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COMMUNITY NOISE EXPOSURE RESULTING FROM AIRCRAFT OPERATIONS: TECHNICAL REVIEW

BOLT BERANEK AND NEWMAN, INCORPORATED

PREPARED FOR
AEROSPACE MEDICAL RESEARCH LABORATORY

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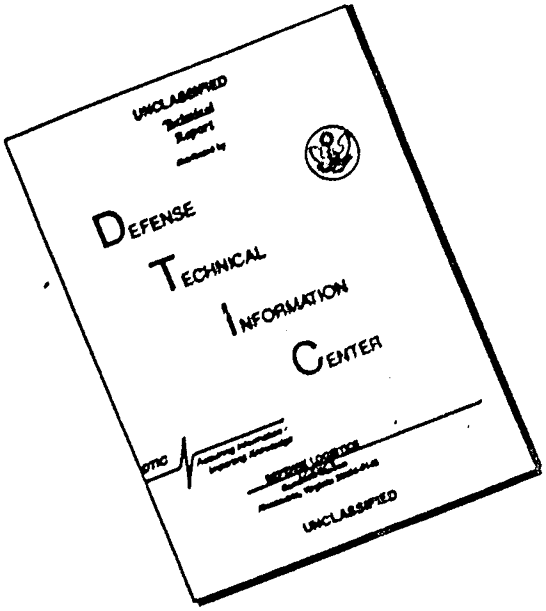

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This report is one of a series describing the research program undertaken by the Aerospace Medical Research Laboratory to develop procedures for predicting the community noise exposure resulting from aircraft operations. It reviews current methods for predicting noise exposure around an airport, the results of various social surveys around airports, and psychoacoustic studies of aircraft noise signals, as well as effects of aircraft

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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20. performance, flight path dispersion, non-standard weather effects, and other factors affecting the accuracy and variability in predicting aircraft noise exposure on the ground. These reviews and analyses are used to recommend a revised procedure for predicting noise around air bases.

The procedure recommends that noise from individual aircraft be described in terms of tone corrected, A-weighted, sound exposure level, SELT, and the cumulative effect of a series of aircraft noise events be described in terms of a modified Day Night Average Level, DNL. This quantity is the annual average A-weighted equivalent level for a twenty-four hour day, with a 10 decibel penalty applied to nighttime sound levels. The modification to DNL results from the incorporation of the effects of aircraft operations on the ground as well as in flight, where ground operations are penalized by 10 decibels. Alternate formulation of the procedure in terms of Effective Perceived Noise Level and Noise Exposure Forecasts is also provided.

Appendices provide recommended criteria for acceptable noise exposures as a function of land use, a description of the mathematical model for the procedure, and factors to be considered in performing noise monitoring to validate predictions.

Although the recommended predictive procedure is the best available and can be effectively applied for planning purposes, several areas are identified where additional research is needed to verify assumptions made when quantitative data are scant or nonexistent or simplifications made for practical or administrative reasons. Such factors can significantly influence the predicted noise exposure, estimated response interpretation, or subsequent management decisions.

PREFACE

The author wishes to acknowledge the assistance of Dwight E. Bishop for general discussions, review, and comment during the preparation of this report and for his specific contributions to the analysis of the acoustical effects of nonstandard weather and flight path dispersion, and for the preparation of Appendix D. The assistance of Karl S. Pearsons in preparation of the review of psychoacoustic literature is also acknowledged.

Detailed discussion of content, critical review, and suggestions by Jerry D. Speakman and John N. Cole of the Biodynamics and Bionics Division, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, have been of great assistance throughout the period of the study.

The engineering description of the computer implementation of the recommended noise calculation procedure described in Appendix C was prepared by Nicolaas Reddingius.

This report is one of a series describing the contractual and in-house research program under Project/Task 723104, Measurement of Noise and Vibration Environments of Air Force Operations, undertaken by the Aerospace Medical Research Laboratory to develop a procedure for predicting the community noise exposure resulting from aircraft operations. The companion reports are listed as References 78, 79, 80, 81, and 82. The Air Force Weapons Laboratory provided funding to partially support development of this program.

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SECTION I

INTRODUCTION

Noise produced on the ground by aircraft operations on and in the vicinity of air bases and the way in which this noise affects land use has been an important concern of the Air Force for many years. The first published procedure specifically directed towards aircraft noise and land use planning was issued by the Air Force, after a pioneering research program, in 1957[1/]. As a result of research performed subsequent to this publication, a revised procedure was published in 1964[2/]. This procedure, using the Composite Noise Rating (CNR) concept and the Perceived Noise Level (PNL) measure for aircraft noise was derived for both military and civil aircraft operations, being jointly published as a tri-service document and as an FAA report. It has been widely used in evaluating the impact of aircraft noise on residential land use in many military and civil airport planning studies.

During the middle 1960's, the evolving knowledge of subjective reaction to aircraft noise introduced the concept of Effective Perceived Noise Level (EPNL) as the measure for the noise produced by a specific aircraft noise signal. In 1967 the FAA developed a revised aircraft noise-land use planning procedure, termed the Noise Exposure Forecast (NEF) for potential use in civil aviation[3/]. The NEF procedure is a direct adaptation of CNR, using EPNL instead of PNL as the measure of aircraft noise. An almost identical procedure to NEF, Weighted Equivalent Continuous Perceived Noise Level (WECPNL), has been adopted by the International Civil Aviation Organization (ICAO)[6/].

During the past decade the evaluation of aircraft noise and its effect on land use has become an international problem.

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As a result many countries have developed their own methods, rating scales, and techniques for assessing the effects of aircraft noise. Research has also continued at the laboratory level on psychoacoustic evaluation of complex noise such as that produced by modern aircraft, sociological investigations into the response of people exposed to aircraft noise have been continued, and land use planners have become directly involved in the studies.

In 1973 the Environmental Protection Agency (EPA), in response to a requirement of the Noise Control Act of 1972, published its study of aircraft/airport noise[84/]. This study reviewed not only the aircraft/airport noise measures and planning procedures, but also considered the eventual combination of noise exposures from aircraft with that from other sources. The extensive use of EPNL and NEF as measures for aircraft noise notwithstanding, the EPA had more compelling reasons to recommend the use of A-weighted sound level to describe the noise from individual events, and proposed the day-night equivalent sound level (symbolized as L_{dn} or DNL) as the measure of cumulative exposure. Day-night sound level is a twenty-four hour logarithmically averaged cumulative noise exposure with a penalty for nighttime noise levels.

The USAF is now considering the revision of its present aircraft noise-land use planning procedures to reflect the current state-of-the-art as developed by recent research efforts. A critical review is required of the existing procedures and how they might be influenced by the newer research results. This report provides such a review, and concludes with a recommended procedure for future USAF use in land use planning as it is affected by noise from aircraft operations.

In performing this critique, two basically separate aspects are considered. The first relates to the conceptual and philosophical attributes of different aircraft noise measures, ratings, standards, and criteria. Various systems in use in the world are compared. The results of contemporary psychological and sociological research efforts are then reviewed to assess how their results affect the validity of present and proposed planning procedures. A review of current land use criteria for aircraft noise exposure areas is also provided.

The second aspect of this review considers the technological problems of physical acoustics, aircraft performance, and operational considerations which influence the prediction of aircraft noise exposure irrespective of the rating method or land use criteria employed in planning procedures. Particular emphasis is placed on identifying omissions, deficiences, and inaccuracies in present procedures.

Throughout the review, material conclusions are presented on each element entering into the development of aircraft noise-land use procedures. In the final part of this report these elements are summarized as a recommended procedure for military application. This procedure is equally valid for civil aviation planning purposes.

At the present time there is no national policy specified for land use planning with respect to aircraft noise, nothwithstanding the unified military service procedure[2/]. The USAF is conducting this study in accordance with the continuing requirements of the Environmental Policy Act of 1969 (Public Law No. 91-190) and Executive Order No. 11514 which directs all Federal agencies to "Monitor, evaluate, and control on a continuing basis their agencies' activities so as to protect and enhance the quality of the environment." In accordance with these rulings it is recognized that adoption of the planning procedure developed in this program is subject to review and approval of the Environmental Protection Agency (EPA) and the Council on Environmental Quality. The procedures recommended are consistent with those of EPA in its study of aircraft/airport noise 83/.

SECTION II

NOISE RATING PROCEDURES AND THEIR VALIDITY

In the past decade or so at least one dozen rating measures have been developed for relating the noise produced by aircraft operations to the response of communities in the vicinity of airports. All measures have two things in common:

a) a description of the physical noise exposure produced by a complex of aircraft noises, including weighting factors for the physical variables that are considered to influence response;

b) criteria for estimating the response or degree of acceptability associated with various numerical values of weighted noise exposure.

The evolution of the most significant of these measures and an intercomparison of their resultant criteria has been traced in a recent FAA report[4/]. In this present report we are primarily concerned with the validity of the concepts involved in these measures. As such, in the following discussion we shall be mostly concerned with the differences in methodology employed rather than the historical development of any one of the measures.

All procedures for computing noise exposure include the following elements:

a) noise level of separate events;
b) distribution of noise over the audible frequency spectrum;
c) the number of noise events in some specified time period;
d) normalizing constants.

Many of the noise indices also provide means to account for the effect of variation in the time patterns for individual events, the number of events occurring within different time periods of the 24-hour day, and for seasonal effects. All, of course, have in common the practical problems of correlating noise data with aircraft performance, sound propagation effects, and evaluating the operational factors involved in real aircraft operations. These practical problems will be discussed later in this report. For now, we are concerned only with the conceptual aspects of noise exposure rating methods. In the following parts of this section of this report we examine only the acoustical factors and how they are related in various noise rating measures.

A. Factors Included in Aircraft Noise Rating Measures

1. Description of the Sound Produced by a Single Aircraft Flyover

All methods for measuring the sound produced by a single event must consider the magnitude of sound and how it is distributed in frequency and time. All measures presently used for aircraft noise evaluate sound magnitude and its frequency distribution explicitly. The variation of sound level with time, on the other hand, is considered explicitly in some aircraft noise rating methods, in others only the maximum magnitude of the sound produced during an event is used. The methods for accounting for these attributes of a sound signal are discussed here.

The primary factor in any noise rating procedure is the method used to specify the magnitude of the noise produced by an aircraft event. The choice of measure for this quantity has been the subject of controversy since it is desirable to have a measure that not only describes physical magnitude, but, for simplicity in analysis, also provides a single number descriptor that accounts for the frequency distribution of sound energy over the audible spectrum. In particular, it is desirable to have a frequency weighting that scales directly to subjective response, accounting for the variation in response of the human hearing system with frequency. The alternate to this, of course, is to provide a spectral analysis of each event, requiring 8, 24, or more separate sound pressure levels (SPL) to span the audible spectrum.

All existing rating methods use a frequency-weighted measure to describe the magnitude of sound. More than 50 such measures have been described in the technical literature. Fortunately, standards and recommended planning procedures for aircraft noise have restricted these measures to A-weighted sound level (or its time integral), PNL, and EPNL, the last being a variant on PNL. The argument for PNL is that it is a psychoacoustically derived measure that purports to allow sounds of widely differing spectral content to be compared by a single measure which directly scales to subjective response. It is computed by a summation process which considers the SPL in each octave or one-third octave band over most of the audible frequency range.

On the other hand, A-weighted sound level has the merit of being easily obtainable with a simple frequency weighting network that alters a measuring system to de-emphasize the lower frequency range. Its use is further supported by the fact that, for most transportation generated noises, it provides almost as good an experimental fit to subjective tests as the more complex measures. It is this "almost as good" feature that is the issue.

Aircraft noise signals have become considerably more complex in their frequency content than most other sources of noise. Where the early jet engine noise was a rather smoothly varying random noise having a predominantly low frequency characteristic, present engines often have pronounced high frequency energy content, and often have a substantial structure of high frequency discrete tones superposed on the random noise of the jet. These newer sounds generally occur in the frequency range above 1000 Hz, yet in this frequency regime A-weighted sound level diverges from PNL in accurately scaling human response. Nevertheless, because of its wide use for describing other noise sources, A-weighted sound level has strong support, and has been recommended for EPA use in a task group report by the EPA Aircraft/Airport Noise Report task force[68/].

While the initial controversy over PNL as compared to A-weighted sound level was waging internationally, two other factors in scaling response to noise were becoming of concern. Psychoacoustic phenomena exhibit the characteristic of being additive on an energy basis. As such, the duration of a noise event becomes as important as its magnitude. Since the noise produced by an aircraft flyover is a time varying signal, the effect of its duration was believed to be important. Subsequent laboratory experiments confirm this point.

Secondly, the pronounced tonal structure developed by newer engine designs indicated that even PNL did not properly assess the subjective reaction to these sounds; it tended to underestimate the response. Experiments in this country and in England led to correction procedures that added penalties for the presence of tones.

A result of the consideration of duration and tones led to the specification of the quantity called Effective Perceived Noise Level, EPNL, which is time-integrated, tone corrected, PNL. We discuss the validity of these measures in Section III of this report; we are now concerned only with the attributes of noise signals that have been considered in noise rating methods.

Each of the noise measures has been employed in one or more of the aircraft noise rating methods in current use. In any one of the noise ratings the choice of a single event noise measure is in part historical, in part a question of the intended use of the rating method, and in part the degree of complexity one is willing to consider in its use. Clearly, if monitoring the noise exposure is of primary concern, A-weighted sound level is easiest to use, time integrated A-weighted sound level is next in complexity, and PNL or EPNL the most complex. On the other hand, for land use planning purposes, since the description of an aircraft as a noise source can be provided in any of the measures, no one is preferable over the next from a computational point of view.

A concern completely separate from land use planning is the accurate evaluation of the noise from an individual aircraft for engineering design purposes and for noise certification purposes. EPNL has been specified as the noise measure in both USA and international certification documents[5,6] since it is considered to be the currently available measure that most accurately scales the subjective response to aircraft noise. Similarly one can argue that the best available noise measure should also be used for land use planning purposes. It is for this reason that EPNL is also specified in both the International Civil Aviation Organization and International

Standard Organization documents on aircraft noise and land use planning[7,8]. In the event that a measure other than EPNL is chosen for use in land use planning, through new national or international agreement, conversion of EPNL values to the new measure is readily accomplished if the original data used to compute EPNL are available.

One argument against the exclusive use of A-weighted sound level is the concern that knowledge of the spectral and temporal content of a noise signal will be lost if only a sound level meter is used for noise measurement. In order to make good engineering projections of noise measurements obtained at one distance to other distances, spectral distributions of noise level are essential. Corrections for tone penalties also require spectral data. A compromise can be reached between the desire for detailed knowledge of a noise signal on one hand and the desire for a uniform measure, A-weighted sound level, on the other hand, by acquiring the noise data in full spectral and temporal detail, then expressing the final answer in terms of A-weighted sound levels.

The measure that most nearly combines the desirable features of EPNL, but expresses the final result in A-weighted form, is the single event A-weighted sound exposure level. This quantity can be obtained from one-third octave sound pressure levels by applying the A frequency weighting instead of the PNL weighting. Tone correction and time integration procedures can be applied identically as in the EPNL computation. The resulting quantity is the logarithmically weighted, time integral of A-weighted sound level, corrected for tones, over the duration of the noise event, normalized to a reference duration of one second. The symbol for this quantity, without tone corrections, has been variously labeled as SEL, L_{ex}, and in very similar form, SENEL, with its unit being the decibel. (Recent international standardization efforts are proposing L_{AX} or AXL for the symbol.) The comparable symbol for this quantity with tone corrections is SELT.

> Recommendation No. 1 - The USAF land use planning procedure for aircraft noise should use the tone corrected, A-weighted sound exposure level, SELT, for describing the noise from an individual aircraft noise event.

2. Effect of Number of Events

The preponderance of case histories and social surveys indicates that the response of a community to aircraft noise is affected not only by how loud the noise is, but also how often noise events occur, e.g., the total noise exposure in a specified time period. This is consistent with the laboratory results of psychoacoustics experiments that show that magnitude of sound and its duration are exchanged on an energy summation basis. On the assumption that community response is related to the total noise energy in a specified time period, a rating scale would sum events of equal magnitude on the bases of 10 $\log_{10}$ N where N is the number of events. Most rating scales use this assumption. The question remains, however, as to whether this is a valid assumption, and, if so, why some rating methods use a different summation rule.

The three deviations from the simple energy summation are contained in the UK, German, and Dutch ratings. The first to obtain prominence was in the UK Noise and Number Index (NNI) where number of events is summed as 15 $\log_{10}$ N. This factor was proposed as a result of analyses of a social survey conducted around Heathrow airport in 1961[9/]. As has been shown by Galloway and Von Gierke[10/], however, the survey results could be fitted equally as accurately to the 10 $\log_{10}$ N summation.

In the German Stör index, $\overline{Q}$, a 13.3 $\log_{10}$ N summation is used. The justification for this choice is somewhat obscure, but appears to have been chosen on the basis of certain psychoacoustic tests[11/]. The choice of 20 $\log_{10}$ N in the Dutch rating method is reported to have been selected on the basis of a social survey around Schiphol airport[12/].

Considerably more light on the choice of multiplier for number of events has been shed in the recently published analyses of a second social survey around Heathrow conducted in 1967[13/]. In these analyses a number of correlations between response and noise exposure were made with a forced variation in K from 2 to 22 in the expression K $\log_{10}$ N for four different combinations of noise exposure. It was found that the degree of correlation was, in general, quite insensitive to the value of K, although some form of K log N is useful for assessing annoyance in the community. In summary, psychoacoustic experiments indicate that magnitude, duration and number of events should be combined on an energy basis. Sociological results indicate that energy summation is equally good for assessing community annoyance, although the results are somewhat insensitive to the actual form of the assessment of number of events, just as long as some measure is used. It seems reasonable, therefore, to retain the energy summation approach in assessing community annoyance. Again the international documents support this position.

Recommendation No. 2 - Number of events be accounted for by 10 $\log_{10} N$.

3. Period of Day

In several of the noise rating methods nighttime operations are penalized in terms of their effect on the rating scale as compared to daytime operations. These penalties are arbitrarily assigned on the basis of results from complaint studies and social survey data that indicate a higher sensitivity to nighttime noise. Solid data to support the actual choice of numbers for this effect are hard to come by. The higher nighttime sensitivity value of 10 dB in equivalent exposure used in the CNR and civil NEF methods is based on overt community response evaluations. It was estimated in the 1961 London survey that a reduction of 17 NNI exposure units was required to reach the same acceptability for night operations as was obtained for day operations. (For a fixed noise level this is equivalent to 11 units in CNR or NEF.)

The existing rating methods that do make adjustments for day/night have substantially different computational approaches. Both CNR and NEF assess nighttime exposure, on an energy basis, to be 10 dB more sensitive than daytime. The French system has a complex weighting applied to a three period day in which daytime (0600-2200), early nighttime (2200-0200), and late nighttime (0200-0600) are weighted according to the expression: $10 \log_{10} N_D + 6 \log_{10} \left[(3N_1 + N_2) - 1\right]$ where N_D, N_1 and N_2 are the number of operations in the three time periods. The ICAO index, WECPNL, allows for either two or three period days. Using the two period day, 0700-2200 and 2200-0700, the nighttime noise levels are weighted by an additional 10 dB. The

CNEL measure proposed for rating airport noise exposure in California uses the ICAO specification for three periods in the day, 0700-1900, 1900-2200, 2200-0700. Each of the evening and nighttime periods is weighted with successively 5 dB and 10 dB penalties on noise level, not noise exposure. The L_{dn} measure uses the same two period day and 10 dB penalty as is used in the WECPNL measure.

One way to examine the magnitude of the effect of these weighting factors is to consider the increase in weighted noise exposure they provide relative to a straight energy summation. In Table I we show this result for two cases. The first assumes a uniform distribution of flights of equal noise level spread over a 24-hour cycle. The second assumes that 80% of the flights occur between 0700 and 2200, and 20% between 2200 and 0700. (This distribution is slightly higher than generally encountered at most large commercial airports, where 8 to 18 percent night operations is typical.)

TABLE I

Relative Effect of Night Corrections -
dB re 10 log N

	Uniform 24 hr.	80% day/20% night
NEF	+ 8.4	+ 6.2
$\mathcal{N}$ - (France)	+16.1	+ 3.8
L_{dn}, WECPNL	+ 6.4	+ 4.5
CNEL	+ 6.8	+ 5.0

These differences for the same situation reflect the uncertainty associated with this factor, largely due to whether it is the noise level itself or the noise exposure which receives the weight. For most practical cases, where night operations are typically less than 20% of day operations, the numerical differences in the effects of one method as compared to another are small.

Little help in resolving the uncertainty is available from two major social surveys conducted in the last five years--that by Tracor, Inc.[14/], under NASA sponsorship, in which seven cities were surveyed, and the second London survey already mentioned. In a preliminary report of the Tracor work, Hazard[54/] indicated that average annoyance scores were more than doubled if aircraft were heard between midnight and 6 a.m. Nothing whatsoever is said in the Tracor final report on this subject. On the other hand, a substantial effort was made in the London survey to examine this problem. A separate annoyance scale for nighttime operations was even constructed for use in studying night as compared to day operations. No clear results were obtained, however. This is not surprising since the nighttime noise exposure is substantially curtailed at London by limits on both number of flights and use of noisier aircraft.

The effect of this curtailment and its effect on nighttime noise exposure can be estimated from the London survey data as provided in Ref. 13. One can compare both noise level distributions and number of events, as experienced at the survey subjects' homes, for both day and night operations. These data, in a cumulative distribution form, are plotted on Fig. 1. While the differences in noise level between day and

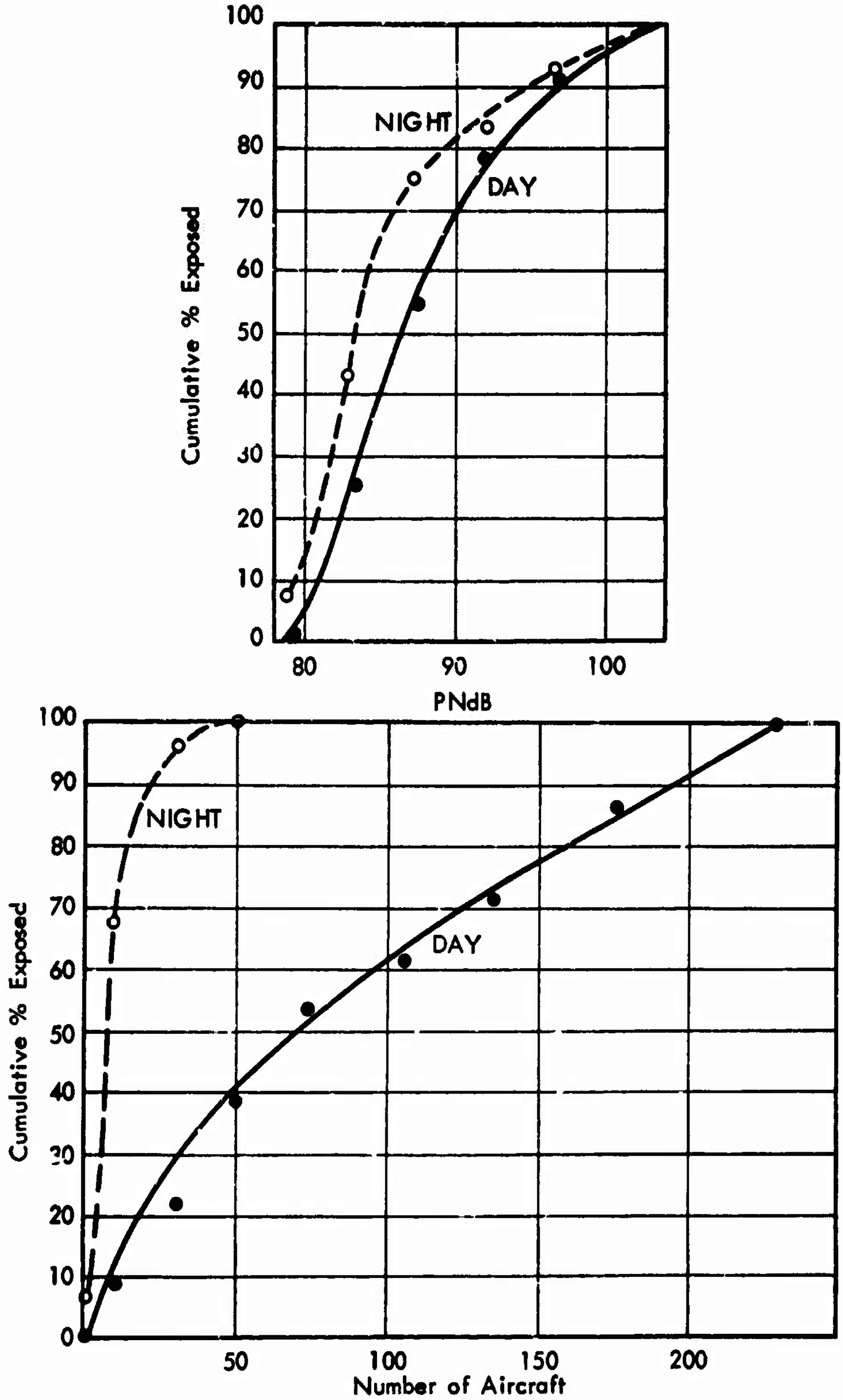


FIGURE 1. DAY AND NIGHT NOISE LEVELS AND NUMBER OF AIRCRAFT PRODUCING MORE THAN 80 PNdB OBSERVED IN 1967 LONDON SURVEY

night are not substantial, the difference in number of events in excess of 80 PNdB is striking. Making the crude assumption that a relative difference between day and night can be made by comparing the daytime and nighttime values of CNR or NNI computed from the medians of the distribution, one can show that the nighttime exposure is 13 dB less than the daytime on a CNR scale (not using night penalties), and 18 dB less on the NNI scale. A comparable difference is obtained at the upper 25% point of the distributions, even though the noise exposure increases by 15 dB in the case of both day and night. Using the CNR estimate that night exposure should be penalized by 10 dB, one would clearly estimate that the day operations in this study still subjectively outrank the night operations substantially. This point is substantiated by numerous qualitative results in the survey analysis.

Clearly, the adjustment of noise exposure to account for differences in day and night operations is not on a firm quantitative basis. There is little doubt, however, that the phenomenon exists. Criticisms can be directed to the size of the penalty, the time periods chosen and the "quantum" jumps taken as the clock passes the hour. On the other hand, the two-period day seems reasonable for the typical living habits in this country (and in England, for that matter, as shown in Ref. 13), and there is no strong evidence to contradict the 10 dB penalty on night exposure. While the three period day approach may be more esthetically satisfying, little data exist to justify the additional complexity of its use in land use planning. Furthermore, for any rational distribution of events and noise levels, the two period day and the three period day with its additional penalty for the evening period noise levels yield numerical values for average noise levels that are no more than 0.5 decibels apart.

There are little data to justify applying the 10 dB penalty on exposure (e.g., weighting levels so that the two time periods have an exposure difference of 10 dB) as compared to applying the penalty directly to the nighttime levels alone. The latter method is simpler to implement in monitoring systems, and the numerical results are little different from weighting exposure instead of level.

> Recommendation No. 3 - Nighttime noise exposure should be assessed a penalty by adding a 10 dB increment to nighttime noise levels when combining day and night exposures to obtain a 24 hour value.

The combination of Recommendations No. 1, 2, and 3 are the essential ingredients for the use of L_{dn} as the measure for cumulative noise exposure. These recommendations differ from the EPA formulation only in the recommendation that tone corrections be incorporated in the description of individual noise signals.

4. Time of Year

Adjustment of noise rating indices to include an allowance for seasonal variations has been considered for many years. This adjustment stems from the argument that during hot weather people in areas without airconditioning will leave windows open, reducing the noise reduction provided by a building with windows closed. Conversely, in winter with all windows closed, the noise reduction of a building will be greater than the average throughout the year.

A second consideration is that during hot weather the performance of jet aircraft is lower than for standard conditions, and during cold weather is better than under standard conditions. The argument is that the hot weather performance increases noise exposure, while cold weather decreases noise exposure.

There is little question, for those localities where hot summer weather causes an open window condition not normal to the area, or increased use of outdoor areas, that complaints from aircraft noise increase. On the other hand, in more temperate climates, little difference in response is indicated on a seasonal basis. Unfortunately little substantive data are available to quantify the situation.

The argument that aircraft takeoff performance, and thus noise exposure, is affected by temperature is equally valid. For most operations, however, at airports near sea level, the variability in takeoff noise exposure as a result of different takeoff weights and pilot techniques is far more significant than the changes due to temperature effects on aircraft performance for most jet aircraft. (Propeller aircraft are often more subject to degraded performance with increased temperature.) Such performance effects can be included in the basic noise exposure computation as discussed later.

A further factor involved in "time-of year" is that related to runway utilization. For many airports the prevailing wind direction is seasonal in nature. The difference in noise exposure due to this element is generally accounted for by examining airport operations on an annual average basis.

Consideration of possible seasonal correction factors for noise exposure has been given in the ICAO Annex 16[6/]. In this document suggested weighting factors for noise exposure are based on a temperature exposure basis as follows:

"S = seasonal adjustment
= -5 dB for months in which there are normally less than 100 hours at or above 20°C (68°F)
= 0 dB for months in which there are normally more than 100 hours at or above 20°C (68°F) and less than 100 hours at or above 25.6° (78°F)
= +5 dB for months in which there are normally more than 100 hours at or above 25.6°C (78°F)."

Unfortunately, universal application of such correction factors does not seem practicable. Variation in building construction, inside-outside use of property, use or lack of airconditioning, and similar factors do not lead to a generalizable rule for seasonal corrections. In special cases where these factors can be assessed accurately in an airport community, and community response can be evaluated, the seasonal adjustments to noise rating procedures may be appropriate.

Recommendation No. 4 - Adjustments for seasonal factors should be included in the generalized noise rating procedure; where clear justification for their use is evident at a particular air base, the ICAO adjustments may be employed.

B. Summary of Aircraft Noise Rating Measures

Despite the international proliferation of aircraft noise rating measures, each combines the factors discussed above in a very similar fashion. The primary differences between the measures are related to the choice of sound level measure for individual events, the rule for addition of the effect of multiple events, and the choice of normalizing constants. In the next section of this report we examine the results of various studies of community response. Since many of these studies were correlated to the noise measure most popular in the country of the study, it is useful to show that the individual ratings are highly intercorrelated, and thus the social surveys can be correlated on the basis of any of the rating measures.

We first identify the most prominent existing noise rating measures in terms of the elements they consider and their combinatorial rules used for calculation. A summary of the various elements and how they are considered in a number of rating indices is provided in Table II. The great similarity in all their formats can be illustrated by comparing their equations for the summation of a number of identical daytime events. Assuming an effective duration of 10 seconds, a maximum PNL of 110 dB, and that A-weighted sound level is 13 dB less than PNL, plotting these equations as a function of the number of events, N, provides an illustration of their similarity. This is shown in Fig. 2, as plotted from the following equations:

TABLE II

Attributes of Various Noise Rating Measures

Origin	Rating	Sound Level	Tones	Duration	Number	Day/Night*
USA	NEF	EPNL	yes	yes	10 log N	2 period/+10 dB
ICAO	WECPNL	EPNL	yes	yes	10 log N	2 or 3 period/+5
USA	CNR	Max PNL	no	no	10 log N	2 period/+10 dB
France	$\mathcal{N}$	Max PNL	no	no	10 log N	3 period/variable
UK	NNI	Max PNL	no	no	15 log N	
Germany	$\overline{Q}$	A	no	yes	13.3 log N	
USA	L_{dn}	A	no	yes	10 log N	2 period/+10 dB
California	CNEL	A	no	yes	10 log N	3 period/+5&10 dB
South Africa	$\overline{NI}$	A	yes	yes	10 log N	
Netherlands	B	$\frac{4}{3}$ A max	no	no	20 log N	
ISO	L_E	EPNL	yes	yes	10 log N	

*Various penalties for night or evening sound levels are used in different rating methods. See Section II-A-3.

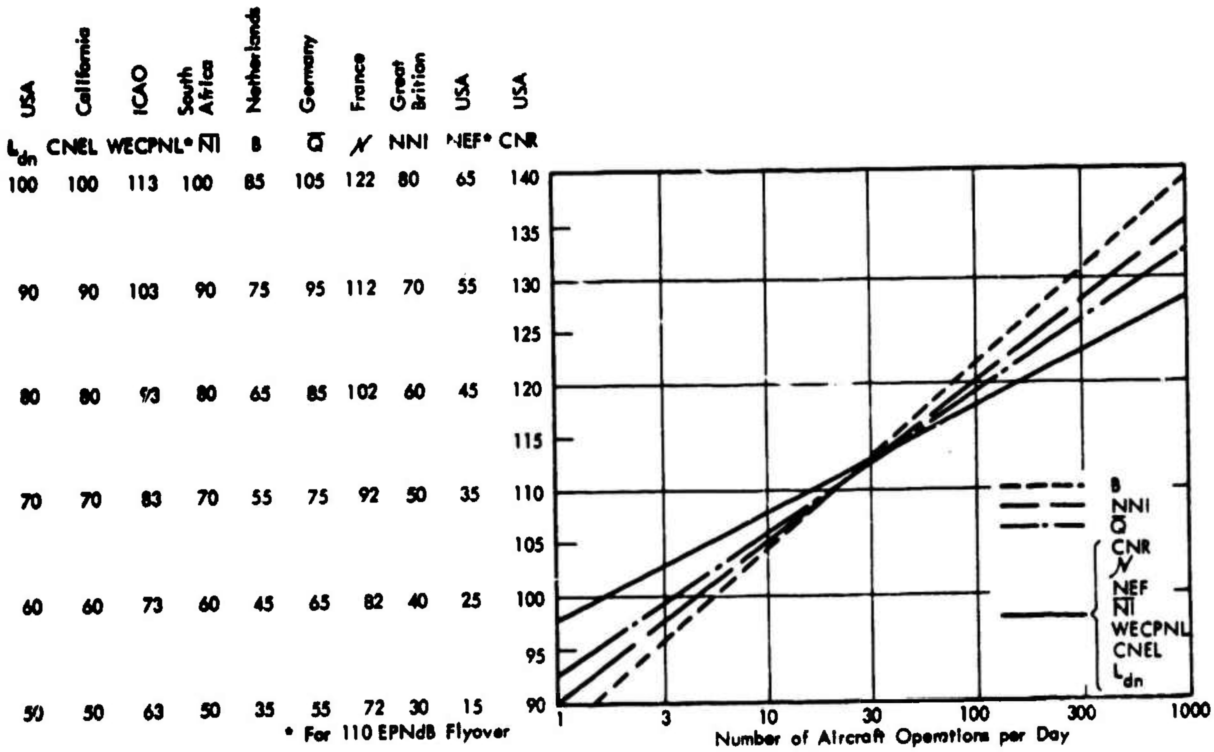


FIGURE 2. COMPARISON OF VARIOUS NOISE EXPOSURE INDICES FOR A FLYOVER NOISE LEVEL OF 110 PNdB, EFFECTIVE DURATION OF 10 SECONDS, AND VARIABLE NUMBER OF OPERATIONS

$$NEF = 10 \log_{10} 10^{\frac{L_{epn}}{10}} + 10 \log_{10} N - 88$$

$$WECPNL = 10 \log_{10} 10^{\frac{L_{epn}}{10}} + 10 \log_{10} N - 39.4$$

$$CNR = 10 \log_{10} 10^{\frac{L_{pn}}{10}} + 10 \log_{10} N - 12$$

$$\mathcal{N} = 10 \log_{10} 10^{\frac{L_{pn}}{10}} + 10 \log_{10} N - 30$$

$$NNI = 10 \log_{10} 10^{\frac{L_{pn}}{10}} + 15 \log_{10} N - 80$$

$$\overline{Q} = 13.3 \log_{10} 10^{\frac{L_{pn}}{13.3}} + 13.3 \log_{10} N - 52.3$$

$$\left.\begin{matrix} L_{dn} \\ CNEL \\ NI \end{matrix}\right\} = 10 \log_{10} 10^{\frac{L_{pn} - 13}{10}} + 10 \log_{10} N - 39.4$$

$$B = 20 \log_{10} 10^{\frac{L_{pn} - 13}{15}} + 20 \log_{10} N - 157$$

Where L_{PN} = Max PNL, L_{EPN} = EPNL, and $L_{pn} - 13$ = Max A-level.

All the indices are highly correlated, and many are conceptually identical for all practical purposes, differing only in minor detail.

C. Correlation of Noise Ratings with Community Annoyance

In Ref. 4 the various noise indices in use up to 1970 were reviewed as to their correlations with community response data gathered in a number of countries. A table of approximate equivalences between the various indices was derived as is shown in Fig. 2. Using these equivalences one could intercompare the results obtained from social surveys and other measures of response. The impressive result was that regardless of the way in which the noise rating indices were developed, when intercompared on the basis of physical noise exposure the criteria for acceptability for residential land use were very similar. A chart showing these relationships is shown in Fig. 3.

Since the preparation of Ref. 4 several studies of community response and annoyance have become available. Two of these studies were conducted under the Department of Housing and Urban Development (HUD) Metropolitan Aircraft Noise Abatement Policy (MANAP) studies in the vicinity of Chicago's O'Hare airport[15] and at Windsor Lock's Bradley airport[16]. A major investigation of noise and annoyance around seven airports was conducted under NASA sponsorship by Tracor, Inc.[14], and a second survey around London's Heathrow airport was reported[13]. It is not our intent to review the entire results of these studies. In the following discussion, pertinent findings which help assess the relationship between noise exposure rating methods and community response are summarized.

1. O'Hare Study

As part of its work under the MANAP program the Northeastern Illinois Planning commission made an analysis of

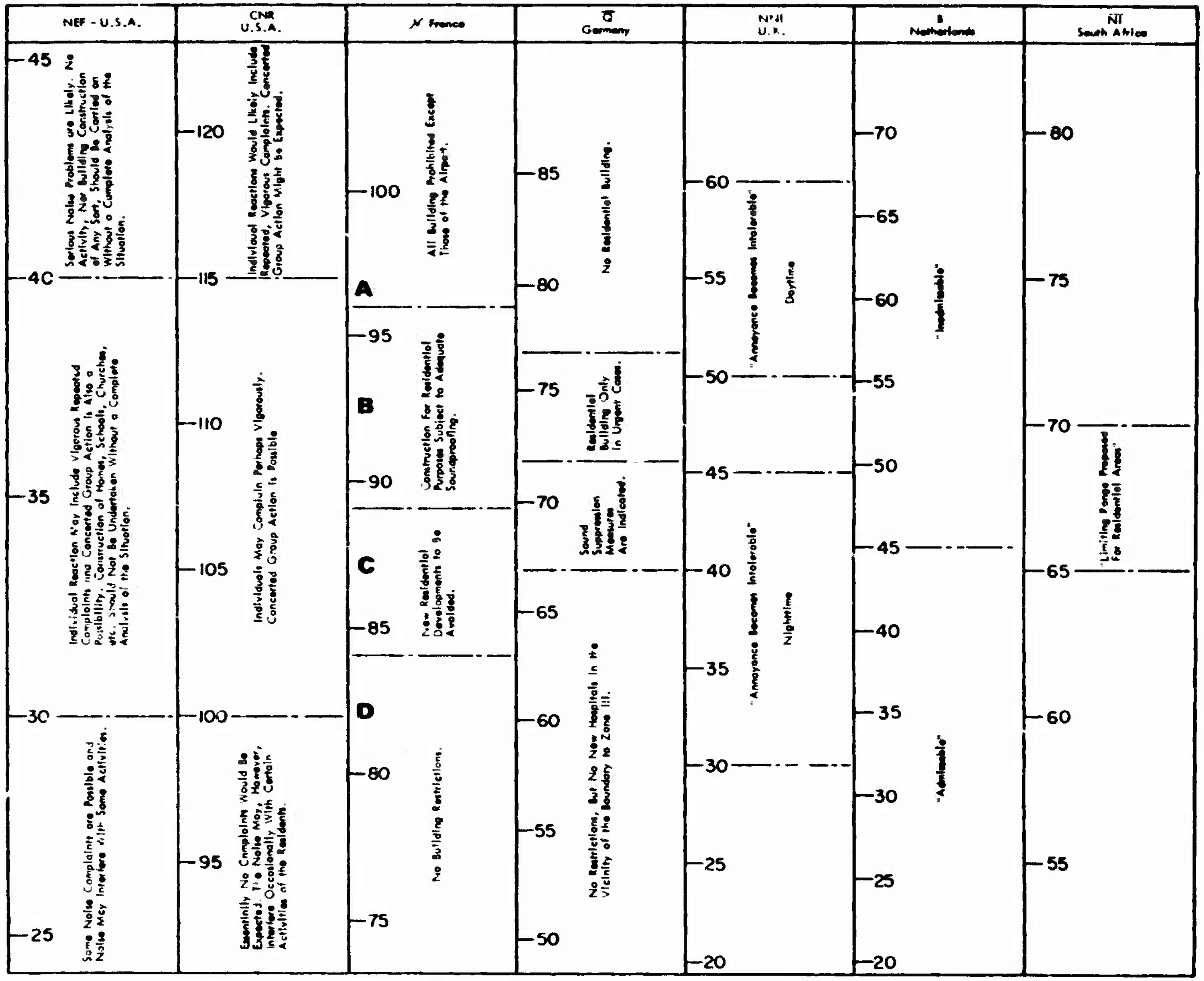


FIGURE 3. APPROXIMATE EQUIVALENCES BETWEEN NOISE EXPOSURE INDICES AND RESPONSE OR LAND USE DESCRIPTIONS

complaint records kept by FAA between 1965 and 1969 (a small fraction of the complaints received by local authorities) on noise from aircraft operations[15/]. This analysis was made in terms of the NEF contours derived for O'Hare's aircraft operations by FAA. Their conclusions are:

a) Complaints received from May to September were three to four times as high as those received during other months.

b) The critical area for complaints lies from one to four miles from the end of runways.

c) Complaints received from daytime operations were 50% higher than those from night. However, daytime operations were almost six times as many as nighttime operations.

d) The rate of complaints from inside the NEF 40 contour was five times the rate from the area between NEF 30 and NEF 40, although 40% of the total number of complaints originated in this latter region because of its much larger area.

e) The reactions were closely keyed to operations, being highly correlated with actual runway utilization.

f) About one-third (34.7%) of complaints originated outside the NEF 30 contour. These complaints, however, closely followed the flight path dispersions.

2. Bradley Study

Another study under the MANAP program conducted by the Capitol Region Planning Agency in the vicinity of Bradley International Airport is particularly revealing[16/]. As part of this program, a questionnaire survey was conducted to obtain 790 respondents' attitudes about aircraft noise. A sampling distribution was used to cover residents in NEF zones of 25 and higher, plus control areas which were outside the NEF 25 contours but still relatively close to the airport. The correlations were made to 1967 contours, which, due to unreliable operational data, were later found not to depict turning flight paths accurately, but were still believed satisfactory at the higher NEF values. Pertinent conclusions from this survey are:

a) The percentages of response indicating that aircraft noise was extremely disruptive, by class of operation, in different NEF zones were:

NEF	Military	Air Carrier	Gen. Avn.
40	75	30	10
35	50	18	2
30	28	10	3
25	18	11	3

Operations (approximately 160,000 in 1969) were 54% general aviation, 39% air Carrier (all jets, 90% turbofan), and 7% military (of which almost half were F102's).

b) For respondents living in areas having NEF values of 35 and higher, the response to a series of questions revealed:

Aircraft noise is:

not a nuisance	4%
minor--can be accommodated	36%
major--unpleasant to serious	50%
pressing disruption--unlivable	10%

Fear of an aircraft crash is not of concern to 71%.

While 17% have lodged complaints, 65% said noise was annoying often or constantly.

51% said noise stops conversation often or constantly, but only 29% said it disrupts sleep.

c) The percentage of responses indicating that aircraft noise was often or constantly annoying, by noise exposure zones, was:

NEF	40	35	30	25	Control
%	83	59	42	26	22

In their report, the Planning Agency conclude:

> "Although there appear to be inaccuracies in the NEF contours, the concept of NEF defining an area of equal noise exposure and the utilization of NEF to determine compatible land use is considered to be valid."

3. Tracor Study

An intensive, three-year study of noise exposure and annoyance due to aircraft noise was completed in 1971 by Tracor under NASA sponsorship[14/]. This program surveyed communities around the major airports in Boston, Chicago, Dallas, Denver, Los Angeles, Miami, and New York. A total of 8207 interviews were obtained, and noise exposure data at the interview areas was obtained from the analysis of more than 10,000 aircraft flyovers. Whereas the two studies mentioned above were concerned only with assessing certain conditions occurring within various NEF regions, the Tracor program was a general study to model annoyance.

Among the general conclusions from this program were:

a) CNR, NNI, and NEF are essentially interchangeable in predicting annoyance.

b) General estimation of annoyance from noise exposure alone provides correlation coefficients of the order of 0.4 to 0.5; the addition of attitudinal variables to the model predicts individual annoyance with a correlation coefficient of up to 0.8 These additional factors are also intercorrelated with noise exposure in most instances.

c) A significant reduction of annoyance requires a CNR of 93 or less; above 107 CNR, annoyance increases steadily; above 115 CNR, noise exposure is associated with increased complaint.

d) The number of highly annoyed households in a community can, within certain limits, be predicted from the number of complainants. Complainants are not more sensitive to noise than random respondents. Complainants tend to come from higher socio-economic status than non-complainants.

The results of this program are expressed in terms of a model for predicting individual annoyance when exposed to aircraft noise. To apply the model, however, it is necessary to conduct a social survey in the community of concern to ascertain the attitudinal characteristics necessary for use in the model. These characteristics include fear of aircraft crashes, susceptibility of noise, positive or negativeness about air transportation, degree of confidence that authorities are trying to solve noise problems. Unfortunately, exercising the model in a land use planning procedure is not feasible in most instances, since the cost of a social survey is generally prohibitive.

The mass of data obtained from this project permits many analyses to be made. Two pertinent relationships can be established which relate directly to the use of noise exposure predictive techniques as estimators of community response. One is related to the correlation of percent of people highly annoyed in a population exposed to differing degrees of noise exposure; the second correlates the percentage of highly annoyed in a population to the number of complainants. Borsky[56] has reviewed the Tracor data of Ref. 14 and presents population percentages annoyed as a function of noise level, fear, and misfeasance. On the basis of this analysis a working group of the Bioacoustics Panel of the Interagency Transportation Noise Abatement Program (ITNAP) derived various values of

CNR for which the percent of highly annoyed in a population can be identified as having a "typical" response and for those having a "positive attitude" response[57]. Using these data, one can compute the linear regressions of both responses to noise exposure. A third regression, which might be termed "nominal" response can be obtained by merging the two sets of responses into a single set. These regression equations take the following form:

	Regression	ρ	$S_{y/x}$
"Typical"	$\% \text{ HA} = 2.28 \text{ CNR} - 201.7$	0.996	1.92
"Positive"	$\% \text{ HA} = 1.71 \text{ CNR} - 150.5$	0.985	2.97
"Nominal"	$\% \text{ HA} = 1.99 \text{ CNR} - 176$	0.954	5.61

Using the "nominal" response as an example, a 10 dB change in noise exposure would result in a 20% change in percent of highly annoyed in a population. All three regressions would predict a "zero" annoyance at about 88 CNR or approximately 22 NEF. On the basis of these analyses a "Nominal Annoyance Response of Community Populations to Aircraft Noise" was proposed to the ITNAP Chairman as the basis for evaluating community response to changes in noise exposure in studies by ICAO[57].

A particular effort was made in the Tracor project to evaluate the relationships between annoyance and complaints. The original development of criteria zones for CNR was based on such overt actions as complaints and legal action; however, Borsky[17] had pointed out that complaints were not a good measure of overall community attitudes. (CNR zones were picked primarily on location and number of complainants, not the actual number of complaints.) The Tracor data allow an examination of the relationship between annoyance and complainants.

In Ref. 14, data are provided to indicate the number of complainants and the number of highly annoyed in random samples of the interview respondents in each of the seven survey cities. In this reference, a linear equation relates the number of complainants per thousand, c, to the number of highly annoyed per thousand, h':

$$h' = 195.5 + 2.07\,c.$$

An exponential relationship might be more appropriate, since a threshold value of 195 highly annoyed per thousand is specified before complainants emerge. Utilizing the data from Table 7.1 of Ref. 14, we have examined two different fits to the data, one in exponential form and the other quadratic.

For a generalized expression of the relationship of annoyance to complaints we have transformed the data of Ref. 14 into percentages of total population. Using a least squares fit to an exponential assumption yields:

$$\%H = 16.5(\%C)^{0.42}$$

Assuming a quadratic relationship yields:

$$\%H = 12.3(\%C)^{\frac{1}{2}} + 4.6.$$

In these equations %H is percent highly annoyed and %C is percent complainants. The correlation coefficient for the exponential form is 0.96 and for the quadratic is 0.98. We prefer to use the quadratic form because of its simplicity of use in computation and interpretation.

Subsequent to the publication of Ref. 14 a second study of two smaller cities was performed by Tracor[78/]. In this report the data from the first seven cities were combined with the additional two, and a revised regression equation derived, now using the quadratic format. In this case, a forced fit to zero complaints at zero annoyance resulted in the following expression for percent annoyed as a function of percent complainants:

$$\%H = 14.3 \sqrt{C}$$

We prefer the assumption we made previously that, with no complaint action at all, there will still be a residual annoyance. Using this approach to the nine city data marginally changes the expression we derived above to:

$$\%H = 12.3 \sqrt{C} + 4.3$$

The correlation coefficient changes only slightly, from 0.975 to 0.984, hardly significant, while the standard error improves slightly from 3.58 to 3.20.

This equation, with the data points from which it was derived, is shown in Fig. 4. Acknowledging the inherent risk in extrapolating these data beyond their experimental values, it is interesting to note that the equation would indicate that at zero complaints, 4.3% of the population would still

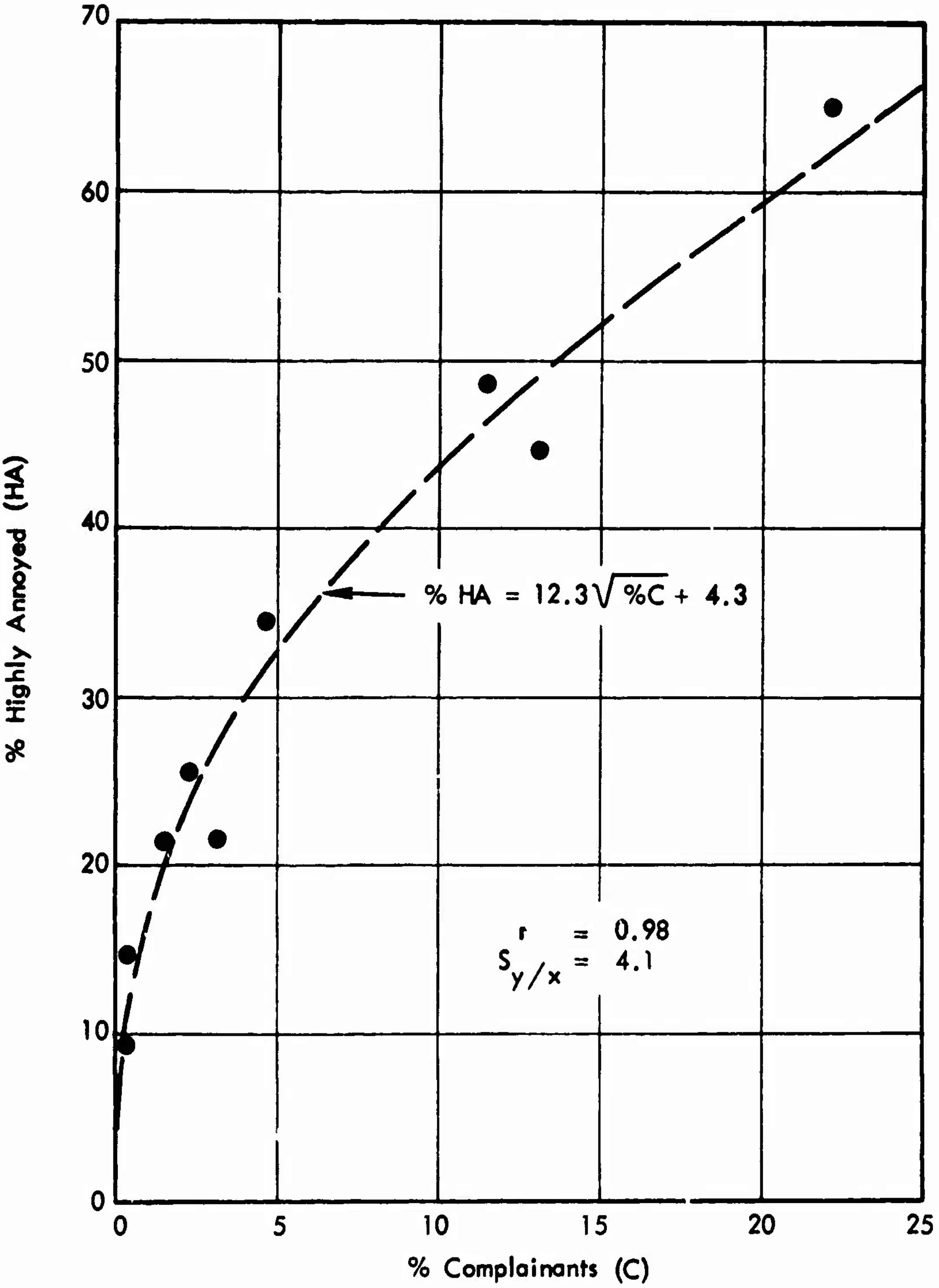


FIGURE 4. PERCENTAGE OF HIGHLY ANNOYED AS A FUNCTION OF PERCENT COMPLAINANTS-DATA FROM TRACOR TABLE 15

be highly annoyed. Also, with 100% of a population highly annoyed, only 61% would be expected to complain. Said another way, the percentage of highly annoyed in the population increases with the square root of the number of people who complain. Note that, as originally considered in the CNR development, it is the number of different individuals lodging complaints, not the number of complaints that count, since individuals who complain are often repeat complainants.

Using the two relationships derived above, one can estimate the percentage of highly annoyed for a specified noise exposure, and from this anticipate the number of individuals expected to lodge complaints. This is particularly useful in assessing the possible change in community response to be expected from operational changes at an airport such as the use of new runways, altered flight paths, introduction of new aircraft, and other factors which affect noise exposure.

4. London Study - 1967

One of the most extensive social surveys of response to aircraft noise was performed around London's Heathrow airport in 1961. This survey led directly to the NNI rating procedure now in use in England. The rapid increase in jet aircraft traffic after 1961 and the introduction of the turbofan engine have produced major changes in noise exposure around Heathrow. In order to assess the changes in both the noise exposure and the community response to these changes, a combined noise measurement program and social survey were made in 1967, although the results first became publicly available in 1971[13/].

The 1967 survey was more extensive than that of 1961.

The area of coverage extended to 15 miles from the airport in 1967, while the 1961 survey went out only 10 miles. A total of 4,699 adults were interviewed in the 1967 survey, 3,118 of them living in the area sampled in 1961. Noise measurements were made at 126 locations and included data on more than 28,000 aircraft movements.

We have already referred to the work related to differences between day and night operations previously, as well as the finding that the constant used in summing number of events was quite insensitive to change. Unfortunately, there is little quantitative direct reinforcement or denial of the use of other factors in relating noise exposure to response for purposes of land use planning. Several of the findings are useful in a qualitative sense.

Although noise levels themselves had not changed very much between 1961 and 1967, the number of operations had increased substantially. This led to a number of evaluations of the formula for NNI. It was finally concluded that the tradeoff between level and number expressed in the NNI formula was less dependent on number than had been thought. Variations of this relationship in which the summing of events as K log N were made with K varying from 2 to 22. A linear summation of 0.4N was also correlated. Since the correlations to annoyance were made in different sets of exposure data, with no correlation exceeding about 0.45, it is not surprising that this result was obtained. An example of sensitivity is given in Fig. 5, which is reproduced from Ref. 13.

It can also be seen from Fig. 5 that a number of operational conditions were examined. The mode descriptors refer

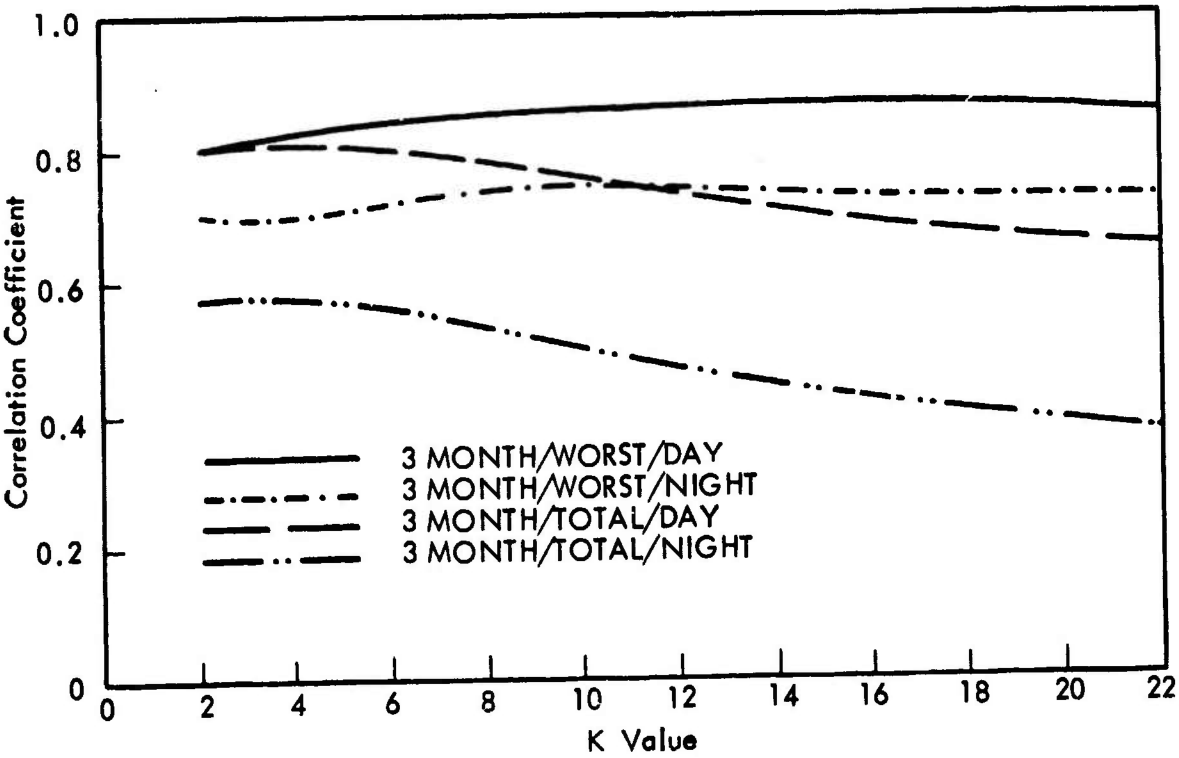


FIGURE 5. SENSITIVITY OF CORRELATION COEFFICIENT TO FORCED VALUE OF K IN EQUATION NNI = L + K LOG N-C

to the three basic traffic structures which are due to wind conditions. These modes are East to West - 79%, West to East - 19%, Northeast to Southwest - 2%. The designation "total mode" refers to the average noise exposure at a given survey location over all modes; "worst mode" relates to the highest exposure mode in each sampled area. It was concluded that the "3 month/ worst mode/day" exposure was most highly correlated with response. This implies that response is best correlated to an average over periods of time when the most active operations occur. This is similar to the "average busy day" concept in the present USAF procedure. As discussed previously, the night exposure is so substantially lower than the day exposure that it is not surprising that daytime should be the controlling condition.

Some of the conclusions arrived at in measuring annoyance are of specific interest here. They include:

a) Respondents' self ratings to one of the survey questions, a category scale of annoyance, were 0.77 correlated with the Guttman scale derived from the survey to express annoyance. The word descriptors used in assessing the numerical values of the derived annoyance scores are taken from this simple scale of self rating.

b) Middle class respondents tended to have higher annoyance scales than working class respondents.

c) In 1961 those claiming to feel afraid of aircraft crashes "very often" were 14% of the survey; in 1967 this had dropped to 9%.

d) Mean annoyance scores were almost identical in the two surveys. The point on the scale considered critical in terms of acceptability was the same in both surveys (between 3 and 4 on the annoyance scale which ranges from 0 to 5).

e) Assessments of acclimation to aircraft noise revealed that the majority of people acclimate at low noise levels, but this proportion drops markedly with increasing noise level. Further, at the higher noise levels those living in the area longest tend to be more highly annoyed.

f) An investigation of the ratio of landings to all other movements showed that inclusion of this factor as a separate element in the NNI formula was not justified.

g) Investigations of the separate effect of duration were inconclusive. Since duration was measured at the time the noise level exceeded 80 PNdB, regardless of its maximum level, the confusion in results is not surprising.

h) While not conclusive, there is some evidence that the higher the background level, the less people are annoyed by aircraft noise, e.g., signal level to background level is of some importance.

5. Generality of the Relationship Between Average Annoyance and Noise Exposure

In Section II-C-3 we showed how the results of the Tracor data could be used to derive an expression for the percent of a noise exposed population that would be highly annoyed as a function of the noise exposure. It is of interest to examine how well this relationship can be applied to the results of other surveys. Two such evaluations, conducted simultaneously in recent months, have been published.

In one study, a task group of the EPA Study of Aircraft/Airport noise reviewed the various U.S. and English survey results and showed that the relationship between percentages of population highly annoyed and noise exposure were essentially identical when compared on a common noise measure58/. In the second study Alexandré compared the results of the two English surveys, the Dutch survey, and two French surveys, one completed in 1972, to obtain a general relationship between annoyance and noise exposure for the aggregated results69/.

These two evaluations gave almost identical results and confirm the analysis of percent population highly annoyed described in Section II-C-3 within a few percent for a specified noise exposure.

It is reasonable to conclude that the relationship between percentage of an exposed population highly annoyed and the magnitude of noise exposure produced by aircraft in flight is well established.

D. Noise Criteria for Land Use Planning

In the previous sections we have examined the concepts of aircraft noise exposure and the efforts to correlate noise exposure with annoyance. Most of the work is principally related to residential living. Annoyance is seen to be a complex structure of personal attitudes, conditioning variables in the local environment, and interference elements affecting individuals. These factors are discussed in detail in the various referenced documents and need not be reviewed further here. What is of concern is how this information is reflected in criteria for land use planning.

In its simplest terms our purpose is to derive a means for estimating the noise exposure from aircraft operations and from this infer the kind of functional uses that can be reasonably acceptable for various values of noise exposure. The calculation of noise exposure is basically an engineering procedure to summarize the overall noise environment produced by a complicated series of noisy events. We attempt to express the results of this calculation in quantities which scale as well as possible to the subjective response of people. For planning purposes we must also specify the points along these scales that provide satisfactory noise environments for various human activities. The selection of these points is in all cases a value judgment on the part of the scale maker. In essentially all criticisms of various aircraft land use planning procedures, the heart of the criticisms relates to the validity of these judgments.

Criteria for estimating acceptable conditions for residential living have been reviewed in Ref. 4. The corresponding criteria used in various countries were examined, are repeated in Fig. 3 of this report, and are generally found to be completely consistent with each other regardless of the technique for their derivation. The CNR and NEF criteria expressed in Fig. 3 have been resisted for more than a decade by the civil aviation community, fueled by the variability obtained in annoyance studies in this country and in the UK. In developing an updated Air Force procedure we need to consider whether or not there is evidence on which to improve or alter the existing criteria.

Much of the criticism of the CNR and NEF criteria values revolves around the low correlation (0.4 to 0.5) of specific values of CNR or NEF to scales of individual annoyance as obtained in the social surveys. The argument is that this casts doubt on the entire approach since the low correlations indicate that individual annoyance is not accurately predictable from noise exposure. For planning purposes this question is just reversed from the order of interest. What should be asked is, given a value of noise exposure, what can be said about the expectation in average response and compatible land uses.

All social surveys reported in Ref. 4 show that the higher the aircraft noise exposure, above some relatively low threshold level, the higher the disturbance. The more recent studies reviewed in the previous section not only substantiate the general trend, but, in the case of the Tracor studies, allow a much better quantification of expected annoyance for a given noise exposure. The Tracor work allowed a derivation of both percentage of highly annoyed in a population and the expected percentage of complainants for a given noise exposure. On this basis, the 100 CNR value, which sets the boundary below which aircraft exposure noise will be tolerated in the present criteria, corresponds to a population where approximately 20% of the people would be highly annoyed, but only a few percent or less would complain. The subsequent analyses reported in Ref. 68 and 69 extend the validity of these results by showing the combined analysis of surveys in four countries give essentially identical relationships between noise exposure and average annoyance of a community. The correlation coefficients between population average annoyance and noise exposure are in excess of 0.95, even though much noise variability is obtained for individuals. For land planning purposes, it is the population average response that is of primary interest.

The words currently associated with exposures of 100 CNR (30 NEF) or less are:

> "Essentially no complaints would be expected. The noise may, however, interfere occasionally with certain activities of the resident."

At the point of 115 CNR (40 NEF) the Tracor data allow a prediction of about 50% highly annoyed in the population, with about 15% complainants. The words in the CNR-NEF criteria for noise exposures of this value and greater are:

> "Individual reactions would likely include repeated, vigorous complaints. Concerted group action might be expected."

In the light of the Tracor data one might conclude that the words associated with the present CNR-NEF criteria, if anything, might be understatements.

One of the criticims of the present CNR-NEF criteria is that the contours of noise exposure do not adequately reflect the noise problems at civil airports. While part of these criticisms are due to the precision of obtaining contours (standard deviations of ± 2 units between measured and predicted values are typical, with total deviations of ± 5 units possible when inadequate operational data are used), most have to do with whether the community response is adequately described by the criteria. Interestingly enough, the direction of this criticism is opposite when it comes from social scientists as compared to airport operators. There is a growing sentiment among some social scientists that community attitude is underestimated by the present criteria[58]. On the other hand the airport operator's definition of "noise problem" has to do with whether he will be able to continue his airport operations in their present form. He is thus concerned with whether the criteria overstate the severity of aircraft noise, particularly if the criteria become public policy statements[59].

The obvious dichotomy between the social scientists and the airport operators has to do with the complexities of how an annoyed population can exert its feelings through public action. Since the purpose of a land use planning procedure is to evaluate compatibility of noise exposure with land use, not to resolve the public administration issues, the above criticisms should be recognized, but not arbitrarily used to change the present criteria which seem to reflect reasonably accurately the data on community acceptability.

Present criteria for residential use were derived from a broad spectrum of communities and tend to integrate over the variations in social and economic factors existing in many communities. In the past ten years an increasing awareness has been developed concerning the socio-economic status (SES) of a community and its effect on attitudes about noise. In the London survey, quoting from page 16 of Ref. 13:

> "Middle class people appear to be rather more readily bothered by noise than do working class people. The working class groups were a little more likely to say that they were bothered or disturbed by noise and feel concerned about the prospects of noise increasing in the future. This appears to be largely a social attitude to noise related to the standard of amenity that they expect in their home environment since they are only marginally more sensitive to noise in general.

Awareness of Aircraft Noise	Upper-Middle	Middle	Skilled Labor	Working
	%	%	%	%
Mentioned spontaneously	49	40	38	29
Mentioned after prompt	40	52	53	58
Total mentions	89	92	91	87
Most bothersome noise heard	36	31	32	27 "

In another example, a recent study of annoyance due to traffic noise[19/], Jones found the following relationships between education and income level with degree of annoyance:

a)

Highest School Level Attended	% of Total	% Annoyed/ % Not Annoyed
Elementary	9	0.4
High School	46	0.8
College	42	1.6
Not Ascertained	3	

b) Those with annual income closest to $5,000 were 0.7 as likely to express annoyance as the sample whole; those with $25,000 were twice as likely to express annoyance as the sample whole.

In a further example, Galloway was able to increase the correlation between annoyance and noise exposure from about 0.5 to 0.9 by weighting responses with SES considerations[18/].

Notwithstanding the increasing evidence that expressed annoyance scales with SES, it does not appear prudent in a general planning procedure to provide explicit adjustment factors for SES. It would be a difficult political decision to argue that people of high SES should have lower noise exposure than those of lower SES. Nevertheless the planner should be made aware that within any specific community the variance in response obtained from a given noise exposure, as compared to present criteria, may be directly related to SES variables.

Looking at criteria from a national policy position, the Department of Housing and Urban Development (HUD) has reviewed noise criteria for a variety of land uses. Prior guidance with respect to the suitability for residential use of land exposed to aircraft had been provided by the Federal Housing Administration in terms of the CNR-NEF criteria. The suitability of these criteria has been reaffirmed, with their applicability broadened to include all HUD programs in HUD Policy Circular 1390.2 of August 1971. This policy provides for local approval of projects exposed to values of CNR less than 100 (NEF less than 30); requires an environmental statement outlining noise control measures for projects in CNR regions of 100 to 115 (NEF 30 to 40), plus concurrence of the Regional Administrator; and at higher noise exposure requires approval of the Secretary for any exceptions--stating that such exceptions are strongly discouraged.

While much of the effort to develop criteria for use in noise exposed areas has been directed to residential applications, it has been recognized that there are also other land uses having various sensitivities to noise exposure, e.g., school, churches, places of public assembly. In most of these situations one can examine the influence of aircraft noise primarily in terms of its effect on speech communication within the spaces involved rather than on the more complex measure of annoyance. The suitability of a school room, for example, is determined by how well the teacher and class can tolerate interference with their ability to communicate. Methods have been developed to assess speech communication in the presence of aircraft noise for a variety of functional purposes, considering the spectral characteristics of aircraft noise, typical building construction, and the importance of speech intelligibility. Such guidelines are provided in Ref. 4, in terms of NEF exposure units, for a wide variety of uses, identified by codes from the HUD standard Land Use Code manual. This information is reproduced here as Appendix B. The same information has been adopted in the recent HUD Planning Guidelines for Local Agencies[70/].

> <u>Recommendation No. 5</u> - Adopt the land use compatibility guides and noise compatibility interpretation guidelines specified in HUD report "Aircraft Noise Impact: Planning Guidelines for Local Agencies[70/].

E. Other Forms of Noise Impact Analysis

The criteria discussed previously are directed towards estimating the acceptability of different noise exposures for various types of land use. There is additional interest in determining the general "impact" of noise exposure over an area. The usual technique for examining such effects is to consider factors related to population and land use within contours of equal noise exposure around an airport. A typical set of contours is indicated in Fig. 6.

A direct measure of impact is to identify the total permanent residential population exposed to a specified or greater noise exposure. HUD policy, for example, states that noise exposures of 40 NEF or greater are unsuitable for residential use. A measure of the severity of an airport noise problem is the residential population exposed to such noise levels. A related use of contours to determine noise impact is employed in the California state airport noise law. In this law the area of incompatible land use within a noise exposure boundary comparable to 30 NEF is used as the measure of impact. Only the area devoted to dwelling units and schools "of standard construction" is used to determine the incompatible area; other land uses are considered "compatible."

A somewhat related evaluation of noise impact was used in a study conducted by the Aviation Advisory Commission around eleven commercial airports[71]. In this study several measures of impact were employed. The first was to determine the population and land areas associated with permanent dwelling units, schools, churches, and commercial activities related basically to the affected neighborhood functions within various NEF

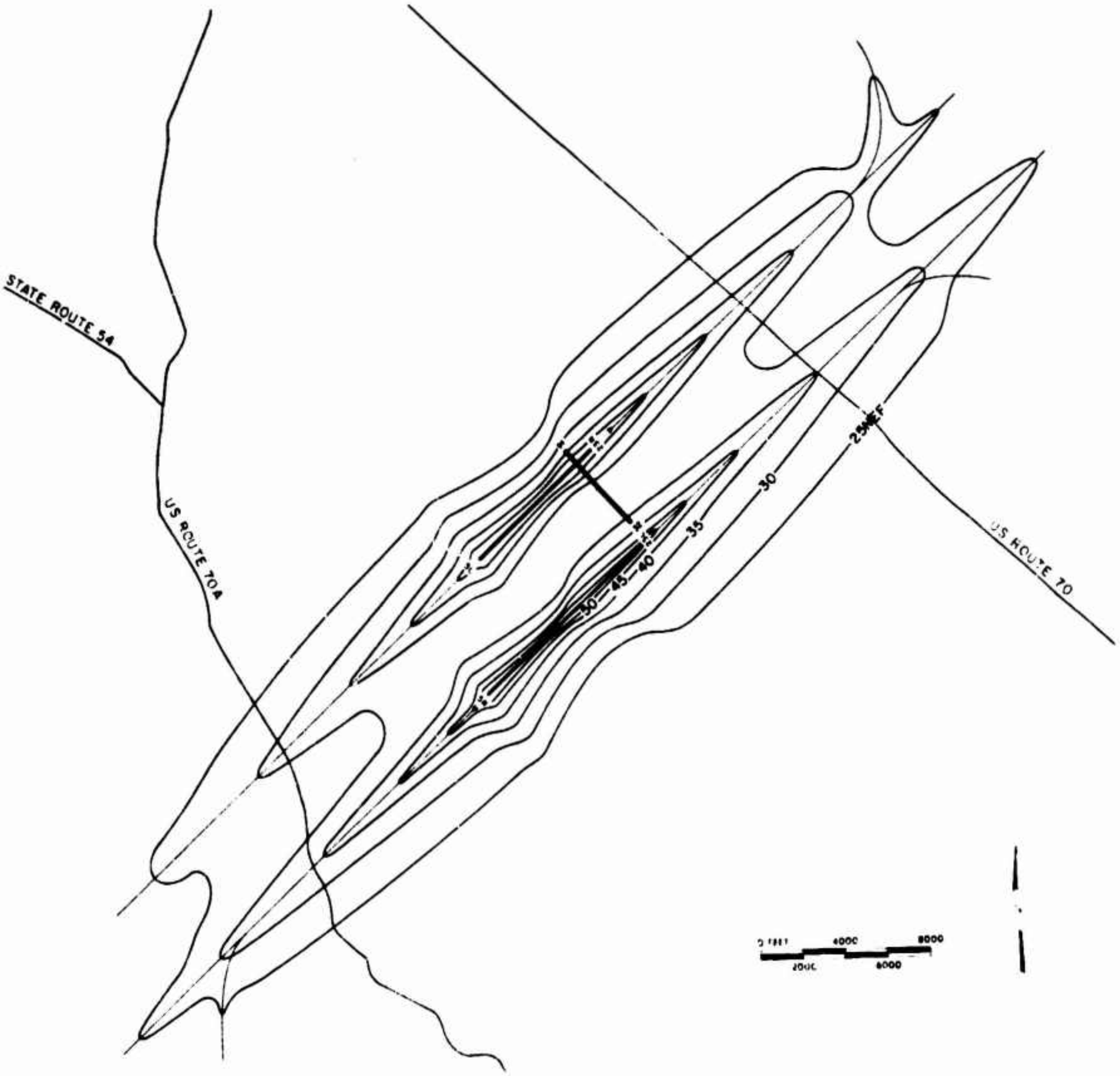


FIGURE 6. NOISE EXPOSURE FORECAST (NEF) CONTOURS FOR 1975 OPERATIONS - RALEIGH-DURHAM AIRPORT, RALEIGH-DURHAM, NORTH CAROLINA

contours. The second step was to determine the cash cost of land acquisition, clearance, and relocation costs for those uses incompatible with the noise. An attempt was also made to assess the social implications and political feasibility of total relocation of people. Conversion of the affected land areas to other revenue producing uses, effects on tax structures, and other considerations necessary if such a plan were actually put into action were not considered because of the time and funds available for the studies.

A refinement of the concept of determining the number of people exposed to various zones of noise exposure has been introduced by Pianko and used in the evaluation of impact of various commercial aircraft retrofit programs by the ICAO Committee on Aircraft Noise[72/]. Pianko determines the impact by the relative magnitude of a function called Significant Area of Global Annoyance (SAGA). Three elements are involved in computing SAGA: noise exposure contours, population density in the exposed areas, and a function, π, relating noise exposure to percent of exposed population expected to be highly annoyed. The π function is the same as described in Section II-C-3 of this report on page 29, except that the function is defined as zero below NEF 30. These factors are integrated over the noise exposed area to obtain the total number of people highly annoyed at exposure levels of NEF 30 or higher, i.e., the SAGA for the airport situation.

A different approach to impact analysis has been suggested by Richards[60/]. His proposal is directed to commercial air carrier airports, but might be adopted for military use with further study. His basic evaluator is a Disbenefit-Benefit ratio, which he defines as the number of individuals seriously disturbed by noise in a given area to the total number of passenger movements contained in the flight operations causing the noise, expressed on a percentage basis. In his evaluation he considers, based on the London airport studies[9,13], that the proportion of people seriously disturbed in a residential area is given by 0.75 NNI/100. This predicts that approximately 40% of the population would be seriously disturbed at NEF 40 (compared to the 50% highly annoyed predicted from the Tracor results in the analysis of Section II-3-C).

A recent effort by FAA to provide a means for evaluating aircraft noise has produced the Aircraft Sound Description System (ASDS)[73]. This procedure defines the impact area, by aircraft type and mode of operation, as that area exposed to an A-weighted sound level in excess of 85 dB (a PNL of about 98 dB). It is then assumed that the average exposure to levels in excess of 85 dB is 15 seconds for takeoffs and 10 seconds for approaches everywhere within the 85 dB contour. The effect of a succession of similar events is assessed by multiplying the number of events in the time period of interest times the respective duration factors to obtain the total average time in excess of 85 dB. This "exposure time" is thus the measure of impact.

Since noise from operations at an airport is generated by different types of aircraft on a number of different flight paths, the ASDS approach accounts for this in an aggregating method to obtain a single number called the Situation Index (SI). This aggregation consists of multiplying the area of each individual 85 dB contour by the "exposure time" for that contour, then adding the results for each contour to obtain a total number, the SI in "acre-minutes."

No attempt is made in Ref. 73 to relate this criterion to community response, i.e., "Further, no criteria are specified for the purpose of advising how much exposure is excessive or appropriate, nor are there any implicit personal criteria embodied in the physical and temporal quantities which form its basis."

It is clear that no generally accepted technique for assessing noise impact as such is yet developed. Part of the slow development of such procedures is undoubtedly due to the slow development of regional planning organizations in airport areas and thus the general unavailability of demographic and land use data on a systematized basis. This situation is changing rapidly as a result of a number of federal programs. Regional planning is becoming a necessity in order to participate in many of the HUD grants. Further, the 1970 census data, just now becoming generally available is organized in a way that data of interest in examining noise impact concepts can be obtained in a uniform manner. It is reasonable to expect that more sophisticated methods for noise impact analyses will be forthcoming in the next several years.

The increasing availability of planning and census data leads naturally to thoughts of computing impact indices as part of the basic noise exposure calculation process. One of the difficulties with this concept is the lack of detail available from census data and another is the coding of the data for automatic computation. Local planning agencies obtain data on population for various census tracts. These tracts may cover a few city blocks or a number of square miles. When the area of a census tract is completely contained within the noise contour of interest, no problem is caused. However, any specific contour generally will intercept a fractional part of many different tracts. Since the census data on population are averages over a tract, no reliable way of counting population can be based on an arbitrary assignment of population proportional to the area of the tract lying inside a noise contour and the area outside the contour.

In the most planning efforts known to the author, where population counts in noise exposed areas have been made, boundary problems have been resolved by utilizing aerial photographs of the region to obtain actual building counts in the partial areas of census tracts. This process is reasonably effective since populations per building can be determined fairly accurately in conjunction with the basic census data. The procedure, however, is not amenable to automation since it requires visual inspection and judgment. Since the data can be obtained reasonably quickly, say in one man day, it is questionable whether automatic computation, if it were feasible, would really be much of an improvement.

One of the major difficulties in defining a suitable impact index is the lack of a national criterion for acceptability. For example, using the approaches described here, it is possible to define the proportion of exposed population annoyed at any level of annoyance, the schools, churches, or other uses exposed to different noise levels, and even the dollar values association with impacted property. The same information can be derived for different noise exposures produced by different assumptions on airport operational variations such as runway layout, flight path changes, or change in aircraft complement at an air base. Thus the comparative effects of noise exposure in a community can be obtained. Knowing that only 5,000 people will be highly annoyed for one situation, as compared to 10,000 for another, certainly scales the relative merits of the two conditions. However, in the absence of quantitative limits for acceptability, whether either situation is acceptable or unacceptable is simply a matter of opinion.

In the EPA Airport/Aircraft Study[68], the task group examining noise impact recommended a long range goal that would provide a noise environment in residential areas not in excess of L_{dn} 60 or NEF 25. Even if this goal were adopted, it must become a matter of national policy to determine whether, in the overall public benefit, it might be more vital to maintain an air base mission capability even though significant numbers of people might be exposed to substantially higher noise exposures.

In the process of evaluating the impact of noise on a community it should be remembered that generalized acceptability criteria such as those proposed by HUD are derived from responses averaged over a number of airport situations. Evaluation of case histories at individual airports indicate that local conditions can easily shift impact up or down for a specific noise exposure value[1,10]. Variation in response due to socio-economic factors has already been cited. Other significant factors include the length of previous exposure of the community to aircraft noise, the importance of the air base to the local economy, and the degree to which the community believes the air base is trying to minimize the noise it produces[1,14,17,56].

Until such time as more highly developed impact assessment techniques are defined, the airport planner would do well to maintain maps of noise exposed areas on which basic land uses are coded. The general location of residential areas, schools, and churches should be defined. Color coding is helpful in the delineation of such areas. Map pins locating complainant addresses on this same map in conjunction with the coded land use will assist in obtaining a graphic description of the extent of at least the overt response to the noise produced at the air base. In the last analysis, the planning tools and suggested criteria can tell an air base commander or planner only what the expected effect aircraft noise will have on a community. The actual impact can only be assessed by detailed local evaluation of the community and its attitudes.

SECTION III

REVIEW OF PSYCHOACOUSTIC EVALUATIONS OF AIRCRAFT NOISE

Significant psychoacoustic research concerning people's response to noise has been completed since the introduction of CNR. Much of the work has been directed toward improving objective measures of an individual's subjective assessment of aircraft flyovers. Included in this research have been investigations of multiple and modulated pure tones, temporal patterns of simulated aircraft flyovers, flyover signal duration, combination effects of pure tones and duration, and the effects of Doppler shift. In addition, investigation into the effects of background noise, speech interference, and the growth of noisiness have been conducted. Some research to revise the shape of the noy contours at low frequencies and high amplitude has also been undertaken. Most of the research appears to substantiate the use of EPNL in its present formulation as a reliable and accurate measure of the noisiness of aircraft flyovers. The following is a review of various effects and the results of related studies.

A. Spectral Effects

Functional relationships between SPL at various frequencies and values of equal noisiness (noy contours) are employed in the calculation procedure for perceived noise level. Since the inception of these curves in 1959, and later modifications in 1963, other investigators have conducted tests to either validate or modify the noy contours[20,21]. Some investigators[22,23] have intercompared the results of the various studies in an attempt to determine an average noy weighting function. While there is some variation in the results obtained by the various investigators, probably the greatest discrepancies are at low frequencies. One investigator[24] has introduced a different combination rule in determining perceived noise level from 1/3 octave band SPL. This combination rule, in essence, changes the low frequency weighting in a manner such that the low frequencies become less important in determining the perceived noise level. In spite of these studies there does not seem to be enough evidence at present to warrant changing the noy weighting contours as they presently appear in standards documents[5,6,7].

B. Effects of Discrete Frequency Components

Many aircraft noise signals, in addition to their random noise structure, contain discrete frequency components. There is no doubt that the presence of pronounced discrete frequency components adds to the noisiness of aircraft flyovers. Several early studies led to a correction procedure whereby the perceived noise level was increased, over the value computed strictly in accordance with the noy contours for random noise, to account for the subjective judgments produced by the presence of discrete frequency components More recently, studies have been completed[25,26,27] in which modulated and multiple tones have been examined to determine the validity of the pure tone correction procedure. It appears that the increased noisiness caused by modulated tones and some of the multiple tones is accounted for by the pure tone correction procedures adopted in existing standards[5,6,7]. However, for multiple tones such as those present in some high bypass-ratio engines, so called "buzz tones," there is additional noisiness present which is not accounted for in current tone correction procedures. More work needs to be done on multiple tones to determine the corrections necessary to account for their contribution to noisiness.

C. Temporal Pattern Effect

Early studies[28/] investigating the effect of duration on the judged noisiness of aircraft flyovers suggested that the noisiness of signals of different duration could be equated if the noise level in PNL was modified by adding a duration correction equivalent to 3 dB per doubling of duration. This correction is presently employed in the EPNL calculation procedure by an integration of the time history of the signal. Most studies show that the duration correction does provide an improvement in the assessment of aircraft flyovers[24,26,29,30/]. In addition to the duration of the flyover, the shape of the flyover temporal pattern was felt to be important. One study which investigated this effect[29/] indicated that if an integration technique is employed to account for the duration and temporal shape, then the present method of duration adjustment is adequate for the temporal shapes common to aircraft flyovers. There was, however, one exception which suggests that flyover time patterns with sudden onsets are judged to be noisier than those with gradual onsets. This is in direct contrast to an adjustment procedure proposed by another investigator[24/]. His suggested adjustment increases with the amount of time it takes for the aircraft flyover noise to attain its maximum level. Thus, as a flyover signal takes a longer time to reach its maximum level, its noisiness would increase. Clearly more experimental work is required to resolve this dilemma.

D. Doppler Shift Effect

There has been some concern that Doppler shift may effect the judged noisiness of aircraft flyovers. Two studies[30,31] have been completed which suggest that this may indeed be the case. However, the effect appears to be quite small and concentrated mainly at low altitudes. On close examination of the data of Ref. 30 it appears that the Doppler shift correction is confounded with the duration correction. Aircraft flyover noise with a pronounced Doppler shift required less correction for duration than noise without Doppler shift. However, the 3 dB increase in judged magnitude per doubling of duration incorporated in the EPNL calculation procedure still provided a reasonable measure of the aircraft flyover noisiness.

Another study[35] which related to Doppler shift, investigated the effect of an approaching aircraft versus a receding aircraft. The study found that approaching aircraft are judged to be noisier than those which appear to be moving away from the observer. The effect was not verified in a subsequent study by another researcher[30] but further tests are being carried out by the original investigators using more realistic aircraft flyover simulations as a further check on the phenomenon. In the most recent report on this subject[61] it was found that while there may be some evidence that perception of aircraft noise is related to distance, the effect was not measurably significant.

E. Speech Interference Effect

One of the objections to aircraft noise is that it interferes with speech communication. Some investigations have been completed to determine quantitatively the amount of speech interference caused by aircraft noise and to also determine a measure which best predicts the speech interference effects[32,33]. These studies reported that the articulation index provides the best predictor of speech interference. However, PNL also provided a reasonable measure of speech interference.

Since the amplitude of aircraft flyover noise changes with time, an average measure of speech interference has little meaning. Possibly more important is that level above which speech cannot be understood at a given distance. This would provide a duration of time for which one would be unable to communicate. It is interesting to note that in one study[35] the level at which speech communication became quite difficult was the same level as that which resulted in a rating of "barely acceptable" and "unacceptable" in a category scaling experiment. This is another indication that speech interference is certainly a strong contributor to the assessment of the annoyance of aircraft flyover noise.

F. Background Noise Effect

There is evidence[36,37] that background noise or ambient noise affects the assessment of other intruding sounds. This is particularly true when the intruding signal is close in level to the background noise, becoming close to inaudible, and thus not annoying. One study[36] suggests that if the signal to background noise ratio is 40 dB, the effect on the perceived noise level of a judged noise would be to reduce it by 3 PNdB. For aircraft flyovers the noise levels are relatively high and thus a background correction is not incorporated in the present NEF since

a) its effect would be relatively small and

b) it is difficult to specify a representative level of background noise because of its wide variability.

A background noise level correction could actually provide a very undesirable effect if it were to encourage an increase in background noise as a means of reducing the annoyance of aircraft noise intrusions. This has actually been recommended in one study of means for alleviating noise problems around airports.

G. Combination Effects

Many of the investigations relating to the acceptability of aircraft flyover noise have concentrated on one or another aspect of the noise. For example, some have studied the pure tone effects, others have studied the duration effect. Since correction factors have been developed to account for these effects it is certainly desirable to determine if the effects are additive when presented in combination. Some studies such as those investigating temporal and spectral combinations[29/] and tone and duration combinations[26/], have shown that the effects do appear to be additive and that both tone and duration corrections are necessary. Further studies[38,39/]

using both recorded and real life aircraft flyovers as stimuli have shown that tone and duration corrected perceived noise levels provide as good if not better correlation with subjective assessment than other measures without the tone and duration correction. These investigations further suggest that the present EPNL calculation procedure could be improved upon but at this time it appears to work adequately well for present day aircraft and also for future V/STOL aircraft.

In the most recent report[61] on combination effects the author concludes that the manner of accounting for frequency weighting and duration effects in EPNL were close to optimum, although a small change in noisiness summation might improve the accuracy of computed values of EPNL as compared to judgment tests. The author also concluded that improvements in tone correction procedures should be made at frequencies below 500 Hz since his results showed that the present corrections overestimated the effect of tones at low frequencies, increasing the standard deviation in the difference between calculated and judged levels by from 0.3 to 0.8 dB, depending upon the type of aircraft. Examination of his data indicates, however, that he incorrectly applied the tone correction at low frequencies (e.g. the correction below 500 Hz should be numerically half of what it would be above 500 Hz). Thus his conclusion at this time is not justified. This is particularly pertinent in that 26 of the 119 aircraft noise signals used in the study were from helicopters where low frequency noise is most important. A re-analysis of this data should be performed to provide better insight on the applicability of EPNL in its present form to helicopter noise.

It is very important to bear in mind that many methods might work nearly as well as EPNL for current aircraft; however, the real question is whether or not the other measures would work with possible future aircraft flyover noise whose spectra may bear no relationship to the flyover noise spectra of the present. In this regard, judgment tests using some radically different spectra were undertaken to determine how well the various measures agreed with subjective assessments[29/]. Again, EPNL provides about the best correlation with the judgment result. Thus, while the present form of EPNL can probably be improved upon, it does not appear at this time, that adequate data are available to warrant a significant change in the present calculation procedure.

The above research shows that noise signals having the features characteristic of aircraft flyover noise are best related to human judgments when frequency weighting, corrections for tones, and time integration are utilized. For sounds having similar temporal characteristics and without predominant tones it has been shown[29,39/] that the frequency weighting provided by A-weighting, as compared with PNL, provides reasonable accuracy in judgments of noisiness, for reasonably well behaved spectra. No tests have been performed in which the temporal and tonal correction procedures of EPNL have been applied to A-weighted noise signals. One would expect that these additional factors should improve the ability of A-weighted noise measures to predict acceptability of sounds in the same way that PNL is improved in the EPNL measure.

In the previous sections of this report we recommend the SELT measure as a compromise between the desirability of using A-weighting for uniformity in comparison to other noise sources, yet providing the temporal and tone factors of EPNL. Clearly the validity of this choice should be determined by psychoacoustic experimentation. The hypothesis is reasonable, but the verification of the range of its validity is missing.

SECTION IV

REVIEW OF THE TECHNOLOGY OF NOISE EXPOSURE COMPUTATION

The accuracy of models for computing the noise exposure produced at any point around an airport from a series of aircraft operations is determined by the methodology used to describe the basic noise characteristics of a specific aircraft, the way in which this information is interpolated or extrapolated from actual measured data at specific distances to other distances, and on the accuracy of the operational data used to describe mixes of aircraft, operating conditions, and flight trajectories. The first two categories involve factors of both aircraft performance and physical acoustics. The ways in which these factors are considered form the differences between models currently in use. The third category, reliability of operational data, is a problem common to all models. In the following discussion we consider how these factors are treated in present models and indicate where improvement in accuracy can be expected in a new procedure. It should be noted that improvement of existing models is a question of refinement, not change in fundamental concepts.

Before addressing the methodology for noise exposure computation, one should consider the reasons why one uses such a methodology at all. The question is often asked as to why one should not simply go into the field and measure the exposure directly. Clearly, for planning purposes where one is projecting new aircraft, new operations, different procedures, new runways, the physical situation doesn't exist even if a measurement program were feasible.

The answer for the case of an existing airport operation, projected to remain essentially stable, is not as obvious. Consider, however, the problems of performing such a measurement program. The goal of the planner is to obtain a representation of the variation in noise exposure, over the geographic area of concern around the airport, in a sufficiently stable form that he can assess various planning options. To obtain this goal through a measurement program would require continuous noise measurements at geographic points ranging from 200 to 2,000 feet apart, varying with distance from the runway. These measurements would need to be made continuously over a long enough period of time that daily fluctuations in traffic, weather, and runway utilization were effectively averaged.

Consider the relatively simple airport layout of Fig. 6. The area of concern is approximately 12,000 feet wide by 40,000 feet long, or about 500 million square feet. Assuming an average grid spacing of 1,000 feet, it would require about 500 separate measurement locations. If one were to measure for only one week at each of these locations, the cost of data acquisition and analysis, even using automatic, unattended equipment, would be of the order of one million dollars. This is clearly not a feasible approach for airport planning.

The above example is in no way meant to infer that no measurements should be made around airports. Carefully selected measurement locations with a well designed noise measurement sample design are often useful for validating the results of noise exposure calculations obtained from computational models. The point is, with the model, only a few measurement sites need be considered, reducing the validation procedure to a reasonable cost and performance period. Factors to be considered in designing such a measurement program are discussed in Appendix D.

A. Basic Approaches to Existing Models

Regardless of the final summation process used to obtain noise exposure, i.e., the summation of a totality of events, there are two basic approaches used to compute the noise produced at a given point in space from a single aircraft operation. Each has the problem of describing the basic noise source characteristics of an aircraft, and then relating them to where that aircraft is in space so that the noise source data can be used to compute noise levels at points on the ground around an airport.

The more sophisticated approach, as developed by von Niekirk and his co-workers in South Africa[40], starts with a description of the noise source characteristics, in terms of sound pressure levels in one-third octave bands, as produced at a reference distance under specified aircraft operating conditions. The position of the aircraft in space is computed from the basic equations of motion of the aircraft, using weight, thrust, lift, and drag information derived from manufacturers' data. Knowing the position in space at any time, the sound pressure levels at a point on the ground are predicted from inverse square considerations and air absorption losses. Duration effects are computed from an empirical model which considers distance and the speed of the aircraft, as well as an allowance for the presence of background noise. Corrections for discrete tones are applied to the sound spectrum at the ground point as they are in EPNL computations. Variations in source noise output for density altitude effects and thrust management schedules are also accommodated in the procedure.

The second, and more generally used approach for land use planning (e.g., CNR, civil NEF, ISO) describes noise source characteristics of an aircraft (usually by classes of aircraft having similar engines and performance) in terms of noise levels as a function of slant distance from the observer to the aircraft. Different curves are necessary to describe different operating conditions, e.g., takeoff and approach. The derivation of these curves requires knowledge or assumptions of both the noise source characteristics, in terms of the noise descriptor used (EPNL, A-weighted sound level), and sound propagation phenomena. Aircraft position in space is obtained from data which describe aircraft height as a function of distance from a reference point (brake release for takeoff, touchdown for approach). The noise level predicted for any point on the ground is obtained by solving the trigonometric problem of locating the distance of closest approach between the aircraft flight path and the observation point, then selecting the appropriate value from the data on noise level as a function of slant distance.

The choice between these two concepts is one of balancing the degree of complexity with the accuracy and variety of the available input data. Where few aircraft types are involved, the precise knowledge of weights, flight procedures, thrust management schedules, and flight paths is available, the first method of computing noise exposure should be capable of higher accuracy than the second. Where many airports are involved, with widely varying aircraft types and operating procedures, where detailed knowledge of aircraft weights is not available, and flight path dispersion is not precisely known, the first concept is difficult to use and its complexity is not often warranted. The second concept tends to smooth out some of the uncertainties in operational data input by using average noise level and performance data for typical aircraft classes as they are normally operated at most airports. Thus the second method may not predict the noise produced by a specific aircraft flight as accurately as the first, but does predict the average of a number of nominally similar flights quite reliably.

Some examples of the accuracy of prediction of individual aircraft noise levels by the current CNR procedures are shown in Fig. 7. The top two examples are obtained from the Tracor data of Ref. 14, the bottom from a random sample taken from our files. Examples of prediction accuracies for NEF values are discussed in Section IV-D.

> Recommendation No. 6 - Description of noise source characteristics in terms of noise level as a function of slant distance and description of aircraft performance by height-distance data be used as the basis for the Air Force noise prediction model for land use planning procedures.

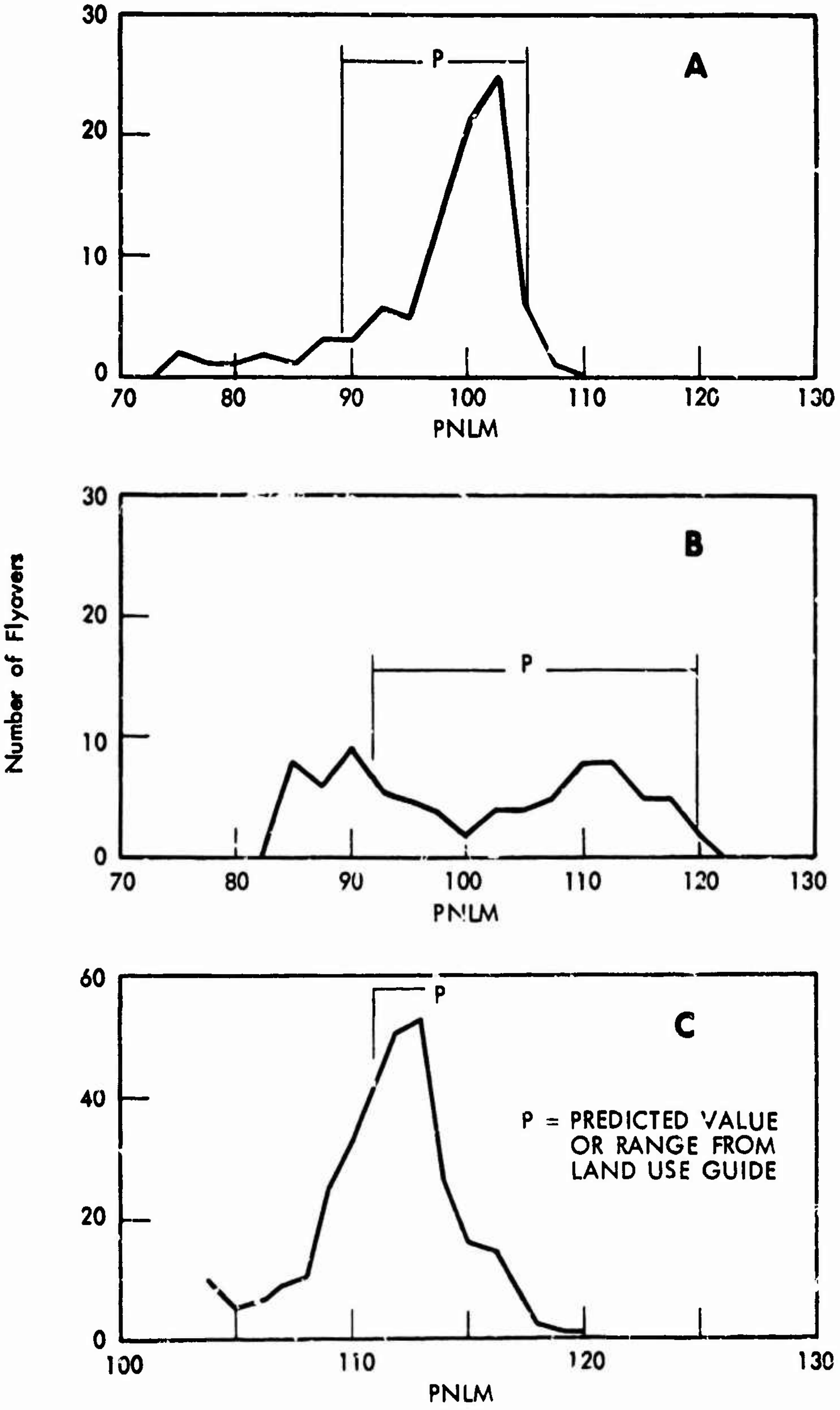


FIGURE 7. COMPARISON OF PREDICTED AND MEASURED VALUES OF MAXIMUM PNL

B. Acoustical Factors

1. EPNL Computation

The emphasis in analyses of aircraft noise signatures in the past six to eight years has been related to EPNL as a measure. Even if A-weighted sound exposure level is used for land planning purposes, the methods for approximating time integrals, defining tone corrections, and questions of stability of analyses are still the same as for EPNL, as long as spectral data are still required for the development of aircraft noise level as a function of distance. In the following discussion we refer to EPNL computation since it is the source of the data discussed. The arguments apply equally to A-weighted sound exposure level.

In Section III we reviewed the psychoacoustic data incorporated in the EPNL concept. The scientific evidence available supports the concepts of frequency weighting of SPL, inclusion of duration effects, and adjustments for the presence of discrete tones in the spectrum. One may ask, however, whether certain of the decisions made with respect to the process of incorporating these factors in EPNL, as now defined in the various national and international documents, are satisfactory when applied to real aircraft signals. Put another way, how stable is an EPNL value, for a particular aircraft noise signal, when subject to artifacts in the measurement/analysis process? In the following discussion it is assumed that the frequency response characteristics and dynamic range of the measurement/analysis system meet present requirements of Ref. 5,6 and are not at issue.

The noise signal produced on the ground by an aircraft in flight will vary rapidly in amplitude if the aircraft is flying fast and relatively low to the ground. The EPNL computation requires one-third octave spectral analyses for successive time segments of this signal. The stability of these analyses is a function of the integration time of the detector used in the spectral analysis and the duration of the time segments. Current EPNL measurement procedures specify a detector time constant equivalent to the "slow" scale of a precision sound level meter[41/] and successive time segments of 0.5 second duration. As in all analyses of time varying signals, one is caught with the dilemma that the detector time constant should be small enough to reasonably follow the time envelope of the signal, while the effective frequency band width of analysis must be sufficiently great to insure satisfactory statistical reliability in the analysis.

Two factors are involved in assessing the validity of the 0.5 second time segment choice. One has to do with the confidence placed on a particular sound level derived from the analysis, and the second has to do with what effects the uncertainty in this value has on a final computation of EPNL. Examining the first point, one can establish confidence intervals for the spectral analysis on the basis of the effective bandwidth of the various one-third octave filters[42/]. Various confidence intervals for the 24 one-third octave frequency bands used in EPNL analysis are shown in Fig. 8. It is clear that, at the lower frequencies, there is a sizable uncertainty in any one measurement providing an accurate measure of SPL for a given event.

The second question, how significant is the instability in low frequency SPL's when computing EPNL is most easily

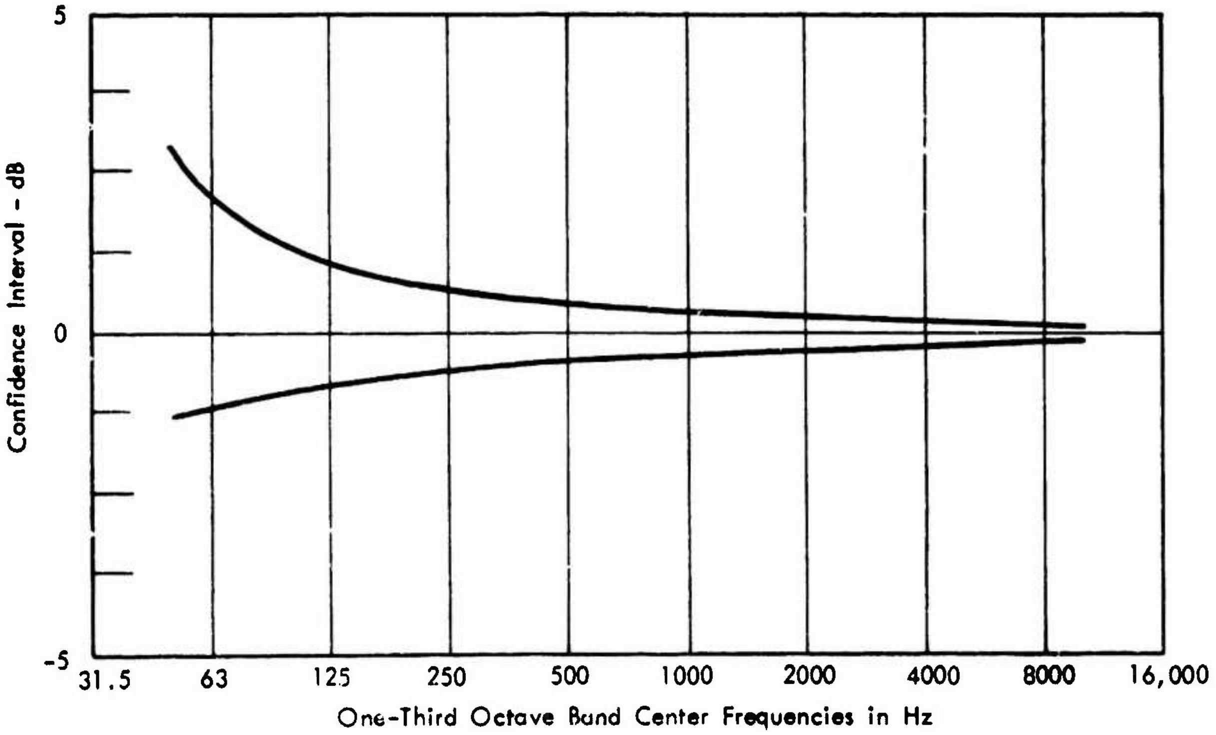


FIGURE 8. 90% CONFIDENCE INTERVAL FOR ONE-THIRD OCTAVE FREQUENCY ANALYSIS OF A 0.5 SEC. SAMPLE

answered by examining the results of repeated analyses of aircraft noise signals of widely different spectral characteristics. Several aircraft noise spectra of substantially different shape are plotted on Fig. 9. These are the spectra obtained from the particular time segment which gave the maximum tone-corrected value of PNL in the noise signal produced during a flyover. The decibel ranges and standard deviations in PNL obtained for six repeat measurements (separate flights) of these signals are listed in Table III. It is obvious that EPNL is not seriously affected by any instability in determining low frequency SPL.

TABLE III
Variation in EPNL Repeat Measurements
for Spectra of Fig. 9 - 6 Trials

Spectrum	Range - dB	Standard Deviation - dB
A	2.0	1.1
B	2.0	0.8
C	1.1	0.7

Another way of looking at the time segment question is to make a series of repeated analyses of a single recorded flyover noise signal using time segments of 0.2 to 1.0 seconds and compare these results with the 0.5 second time segment data. An example of the results one obtains from such analyses is provided in Table IV. Again the 0.5 second time interval appears to be a reasonable choice.

All the analyses in the upper portion of Table IV were

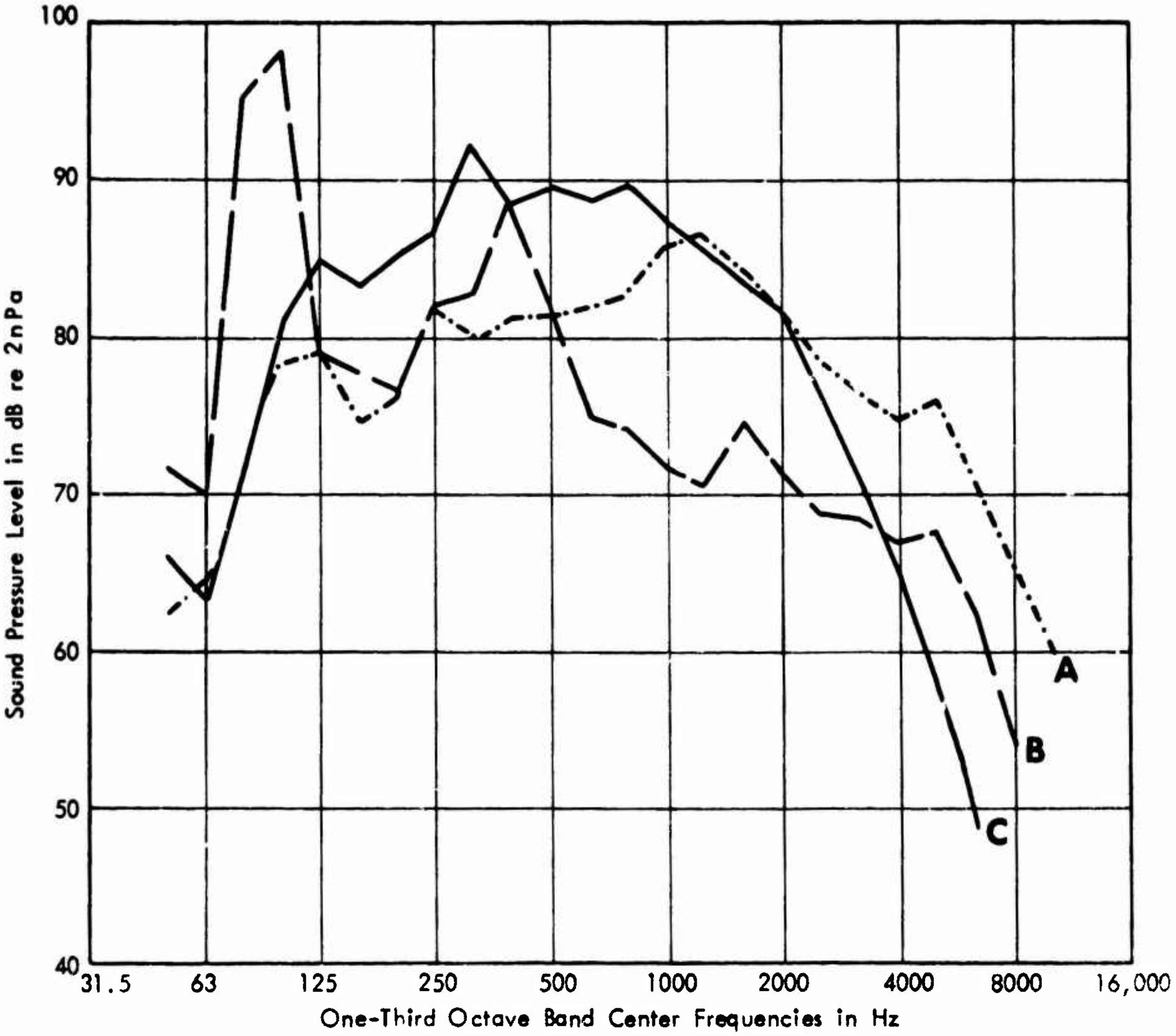


FIGURE 9. SPECTRA FOR VARIOUS PNLTM USED IN COMPUTING EPNL

TABLE IV

Variation in One-third Octave Band SPL
for Different Sample Periods
727 Flyover Signal
Mean SPL with Range in Parenthesis

Sample Duration Sec.	Band Center Frequency - Hz 50	250	1000	5000
1. "Slow" detector				
0.2	78.0(0.5)	68.3(0.3)	73.2(0.1)	72.3(0.1)
0.5	78.0(0.3)	68.7(0.2)	73.2(0)	72.3(0.1)
1.0	77.7(0.2)	68.5(0)	73.2(0.1)	72.3(0.1)
2. "Fast" detector				
0.2	77.4(0.9)	69.1(0.7)	74.6(0.2)	74.9(0.2)
0.5	77.4(0.5)	69.1(0.7)	74.4(0.1)	74.9(0.2)
1.0	77.8(0.6)	69.5(0.6)	74.4(0.2)	74.9(0.1)

made using a detector having the "slow" characteristics of the sound level meter. This implies an equivalent RC smoothing where the time constant is of the order of one second. (The tolerances for the precision sound level meter allow the equivalent RC time constant to lie between 720 and 1315 milliseconds. The experimentally obtained time constant for the analyzer used for these analyses was 1110 ms.) Clearly, many aircraft noise signals vary in amplitude so rapidly, e.g., 10 dB/sec, that one should question the suitability of such a long time constant for the detector. One way of examining this question is to perform the spectral analysis with a time constant of about an order of magnitude smaller and compare the results. The "fast" scale specification for the sound level meter has an equivalent RC time constant of 127 milliseconds and thus admirably serves as a convenient value.

We are most concerned with the effects of these factors in computing EPNL, which is an integration of PNL over time. One can visually assess the effect of differences in detector smoothing characteristics by examining the PNL values at successive 0.5 second intervals as obtained by the two different detectors. In order to make the differences between these two analyses be as large as possible, we examined the approach noise of a low bypass fan-engined aircraft at a nominal height of 107 meters (350 feet) above terrain at an approach speed of 80 meters per second (153 knots). Thus the signal has a complex, multi-toned spectrum, short overall duration, and rapid rate of change of sound pressure with time.

The results of these analyses are shown in Fig. 10 and

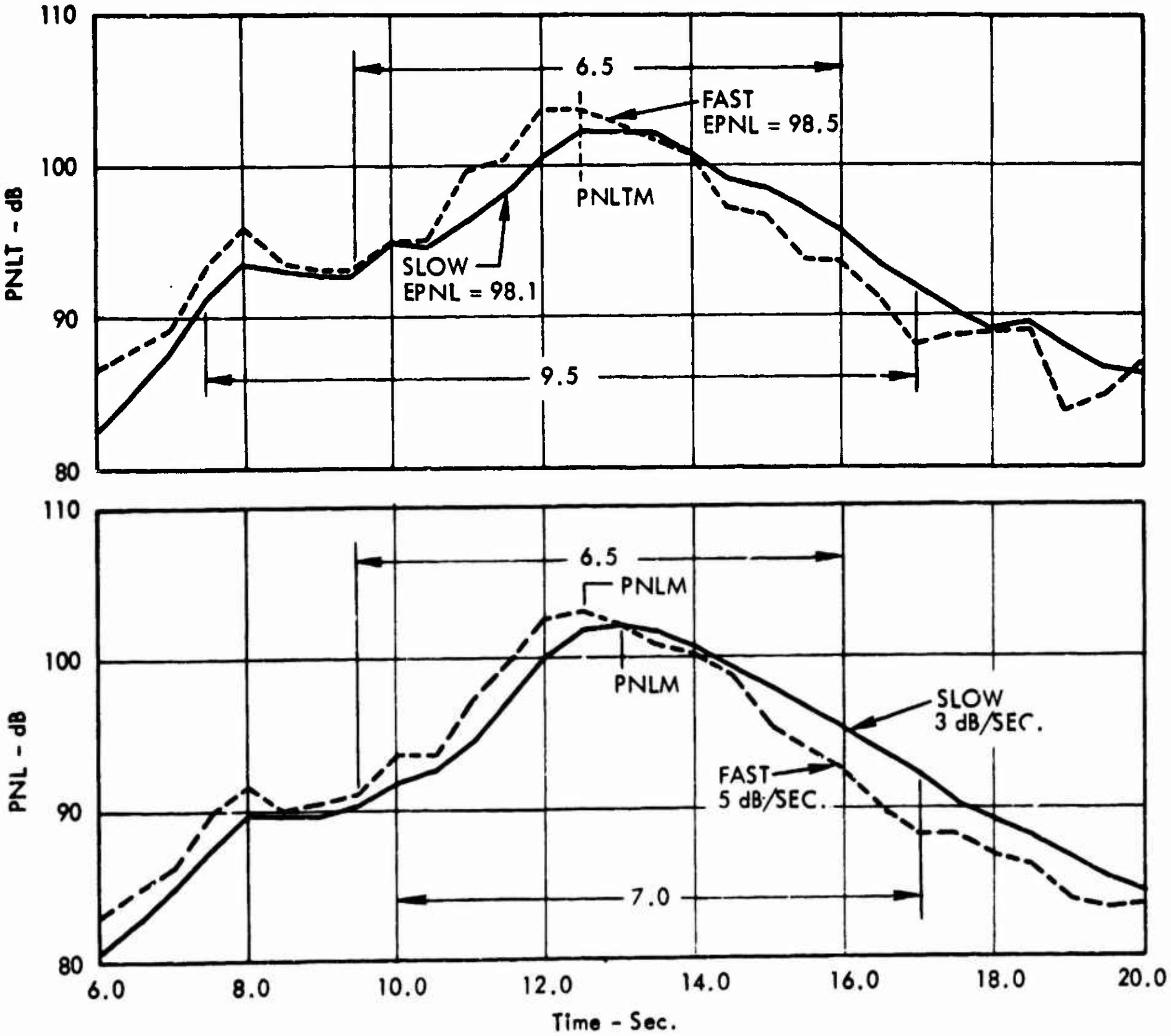


FIGURE 10. COMPARISON OF PNLT AND PNL WITH DETECTORS HAVING CHARACTERISTICS OF "FAST" AND "SLOW" ON A SOUND LEVEL METER

Table V. The data in Fig. 10 show, in the upper part of the figure, the value of PNLT for each 0.5 second interval as obtained with both "fast" and "slow" detectors. Clearly, the "slow" detector neither tracks as accurately in amplitude on the rise or fall of the signal as does the "fast" detector. Yet, the integration of PNLT to obtain EPNL yields almost identical results. The lower part of Fig. 10 shows similar results for PNL, without the tone correction application. The data presented in Table V are intended to provide a feel for the stability of results obtained from repeated analysis of the same flyover signal indicated in Fig. 10. We conclude that there is no reason, for land use planning purposes, to change the detector time constant or sample interval for determining EPNL as they are presently specified in Ref. 5 and 6, provided due precautions are required in specifying heights and air speeds to be used in obtaining reference EPNL values from flight tests so that undue inaccuracies are not introduced because of detector time constants.

Many USAF aircraft cannot, however, be flown at sufficiently slow speeds to make accurate noise analyses at reasonable test heights with the 0.5 second time constant. When the combinations of speed/height provide extremely short durations, we propose[79/] that the following criteria be applied, where d is the duration between levels 10 decibels below the maximum:

Duration (10 dB) - sec	Sampling Interval and Integration Time - sec
$d \geq 5$	0.5
$5 > d > 2$	0.25
$d \geq 2$	0.125

TABLE V

Stability of Repeated Analyses of a Flyover Signal with "Fast" and "Slow" Detectors

Trial	EPNL - dB	PNLTM - dB	PNLC - dB	P.T. - dB
1. "Slow Detector				
1	98.0	102.4	103.0	3.9
2	98.0	102.5	103.0	3.9
3	98.1	102.5	103.0	3.7
4	98.1	102.5	103.1	3.8
5	98.1	102.6	103.1	3.8
6	98.1	102.5	103.1	3.9
2. "Fast" Detector				
1	98.4	104.0	104.7	4.1
2	98.3	103.8	104.8	4.1
3	98.4	103.9	104.9	4.0
4	98.4	103.9	104.8	4.0
5	98.2	103.8	104.9	4.0
6	98.1	103.9	104.9	3.8

Where: EPNL = Effective Perceived Noise Level

PNLTM = Maximum tone-corrected PNL in any 0.5 sec. interval

PNLC = PNL computed from maximum SPL in band regardless of time of occurrence

P.T. = Maximum value of tone correction used to compute EPNL

The duration may be estimated from slant distance to the aircraft in feet, s, and airspeed in knots, V, from the following expression:

$$d \approx K \frac{s}{V}$$

where K, a function of directivity, is approximately 2 for takeoff operations and 3 for approach operations.

One of the potential artifacts involved with computing EPNL from measured spectra has to do with the process for identification of discrete tones. In order to make the tedious process of computing EPNL simple to perform with a computer, an algorithm was required for defining the presence of discrete tones, and their level above the equivalent random noise that would be present if the tone were not. The algorithm estimates the band level without tones, and the "presence" of a tone, by comparing levels at adjacent frequency bands and the rate of level change from band to band. In the original development of EPNL several forms of the algorithm were tested against a wide range of flyover spectra, with the final form being selected as correctly identifying tones for all the test spectra examined.

As the method of rating aircraft noise in terms of EPNL has come into being, many different groups are now making EPNL measurements on a wide variety of aircraft noise signals. In the course of these programs it has become apparent that the present algorithm for tone identification can sometimes define a "psuedotone" as being present when a highly irregular spectrum is examined. This can occur most commonly in two cases.

The first case is that where measurements are made with the microphone above a highly reflective surface. The normal interference effects associated with cancellation and reinforcement of direct and reflected sound waves will produce dips and peaks in the spectrum not found in a completely free field measurement. If the dips and peaks due to the reflections and reinforcements are substantial, in dB, a "psuedotone" will be identified.

The second case can occur when a flyover is measured with the aircraft at an altitude such that high values of air absorption are involved. In this instance the high frequency portion of the spectrum decreases in amplitude with frequency at rates as high as 10 to 30 per octave. In this situation a "psuedotone" will sometimes be identified by the tone detection algorithm when no tone is actually present.

Examples of spectra showing these characteristics are provided in Fig. 11. The dip in the spectra at 160 Hz is approximately the first cancellation in direct and reflected sound rays introduced by finite microphone height above ground, with a reinforcement about an octave higher. In each case a psuedotone is identified by the algorithm. Its effect on the final value of PNLT is about 0.7 dB. A more pronounced effect is obtained by the introduction of a psuedotone at the high frequency end of the spectrum due to the rapid decrease in SPL with increasing frequency. The actual value of PNLT is usually not affected significantly by this artifact, at least for planning applications.

While the effects of the psuedotone artifact are usually small or nonexistent on final values of EPNL, a substantial

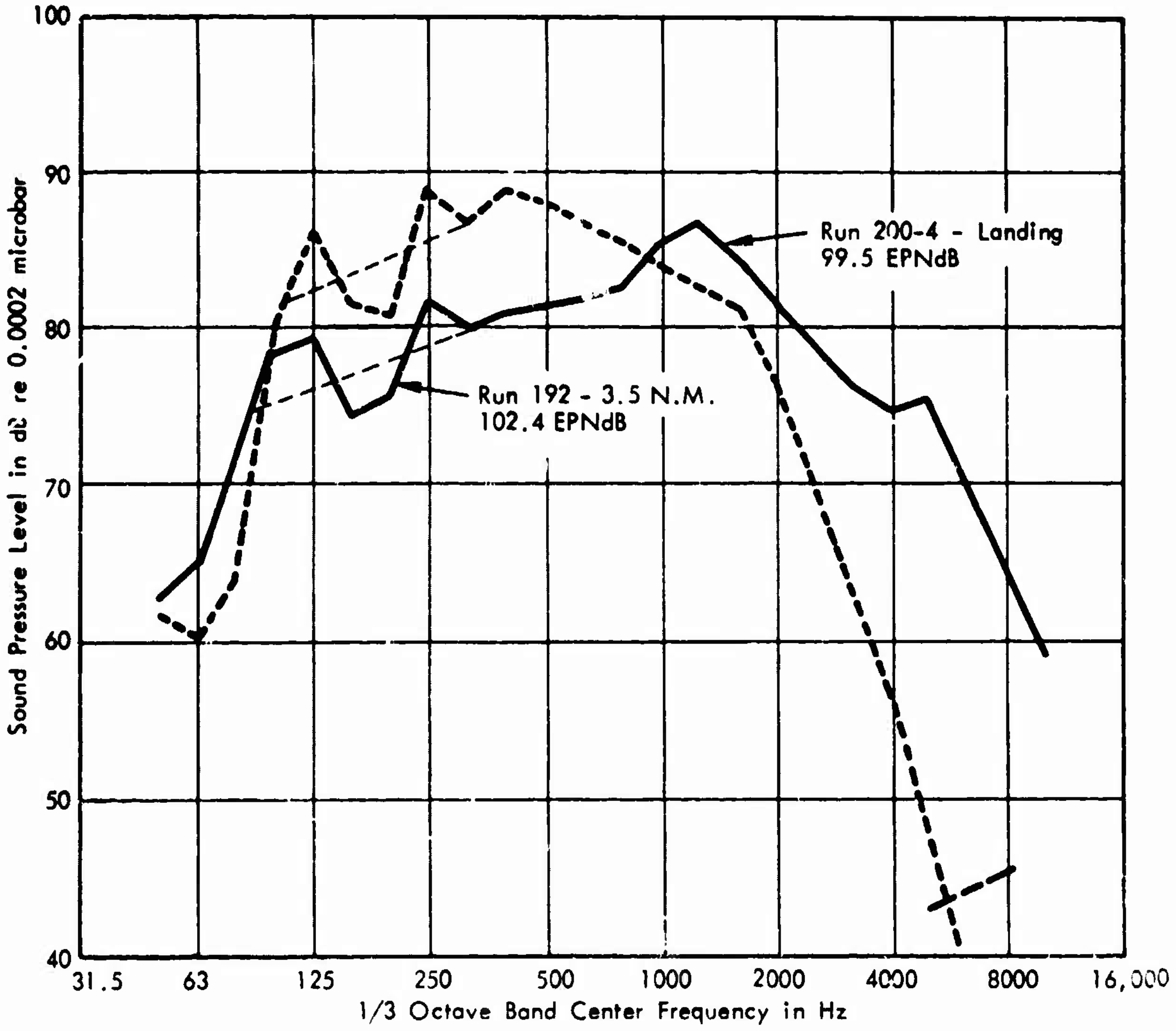


FIGURE 11. TYPICAL MEASURED SPECTRA FOR PNLTM

should be greater than 35 to 40 dB before these background levels intrude on the aircraft spectrum. In most cases where this is so, computation with or without the background level influenced frequency bands included will not affect the numerical value of PNL. Where the desired aircraft signal does not permit this dynamic range, the accuracy of the entire measurement should be questioned.

A last concern in computing EPNL is the possibility of encountering what may initially be regarded as an excessively great duration effect. Some high flyovers tend to produce a noise signal which, through atmospheric scattering of sound, tends to be audible for some period of time. The effect of this phenomenon on the numerical value of EPNL is not as great as often imagined. This result stems directly from the logarithmic integration involved with EPNL. Only noise levels within the order of 5 dB of the maximum level have any significant contribution to EPNL unless they exist for a very long time. EPNL values are generally lower than the maximum PNL for signals having durations (between the 0.5 second interval noise levels 10 dB below and on either side of the maximum level) of less than 25 to 30 seconds. Duration corrections which increase EPNL over maximum PNL must have "10 dB down" durations of the order of a minute or more before a significant effect is observed. Signals of this nature are just not significant in land use planning applications since they contribute negligibly to the summation of the much more noisy events.

Recommendation 7 - The computation of EPNL should be performed as presently described in FAR Part 36[5/]. Computation of SELT should be identical except that

A frequency weighting should be used instead of noy weighting, and a reference time of one second instead of ten seconds should be employed.

2. Air-to-Ground Sound Propagation

One of the major sources of uncertainty in computing noise exposure is the effect of air absorption on sound propagation. In theory the effects of classical and molecular absorption on the attenuation of sound are well understood. Precise measurements of attenuation have been performed under carefully controlled laboratory conditions. The measurements and the theory are in reasonably good agreement.

Unfortunately the atmosphere of the earth is not at all as homogeneous as the conditions obtainable in a laboratory. In a real atmosphere sound attenuation is a function of absolute humidity, wind and temperature gradient, and level of turbulence. In the case of aircraft noise, where one is concerned about propagation paths up to several tens of thousands of feet in lenth, the variations in these factors can be highly significant in their effect on sound propagation.

It is clearly impracticable to provide an accurate model of the atmosphere for use in predicting aircraft noise sound propagation losses. While a number of attempts to model the atmosphere (use of stratified layers, turbulence models, etc.) have been partially successful in understanding the problems, measurement of the properties of the atmosphere for application in noise planning studies is clearly out of the question. The only choice is to resort to experimental data, expressed in terms of statistically averaged results.

The best currently available results on the attenuation of aircraft noise have been combined into a set of average absorption coefficients presented in the Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) No. 866. These values are used in current aircraft noise certification documents and in the ISO and ICAO planning documents[5,6,7]. Much discussion has taken place, however, questioning whether ARP 866 needs improvement, particularly for the coefficients specified at frequencies above 1000 Hz.

An example of how variable the results can be in determining sound absorption coefficients is shown in Fig. 12 where six sets of absorption coefficients, experimentally obtained from aircraft noise data, are plotted as ratios with respect to the values of ARP 866. While many different factors were involved in the different experiments, the variability is alarming. The difficulty lies in having a good knowledge of the atmosphere at the time of the measurements.

Another view of the variability in determining air absorption values, not quite so alarming, is available from a set of controlled experiments, performed under a NASA program, where a fairly good understanding of the atmosphere variables was possible[44]. A summary comparison of these data to ARP 866 is shown in Fig. 13. These results indicate, that, on average, the SAE data are quite reasonable.

A recent program for evaluating air absorption of sound from an aircraft in flight was performed by FAA at Pendleton,

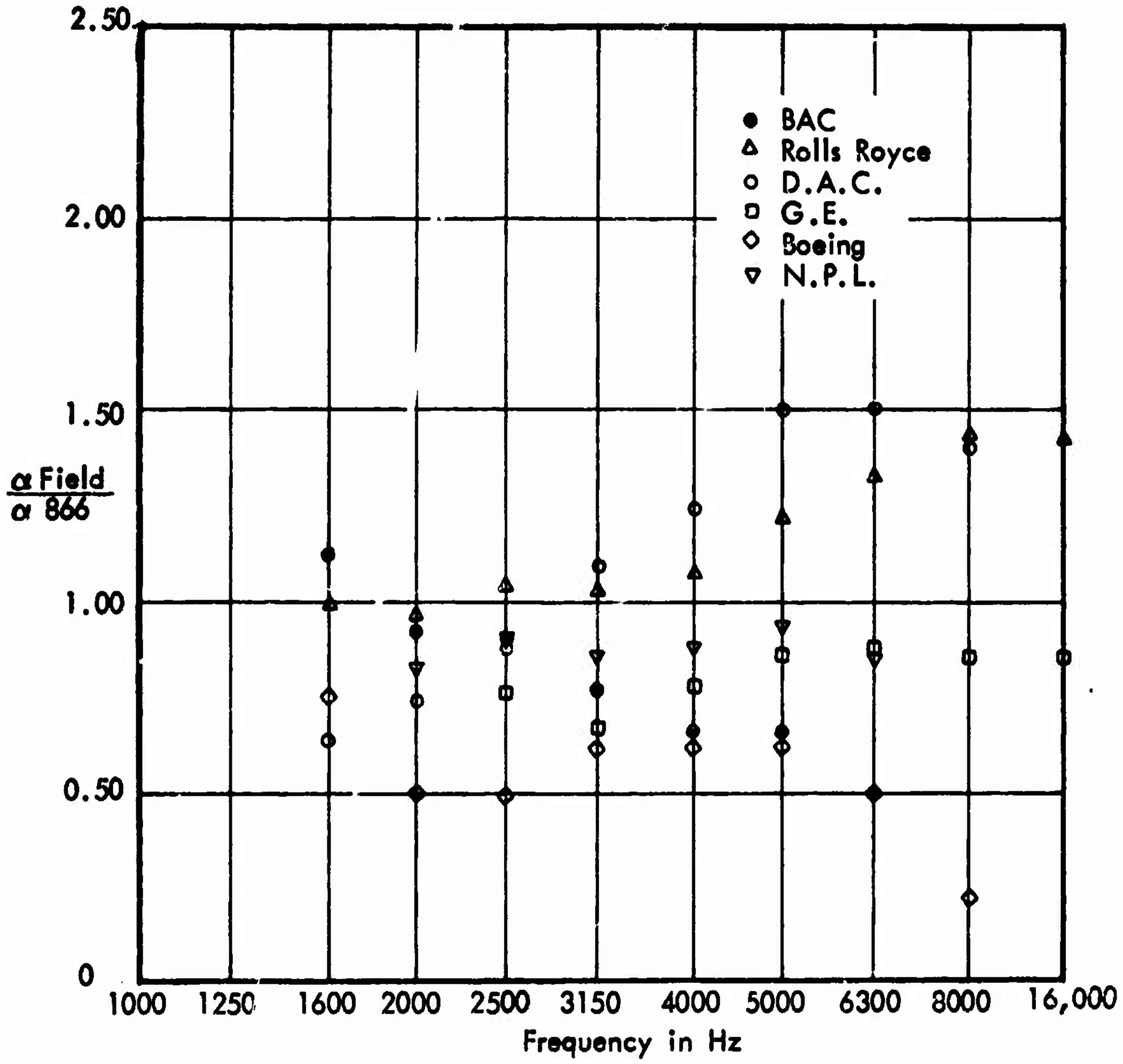


FIGURE 12. RATIO OF EXPERIMENTAL AIR ABSORPTION COEFFICIENTS TO SAE ARP 866 VALUES

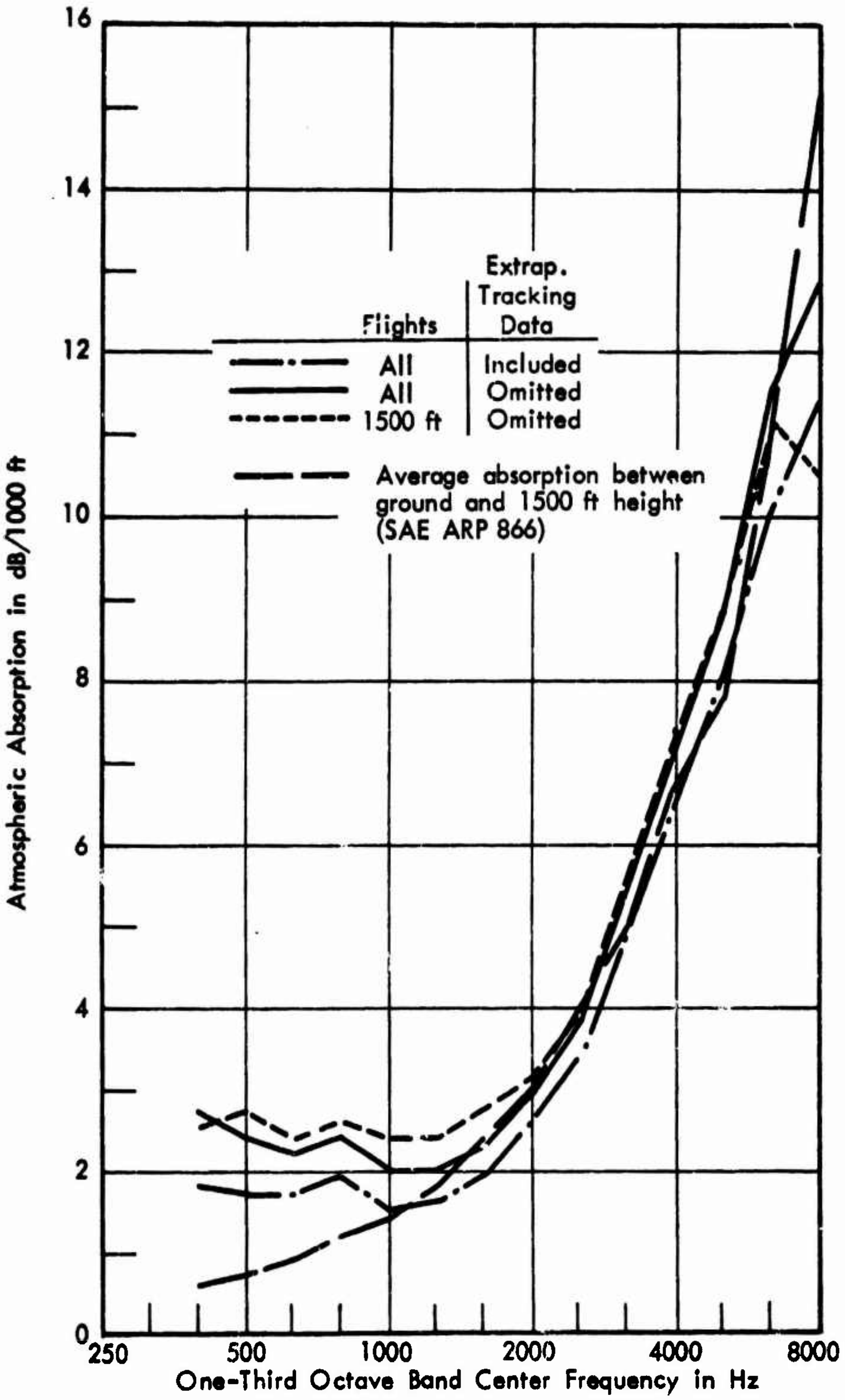


FIGURE 13. COMPARISON OF AVERAGE EXPERIMENTAL VALUES OF ATMOSPHERIC ABSORPTION WITH SAE 866 CALCULATED VALUES (FIG.19 OF REF.24)

Oregon[63/]. A series of ten test groups was used to obtain noise data at four microphone positions located at distances of 250 to 1500 feet from the flight track, normal to it, from level flyovers of a T-33A at heights of 100, 700, 1500, and 2000 feet above the runway.

Most of the data in this program were taken at quite low humidity conditions, e.g. primarily below 40% relative humidity. Background noise levels precluded useful data above about 3150 Hz. Below this frequency it was concluded that the test results indicated absorption coefficients somewhat greater than would be predicted by ARP 866. This is similar, at frequencies below 2000 Hz, to the results of the NASA program. At these frequencies absorption coefficients are typically in the range of less than one to usually not more than three dB per 1000 feet, and thus difficult to measure. Unfortunately no information is given in Ref. 63 to indicate the variability in the data, so no indication of confidence levels can be calculated.

The most recent, and one of the best controlled studies of aircraft sound propagation, was performed by Hawker-Siddeley[84/]. This project used the same aircraft and instrumentation to obtain propagation data at a number of locations in Europe and the USA under a variety of temperature and humidity conditions. While these data have somewhat higher absorption values than ARP 866 at the higher frequencies, the differences are not great. These data provide further substantiation of the general applicability of ARP 866, and show that, if anything, it is slightly conservative. This is appropriate for planning applications.

Recommendation 8 - The air absorption data contained in SAE ARP 866 be used in noise exposure calculations. The Air Force land use planning procedure should be so designed that it can be easily modified to accept new air absorption information when this information is available and considered acceptable to the scientific and technical community.

3. Ground-to-Ground Sound Propagation

In the above discussion we acknowledge the substantial uncertainty in predicting the effects of atmospheric absorption on sound propagated from an aircraft in flight to a point on the ground. When one now considers propagation of sound from a source on the ground to another point on the ground the problem becomes even more complex.

The presence of the intervening ground surface introduces substantial new effects not experienced in air-to-ground propagation. Wind and temperature gradients and the wind direction immediately above the ground cause shadow zones and refraction of sound. Localized temperature fluctuations above the ground surface cause increased turbulence in the air, introducing substantial fluctuations in noise levels received at a distance from a steady sound source. The acoustical impedance of the ground surface introduces additional complexities in the estimation of attenuation.

A number of attempts have been made to derive prediction techniques for estimating ground-to-ground attenuation effects. Various SAE documents have been drafted for use in accounting for ground effects at relatively short distances from a noise source[45,47]. At distances of concern in land use planning around airports, however, the best currently available information was obtained in a NASA study[46] of noise propagation at several commercial airports. In this study, statistical data on noise propagation were obtained for a variety of weather conditions over extended time periods. The propagation distances examined were typical of those involved in airport land use planning problems. The data used in the previous references were reviewed and compared with the results obtained from the NASA project. The engineering procedure derived in this study is that currently in use in the civil NEF computations[3].

An empirical expression, advanced "somewhat tentatively" by von Niekirk and Muller[40], at about the same time as the NASA project was being conducted, expresses excess ground attenuation in sound level A as $\eta\ (7 + 10 \log \frac{s}{100})$, where η is a coefficient describing the ground surface and s is distance from source in meters. Values of η suggested are 0.5 for hard surfaces, 1.0 for grass up to one foot high, 3.5 for wheat or shrubs up to five feet high, and 7.0 for forests. This expression is reasonably consistent with the results of the NASA project for values of η of the order of unity.

Recommendation 9 - Utilize the method for predicting ground propagation losses now in use for civil NEF computations in the Air Force procedure. Provide for easy modification in the procedure when improved data are available. Develop additional data wherever possible in measurement of noise from aircraft operations.

4. Transition from Ground-to-Ground to Air-to-Ground Sound Propagation Rules

Aircraft noise exposure around an airport is usually caused primarily by aircraft performing takeoff or approach operations. The variation in height of the aircraft causes the angle between the horizon and the line of sight from an observer to the aircraft, θ, to vary from zero to as much as 90 degrees. At small angles, the effects of excess propagation due to ground induced effects are apparent; at some finite angle these effects will become negligible with only the air-to-ground attenuation being important. In order to compute noise exposure around the airport an algorithm must be selected to provide the transition from ground-to-ground attenuation.

Several algorithms have been proposed or are in use in various computational models. The current NEF model in use by FAA uses ground attenuation only for the angles between zero and 4°18', interpolates between ground and air from 4°18' to 7°11', and uses air attenuation only for angles above 7°11'. The choice of angles was based on empirical data[3]; the precise values selected not being due to accuracy of data but simply as a choice of values for the arguments of the tangents of the angles as 0.075 and 0.125, respectively.

In the South African procedure[4], an empirical relationship, derived for the transition when levels are expressed in sound level A is given by $\exp(-\theta/2)$. This relationship provides complete ground attenuation effects at zero degrees, and essentially no excess attenuation from ground effects at angles of θ greater than 6 or 7 degrees, as shown in Fig. 14.

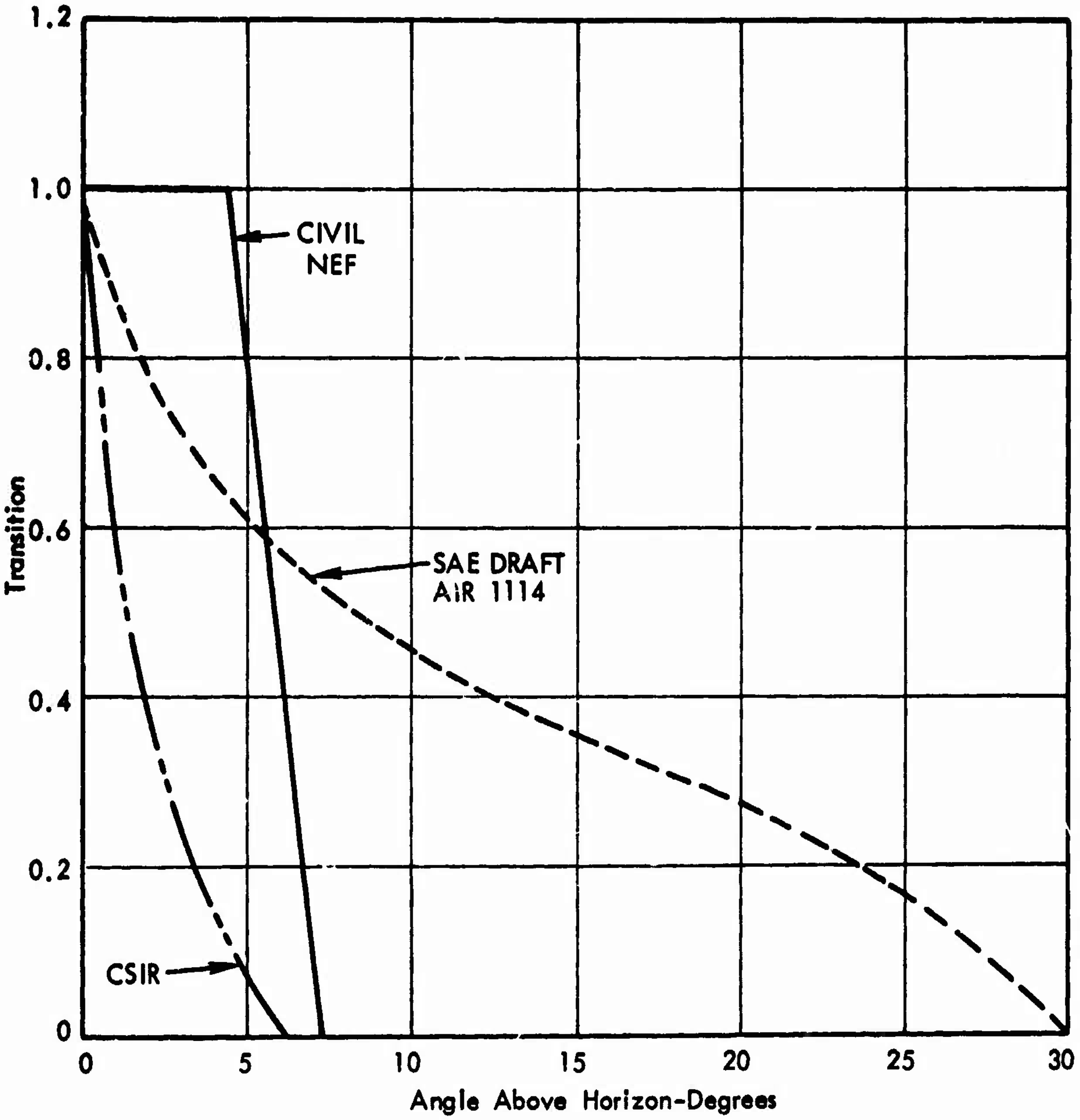


FIGURE 14. TRANSITION FROM GROUND TO AIR ATTENUATION

A different form for the transition was arbitrarily chosen in an early draft of an SAE procedure[47/], in the form of exp $\left[-(\tan 3\theta)^{1/2}\right]$, based solely on the assumption that ground attenuation becomes significant at angles of θ less than 15 degrees. The form of this transition is also shown in Fig. 14. (This form of the transition algorithm was originally included in the program prepared for DOT use at the Transportation Systems Center[48/]; the algorithm has subsequently been changed to be consistent with the FAA version.)

The question at hand is to choose an algorithm for the proposed USAF procedure. Clearly, the data used by van Niekirk and Muller[40/], based on their own work and on data from Scholes and Parkin[49/], do not support the use of excess ground attenuation above values of θ greater than approximately seven degrees. In the course of evaluating the selection of sideline microphone locations for noise certification Galloway[50/] has shown that at values of θ between seven and ten degrees the effects of ground attenuation on EPNL are completely missing, while substantial ground attenuation effects occur at angles less than seven degrees. This conclusion is also consistent with the NASA data of Hubbard and Maglieri[85/]. Notwithstanding these results, some aircraft manufacturers claim extra ground attenuation effects exist at angles as high as 45 to 60 degrees. We find no physical basis for these claims.

Much of the data obtained by FAA at Pendleton[63/] were at low angles of elevation. Unfortunately the data in the report are categorized as above 15 degrees and below 15 degrees. Since the transition out of ground-to-ground propagation takes place below 15 degrees it is essential to know the actual angles. The data are available to do this analysis and hopefully will be analyzed for this effect. As yet this has not been done.

Present evidence appears to indicate that ground attenuation is certainly present for angles of several degrees, and non-existent at angles greater than six to eight degrees. The algorithm used for this transition in the current NEF procedures used by FAA seem to express this result in a reasonable form.

> Recommendation 10 - The algorithm now used in the civil aviation NEF program for transitioning between ground and air attenuation should be employed in the USAF procedure. Develop additional data wherever possible in noise measurement programs to verify or modify this algorithm.

5. Duration Effects

The EPNL produced by an aircraft at any point around an airport is influenced by the duration of the noise signal. The duration is a function of aircraft speed, distance, and the directivity pattern of the aircraft as a noise source. The EPNL values are particularly affected if the aircraft is undergoing acceleration.

For a specified directivity pattern, the duration of a noise signal is directly proportional to distance between aircraft and observer, and inversely proportional to aircraft speed. These factors can be explicitly incorporated in extrapolating EPNL from one test condition to another condition of distance and speed, since the directivity pattern is assumed to remain constant. This assumption is not as valid for large slant distances where the effective directivity pattern changes due to air attenuation effects.

Acceleration effects are most significant for many aircraft during the takeoff phase of flight. The shape of contours of equal EPNL to the side of the runway are directly affected by this effect. In both the South African model and the FAA model for calculating noise exposure these effects are accounted for. In the model used at the DOT Transportation Systems Center this effect is not included. For those airports having "sideline" noise problems adjacent to their runways the effects of acceleration on EPNL are significant, of the order of 5 dB, and should be examined carefully.

> <u>Recommendation No. 11</u> - The effects of acceleration on EPNL or SELT should be accounted for in the noise exposure model. Data to derive these effects should be acquired in aircraft noise test programs wherever possible.

6. Effects of Topography and Geometry

For most calculations of noise exposure it is perfectly satisfactory to consider the terrain in the vicinity of an airport as being planar at the elevation of the airport itself. Some criticism of NEF calculations assumes that this is always the case, not recognizing that the height of the observer related to the height of the runway may be accounted for in any of the present models. All computations use a complete three-dimensional space in their determinations of slant distance.

In most models it is convenient to use a Cartesian coordinate system in which the origin of the coordinates is taken as the brake release point on takeoff, positive x is along the runway, y is perpendicular to the runway, and z is positive above the runway. Since all coordinates are free to assume positive and negative values, variation in terrain height is easily accounted for by assigning heights to various points on the basis of elevations obtained from normal topographic maps.

The slant distance, s, from any observation point to the flight path is given by (see Fig. 15):

$$s = \left[(z_a - z_o)^2 \cos^2\gamma + y_o^{\,2}\right]^{\frac{1}{2}}$$

It is usually adequate to approximate this equation by setting the term $\cos^2\gamma$ equal to one, where γ is the angle of climb of the aircraft, since values of γ of 12 degrees or less introduce less than 0.1 dB error in calculating EPNL, with the error at a γ of 28 degrees rising to only 0.5 dB. Even for modern interceptor aircraft such climb angles are rarely attainable, requiring thrust-to-weight ratios of 0.55 or higher, and are certainly not comfortable for the pilot. We conclude that the approximation is reasonable, even for military aircraft, and provides a substantial simplification in computation.

7. Density Altitude Effects

The noise produced on the ground is a function of the engine power delivered and the heights of the aircraft. Both

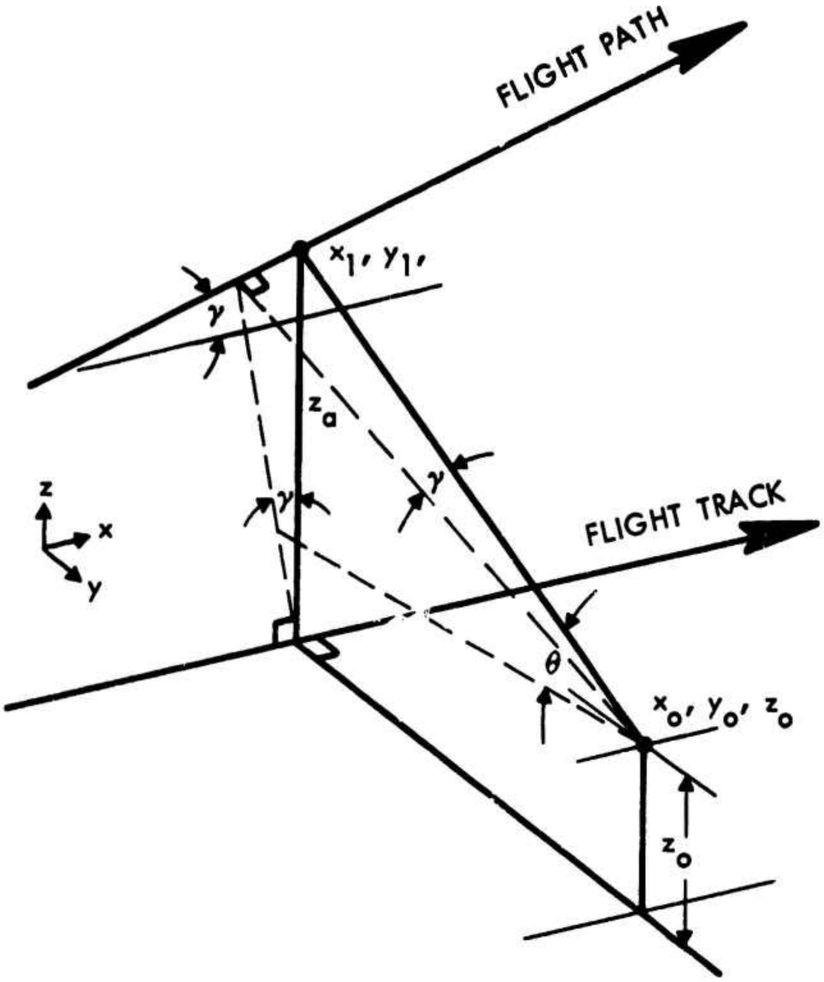


FIGURE 15. GEOMETRICAL RELATIONSHIPS IN CALCULATING NOISE EXPOSURE

of these factors are dependent on density altitude (pressure altitude corrected for temperature and atmospheric pressure). Engine noise power output is directly correlatable to net thrust, which decreases with increasing density altitude. Length of takeoff roll increases, and climb angle decreases, with increasing density altitude. Accounting for these effects in current noise exposure procedures is not normally considered (except in the South African method) except in special cases.

Application of the USAF procedure is likely to occur at air bases having substantial physical elevations relative to sea level, and extended periods of hot weather. In order to provide for these effects in noise exposure computations it is necessary to derive aircraft takeoff performance data and noise output data as a function of density altitude. The performance data are available in the appropriate Technical Orders for the aircraft, and the noise data can be determined from the basic noise test data in terms of decreased engine performance at various density altitudes. For those air bases having density altitude conditions significantly above sea level standard conditions, the noise exposure is then calculated simply by specifying the appropriate aircraft data at the time of computation.

No general procedure can be specified for selecting the density altitude conditions for which noise exposure calculations should be made with other than standard day (15°C) conditions because of the variation in the performance of different aircraft with temperature. For example, many modern jet engines are "flat-rated" to a temperature considerably above standard -- 30°C for example. Under these conditions standard day thrust is available for takeoff up to this temperature. On the other hand, many engines in use are not rated this way, with their available thrust degrading with temperature continuously.

The two factors to be considered in judging density altitude effects on noise are the change in thrust with temperature (and thus climb performance), and the change in noise level with engine thrust. For many aircraft these factors compensate for each other. That is, the decrease in climb performance is offset by a decreased engine noise level. Again, each aircraft needs to be assessed in terms of its specific performance.

As a general guide, where sustained temperatures at sea level air bases are in excess of 30°C for more than three months of the year or for bases at field elevations in excess of 3000 feet where sustained temperatures are greater than 20°C, the performance of the aircraft using the base should be assessed to determine if other than standard day conditions should be used in noise calculations. If noise levels expected one mile beyond the runway extension are more than 2 dB larger than for standard day conditions, the reduced performance should be used in noise calculations.

> Recommendation No. 12 - Data on density altitude performance and noise effects should be included in the USAF procedure.

8. Non-standard Weather Effects

In current civil aircraft NEF procedures, EPNL values are those expected under acoustic standard day conditions of 15°C (59°F), 70% relative humidity. No corrections or adjustments are made in EPNL values for local temperature and humidity conditions at individual airports. At least two different general questions can be raised concerning this procedure. First, and most important, for a particular airport, how applicable are such curves when local conditions may rarely (or only occasionally) approximate 15°C, 70% relative humidity. The second question, directed towards comparison of test data, is to what extent noise data developed on the basis of ICAO standard day conditions may differ from that obtained under FAR 36 acoustical day conditions of 25°C (77°F), 70% relative humidity.

These questions are examined in this section in terms of the expected variations in air absorption due to changes in temperature and humidity. In actual field situations, where one is concerned with the variation in noise levels received on the ground, the influence of temperature on aircraft performance may partially compensate for (or, in some cases, accentuate) the effects of temperature and humidity on air absorption.

First of all, it should be remembered that the selection of the standard reference conditions of 15°C (59°F) and 70% relative humidity is based upon a study of average surface conditions existing at a number of civil airports in the U.S. and throughout the world[43/]. The "standard" day conditions are frequently encountered in a number of major civil airports and presumably at many military air bases as well.

Field noise data that can be analyzed in terms of temperature and humidity effects alone are simply not available. Thus, in looking at the effects of non-standard weather effects, we adopted an analytic approach based upon selection of four representative one-third octave band noise spectra at reference distances, and projection of these spectra to different distances, for different values of temperature and humidity. Air absorption values from Ref. 43 were selected for the different temperatures and humidities. From the resulting spectra, PNLM and PNLTM values were calculated and compared.

Figures 16 and 17 show the results for two of the cases studied--a turbojet takeoff and a turbofan approach spectra, examined for standard day conditions and for -7°C (20°F) at 10 and 90% relative humidity, and 38°C (100°F) at 10 and 90% relative humidity. Typically, there is greater variation for the turbofan spectrum because of the higher proportion of high frequency noise energy, more affected by atmospheric absorption.

Figure 18 compares the turbofan approach noise levels for 10% and 90% relative humidity at 38°C (100°F) with the standard day conditions, normalized to a reference spectrum at 120 meters (400 feet). Comparison of sets of spectra on this basis shows that for most of the non-standard day conditions noise spectra projected beyond referenced distances of 120 m (400 ft) or 300 m (1000 ft) will show lower levels (i.e. greater absorption) for non-standard day conditions. Thus EPNL values predicted on the basis of standard conditions tend to be conservative by estimating higher noise levels than might exist for non-standard conditions. (This conclusion was earlier documented in Ref. 67.) The data from Fig. 18 shows that this holds true for all except for the condition of -7°C (20°F) and 10% relative humidity.

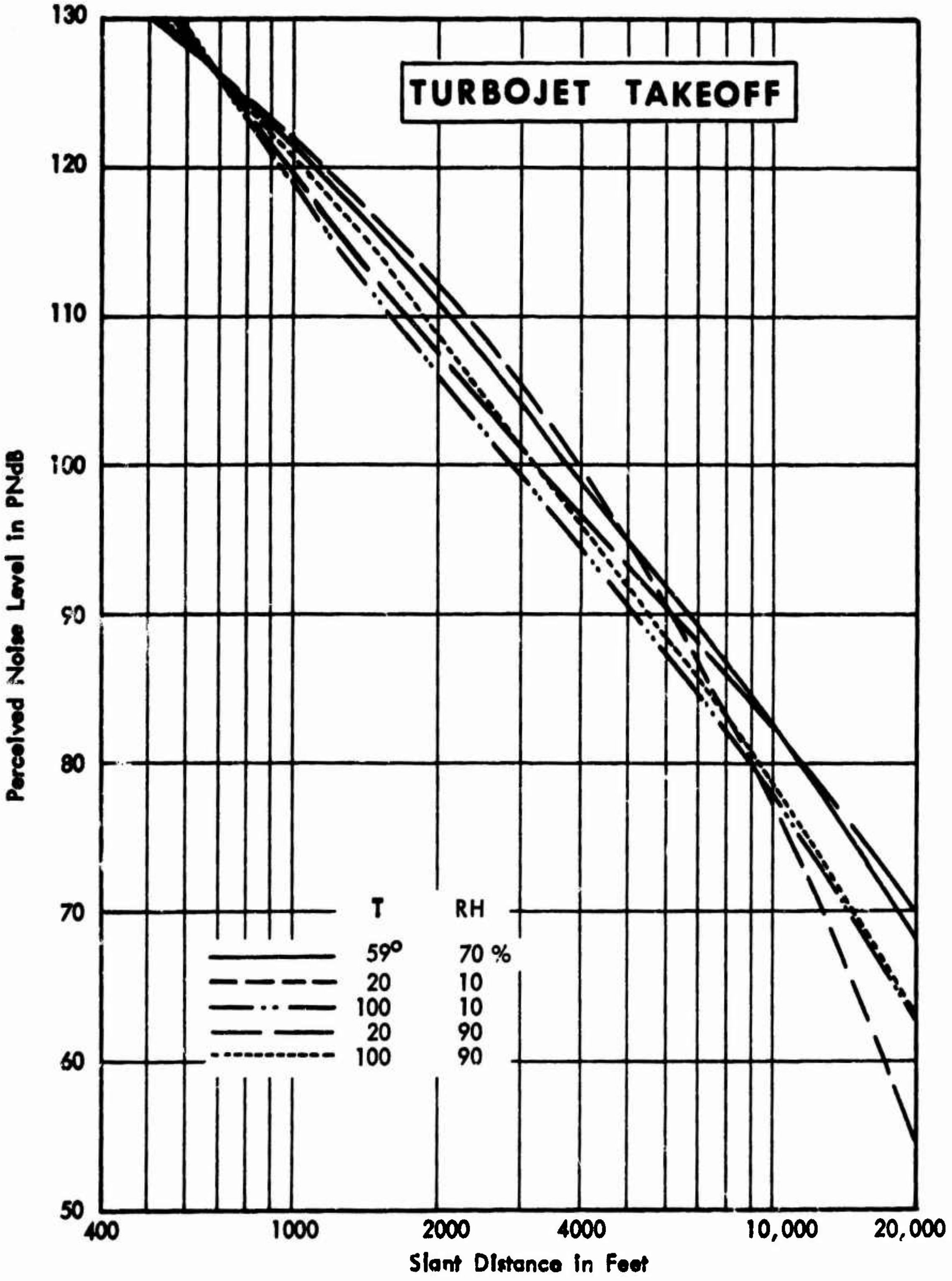


FIGURE 16. PNLM VALUES FOR DIFFERENT TEMPERATURES AND RELATIVE HUMIDITIES - TYPICAL TURBOJET TAKEOFF SPECTRUM

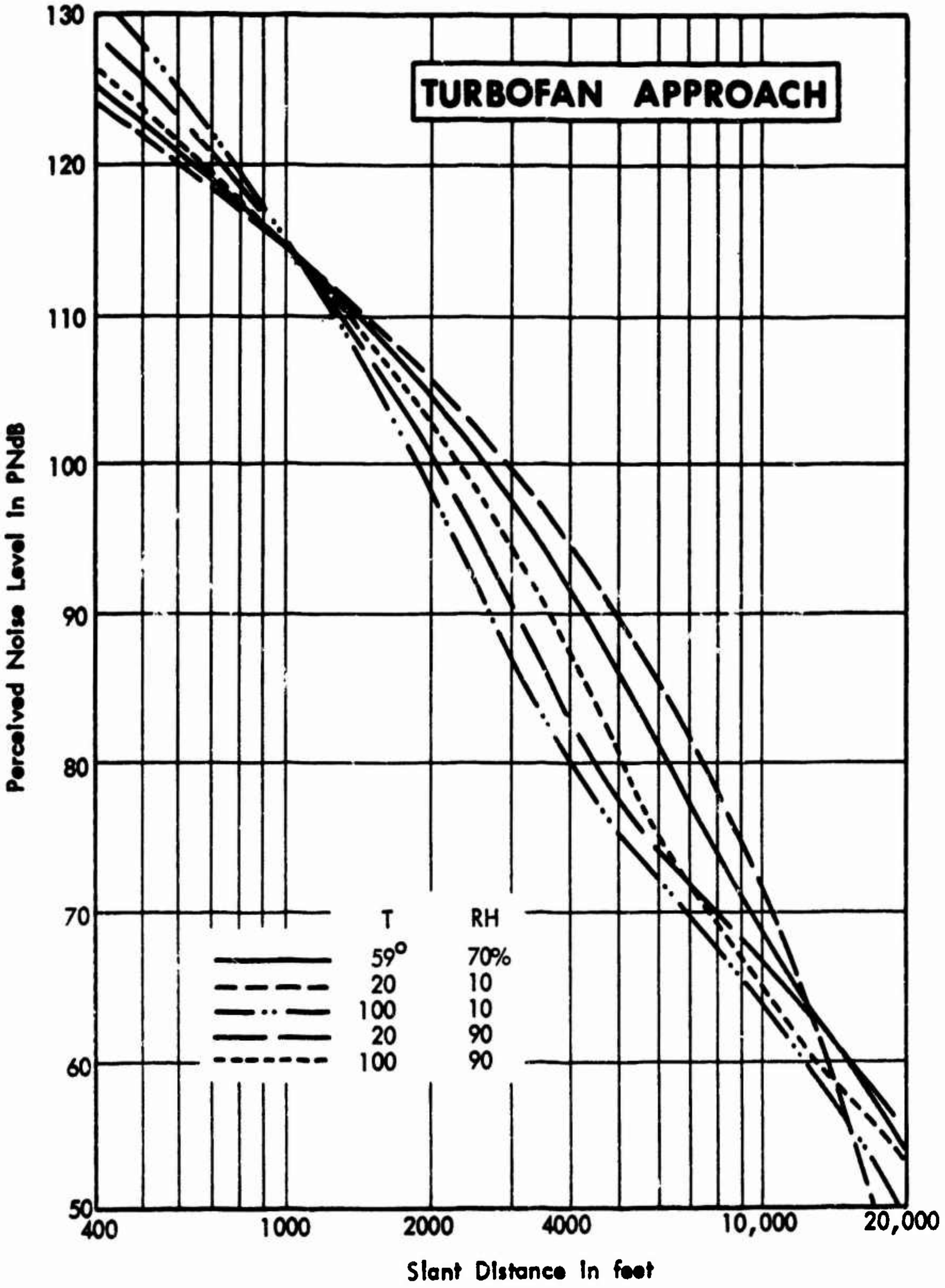


FIGURE 17. PNLM VALUES FOR DIFFERENT TEMPERATURES AND RELATIVE HUMIDITIES - TYPICAL TURBOFAN APPROACH SPECTRUM

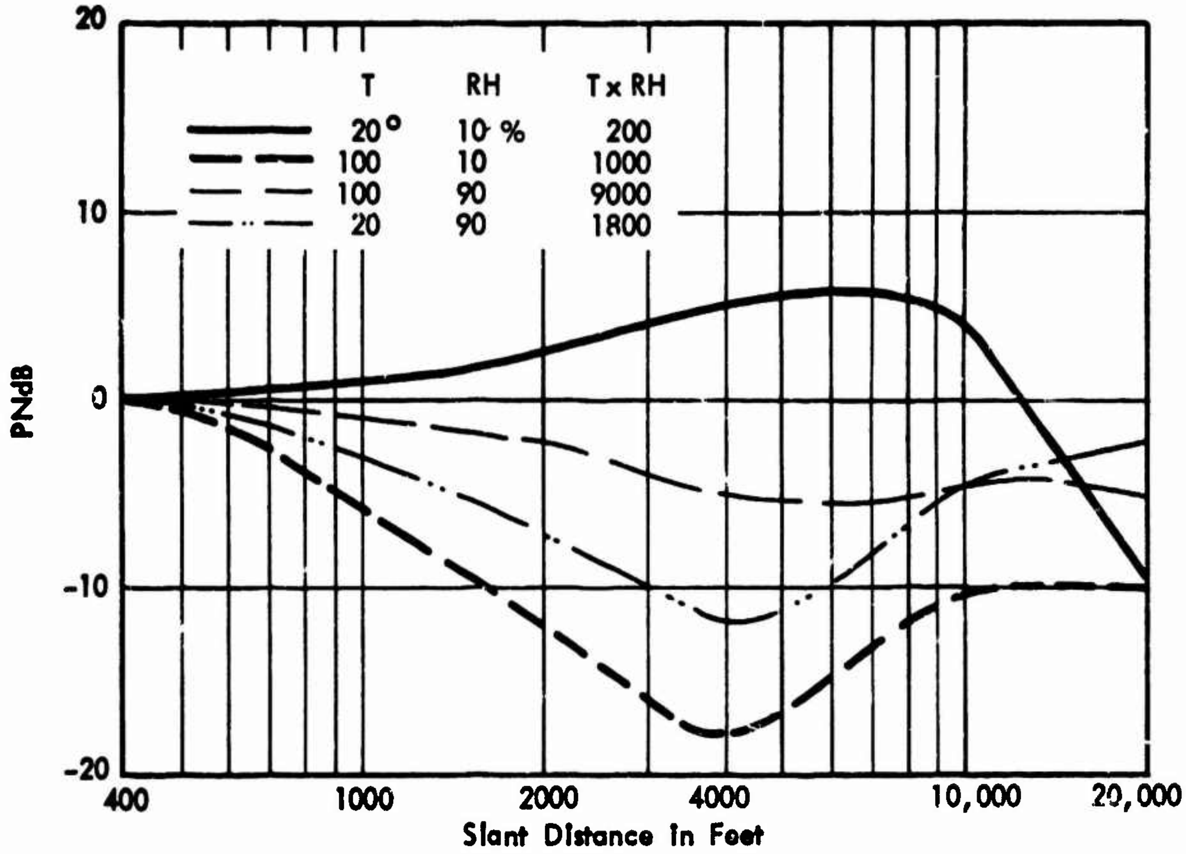


FIGURE 18. RELATIVE VARIATION IN PNLM VALUES WITH RESPECT TO PNLM FOR 59° F, 70% R.H. - TYPICAL TURBOFAN APPROACH SPECTRUM

The primary determinant of absorption is the absolute humidity. Since a rough measure of absolute humidity is given by the product of temperature (in degrees) times relative humidity, an approximate sorting of atmospheric effects can be determined by use of this estimate. Examination of the curves of Fig. 18 in terms of this estimate shows that greatest negative differences occur for relatively small products of temperature and relative humidity, with the possibility of positive differences occurring for very small values of temperature and humidity.

Mean monthly temperatures and average humidity data are given in the climatology summary for military air bases, hence temperature and humidity information is readily available for making decisions.

The technique for calculating EPNL vs. distance curves for a specified temperature and humidity follows exactly that given in Section 12 of Ref. 55, with substitution of the appropriate sound attenuation coefficients for these at 15°C (59°F), 70% relative humidity. This technique does, of course, require spectrum and EPNL information from basic flight test measurements.

The remaining question, that of comparison of differences in noise levels, assuming FAR 36 conditions and ICAO standard day conditions, can be answered in terms of noise level comparisons using the same analytic approach. Comparison of PNLTM values for several spectra shows that for distances from approximately 120 m (400 ft) to 1200 m (4000 ft), the differences in PNLM values typically do not exceed one dB. For projected distances from 1200 m (4000 ft) to 6100 m (20,000 ft) the values based upon FAR 36 conditions are generally not more than 2 dB <u>less</u> than those projected for 15°C (59°F), 70% relative humidity. Thus one may conclude that the differences in noise level projections based upon FAR 36 and ICAO standard day conditions are generally not large, except at very large slant distances. The projections based upon ICAO conditions will generally predict slightly higher noise levels than those projected on the basis of FAR 36 conditions.

One major reason for using standard day weather as the reference base for noise exposure calculations is the ready availability of aircraft performance data referenced to these conditions. Use of FAR Part 36 acoustical reference day weather requires the development of aircraft performance data for each aircraft of concern. While these calculations can be derived from available data, the non-standard presentation of the necessary information from aircraft to aircraft makes the performance data development a tedious and time consuming process for no basic improvement in the noise exposure calculation process.

> <u>Recommendation No. 13</u> - Utilize EPNL or SELT curves derived on the basis of acoustical standard day conditions (15°C, 70% relative humidity) unless examination of the mean monthly temperatures and relative humidities show three months during the year in which the product of temperature in degrees F and relative humidity in percent is less than 2000. When such small products occur, the noise exposure calculations for the air base should utilize EPNL/or SELT/distance curves based on air

absorption calculations from SAE 866 for the appropriate weather conditions.

9. Presence of Background Noise

In many community noise level evaluations, the presence of background noise levels, e.g., noise produced by other than the noise sources under consideration, is a necessary consideration. Clearly, if the background noise levels are sufficiently high, they will mask the intruding noise. In one noise measure formulated to describe noise exposure, noise pollution level, Robinson[51] explicitly includes both background noise and the intruding noise in terms of the time history of noise exposure.

Unfortunately for the community residents in the vicinity of an airport, aircraft noise is usually substantially higher than the general background noise in any residential community. By truncating noise exposure computations at distances from the aircraft where the noise level drops to 80 EPNL one can in almost all instances be sure that the background noise is substantially below the aircraft noise, yet the area of interest around the airport has been covered in the analysis. This expedient obviates the need for considering background noise levels explicitly in the aircraft noise exposure computations.

10. Shielding Effects

Two types of shielding effects have been considered in noise exposure models. One has to do with the presence of intervening structures between the noise source and the observer, the other has to do with the effects of multiple engines on an aircraft.

The effects of physical obstructions intervening between a noise source and an observer are covered in all standard acoustical texts. In the case of aircraft noise these effects are useful almost exclusively in the instance of ground run-up operations. A discussion of this problem as it pertains to air base installations is provided in Ref. 52.

In the draft for a noise exposure procedure proposed by SAE, an allowance is included for an assumed shielding effect, at low angles of elevation, for the presence of aircraft engines on the side of an aircraft away from the observer[47/]. The maximum attenuation credited is 3 dB. This effect can be accounted for, when it exists, in the derivation of the description of an aircraft as a basic noise source from flight test measurements. A special treatment of this factor in noise exposure calculations is not considered necessary in the proposed USAF procedure.

C. Basic Operational Considerations - Military/Civil Aviation Comparisons

Calculations of aircraft noise exposure are highly dependent not only on the noise properties of the individual sources, and how this noise propagates, but also on detailed knowledge of the aircraft operations at a particular air base. Often the knowledge of noise source characteristics is of higher precision than that of the operational data. In the following section we consider these variables and how they affect noise exposure. In essence, we want to know how many aircraft are doing what type of operation, at what locations, over a specific period of time.

1. Traffic Estimation - Flight Operations

One of the first considerations in analyzing an air base noise problem is to obtain an estimate of the total number of operations, by type of operation and aircraft, over a specified time period. In the civil case, current operations are generally estimated from a combination of total aircraft movements (a record kept by control towers) and by analyzing flight schedules. Operations at most civilian jet airports occur on a relatively closely maintained schedule. Airline operations can thus be estimated by reviewing these schedules, from which one can quite accurately assess aircraft movements by time, aircraft type, and destination. For given seasons of the year these schedules do not fluctuate very much, and for many airports the annual fluctuation is not more than 20%.

Military air base operations are not as easily assessed. A detailed discussion of these operations is contained in

Ref. 52,53. In brief, military flights generally occur as a random function of time, usually during the week days. An example from Ref. 52 is shown in Fig. 19. Various methods for estimating these operations are outlined in Ref. 52,53. One may analyze total aircraft assigned, availability records, mission requirements. Where such records are not easily obtainable, i is usually necessary to request that a special log of operations be kept for a period of, say, four weeks, in order that a reasonable estimate can be made. Attention needs to be paid to whether the base is fundamentally an activity of one of the normal commands or is primarily for reserve training. In the first instance activities are primarily week day, in the second they often are concentrated primarily on weekends.

Some decision rules need to be stated to determine how the operational data should be used in the USAF procedure. Current civil practice, in most instances, assumes an average daily number of operations on the basis of annual data. This is reasonable for civil airports because of the uniformity introduced by scheduled flights. As indicated above, this is not the case for military bases. In the present procedure the concept of "average busy day" is used for military air bases. This concept comes from the following assumption.

First, on the basis of case history data, it appears that community response is based on periods of sustained high activity. (This is also borne out by the recent London survey data[13/].) For most air bases, although the day-to-day fluctuations may be wide, weekdays show a sustained activity significantly higher than weekends. The opposite is true when the activity is primarily National Guard flights. Further, within the weekday fluctuations, no particular day

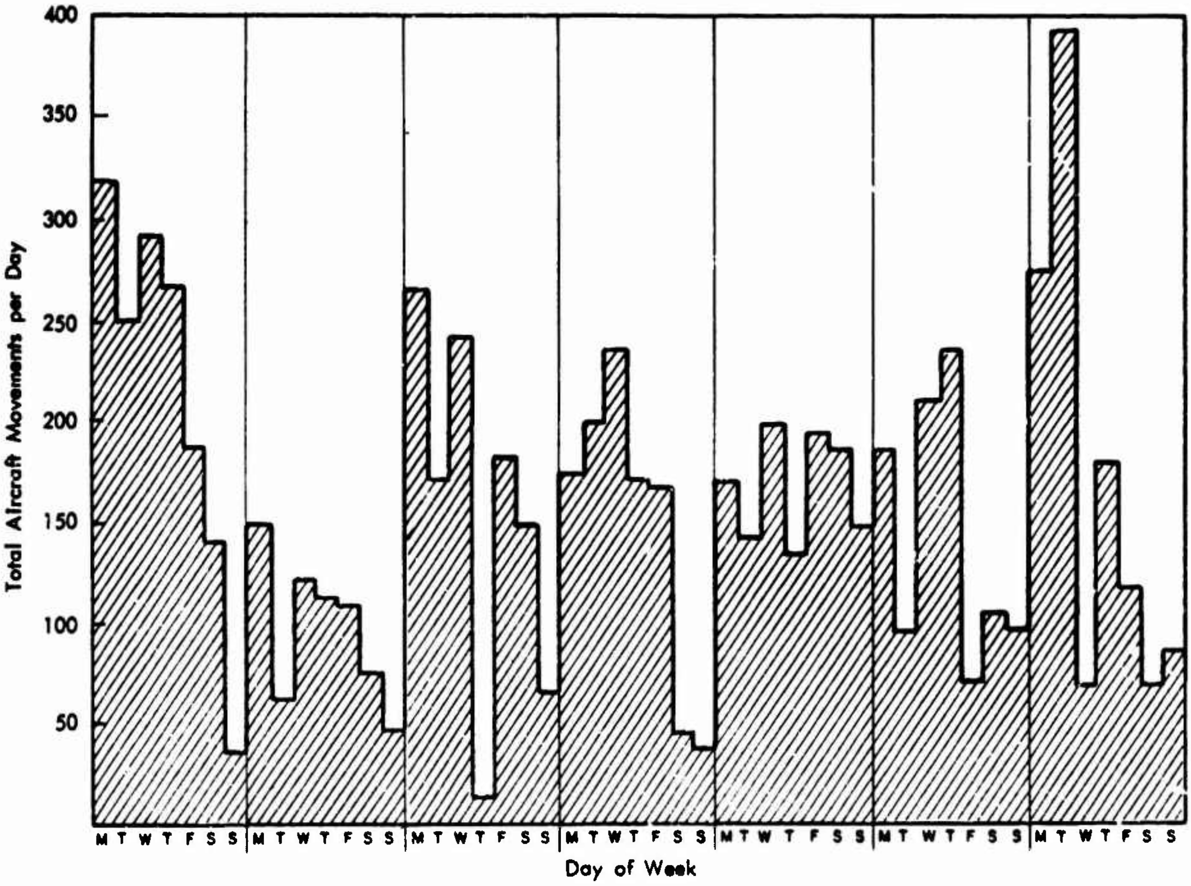


FIGURE 19. ALL AIRCRAFT FLIGHT MOVEMENTS AT MAFB, 56 DAYS

appears to be predominant. A reasonable way to estimate the activity to which the community responds is to average the number of operations over the five week days and specify this as the base for noise exposure computations.

If pronounced changes take place in operations during one part of the year as compared to another (e.g., summer versus winter, a pronounced increase in training operations relative to normal operations, temporary assignment of squadrons, etc.) the noise exposures for the two conditions should be considered separately. If the variation is a repeated condition annually, it may be desirable to logarithmically combine the different noise exposures to determine a weighted average. It is probably not necessary to consider these refinements if the average number of operations in any monthly period does not vary more than 50% from the annual "busy day" average.

Forecasting future flight operations is always an inaccurate business. In the civil case, forecasts are made by the FAA, by airport operators, and by airlines. These forecasts are based on estimated passenger and cargo growth and expected equipment complements.

For military aircraft operations, accurate forecasts are sometimes easier to come by than civil forecasts. If it is known that a given base mission and aircraft complement will be retained, or changed at some particular point in time, operations generally can be extrapolated with reasonable accuracy. The overall planning cycle for military operations is usually sufficiently extensive in time that forecasts have a reasonable expectation to be fulfilled.

Recommendation No. 14 - Computation of the number of average daily operations should be based on a "busy day" principle. For military air bases this average is usually the weekday average, based on a monthly period. Average "busy day" operations per month for each month of the year should be obtained, then averaged on a yearly basis. If any quarter of the year has operations that are higher or lower by a factor of two when compared to the annual average, consideration should be given to computing separate noise exposure contours for these periods of the year.

2. Runway Utilization

Given a total of operations, the next step in analysis is to assign these operations to particular runways and nominal flight paths. This assignment is made on the basis of actual runway use records when available. If such records are not available (they usually are not), a reasonable approximation can be made from statistical records of wind conditions. These records need to be used with an understanding of local operational restrictions, such as allowable tail or cross-wind components. Again, interrogation of local operations personnel will provide insight helpful in making reasonable decisions. This problem is identical for both civil and military airports.

3. Flight Path Utilization and Dispersion

Given a runway use assignment, the next problem is to determine the various flight paths employed with these runways. This information, in terms of nominal paths, is usually obtained from air traffic control personnel. It is essential that it also be verified with pilots and flight operations personnel. Particular attention should be given to variations in prescribed paths if substantial VFR flights are involved.

It can not be emphasized too strongly that uncertainty or inaccuracy in developing adequate flight path data is a primary source of inaccuracy in final computations of noise exposure contours. It is strongly suggested that flight paths claimed to be appropriate for an air base be verified by actual observation wherever possible. Major deviations in prescribed flight paths usually occur in radar controlled environments under VFR (and often IFR) conditions. Radar vectors for both departure and approach will be given to pilots routinely. These vectors will usually cause flight paths to depart from prescribed arrival or departure procedures. A day spent on watching radar presentations will often enable an observer to plot these deviations. Thus a reasonable estimate of mean flight paths as well as dispersion in paths can be made from these observations.

Present noise exposure computations generally allocate percentages of flights to various flight path segments that are specified as average flight tracks. An example of such segments is shown in Fig. 20. Unfortunately, variations in thrust-to-weight ratios of specific flights, air traffic procedures, and pilot technique tend to disperse individual flight tracks around the specified average track. Little quantitative data are available on this dispersion and its effect on noise exposure.

Some preliminary studies of flight path dispersion are provided in Ref. 52. Experimental observations are reported

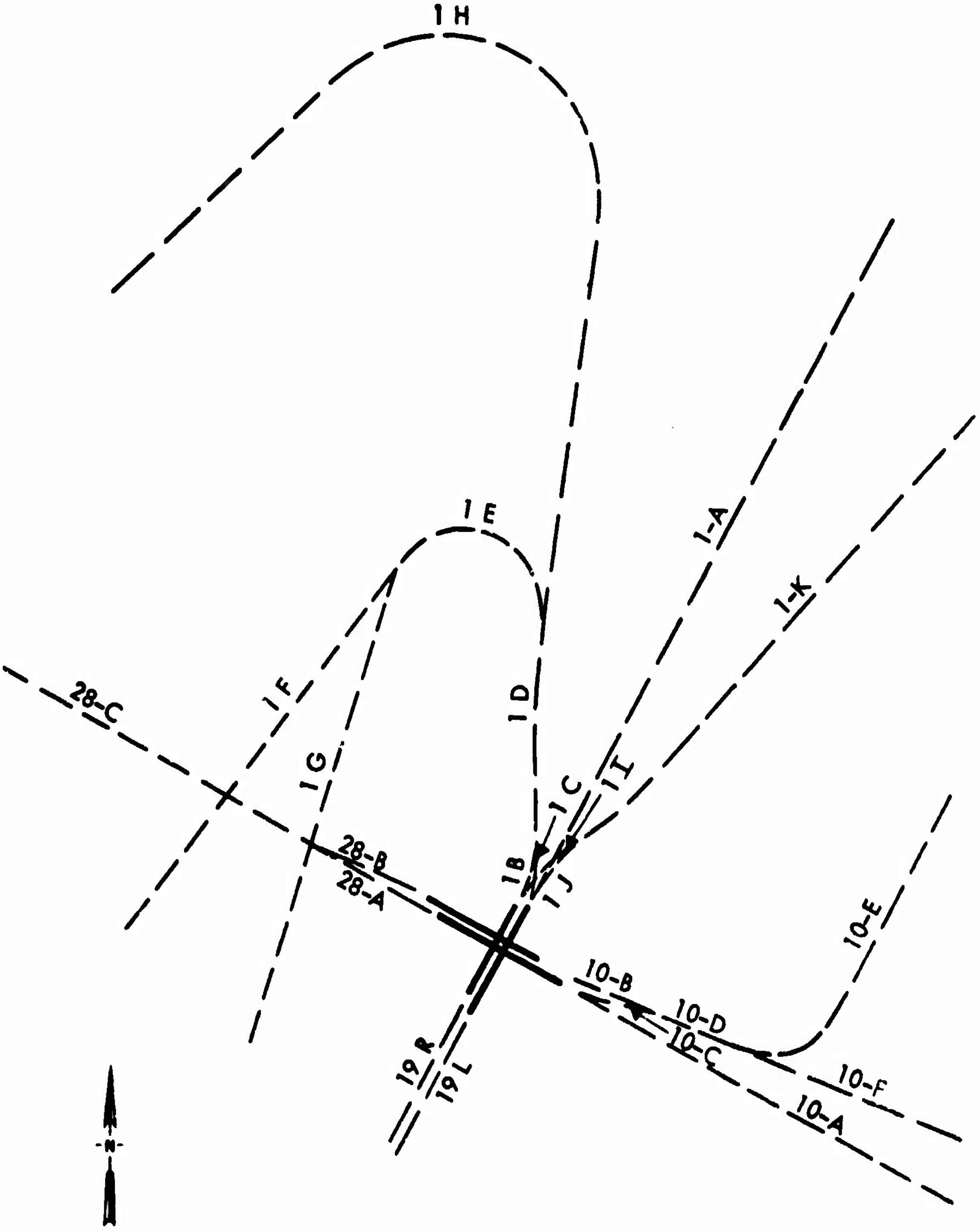


FIGURE 20. FLIGHT TRACK DESIGNATION AT AN AIRPORT

for several different types of aircraft, such as interceptors, transports, and bombers, making nominal "straight out" as well as 90 degree turns after departure. We have recently examined these data further in an initial attempt to provide a model for flight path dispersion.

The assumption in Ref. 53, which seems plausible from the experimental results, is that dispersion around a mean flight path is normally distributed in both vertical and lateral dimensions. We can then describe the dispersion in terms of the standard deviations from the mean. The data indicate that, to a reasonable approximation, the coefficient of variation in the vertical dispersion is a constant, assignable to the kind of flight operation. That is, the ratio of the standard deviation to mean height is an assignable constant. The approximate values we have derived for this constant from the data in Ref. 53 for several different operations are listed in Table VI. Note that these are all based on military applications. One would expect that civil jet transports would be comparable to the military transport conditions.

Lateral dispersion was found to vary differently for straight-out departures as compared to 90 degree turns after departure. Lateral dispersion in straight-out departures was again normally distributed, the standard deviation varying directly with distance from takeoff. From the data of Ref. 53 we were able to derive an empirical equation for the straight out lateral standard deviation, s_{yso}, as

$$s_{yso} = 0.08\ (x - x_o),$$

where x is the distance from brake release and x_o is the lift-off distance from brake release.

TABLE VI

Coefficient of Variation in Vertical Dispersion of Takeoff Flight Paths

Condition	$s_z/\overline{z}$
Maximum gross weight transports	0.1
Transports - variable weights	0.2
Interceptor - military power takeoff	0.3
Interceptor - afterburner takeoff	0.3
cut to military power	0.2
Heavy bombers - mixed weights	0.4

s_z = standard deviation in height

$\overline{z}$ = mean height

We have also examined lateral dispersions after a 90-degree turn, where the turn is begun at a specified height, e.g. 150 m (500 ft). These lateral dispersions were found to be directly proportional to the coefficient of variation in the vertical dispersion, with

$$s_{y_{90}} = 6 \times 10^3\ s_z/\bar{z}$$

where $\bar{z}$ is average height.

In the data examined above no information was available on takeoff gross weights. If it is assumed that a constant takeoff power is used, the noise level underneath the takeoff flight should vary directly with takeoff weight. In order to assess this effect we have examined data on the takeoff weight distribution of 727 aircraft during one month of an airline's operations[64/]. These data can be used to show that the takeoff weights are normally distributed (between 70% and 90% of maximum) with a mean of 78.5% and a standard deviation of 4.8%.

Using the "equivalent ground roll" concept (e.g. ground roll defined as distance from brake release to the intercept of the climb profile projected to the ground), the climb profile for a 727 with 15 degree flaps, gear retracted, climbing at V_2 + 10 knots, can be expressed as

$$z = 16.4\ (x - x_o)\ W^{-1}$$

$$z = 16.4\ (x - 0.3\ W^2)\ W^{-1}$$

where z is height, $(x - 0.3\ W^2)$ is distance from liftoff in feet, and W is gross weight in thousands of pounds.

The airline data may be combined to show that the mean height of the aircraft after lift-off is 0.132 $(x - x_o)$. One standard deviation in weight yields a coefficient of variation in height, $s_z/\bar{z}$, of 0.065. Comparing this value with those of Table VI for transports of variable weight indicates that the effect of weight alone only accounts for about one-third of the vertical dispersion. Clearly, pilot technique, airspeed control, and weather conditions, all random in nature, are the primary contributors to dispersion in takeoff height.

A similar analysis can be made of lateral dispersion in a turn. Using the above equation for climb profile, the standard deviation in distance from brake release to a height of 150 m (500 ft) is approximately 210 m (700 ft). This gives a dispersion equation of $s_y = 3.5 \times 10^3 \; s_z/\bar{z}$. Comparing this value with that obtained previously indicates that slightly more than half the lateral dispersion in a turn after takeoff can be attributed to takeoff weight effects alone, with the remaining portion due to other procedure variables.

The significance of the above analyses in terms of defining noise exposure lies in the fact that the weight dependent dispersion is taken into account in the noise computation through the specification of appropriate takeoff profiles. The remaining portion of the dispersion could be taken into account by several techniques. One would be to build dispersion explicitly into the computation. This would entail a fairly extensive simulation calculation. We are exploring this possibility but as yet have not reached a conclusion as to its practicality.

An alternative approach is to collapse the dispersion distributions to a set of, say, three paths for an aircraft type with a weighting function used to proportion different percentages of the total number of aircraft to the different paths.

In the above analyses we have identified and quantified various dispersions in takeoff flight paths. Before arriving at any conclusions on how to account for such dispersion in noise exposure calculations, the importance of the dispersion on the noise calculations should be assessed. One way to make this assessment is to simulate the dispersive flight paths and compute the resultant noise exposure.

In simulation, a binormal distribution of flight paths is defined in the y-z plane, perpendicular to the flight track. The space described by plus or minus two standard deviations in y and z defines an ellipse whose center is located by the values of y and z for the mean flight path. The ellipse is segmented into 225 equally spaced rectangles (15 divisions each in y and z). The probability of a flight path going through each rectangle is assigned according to the binormal distribution. The noise produced on the ground at various distances from the mean flight track from the total array is summed on an energy basis. This sum is then normalized to an equivalent number of aircraft flying on the mean flight path. The result is the difference in the mean EPNL value generated by the dispersion distribution relative to the EPNL for the non-dispersive flight path.

Examples of this simulation are shown for specific takeoff situations in Figs. 21 and 22, and for generalized situations in Figs. 23 and 24.

The first simulation considers the case of "straightout" departures incorporating both vertical and lateral dispersion. The results plotted on the left hand graph of Fig. 21 show the change in noise levels, relative to the noise levels of a non-dispersive distribution, as a function of distance y perpendicular to the extended centerline of the runway at a distance of 5800 m (19,000 ft) from liftoff. In this case the standard deviation in height, s_z, is 60 m (200 ft) with mean height of 300 m (1000 ft), and the standard deviation in y, s_y, is 435 m (1530 ft). The three curves show the effect of vertical dispersion only, lateral dispersion only, and the combined effect of both dispersions. It is quite clear that dispersion in height very minimally affects the noise results. Lateral dispersion, however, shows pronounced effects, varying from -2.5 to +3 dB. This would result in foreshortening the length of a given EPNL contour, while causing a bulging out of the contour at an intermediate distance.

In order to show the effect of the result that lateral dispersion varies directly with distance from liftoff, the change in EPNL at 3500 m (11,600 ft) and 5800 m (19,000 ft) from liftoff is shown in the right hand graph of Fig. 21. The decrease in effect of a lower lateral dispersion is clearly evident.

The second simulation considers the case of aircraft following a procedure which calls for a 90 degree standard

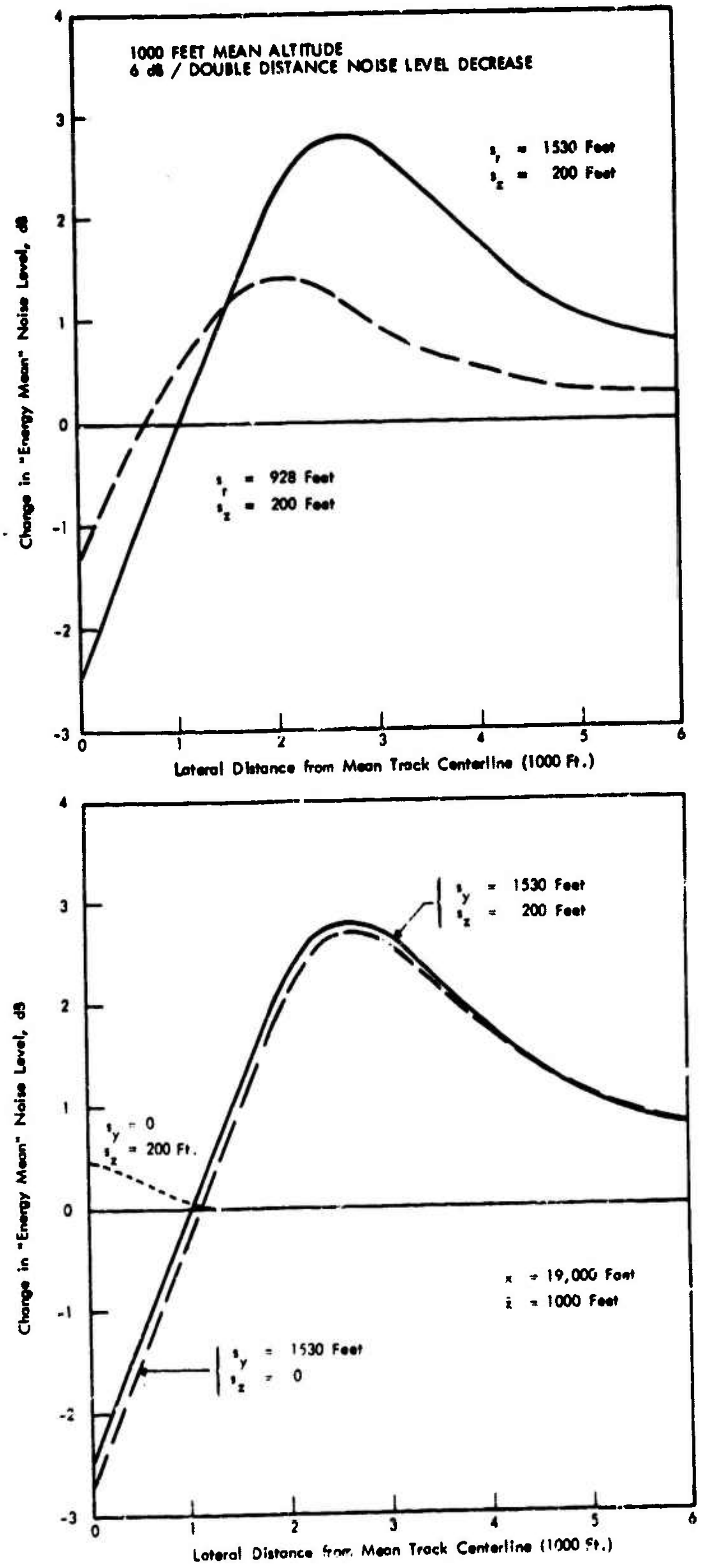


FIGURE 21. EFFECTS OF VERTICAL AND LATERAL FLIGHT PATH DISPERSION ON NOISE LEVELS - "STRAIGHT-OUT" DEPARTURE

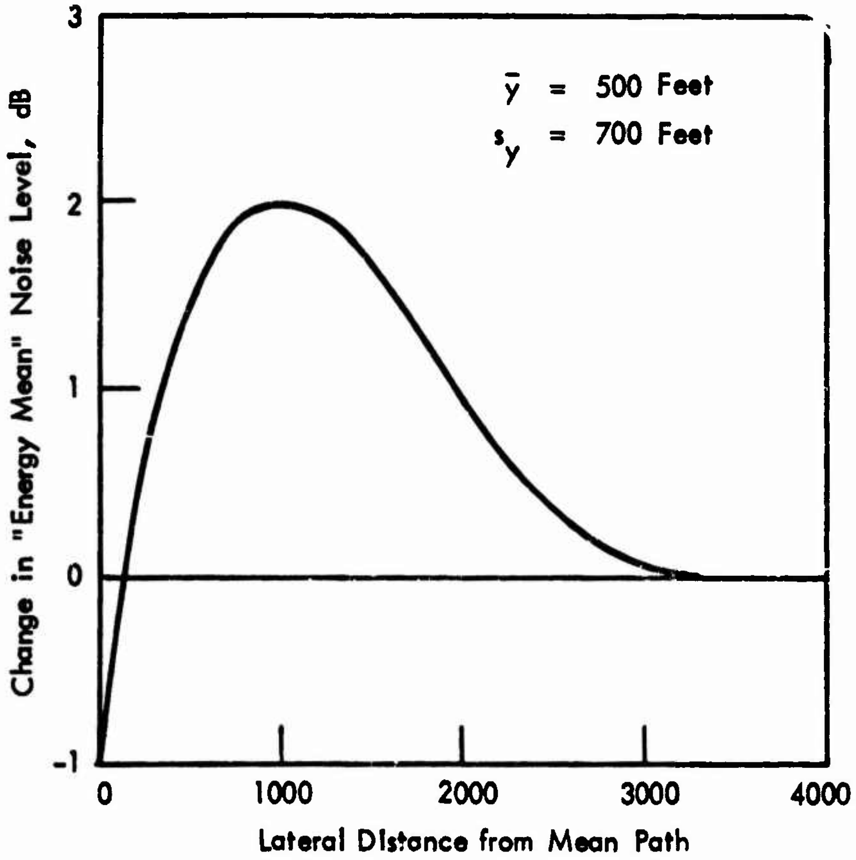


FIGURE 22. EFFECT OF DISPERSION IN A 90° TURN ON MEAN NOISE LEVEL AFTER THE TURN

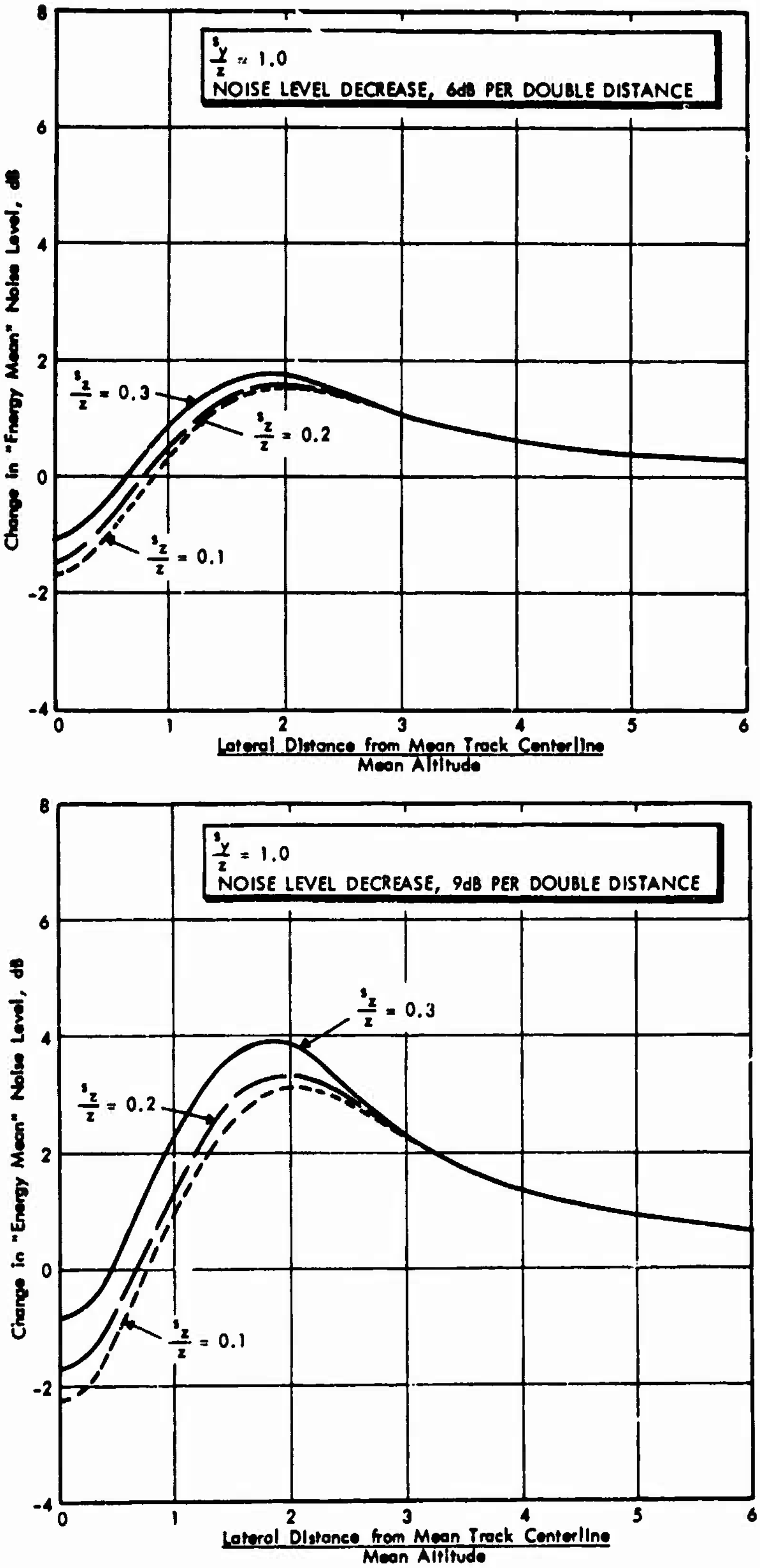


FIGURE 23. EFFECT OF FLIGHT PATH DISPERSION ON NOISE LEVELS FOR DIFFERENT DEGREES OF VERTICAL DISPERSION

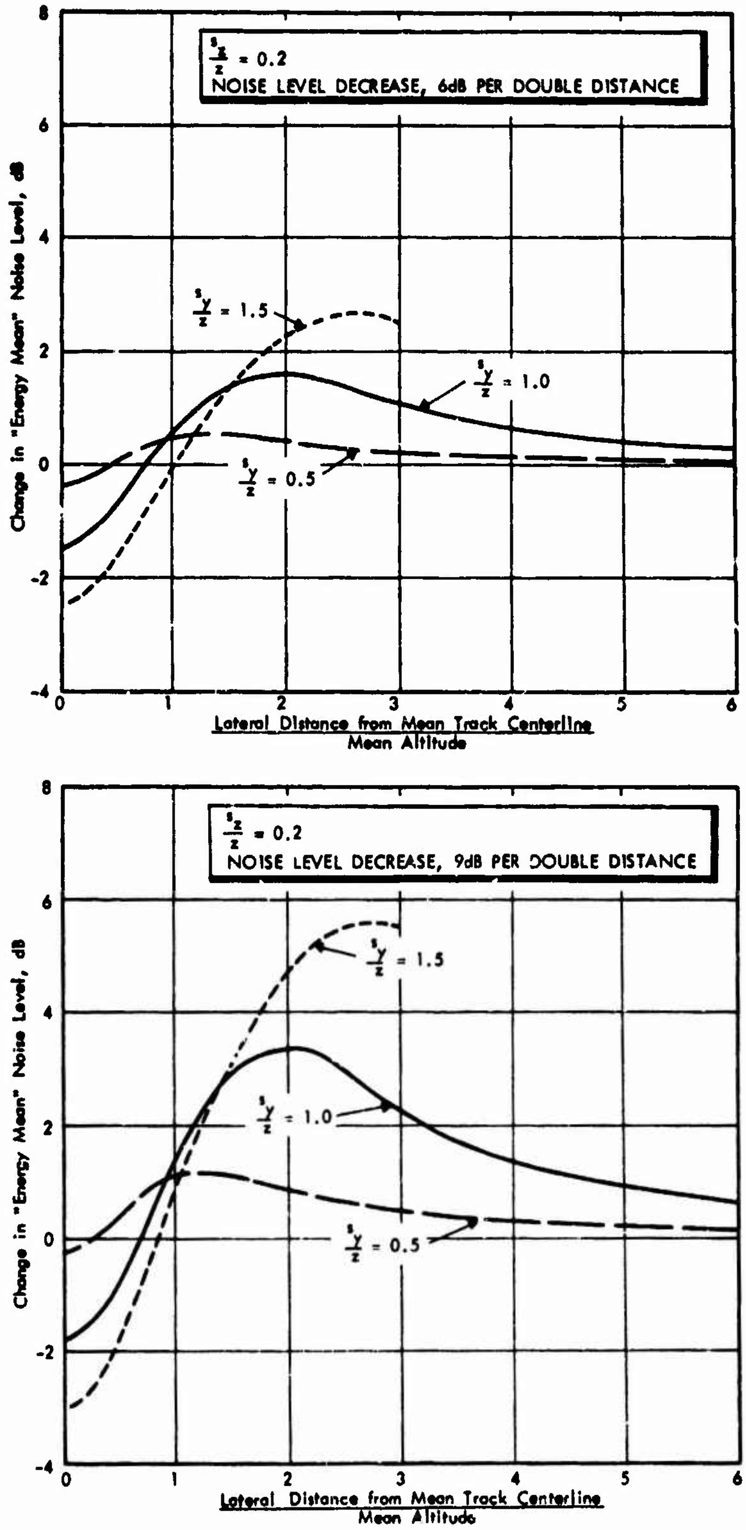


FIGURE 24. EFFECT OF FLIGHT PATH DISPERSION ON NOISE LEVELS FOR DIFFERENT DEGREES OF HORIZONTAL DISPERSION

rate turn after reaching a specified altitude. Using the equation for 727 takeoff profiles stated above, we find that the standard deviation in lateral dispersion after the turn is 210 m (700 ft) for the takeoff weight distribution described previously if the height for the beginning of the turn is 150 m (500 ft). (This height is chosen to emphasize the effect of the turn; it would probably not be used in practice.) The results are shown in Fig. 22. The dispersion curve is similar in shape to those for the previous simulation. Again, the levels on the mean path are 1 dB lower with dispersion, are higher by 2 dB at 300 m (1000 ft), and diminish to essentially zero by 900 m (3000 ft). The resultant noise contour would be slightly broader and slightly shorter than that obtained if no dispersion at all is assumed.

We conclude that vertical dispersion in takeoff paths negligibly affects noise exposure computations as compared to assuming mean flight profiles for a given aircraft type. Lateral dispersion, however, can both broaden and foreshorten the contours. Suitable means for accommodating the effects of lateral dispersion on takeoff should be explored further for incorporation in noise exposure models.

Similar analyses of the effects of dispersion in approaches to landing have been explored in this study. It is assumed in most noise exposure computations that the aircraft is following a 3 degree approach path, normally that defined by an ILS. Full lateral deviation on the localizer part of the system is 2.5 degrees, while full vertical deviation is 0.5 degrees on the glideslope part of the ILS. This amounts to a lateral deviation of 750 m (2300 ft) and a vertical deviation of 140 m (460 ft) at 10 miles from touchdown (a mean height of 970 m [3180 ft] for a 3 degree glide slope). These deviations proportionately decrease as distance to touchdown decreases.

A qualified pilot will typically expect to maintain his approach well within less than half of these deviations. An auto-coupled approach will restrict deviations to considerably less than one-quarter of these deviations. Variations in noise levels produced on the ground due solely to variations in flight paths on an ILS approach can be expected to be less than plus or minus 0.5 dB. Dispersion in flight paths on final approach is thus not considered significant.

The results of the simulation studies can be further generalized, with results as shown in Figs. 23 and 24. These figures show the results of dispersion for assumed noise level decreases with distance of 6 dB and 9 dB per doubling of distance (Figs. 21 and 22 assumed a 6 dB decrease per doubling of distance). Comparison of the left and right graphs of Figs. 23 and 24 clearly shows that dispersion effects increase in magnitude as noise levels decrease with distance at greater rates.

Figure 23 illustrates the changes in noise levels as the vertical dispersion is changed, holding the horizontal dispersion constant. The results confirm that noise levels are relatively insensitive to changes in vertical dispersion. Figure 24, comparing changes in noise levels for changes in horizontal dispersion, for a fixed vertical dispersion, illustrates the greater sensitivity of noise level to changes in horizontal dispersion. For the relatively large horizontal dispersion ratios used in Fig. 24, the maxima of the curves increase almost linearly with the horizontal dispersion ratios, h_y/z.

> Recommendation 15 - Allowance for flight path dispersion should be included in the USAF procedure. Until better dispersion models are available, the empirical equations derived here should be used. Where it is possible to make an experimental determination of flight path data, the observed information should be used in the procedure.

4. Variation in Thrust Schedules

Thrust on takeoff or approach varies between different aircraft flights as a result of operating weights, airspeed specification, and normal operating procedures. These procedures are usually identified with specific segments of a given operation. With civil aircraft, for example, thrust changes typically occur on power reduction from takeoff to climb, or in specific noise abatement thrust reduction procedures. Military aircraft employ similar thrust schedules, e.g. "afterburner to 2000 feet, then reduce to military power."

All the specified thrust management procedures are accommodated in present noise exposure computational procedures by specifying the noise output for various thrust values. Since thrust changes are accompanied by a change in flight profile, it is customary to account for the thrust conditions and flight profile variations by dividing the flight path into segments for which the specific conditions apply.

5. Noise from Ground Run-up Operations

Fundamentally, there are no differences in noise exposure calculations between civil and military flight operations. Normal takeoff and approach operations are similar in both instances. Touch-and-go operations occur in both cases. The military use of afterburner or water injection is treated by flight path segmentation as indicated previously. As long as thrust schedules and their associated flight paths are definable into segments, any set of conditions can be accommodated, including overhead approaches and multiple aircraft (e.g. "flight of two") takeoffs.

Significant differences between civil and military operations occur for the method of treating noise produced on the ground by aircraft on the ground. The present civil NEF computations do not include ground run-ups, either for maintenance or pre-takeoff operations. Most civil aircraft maintenance operations involving engine operation are performed in test cells or under isolated conditions at carefully controlled locations. This is not true at most military bases, where protracted ground running often occurs. Pre-takeoff runup, or afterburner lighting, is customary for military aircraft, while civil aircraft most often use a "rolling" start.

Noise from ground operations should be incorporated in any complete noise exposure computational model. The procedure now in use in the present USAF procedure describes aircraft ground operations in terms of polar diagrams of PNL, as a function of distance from the aircraft, for various thrust values. This same basic description, using PNLT (or ALT) instead of PNL, can be used to obtain EPNL directly from the expression $\text{EPNL} = \text{PNLT} + 10 \log_{10} \frac{D}{10}$, where D is the duration in seconds. Pre-takeoff run-ups can thus be easily merged with takeoff EPNL values to give a complete description of the takeoff noise exposure.

Incorporation of maintenance run-up operations into the noise exposure model requires different consideration. In the evolution of the present CNR procedure it was found that community acceptance of noise from known maintenance run-ups was much lower for a given noise exposure than that for fly-overs of the same exposure. One hypothesis is that people feel that the air base or airport operator can't do much to control flight noise, but he can, through location and scheduling, exert much more control over maintenance run-ups. Thus, for an equal degree of community response, the limited case studies showed that noise exposure from maintenance operations must be substantially lower than noise exposure from flight operations.

This observation is accounted for in the present CNR procedures by allowing noise exposure from flight operations to be 20 dB higher than for known ground run-up operations in the present CNR procedure. This difference is due to three factors--the manner in which individual event durations is considered, the normalizing assumptions in obtaining "zero" corrections to CNR, and in the different degrees of expected response. In converting from stepped adjustment factors, as now used in CNR, to an energy integrated noise exposure, such as NEF or DNL, each of these factors needs to be reviewed.

The implicit duration assumed in the present CNR procedure for flight operations, as defined by the duration between the points in the time history that are 10 dB below the maximum, was 15 seconds for takeoffs. For many typical flyover signals in the vicinity of airports this results in an EPNL value that is almost equal to the maximum PNLT value. (For a Gaussian shaped time history the integration procedure provides EPNL = PNLTM - 0.8 dB; the "effective" duration is 8.3 seconds for the 15 second duration between 10 dB down points.) The "zero" correction CNR for flight operations in the day time applies to 10 to 30 operations. Assuming an average of 20 operations, the effective total exposure is

$$\text{PNL} + 10 \log (8.3 \times 20) = \text{PNL} + 22 \text{ dB}.$$

The run-up duration for zero correction is 1 to 5 minutes. Assume an average of 3 minutes. The zero correction for operational factors applies to "5 or less." Assume a typical value to be 3. The effective total exposure for run-ups at zero correction in the CNR procedure is thus PNL + 10 log (3 x 3 x 60) = PNL + 27 dB, or actually 5 dB more than for the zero correction case for flight operations.

In the CNR procedure the operational adjustment and criteria values were selected so that ground and flight operations could be compared on an equal response basis. The penalty of 20 dB for ground operations becomes 15 dB when equal noise exposures between ground and flight operations are compared, since the ground noise exposure is actually overstated by 5 dB as compared to the flight noise exposures.

In order to assess the validity of the ground operations noise criteria used in the CNR procedure we reviewed the case histories used in developing the procedure. There were only five case histories available to assess ground operations. Each had three things in common. First, all operations were conducted at night, with low background levels when the aircraft noise was not present. Second, there were essentially no flight operations during the time of the maintenance operations. Third, in each case jet operations had not been in effect for much more than one year at the time the case was identified.

It is reasonable to speculate that these factors, as better identified in social surveys, tend to provide a stronger community response than the noise exposure would indicate for more normal circumstances. Lack of previous exposure, quiet background levels when the run-ups were not in operation, night time conditions probably thought unnecessary (misfeasance on the part of the operators?) all would tend to increase response. In retrospect, the penalty applied to ground operations is based on only a few data points with these unusual conditioning factors involved. The ground operation noise penalty might well be too stringent, or even not required under most circumstances. Unfortunately, no new data on response to ground maintenance operations are available in any documented form. For example, the data on annoyance obtained in community social surveys make no reference to ground operations.

The importance of resolving this problem cannot be overestimated. For those bases where maintenance run-ups are a significant part of the operations, overestimating the expected response of a community by defining noise contours at too low a value of exposure can extend to a large area the region that would be judged incompatible for residential use. It would seem that two steps might be taken to resolve this problem. First, those air bases suspected or known to have run-up noise problems should be identified. Second, a survey of the community response at several selected bases should be made. The correlation of this information with noise exposure due to ground operations could then be used to determine the appropriate noise criteria.

In the interim, it appears to the author, after reviewing the limited case histories currently available, that the present criteria in the CNR procedure overstated the ground noise situation by at least 5 dB of equivalent noise exposure. On this basis, noise from ground operations would be penalized by 10 dB, on an exposure level basis, as compared to noise from flight operations. We propose this factor be used in the USAF procedure until further evaluation provides a clearer picture of the proper means for evaluating noise from ground operations.

> Recommendation 16 - Ground run-up operations for maintenance purposes should be included in noise exposure calculations by computing their EPNL or SELT values. These values should then be weighted by an additional 10 dB when summing the total exposure at the air base.

> Recommendation 17 - Run-up associated with takeoff operations should be included in the takeoff noise calculations directly in terms of their contribution to the takeoff EPNL or SELT.

D. Discussion of Prediction Accuracies

Differences between predicted noise exposures around an air base and those that would be measured can be considered in two different ways. One can first examine the possible error in predicting the EPNL for a single aircraft at any point on the ground. A second, more generally useful approach is to examine the possible error in the noise exposure for an accumulation of events. Since a twenty-four hour assessment of noise exposure is the base of computation for CNR, NEF and other indices, the accuracy of predicting the exposure from a number of events is of more interest for planning purposes.

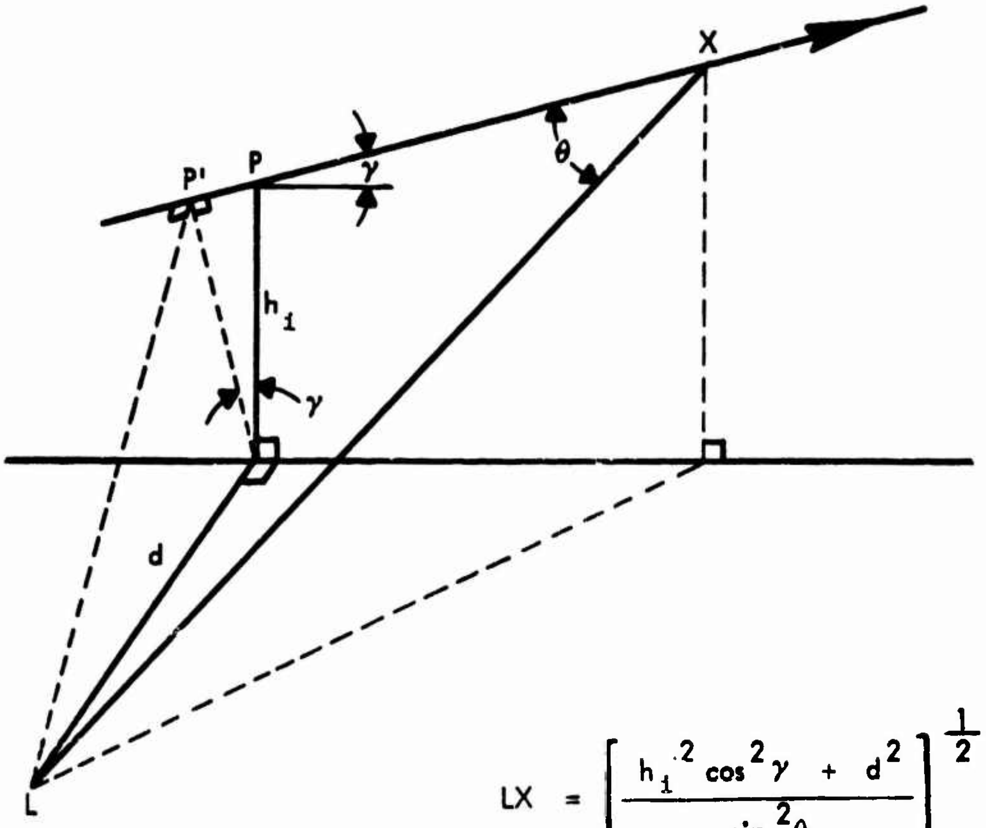
One may examine the case of the individual event prediction by considering first the accuracy of generation of the EPNL/distance function from controlled test measurements. As we show in Ref. 55, the EPNL produced on the ground at slant distance LX by an aircraft in flight is given by:

$$\mathrm{EPNL}_x = \mathrm{EPNL}_{h_o} + \mathrm{PNLT}_x - \mathrm{PNLTM}_{h_o} + \Delta_{2x} + \Delta_6$$

where: $\Delta_{2x} = 10 \left[\log_{10} \frac{LX \sin\theta}{h_o} - \log_{10} \frac{Vx}{V_{ref}} \right]$

Δ_6 = incremental change in noise power output relative to the noise power at reference conditions.

$$LX = \frac{\left[h_i^2 \cos^2 \gamma + d^2 \right]^{1/2}}{\sin^2\theta} \qquad \text{(See Fig. 25)}$$



$$LX = \left[\frac{h_1^{\,2} \cos^2 \gamma + d^2}{\sin^2 \theta} \right]^{\frac{1}{2}}$$

FIGURE 25. GEOMETRY FOR EPNL AT A POINT ON THE GROUND

$PNLT_x$ is obtained from the one-third octave SPL spectrum, where individual one-third octave band levels are computed as follows:

$$SPL_{ix} = SPL_{ih_o} - \alpha_{ir} \left(LX - \frac{h_o}{\sin\theta}\right) - 20 \log_{10} \frac{LX \sin\theta}{h_o}$$

and SPL_{ih_o} are the 1/3 octave band levels from which $PNLTM_{h_o}$ is computed. In these expressions h_o is the height of the aircraft when the test data were acquired, θ is the angle of directivity at the time PNLTM occurs, α_{ir} are the reference values of air absorption in each one-third octave band, and V is aircraft speed in knots.

The basic accuracy of determining $EPNL(h_o)$ is generally indicated by standard deviations of the order of one dB, or standard errors of a maximum of 0.5 dB. The error in predicting $EPNL_x$ up to distances of 4000 feet is shown in Ref. 35 to be of the order of one dB. These conditions apply when the operating conditions, weather, and position of the aircraft are well known.

In the normal case, the data on aircraft operation, weather, and location are not well known. We would like to estimate the likely variability in predicted versus measured EPNL in such a case. The predicted value of EPNL at any point is based on an estimated mean height for the aircraft obtained from takeoff profiles, and the EPNL/slant distance curve derived as above. We know from the dispersion studies that a typical standard deviation in height is 0.2 times the mean height. This introduces an uncertainty of only 0.8 dB.

Variations in power management can introduce from zero to 4 dB uncertainty in any given flight. Finally, variations in weather conditions can introduce from 5 to 10 dB differences between measured and predicted noise levels at slant distances in excess of 10,000 feet under most ranges of weather typically encountered or as much as 17 dB under extreme weather conditions. In these extreme weather cases, the change in air absorption is often compensated partially by changes in aircraft performance.

Quantifying the differences between predicted and measured EPNL values with any degree of reliability when the operational and weather conditions are unknown is at best a guessing game. Of more usefulness is the examination of data where aircraft positional information is available, permitting comparisons of predictions with noise measurements.

One example of these kind of data is available from a recent FAA project[65/]. In this study a series of controlled takeoff and approach procedures were evaluated for several types of jet transports. The data scatter at any measurement location was generally between 5 and 10 dB, corresponding to standard deviations of the order of ± 2 dB.

Another example of measured versus predicted EPNL values is available in another recent FAA study of approach noise with typical airline operations at a commercial airport[66/]. The following table indicates the standard deviation for sets of noise measurements of three classes of civil jet transport aircraft. The table also shows the standard deviation for the components of the variance due to distance and air absorption, and the standard deviation for the residual variance.

TABLE VII

Variability of EPNL Values Under the Nominal Approach Path - 31,000 to 82,000 feet from Touchdown Expressed as Standard Deviations in dB

Aircraft Type	No.	Total	Components of Variance		
			Distance	Weather	Other
Four-engine	332	7.6	5.9	2.5	4.0
Three-engine	344	6.5	5.4	1.9	3.0
Two-engine	254	7.0	5.6	1.9	3.8

Assessing the accuracy in predicting noise exposure from a series of events is another matter. Several factors enter into the problem which make it difficult to derive analytically a basic accuracy of prediction. First is the accuracy of knowing the aircraft type mix. For aircraft of the same basic type and engine configuration it is not important to know the exact numbers of each model, only the total. Further, an inaccuracy in forecasting total numbers within the class of as much as 25% introduces only a one dB error in the noise exposure calculations.

Of most importance is the proper identification of flight tracks. We have shown in the discussion on dispersion that errors up to 3 dB or more can be introduced by assuming no dispersion. The error associated with total mis-identification of flight tracks cannot even be assessed.

Errors in estimating flight track utilization, however, of 25% are required to make a one dB error. For the main runways where utilizations may be 30 to 90 percent, a 25% error in estimated usage is not too likely. However, the utilization for little used runways (e.g. 1 to 5 percent utilization) can often be mis-estimated by factors of two or more, introducing errors of 3 dB or even greater.

Probably of more significance in assessing errors in noise exposure computation is to compare some actual measurements of exposure with those predicted by NEF methodology for the same cases. One comparison can be made for the data reported in Table VII. These data were obtained at six different positions directly under the normal flight track over a number of days. Traffic density did not vary significantly during the days of measurement. The following table lists the difference between predicted and measured values of NEF.

TABLE VIII

Predicted Minus Measured NEF

Position	Δ NEF
1	0.9
2	1.2
3	1.0
4	-0.6
5	-3.5
6	-1.9
Average	-0.5
Standard Deviation	2.0

It should be observed that the average EPNL at position 5 was higher than generally expected, hence the larger Δ NEF value.

Other examples are available from recent noise monitoring experience at civil airports, where monitored noise data has been compared with computed CNEL values. At one civil airport, noise measurements were made at 17 positions for periods varying from two to eleven days[77/]. The computed CNEL contours overestimated measured takeoff CNEL values by an average of 0.8 dB, with a standard deviation among stations of 1.4 dB. The computed landing CNEL contours underestimates measured CNEL values by an average of 1.4 dB, with a standard deviation among positions of 2.1 dB.

In summary, if accurate data on aircraft performance, weather, and position are available, one can expect to predict EPNL (over reasonable weather limits) to within a standard deviation of plus or minus one to two dB up to slant distances of the order of 10,000 feet. Where the performance, position, and weather information is only nominally known, the standard deviations increase to as much as ± 4 dB. On the other hand, cumulative noise exposure from a number of events seems to be predictable to about one-half the variation in prediction of EPNL alone. It is reasonable to assume that a good noise exposure model with reasonably reliable input data can be expected to predict actual noise exposure with a standard deviation of about ± 2 units of NEF.

V

CONCEPTUAL DESCRIPTION OF A NEW PROCEDURE FOR USAF AIRCRAFT NOISE LAND USE PLANNING PURPOSES

The present USAF procedure[2/] is purposely designed for easy application, through the use of equal PNL design contours that permit hand computation of the noise exposure from a series of aircraft operations. This ease of application has provided a useful tool for planning purposes. The simplification process, however, can lead to sizable errors, as much as 10 dB, if proper judgment is not used when borderline operational correction factors are applied.

The evolution of exposure level descriptors such as EPNL and SELT, instead of maximum PNL, has been shown to be a substantially more general quantity for a variety of aircraft noises. In order to make best use of the exposure level measures in land use planning procedures the simplified 5 dB step operational adjustment factors used on the current procedure need to be replaced with more accurate assessments of aircraft movements. Further, more refined treatment of sound propagation factors, allowance for variability in flight paths, and more refined aircraft performance data will improve the accuracy of noise exposure computations.

In order to accommodate the above items in a planning tool, it is most practical to utilize a computer model for noise exposure computation. A suitable computer program allows as much refinement as desired in order to improve the accuracy of the noise exposure computations.

The following description outlines the procedural framework for a revised aircraft noise/land use planning procedure developed in this project as a result of the foregoing review. This procedure is programmed to provide a computer generated graphic plot of noise exposure level contours for the entire complex of operations at an airport. It is not the intent of this description to provide the detailed implementation of all the technical elements employed in the computation itself. The primary purpose is to discuss the input data for the model and to describe the combinatorial rules used for developing a single number descriptor of the noise produced by a complex of aircraft operations. All the recommendations provided in the previous sections of this report are either included explicitly in this description, or are implicitly included in the computer development of the procedure. An engineering description of the computational method is provided in Appendix C. Companion reports in this series provide an applications guide[78], a test procedure for source noise data acquisition[79], computer program operators manual and program description[80,81], and a basic acoustic data file for military aircraft[82].

A. Aircraft Noise Source Description

During the initial part of this project the wide use of EPNL as a descriptor for aircraft noise because of the tecnnical reasons for its superiority led to our preference for its use in the proposed USAF procedure. During the project's development, however, it became clear that EPA was strongly urging the adoption of A-weighted sound level as a universal descriptor of noise from all sources. It became apparent that, while a final decision on the use of EPNL or

A-weighted sound level must be made on an administrative basis, the technical progress of this project should be conducted in such a way that whatever noise measure is eventually selected would be available in the data base.

With these factors in mind, it was decided that the primary data for all noise source characteristics should be obtained in terms of one-third octave sound pressure levels as a function of time. These data can then be used to derive any of the single number descriptors that might eventually be desired. The data reported in Ref. 82 provide the following noise measures from the test data:

AL - Maximum A-weighted Sound Level
ALT - Tone Corrected Maximum A-weighted Sound Level
SEL - A-weighted Sound Exposure Level
SELT - Tone Corrected A-weighted Sound Exposure Level
PNL - Maximum Perceived Noise Level
PNLT - Maximum Tone Corrected Perceived Noise Level
EPNL - Effective Perceived Noise Level

The entire data set described below is available in any of these noise measures. We recommend, however, that only EPNL and SELT be utilized in the overall project.

The basic description of noise from a single aircraft operation is a combination of the noise producing properties of the aircraft, as a function of engine power, and a set of operational information that describes the performance of the aircraft during takeoff, landing, and ground run-up, over the basic operating envelope for the aircraft. The noise level characteristics of the aircraft are determined from a noise test program, described separately[79] and summarized in Ref. 82. This test program acquires the appropriate data to describe the noise level output of the aircraft over the entire operating range that might normally be encountered on or in the vicinity of an air base.

The data obtained from the test program are used to develop a minimum of six separate functional descriptions of the noise output of the aircraft. These descriptions are:

1. Noise measure as a function of slant distance from the aircraft, on an ICAO standard day, (sea level pressure, 15°C, 70% relative humidity, zero wind) using normal takeoff power, for air-to-ground sound propagation.

2. Item 1 for ground-to-ground propagation including takeoff roll acceleration effects.

3. Noise measure as a function of slant distance from the aircraft, on a standard day, during landing at the power used with maximum landing weight, for air-to-ground sound propagation.

4. Item 3 for ground-to-ground sound propagation, including landing roll effects.

5. Noise measure produced during ground runup, in a horizontal plane, from zero to 180 degrees around the longitudinal axis of the aircraft, for different engine power settings, as a function of distance from the aircraft.

6. Noise measure variation with engine power, relative to the value produced at maximum power, at a reference height and airspeed.

The operational data are derived from aircraft flight manuals and engine performance data. These data include:

1. Takeoff flight profiles of both height and speed, as a function of distance from brake release, at maximum gross weight, on a standard day.

2. Variation in takeoff profiles with gross weight, over the operational envelope of the aircraft, for various density altitudes.

3. Engine takeoff power variation with density altitude.

4. Engine power on approach as a function of landing weight.

5. Engine powers used for maintenance ground runups.

The above information allows the computation of noise at any point in the vicinity of an airport for any operation of the aircraft. For many aircraft, not all these data are used, and for most airports not all will be required. The computer program, however, must be capable of employing these data when appropriate.

Because of the use of a general purpose computer the availability of storage space makes it possible to consider performance data for each aircraft individually, and for many specific aircraft, data for various mission types (e.g. afterburner and non-afterburner takeoffs, various operating weights, training operations as compared to other missions). A major test program has been conducted by the USAF, following the test methods of Ref. 79, to provide the basic input to the noise exposure computation. Results of these tests are described in Ref. 82. These test data are further processed, using procedures described in Ref. 79 to develop the noise level data required for the computations in the noise exposure program.

This data file is now available for different aircraft. The noise test program is continuing, with the goal of having a data file that will eventually cover essentially all USAF aircraft. In addition, performance data for these aircraft, sometimes for several different mission types, are stored in the data file. Where performance differences exist between different lettered versions of an aircraft type, separate data files are provided. Thus in the new procedure individual models of each aircraft can be specified rather than by classes (interceptors, etc.) as is done in the present USAF procedure. The data file also accommodates estimated noise and performance data for some aircraft systems where test data are not yet available. Such estimates can be made for projected new systems if desired, so that the effect of these aircraft systems on noise at any airbase can be evaluated prior to the development or introduction of the system into service use (e.g. new STOL designs, or a new engine design for an existing aircraft).

B. Description of the Noise Produced by A Single Aircraft Operation

The noise produced by a single aircraft may be described by a set of contours of constant noise measure, plotted at 5 dB increments, with the range of levels selected in terms of the problem at hand. For flight operations, the noise at any point is determined by first calculating the distance of closest approach from the point of observation on the ground to the aircraft trajectory (minimum slant distance) and the angle subtended between the horizon and the vector describing the minimum slant distance (see Fig. 15). The noise value at the observation point is then determined from the appropriate noise-slant distance function, either air-to-ground, ground-to-ground, or an interpolation between the two, depending upon the value of angle θ of Fig. 15 (page 111).

It is often convenient to break the flight trajectory into a series of segments. The choice of segment lengths is governed by both engine power conditions and by geometrical changes in flight profile or track. Segments are chosen to be representable by straight line segments or circular arcs whenever possible. While it is possible to have a change in flight track without a power change, a power change will almost always cause a flight profile change. Thus each segment requires an engine power specification, and a noise-slant distance specification. In this manner the noise contour for any operation, along any flight path, may be computed.

The noise from a ground runup operation is calculated by first determining the distance from the observation point to the aircraft, s, and the angle, ϕ, defined as the angle between a line from the observation point to the longitudinal axis of the aircraft, as measured from the forward part of the aircraft. The value of PNLTM (ϕ,s) or ALT (ϕ,s) at the observation point is determined from the polar data on noise level as a function of angle and distance from the aircraft. The value of EPNL (ϕ,s) is given by:

$$\text{EPNL}(\phi,s) = \text{PNLT}(\phi,s) + 10\log_{10}\Delta t - 10 \qquad (1)$$

where Δt is the duration in seconds.

NOTE:

EPNL in decibels is defined in Ref. 5 as:

$$\text{EPNL} = \text{PNLTM} + D \qquad (2)$$

where PNLTM is the maximum tone-corrected PNL during an event, and D is a duration correction factor defined as:

$$D = 10\log_{10}\frac{1}{T}\int_{t_1}^{t_2} 10^{\frac{\text{PNLT}}{10}}\,dt - \text{PNLTM} \qquad (3)$$

where T is a normalizing constant, specified as 10 seconds, and t_1 and t_2 are the points of the time distribution of PNLT where the PNLT values are 10 dB less than that for PNLTM. The expression for EPNL may be rewritten as

$$\text{EPNL} = 10\log_{10}\cdot\frac{1}{10}\int_{t_1}^{t_2} 10^{\frac{\text{PNLT}}{10}}\,dt \qquad (4)$$

or $$\text{EPNL} = 10 \log_{10} \int_{t_1}^{t_2} 10^{\frac{\text{PNLT}}{10}} \, dt - 10 \qquad (5)$$

In the above specification for EPNL (ϕ,s), equation (1), it is assumed that PNLT values will be constant over the duration Δt for a specified operating condition. Thus equation (5) becomes

$$\text{EPNL} = \text{PNLT} + 10 \log_{10} \int_{t_1}^{t_2} dt - 10 \qquad (6)$$

as stated in equation (1).

In an essentially parallel fashion, SELT IS defined as:

$$\text{SELT} = 10 \log_{10} \frac{1}{T} \int_{t_1}^{t_2} 10^{\frac{\text{ALT}}{10}} \, dt \qquad (7)$$

where T is now specified as one second. In this case SELT for ground operations is merely:

$$\text{SELT} = \text{ALT} + 10 \log \int_{t_1}^{t_2} dt \qquad (8)$$

The computation of equal noise contours may be determined in two ways. One way is to define an x,y,z grid system over the ground plane and compute noise values at each grid point, then determine contours of equal noise by connecting grid points (or interpolating between them) of equal value. The second way is to select a specific noise value and compute a series of coordinates which when connected will form equal valued noise contours. Both systems have been used in previous models. The fixed grid system has an advantage in handling curved flight tracks, since the increased duration on the concave side of the track as compared to the convex side may more easily be computed and the effect of superposition of different operations is more easily accommodated. This method is used in the new program.

C. Description of the Noise Exposure Produced by a Series of Aircraft Operations

The goal of the noise exposure computations is to obtain a single number, at every point in the vicinity of the air base, that represents the accumulated effect of all the operations. This number is then related to the anticipated acceptability of the noise from the operations for various functional uses of the land. Pending resolution of the choice of EPNL or SELT as the basic descriptor for individual aircraft noise events, the computer program currently computes NEF values as in the current civil NEF programs, with appropriate modifications for military operations. If SELT is chosen as the basic noise descriptor, the program can easily be changed to compute DNL instead of NEF. The program also provides the computational improvements in description of noise sources, sound propagation factors, and operational characteristics which are not now used in the civil NEF program. These items do not affect the concept of NEF but should improve the accuracy of its representation.

The basic NEF formulation is an energy summation of the noise from a series of events, expressed in EPNL, weighted for a difference between daytime and nighttime noise exposure, plus an arbitrary constant. The purpose of the constant is to provide a numerical value for NEF that is sufficiently far from the numerical values of EPNL that the two are not confused. Contours of equal NEF are used to depict the effect of a set of operations around an airport. The basic summation process (less weighting for period of day) is:

$$\text{NEF} = 10 \log_{10} \sum_i 10^{\frac{\text{EPNL}_i}{10}} + \text{Constants} \qquad (9)$$

where the index i refers to the i-th noise level or event. This summation is identical, except for constant terms, with the aircraft exposure level, L_E, of ISO[7/], or the total noise exposure level, TNEL, of ICAO [6/].

The summation process, of course, must be defined as taking place over a particular period of time. The NEF calculation is for a 24-hour day, with a weighting applied to nighttime hours between 2200 and 0700. Constants relating daytime to nighttime effects were so chosen that the noise exposure from the same average number of operations per hour, at a specified EPNL value, would be ten NEF units higher for nighttime than for daytime. Since the total hours defined for daytime are 15, and those at night are 9, the effect of a specified number of aircraft at night is greater than simply weighting noise level by 10 dB, if noise exposure, not levels, are to be weighted.

NOTE: This weighting of exposure rather than level as in other procedures is done because the original community response studies leading to this diurnal weighting factor dealt with exposure and not level. The comparable DNL expression in terms of SELT is:

$$\mathrm{DNL} = 10 \log_{10} \sum_{i} 10^{\frac{\mathrm{SELT}_i}{10}} + \text{Constants} \qquad (10)$$

In the DNL computation nighttime levels are weighted, not exposure. The numerical differences in decibels are negligible in most cases, as indicated in Section II.

The second constant of concern is that used simply to provide a numerical offset between EPNL-like numbers and NEF. The value chosen for the civil NEF was -75, so that positive values of NEF are a rough indication of the emergence of noise above a threshold number whose value in EPNL would be low enough as to be acceptable for essentially any land use. Finally, in a manner parallel to that in the CNR calculations, the constants in the NEF equation were so adjusted as to provide a zero effect of numbers of events, in daytime, at an operational level of 20 aircraft movements per day. The final set of constants thus expresses the NEF for a fixed EPNL value, in terms of numbers of aircraft at that value as:

$$\mathrm{NEF}_i = \mathrm{EPNL}_i + 10 \log_{10} \left[N_D + 16.67 N_N \right] - 88 \qquad (11)$$

where N_D and N_N are the total number of events during the day and night hours, respectively, having an EPNL value of EPNL_i. The total NEF is then obtained by logarithmic summation over all the NEF_i.

The comparable expression for DNL is not encumbered by the precedents involved in CNR and NEF, thus the normalizing constants are simply related to one second for SELT and to the number of seconds in 24 hours for DNL. This expression then becomes:

$$DNL_i = SELT_i + 10 \log_{10} \left[N_D + 10N_N \right] - 49.4 \qquad (12)$$

At this point only flight operations are accounted for in the above descriptions. Maintenance ground runup operations must now be considered. The new program uses a +10 dB weighting factor applied to maintenance ground runup noise as compared to noise from flight operations, for reasons discussed in Section IV of this report. This is most easily accomplished, computationally, by adding the +10 dB into the EPNL to obtain a "weighted" EPNL for ground operations. In this manner, a single criterion value is used for composite flight-ground noise contours without having to interpret which part is which in the final set of contours. The relative contribution of runup operations to the total NEF may be accounted for by computing a separate NEF_i (at any point ϕ,s as described above) for the i-th runup, from the following equations:

Daytime: $$NEF_D(\phi,s)_i = PNLT(\phi,s)_i + 10 \log_{10} D - 88 \qquad (13)$$

Nighttime: $$NEF_N(\phi,s)_i = PNLT(\phi,s)_i + 10 \log_{10} D - 78 \qquad (14)$$

and then combining these contributions as was done for flight operations. The computer program has the option of plotting out individual NEF contributions, the sum of NEF values due solely to flight operations, or ground operations, as well as the sum of all operations.

The comparable expressions for runup computations in terms of DNL are:

Daytime: $$\mathrm{DNL}_D(\phi,s)_i = \mathrm{ALT}(\phi,s)_i + 10 \log D - 49.4 \qquad (15)$$

Nighttime: $$\mathrm{DNL}_N(\phi,s)_i = \mathrm{ALT}(\phi,s)_i + 10 \log D - 39.4 \qquad (16)$$

This discussion has related solely to aircraft operations themselves. Where maintenance runups are made in conjunction with a portable muffler or an engine test cell it may be necessary to include noise data on these operations as a third class of noise sources. The noise levels from these facilities can be described in terms of polar diagrams in the same fashion as those developed for base aircraft. These sources may be added into the total noise exposure computation in the same manner as for the other maintenance runup operations. In general, the contribution of such facilities to noise exposure around an air base may usually be ignored if their noise levels do not exceed 80 PNL at the closest on-base or inhabited community location.

D. Operational Data Requirements

The above discussion describes how the noise from an individual aircraft operation is determined, and how the effects of different operations are mathematically combined to produce NEF values. In order to implement this calculation it is necessary to establish how many noisy events occur, at which locations, as input to the NEF computations. (NOTE: Ref. 78 of this series contains examples of and sample forms for acquiring and tabulating the required data.) We consider these factors here.

1. Number of Operations by Aircraft Type

The average number of aircraft movements, by aircraft model, during the daytime and nighttime periods of a 24-hour day must be determined. In defining the "average" day, the base operations should be examined for at least one month to evaluate weekday versus weekend flying activity. If weekday activity totals more than twice the weekend activity, the average should be taken over week days only.

Monthly total operations should be examined over a yearly period to determine if there are significant fluctuations from month to month. The operations during the three month period containing the highest activity of the year should be averaged to determine the "average month" for noise computations unless it is clearly evident that separate noise exposure computations are desirable for active and inactive periods. If the most active month has less than twice the operations of the least active month, then separate noise computations are not warranted.

The above assumptions are valid only if the base aircraft complement is reasonably stable. If a base were to make a substantial change in its aircraft complement or mission, e.g. replace F102's with B52's, etc., new noise computations should be required.

In addition to identifying movements by aircraft type, information is required on the distribution of movements by aircraft weight. While this type of information is often difficult to obtain, estimates can often be made of the percentage of flights which go out at maximum weight as compared to training operations, such as touch-and-go flights, where lighter weights are employed. This problem has been simplified in the new procedure by listing various missions for each aircraft type. These missions were determined by examining typical conditions most often used for each aircraft. For example, weights used for training operations in a B52 are one mission type; weights used for a maximum effort strategic bombing mission are another. The computer program is also capable of generating takeoff profiles as a function of weight if data on net thrust, and the ratio of drag to lift coefficients are specified.

2. Flight Path by Aircraft Type

Normal operating procedures at an air base prescribe typical takeoff and approach procedures for individual aircraft types for various runways. In most instances flight profile restrictions are not provided, but flight track descriptions are provided. The first step is to identify flight tracks, by segmented steps if necessary, for each aircraft type. An example of segment identification is shown in Fig. 20. An example of a flight profile and track designation where a profile restriction is specified for takeoff is shown in Fig. 26.

It should be recognized that differences in aircraft performance, takeoff weights, and pilot technique will introduce substantial variation in flight paths. Whenever possible the average flight path and range of variation around it should be obtained by discussions with pilots, operations, and traffic control personnel. Flight track descriptions are most easily reported by drawing them on an overlay of a standard 2000 feet per inch C&G.S. map of the air base vicinity.

The graphic presentation of flight path data should be accompanied by a tabulation of flight path segments used by the different aircraft at a base. This tabulation should also indicate the percentage of use estimated for each aircraft type/flight path segment. Where specific utilization percentages cannot be obtained, an estimate can be made on the basis of runway utilization. This estimate can be obtained from either the percentage of time the runway is in use, or if this is not available, from wind rose data. When making estimates of this kind, specific attention should be paid to runway restrictions which may be imposed on certain aircraft or on certain types of operations. Examples are:

"Climb to and maintain 2000 feet on runway heading, left turn to intercept the XYZ 030 radial, proceed outbound resuming normal climb."

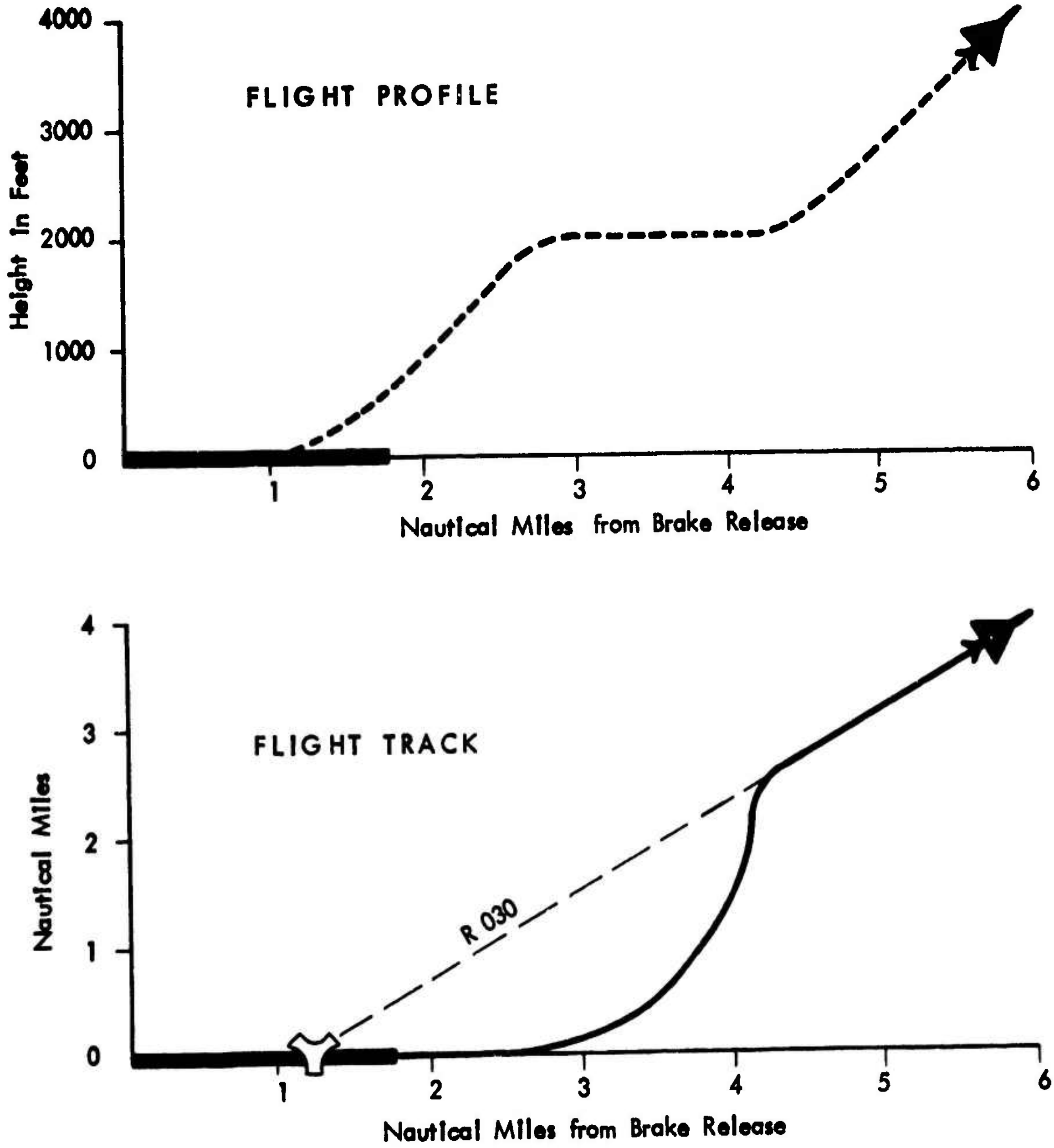


FIGURE 26. EXAMPLE OF FLIGHT PROFILE AND TRACK FOR A TYPICAL TAKEOFF PROCEDURE

"Runway 9L is used for touch-and-go's, 9R being used for operational missions;"

"F4's use both 6-24 and 11-29, but C-124's use only 11-29."

In order to simplify the identification of flight path information and to build into the computer program a means for generating flight path dispersion effects caused by different aircraft/mission types supposedly following the same flight procedures, a powerful new option has been incorporated in the new procedure. Instead of providing a map of estimated flight tracks, actual departure or arrival clearances may be used to generate the appropriate flight paths. The clearance can be in the form of vectors and altitudes, or can be referenced to different navigational aids. For example, the departure track defined in Fig. 26, "Climb to and maintain 2000 feet on runway heading, left turn to intercept XYZ 030 radial, proceed outbound resuming normal climb" can be specified in just this fashion. The computer program will determine the actual track and profile on the basis of the stored performance data for each aircraft/mission type using this procedure. Thus a variety of flight paths will result, depending on specific aircraft performance. The program accepts arrival procedures in the same format. Obviously, mixtures of this method and the older "lines-on-the-map" method can be specified to the program.

3. Ground Runup Information

Data should be provided on all maintenance runup operations by each aircraft or engine type. This information should include the following:

a) Aircraft or engine type

b) Runup cycle, e.g. duration at different power settings

c) "Average" number of runups per day and night periods by aircraft or engine type by applying the same criteria used to define "average" for flight operations

d) Geographical location and orientation of runup pads, depicted on an overlay of a map of the air base.

e) The use, if any, of noise suppressors, and if used, type of suppressor.

E. Supplemental Information

The information on aircraft noise and operational factors is all that is necessary to define the NEF contours around an air base. The eventual use of this information is for land use planning purposes. A significant input requirement to the overall evaluation is information on the location, structure, and occupancy of buildings and open spaces on and in the vicinity of the air base. The detail and extent of data gathering employed for this part of the program will vary markedly from base to base.

Since the resolution of noise problems may well be handled exclusively at base level, valuable information for overall USAF studies may not be acquired in a central location unless firm requirements are established to supply land use information in the basic data package. We suggest that the minimal information should consist of an overlay of the vicinity of the airport, with areas indicated for residential, commercial, industrial, manufacturing, and agricultural use. The location of all schools and churches should also be identified.

F. Criteria

Criteria for recommended land uses within various NEF zones are provided in Ref. 4 and Appendix B. At the present time both FAA and HUD are in the process of reviewing pending policy circulars that will provide word descriptions associated with the recommended land uses. The new USAF procedure will use the land use compatibility guides specified in Ref. 4 until the revised HUD material is available.

Each base should be encouraged to keep an accurate record of any complaints due to aircraft noise exposure. The minimum information desired should include name and location of complainant, time of day and date, and the nature of the complaint itself (e.g. activity interrupted, unusual flight activity, aircraft type and operation, if possible).

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APPENDIX A

SUMMARY OF RECOMMENDATIONS

1. The USAF land use planning procedure for aircraft noise should use the tone corrected, A-weighted sound exposure level, SELT, for describing the noise from an individual aircraft noise event.

2. Number of events be accounted for by 10 $\log_{10}$ N.

3. Nighttime noise exposure should be assessed a penalty by adding a 10 dB increment to nighttime noise levels when combining day and night exposures to obtain a 24 hour value.

4. Adjustments for seasonal factors should be included in the generalized noise rating procedure; where clear justification for their use is evident at a particular air base, the ICAO adjustments may be employed.

5. Adopt the land use compatibility guides and noise compatibility interpretation guidelines specified in HUD report "Aircraft Noise Impact: Planning Guidelines for Local Agencies[70/].

6. Description of noise source characteristics in terms of noise level as a function of slant distance and description of aircraft performance by height-distance data be used as the basis for the Air Force noise prediction model for land use planning procedures.

7. The computation of EPNL should be performed as presently described in FAR Part 36[5/]. Computation of SELT should be identical except that A frequency weighting should be used instead of noy weighting, and a reference time of one second instead of ten seconds should be employed.

8. The air absorption data contained in SAE ARP 866 be used in noise exposure calculations. The Air Force land use planning procedure should be so designed that it can be easily modified to accept new air absorption information when this information is available and considered acceptable to the scientific and technical community.

9. Utilize the method for predicting ground propagation losses now in use for civil NEF computations in the Air Force procedure. Provide for easy modification in the procedure when improved data are available. Develop additional data wherever possible in measurement of noise from aircraft operations.

10. The algorithm now used in the civil aviation NEF program for transitioning between ground and air attenuation should be employed in the USAF procedure. Develop additional data wherever possible in noise measurement programs to verify or modify this algorithm.

11. The effects of acceleration on EPNL or SELT should be accounted for in the noise exposure model. Data to derive these effects should be acquired in aircraft noise test programs wherever possible.

12. Data on density altitude performance and noise effects should be included in the USAF procedure.

13. Utilize EPNL or SELT curves derived on the basis of acoustical standard day conditions (15°C, 70% relative humidity) unless examination of the mean monthly temperatures and relative humidities show three months during the year in which the product of temperature in degrees F and relative humidity in percent is less than 2000. When such small products occur, the noise exposure calculations for the air base should utilize EPNL/or SELT/distance curves based on air absorption calculations from SAE 866 for the appropriate weather conditions.

14. Computation of the number of average daily operations should be based on a "busy day" principle. For military air bases this average is usually the weekday average, based on a monthly period. Average "busy day" operations per month for each month of the year should be obtained, then averaged on a yearly bases. If any quarter of the year has operations that are higher or lower by a factor of two when compared to the annual average, consideration should be given to computing separate noise exposure contours for these periods of the year.

15. Allowance for flight path dispersion should be included in the USAF procedure. Until better dispersion models are available, the empirical equations derived here should be used. Where it is possible to make an experimental determination of flight path data, the observed information should be used in the procedure.

16. Ground run-up operations for maintenance purposes should be included in noise exposure calculations by computing their EPNL or SELT values. These values should then be weighted by an additional 10 dB when summing the total exposure at the air base.

17. Run-up associated with takeoff operations should be included in the takeoff noise calculations directly in terms of their contribution to the takeoff EPNL or SELT.

SUMMARY OF RESEARCH REQUIREMENTS

Although the recommended predictive procedure is the best available and can be effectively applied for planning purposes, several areas are identified in the text where additional research is needed to verify assumptions made when quantitative data are scant or nonexistent or simplifications made for practical or administrative reasons. Many of these factors can significantly influence the predicted noise exposure, estimated response interpretation, or subsequent management decisions. Some of the areas where deficiencies exist are:

(1) Field test validation of the predicted noise exposure for a variety of aircraft operations;

(2) Long range propagation effects on the uncertainty of predicting noise exposure, especially the ground-to-ground excess attenuation model;

(3) Hypothesis that applying the temporal and tone corrections contained in EPNL to A-weighted noise signals improves the ability of the A-weighted measure to predict annoyance;

(4) Psychoacoustic data base for judgement of noisiness due to duration, temporal pattern, presence of multiple tones, and unique source spectral characteristics such as for helicopter/VTOL operations;

(5) Community response data base for judgement of ground runup penalty, diurnal weighting penalty, seasonal weighting, and energy summation rules.

APPENDIX B*

LAND USE COMPATIBILITY GUIDES

Figure B-1 provides the key to the selection of the appropriate noise compatibility interpretations for differing NEF values. For each land use listed in the figure, several interpretations in Table I are provided. The choice of the appropriate interpretation is governed by the NEF values describing the noise exposure. Also listed in Figure B-1 is the appropriate Standard Land Use Coding Manual (SLUCM) and a "Noise Sensitivity Code." The noise code provides a gross ranking of the land use in terms of noise sensitivity, with the number 1 indicating the land uses most sensitive to noise and 5, the land use, least sensitive. The approximate relationship between the noise sensitivity code rating and the NEF level at which new construction or development <u>is not</u> desirable is given below:

Noise Sensitivity Code	Approximate Noise Exposure Forecast Value Where New Construction or Development Is Not Desirable
1	30
2	35
3	40
4	45
5	50-55

In Fig. B-1, one will note that, for most land uses, the compatibility interpretation for the lowest NEF values has the notation "satisfactory with no special noise insulation requirements required for new construction," indicating that there

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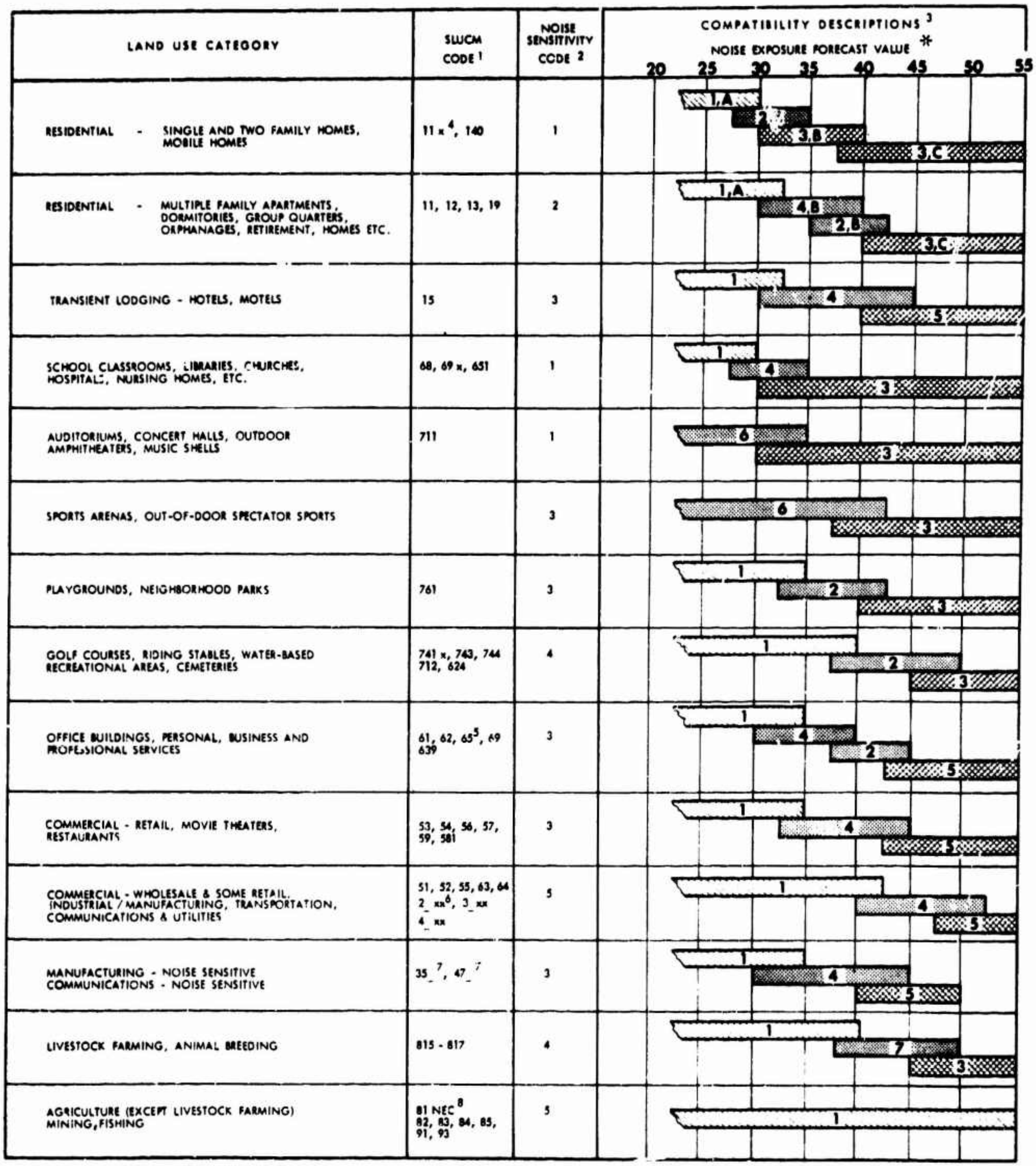
*Extracted from Ref. 4.

FIGURE B-1. LAND USE COMPATIBILITY CHART FOR AIRCRAFT NOISE



LAND USE CATEGORY	SLUCM CODE[1]	NOISE SENSITIVITY CODE[2]	COMPATIBILITY DESCRIPTIONS[3]
RESIDENTIAL - SINGLE AND TWO FAMILY HOMES, MOBILE HOMES	11 x[4], 140	1	1,A 2,B 3,B 3,C
RESIDENTIAL - MULTIPLE FAMILY APARTMENTS, DORMITORIES, GROUP QUARTERS, ORPHANAGES, RETIREMENT, HOMES ETC.	11, 12, 13, 19	2	1,A 4,B 2,B 3,C
TRANSIENT LODGING - HOTELS, MOTELS	15	3	1 4 5
SCHOOL CLASSROOMS, LIBRARIES, CHURCHES, HOSPITALS, NURSING HOMES, ETC.	68, 69 x, 651	1	1 4 3
AUDITORIUMS, CONCERT HALLS, OUTDOOR AMPHITHEATERS, MUSIC SHELLS	711	1	6 3
SPORTS ARENAS, OUT-OF-DOOR SPECTATOR SPORTS		3	6 3
PLAYGROUNDS, NEIGHBORHOOD PARKS	761	3	1 2 3
GOLF COURSES, RIDING STABLES, WATER-BASED RECREATIONAL AREAS, CEMETERIES	741 x, 743, 744 712, 624	4	1 2 3
OFFICE BUILDINGS, PERSONAL, BUSINESS AND PROFESSIONAL SERVICES	61, 62, 65[5], 69 639	3	1 4 2 5
COMMERCIAL - RETAIL, MOVIE THEATERS, RESTAURANTS	53, 54, 56, 57, 59, 581	3	1 4 5
COMMERCIAL - WHOLESALE & SOME RETAIL, INDUSTRIAL / MANUFACTURING, TRANSPORTATION, COMMUNICATIONS & UTILITIES	51, 52, 55, 63, 64 2_ xx[6], 3_ xx 4_ xx	5	1 4 5
MANUFACTURING - NOISE SENSITIVE COMMUNICATIONS - NOISE SENSITIVE	35_[7], 47_[7]	3	1 4 5
LIVESTOCK FARMING, ANIMAL BREEDING	815 - 817	4	1 7 3
AGRICULTURE (EXCEPT LIVESTOCK FARMING) MINING, FISHING	81 NEC[8] 82, 83, 84, 85, 91, 93	5	1

* $L_{DN} \simeq NEF + 35$

1. STANDARD LAND USE CODING MANUAL
2. RELATIVE RANKING OF LAND USES WITH RESPECT TO NOISE SENSITIVITY. SEE TEXT
3. DESCRIPTORS ARE LISTED IN TABLE IV
4. "x" REPRESENTS A SLUCM CATEGORY BROADER OR NARROWER THAN, BUT GENERALLY INCLUSIVE OF, THE CATEGORY DESCRIBED
5. EXCLUDING HOSPITALS
6. "xx" SOME EXCEPTIONS MAY OCCUR FOR PARTICULAR OR SPECIALIZED NOISE SENSITIVE ACTIVITIES
7. DEPENDENT UPON SPECIFIC TASK REQUIREMENTS
8. NOT ELSEWHERE CLASSIFIED

TABLE B-I

NOISE COMPATIBILITY INTERPRETATIONS FOR USE WITH FIG.B-1

General Land Use Recommendations

A. Satisfactory, with no special noise insulation requirements for new construction.

B. New construction or development should generally be avoided except as possible infill of already developed areas. In such cases, a detailed analysis of noise reduction requirements should be made, and needed noise insulation features should be included in the building design.

C. New construction or development should not be undertaken.

D. New construction or development should not be undertaken unless a detailed analysis of noise reduction requirements is made and needed noise insulation features included in the design.

E. New construction or development should not be undertaken unless directly related to airport-related activities or services. Conventional construction will generally be inadequate and special noise insulation features must be included. A detailed analysis of noise reduction requirements should be made and needed noise insulation features included in the construction or development.

F. A detailed analysis of the noise environment, considering noise from all urban and transportation sources should be made and needed noise insulation features and/or special requirements for the sound reinforcement systems should be included in the basic design.

G. New development should generally be avoided except as possible expansion of already developed areas.

Community Response Predictions

I. Some noise complaints may occur, and noise may, occasionally, interfere with some activities.

II. In developed areas, individuals may complain, perhaps vigorously, and group action is possible.

III. In developed areas, repeated vigorous complaints and concerted group action might be expected.

should be no adverse effects from aircraft noise. Corresponding to higher levels of noise exposure, the interpretations generally define a range of noise exposure in which new construction or development should not be undertaken unless an analysis of noise requirements is made and needed noise insulation features are included in the building design and site development. For more extreme noise exposure, many of the land uses are assigned an interpretation saying that new construction or development should not be undertaken.

APPENDIX C

THE COMPUTER IMPLEMENTATION

1. INTRODUCTION

The mathematical formalism of the Noise Exposure Forecast (NEF) is deceptively straightforward. One finds the Effective Perceived Noise Level (EPNL) for a given aircraft j performing an operation i, and one also finds the number of times N_{Dij} and N_{Nij} that the event occurs during the day (0701-2200 hrs) or night (2201-0700 hrs). The contribution of the event (ij) to the NEF is:

$$NEF_{ij} = EPNL_{ij} + 10 \log (N_{Dij} + 16.67 N_{Nij}) - 88 \quad (C.1)$$

The deception stems from the $EPNL_{ij}$ term, which is by no means accurately known. In practice it is a task requiring careful measurement to find an EPNL value for the simplest flight operation: the straight flyover. The EPNL is an integrated function: the perceived noise level is integrated over time. The perceived noise level itself at any instant in time cannot be very accurately predicted since it would require accurate information about the noise spectrum and directionality of the noise of a flying airplane.

Even if the EPNL function were known the problem tends to become unmanageable in terms of complexity of the "bookkeeping" for all operations at even the simplest air base. The computer program is an attempt to automate the bookkeeping required in any realistic air base calculation. The computer is also used to perform the thousands of calculations required to evaluate the NEF_{ij} terms for all values i and j for all ground points of interest.

Earlier NEF computer programs have generally computed the summation over the index j only, and the calculations were performed for a straight flight track. The use of the straight flight track has the advantage that available EPNL values are mostly measured from straight fly-by's. Therefore a measured EPNL is our estimate of the computed EPNL, which is desirable. Attempts have been made to provide the second summation sometimes in general, sometimes only for parallel flight tracks. Some programs have been written to distort the straight contours to fit an arbitrary path.

The NEFUSAF program reflects the state-of-the-art in NEF prediction techniques by including a mathematical model to estimate EPNL values even when the flight track is not straight. Many other features are also included such as the use of pilot clearances for input rather than explicit flight track descriptions, and the summation is performed over both indices i and j thereby providing for the mutual influence of contours around different flight tracks.

The central problem is that of estimating the EPNL value for an arbitrary ground location due to an arbitrary flight path. In general one will have data for a straight flyover available. Implicit in the use of such a curve is the assumption of cylindrical symmetry around the flight path. This assumption appears valid except at very low angles of elevation where there is an important ground effect. For this reason there are curves for air-to-ground and ground-to-ground (sideline) EPNL.

Since one cannot hope to calculate the EPNL for an arbitrary geometry from first principles, one must find a suitable correction to the available data. The approach taken in the development of such a correction was to assume that the noise level produced by the aircraft was known and that it was exactly repeatable. One can compare the ratio of the arbitrary to the standard case, and because the levels are assumed deterministic the quotient gives a correction factor independent of the noise level. As will be shown this model allows for curved flight tracks quite naturally and leads to results in agreement with the fundamental concepts of the NEF procedure.

2. MATHEMATICAL MODEL

The EPNL is the integral of the tone corrected Perceived Noise Level. It seems therefore attractive to construct a model which takes this fact into account since it would naturally incorporate the variation in EPNL with increased length of exposure. We will in our model therefore associate a power level I_j with any type of aircraft j. (The entire discussion of the mathematical model will deal with just one value of j, say J, and we will therefore omit all subscripts j where there is no confusion.)

The PNL varies over most of the distances of interest as $1/r^3$. Since we would model a function which is the integral of the PNL, it appears logical to consider the integral over the power level I as the quantity of interest.

$$E = \int \frac{I dt}{r^3} \qquad (C.2)$$

This function E will be called the Noise Exposure Integral. We must now investigate in which way the function $E(d)$ is useful. (d is the slant distance of observer to the aircraft or its flyby.)

Since directional information about I is not available our model must limit the dependence of I on any variable to the time t. This variation is implied through the more obvious parameter s, the distance travelled, since one may expect power changes to occur during the flight of an aircraft. Therefore we restrict I to the dependence:

$$I = I[s(t)] \qquad (C.3)$$

which is not a function of observer orientation. The consequence is, of course, that we assume the aircraft noise source as omnidirectional. This assumption is not as bad as it may seem at first glance. The noise exposure integral will be used to arrive at a correction to the EPNL, a function which is also not explicitly dependent on orientation.

The approach to take is to compute the noise exposure integral for the arbitrary flight path and compare this value to the noise exposure integral for the straight flyby reference case. The ratio of these two integrals expressed in dB yields the correction factor to be applied to the EPNL found in the measured data. Or put differently, the weighting function for an arbitrary flight path is the noise exposure integral for that flight path normalized to the noise exposure integral of the reference case.

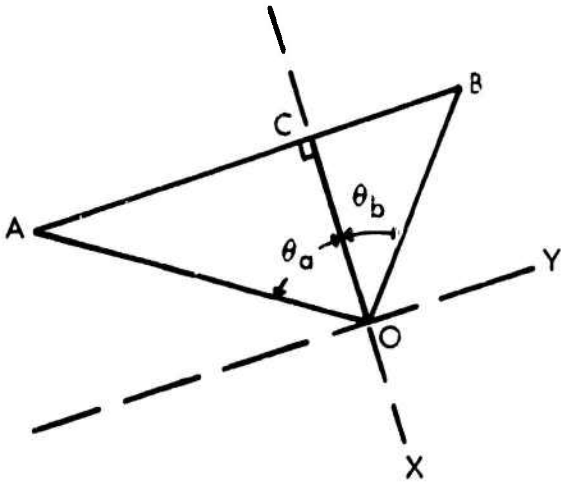
The next few sections discuss the evaluation of the noise exposure integral for straight and circular flight track sections (the only two allowed) and the computation of the final NEF. This last section is concerned with the fact that the model is not perfect and that therefore some technique must be used to minimize the difference between the predicted value and a field measurement.

We have put one additional limitation on the model. This is the functional dependence of I on s: the power level function can only depend linearly on the distance s. This limitation does not seem to severely hamper the model and it allows closed form solutions to all integrals. Therefore we have stipulated

$$I = I(s) = I_o + ks \qquad (C.4)$$

In what is to follow the reader is assumed to be familiar with the transformation of coordinate systems and vector algebra, as well as elementary calculus. A simple discussion of coordinate transformation may be found below in Section 8 (page C-25).

3. NOISE EXPOSURE INTEGRAL FOR A STRAIGHT LINE



We consider a straight line section, arbitrarily oriented with respect to the ground plane. An observer is located at O.

It is most advantageous to consider the problem in the frame of reference where the observer is at the origin and the y-axis is parallel to $\overline{AB}$ while the line $\overline{OC}$ is coincident with the x-axis. Assume the aircraft is at A and B at time t_1 and t_2. The distance travelled s = Vt is a more useful variable so we will transform the variable of integration. Furthermore, we introduce a = $\overline{OC}$ the slant distance.

$$E = \int_{t_1}^{t_2} \frac{Idt}{r^3} = \int_{y_A}^{y_B} \frac{Ids}{Vr^3} = \int_{y_A}^{y_B} \frac{Idy}{V(a^2+y^2)^{3/2}} = \frac{1}{a^3V} \int_{y_A}^{y_B} \frac{Idy}{(1+y^2/a^2)^{3/2}} \quad (C.5)$$

In the above derivation we have taken the speed outside of the integration. It is not necessary to do this since variation in speed can be taken into account explicitly. It makes the computation unnecessarily complicated to do this, however, and speed changes can be accommodated implicitly by their effect on the EPNL using an EPNL adjustment. The effects of power changes and speed changes are combined in this adjustment rather than entering each effect separately. That this is desirable is best illustrated by the fact that, for example, a power cutback will give a lower noise output, but often due to the slower resultant speed a prolonged exposure. The EPNL adjustment by means of the delta-EPNL profile combines these two effects into one adjustment profile.

We can now proceed by substituting $y/a = tg\ \phi$ and if we also assume $I = I_o + ky$, as discussed previously, we have:

$$E = \frac{1}{a^3V} \int_{\theta_a}^{\theta_b} \left[\frac{Io\ a\ \sec^2\phi}{\sec^3\phi} + \frac{ka^2 \mathrm{tg}\phi\ \sec^2\phi}{\sec^3\phi}\right] d\phi$$

$$= \frac{Io}{a^2V} \int_{\theta_a}^{\theta_b} \cos\phi\ d\phi + \frac{k}{aV} \int_{\theta_a}^{\theta_b} \sin\phi\ d\phi$$

$$= \frac{Io}{a^2V} (\sin\theta_b - \sin\theta_a) + \frac{k}{aV}(\cos\theta_a - \cos\theta_b) \qquad (C.6)$$

Actually, since we assume a nondirectional source we are not really concerned with the integral as computed above, but merely its absolute value.

The next step is to find the location of point C. This knowledge is useful for the computation of the second half of (C.6). Consider again a frame of reference with the origin at O. For the moment the orientation of the reference frame is immaterial. In this reference system the triangle OAB is given in terms of three vectors:

$$\vec{r}_A = a_x\ \hat{i} + a_y\ \hat{j} + a_z\ \hat{k}$$

$$\vec{r}_B = b_x\ \hat{i} + b_y\ \hat{j} + b_z\ \hat{k} \qquad (C.7)$$

$$\vec{r}_{AB} \equiv \vec{r}_A - \vec{r}_B = (a_x - b_x)\ \hat{i} + (a_y - b_y)\ \hat{i}\ (a_z - b_z)\ \hat{k}$$

The slant distance itself can now be written as:

$$\vec{r}_C = c_x \hat{i} + c_y \hat{j} + c_z \hat{k} \tag{C.8}$$

If we can find the coefficients in (C.8) we know the location of the point C. These coefficients can be found when we realize that C lies on the line AB and that OC is perpendicular to AB. The perpendicular property is expressed by the product:

$$\vec{r}_{AB} \cdot \vec{r}_C = 0 \tag{C.9}$$

The remaining relationship is that $\vec{r}_{AC} \equiv \vec{r}_A - \vec{r}_C$ is along $\vec{r}_{AB}$ which leads to the relation:

$$\frac{\vec{r}_{AC}}{|r_{AC}|} = \frac{\vec{r}_{AB}}{|r_{AB}|} \tag{C.10}$$

Equation (C.10) gives us two relations between the components of $\vec{r}_C$. The scalar relationship (C.9) gives a third equation. The simultaneous solution of this trio gives the components of $\vec{r}_C$. The three Cartesian coordinates of point C are then given by the vector components of $\vec{r}_C$.

Equation (C.9) expands into:

$$(a_x - b_x)c_x + (a_y - b_y)c_y + (a_z - b_z)c_z = 0 \tag{C.11}$$

and (C.10) can be written as:

$$\frac{a_x - b_x}{a_x - c_x} = \frac{a_y - b_y}{a_y - c_y} = \frac{a_z - b_z}{a_z - c_z} \tag{C.12}$$

The solution is straightforward, but--particularly in the computer calculation--care must be taken that we do not use (C.12) to reduce (C.11) to an equation in c_i if $a_i = b_i$ since in that case substitution into (C.12) to find the remaining two components of C results in an indeterminate form. It is preferable to use $c_i = c_x$ and if that is not desirable $c_i = c_y$, rather than to use the altitude component, because of the problem of finding a solution for an aircraft in level flight in a direction parallel to the axes of the reference system.

It is more useful, however, to combine vector calculations as above with some simple trigonometry in the triangle OAB. The ratio of equation (C.12) is of course the ratio of the magnitudes of vectors $\vec{r}_{AB}$ and $\vec{r}_{AC}$.

$$\begin{aligned} c_x &= (b_x - a_x)R + a_x \\ c_y &= (b_y - a_y)R + a_y \qquad \text{(C.13)} \\ c_z &= (b_z = a_z)R + a_z \end{aligned}$$

In our earlier discussion we have chosen as a preferred coordinate system the one where $\vec{r}_{AB}$ is aligned with the positive y-axis. As we will see shortly, the question of the sign of y_A and y_B in this coordinate system is of importance. To find what these values are we can resort to Eulerian angles and transform coordinate systems. On the other hand since we are really only concerned with relative sign of the distance AC and BC with respect to the origin at O, we can simplify matters considerably if we look at the ground plane projection. If we take the y-axis to be aligned with $\vec{r}'_{AB}$ and the origin at C' (where a prime denotes the projection on the ground plane) we can derive the desired relationship. Furthermore, since the climb angle β is known we can find the signed values for AC and BC in the preferred system without the need to solve all relationships required to find the Eulerian angles. The only case where this approach does not give satisfactory results is for a vertical altitude profile. Since this case does not have meaning for aircraft under consideration, we are not severely hampered by our simplification. This enables one to find correct noise exposure integrals with the minimum computation time.

If we now look back to equation (C.4), we can see that I_o is the power at point C. Since we are given I_a and I_b we can compute k if we know s_a and s_b. Since k may be either positive or negative, we need to know the sign on s_a and s_b. The sign relationships can, however, be found from the ground plane projection figure as explained above.

To proceed we must now find I_o, the value of I for point C, or more precisely the deviation from unit power. If we take the signed ratio of CA and CB in the coordinate system where the y-axis is along AB, we find:

$$I_o = \frac{I_a - \alpha I_b}{1-\alpha} \qquad \text{(C.14)}$$

where $\alpha = y_a/y_b$. In the ground plane this ratio is equal to the y-ratio in the frame with y along AB and x-axis through C' since the difference is a multiplicative constant equal to the secant of the climb angle. Having found I_o we now also have k:

$$k = \frac{I_a - I_o}{y_a} \qquad (C.15)$$

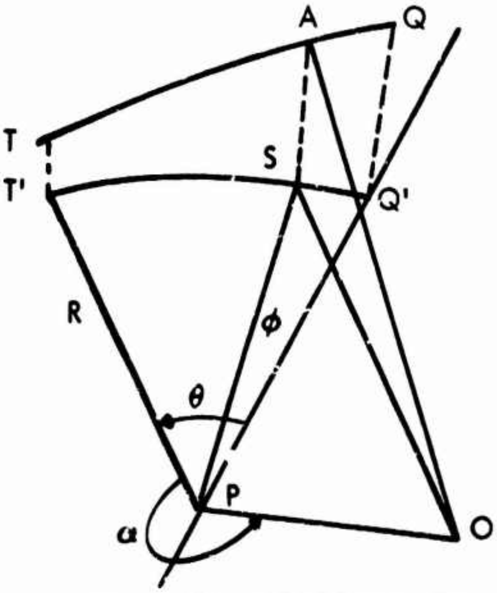
The sign of the sines appearing in equation (C.6) are governed by the sign of AC and BC. The cosines are always positive since for each angle θ the condition $0 \leq \theta < \pi/2$ must be satisfied. All parameters in (C.6) have therefore been accounted for in the above discussion.

4. NOISE EXPOSURE INTEGRAL FOR A CURVE

Having investigated the mathematical problems associated with a straight section of flight path, we will now attack the conceptually somewhat more complex task of analyzing a curved flight path. The model used is rather restrictive in what flight paths are allowed. For our purposes a flight path is curved when it has a curved flight track.

Curvature is not restricted to this particular subset of flight track. In general the figure obtained by plotting aircraft altitude as a function of distance along the flight path will also exhibit curvature. This means that the altitude is not a linear function of distance travelled. The computer program is limited to a straight-line approximation to such a curve. The result is, that the allowable function z(s) will have several points where the second derivative is discontinuous. The program will internally split an externally supplied flight track at such points, so that over any section of flight path which is considered in the noise exposure integral calculation, the function has a uniform climb angle.

A further constraint is placed upon the curvature of the flight track: only circle sectors are allowed as curved flight tracks. An arbitrarily curved flight track, therefore, must be approximated by the user as a set of circle sectors and straight lines. In general such restrictions are not particularly severe since in most cases a constant radius turn is flown. The effects of climb or descent upon the shape of the ground track can be neglected in realistic cases. The combination of constraints on flight track and the function z(s) [z(s) is generally referred to as the altitude profile] means that we are always looking at an aircraft describing a helix. The limiting case of the aircraft flying a turn parallel to the ground plane is included in the subset of admissible paths.



Geometric relations for helical flight path.

Consider the geometry of an aircraft at A proceeding between Q and T. The turn radius is R, the vertex angle of the sector is θ, and the observer is located on the ground at O.

Since we are looking at a circular helix we are best advised to take the cylindrical symmetry explicitly into account and use plane polar coordinates with P at the origin and PQ' along the x-axis. Under these conditions we can assign a value to ϕ, the angle over which the aircraft has turned from the x-axis. The choice of ϕ and PQ' is arbitrary insofar as the directionality is concerned. It is immaterial, within the computer model, whether the aircraft proceeds "forward" from Q to T or "backwards" from T to Q, since we are only interested in the absolute value of the noise exposure integral and since a nondirectional source is assumed.

The distance of observer 0 to aircraft at A is r. The projection of A on the ground plane is given the name S. For the distance we have the relation:

$$r^2 = \overline{OS}^2 + \overline{SA}^2 \qquad (C.16)$$

It is desirable to find the functional relationship $r = r(\phi)$. Since the arc $\overline{TQ}$ is restricted to a helix we can express r in such a fashion. The helix itself is linear in ϕ since the constraint of linearity was placed upon the altitude profile. The aircraft climb angle β is therefore related to the helix speed. We find that the altitude at A is:

$$\overline{SA} = Z_A = Z_Q + R\phi \, t_g \, \beta \qquad (C.17)$$

The more complex problems are associated with expressing $\overline{OS}$ in terms of ϕ only; particularly the task of finding a resultant expression amenable to an analytic integration.

Since $\overline{OS}$ occurs in triangle (POS) we can write:

$$\overline{OS}^2 = \overline{OP}^2 + \overline{PS}^2 - 2\,\overline{OP}\,\overline{PS}\cos\gamma \qquad (C.18)$$

The angle γ can be found since it is the sum of angle (OPQ) and ϕ. Since the location of O is known we know the angle α and therefore (OPQ). The distance $\overline{OP}$ is likewise known and $\overline{PS}$ is, of course, the radius in the ground plane R. After some elementary trigonometry we find

$$\overline{OS}^2 = \overline{OP}^2 + R^2 - 2\,R\,\overline{OP}\cos(\alpha-\phi) \qquad (C.19)$$

Since our ultimate goal involves an integration of $1/r^3$ we must examine the likelihood of finding an analytical expression for such an integral. The exact integral could, in principle, always be obtained by numerical integration, but such a process would take far too much computer time when it has to be performed tens of thousands of times as would be the case for a typical, simple airport. It is clear that the cosine term of equation (C.19) forms a major stumbling block in finding a closed form solution.

In order to avoid this problem we use the following approximation:

$$\begin{array}{llr} \cos\phi = 1 - 0.47483\phi^2 & -1.0 \le \phi \le 1.0 & \\ \sin\phi = \phi - 0.1269\phi^2 & 0 \le \phi \le 1.0 & (C.20) \\ \sin\phi = \phi + 0.1269\phi^2 & -1.0 \le \phi < 0 & \end{array}$$

This approximation is within 3% for the range given. Under these circumstances we reduce r^2 to a polynomial of second degree in ϕ for which we can readily find an analytic integral:

$$\int \frac{d\phi}{r^3} = \frac{2(2C_2\phi + C_1)}{q\ r} \qquad (C.21)$$

in which

$$r = \left[C_2\phi^2 + C_1\phi + C_o\right]^{\frac{1}{2}}$$
$$q = 4\ C_2C_o - C_1^{\ 2} \qquad (C.22)$$

and

$$C_2 = R^2\ tg^2\beta + 2R\ \overline{OP}(0.47483\ \cos\alpha + 0.1269\ \sin\alpha)$$
$$C_1 = 2R\ tg\beta\ Z_q - 2\ R\ \overline{OP}\ \sin\alpha \qquad (C.23)$$
$$C_o = Z_q^2 + \overline{OP}^2 + R^2 - 2R\ \overline{OP}\ \cos\alpha$$

Since we always integrate over an angle interval where one of the limits is zero we have:

$$\int_o^\theta \frac{d\phi}{r^3} = \left[\frac{4C_2\ \theta + 2C_1}{r(\theta)} - \frac{2\ C_1}{(C_o)^{\frac{1}{2}}}\right]\frac{1}{4C_2C_o - C_1^{\ 2}} \qquad (C.24)$$

Having thus established the basic framework for the mathematical operations to be performed we must now consider the steps involved in the computations and the particular problems encountered when attempting machine calculation of this formalism.

As before we are concerned with solutions to equation

(C.2) for a power function given by (C.4). The differential element of path length ds can be expressed in terms of the polar angle ϕ. The path length and its projection are related by the cosine of the climb angle β:

$$ds = \frac{R\, d\phi}{\cos\,\beta} \tag{C.25}$$

The noise exposure integral as a function of ϕ only is then computed as:

$$E = \frac{R}{V\cos\phi}\int_{\phi_1}^{\phi_2}\frac{I d\phi}{3} = \frac{R}{V\cos\beta}\int_{0}^{\theta}\frac{I\ d\phi}{\left[\overline{OS}(\phi)^2 + \overline{AS}(\phi)^2\right]^{3/2}} \tag{C.26}$$

A linear variation in I along the path is again allowed. Since path and angle of integration are related (C.25), we can express the variation in ϕ only.

$$I = I_o + g\phi \tag{C.27}$$

The integral separates into two terms:

$$E = \frac{R}{V\cos\beta}\int_{0}^{\theta}\left(\frac{I_o}{r^3} + \frac{g\phi}{r^3}\right)d\phi \tag{C.28}$$

The integral of the first term is given in equation (C.24). For the second term we have:

$$\int_{0}^{\theta}\frac{\phi d\phi}{r^3} = -\left[\frac{2C_1\theta + 4C_o}{r(\theta)} - 4(C_o)^{\frac{1}{2}}\right]\frac{1}{4C_2C_o - C_1{}^2} \tag{C.29}$$

The preferred coordinate system in which to compute the noise exposure integral is that in which the center of curvature P is at the origin and $\overline{PQ'}$ is along the x-axis. If we take Q to be the point where the turn is started, we also know the transformation matrix. That this is so is clear from the consideration that the aircraft heading, and therefore the sine and cosine of the heading referred to the ground plane, are known and at the same time, since Q' is on the ground circle, PQ' perpendicular to the aircraft.

The only quantity which needs to be computed in this rotated reference frame is the angle α. Since we have that

$$\begin{aligned} \sin\alpha &= y / \overline{OP} \\ \cos\alpha &= x / \overline{OP} \end{aligned} \qquad (C.30)$$

where x and y are the observer coordinates in the rotated reference frame, we can easily find these quantities with their correct sign. Furthermore, since in equation (C.22) we see that these functions are always multiplied by a factor $\overline{OP}$ we do not have to concern ourselves with the question of limits for α when the observer approaches arbitrarily closely to the center of curvature P.

We now realize that in our chosen frame of reference a left hand turn will have a positive angle θ associated with it, whereas a right hand turn will correspond to a negative θ. Having made this observation there is one more agreement to be made so that equation (C.17) will correctly specify the aircraft altitude. We consider $\mathrm{tg}\beta$ positive if an aircraft climbs from Q to A in a right hand turn, or if it descends from Q to A in a left hand turn.

It is clear that in practice an aircraft will often turn over more than 1 radian. Since the problem of finding an analytic expression for the noise exposure integral necessitated the limitation to 1 radian, all curves must be split into portions not exceeding 1 radian. The computer will do this internally so that the user need not be concerned with splitting curved flight paths. In fact it is emphatically recommended that the user NOT do this since more considerations than arc length go into the decisions of where to split a curve. The interested reader can find a further discussion in the programmer manual.

Power level adjustments enter directly into the noise exposure integral since the values are given at the end points T and Q. The value of I_0 in (C.27) is that at Q, the linear coefficient

$$g = \frac{I_T - I_Q}{\theta} \qquad (C.31)$$

With the above considerations of the sign on θ and tgβ we have established all values needed in the equations (C.23) for a calculation of the parameters in the quadratic. The evaluation of integral (C.28) is then a simple substitution in (C.24) and (C.29) of these parameters.

The one remaining question is what constitutes the slant distance for a curved flight path. For this we use that distance for which $\frac{\partial r}{\partial \phi} = 0$ and $\frac{\partial^2 r}{\partial \phi^2} > 0$. This indicates that a minimum exists. Since the function is limited to relatively small arcs we impose the condition that the value of ϕ for which $\frac{\partial r}{\partial \phi} = 0$ lies in the interval $0 \leq \phi \leq \theta$

for a left hand, $\theta \leq \phi \leq 0$ for a right hand turn.

5. COMPUTING THE FINAL NEF

We have seen how the noise exposure integral for straight and curved sections are computed. If aircraft sources were nondirectional, we would be able to compute the EPNL directly, assuming that the $1/r^3$ law provides a good approximation to the PNL. As stated earlier, this is not possible. What we have achieved, however, is an estimate as to the relative importance of each section in the flight path. For each section we have obtained a number which tells us the relative intensity observed at a ground location due to each section.

One point has not been brought out in the discussion so far. This is the fact that air-to-ground propagation has been assumed. It is only for this condition that the $1/r^3$ law can be considered a valid approximation. To take those cases where the aircraft appears low above the observer's horizon into account the noise exposure integral for that segment where this condition exists is further modified. The difference between the EPNL for the two modes of propagation is determined and the noise exposure integral is reduced by the corresponding amount. The noise exposure integral is therefore always a correction to the air-to-ground curve.

To give a meaningful interpretation to these numbers we analyze our assumptions a little further. First of all we must have the proper normalization. To arrive at this we observe that for a flyover along a straight line, which is the reference condition for which we have measured data, the noise exposure integral is:

$$E_{ref} = 2/d^2 \qquad (C.32)$$

If we take this into consideration we can establish the following correction term for the EPNL. Let the total engergy as computed from the noise exposure be $PE = \Sigma E_k$. We pick the dominant term in this summation. The EPNL value found in the measured data for the slant distance corresponding to this section is $EPNL_M$. Then the EPNL can be written as:

$$EPNL = EPNL_M + 10 \log \left(\frac{PE}{E_{max}}\right) \qquad (C.33)$$

where $EPNL_M$ is the maximum EPNL adjusted for the fact that this section (probably) did not correspond to the reference condition with the aircraft coming from $-\infty$ and proceeding to $+\infty$.

We have developed in (C.32) the normalization constant corresponding to the reference case. Therefore, if the table entry is designated as EPNL(d), we have

$$EPNL_M = EPNL(d) - 10 \log \left(\frac{2/d^2}{E_{max}}\right)$$

which we can now substitute in (C.33) to obtain:

$$EPNL = EPNL(d) + 10 \log \left(\frac{PE}{2/d^2}\right) \qquad (C.34)$$

The NEF at a point due to operations of all aircraft type j on all flight path i is expressible as

$$NEF = 10 \log \sum_{ij}\sum \text{antilog} \frac{NEF(ij)}{10} \qquad (C.35)$$

Therefore we are at the time that we generate the grid of data points more interested in antilog NEF(ij) than in NEF(ij) itself. This type of summation is generally referred to as an energy sum. Since NEF(ij) is given in terms of EPNL plus a correction factor, the goal of our immediate interest is the energy equivalent of the EPNL of (C.34) to be used in the expression:

$$NEF(ij) = EPNL(ij) + 10 \log (N_{day} + 16.67\ N_{night}) - 88 \qquad (C.36)$$

which when converted to energy becomes:

$$\overline{NEF(ij)} = \overline{EPNL(ij)} * (N_{day} + 16.67\ N_{night}) * C \qquad (C.37)$$

From (C.34) we have:

$$\overline{EPNL(ij)} = \overline{EPNL(d)} * \frac{PE}{2/d^2} \qquad (C.38$$

After this rather lengthy discussion we can now see the reasons for some of the basic decisions in the architecture of the computer program. We are basically accumulating $\overline{NEF(ij)}$ at our grid points. It is therefore most efficient to run the entire program in an energy mode. All data or input are converted to energy equivalent; only on final output are logarithms taken. This saves a very considerable amount of computer time plus the additional bonus of a minimal roundoff error. (It is necessary to divide by 10--as in equation (C.35)--since many computers cannot represent antilog $\overline{EPNL(ij)}$ internally.) Similarly, the constant C of equation (C.37) is left off and 88 is subtracted from the value computed according to (C.35) since we need to perform this operation only once this way; besides subtraction is faster than division.

The one question which we have not addressed ourselves to in computing $\overline{\text{NEF}}$ values due to aircraft flight operations is what happens when we change EPNL curves during flight. When drastic power changes occur, which make using a simple across-the-board adjustment in the EPNL unrealistic (e.g. T&G patterns), it is possible to change to a different EPNL curve. Internally the program handles this by breaking the flight path up in as many "subflights" k as needed to have each subflight reference only one EPNL curve. The NEF(ijk) is then accumulated over the index k first, but the process is exactly the same as for a single EPNL curve.

6. GROUND RUNUP OPERATIONS

Having completed the discussion of the NEF contributions from flight operations we now proceed with ground operations. The approach here is entirely straightforward and no mathematical model is needed to simulate the operations. The runup data contain directional information and the assumption here is only that the noise levels expressed in tone corrected perceived noise level (PNLT) have mirror symmetry around the vertical plane through the longitudinal axis of the aircraft.

The EPNL at a location a distance S removed observing the aircraft under an angle ϕ is

$$\text{EPNL}(\phi,S) = \text{PNLT}(\phi,S) + 10 \log D - 10.0 \qquad (C.39)$$

The symbol D stands for the duration of the runup in seconds. The value 10.0 is a normalizing constant so that for a 10 second duration the EPNL equals the PNLT. On the other hand a + 10.0 dB ground runup sensitivity correction is added to account for subjective difference in the response to runup noise and flyover noise. These two correction factors cancel and we obtain for ground runups:

$$NEF_{ij} = PNLT_{ij} + 10 \log (D_{Dij} + 16.67\, D_{Nij}) - 88 \qquad (C.40)$$

exactly analogous to equation (C.1) for flight operations.

As for flight operations the program will internally perform table lookups to determine the proper PNLT value for each ϕ and S. The NEF_{ij} term will be added to the terms for flight operations to yield a final NEF

$$NEF = 10.0 \log \sum_i \sum_j 10.0^{\frac{NEF}{10}}$$

where summation takes place over all aircraft j performing all operations i appropriate for the index j. The index i includes runup operations on an equal footing with flight operations.

7. SOME CONSIDERATIONS FOR THE PROGRAM ARCHITECTURE

The computer program calculates NEF values at ground observer locations on a square grid with 1000 foot spacing. This allows one to follow the gradients of NEF and to form a good idea of the behavior of the contours of equal NEF. A contouring program may construct such NEF contours from the data points.

With the level of complexity which is allowed in the data input it is most expedient to keep NEF values in the computer and process the data cards one by one. The alternative approach of keeping all aircraft operations information in the machine and calculating by successive approximation the specified NEF values requires more storage or excessive I/O operations.

An advantage of a fixed grid which accumulates NEF contributions is that one can at any time read the grid back into the computer to add new operations. If new aircraft are added to an airbase, one can process just the new additions without the need to recompute the NEF of the previous aircraft.

The advantage of being able to output grid values directly is that one can still compute NEF contours but further study of the data can also be done. For example, a program producing only NEF contours or output does not provide any information about where the 30 NEF contour would move if the operations at the base doubled. On the other hand, one can from the gridded data easily calculate the 27 NEF contour either by hand or by contouring program without having to recompute any NEF values.

Finally, gridded data can be superposed on any other NEF grid. This opens the possibility to add other transportation systems to the model. If one were to write a program to produce NEF values for other transportation noise sources using such a grid, then the aircraft and other sources can be represented in one unified plot.

To keep the execution speed high the program will not compute grid points of less than 7 NEF. How this is implemented is discussed in the programmer manual. Similarly, the program keeps all EPNL, PNLT and NEF values internally as exponentiated values ("energy units"). Only if the program needs to output the data for external use are logarithms taken. This method saves a very considerable amount of computer time since otherwise each addition involves two exponentiations plus a logarithm. Neither of these operations are trivial to perform and since they are performed tens of thousands of times, the time saving is significant.

8. COMPUTER GRAPHICS AND ANALYTICAL GEOMETRY

The human mind in viewing or visualizing even a simple piece of graphics, such as a flighttrack map, is capable of an astounding amount of data processing. Equivalently, one can observe that the eyes are a very powerful input channel. In the following we will observe some of the methods used to generate the computer graphics and the processing necessary to keep track of the aircraft along its flightpath. When even elementary information, such as left and right, must be communicated to a computer, the resulting code becomes almost immediately quite obscure. It becomes quite clear that "one picture is worth a thousand words," particularly when dealing with computers.

Very liberal use is made throughout the program of the methods of analytical geometry. To improve the clarity of the FORTRAN code, most of the analytical geometry is left in a step-by-step form. Rather than giving the equations for a particular curve in terms of all the parameters of the computer internal reference frame, we have generally adopted the approach of starting in the preferred reference frame for a particular application and then transforming this result to the desired reference frame. This makes the code much clearer to the reader and anyone wishing to add to, delete from, or change a particular part of the program will be able to do so quite easily.

A. Aircraft Course and Analytical Heading

The very first problem deals with that of aircraft heading. For purposes of the program the heading of an aircraft is the direction of the <u>groundtrack</u>, it is really, therefore, the course rather than the heading. Furthermore, since we are going to use analytical geometry we will have to change coordinate systems. Assume a Cartesian coordinate system where the positive X-axis points east and the positive Y-axis points north. This is the frame of reference used by the program. Furthermore, angles are measured from the X-axis and are considered to be <u>positive when counterclockwise</u>. Normal aviation practice is to use the compass divided into 360 degrees, and consider angles positive when clockwise, with zero being due north. The angles given as input are therefore transformed to the internal system. Furthermore, all angles used internally are in radians since this is the natural measure for angles in mathematical considerations. This internal representation of the course of the aircraft is called the "analytical heading" in this program:

Analytical Heading = ((450-Course) Modulo 360) * 0.0174533 (C.41)

B. Transformation of Coordinates

A full discussion of coordinate transformations is clearly beyond the scope of this manual. The following few comments should suffice to make the transformations used in the program understandable. The two basic transformations are a rotation and a translation. The translation consists of adding the appropriate value to the x, y and z coordinate of each point. If we translate a coordinate system a units in x, b units in y, and leave the z direction unchanged, we have

$$\begin{aligned} x' &= x + a \\ y' &= y + b \\ z' &= z \end{aligned} \tag{C.42}$$

The rotation of a coordinate system is a little more complex. If we wish to rotate the coordinate system around the z-axis over an angle θ we arrive at the coordinates in the rotated frame of reference by means of the following:

$$\begin{aligned} x' &= x \cos \theta + y \sin \theta \\ y' &= y \cos \theta - x \sin \theta \\ z' &= z \end{aligned} \tag{C.43}$$

It is important to remember that the primed values are the coordinates of the <u>same point expressed in the new reference frame</u>. The following few sections discuss how these transformations are useful in terms of the program.

C. Typical Application: The Distinction Between Left and Right

When we look at a flighttrack, it is immediately obvious which side is left and which side is right. We must, however, define things in absolute mathematical terms before the computer can make such a decision. A look at the problem will easily tell us what the preferred coordinate system is. (We are generally interested in the location of a point on the ground relative to the flight track, therefore we are not really concerned with the z-coordinate in what follows.) The simplest way to express the problem is by looking at the case where the aircraft ground projection is at the origin of the coordinate system and the instantaneous velocity vector is along the positive X-axis. In this coordinate system to the right means a negative y, to the left a positive y. This coordinate system is therefore the preferred system.

Let us assume we wish to know if a navigational aid located at (x_n, y_n) will be passed on the left or on the right. We have seen which coordinate system will give us a ready answer. The first step is to find a coordinate system, parallel to the old one, but with the origin at the aircraft ground projection. We will assume at the aircraft at the given moment to be at (x_a, y_a), while the analytical heading is θ radians. In this translated system we find

$$x'_n = x_n - x_a$$

$$y'_n = y_n - y_a$$

$$(z'_n = z_n = o)$$

The next step is to find the frame of reference where the velocity vector is along the positive X-axis. This is done, of course, by rotating our primed system over an angle θ.

Therefore we have:

$$x''_n = x'_n \cos\theta + y'_n \sin\theta$$

$$y''_n = y'_n \cos\theta - x'_n \sin\theta$$

If y''_n is less than zero the navaid is to the right of the aircraft, therefore a negative value indicates that the aircraft will pass the navaid on the left. Whether the navaid is ahead or already past is given by x''_n. If x''_n is positive, the navaid is ahead; if x''_n is negative it is behind. Of course, the values could be zero. If y''_n is zero, the navaid is directly on course; if x''_n is zero the navaid is on a line perpendicular to the current heading at this particular location (x_a, y_a).

In general we have taken the approach outlined above to guide the user (programmer) through the steps involved in a particular geometric problem. We could equally well have said that the condition for a point being to the right of the aircraft ground projection is

$$(x_n - x_a) \sin\theta - (y_n - y_a) \cos\theta > 0 \qquad (C.44)$$

One could have arrived at this inequality by considering only the basic reference frame and finding those relationships between the coordinates and headings which give necessary and sufficient conditions for the desired properties. In practice, however, it is a very laborious enterprise to find conditions such as (C.44).

It should be emphasized that there is a large difference between verifying the correctness of (C.44) and concluding from purely geometric reasoning that, of all possible relations between x_n, x_a, y_n, y_a and θ, (C.44) is the necessary and sufficient condition to find points to the right of an aircraft. Also, once the relation is given it is fairly simple to give it geometric interpretation, but it is not always a priori obvious which particular geometric relationship we are looking for.

A particularly unpleasant concomitant of all geometric reasoning is that one must satisfy oneself that a relationship, derived from geometric considerations, is valid for all quadrants. It is for this reason that we feel the approach used in our treatments is by far the more lucid, and nowhere do we attempt to give any geometric interpretation of relationships such as (C.44), unless, of course, the geometric interpretation is the goal we are after!

D. The Transformation in Reverse: Drawing a Circle on the Plotter

The process of coordinate transformation is wholly symmetrical. In other words, it is entirely the same thing whether we rotate the coordinate system and look at the change in values of a coordinate pair or if we keep the coordinate system fixed and let the coordinate pair move in the opposite sense over a circle with the origin as its center. A rotation of the coordinate axes through $+\theta$ is mathematically equivalent to rotating the (position vector of) coordinate pair (x_n, y_n) around the origin by $-\theta$.

This is precisely the way in which we draw circles on the plotter. We take a point located a distance R along the positive x-axis. The circle will be drawn by connecting closely spaced points on the circle by straight lines, so we must find points on the circle. To specify things further we will make this a left hand turn. We want therefore to rotate our radius R counterclockwise around the origin. The point on the circle which is a small angle β removed from the current position is now given by:

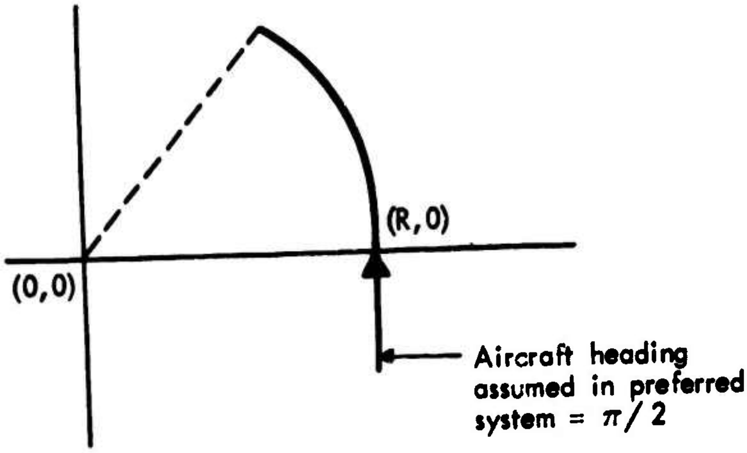
$$\begin{aligned} x' &= x \cos \beta - y \sin \beta \\ y' &= y \cos \beta + x \sin \beta \end{aligned} \qquad (C.45)$$

Note the difference with (C.43) in the sign of the sine terms. We can now repeat this process by successive application of (C.45) to each new set of (x', y') values and trace out a circle sector of arbitrary length. This will give us a set of points (x'_i, y'_i) which are spaced an arc β apart and all of which lie on a circle of radius R, centered on the origin.

The next step then is to move this circle sector to where we need it. To accomplish this we rotate the sector around the point $(x = R, y = o)$ which is the "start" of the turn. First we translate the origin to the start of the turn, then we rotate around this point. Having the correct orientation, we translate to the point where the turn is needed. The rotation in this case is a little less straightforward because of the way we chose our preferred coordinate system. The requirement of tangency of the circle which we are constructing, with the previous flight-track means, in the preferred system, that the aircraft was moving parallel to the y-axis in the direction of increasing y. Therefore, the aircraft is assumed to be on an analytical heading of 90 degrees in the reference frame. The correct angle of rotation is therefore not θ but $\theta - \pi/2$. Therefore, the trigonometric functions are different at first sight since:

$$\sin(\theta - \pi/2) = \cos\theta$$

$$\cos(\theta - \pi/2) = -\sin\theta$$



If we connect all "doubly transformed" coordinate pairs (x'_1, y'_1) by straight line segments, we will construct a polygon which is circumscribed by the desired circle. In the limit of $\beta \rightarrow 0$ we trace the complete circle sector. The computer will draw the circle for a finite β such that the resulting polygon edges are 0.1 inch or correspond to not more than 2 degrees of arc, whichever is smaller. The resulting figure is entirely satisfactory for constructing a flighttrack map.

APPENDIX D

GUIDES FOR CONDUCTING NOISE VALIDATION MEASUREMENTS

Noise monitoring for purposes of validating noise level or noise exposure values will typically be undertaken for one or both of the following reasons:

a) There are uncertainties in basic assumptions with regard to aircraft flight paths, aircraft profiles, or noise data. For example, due to diversities in training missions, one may suspect considerable variability in aircraft take-off profiles and tracks, leading to questions as to how well the computed noise values compare with field values. Noise level projections may be questioned for ground runup operations at distant locations, particularly when there are large variations in weather or irregular terrain.

b) There is a need to determine the noise exposure to close tolerances. Such conditions often arise where noise criteria have been set for land zoning or for land development. For example, HUD noise policy guidelines[75/] makes eligibility for federal funding for residential development dependent on the NEF value on the site.

In respect to reason (b) above, it should be noted that the translation of tolerances in NEF values into changes in contour locations on the ground can easily result in demands (often unrealistic) for small tolerances in measurement. For example, the following table shows the distances involved for a change of 2 dB:

Propagation Distance, ft.	Decrease in Noise Levels per Doubling of Distance	
	6 dB	9 dB
1,000	126 ft	117 ft
2,000	252 ft	234 ft
5,000	630 ft	584 ft
10,000	1260 ft	1170 ft

There are several instances known where the shift of a noise contour by several hundred feet has resulted in changes in land valuations and/or development costs by many tens of thousands of dollars.

A. Determining the Number and Duration of Field Measurements

The reasons for performing the measurements will determine, to a large extent, the degree of accuracy needed and will influence the number or duration of the field measurements. The other major factor is the expected variability in noise levels or noise exposure.

Figure D-1 provides a guide for estimating the number of measurements needed to establish a 90% confidence interval when estimates of the expected variability in terms of the expected sample standard deviation are known.

One must make a distinction between the need to establish an NEF value to a given confidence interval and the need to establish EPNL values to given confidence levels, since the

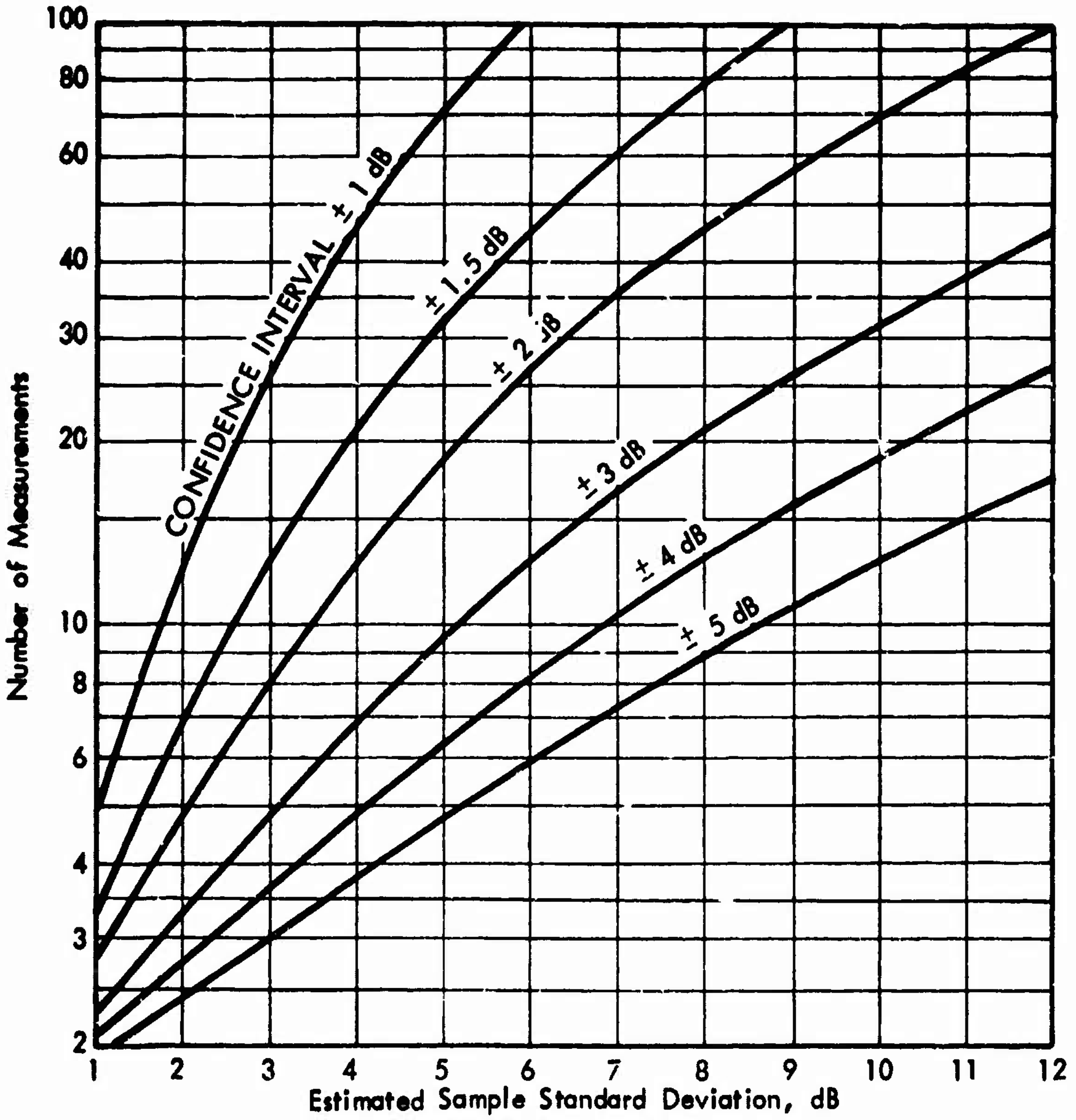


FIGURE D-1. NUMBER OF MEASUREMENTS NEEDED TO ASSURE A 90 % CONFIDENCE INTERVAL degree of variability and time requirements may be vastly different. For example, an air base may have a wide variation in the number of operations on a day-to-day basis. Thus, it may take a considerable period of time to establish a field NEF value to a given degree of confidence, since one can accumulate only one NEF value per 24-hours of measurements. However, one might well be able to determine noise levels to a given confidence level in one or two days if there is a large number of the desired operations per day.

Section IV-D of the report provides estimates of the expected variability in noise levels resulting from flight operations. Standard deviations can range from 2 to 7 dB. Factors influencing the variability include the type of operations, variability in flight tracks and profiles, and the sound propagation distance.

The sound propagation distance will likely have considerably more influence on variability for ground runup than for flight operations (provided the elevation angles are sufficiently high [greater than about 15°] to avoid ground attenuation effects). For short to moderate sound propagation distances from flight operations (several hundred to one thousand feet), variations in flight paths can contribute significantly to the variability of observed ground levels. At larger distances, the effect of the aircraft path variations on actual propagation distances usually becomes very small, but the effect of variations in atmosphere attenuation increases. Hence, results from recent measurements involving propagation distances from 2000 to over 5000 feet show only a slight increase in variability with distance.

Variability in day-to-day NEF values will be directly related to variations in volume of operations and usage of flight paths, and may be heavily influenced by weather conditions which result in changes in runway usage. Some information on variability is available from civil airport measurements. For the case of relatively "close-in" measurement positions at civil airports where there are few shifts or reversals of runway usage, NEF values will show small variability. Results of CNEL monitoring at Orange County Airport, California[76/] show standard deviations in day-to-day measurements of 2 to 3 dB for monitoring over 66 days. Measurements over a period of 11 days at another airport[77/] at a close-in position showed a standard deviation of 1.2 dB.

Measurements showed considerable greater variability at another civil airport in which there were frequent reversals of runway usage over a 30 day period (takeoff operations predominated on 17 days, landing operations predominated on 10 days and there were three days of nearly equal takeoffs and landings). The standard deviation in CNEL values at individual measurement positions ranged from 3.3 to 4.6 dB for measurements over a 30 day period, with observed ranges in CNEL values per station of 13 to 17 dB.

Thus, experience from civil airport measurements indicates typical noise exposure value standard deviations ranging from under 2 up to 5 dB. This range in variability indicates a possible wide range in measurement periods to establish a given confidence interval. Reference to Figure D-1 shows that for a 90 percent confidence interval of ± 2 dB, one needs about five sets of measurements for a standard deviation of 2 dB, increasing to about 20 days of measurement for a standard deviation of five dB.

B. Number and Location of Measuring Positions

When it is desired to verify the noise environment over an area rather than at a single position, it is desirable to measure noise levels at two or more, and preferably, three or more positions simultaneously. Information obtained at two or more positions simultaneously allows one to establish gradients in noise levels and permits some degree of extrapolation or interpolation between measurement positions. Further, with more than two measurement positions, one measurement position can be maintained as a "control" position, while the other instruments are moved about. Comparison of noise levels at the various "moveable" positions with these observed at the control position enable one to adjust for variations in noise exposure occurring on a day-to-day basis, which might arise from changes in volume of operations or changes in the mix of aircraft.

In verifying noise contours due to flight operations, the control position would typically be placed directly underneath the flight path, and the other stations placed on perpendiculars to either side, or placed further out under the projected flight path.

Figure D-2 shows one measurement approach, utilizing three measurement instruments, where it is desired to verify one side of a takeoff contour. The instruments are first placed at positions marked "A". After the first series of measurements, two of the instruments are moved to new positions for the second series of measurements, denoted as "B" in the figure. This "leap frog" procedure can be repeated, as needed, until the contour is mapped. Note that it is desirable to place the instruments on a perpendicular to the flight path outside of the

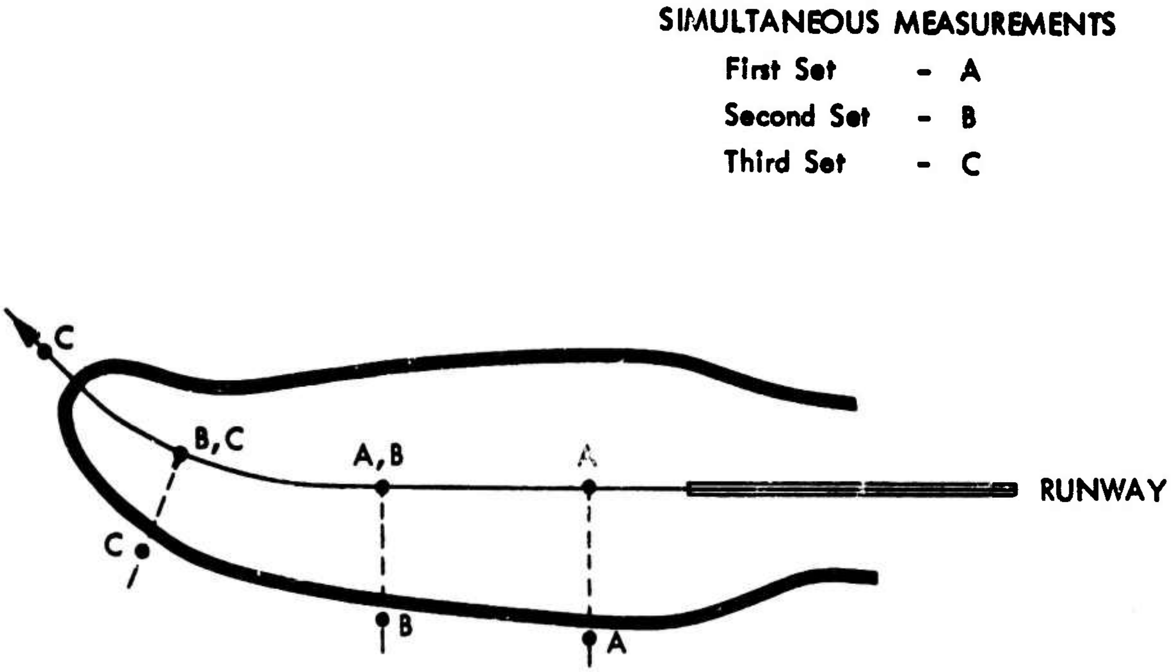


FIGURE D-2. SKETCH SHOWING LOCATION OF NOISE MEASUREMENTS POSITIONS TO VERIFY A NOISE EXPOSURE CONTOUR

contour, to permit interpolation, rather than extrapolation, in defining the contour ground location.

A number of variations in the measurement plan sketched in Figure D-2 can be developed. However, the concept of keeping one position as a "control" point should be retained.

Regardless of the number of simultaneous measurement positions, and the use of "control" points, it is important that accurate records of operations using the flight paths under study be kept during the period of measurement. Variations in noise exposure will occur, and knowledge of the actual history of operations will usually be vital in understanding the reasons for the variations.

In validating the noise exposure due to ground runup operations, the control position should be placed within 250 to 500 feet of the source, and in line with a radial extending from the source to one or more of the distant measuring positions. As the distant positions are shifted, it will usually be desirable to shift the close-in control position so that the measuring positions are along the same radial extending out from the source. This procedure permits one to compare the differences in noise level without the need for detailed knowledge of, or adjustment for, the horizontal directional characteristics of the source.

*U.S.Government Printing Office: 1974 — 657-017/360