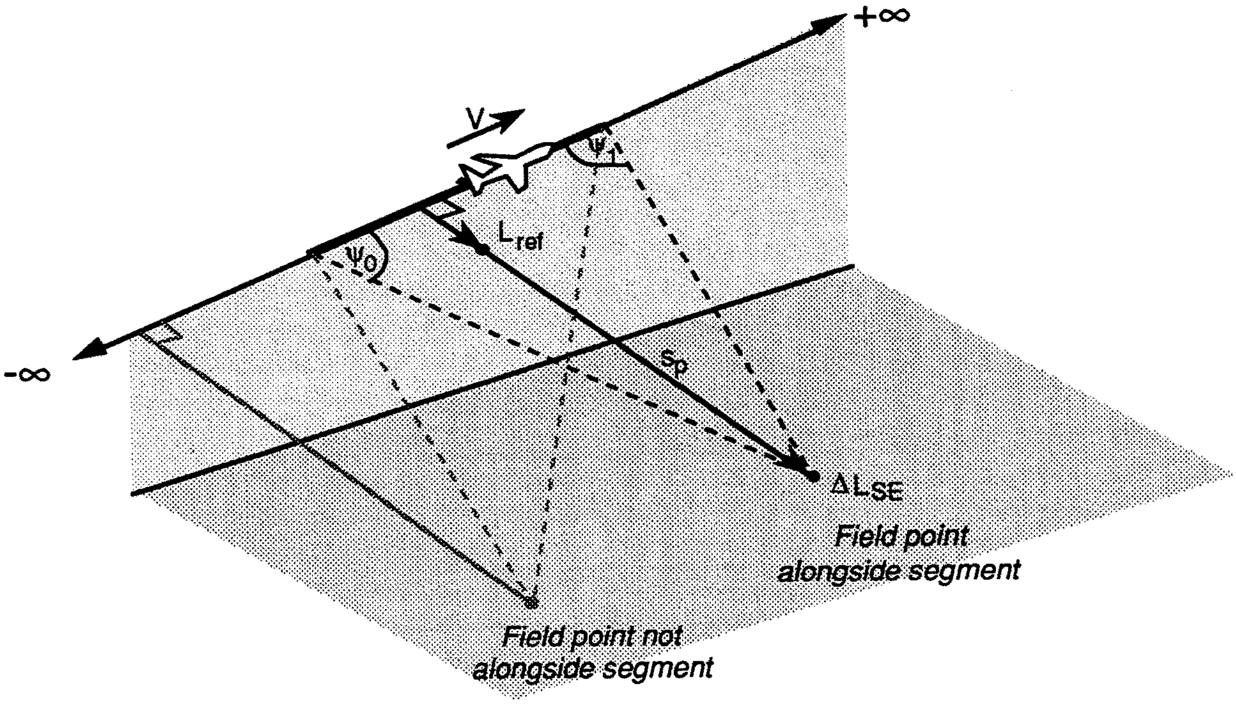


FIGURE 7 - SOUND RADIATION FROM SINGLE PATH SEGMENT

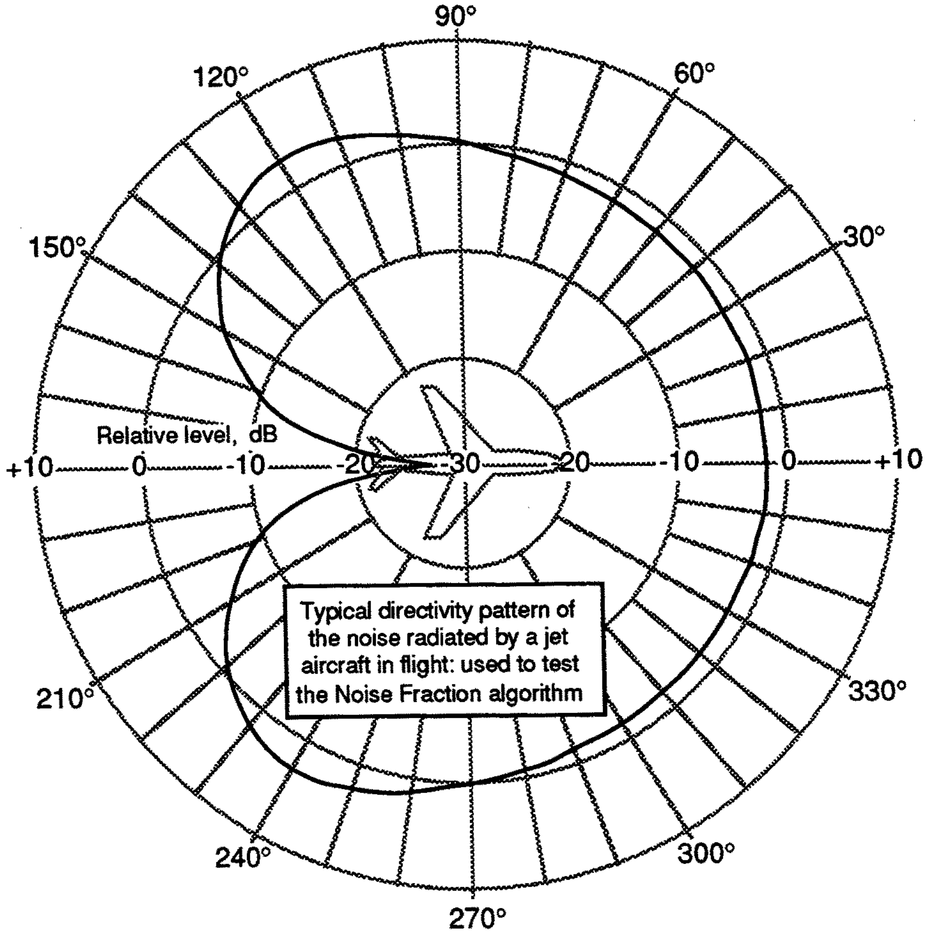


FIGURE 8 - DIRECTIONAL CHARACTERISTICS OF AIRCRAFT NOISE

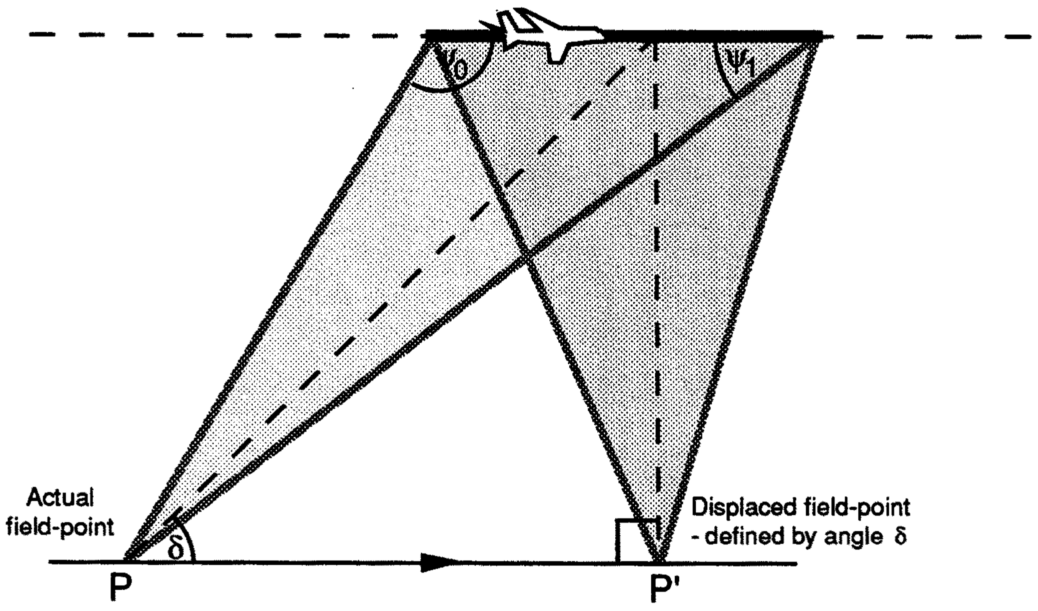


FIGURE 9 - GEOMETRY FOR CALCULATION OF 'SKEWED' NOISE FRACTION

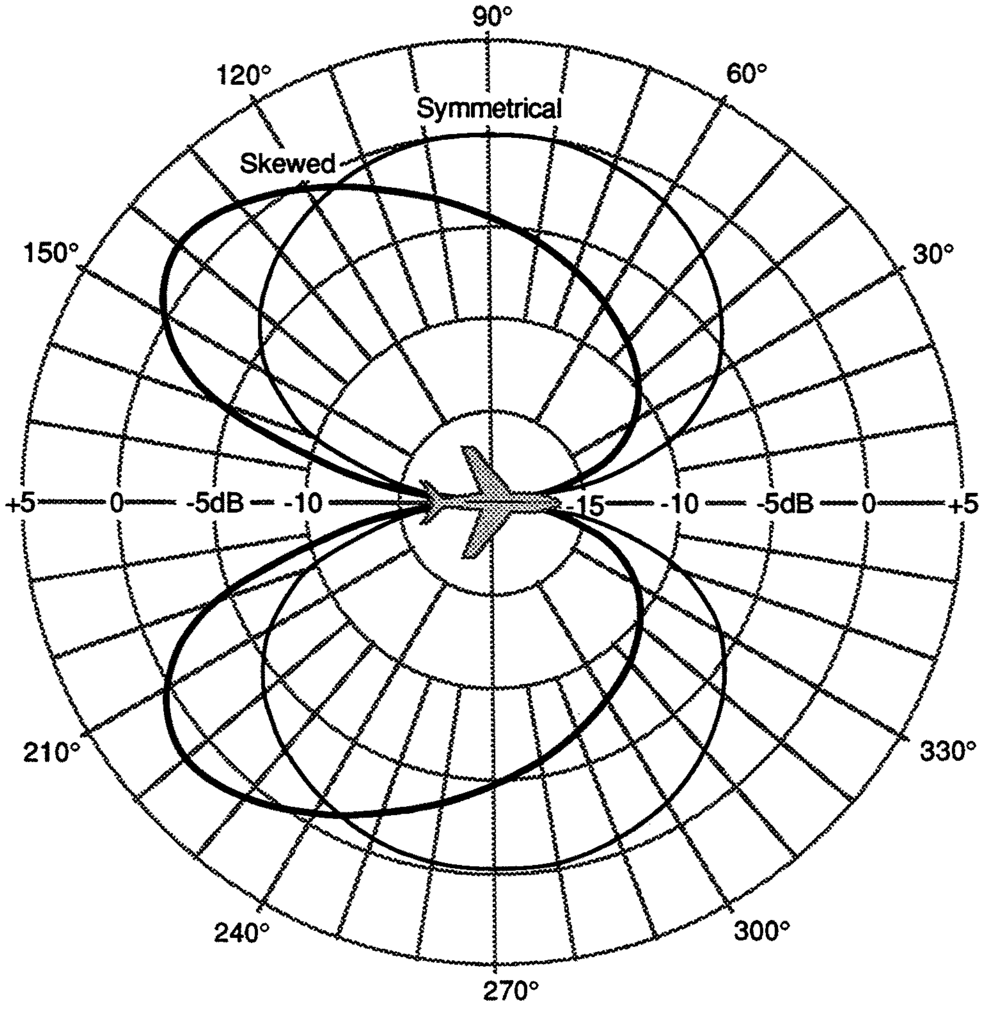


FIGURE 10 - Leq MODEL: COMPARISON OF SYMMETRICAL AND 'SKEWED' NOISE FRACTION DIRECTIVITIES

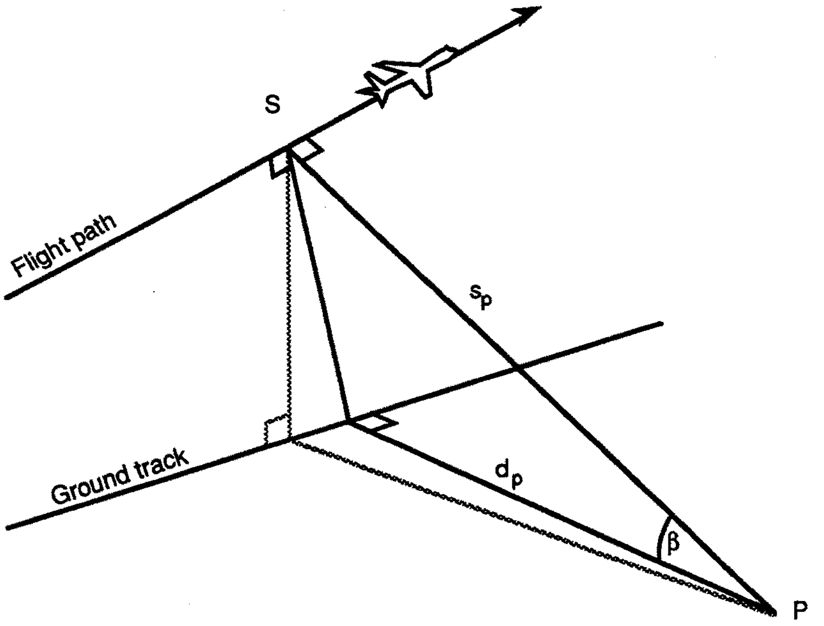


FIGURE 11 SAE ATTENUATION GEOMETRY: LONG FLIGHT PATH

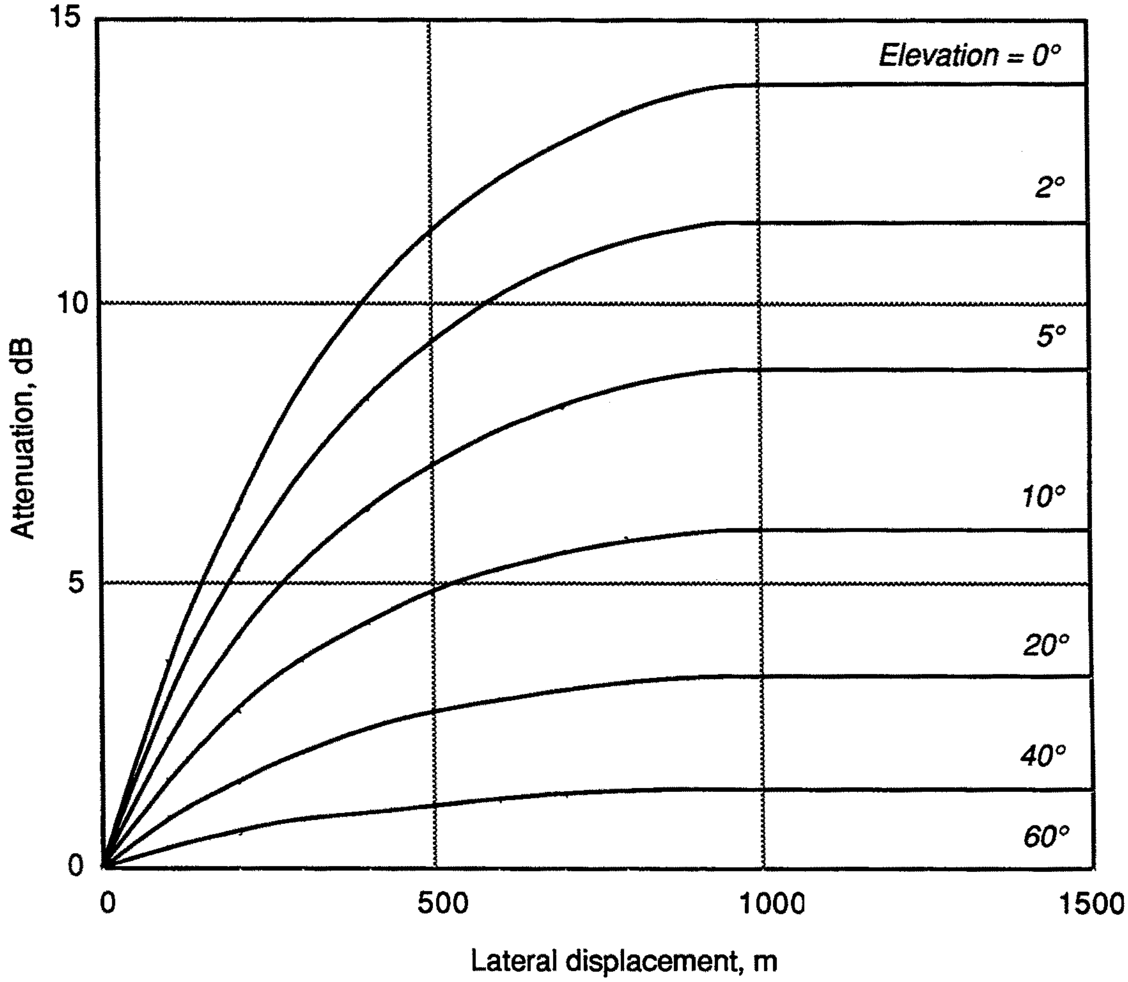
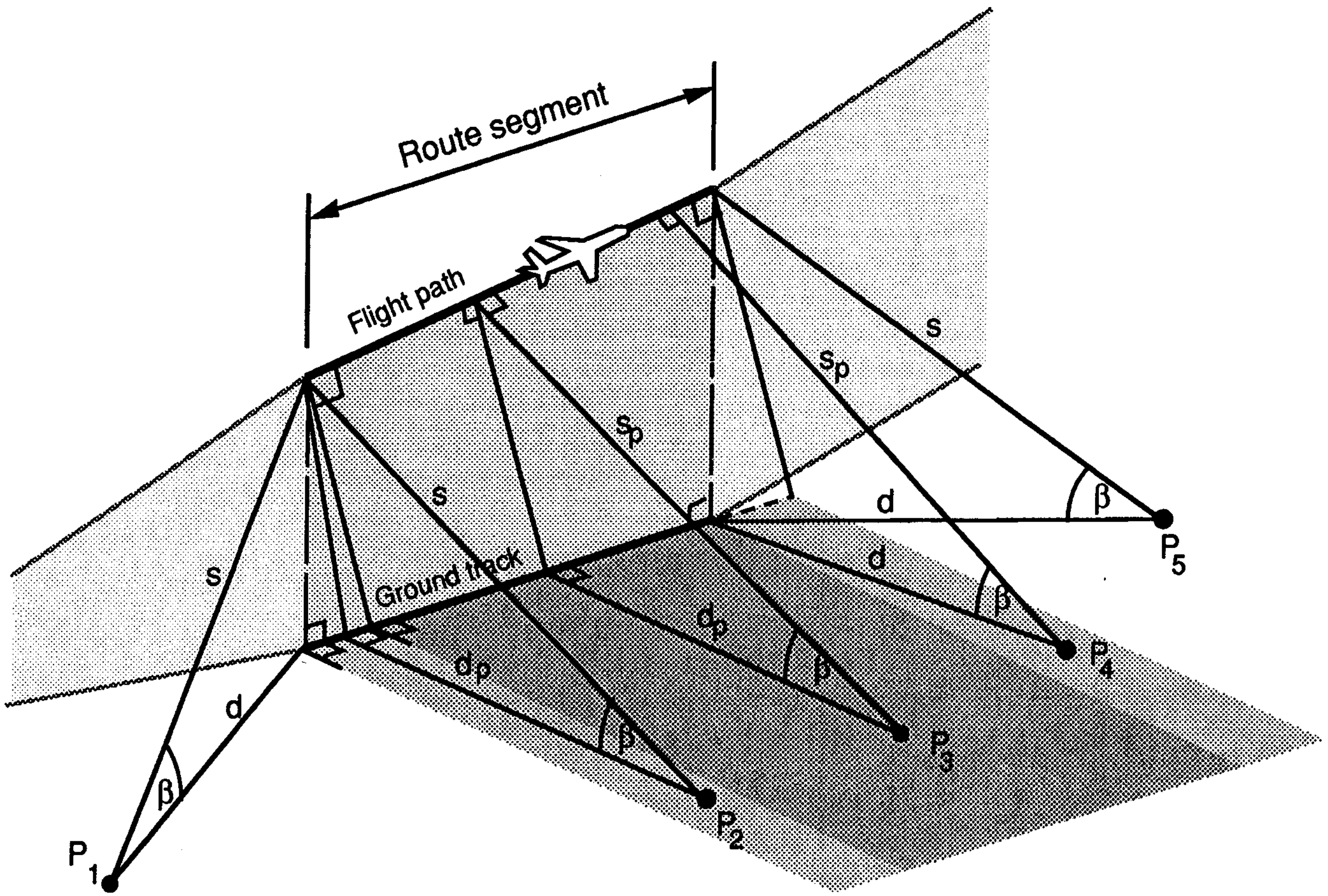


FIGURE 12 SAE LATERAL ATTENUATION



	Perpendicular	*Non-perpendicular*
Distance to flight path	s_p	s
Distance to ground track	d_p	d

One value of lateral attenuation Λ is calculated for each flight path segment as a function of lateral distance d and elevation β, which are defined in relation to the shortest distances from the field point to the flight path and the ground track. The definitions of d and β depend upon the position of the field point in relation to the route segment; ie whether perpendiculars can be drawn to the flight path and/or the ground track segments. The points P_1 through P_5 lie in five different zones of the ground plane where none, one or both of the shortest lines (s and d) are perpendiculars.

FIGURE 13 - SAE ATTENUATION GEOMETRY: FINITE SEGMENT CASE

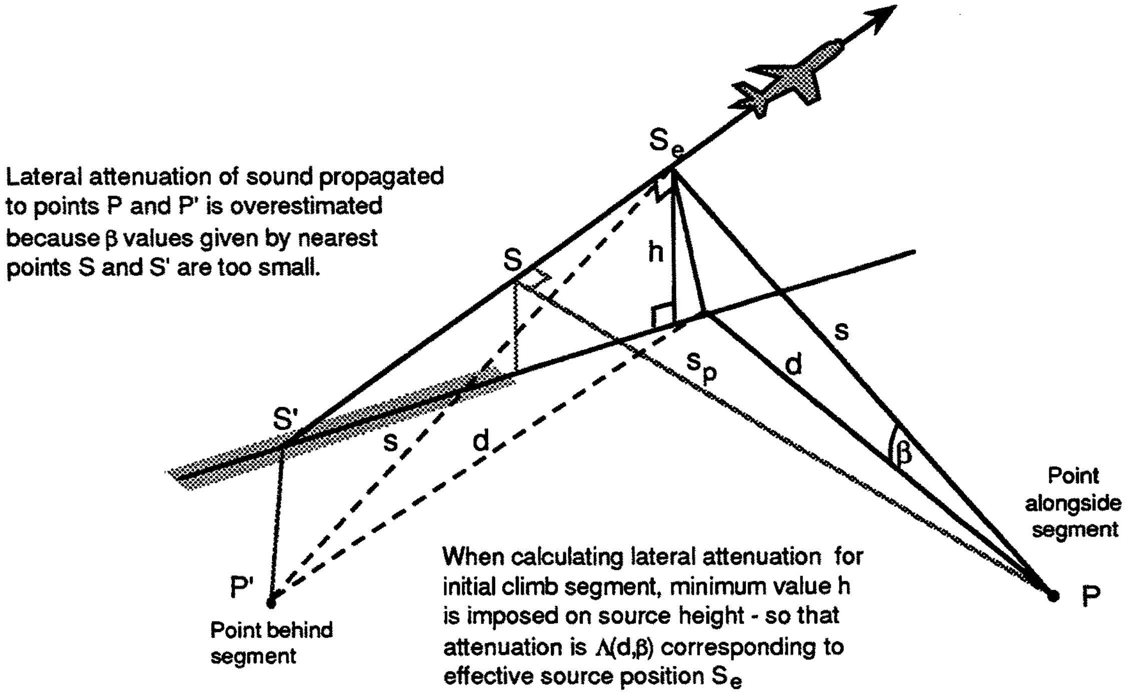


FIGURE 14 - ATTENUATION GEOMETRY FOR INITIAL CLIMB SEGMENT

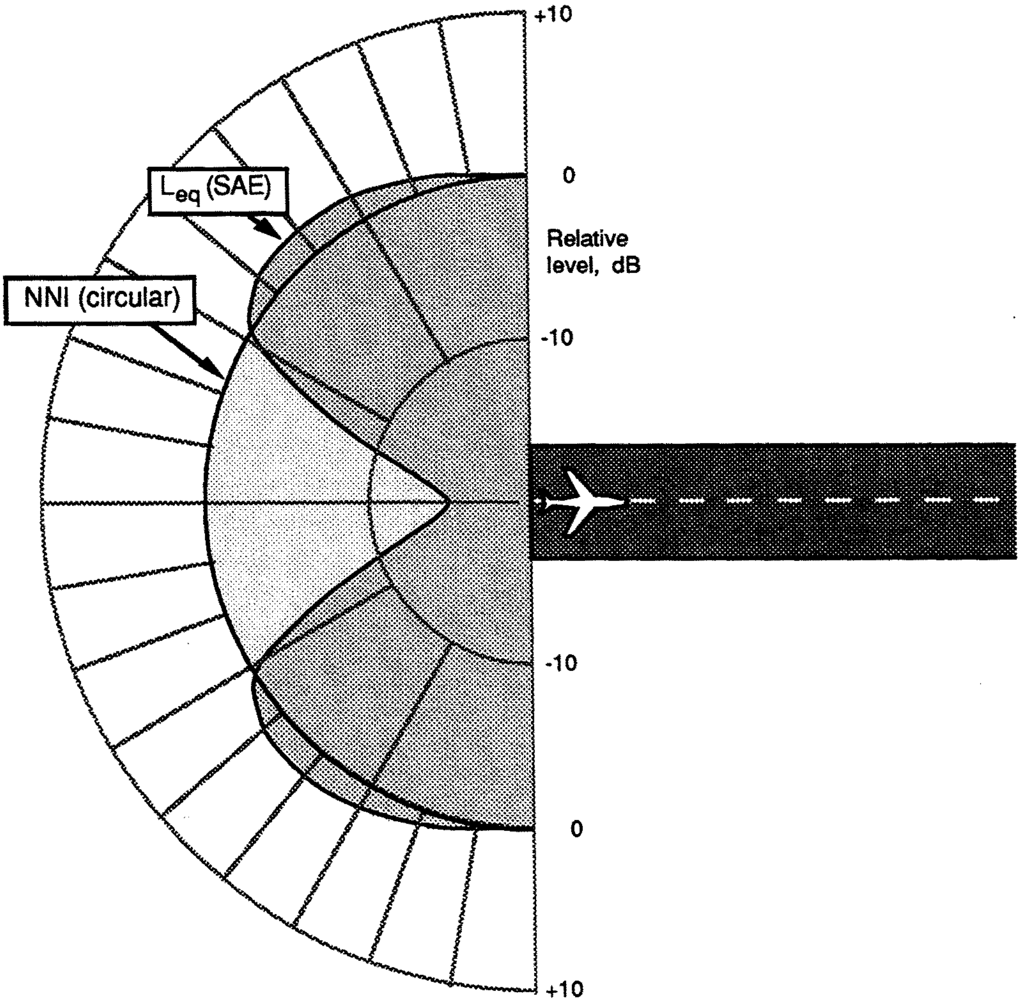


FIGURE 15 - START-OF-ROLL NOISE DIRECTIVITY PATTERNS

APPENDIX A

THEORETICAL EXPRESSION FOR SOUND EXPOSURE LEVEL

A1 The effect of source motion upon the sound exposure level at a nearby point can be demonstrated by calculating the sound radiation from a simple omnidirectional source (a monopole) travelling through a homogeneous atmosphere at constant speed V along a straight path. It is assumed that V is small compared with the speed of sound and that the instantaneous sound level varies as -10k log (s) where s is the distance from the source. If there is no sound energy dissipation, k = 2, and the sound level falls 6dB with each doubling of distance from the source. The effects of atmospheric absorption can be represented by making k greater than 2. Thus, Equation 4 of the text, describing air-to-ground propagation of aircraft noise, is based on the value k = 2.67 which corresponds to a sound level fall of 8dB per doubling of distance.

A2 At a distance s_p from the line of travel, the instantaneous sound level reaches a maximum value of L_{max} when the source is at its nearest point. At any other time, ie when the source is at a greater distance s the level is given by

$$L(t) = L_{max} + 10 \log (s_p/s)^{-k} \qquad \text{... (A1)}$$

where k is the propagation constant. Following equation 6 of the text, the sound exposure level is

$$L_{SE} = 10 \log \left\{ \int_{-\infty}^{\infty} 10^{L(t)/10}\, dt \right\}$$

or, using Equation A1,

$$L_{SE} = L_{max} + 10 \log \left\{ \int_{-\infty}^{\infty} (s_p/s)^{-k}\, dt \right\}$$

Putting $s = \sqrt{s_p{}^2 + V^2 t^2}$, where t is the time since the source passed the closest point (at $s = s_p$), the integral can be evaluated to give the result:

i.e, $$L_{SE} = L_{max} + 10 \log \left(\frac{s_p}{V} \right) + \text{constant} \qquad \text{... (A2)}$$

Where the constant depends upon the value of k.

A3 Although the source and propagation characteristics of aircraft noise are considerably more complex that those assumed in the simplified analysis above, Equation A2 provides a basis for an empirical relationship between L_{max} , s_p , V and L_{SE} . The constant may be expected to have different values for aircraft types with different spectral and directional characteristics; these are determined from an analysis of experimental data. As an example, Figure A1 shows L_{SE} plotted against $[L_{max} + 10 \log \left(\frac{s_p}{V} \right) + 0.8]$ for a set of departure noise levels for the Boeing 747 aircraft measured near Heathrow and Gatwick Airports. In this case the value of the constant is 0.8 and the correlation is high; the standard deviation of the data points about the regression line is 0.9 dB.

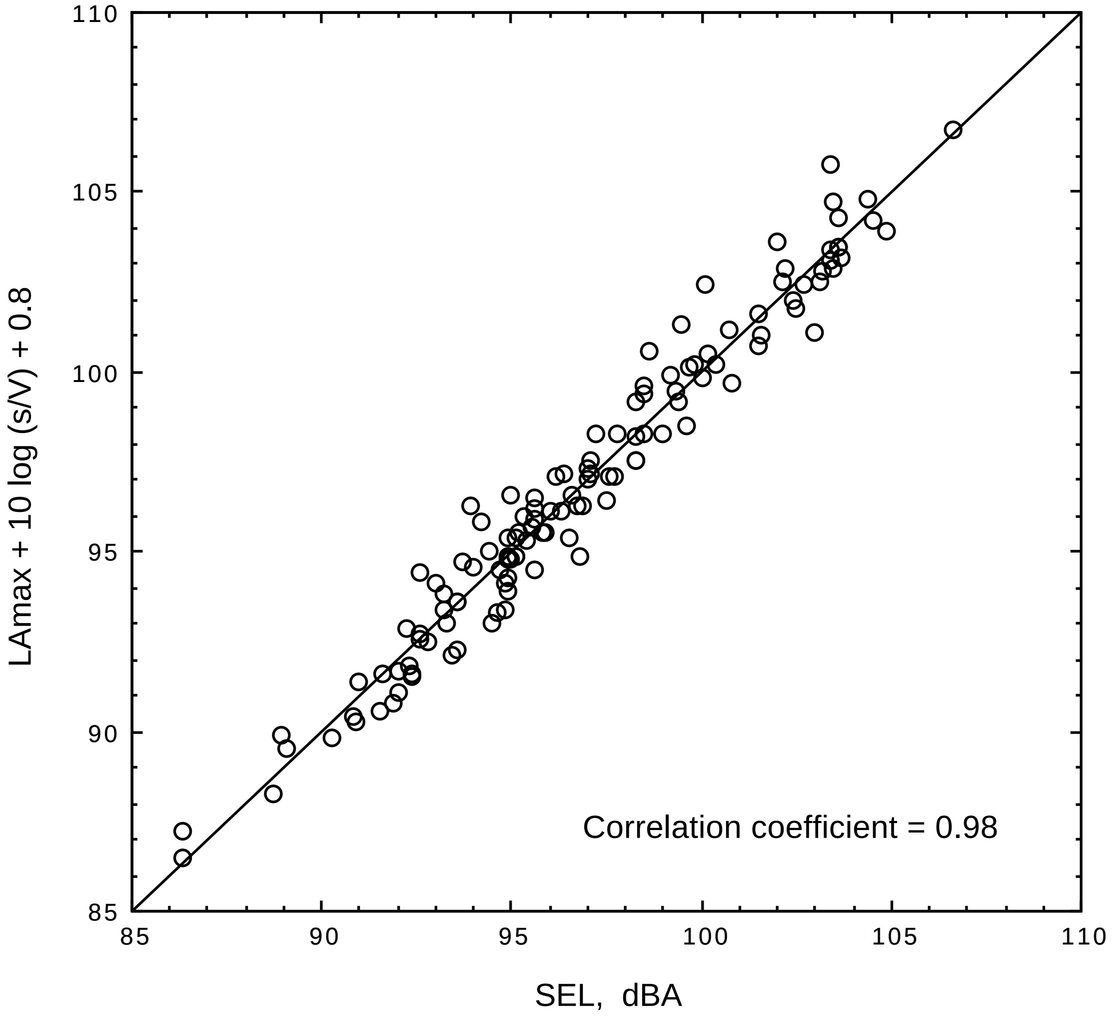


FIGURE A1 SOUND LEVELS OF BOEING 747 DEPARTURES

APPENDIX B

DIRECTIONAL CHARACTERISTICS OF 'NOISE FRACTION' TERMS

B1 Paragraph 4.15 of the main text defines a Noise Fraction term F used in the calculation of the contribution of a single flight path segment (see Fig B1) to the sound exposure level generated by one aircaft movement. It is given by the expression

$$F = \frac{\cos\psi_o + \cos\psi_1}{2}$$

which accounts for the finite length of the segment.

B2 It is clear that as the segment shortens, such that $\cos\psi_0 \rightarrow -\cos\psi_1$, then $F \rightarrow 0$. It is equally clear that the function F has pronounced directional characteristics, ie it varies with angular position around the segment. To illustrate these characteristics, it is convenient to describe the position of the field point P by polar coordinates r,φ with an origin at the mid point of the segment (see fig B1).

B3 The variation of $F(r,\varphi)$ with φ, at constant r, may be described as the *directivity* of the sound radiation from the segment. This obviously depends upon the length of the segment which determines the values of ψ_0 and ψ_1. A representative directivity pattern can be determined for the special case when r >> b (where b is the half length of the segment); ie at large distances from the segment. In this situation, the angle θ subtended by the segment at P becomes so small that $\sin\theta \approx \theta$ and $\cos\theta \approx 1$. Similar small angle approximations apply also to the angles θ_0 and θ_1 subtended at P by the two half-segments.

Thus $$\cos\psi_0 = \cos(\varphi - \theta_0) \approx \cos\varphi + \theta_0 \sin\varphi$$

and $$\cos\psi_1 = -\cos(\varphi + \theta_1) \approx -\cos\varphi + \theta_1 \sin\varphi$$

so that $$F = \frac{\cos\psi_0 + \cos\psi_1}{2} \approx \frac{1}{2}(\theta_0 + \theta_1)\sin\varphi = \frac{1}{2}\theta\sin\varphi$$

B4 Therefore, since $\theta_0 \approx \sin\theta_0 = \frac{b}{s_0}\sin\varphi$, $\theta_1 \approx \sin\theta_1 = \frac{b}{s_1}\sin\varphi$ and (as $b \rightarrow 0$) $s_0 \rightarrow s_1 \rightarrow r$,

$$\theta = \theta_0 + \theta_1 \approx \frac{2b}{r}$$

and $$F \approx \frac{b}{r}\sin^2\varphi \qquad \text{... (B1)}$$

ie, F has the figure-of-eight directional characteristics of an acoustic dipole as illustrated in Fig 10 of the text.

B5 However, the fore-aft symmetry of the $\sin^2\varphi$ pattern does not reflect the pronounced rearwards bias of the sound radiation from typical jet aircraft in flight (text Fig 8). This is simulated in the model by a simple coordinate transformation (text Fig 9) which 'skews' the figure-of-eight lobes towards the rear. Instead of calculating F from the coordinates r,φ of the actual field point P, a transformed value F' corresponding to the displaced field position P' at r',φ' is substituted; ie

$$F'(r,\varphi) = F(r',\varphi') \qquad \text{... (B2)}$$

As shown in Fig B2, the position P' is displaced forward by an amount which is a function of the 'directivity angle', δ. (The lateral distance y from the segment remains unchanged.)

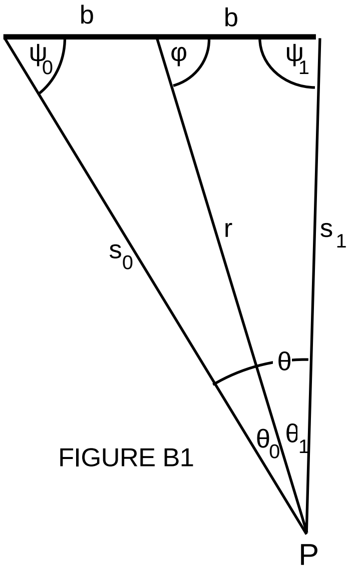


FIGURE B1

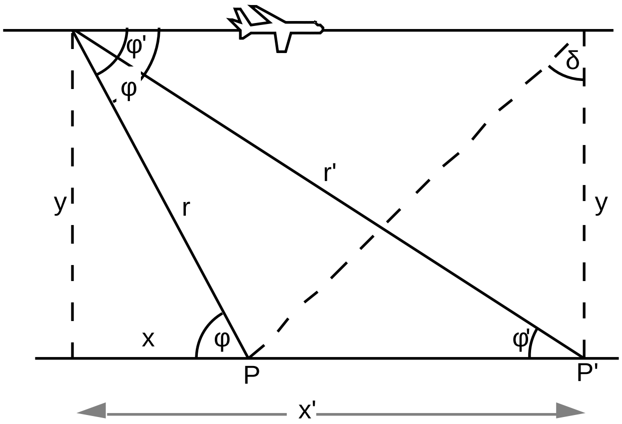


FIGURE B2

B6 From Equations B1 and B2

$$F'(r,\varphi) = \frac{b}{r'}\sin^2\varphi' = \frac{b}{r}\sin^2\varphi \,.\, \frac{r}{r'}\left(\frac{\sin\varphi'}{\sin\varphi}\right)^2$$

Since, from Fig B2, $\dfrac{\sin\varphi'}{\sin\varphi} = \dfrac{y.r}{r'.y} = \dfrac{r}{r'}$

$$F'(r,\varphi) = F(r,\varphi).\left(\frac{r}{r'}\right)^3$$

$$= F(r,\varphi).\left\{\frac{y^2 + x^2}{y^2 + x'^2}\right\}^{3/2}$$

$$= F(r,\varphi).\left\{\frac{(y/x)^2 + 1}{(y/x)^2 + (x'/x)^2}\right\}^{3/2}$$

or, since x' = x + y tan δ,

$$F'(r,\varphi) = F(r,\varphi).\left\{\frac{\tan^2\varphi + 1}{\tan^2\varphi + (1+\tan\varphi.\tan\delta)^2}\right\}^{3/2} \qquad \text{... (B3)}$$

This modified function, termed a 'skewed' noise fraction, is compared with the symmetrical one in the text Figure 10 using a directivity angle δ = 45°.

APPENDIX C

ANCON: CURRENT AIRCRAFT CATEGORIES

1	Boeing 707/DC8
2	Boeing 727
3	Boeing 737-200
4	Boeing 737-300/400/500
5	Boeing 747-100/200/300
6	Boeing 747-400
7	Boeing 757
8	Boeing 767
9	BAC 1-11/Tu-134
10	BAe 146
11	Concorde
12	DC9
13	DC10
14	Airbus A300
15	Airbus A310
16	Airbus A320
17	Fokker F28
18	Fokker F100
19	VC10/Ilyushin IL-62
20	Lockheed Tristar
21	MD-80
22	Tupolev Tu-154
23	Large 4-Engined Turboprop
24	Executive Jet
25	Large Twin Turboprop
26	Small Twin Turboprop
27	Large Twin Piston
28	Small Twin Piston
29	Single Piston

Types not on this list, because they are operated in relatively small numbers, are normally included in what is judged to be the most representative category.