REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 1997	3. REPORT TYPE AND DATES COVERED Final Jan 93 - Dec 97

4. TITLE AND SUBTITLE
Integrated Noise Model (INM) Version 5.1 Technical Manual

5. FUNDING NUMBERS
FA765/A7012
DTFA01-93-C-00078
Task Orders 9,14,19

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10. SPONSORING/MONITORING AGENCY REPORT NUMBER
FAA-AEE-97-04

11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION/AVAILABILITY STATEMENT
This report is part of the INM 5.1 software release.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The Federal Aviation Administration, Office of Environment and Energy (FAA, AEE-120) has developed Version 5.1 of the Integrated Noise Model (INM) with support from the John A. Volpe National Transportation Systems Center, Acoustics Facility (Volpe Center) for development of the acoustic computation module and from the ATAC Corporation for systems integration, development of the graphical interface, and methods for computing aircraft flight profiles and constructing flight paths, which are processed by the acoustics module.

The Technical Manual for INM 5.1 describes the flight-path methodology (Chapter 2), along with the basic methodology employed by the INM to compute a noise-level or time-above metric at a single, user-specified observer, or at an evenly-spaced, regular grid of observers (Chapter 3).

The noise/time computation methodology is presented in a concise step-by-step fashion, and includes a description of: (1) the computation of the flight-segment geometric and physical parameters; (2) the flight-segment noise-level interpolation process; (3) the acoustic impedance adjustment; (4) the flight-segment noise-fraction adjustment for exposure-based metrics; (5) the airspeed adjustment for exposure-based metrics; (6) the lateral attenuation adjustment; (7) the ground-based directivity adjustment for observers behind start-of-takeoff-roll, as well as for computing metrics associated with runup operations; (8) the metric computation process; and (9) the development of a recursively-subdivided irregular grid methodology, which is used for computing noise contours (Chapter 4).

14. SUBJECT TERMS Airport Noise, Computer Model, Noise Contours, Integrated Noise Model, INM, Noise-Level Prediction, Noise-Level Metric, Day-Night Average Sound Level, L_{dn}, Heliport Noise Model, FAR Part 150			15. NUMBER OF PAGES 112 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-550

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

PREFACE

This document was jointly prepared by the John A. Volpe National Transportation Systems Center, Acoustics Facility (Volpe Center), and the ATAC Corporation, in support of the Federal Aviation Administration, Office of Environment and Energy (FAA AEE-120). It is a Technical Manual for the FAA's Integrated Noise Model (INM) Version 5.1 computer software used to predict noise impact in the vicinity of airports. The INM 5.1 Technical Manual presents the methodology employed by INM 5.1 to build aircraft flight paths, and to compute noise-level and time-above metrics based upon the finite flight-segment information.

DISCLAIMER

The contents of this report reflect the views of the Volpe Center and the ATAC Corporation, and they are responsib
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does not constitute a standard, specification, or regulation. The design, production, and distribution of this manual ha

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1 INTRODUCTION

Since 1978, the Federal Aviation Administration's (FAA) standard methodology for **noise*** assessments has been the Integrated Noise Model (INM). The INM is a computer program used by over 700 organizations in 35 countries to assess changes in noise impact resulting from: (1) new or extended runways or runway configurations; (2) new traffic demand and fleet mix; (3) revised routings and airspace structures; (4) alternative **flight profiles**; and (5) modifications to other operational procedures.[1]

With the release of INM 5.0 in August 1995,[2] the FAA's Office of Environment and Energy (AEE-120), with the support of the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, Acoustics Facility (Volpe Center), has enhanced several of the reliable core algorithms used in previous versions, redesigned their computational architecture, and re-coded them in the C++ programming language, resulting in both computation and speed improvements. The ATAC Corporation, serving as the FAA's systems integrator for the INM, has developed a Windows-based graphical user interface for the INM, along with methods for computing aircraft flight profiles and constructing **flight paths**, which are processed in the acoustic module.

In the latest version of INM, Version 5.1, major enhancements include the incorporation of 110 new aircraft, primarily aircraft from the United States Air Force's NOISEMAP computer program,[3] as well as the ability to run INM in the Microsoft Windows 95 operating system.

This Technical Manual for INM 5.1 computer software describes in Chapter 1 the **metric types** available for computation, in Chapter 2 the flight-path segmentation methodology, and in Chapter 3 the methodology employed to compute metrics at a single **observer**, or at an evenly-spaced **regular grid** of observers. Chapter 4 describes the methodology used to develop the **recursively-subdivided irregular grid** required for computing noise **contours**. The Appendices discuss the background and derivation of some of the more complex algorithms and concepts utilized by INM.

1.1 Grid-Point Computations

INM 5.1 computes a noise-level metric or a **time-above** metric in the vicinity of an airport. The metric is presented as numeric values at a regular grid of observer points, or as contours at user-specified levels.

For regular grid computations, observer locations are arranged in the form of a user-defined rectangular grid of points, with fixed distances between the points. A regular grid can be rotated with respect to the coordinate system.

* Terms in boldface type are described in Section 1.4

For irregular grid computations, observer locations are arranged in the form of a recursively-subdivided grid of points, with varying distances between points. Irregular grids are utilized for contour computations. The density of grid points is a function of a user-specified level of subdivision (called the **refinement level**), accuracy (called the **tolerance**), and the lowest and highest expected contour levels desired (called **cutoff levels**). In general, the contour accuracy increases as grid density increases.

The basic noise computation process used for the development of a recursively-subdivided irregular grid is similar to the process used for the development of a regular grid. In generating the irregular grid required for contour computations, a 17-by-17 point regular grid containing 289 total grid points, is first generated. Knowledge about the user-specified refinement level and tolerance, and knowledge determined by the program about noise-significant flights directs the process of subdividing the regular grid to improve contour precision.

1.2 Metric Families

The noise-level and time-above metrics computed by INM 5.1 are associated with two fundamental groups or **metric families**.[4, 5, 6, 7, 8]

The first family of metrics is related to the **A-weighted** sound level, denoted by the symbol L_A. A-weighted sound levels de-emphasize the low and high frequency portions of the spectrum. This weighting provides a good approximation of the response of the average human ear, and correlates well with the average person's judgment of the relative loudness of a noise event.

The second group of metrics is related to the **tone-corrected perceived** noise level, denoted by the symbol L_{PNT}. Tone-corrected perceived noise levels are used to estimate perceived noise from broadband sound sources, such as aircraft, which contain pure tones or other major irregularities in their frequency spectra.

1.3 Metric Types

Within the two metric families, INM computes three types of metrics: (1) exposure-based metrics, (2) maximum noise-level metrics, and (3) time-above metrics. There are 13 noise metrics supported by INM, as shown in Table 1-1.

1.3.1 Exposure-Based Metrics

The exposure-based metrics represent the total **sound exposure** for a time period, usually 24 hours, based upon **average annual day** conditions at an airport.

INM standard sound exposure metrics are:

L_{AE}	A-weighted sound exposure level (SEL)
L_{EPN}	Effective tone-corrected perceived noise level (EPNL)

These exposure metrics are used to generate long-term average noise level metrics by applying associated **time-averaging constants** and day, evening, and night-time **weighting factors**.

Table 1-1: INM 5.1 Noise Metrics

Noise Family	Metric Type	Noise Metric	Flight Multiplier Day	Evening	Night	Averaging Time (hr)
A-Weighted	Exposure-Based	SEL	1	1	1	--

		DNL	1	1	10	24
		CNEL	1	3	10	24
		LAEQ	1	1	1	24
		LAEQD	1	1	0	15
		LAEQN	0	0	1	9
		User	A	B	C	T
	Maximum Level	LAMAX	1	1	1	--
		User	A	B	C	--
	Time-Above	TALA	1	1	1	--
		User	A	B	C	--
Tone-Corrected Percieved	Exposure-Based	EPNL	1	1	1	--

		NEF	1	1	16.7	24
		WECPNL	1	3	10	24
		User	A	B	C	T
	Maximum Level	PNLTM	1	1	1	--
		User	A	B	C	--
	Time-Above	TAPNL	1	1	1	--
		User	A	B	C	--

INM standard average-level metrics in the A-weighted family are:

L_{dn}	Day-night average sound level (DNL)

L_{den}	Community noise equivalent level (CNEL)
L_{Aeq24h}	24-hour average sound level (24hEQ or LAEQ)
L_d	15-hour (0700-2200) day-average sound level (DL or LAEQD)
L_n	9-hour (2200-0700) night-average sound level (NL or LAEQN)

INM standard average-level metrics for the tone-corrected perceived family are:

L_{NEF}	Noise exposure forecast (NEF)
L_{WECPN}	Weighted equivalent continuous perceived noise level (WECPNL)

The day, evening, and night-time weighting factors and the time-averaging periods for the these metrics are shown in Table 1-1.

In addition to the INM standard sound exposure and average sound level metrics, user-defined metrics for either family are available. A user specifies the time-averaging constant and the day, evening, and night-time weighting factors.

1.3.2 Maximum Noise Level Metrics

The **maximum noise level** metrics represent the maximum noise level at an observer location, taking into account aircraft operations for a particular time period (e.g., 24 hours).

INM standard maximum noise level metrics are:

L_{ASmx}	Maximum A-weighted sound level with slow-scale exponential weighting characteristics (MXSA or LAMAX)
L_{PNTSmx}	Maximum tone-corrected perceived noise level with slow-scale exponential weighting characteristics (MXSPNT or PNTLM)

In addition to the INM standard maximum noise level metrics, user-defined metrics are available. A user specifies the time period for determining the maximum level.

1.3.3 Time-Above Metrics

The time-above metrics represent a measure of the time duration that the noise level is above a specified **noise-level threshold**, taking into account aircraft operations for a particular time period (e.g., 24 hours).

INM standard time-above metrics are:

TAL_A	Time that the noise level is above a user-specified A-weighted sound level during the time period (TALA)
TAL_{PNT}	Time that the noise level is above a user-specified tone-corrected perceived noise level during the time period (TAPNL)

In addition to the INM standard time-above metrics, user-defined metrics are available, where a user specifies the time period for determining the time-above value.

1.4 Terminology

This section presents pertinent terminology used throughout the document. Each term is highlighted with boldface type when it first appears in the report. The terms are arranged alphabetically.

A-Weighted. A-weighted noise level emphasizes sound components in the frequency range where most speech information resides, yielding higher levels in the mid-frequency (2000 to 6000 Hz) range and lower levels in both low frequency and high frequency ranges. A-weighted noise level is used extensively in the U. S. for measuring community and transportation noises.

Acoustically Hard Surface. Any highly reflective surface in which the phase of the incident sound is essentially preserved upon reflection; example surfaces include water, asphalt, and concrete.

Acoustic Impedance Adjustment. An acoustic impedance adjustment, computed as a function of observer temperature, pressure, and indirectly elevation, is applied to the noise levels in the INM NPD data. Acoustic impedance is the product of the density of air and the speed of sound.

Acoustically Soft Surface. Any highly absorptive surface in which the phase of the incident sound is changed upon reflection; example surfaces include terrain covered with dense vegetation or freshly-fallen snow.

Airport Pattern. A defined flight path (ground track and altitude above the airport) used by aircraft for touch-and-go operations.

Airspeed Adjustment. An adjustment made to the exposure-based noise levels when the aircraft speed differs from 160 knots.

Approach. A flight operation that begins in the terminal control area, descends, and lands on an airport runway, possibly exerts reverse thrust, and decelerates to taxi speed at some location on the runway.

Atmospheric Absorption. The change of acoustic energy into another form of energy (heat) when passing through the atmosphere. The NPD data are corrected for atmospheric absorption in accordance with the Society of Automotive Engineers (SAE) Aerospace Recommended Practice (ARP) 866A [9] and SAE Aerospace Information Report (AIR) 1845 [10].

Average Annual Day. The user-defined best representation of the typical long-term conditions for the case airport. These conditions include the number and type of operations, the routing structure, the temperature, and the atmospheric pressure.

Calibrated Airspeed (CAS). The indicated airspeed of an aircraft (as read from a standard airspeed indicator), corrected for position and instrument error. Calibrated airspeed is equal to true airspeed in standard atmosphere at sea level.

Case Analysis Window. The user-defined rectangular area around an airport within which a contour analysis is performed.

Circuit Flight. A flight operation, new to INM beginning with Version 5.1, that combines a departure from, and an approach to, the same runway with an unlimited set of level-flight and/or varying-altitude segments in between.

Contour. An analysis of an area in the vicinity of an airport encompassed by a graphical plot consisting of a smooth curve, statistically regressed through points of equal noise level or time duration. There are two kinds of contour analyses: single-metric and multi-metric.

Corrected Net Thrust Per Engine. The net thrust per engine divided by the ratio of the ambient air pressure at aircraft altitude to the ISA air pressure at mean sea level.

Cutoff Levels. A test that determines when to end noise level (or time) computations during a single-metric contour analysis. The point at which computations are stopped is based on user-defined lowest and highest noise level (or time) contours. Similar to the tolerance and refinement level tests, the reason for performing this test is to reduce runtime during a single-metric contour analysis.

Decibel (dB). A decibel is unit of measure of a noise level or a noise exposure level. The number of decibels is calculated as ten times the base-10 logarithm of the ratio of mean-square pressures or noise exposures. For the purpose of this document, the reference root-mean-square pressure is 20 μPa, the threshold of human hearing.

Departure. A flight operation that begins on a runway, proceeds down the runway, and climbs and accelerates to altitudes at a specified distances.

Directivity Adjustment. A noise level adjustment resulting from the normalized noise pattern defined by a 360-degree area in the horizontal plane around a noise source. In INM, measurement-based directivity is accounted for behind the start of the takeoff ground roll and for runup operations.

Distance Duration. An empirically-derived effect, expressed as a function of distance, which relates exposure-based noise levels to maximum-based noise levels. This effect is taken into account in the INM NPD data only for data corrected using the simplified data adjustment procedure.

Extended Flight-Path Segment. A mathematical extension from either end of a geometrical flight-path segment to infinity.

Flight Operation. There are five kinds of flight operations in INM 5.1: approach, depart, touch-and-go, circuit flight, and overflight.

Flight Path. A set of flight path segments describing geometrical and physical parameters used to model the movement of an aircraft in three-dimensional space.

Flight Path Segment. A directed straight line in three-dimensional space, which includes the aircraft speed and corrected net thrust per engine (or equivalent parameter) at the beginning point of the line, and change in speed and thrust along the line to the end point.

Flight Profile. A set of points that models the geometrical and physical characteristics of an aircraft flight operation in the vertical plane. Each profile point contain: (1) the ground distance (x-value) relative to the origin of the operation, (2) the aircraft altitude above field elevation, (3) the true airspeed of the aircraft, and (4) the corrected net thrust per engine (or equivalent parameter) used to access the NPD curves.

Ground Plane. Without terrain elevation processing, the ground plane is the geometrical horizontal plane at the elevation of the airport. With terrain elevation processing, the ground plane is not generally horizontal. The slope and elevation of the ground plane is determined using three-by-three arc-second geodetic elevation data for the area surrounding the airport.

Ground Speed. That component of aircraft speed obtained by projecting the aircraft velocity vector on the horizontal plane.

Ground Track. The trace of the flight path on the horizontal plane. Flight tracks are described as vector-type tracks consisting of one or more straight or curved segments, or points-type tracks consisting of an array of x,y points.

Integrated Adjustment Procedure. The preferred adjustment procedure used for developing exposure-based INM NPD data from measured noise level data. It is based on noise level data measured over the full spectral time history of an event. In the integrated procedure, off-reference aircraft speed, atmospheric absorption effects, and spherical divergence are considered. This adjustment procedure provides data consistent with Type 1 quality, as defined in SAE-AIR-1845. [10]

International Standard Atmosphere (ISA). Internationally standardized functions of air temperature, pressure, and density versus aircraft altitude above mean sea level. The ISA is intended for use in calculations in the design of aircraft, in presenting test results of aircraft and their components under identical conditions, and to facilitate standardization in the development and calibration of instruments. [11]

Lateral Attenuation Adjustment. An adjustment that results from the attenuation of noise at grid points laterally displaced from the ground projection of an aircraft flight path. It is a combination of the ground-to-ground attenuation and the air-to-ground attenuation.
Maximum Noise Level. The maximum of a series of measured sound pressure levels from a single flight.

Mean-Squared Sound Pressure. A running time-average of frequency-weighted, squared instantaneous acoustic pressure. For example, A-weighted (denoted by subscript A) mean-squared pressure using slow (denoted by subscript S) exponential time averaging (τ = 1 second) is calculated by:

$$p(t)_{AS}^2 = \int_{-\infty}^{t} p_A^2(x)\, e^{x/\tau}\, dx / \tau$$

Mean-Square Sound Pressure Ratio. The mean-square sound-pressure ratio is the ratio of the mean-squared sound pressure divided by the square of the reference pressure. It is equivalent to $10^{SPL/10}$, where SPL is the sound pressure level.

Metric Family. A set of noise-level and time-above metrics differentiated by frequency weighting, either A-weighted or tone-corrected perceived.

Metric Type. A metric belongs to one of three types: exposure-based, maximum-level, or time-above.

Multi-Metric. A contour analysis in which noise and time values are computed for three base metrics belonging to either the A-weighted or tone-corrected perceived family of metrics. The three primary metrics are the exposure-based, the maximum noise level, and the time-above metrics.

Noise. Any unwanted sound. “Noise” and “sound” are used interchangeably in this document.

Noise Fraction. The ratio of noise exposure at a grid point due to a flight segment, and the noise exposure at the same grid point due to a straight, infinite flight path extended in both directions from the segment. The noise fraction methodology in INM 5.1 is based upon a fourth-power 90-degree dipole model of sound radiation. It facilitates the modeling of a three-dimensional flight path, using straight flight segments.

Noise Fraction Adjustment. An adjustment that is a function of the ratio of the noise exposure at a grid point due to a flight-path segment, and the noise exposure at the same grid point due to a straight, infinite flight path, extended in both directions from the segment.

Noise-Level Threshold. A noise level specified by the user that is the boundary value above which time-above calculations are performed.

Noise-Power-Distance (NPD) Data. A set of noise levels, expressed as a function of: (1) engine power, usually the corrected net thrust per engine; and (2) distance. The INM NPD data are corrected for airspeed, atmospheric absorption, distance duration, and divergence.

Noise Significance Tests. Tests performed by INM 5.1 to determine if a flight operation is acoustically significant. Two kinds of tests are used: the relative noise-level/time test and the track proximity test. The reason for performing these tests is to decrease runtime during a contour analysis.

Observer. A receiver or grid point at which noise or time values are computed.

Overflight. A flight operation that begins in the air, and remains in the air, in the vicinity of the airport, with optional user-specified changes in altitude and speed during the flight.

Procedure Steps. A prescription for flying a profile. Procedures include climbing at constant calibrated airspeed to a given altitude, accelerating to a given airspeed while climbing at a given vertical rate, etc.

Profile Points. See Flight Profile.

Recursively-Subdivided Irregular Grid. A grid of observer points created by one or more subdivisions of an existing regular or irregular grid, based on the user-specified refinement level and tolerance.

Refinement Level. The number of levels of subdivision of a regular grid making up a recursively-subdivided irregular grid. Each successive refinement level beyond level three represents one level of subdivision. The size of the smallest contouring grid is $D / 2^{N+1}$, where D is the size of the case analysis window and N is the refinement level.

Reference Day. The atmospheric conditions corresponding to 77 degrees Fahrenheit (25 degrees Celsius), 70 percent relative humidity, and 29.92 in-Hg (760 mm-Hg). These are the atmospheric conditions to which aircraft noise certification data are corrected in accordance with Federal Aviation Regulation Part 36.[12] These conditions are commonly referred to as ISA plus 10 degrees Celsius (ISA+10).

Reference Speed. The noise-exposure reference speed in INM is 160 knots true airspeed (TAS). Thus, L_{AE} and L_{EPN} values in the NPD database are referenced to 160 knots TAS. The L_{ASmx} and L_{PNTSmx} values are assumed to be independent of aircraft speed.

Regular Grid. A noise analysis of one or more noise-level and/or time-above metrics, for a set of observer points spaced at fixed intervals, over a specified area in the vicinity of the case airport.

Relative Noise-Level/Time Test. A noise significance test in which all flight operations are sorted high-to-low according to the noise (time) contribution of each flight at a regular grid point. Flights considered significant are those whose cumulative noise (time) first equals or exceeds 97 percent of the total mean-square sound-pressure ratio (total time) at the grid point.

Runup. An activity in which an aircraft is in a stationary position on the ground, with aircraft thrust held constant for a time period.

Simplified Adjustment Procedure. An adjustment procedure used for developing exposure-based INM data from measured noise level data. In contrast to the integrated procedure, the simplified procedure is based on noise-level data measured at the time of the maximum noise level only. In the simplified procedure, off-reference aircraft speed, atmospheric absorption, distance duration effects, and spherical divergence are considered. This adjustment procedure provides data consistent with Type 2 quality as defined in SAE-AIR-1845. [10]

Single-Metric. A contour analysis in which noise or time values are computed for a single, user-specified metric.

Sound Pressure Level (SPL). Ten times the base-10 logarithm of the ratio of the mean-squared sound pressure, in a stated frequency band, to the square of the reference sound pressure of 20 µPa, the threshold of human hearing.

$$SPL = 10 \log_{10}[\, p^2 / p_o^2 \,]$$

where,

p^2 mean-squared pressure (Pa^2),

p_o 20 µPa.

Sound Exposure (Noise Exposure). The integral over a given time interval T of the instantaneous, frequency-weighted, squared sound pressure:

$$E = \int_0^T p^2(t)\, dt$$

Sound Exposure Level. Ten times the base-10 logarithm of the sound exposure divided by a reference sound exposure.

$$L_E = 10 \log_{10}[\, E / E_o \,]$$

where,

E	sound exposure (Pa^2s),
E_o	$(20\ \mu Pa)^2(1\ s)$ for A-weighted sound exposure,
E_o	$(20\ \mu Pa)^2(10\ s)$ for tone-corrected perceived sound exposure.

Sound Exposure Ratio. Commonly called "energy". The ratio of sound exposure over a reference sound exposure, or ten raised to power of one tenth the sound exposure level:

$$E / E_o = 10^{L_E / 10}$$

where,

E	sound exposure (Pa^2s),
E_o	reference sound exposure (Pa^2s),
L_E	sound exposure level (dB).

Spectrum. A set of sound pressure levels in component frequency bands, usually one-third octave bands.

Spherical Divergence. Spherical divergence, which is taken into account in the INM NPD data, is defined as the transmission loss of mean-square sound pressure, which varies inversely with the square of the distance from a point source. In contrast, cylindrical divergence is the transmission loss of mean-square sound pressure, which varies inversely with distance from a line source.

Standard Day. The atmospheric conditions corresponding to 59 degrees Fahrenheit (15 degrees Celsius), 70 percent relative humidity, and 29.92 in-Hg (760 mm-Hg). The values for temperature and atmospheric pressure are sea-level conditions for the International Standard Atmosphere (ISA).

Time-Above. The duration that a time-varying sound level is above a given sound level threshold.

Time-Averaging Constant. A constant decibel value that is ten times the base-10 logarithm of the time interval associated with the metric divided by a reference time interval, which is usually one second. For example, the time constant for L_{dn} is equal to $10 \log_{10}[$ 86400 seconds in 24 hours / 1 second $]$ = 49.37 dB. The time-averaging constant is subtracted from the sound exposure level to compute an equivalent or average sound level.

Tolerance. The allowable maximum difference in dB or minutes between computed noise or time values and linearly-interpolated noise levels or time values at a given observer point.

Tone-Corrected Perceived. Tone-corrected perceived noise levels are used to estimate human-perceived noise from broadband sound sources, such as aircraft, which contain pure tones or other major irregularities in their frequency spectra.

Touch-and-Go. A flight operation that begins with a level flight in the terminal control area, descends and lands on an airport runway, and then takes off immediately after landing and returns to level flight.

Track Proximity Test. A noise significance test in which a flight, which is first determined to be insignificant by the flight noise test, is further tested based on its distance to a regular grid point. If it is determined that the flight is on a flight track within a certain distance of the grid point, the flight regains its significance status.

True Airspeed (TAS). The speed of an aircraft relative to the undisturbed air mass.

Weighting Factor. A numeric value that multiplies the sound exposure ratio associated with a time period for a given metric. For the exposure-based metrics, the weighting factor acts as a penalty for operations which occur during a specific time period. Usually larger penalties are applied during the night-time period when people are most sensitive to noise. For the maximum-level and time-above metrics, the weighting factors are either zero or unity. As such, they act as a binary switch allowing the user to select specific time periods for computation.

1.5 Abbreviations

This section presents various abbreviations and acronyms used in the document.

AFE	Above Field Elevation (aircraft altitude)
AIR	Aerospace Information Report (SAE-AIR)
ARP	Aerospace Research Report (SAE-ARP)
C	degrees Celsius (temperature)
CAS	Calibrated Airspeed (corrected indicated airspeed)
CPA	closest point of approach to a line segment
dB	decibel (unit of sound level or sound exposure level)
F	degrees Fahrenheit (temperature)
ft	feet
hp	shaft horsepower
in-Hg	inches of mercury (barometric pressure)
INM	Integrated Noise Model
km	kilometers
kt	knots (international nautical miles per hour)
lb	pounds force or weight
L_{ASmx}	maximum A-weighted sound level, dB re (20 :Pa)^2
L_{PNTSmx}	maximum tone-corrected perceived noise level, dB re (20 :Pa)^2
L_{AE}	A-weighted sound exposure level, dB re (20 :Pa)^2(1 s)
L_{EPN}	effective tone-corrected perceived noise lIvel, dB re (20I:Pa)^2(10s)
m	meters

mi	U.S. statute miles
MSL	Mean Sea Level (altitude above mean sea level)
nmi	international nautical miles
Pa	Pascal (unit of pressure, one newton per square meter)
PCPA	perpendicular closest point of approach to an extended line segment
re	relative to
s	second (time duration)
SAE	Society of Automotive Engineers
TAS	True Airspeed

2 FLIGHT-PATH COMPUTATION METHODOLOGY

The fundamental components for computing noise in INM are (1) a **flight path segment**, and (2) an observer. For a given observer location, noise computations are performed on a flight-segment by flight-segment basis. This Chapter presents the methods used to compute flight path segments, and Chapter 3 presents the methods used to compute noise at an observer position.

Chapter 2 has four sections:

Section 2.1 summarizes all the input data that are required for noise computation.

Section 2.1 discusses **noise-power-distance** (NPD) input data used in conjunction with a flight path or **runup** position to compute noise at an observer position.

Section 2.3 presents methods used to calculate a flight profile, based on profile **procedure steps**.

Section 2.4 presents methods used to merge **ground tracks** with flight profiles to produce three-dimensional flight path segments.

2.1 Summary of Input Data for Noise Computation

The noise computation process requires case information about airport conditions, aircraft types, operational parameters, geometry between the observer / flight-segment pair, and noise metric information. Appendix A presents an example file of these data.

2.1.1 Airport Information

The following airport-specific information is required for computations:

! The airport elevation in feet above mean sea level (MSL).

! The airport average annual day temperature in degrees Fahrenheit.

! The airport average annual barometric pressure in inches of mercury MSL.

! If the terrain elevation capability is invoked, the latitude and longitude of the airport (which is used as the x-y coordinate system origin).

! If the terrain elevation capability is invoked, the full-path name of a terrain elevation computer file (3CD file), which contains 3-arc-second elevation data in the vicinity of the airport.

The resolution of a 3CD file is 3 arc-seconds, and the entire file covers one degree in latitude by one degree in longitude (1201 x 1201 points). Consequently, the spacing between points is dependent on the specific location in the United States. For example, the spacing in the Boston area is about 224 ft in the x (east-west) direction by 304 ft in the y (north-south) direction; while the spacing in the San Francisco area is about 241 ft by 303 ft, respectively.

The accuracy of the terrain data is difficult to quantify. The authors' experience has shown the data to typically be within 10 ft of actual elevation. However, inaccuracies of a large as 70 ft have been documented. Nevertheless, in areas of varying elevations, significant improvements in INM computational accuracy are obtained when the terrain enhancement is invoked.

2.1.2 Aircraft Information

The following aircraft information is required for computations:

- Aircraft **flight operation** type: **approach**, **depart**, **touch-and-go**, **circuit flight**, **overflight**, or runup.

- Number of flight operations for each of three time periods (day, evening, and night) during an average annual day.

- For a flight operation, the three-dimensional flight path of the aircraft, as represented by a series of straight-line flight path segments containing position, direction, length, speed, and thrust information. Sections 2.3 and 2.4 presented the details of how a three-dimensional flight path is constructed.

- For a runup operation, the position of the aircraft on the runup pad (x,y values in feet), the aircraft heading (degrees clockwise from true north), the **corrected net thrust per engine** (pounds or percent), and the duration of the runup operation (seconds).

- NPD data, as presented below in Section 2.2.

2.1.3 Observer Information

In addition to information about the source of the noise for each aircraft flight operation, information about the observer locations is also required. INM observer positions are expressed in the form of either a regular grid of points, or a recursively-subdivided irregular grid of points.

- The observer locations for a regular grid are user-defined by the lower-left starting point coordinates of the grid (ft, ft), the distance between grid points (ft), the number of grid points in the two directions, and the angle that the grid is rotated relative to the x-y axes (degrees counter-clockwise from the x-axis).

A special case of a regular grid is a grid consisting of a single observer location, in which the starting point for the grid is given, the distance between grid points is zero, and the size of the grid is one-by-one.

The computation of "population points" and "locations points" is also performed by using the single-grid-points method. The number of single points is an input parameter and their x,y values are listed in the input file.

! Recursively-subdivided irregular grid points are generated by an algorithm that is based on a regular 17-by-17 grid, as explained later in Chapter 4. The observer locations for the 17-by-17-point grid are user-defined by the four corner points of the **case analysis window**. Unlike regular grid points, the case analysis window cannot be rotated relative to the x,y coordinates.

2.1.4 Noise Metric Information

The following metric information is required for computations:

! The type of computation: **single-metric** or **multi-metric**. A single-metric run can compute regular grid points and/or contours. A multi-metric run can compute only contours.

! If a single-metric run is selected:
metric identifier (DNL, SEL, etc.),
metric type (exposure-based, max-level, time-above),
metric weighting factors (day, evening, night),
for an exposure-based metric, the averaging time constant (dB),
for a time-above metric, the threshold level (dB).

! If a multi-metric run is selected:
noise family type (A-weighted or tone-corrected perceived),
time-above noise-level threshold (dB).

! An indicator (yes or no) that contours are to be generated, using the recursively-subdivided grid method of calculating noise.

! If contours are to be generated, the following parameters are required:
refinement level,
tolerance value (dB or minutes).

! If contours are to be generated and if doing a single-metric run, the following parameters are required:
low cutoff contour level (dB or minutes),

high cutoff contour level (dB or minutes).

2.2 Noise-Power-Distance Input Data

The noise-power-distance (NPD) data for an aircraft, which is usually obtained from the INM database but can be user-defined, consists of a set of **decibel** (dB) levels for various combinations of aircraft engine corrected thrusts and distances from observer to aircraft. An underlying assumption is that the NPD data represent an aircraft proceeding along a straight flight path of infinite length and parallel to the ground.

2.2.1 NPD Data Sets

Four kinds of NPD input data sets are available:

L_{AE}	A-weighted **sound exposure level** (SEL)
L_{ASmx}	Maximum A-weighted sound level with slow-scale exponential time weighting (MXSA, also known as LAMAX)
L_{EPN}	Effective (tone-corrected) perceived noise level (EPNL)
L_{PNTSmx}	Maximum tone-corrected perceived noise level with slow-scale exponential time weighting (MXSPNT, also known as PNLTM)

All metrics in INM, including the time-above metrics, are computed using these four basic noise-level metrics.

<u>Normal NPD</u> data set consists of two or more noise curves. A noise curve is associated with a corrected net thrust per engine parameter (in units of pounds or percent) and ten noise levels at the following ten distances: 200, 400, 630, 1000, 2000, 4000, 6300, 10000, 16000, and 25000 feet.

To obtain noise levels that lie between thrust values or between distance values, linear interpolation is used (the distance values are converted to their base-10 logarithmic equivalent values first). To obtain levels outside of the bounding thrust or distances values, linear extrapolation is used, as discussed in Section 3.2.

<u>Afterburner NPD</u> data are also available for some NOISEMAP aircraft.

The noise levels in the NPD data have been adjusted for time-varying aircraft speed (exposure-based noise levels only), **atmospheric absorption**, **distance-duration** effects (if the **simplified adjustment process** is used, and for exposure-based noise levels only), and **spherical divergence** in accordance with the methodology presented in Reference 10 and summarized in Reference 13.

One notable exception pertains to the 112 military NOISEMAP aircraft in the INM database beginning with Version 5.1 (108 new NOISEMAP aircraft and the four F16s, which were in INM prior to Version 5.1). Specifically, the related noise data for these aircraft were developed using the simplified data adjustment procedure, and the distance duration effects were accounted for using a $6 \log_{10}[\, d / d_{ref} \,]$ relationship. In contrast, the data in INM which were corrected using the simplified procedure were adjusted using a $7.5 \log_{10}[\, d / d_{ref} \,]$ relationship. It was decided that the 6-log relationship would be maintained for the military aircraft in INM, since it represents a best-fit empirical relationship for those aircraft.

2.2.2 Maximum Noise Level Approximation

For several aircraft in the INM database, measured L_{ASmx} and L_{PNTSmx} NPD data do not exist, and are therefore approximated using empirical equations expressed as a function of distance, and either L_{AE} or L_{EPN}, as appropriate. These equations were developed from a statistical analysis of NPD data for aircraft in which all four base noise-level metrics exist in the INM data base. The equations are as follows:

For INM aircraft:

$$L_{ASmx} = L_{AE} - 7.19 - 7.73 \log_{10}[\, D / 1000 \,]$$
$$L_{PNTSmx} = L_{EPN} + 1.12 - 9.34 \log_{10}[\, D / 1000 \,]$$

For NOISEMAP aircraft:

$$L_{ASmx} = L_{AE} - 7.84 - 6.06 \log_{10}[\, D / 1000 \,]$$
$$L_{PNTSmx} = L_{EPN} + 2.51 - 5.84 \log_{10}[\, D / 1000 \,]$$

where D is the closest-point-of-approach distance (ft) to the aircraft.

2.2.3 NPD Data Development Criteria

In the most general terms, criteria for development of NPD data for use by the INM include the following [14] :

- **Acoustically soft** ground under the measurement microphone, similar to the terrain around the microphone during aircraft noise certification tests.[12]

- For L_{AE} and L_{EPN} values, an **integrated adjustment procedure** (involving time integration over the full spectral time history) as compared with a simplified adjustment procedure (involving the **spectrum** measured at the time of maximum noise level only) for airplanes where adequate field data are available.

- **Reference-day** air attenuation coefficients as specified by SAE rather than **standard-day** conditions of 59 degrees Fahrenheit and 70 percent relative humidity used prior to INM Version 3.9.

- L_{AE} and L_{EPN} values time-integrated over the upper 10 dB of the noise event as prescribed by FAA [12] and SAE [10]. (The time interval from t_1 to t_2 designates the time in seconds, from the beginning to the end of the integration period for the sound produced by an airplane. The duration $[t_2 - t_1]$ should be long enough to include all significant contributions to the total noise exposure. Sufficient accuracy is usually achieved by integration over the time interval during which the frequency-weighted sound level is within ten dB of its maximum value.)

- L_{AE} and L_{EPN} values normalized to a **reference airspeed** of 160 kt.

- Noise levels specified as a function of power, usually corrected net thrust per engine.

The FAA position is to adhere closely to the above criteria both for the development and validation of the INM NPD data. Diligent compliance is needed to ensure confidence in having consistent and comparable aircraft NPD and performance data.

2.3 Flight Profile Calculation

INM 5.1 supports two kinds of flight profile input data: (1) an ordered set of **profile points**, and (2) an ordered set of procedure steps. The first section below discusses the structure of profile point data, and the remaining sections discuss how profile points are calculated from procedure steps.

2.3.1 Profile Point Input Data

An ordered set of profile points specify a two-dimensional trajectory. For each point, the following data are given:

q horizontal coordinate (ft) relative to an origin,
z altitude of the aircraft above the airport (ft AFE),
v_T aircraft true airspeed at the point (kt),
F_{nc} corrected net thrust per engine (lb, %, or other units) at the point.

The <u>origin</u> is where the q-coordinate is equal to zero, and it depends on the kind of flight operation:

An approach origin is at the touch-down point, and q-values are <u>negative</u> during descent and <u>positive</u> during roll-out on the runway.

A departure origin is at the start-roll point on a runway, and q-values are positive.

A touch-and-go origin is similar to an approach; the origin is where the aircraft touches down on the runway.

A circuit flight origin is similar to a departure; the origin is at the start-roll point.

An overflight origin is at the first point, and q-values are positive.

For all types of operations, q-values increase as an airplane flies along its profile.

Profile speed is the speed at the profile point; it is the magnitude of the aircraft velocity vector. It is the same as true airspeed with no wind, and the sections below refer to profile speed as **true airspeed** (TAS). Profile speed is approximately equal to **ground speed**, except when climbing or descending at steep angles.

The corrected net thrust per engine is in units of pounds, percent, or some other units that are consistent with the noise curves. If the aircraft NPD curves are in percent, thrust-setting is a percentage of the aircraft static thrust value. In the sections that follow, F_{nc} is in pounds, but for some aircraft, the pounds are changed to percent before writing out the flight data.

When profile-point input data are used, INM does not correct for non-standard temperature and pressure. This means that the input values of F_{nc} are directly used in the noise tables.

2.3.2 Procedure Step Input Data

When a flight profile is specified in terms of procedure steps, INM processes the steps one at a time to calculate profile points, putting them in the same format as presented above.

Procedure steps are prescriptions for how to fly a profile. For example, the following set of procedure steps describes how to fly a jet departure profile:

1. Takeoff using 15-deg flaps and max-takeoff thrust.
2. Climb to 1000 ft AFE, using 15-deg flaps and max-takeoff thrust.
3. Accelerate to 175 kt CAS, while climbing at 2000 fpm and using 15-deg flaps and max-takeoff thrust.
4. Accelerate to 195 kt CAS, while climbing at 1000 fpm and using 5-deg flaps and cutting back to max-climb thrust.
5. Climb to 3000 ft AFE, using zero flaps and max-climb thrust.
6. Accelerate to 250 kt CAS, while climbing at 1000 fpm and using zero flaps and max-climb thrust.
7. Climb to 5500 ft AFE, using zero flaps and max-climb thrust.
8. Climb to 7500 ft AFE, using zero flaps and max-climb thrust.
9. Climb to 10000 ft AFE, using zero flaps and max-climb thrust.

Each procedure step is of a specific type (takeoff, climb, accelerate), and contains parameters relative to its type (15-deg flaps, 1000 ft AFE, 2000 fpm, max-climb thrust, etc.). The sections below show how each type of procedure step is processed to compute segment end-point values of altitude, speed, and thrust. Also, methods are presented to compute the segment horizontal distance, which is used to develop the q-coordinates for the set of profile points.

In general, one procedure step produces one profile point, but there several exceptions. For example, a takeoff step produces two points (start-roll and takeoff rotation). Also, whenever there is a change in thrust setting for (for example, going from max-takeoff to max-climb), an extra profile point is created so that thrust changes continuously over a small distance (1000 ft), rather than discontinuously at a point.

Sometimes, data from a current procedure step are combined with data from the previous step before a profile point can be computed. For example, a user inputs the starting descent altitude, speed, and angle. INM processes the next descent step to find its starting altitude, which is the ending altitude for the first step. In the development of procedure step methods that follow, these algorithmic details are not described. Instead, the production of profile points is discussed in terms of "initial" and "final" points which define a profile segment.

Before detailing the individual procedure step methods, the following two sections present equations that are used throughout.

2.3.3 Non-ISA Model for Atmospheric Ratios

This section presents the INM equations for calculating atmospheric ratios for air temperature, pressure, and density. "Non-ISA" means that the calculated ratios are different than those specified by the **International Standard Atmosphere** (ISA) model.[11]

The input parameters for the INM atmospheric ratio equations are:

- E airport elevation (ft) MSL,
- T airport temperature (°F),
- P airport pressure (in-Hg) MSL,
- A aircraft altitude (ft) MSL, where $A < 11$ km .

INM calculates the <u>temperature ratio</u> (theta) by assuming there is an ISA temperature lapse rate of -0.003566°F per foot of altitude A above airport elevation E, starting at a non-ISA airport temperature T:

$$\theta = (459.67 + T - 0.003566 (A - E)) / 518.67 .$$

Thus, non-ISA ambient temperature (at the aircraft) is obtained by using a non-ISA average airport temperature. The temperature gradient above the airport is assumed to be the same as the ISA temperature gradient.

INM calculates the pressure ratio (delta) by adding a pressure correction term to the ISA pressure ratio:

$$* \;=\; (\,(518.67 \;!\; 0.003566\;\; A) \,/\, 518.67\,)^{5.256} \;+\; (P \;!\; 29.92) \,/\, 29.92\;.$$

This is a first-order approximation to the actual * equation, and it is adequate for INM calculations. INM calculates the air density ratio (sigma) by employing the ratio version of the Ideal Gas Law:

$$F \;=\; * \,/\, 2\;.$$

Note that air density is a function of all four input parameters: E, T, P, and A.

2.3.4 Corrected Net Thrust Per Engine For Departure

Departure net thrust per engine for jets is calculated by using the SAE-AIR-1845 [10] thrust equation at density altitude. According to SAE-AIR-1845 condition A.3 and equation A1, standard atmosphere net thrust per engine is a function of **calibrated airspeed** v and altitude h:

$$F_{nS}(\,v, h\,) \;=\; *_S(h)\,(\,E_p + \;F_p\,v \;+\; G_{Ap}\,h \;+\; G_{Bp}\,h^2 \;+\; H_p\,T_S(h)\,)$$

$$*_S(h) \;=\; (\,(518.67 \;!\; 0.003566\,h) \,/\, 518.67\,)^{5.256}$$

$$T_S(h) \;=\; (5/9)\,(59 \;!\; 0.003566\,h \;!\; 32)$$

where,

F_{nS}	ISA net thrust per engine (lb),
v	calibrated airspeed (kt),
h	altitude (ft) MSL, which equals both pressure and density altitudes,
E_p, ...	thrust coefficients which depend on the jet's power-setting state (max-takeoff or max-climb),
$*_S(h)$	ISA pressure ratio at h ,
$T_S(h)$	ISA temperature (°C) at h .

INM uses a quadratic estimate for the altitude term, ($G_{Ap}\,h + G_{Bp}\,h^2$), rather than the linear estimate specified in SAE-AIR-1845.

Density altitude is the particular altitude that yields an ISA density equal to the actual density. The equation for density altitude h_D , as a function of density ratio F , is:

$$h_D = (518.67 / 0.003566) (1 - \sigma^{1 / (5.256 - 1)}) .$$

INM calculates the net thrust per engine F_n by using the standard thrust equation at calibrated airspeed v and density altitude h_D :

$$F_n = F_{nS}(v, h_D) .$$

This non-ISA thrust equation helps to account for thrust-reducing effects of hot temperatures at high altitudes. Under ISA conditions, $h_D = h$, and F_n reverts to the SAE-AIR-1845 equation. Departure net thrust per engine for props is calculated by using SAE-AIR-1845 equation A4:

$$F_n = 325.87\ \eta_p\ P_p / v_T ,$$

where,

F_n	net thrust per engine (lb),
η_p	propeller efficiency, which depends on the power-setting state,
P_p	net power per engine (hp) for sea-level standard day, which depends on the power-setting state (max-takeoff or max-climb)
v_T	true airspeed (kt).

True airspeed is calculated by using SAE-AIR-1845 equation A5:

$$v_T = v\ \sigma^{-½} ,$$

where,

v_T	true airspeed (kt),
v	calibrated airspeed (kt),
σ	air density ratio at aircraft altitude.

Finally, the corrected net thrust per engine F_{nc} , for both jets and props, is calculated by dividing the net thrust per engine F_n by the pressure ratio δ :

$$F_{nc} = F_n / \delta .$$

The corrected net thrust per engine F_{nc} is used as an input parameter for calculating noise via NPD data, and it also appears in several SAE-AIR-1845 flight profile equations.

2.3.5 Takeoff Ground Roll Segment

For the takeoff ground roll segment, the initial and final values of aircraft altitude are given (the airport elevation), the initial and final values of speed and thrust are calculated, and the horizontal distance is calculated.

For jets, the corrected net thrust per engine F_{nc1} at the start-roll point is usually calculated by using the departure thrust equations with v_1 = 16 knots. The 16-knot speed value is half that specified in SAE-AIR-1845 equation 3.4.2 because the INM noise algorithm accounts for noise exposure beginning at the start-roll point (time: zero to plus infinity), rather than for the total integrated exposure (time: minus to plus infinity), which is implicit in equation 3.4.2. The 16-knot value is not a physical speed; instead, it is a coefficient which is used to adjust the noise level at the start of takeoff roll so that the noise exposure is commensurate with empirical values.

For props, the corrected net thrust per engine F_{nc1} at the start-roll point is set equal to the corrected net thrust per engine F_{nc2} at the takeoff rotation point: $F_{nc1} = F_{nc2}$.

For jets and props, the corrected net thrust per engine F_{nc2} at the takeoff rotation point is calculated by using the departure thrust equations presented above. The calibrated airspeed at the rotation point, which is used in the thrust equation, is calculated by using SAE-AIR-1845 equation A7:

$$v_2 = C_f W^{½}$$

where,

v_2	calibrated airspeed (kt) at takeoff rotation; $v_{T2} = v_2$ F!½ is the true airspeed (kt) at takeoff rotation,
C_f	coefficient which depends on the flaps setting,
W	departure profile weight (lb); weight is assumed to remain constant for the entire departure profile.

For jets or props, F_{nc1} can be a user-input value. If it is, F_{nc2} is set equal to this value ($F_{nc2} = F_{nc1}$).

For the takeoff case, the ground-roll distance is calculated by using SAE-AIR-1845 equation A6:

$$S_g = B_f\, 2\, (W / *)^2 / (N F_{nc2})$$

where,

S_g	ground-roll distance (ft),
B_f	ground-roll coefficient, which depends on the flaps setting,
2	temperature ratio at the airport elevation,
W	departure profile weight (lb),
*	pressure ratio at the airport,
N	number of engines,
F_{nc2}	corrected net thrust per engine (lb) at takeoff rotation.

The takeoff ground-roll distance is corrected for headwind, which may be different than the standard 8 knots, by using SAE-AIR-1845 equation A16:

$$S_{gw} = S_g \, (v_2 - w)^2 / (v_2 - 8)^2$$

where,

S_{gw}	ground-roll distance (ft) corrected for headwind,
S_g	ground-roll distance (ft), uncorrected
v_2	calibrated speed (kt) at takeoff rotation,
w	headwind (kt).

The takeoff ground-roll distance is also corrected for runway gradient by using the equations:

$$S_{gc} = S_{gw} \, a / (a - 32.17 \, G)$$

$$a = (v_2 \, \sigma^{-1/2})^2 / (2 \, S_{gw})$$

$$G = (E_2 - E_1) / L$$

where,

S_{gc}	ground-roll distance (ft) corrected for headwind and runway gradient,
S_{gw}	ground-roll distance (ft) corrected for headwind,
a	average acceleration (ft/s^2) along the runway,
v_2	calibrated speed (kt) at takeoff rotation,
G	runway gradient; G is positive when taking-off uphill,
E_1,E_2	runway end elevations (ft) MSL,
L	runway length (ft).

The ground-roll segment is subdivided if the distance multiplied by the change in true speed is greater than 100,000 ft-kt (which is usually the case). The number of sub-segments is calculated by:

$$n = \text{int}[\, 1 + ((v_{T2} - v_{T1}) \, S_{gc} \, 10^{-5})^{1/2} \,]$$

where,

n	number of equal-distance sub-segments,
int[x]	function that returns the integer part of a number x ,
v_{T1}	initial power-on true speed (kt), v_{T1} is 16 knots for takeoff,
v_{T2}	takeoff true airspeed (kt),
S_{gc}	corrected ground-roll distance (ft).

If the ground-roll segment is subdivided, the speed and thrust values at the end points of the equal-distance sub-segments are linearly interpolated by using the end-point values of the original segment. This method of subdividing the ground-roll segment is used in INM instead of the SAE-AIR-1845 algorithm 3.4.2.

2.3.6 Touch-and-Go Power-On Ground Roll Segment

For that portion of a touch-and-go ground roll segment when an aircraft is accelerating to takeoff, the initial and final altitudes are given (the airport elevation), the initial calibrated speed is given (a user-defined value), and the final speed, initial and final thrusts, and horizontal distance are calculated.

The takeoff rotation speed v_{T2} is calculated by:

$$v_{T2} = (C_f W^{½})\ \sigma^{-½}$$

where,

C_f	takeoff speed coefficient,
W	touch-and-go profile weight,
σ	density ratio at the airport.

The thrusts F_{nc1} and F_{nc2} are calculated by using the departure thrust equations at the airport elevation and for calibrated speeds v_1 and v_2.

The power-on ground-roll distance is calculated by:

$$S_g = (v_{T2}^2 - v_{T1}^2) / (2\ a)$$

$$a = C_f^2\ N\ F_{nc2}\ \delta / (2\ B_f W)$$

where,

S_g	distance (ft) of that portion of the touch-and-go ground-roll that begins when accelerating power is applied and ends when takeoff rotation occurs,
v_{T1}	initial true speed (kt),
v_{T2}	final true speed (kt),
a	average acceleration (ft/s^2) along the runway, which is assumed to be the same acceleration as available for takeoff,
C_f	takeoff speed coefficient,
N	number of engines,
F_{nc2}	corrected takeoff thrust,
δ	pressure ratio at the airport,
B_f	ground-roll coefficient,
W	touch-and-go profile weight.

For the touch-and-go case, corrections for headwind, runway gradient, and segment subdivision are similar to those for the takeoff case.

2.3.7 Climb Segment

For a climb segment, the initial and final altitudes are given (A_1 is from the previous segment and A_2 is user input), the initial and final speeds are calculated using the final calibrated airspeed on the previous segment, the initial thrust is given from the previous segment, the final thrust is calculated, and the horizontal distance is calculated.

A climb segment is flown at constant calibrated airspeed v, climbing from altitude A_1 to altitude A_2. Even though a climb segment uses constant calibrated airspeed, the true airspeeds v_{T1} and v_{T2} at the segment end points are different because the air densities F_1 and F_2 are different. The speeds are calculated by:

$$v_{T1} = v\ F_1^{!½} \quad \text{and} \quad v_{T2} = v\ F_2^{!½} .$$

The <u>nominal</u> value of the corrected net thrust per engine F_{nc} is usually calculated by using the departure thrust equations at the mid-point altitude $A_m = ½(A_1 + A_2)$. Likewise, a nominal value of the pressure ratio * is usually calculated at the mid-point altitude A_m.

The <u>end point</u> corrected net thrust per engine F_{nc2} is usually calculated by using the departure thrust equations at speed v and altitude A_2.

However, there are three cases when this method is not used:

(1) When a <u>"user-value" of thrust</u> is specified, the nominal value of corrected net thrust per engine is set to the specified value, F_{nc} = user-value thrust. The nominal value of the pressure ratio * is calculated at the mid-point altitude.

The calculated initial corrected net thrust per engine F_{nc1} is retained from the previous step, but the calculated final corrected net thrust per engine is replaced by the input value, F_{nc2} = user-value thrust .

(2) When <u>"user-cutback" thrust</u> is specified, the nominal value of corrected net thrust per engine is set to the specified value, F_{nc} = user-cutback thrust. The nominal value of the pressure ratio * is calculated at the mid-point altitude.

The climb segment is calculated and then it is broken into two sub-segments, both having the same climb angle. The first sub-segment is assigned a 1000-foot ground distance, and the corrected net thrust per engine at the end of 1000 feet is set equal to the user-cutback value. (If the original horizontal distance is less than 2000 feet, one half of the segment is used to cutback thrust.) The final thrust on the second sub-segment is also set equal to the user-cutback thrust. Thus, the second sub-segment is flown at constant thrust.

Another 1000-foot sub-segment restores the thrust from the user-cutback value to the calculated value F_{nc2} at altitude A_2, but this sub-segment is created in the next climb or acceleration segment.

(3) When engine-out "reduced-thrust" is specified, the nominal value of corrected net thrust per engine F_{nc} is set to a value that is calculated by using an engine-out procedure (below). The nominal value of the pressure ratio * is set to the final value calculated at altitude A_2 .

Two 1000-foot sub-segments are introduced in a manner similar to the user-cutback case. The constant engine-out reduced thrust used for the cutback sub-segment is calculated by:

$$F_{nc} = (W / *_2) ((\sin(\tan^{!1}(G/100)) / K) + R_f) / (N \; ! \; 1)$$

where,

F_{nc}	corrected net thrust per engine (lb) for an engine-out procedure,
W	departure profile weight (lb),
$*_2$	pressure ratio at altitude A_2 ,
G	engine-out percentage climb gradient:
	G = 0% for aircraft with Automatic Thrust Restoration Systems; or if not,
	G = 1.2% for 2-engine aircraft,
	G = 1.5% for 3-engine aircraft,
	G = 1.7% for 4-engine aircraft,
K	speed-dependent constant
	K = 1.01 when climb speed <= 200 kt, and K = 0.95 otherwise,
R_f	drag-over-lift coefficient, which depends on the flaps setting,
N	number of engines (1 < N).

The average climb angle is calculated by using SAE-AIR-1845 equation A8:

$$(= \sin^{!1}(K (N F_{nc} * / W \; ! \; R_f))$$

where,

(	average climb angle,
K	speed-dependent constant
	K = 1.01 when climb speed <= 200 kt, and K = 0.95 otherwise,
N	number of engines,
F_{nc}	nominal value of corrected net thrust per engine (lb),
*	nominal value of the pressure ratio,
W	departure profile weight (lb),
R_f	drag-over-lift coefficient, which depends on the flaps setting.

The above method of setting the constant K is slightly different than specified in SAE-AIR-1845, where the initial climb segment uses $K = 1.01$, and climb segments after acceleration and flaps-retraction use $K = 0.95$. The INM method is more useful for handling jet and prop flight profiles and profiles where the order of climb and acceleration segments are mixed.

The climb angle is corrected for headwind by using SAE-AIR-1845 equation A17:

$$\gamma_w = \gamma \, (v - 8) / (v - w)$$

where,

γ_w	average climb angle corrected for headwind,
γ	average climb angle, uncorrected
v	calibrated airspeed (kt) on the climb segment,
w	headwind (kt).

Finally, the horizontal distance for the climb segment is calculated by using SAE-AIR-1845 equation A9:

$$S_c = (A_2 - A_1) / \tan \gamma_w$$

where,

S_c	horizontal distance (ft) for the climb segment,
A_1,A_2	initial and final altitude (ft) MSL,
γ_w	average climb angle corrected for headwind.

2.3.8 Acceleration Segment

For an acceleration segment, the initial altitude, initial true airspeed, and initial thrust are given from the previous segment. The final calibrated airspeed and the average climb rate are user inputs. The final altitude, final true airspeed, final thrust, and horizontal flying distance are calculated.

There are two parts in the acceleration-segment algorithm. The first part calculates the altitude A_2 that would be obtained for a flight from an airport at sea-level on a standard day, and the second part calculates the horizontal distance S_a for actual conditions.

The final altitude A_2 is calculated by using an iterative method. First, all altitudes are adjusted to represent a departure from a sea-level airport. These adjusted altitudes are denoted with a subscript “s”; for example, A_{1s} and A_{2s}. An initial value of $A_{2s} = A_{1s} + 250$ feet is used, and then the value of A_{2s} is recalculated until the absolute difference between the current and previous value is less than one foot. After the last iteration, the actual final altitude is constructed by $A_2 = A_{2s} + E$, where E is the airport elevation.

The current final altitude is calculated by using SAE-AIR-1845 equation A11:

$$A_{2s} \;=\; A_{1s} + S_p\, \gamma_p \,/\, 0.95$$

where,

A_{2s}	current final altitude (ft) above a sea-level airport,
A_{1s}	initial altitude (ft) above a sea-level airport, $A_{1s} = A_1 - E$,
E	elevation of the airport (ft) MSL,
S_p	function of the previous final altitude (see below),
γ_p	another function (see below),
A_{2sp}	previous final altitude (ft) above a sea-level airport.

The S-function is calculated by using SAE-AIR-1845 equation A10:

$$S_p \;=\; k\,(\, v_{T2p}^{\,2} - v_{T1}^{\,2}\,) \,/\, (\, N\, F_{ncp}\, \delta_p \,/\, W \;-\; R_f \;-\; \gamma_p\,)$$

where,

S_p	sea-level standard-day horizontal distance (ft),
k	constant = $(\,101.2686 / 60\,)^2\, 0.95 \,/\, (\,2\;\; 32.17\,)$,
v_{T1}	standard-day true airspeed (kt) at altitude A_{1s} ($v_{T1} = v_1\, \sigma_{1s}^{-1/2}$),
v_{T2p}	standard-day true airspeed (kt) at altitude A_{2sp} ($v_{T2p} = v_2\, \sigma_{2sp}^{-1/2}$),
N	number of engines,
F_{ncp}	previous standard-day average corrected net thrust per engine (lb) calculated at points (v_1, A_{1s}) and (v_2, A_{2sp}), $F_{ncp} = ½(\, F_{nc1} + F_{nc2p}\,)$,
δ_p	standard-day pressure ratio at the previous mid-point altitude, $½(\, A_{1s} + A_{2sp}\,)$,
W	departure profile weight (lb),
R_f	drag-over-lift coefficient, which depends on the flaps setting.

The γ-function is calculated by:

$$\gamma_p \;=\; v_{Tz} \,/\, (\, 101.2686\;\, ½(\, v_{T1} + v_{T2p}\,)\,)$$

where,

v_{Tz}	climb rate (ft/min) for a sea-level standard day,
v_{T1}	standard-day true airspeed (kt) at altitude A_{1s} ($v_{T1} = v_1\, \sigma_{1s}^{-1/2}$),
v_{T2p}	standard-day true airspeed (kt) at altitude A_{2sp} ($v_{T2p} = v_2\, \sigma_{2sp}^{-1/2}$).

Once the final altitude $A_2 = A_{2s} + E$ is calculated, the actual horizontal distance is calculated by:

$$S_a \;=\; (\, C_1 + C_3\,) \,/\, C_2$$

$$C_1 = k\,(v_{T2}^{\,2} - v_{T1}^{\,2})$$

$$C_2 = N\,F_{nc}\,\delta / W - R_f$$

$$C_3 = 0.95\,(A_2 - A_1)$$

where,

- S_a horizontal distance (ft) for the acceleration segment,
- C_i temporary results (i = 1, 2, 3),
- k constant = $(101.2686 / 60)^2\, 0.95 / (2 \;\; 32.17)$,
- v_{T1} true airspeed (kt) at altitude A_1 ($v_{T1} = v_1\,\sigma_1^{-1/2}$),
- v_{T2} true airspeed (kt) at altitude A_2 ($v_{T2} = v_2\,\sigma_2^{-1/2}$),
- N number of engines,
- F_{nc} average corrected net thrust per engine (lb) calculated at altitudes A_1 and A_2 , $F_{nc} = \frac{1}{2}(F_{nc1} + F_{nc2})$,
- δ pressure ratio at the mid-point altitude $\frac{1}{2}(A_1 + A_2)$,
- W departure profile weight (lb),
- R_f drag-over-lift coefficient, which depends on the flaps setting,
- A_1, A_2 initial and final altitudes (ft) MSL.

Finally, the acceleration segment distance is <u>corrected for headwind</u> by using SAE-AIR-1845 equation A18:

$$S_{aw} = S_a\,(v_T - w) / (v_T - 8)$$

where,

- S_{aw} horizontal distance (ft) corrected for headwind,
- S_a horizontal distance (ft) for the acceleration segment, uncorrected,
- v_T average true airspeed (kt) on the segment, $v_T = \frac{1}{2}(v_{T1} + v_{T2})$,
- w headwind (kt).

The reason for using the two-part acceleration algorithm is to adjust the standard procedure data. The INM standard database contains flight profile procedure data for sea-level airport, standard-day operations. In particular, the acceleration-segment climb rate parameters are for sea-level standard day. For higher airports and hotter days, the standard climb rates may not be obtained. The two-part algorithm, in effect, calculates a climb rate:

$$v_{Tzc} = 101.2686\, v_T\, C_3 / S_{aw}$$

where v_{Tzc} is the non-standard climb rate (ft/min) and v_T , C_3 , S_{aw} are defined above.

2.3.9 Descent Segment

For a descent segment, the initial altitude, true airspeed, and thrust are given from the previous segment. The final altitude, final calibrated airspeed, and the descent angle are user inputs. The final true airspeed, final thrust, and horizontal distance are calculated.

In INM, the <u>initial</u> altitude and speed appear to be user inputs; however, a descent segment is not actually calculated until the next segment is processed. This procedure is necessary so that an approach profile can start with a descent segment.

The final true airspeed is:

$$v_{T2} = v_2 \, \sigma_2^{-1/2}$$

where,

v_2	given calibrated airspeed,
σ_2	density ratio at altitude A_2 .

The final corrected net thrust per engine is calculated by using by using SAE-AIR-1845 equation A15:

$$F_{nc2} = (W / \delta_2) (R_f - \sin \gamma / 1.03) / N$$

where,

F_{nc2}	corrected net thrust per engine (lb) at altitude A_2 ,
W	approach or touch-and-go profile weight (lb),
δ_2	pressure ratio at altitude A_2 ,
R_f	drag-over-lift coefficient, which depends on flaps and gear setting,
γ	average descent angle (a positive value),
N	number of engines.

The final corrected net thrust per engine is <u>corrected for headwind</u> by using SAE-AIR-1845 equation A19:

$$F_{nc2w} = F_{nc2} + 1.03 (W / \delta_2) \sin \gamma \, (8 - w) / (N v_2)$$

where,

F_{nc2w}	corrected net thrust per engine (lb) for headwind w ,
F_{nc2}	corrected net thrust per engine (lb) at altitude A_2 ,
W	approach or touch-and-go profile weight (lb),
δ_2	pressure ratio at altitude A_2 ,
γ	average descent angle (a positive value),
w	headwind (kt),
N	number of engines,
v_2	calibrated airspeed (kt) at altitude A_2 .

The horizontal distance is calculated by:

$$S_d = (A_1 \;!\; A_2) / \tan \;($$

where,

S_d horizontal distance (ft) for the descent segment,
A_1 initial altitude (ft) MSL,
A_2 final altitude (ft) MSL ($A_1 > A_2$),
(average descent angle (a positive value).

2.3.10 Level Segment

For a level segment, the initial altitude, true airspeed, and thrust are given from the previous segment. The final altitude, final speed, and distance flown are user inputs (the final altitude and speed must be the same as the initial values). The final thrust is calculated.

If the initial thrust is not the same as the final thrust (for example, the previous segment was a climb segment), then a 1000-ft transition segment is created to equalize the thrusts, so that the major portion of the level segment is flown at constant thrust.

The corrected net thrust per engine is calculated by using by using SAE-AIR-1845 equation A15 with zero descent angle:

$$F_{nc} = (W / *) R_f / N$$

where,

F_{nc} corrected net thrust per engine (lb) at altitude A ,
W approach, departure, or touch-and-go profile weight (lb),
* pressure ratio at altitude A ,
R_f drag-over-lift coefficient, which depends on flaps and gear setting,
N number of engines.

2.3.11 Cruise-Climb Segment

For a cruise-climb segment, the initial altitude, true airspeed, and thrust are given from the previous segment. The final altitude, final calibrated airspeed, and the climb angle are user inputs (the initial and final calibrated airspeeds must be the same). The final true airspeed, final thrust, and horizontal distance are calculated. Cruise-climb thrust is less than "maximum-takeoff" or "maximum-climb" departure thrust.

The final corrected net thrust per engine is calculated by using by using SAE-AIR-1845 equation A15 with an additive term for climb thrust:

$$F_{nc2} = (W / \delta_2) (R_f + \sin \gamma / 0.95) / N$$

where,

F_{nc2}	corrected net thrust per engine (lb) at altitude A_2 ,
W	approach, departure, or touch-and-go profile weight (lb),
δ_2	pressure ratio at altitude A_2 ,
R_f	drag-over-lift coefficient, which depends on flaps and gear setting,
γ	average climb angle (a positive value),
N	number of engines.

The horizontal distance is calculated by:

$$S_{cc} = (A_2 - A_1) / \tan \gamma$$

where,

S_{cc}	horizontal distance (ft) for the cruise-climb segment,
A_1,A_2	initial and final altitudes (ft) MSL ($A_1 < A_2$),
γ	average climb angle (a positive value).

2.3.12 Landing Segment

For a landing segment, the initial and final altitudes are given (the airport elevation), the initial (landing) speed is calculated, the final roll-out speed is calculated from user-input calibrated speed, the initial (landing) thrust is calculated, the final thrust is calculated from a user-input percentage value, and the ground-roll distance is user input.

The calibrated landing airspeed is calculated by using SAE-AIR-1845 equation A13:

$$v_1 = D_f W^{½}$$

where,

v_1	calibrated airspeed (kt) just before landing,
v_{T1}	true landing airspeed (kt), $v_{T1} = v_1 \sigma^{-½}$,
D_f	landing coefficient, which depends on the flaps and gear setting,
W	approach profile weight (lb); weight is assumed to remain constant for the entire approach profile.

The initial thrust F_{nc1} is calculated using the descent thrust equation with the landing descent angle and airport elevation.

The final thrust F_{nc2} is obtained by:

$$F_{nc2} = F_S \, (P / 100)$$

where,

F_{nc2}	corrected net thrust per engine (lb) at end of landing roll-out,
F_S	static corrected net thrust per engine (an input parameter),
P	percentage of thrust (an input parameter).

Note that if the aircraft NPD curves are in percent, the value of "thrust" that is actually assigned to the flight segment is the percentage value P, so that it can be used to directly access the noise tables.

2.3.13 Decelerate Segment

For a deceleration segment, the initial and final altitudes are given (the airport elevation), the initial speed is given from the previous step, and the final speed is calculated from user-input calibrated speed and density ratio. The initial thrust is given from the previous step, the final thrust is calculated from user-input percentage of thrust (as above), and the ground-roll distance is user input.

2.4 Flight Path Calculation

An INM flight path is an ordered set of flight path segments. Each segment contains the following data:

x_1, y_1, z_1	starting coordinates for the segment (ft, ft, ft),
u_x, u_y, u_z	unit vector directed along the segment,
L	length of the segment (ft),
v_{T1}	speed (kt) at the starting point, relative to x-y-z coordinates,
Δv	change in speed (kt) along the segment, $\Delta v = v_{T2} - v_{T1}$,
F_{nc1}	corrected net thrust per engine (lb, %, or other) at the starting point,
ΔF_{nc}	change in thrust (lb, %, or other) along the segment, $\Delta F_{nc} = F_{nc2} - F_{nc1}$.

The starting velocity vector ($v_{T1}\,\mathbf{u}$) is directed along the segment, and the aircraft is assumed to continue to fly along the segment as speed and thrust change. Segment speed and length are used in the noise module to calculate the segment flying-time duration that a ground-based observer would experience.

Corrected net thrust per engine is in units of pounds, percent of static thrust, or other units, depending on the units defining the NPD curves.

Three-dimensional flight path segments are constructed by using ground track data and flight profile data, as discussed in the sections below.

2.4.1 Ground Track Processing

INM 5.1 supports two kinds of ground tracks: (1) an ordered set of x,y points, and (2) an ordered set of vectoring commands (for example, fly straight 5.5 nmi, turn left 90 deg using radius 2.0 nmi).

INM transforms the vectoring commands to a set of x,y points. To do this, INM converts circular segments into straight lines, processes approach tracks so that they line up with the runway, and adds leader lines to approach tracks and follower lines to departure tracks.

- The details of circular arc conversion are discussed in Section 2.4.2 below.

- When processing an <u>approach track</u>, INM initially calculates the track points by starting the track at the origin and heading north. After all of the x-y points are calculated, the entire set of track points is rotated and translated to line-up with the approach end of the runway. The last track point is made to coincide with the displaced approach threshold point on the runway. Then, a 100-nmi leader line is added to the beginning of the approach track (a new first point is added), so that the ground track is always longer than a approach profile.

- A 100-nmi follower line is added to a <u>departure track</u> and to an <u>overflight track</u>, so that a departure profile (overflight profile) always has a defined ground track under it. <u>Touch-and-go</u> ground tracks are not extended.

2.4.2 Circular Arc Conversion

INM approximates a circular-arc ground track with two or more straight line segments. The method of Reference 15 is used. First, the number of sub-arcs contained in the circular arc is computed:

$$N = \mathrm{int}[\, 1 + A / 60 \,]$$

where,

N	number of sub-arcs,
A	given circular arc (degrees),
int[x]	function that returns the integer part of x .

Then, the angular size of each sub-arc is computed:

$$\alpha = A / N \,.$$

For each sub-arc, three x-y points are computed. These three points define two line segments. The first point is at the start of the sub-arc, and the third point is at the end of the sub-arc. The second point is half-way along the sub-arc, but not directly on it. The distance from the center of the sub-arc to the second point, instead of being the arc radius, is computed by:

$$d = r \left[\cos(\alpha/2) + (\alpha^2/4 - \sin^2(\alpha/2))^{1/2} \right]$$

where,

d	distance from the center of the sub-arc to the second point,
r	radius of the sub-arc,
α	magnitude of the sub-arc (radians).

This method ensures that a line segment replaces not more than 30 degrees of turn angle. Also, the sum of the lengths of the line segments equals the distance along the arc, so that the flying time along the line segments is the same as the time that would be flown along the circular arc.

2.4.3 3-D Flight Path Construction

A three-dimensional flight path is constructed by merging a two-dimensional profile (a set of distance vs. altitude points) with a two-dimensional ground track (a set of x-y points).

- Wherever there is a track point, a z-value is computed by interpolating between two points on the profile.

- Wherever there is a profile point, x-y values are computed on the ground-track segment under the profile point.

The result of this construction is an ordered set of x,y,z points and associated speed and thrust data that describe the flight path.

When a track point lies between two profile points, a linear interpolation method is used to calculate the altitude, speed, and thrust.

$$z = z_1 + f\,(z_2 - z_1)$$

$$v_T = v_{T1} + f\,(v_{T2} - v_{T1})$$

$$F_{nc} = F_{nc1} + f\,(F_{nc2} - F_{nc1})$$

where,

z	altitude above the airport at the interpolated point,
z_1	initial profile altitude,
z_2	final profile altitude,
v_T	speed at the interpolated point,
v_{T1}	initial profile speed,
v_{T2}	final profile speed,
F_{nc}	corrected net thrust per engine at the interpolated point,
F_{nc1}	initial profile thrust,
F_{nc2}	finalprofile thrust,
f	fraction of the distance from profile point 1 to the interpolated point divided by the distance from profile point 1 to point 2.

2.4.4 Displaced Thresholds and Threshold Crossing Heights

A departure flight path starts a given distance from the departure end of the runway:

$$D = D_{dep} + \Delta_{trk}$$

where,

D	start-roll distance (ft) from the end of the runway,
D_{dep}	displaced departure threshold (ft) for the runway (user input),
Δ_{trk}	delta distance (ft) for the departure ground track (user input).

An approach or touch-and-go flight touches down on the runway a given distance from the approach end of the runway:

$$D = D_{app} + \Delta_{trk} + h_{tc} |q_{-1}| / z_{-1}$$

where,

D	touch-down distance (ft) from the end of the runway,
D_{app}	displaced approach threshold (ft) for the runway (user input),
Δ_{trk}	delta distance (ft) for the approach ground track (user input),
h_{tc}	threshold crossing height (ft) for the runway (user input),
q_{-1}	coordinate value (ft) of the profile point immediately before the touch-down point (it is a negative number),
z_{-1}	altitude (ft AFE) of the profile point immediately before the touch-down point (the touch-down point has coordinates: $q_o = 0$, $z_o = 0$).

2.4.5 Touch-and-Go and Circuit Flight Path Methods

INM uses special processing to construct touch-and-go and circuit flight paths.

A user-defined <u>touch-and-go profile</u> starts in level flight at **airport pattern** altitude, descends, touches down on the runway, rolls out, takes off, climbs, and ends somewhere after leveling off at pattern altitude.

After associating a touch-and-go profile with a touch-and-go track, but before calculating flight path points, INM reorders and modifies the set of profile points so that the profile starts and ends at the touch-down point. While reordering the points, INM inserts an extra level segment in the downwind portion of the profile (between the last departure point and first approach point), so that the profile distance is the same as the track distance. Also, a final touch-down point is added at the end. When finished, INM has created a new profile that starts at touch-down, ends at touch-down, and has horizontal coordinate distance equal to the touch-and-go ground track distance.

A user-defined circuit profile starts on the runway as a standard departure, takes off, climbs to pattern altitude, levels out, descends from pattern altitude, lands, and decelerates to taxi speed.

After associating a circuit profile with a touch-and-go track (there are no circuit tracks), INM inserts an extra level segment in the downwind portion of the profile, so that the profile distance is the same as the track distance. The place where the extra segment is inserted is determined by the "level-stretch" procedure step, which is provided by the user.

After modifying a touch-and-go or circuit profile, INM merges the new profile points and the ground track points to compute a three-dimensional flight path.

2.4.6 Segments Too Short and Too Long

After INM constructs the ordered set of flight path points, they are processed to remove points that are too close together. If two x,y,z points are closer than 10 feet, and if the speed and thrust data are the same, one of the points is removed from the set of points.

The last step in constructing a flight path is to insert points into segments that are too long. A path segment is subdivided if its length multiplied by the change in speed is greater than 100,000 ft-kt. The number of sub-segments is calculated by:

$$N = \text{int}[\, 1 + (\, (\, v_{T2} - v_{T1} \,)\, L\, 10^{-5} \,)^{½} \,]$$

where,

N	number of equal-distance sub-segments,
int[x]	function that returns the integer part of a number x ,
v_{T1}	initial speed (kt),
v_{T2}	final speed (kt),
L	length of the segment (ft).

If the flight path segment is subdivided, the speed and thrust values at the end points of the equal-distance sub-segments are linearly interpolated by using the initial and final end-point values.

3 ACOUSTIC COMPUTATION METHODOLOGY

Chapter 3 describes the computation methodology employed by INM 5.1 to generate noise-level and time-above metrics at a single user-specified observer, or at an evenly-spaced regular grid of observers, including the 17-by-17-point regular grid of observers used in the development of the recursively-subdivided irregular grid that is required for a contour analysis. Much of the discussion presented herein is based upon information presented in Reference 10.

Chapter 3 has eleven sections:

Section 3.1 describes the computation of the flight path segment geometric and physical parameters.

Section 3.2 describes the flight path segment noise interpolation and extrapolation process.

Section 3.3 describes the **acoustic impedance adjustment** which is used to compute a temperature / pressure-dependent adjustment for the NPD data.

Section 3.4 describes the computation of the flight-segment **noise fraction adjustment** for exposure-based noise level metrics.

Section 3.5 describes the computation of the **airspeed adjustment** for exposure-based noise level metrics.

Section 3.6 describes the computation of the **lateral attenuation adjustment**.

Section 3.7 describes the ground-based **directivity adjustment** for observers behind the start-of-takeoff roll, as well as for computing metrics associated with runup operations.

Sections 3.8 describes how the flight-segment-by-flight-segment computations described in Sections 3.1 through 3.7 are used to compute the exposure-based noise level metrics.

Sections 3.9 describes how the maximum noise level metrics are computed.

Sections 3.10 describes how the time-above metrics are computed.

Section 3.11 explains the difference between single-metric and multi-metric contour analyses.

Figure 3-1 graphically summarizes the acoustic computation process employed in INM 5.1.

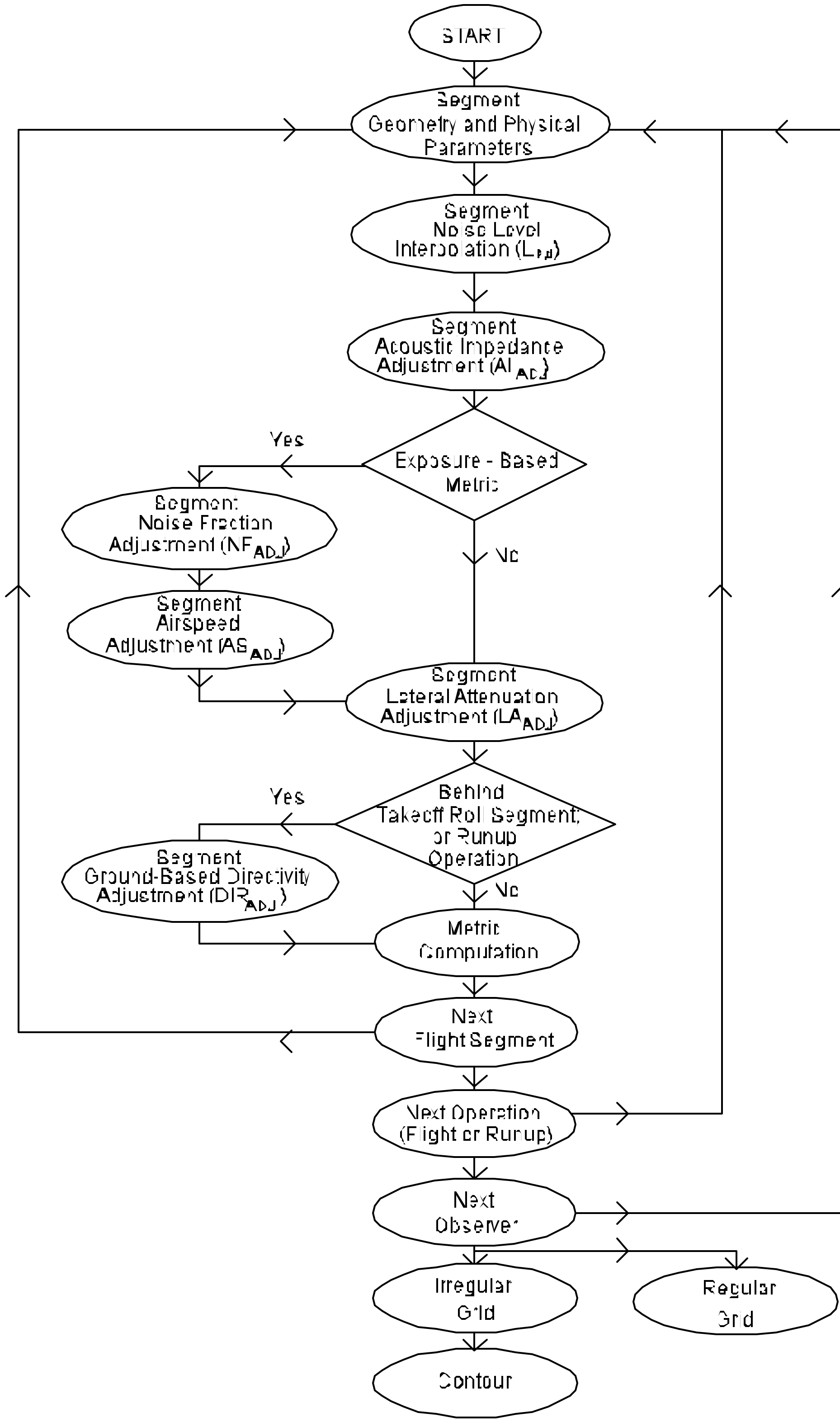

Figure 3-1: INM 5.1 Acoustic Computation Process

3.1 Flight Path Segment Parameters

As a prerequisite to noise level computations, several geometric and physical parameters that are associated with an aircraft flight path are computed. Section 3.1 describes the computation of these parameters.

- Computation of the following flight-segment geometric parameters is discussed in Section 3.1.1: (1) the closest point of approach on the flight-path segment, or the **extended flight-path segment**, to the observer; and (2) the slant range from the observer location to the closest point of approach.
- Computation of the following flight-segment geometric and physical parameters is discussed in Section 3.1.2: (1) the speed along the flight-path segment; (2) the altitude associated with the flight-path segment; (3) the over-ground, sideline distance from the observer location to the ground-projection of the closest point of approach; and (4) the engine power associated with the flight-path segment.

Figures 3-2 through 3-4 present, respectively, the observer/flight-segment geometry for the three general INM cases: (1) the observer is behind the flight-path segment; (2) the observer is astride the flight-path segment; and (3) the observer is ahead of the flight-path segment. The variables shown in these figures are defined as follows:

$\mathbf{P}$ observer point.

$\mathbf{P}_1$ start-point of the flight-path segment.

$\mathbf{P}_2$ end-point of the flight-path segment.

$\mathbf{P}_S$ PCPA, the point on the flight-path segment, or the extended flight-path segment, which is the perpendicular closest point of approach to the observer, as defined in detail in Section 3.1.1, below. The specific definition depends on the position of the observer relative to the flight-path segment.

$\mathbf{P}_1\mathbf{P}_2$ vector from the start of the flight-path segment to the end of the flight-path segment. It has a minimum length of 10 ft.

$\mathbf{P}_1\mathbf{P}$ vector from the start of the flight-path segment to the observer. It has a minimum length of 1 ft.

$\mathbf{P}_2\mathbf{P}$ vector from the end of the flight-path segment to the observer. It has a minimum length of 1 ft.

$\mathbf{P}_S\mathbf{P}$ perpendicular vector from the observer to PCPA on the flight-path segment, or the extended flight-path segment, as defined in detail in Section 3.1.1. It has a minimum length of 1 ft.

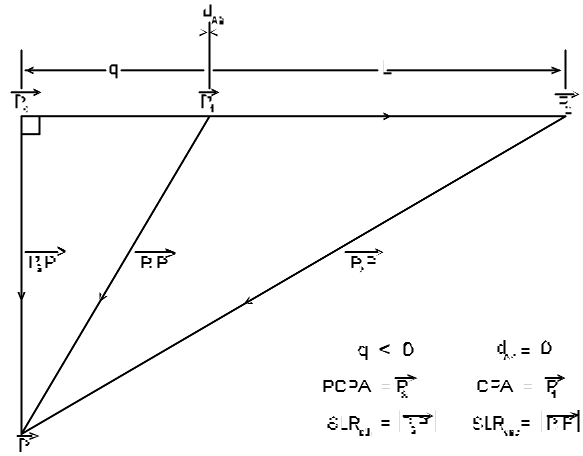

Figure 3-2: Flight-Segment Geometry when an Observer is Behind a Segment

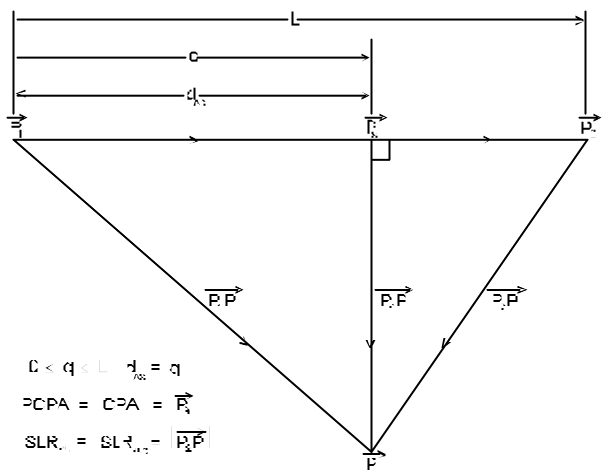

Figure 3-3: Flight-Segment Geometry when an Observer is Astride a Segment

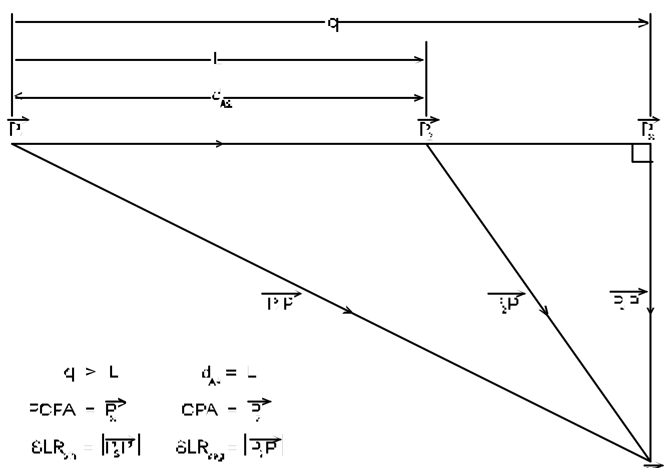

Figure 3-4: Flight-Segment Geometry when an Observer is Ahead of a Segment

SLR_{pth} — ***P**$_S$**P***, the length of the perpendicular vector from the observer to PCPA on the flight-path segment, or the extended flight-path segment, as defined in detail in Section 3.1.1. It has a minimum value of 1 ft.

L — length of the flight-path segment (ft). It has a minimum value of 10 ft.

CPA — point on the flight-path segment, not the extended flight-path segment, which is the closest point of approach to the observer, as defined in detail in Section 3.1.1, below. The specific definition depends on the position of the observer relative to the flight-path segment.

SLR_{seg} — length of the vector from the observer to CPA on the flight-path segment, not the extended flight-path segment, as defined in detail in Section 3.1.1. It has a minimum value of 1 foot.

q — relative distance along the flight-path segment, or the extended flight-path segment, from $\mathbf{P}_1$ to $\mathbf{P}_S$ (ft). The value of q is used to determine the position of the observer relative to the flight-path segment, as shown in Table 3-1.

d_{AS} — distance along the flight-path segment from the start of the segment at $\mathbf{P}_1$, to CPA (ft). Depending on the value of q, i.e., the relative geometry between the observer and the flight-path segment, d_{AS} takes on the following values: (1) when $q < 0$, $d_{AS}=0$; (2) when 0 # q # L, $d_{AS}=q$; and when $q > L$, $d_{AS}=L$.

See Appendix B for a more detailed discussion of the closest point of approach and slant range parameters.

Table 3-1: Position of the Observer Relative to the Flight-Path Segment

Value of q	Position of Observer Relative to Flight-Path Segment
q < 0	Observer is Behind Segment
0 # q # L	Observer is Astride Segment
q > L	Observer is Ahead of Segment

3.1.1 Closest Point of Approach and Slant Range

The closest point of approach and slant range parameters are integral components of INM 5.1 computations. In fact, the slant range is used for noise-level interpolation of the NPD data (see Section

3.2). In addition, their computation is an integral prerequisite to the **noise fraction** algorithm used for exposure-based metrics (see Section 3.4).

The slant range from the observer location to the closest point of approach on the flight path, SLR_{pth}, is defined as the distance from the perpendicular closest point of approach (PCPA), on the flight-path segment, or the extended flight-path segment, to the observer. The specific definition of PCPA depends upon the position of the observer location relative to the flight-path segment. If the observer is behind or ahead of the flight-path segment, then PCPA is the intersection point of the perpendicular from the observer to the extended segment. If the observer is astride the flight-path segment, then PCPA is the intersection point of the perpendicular from the observer to the segment.

The exceptions to the above definition for slant range occur when: (1) the observer is behind a takeoff ground-roll segment (see Section 3.7); and (2) performing computations involving either the L_{ASmx} or L_{PNTSmx} NPD data, including the computation of the time-above metrics, or the computation of all metrics for a runup operation. In these cases, the slant range, designated SLR_{seg}, is defined as the distance from the observer location to the closest point of approach on the flight-path segment, designated CPA, not the extended flight-path segment. The specific definition of CPA depends on the position of the observer location relative to the flight-path segment. If the observer is behind the flight-path segment, CPA is the start-point of the segment. If the observer is astride the flight-path segment, CPA is equivalent to PCPA. If the observer is ahead of the flight-path segment, CPA is the end-point of the flight-path segment.

To simplify the noise-level interpolation process discussed in Section 3.2, the base-10 logarithm of the slant range, both SLR_{pth} and SLR_{seg}, is computed. Since the noise-level interpolation process is performed logarithmically with regard to distance, the step of converting slant range to its base-10 logarithmic value facilitates linear interpolation.

3.1.2 Speed, Altitude, Distance, and Power

Computations of the following four support parameters, associated with each flight-path segment, are described herein: (1) the speed at CPA; (2) the altitude at CPA; (3) the over-ground, sideline distance from the observer location to the horizontal, i.e., ground, projection of CPA; and (4) the engine power at CPA.

The speed, AS_{seg}, at CPA is computed via linear interpolation, as follows:

$$AS_{seg} = AS_{P1} + [\, d_{AS} / L \,] \;)\; AS \qquad \text{(kt)}$$

where,

AS_{P1}	speed at the start of the flight-path segment (kt);
d_{AS}	defined in Section 3.1, above;
L	defined in Section 3.1, above;
$)AS$	change in speed along the flight-path segment (kt).

AS_{seg} is used to compute the airspeed adjustment for exposure-based noise-level metrics as discussed in Section 3.5.

The altitude, d_{seg}, at CPA is computed via linear interpolation, as follows:

$$d_{seg} \ = \ [\mathbf{P}_1]_Z + d_{AS} \ [\ (\mathbf{P}_1\mathbf{P}_2)_Z \ / \ L \ ]^{*} \qquad \text{(ft AFE)}$$

where,

$[\mathbf{P}_1]_Z$	altitude at the start of the flight path segment, given by the z-component of the vector from the origin of coordinates to the start of the flight-path segment (ft);
d_{AS}	defined in Section 3.1, above;
$(\mathbf{P}_1\mathbf{P}_2)_Z$	change in altitude along the flight-path segment (ft);
L	defined in Section 3.1, above.

d_{seg} is used to compute the lateral attenuation adjustment discussed in Section 3.6.

The sideline distance from the flight-path segment to the observer, l_{seg}, defined as the distance in the horizontal plane from the observer location to the ground-projection of CPA, is computed as follows:

$$l_{seg} \ = \ [\ *(SLR_{seg}^{\ 2} - d_{seg}^{\ 2})* \ ]^{1/2} \qquad \text{(ft)}$$

where,

SLR_{seg}	defined in Section 3.1, above;
d_{seg}	as computed above.

The sideline distance, l_{seg}, is used to compute the ground-to-ground component of the lateral attenuation adjustment as discussed in Section 3.6.

The engine power, P_{seg}, at CPA is computed via linear interpolation, as follows:

$$P_{seg} \ = \ P_{P1} + [\ d_{AS} \ / \ L] \ )P \qquad \text{(see below for units)}$$

where,

P_{P1} engine power at the start of the flight-path segment (note: “power”, also known as “thrust-setting”, is expressed on a per engine basis in a variety of units, including pounds, percent, and engine-pressure-ratio, commonly referred to as EPR, as well as other units of power. The specific unit designation can be found in the THRSET_TYP category of the NOIS_GRP data base file.);

d_{AS} defined in Section 3.1, above;

---

* In certain computational areas of INM 5.1, it is assumed that d_{seg} is expressed in feet AFE, e.g., in computing the lateral attenuation adjustment (see Section 3.6). Consequently, when the terrain elevation enhancement is invoked, d_{seg}, which is expressed in feet MSL, is converted back to feet AFE (as it appears in the FLIGHT.PTH file), by subtracting the airport elevation, in feet MSL.

L defined in Section 3.1, above;

)P change in power along the flight-path segment.

P_{seg} is used in performing noise level interpolation as discussed in Section 3.2.

3.2 Noise Level Interpolation ($L_{P,d}$)

Given the engine power associated with the flight-path segment, along with the base-10 logarithm of the distance, the NPD data are then used to either linearly interpolate or extrapolate an associated noise-level value. In actuality, the interpolation/extrapolation process is logarithmic with regard to distance; however, since the base-10 logarithm of the distance is used, the result is equivalent to logarithmically interpolating/extrapolating on the actual distance.*

For each aircraft flight operation, NPD data are available for the four fundamental noise-level metrics, L_{AE}, L_{EPN}, L_{ASmx}, and L_{PNTSmx}. The appropriate metric is selected for interpolation / extrapolation based upon the user-specified noise metric, or family of metrics to be computed at the observer. The specific distance and power value used in the interpolation / extrapolation process is dependent on the type of base metric selected. Section 3.2.1 and 3.2.2 discuss the distance and power values for exposure-based noise-level metrics and maximum noise-level metrics, respectively.

Following is a generalized description of the noise interpolation / extrapolation process employed by INM 5.1.

The noise level at engine power, P_1, and distance, d, is given by:

$$L_{P1,d} = L_{P1,d1} + (L_{P1,d2} - L_{P1,d1}) (\log_{10} d - \log_{10} d_1) / (\log_{10} d_2 - \log_{10} d_1) \qquad \text{(dB)}$$

where,

P_1 , P_2 engine power values for which noise data are available in an aircraft's NPD data (pounds, percent, EPR, as well as other units of power on a per engine basis);

d_1 , d_2 distance values for which noise data are available in an aircraft's NPD data;

$L_{P1,d1}$ noise level at power, P_1, and distance, d_1 (dB);

$L_{P2,d1}$ noise level at power, P_2, and distance, d_1 (dB);

$L_{P1,d2}$ noise level at power, P_1, and distance, d_2 (dB);

$L_{P2,d2}$ noise level at power, P_2, and distance, d_2 (dB).

---

* Several of the NOISEMAP aircraft, which were included in the INM Data Base beginning with Version 5.1, contain NPD data for afterburner operations. These data are identified in the CURVE_TYPE category of the NPD_CURV data base file with an "A" (Afterburner) identifier, as compared with an "N" (Normal) identifier, which is used for all non-afterburner NPD data. If a particular flight path segment is identified as an afterburner segment, interpolation / extrapolation is only performed with regard to distance, not power. In other words, afterburner is either on or off.

The noise level at engine power, P_2, and distance, d, is given by:

$$L_{P2,d} = L_{P2,d1} + (L_{P2,d2} - L_{P2,d1}) (\log_{10} d - \log_{10} d_1) / (\log_{10} d_2 - \log_{10} d_1) \quad \text{(dB)}$$

Then, the interpolated / extrapolated noise level at engine power, P, and distance, d, is given by:

$$L_{P,d} = L_{P1,d} + (L_{P2,d} - L_{P1,d}) (P - P_1) / (P_2 - P_1) \quad \text{(dB)}$$

The above methodology is utilized when: (1) the engine power and/or distance associated with the observer/segment pair lies between existing values in the NPD data (i.e., interpolation); (2) the power and/or distance associated with the observer/segment pair is larger than existing values in the NPD data (i.e., extrapolation); and (3) the power associated with the observer/segment pair is smaller than existing values in the NPD data (i.e., extrapolation).

When the distance associated with the observer/segment pair is smaller than the smallest distance in the NPD data (200 ft), a special case applies. This special case is discussed separately for exposure-based noise-level metrics (Section 3.2.1) and maximum noise-level metrics (Section 3.2.2).

3.2.1 Exposure-Based Noise Level Metrics

The general noise interpolation / extrapolation process described in Section 3.2 is applicable for the four fundamental noise-level metrics, L_{AE}, L_{EPN}, L_{ASmx}, and L_{PNTSmx}. However, the specific engine power and distance value used in the interpolation / extrapolation process is different for exposure-based noise-level metrics as compared with maximum noise-level metrics.

Specifically, if the end points of a flight-path segment are defined by $\mathbf{P}_1$ at the start of the segment, and $\mathbf{P}_2$ at the end of the segment, then the exposure-based noise level, either L_{AE} or L_{EPN}, as appropriate, interpolated / extrapolated for an observer/segment pair, is given by:

$$L_{P,d} = \begin{cases} L_{Pseg,d=SLRpth} & \text{observer behind or ahead of segment} \\ L_{Pseg,d=SLRseg} & \text{observer astride segment} \end{cases}$$

where,

$L_{Pseg,d=SLRpth}$ interpolated noise level based upon engine power associated with the flight-path segment, P_{seg}, as defined in Section 3.1.2, and the distance to PCPA on the extended flight-path segment, as defined in Section 3.1.1 (dB);

$L_{Pseg,d=SLRseg}$ interpolated noise level based upon engine power associated with the flight path segment, P_{seg}, as defined in Section 3.1.2, and the distance to CPA=PCPA on the flight-path segment, as defined in Section 3.1.1 (dB).

For the special case in which SLR_{pth} or SLR_{seg} is smaller than 200 ft, i.e., the smallest value in the distance portion of the NPD data, cylindrical divergence(i.e., line-source) is assumed and a $10 \log_{10}[d_1 / d_2]$ relationship is utilized for the L_{AE}-based and L_{EPN}-based noise-level metrics. For example, if the L_{AE} for a distance of 200 ft, and a given power in the NPD data is 95.6 dB, the L_{AE} at 100 ft at the same power level is 98.6, i.e., $95.6 + 10 \log_{10}[200/100]$.

3.2.2 Maximum Noise Level Metrics

As stated previously, the general noise interpolation / extrapolation process described in Section 3.2 is applicable for the four fundamental noise-level metrics, L_{AE}, L_{EPN}, L_{ASmx}, and L_{PNTSmx}. However, the specific distance and power value used in the interpolation / extrapolation process is different for maximum noise-level metrics as compared with exposure-based metrics.

Specifically, if the end points of a flight-path segment are defined by $\mathbf{P}_1$ at the start of the segment, and $\mathbf{P}_2$ at the end of the segment, then the maximum noise level, either L_{ASmx} or L_{PNTSmx}, as appropriate, interpolated / extrapolated for an observer/segment pair, is given by:

$$L_{P,d} = \begin{cases} \text{Max}[L_{P,d,START}, L_{P,d,END}] & \text{observer behind/ahead of segment} \\ \text{Max}[L_{P,d,START}, L_{P,d,PCPA}, L_{P,d,END}] & \text{observer astride segment} \end{cases}$$

where,

Max[ ]	function that returns the maximum of several noise level values;
$L_{P,d,START}$	interpolated noise level based upon the distance and engine power values associated with the start of the flight-path segment (dB);
$L_{P,d,END}$	interpolated noise level based upon the distance and engine power values associated with the end of the flight-path segment (dB);
$L_{P,d,PCPA}$	interpolated noise level based upon the distance and engine power values associated with PCPA = CPA on the flight path segment (dB).

As with exposure-based metrics, a special case applies for maximum noise level metrics when the distance is smaller than 200 ft, i.e., the smallest value in the distance portion of the NPD data. Specifically, for the L_{ASmx}-based and L_{PNTSmx}-based noise metrics, spherical divergence (i.e., point-source) is assumed and a $20 \log_{10}[d_1 / d_2]$ relationship is utilized. For example, if the L_{ASmx} for a distance of 200 ft, and a given power in the NPD data is 95.6 dB, the L_{ASmx} at 100 ft at the same power level is 101.6, i.e., $95.6 + 20 \log_{10}[200 / 100]$.

3.3 Acoustic Impedance Adjustment (AI_{ADJ})

Before the interpolated/extrapolated noise level data, $L_{P,d}$, is utilized for computations, an acoustic impedance adjustment, designated by the symbol AI_{ADJ}, is applied. Acoustic impedance, which is a function of temperature, atmospheric pressure, and indirectly altitude, is defined as the product of the density of a medium (in this case air) and the speed of sound in that medium.

The noise-level portion of the INM NPD data has been corrected to reference-day conditions (77 degrees Fahrenheit, 29.92 inches of mercury, and mean sea level).[12] It can be adjusted to any test site temperature and pressure by correcting for the deviation in acoustic impedance of air at the test site from a reference-day impedance of 409.81 newton-seconds/m^3. See Appendix C for a derivation of the AI_{ADJ} equation.[5, 6, 16, 17]

$$AI_{ADJ} = 10 \log_{10}[Dc / 409.81]^{*} \qquad \text{(dB)}$$

where,

$$Dc = 416.86 [* / 2^{1/2}]$$

$$* = [(518.67 - 0.003566 A) / 518.67]^{5.256} + [P - 29.92] / 29.92$$

$$2 = [459.67 + T - 0.003566 (A - E)] / 518.67$$

The variables in the above equations are defined as follows:

AI_{ADJ}	acoustic impedance adjustment to be added to noise level data in the INM NPD data base (dB);
Dc	acoustic impedance at observer altitude and pressure (newton-seconds/m^3);
*	ratio of atmospheric pressure at observer altitude to standard-day pressure at sea level, with an adjustment term added to take into account non-standard pressure;
A	observer altitude MSL (ft);
P	airport pressure MSL (in-Hg);
2	ratio of airport temperature to standard-day temperature at sea level;
T	airport temperature (F);
E	airport elevation MSL (ft).

As can be seen from the above equation, when the terrain elevation enhancement is invoked, AI_{ADJ} is computed and applied to the NPD data on an observer-by-observer basis, according to the observer altitude, temperature, and pressure. Otherwise, the airport elevation and the observer altitude are equivalent, and a single value of AI_{ADJ} is computed and applied regardless of the observation point.

Note that when terrain elevation is not invoked and when airport temperature, pressure, and altitude are equivalent to 77°F, 29.92 in-Hg, and 0 ft MSL, respectively, the AI_{ADJ} is zero.

* See Appendix C for a derivation of this equation

3.4 Noise Fraction Adjustment for Exposure-Based Metrics (NF_{ADJ})

The exposure-based noise level data interpolated / extrapolated from the INM NPD data, $L_{P,d}$, represents the noise exposure level associated with a flight path of infinite length. However, the aircraft flight path in INM 5.1 is described by a set of finite-length flight-path segments, each contributing varying amounts of exposure to the overall noise metric computed at an observer.

The noise fraction algorithm, used exclusively for computation of the exposure-based metrics (i.e., L_{AE}, L_{dn}, L_{den}, L_{Aeq24h}, L_d, L_n, L_{EPN}, L_{NEF}, and L_{WECPN}), and indirectly for computation of the time-above metrics (i.e., TAL_A and TAL_{PNT}), computes the fraction of noise exposure associated with a finite-length flight-path segment. This fraction of noise exposure is computed relative to the noise associated with a flight path of infinite length. It is based upon a fourth-power, 90-degree dipole model of sound radiation. [15, 18, 19]

Computation of the noise fraction for a flight operation is necessary because the L_{AE}-based and L_{EPN}-based noise levels in the NPD data are computed assuming the aircraft proceeds along a straight flight path, parallel to the ground, and of infinite length. To obtain the noise level or time-above at an observer location due to an aircraft proceeding along a finite flight-path segment, the exposure-based noise-level data, interpolated / extrapolated from the INM NPD data, must be adjusted by a fractional component, which is associated with the geometry of the observer/flight-segment pair.

3.4.1 Observer Behind, Astride, Ahead of Segment

Figures 3-5 through 3-7 present, respectively, the flight-segment/observer geometry for the three general INM cases discussed earlier in Section 3.1: (1) the observer is behind the flight-path segment; (2) the observer is astride the flight-path segment; and (3) the observer is ahead of the flight-path segment. The variables used in these figures are defined as follows:

$\mathbf{P}$ observer point;
$\mathbf{P}_1$ start-point of the flight-path segment;
$\mathbf{P}_2$ end-point of the flight-path segment;

$\mathbf{P}_S$ PCPA, the point on the flight-path segment, or the extended flight-path segment, which is the perpendicular closest point of approach to the observer;

$r_1 = |\mathbf{P}_1\mathbf{P}|$ length of the connecting segment from the start of the flight-path segment to the observer (ft). It has a minimum value of 1 ft;

$r_2 = |\mathbf{P}_2\mathbf{P}|$ length of the connecting segment from the end of the flight-path segment to the observer (ft). It has a minimum value of 1 ft;

L length of the flight-path segment (ft). It has a minimum value of 10 ft;

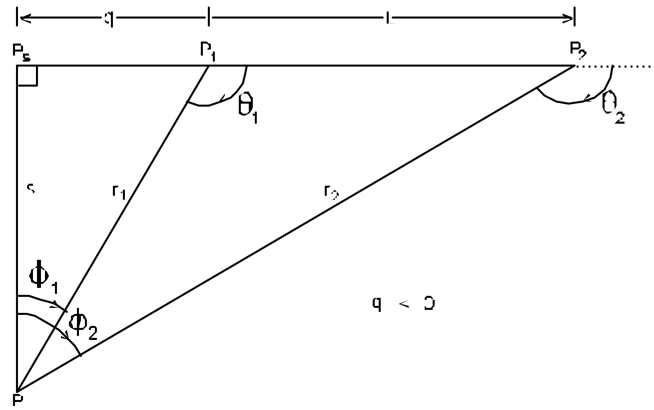

Figure 3-5: Geometry for the Noise Fraction of an Observer Behind a Flight-Path Segment

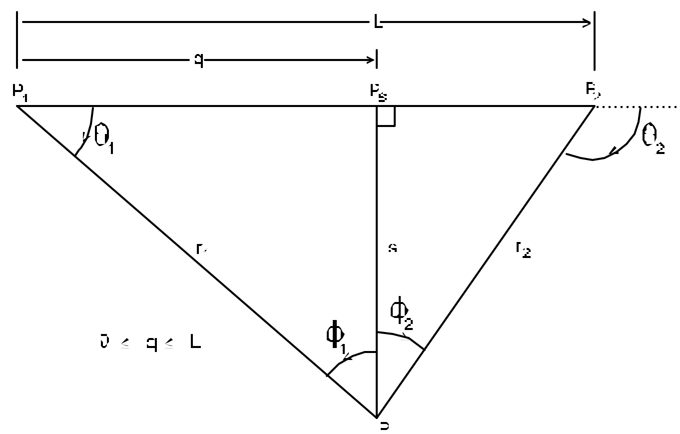

Figure 3-6: Geometry for the Noise Fraction of an Observer Astride a Flight-Path Segment

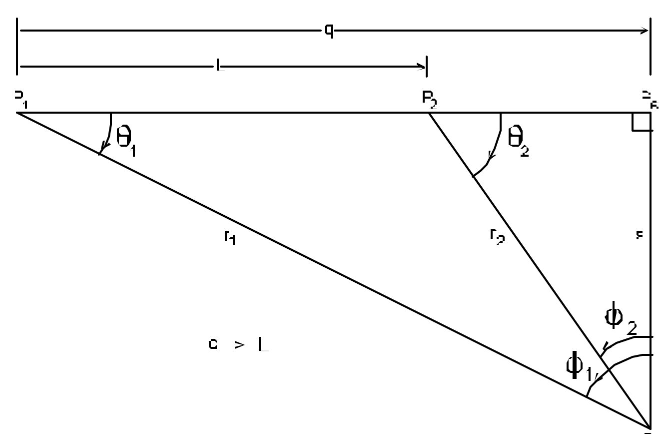

Figure 3-7: Geometry for the Noise Fraction of an Observer Ahead of a Flight-Path Segment

q relative distance along the flight-path segment, or the extended flight-path segment, from $\mathbf{P}_1$ to $\mathbf{P}_S$ (ft). The value of q is used to determine the position of the observer relative to the flight-path segment, as shown in Table 3-1.

When q < 0, i.e., the <u>observer is behind the flight-path segment</u>, the following definitions apply (see Figure 3-5):

$$N_1 = \sin^{-1}* \, q / r_1 * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1}* \, (L - q) / r_2 * \qquad \text{(radians)}$$

The noise fraction, F_{12}, is given by:

$$F_{12} = (1/B) \, [\, N_2 - N_1 + \sin N_2 \cos N_2 - \sin N_1 \cos N_1 \,]$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment, i.e., CPA;

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment.

When 0 # q # L, i.e., the <u>observer is astride the flight-path segment</u>, the following definitions apply (see Figure 3-6):

$$N_1 = \sin^{-1}* \, q / r_1 * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1}* \, (L - q) / r_2 * \qquad \text{(radians)}$$

The noise fraction, F_{12}, is given by:

$$F_{12} = (1/B) \, [\, N_1 + N_2 + \sin N_1 \cos N_1 + \sin N_2 \cos N_2 \,]$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment;

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment.

When q > L, i.e., the observer is ahead of the flight-path segment, the following definitions apply (see Figure 3-7):

$$N_1 = \sin^{-1} * \, q / r_1 \, * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1} * \, (q - L) / r_2 \, * \qquad \text{(radians)}$$

The noise fraction, F_{12}, is given by:

$$F_{12} = (1/B) \, [\, N_1 - N_2 + \sin N_1 \cos N_1 - \sin N_2 \cos N_2 \,]$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment; and

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment, i.e., CPA.

The noise fraction, F_{12}, is then converted to a dB adjustment as follows:

$$NF_{ADJ} = 10 \log_{10}[\, F_{12} \,] \qquad \text{(dB)}$$

See Appendix D for a derivation of the equations used for the noise fraction in INM 5.1.

3.4.2 Observer Behind Start-of-Takeoff Roll

For an observer behind the start-of-takeoff ground roll, a special case of the noise fraction equation applies. This special case noise fraction, denoted by the symbol $F_{12}N$, ensures consistency at an azimuth angle of 90 degrees (measured from the noise of the aircraft) with the noise fraction discussed above in Section 3.4. It provides essentially uniform **directivity** characteristics in all directions (see Figure 3-5 for the support variables discussed below), and is given by the equation:

$$F_{12}N = (1/B) \, [\, N_2 + \sin N_2 \cos N_2 \,]$$

where,

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment.

The noise fraction for the special case of observers behind the start-of-takeoff roll, $F_{12}N$, is then converted to a dB adjustment as follows:

$$NF_{ADJ} = 10 \log_{10}[F_{12}N] \qquad \text{(dB)}$$

3.5 Airspeed Adjustment for Exposure-Based Metrics (AS_{ADJ})

The aircraft speed adjustment takes into account the effect of time-varying aircraft speed, both acceleration and deceleration, on the exposure-based metrics. It is not applied to maximum noise level metrics since they are inherently independent of time. In addition, since a runup is a stationary operation in INM 5.1, i.e., it does not have an associated speed, the speed adjustment is not applicable, regardless of noise metric.

The L_{AE} and L_{EPN} values in the NPD data are for a reference true airspeed of 160 kt. For aircraft speeds other than 160 kt, the airspeed adjustment, AS_{ADJ}, is given by:

$$AS_{ADJ} = 10 \log_{10}[160 / AS_{seg}] \qquad \text{(dB)}$$

where AS_{seg} is the true airspeed at the closest point of approach (CPA), as discussed in Section 3.1.2.

3.6 Lateral Attenuation Adjustment (LA_{ADJ})

The lateral attenuation adjustment is meant to take into account the following effects on aircraft sound due to over-ground propagation:* (1) ground reflection effects; (2) refraction effects; and (3) airplane shielding effects, as well as other ground and engine/aircraft installation effects. It is computed as a function of two empirical parameters, the sideline distance from the flight-path segment to the observer, l_{seg}, computed in Section 3.1.2, and the angle formed by SLR_{seg} and the **ground plane** beneath the observer location, $\$$.

The ground plane beneath the observer is either defined by a flat plane, or, if the terrain elevation enhancement is invoked, elevation data are used to compute the actual slope of a three-by-three arc-second ground plane, with the observer at its physical center (see Figure 3-8).

The INM 5.1 database includes all of the aircraft from the United States Air Force's (USAF) NOISEMAP suite of programs,[3] as of January 1996. The specific NOISEMAP aircraft are identified in the MODEL_TYPE category of INM 5.1 NOIS_GRP.DBF database file with an "N" (NOISEMAP), as compared with an "I" (INM). The specific algorithms used for computing lateral attenuation in INM 5.1 are dependent upon whether the MODEL_TYPE associated with a particular aircraft is categorized as INM or NOISEMAP.

* The lateral attenuation adjustment in INM was derived from field measurements made over grass-covered, acoustically soft terrain. Consequently, when source-to-receiver propagation occurs primarily over an **acoustically hard surface** (e.g., water), and the hard surface dominates the study environment, it is possible that INM could under predict the actual noise level.

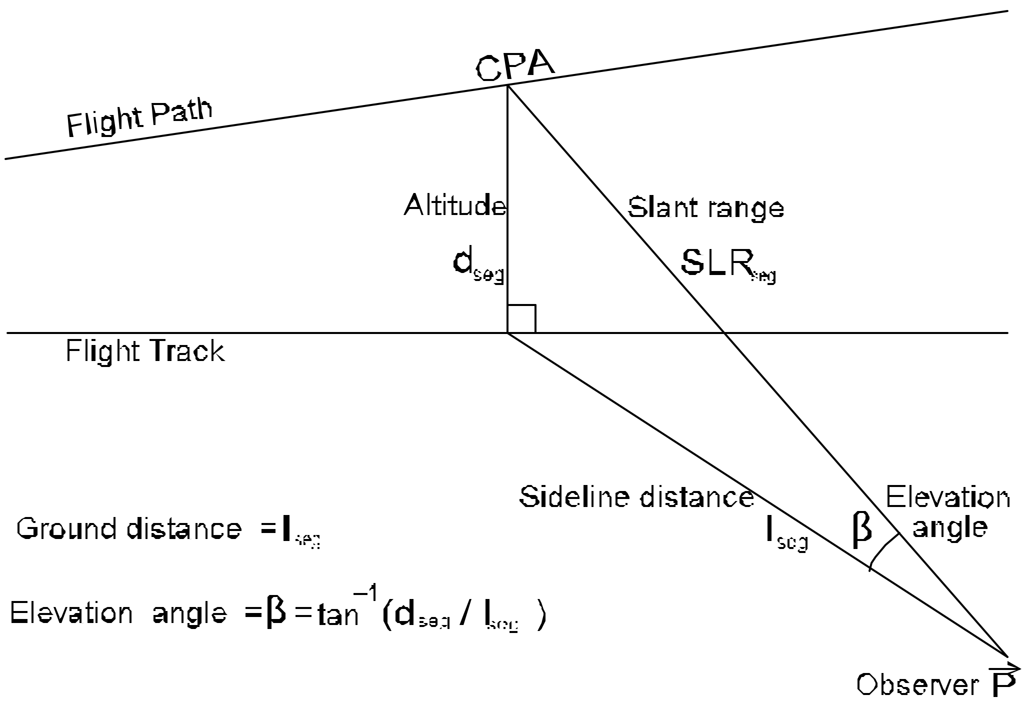

Figure 3-8: Lateral Attenuation Geometry

3.6.1 INM Aircraft

If the MODEL_TYPE associated with a particular aircraft in the NOIS_GRP.DBF database file is categorized as INM, computation of the lateral attenuation adjustment depends upon whether the aircraft is located on the ground or in the air. If the aircraft is on the ground, the adjustment has a ground-to-ground component only. If the aircraft is in the air, it has both a ground-to-ground and an air-to-ground component. In the latter case, the two components are computed separately and then combined.[20]

The ground-to-ground component of the lateral attenuation adjustment is computed as follows:

$$G(l_{seg}) = \begin{cases} 15.09\,[\,1 - e^{-0.00274\, l_{seg}}\,] & \text{for } 0 < l_{seg} \le 914 \text{ m (3000 ft)} \quad \text{(dB)} \\ 13.86 & \text{for } l_{seg} > 914 \text{ m (3000 ft)} \quad \text{(dB)} \end{cases}$$

where,

l_{seg} sideline distance in the horizontal plane from the observer to the ground-projection of CPA (m).

The air-to-ground component of the lateral attenuation adjustment, 7(\$), is computed as follows:

$$7(\$) = \begin{cases} 3.96 - 0.066\,\$ + 9.9\,e^{-0.13\,\$} & \text{for } 0 \# \$ \# 60 \text{ degrees} \quad \text{(dB)} \\ 0 & \text{for } 60 < \$ \# 90 \text{ degrees} \quad \text{(dB)} \end{cases}$$

The overall lateral attenuation adjustment, LA_{ADJ}, which takes into account both the ground-to-ground component, $G(l_{seg})$, and the air-to-ground component, 7(\$), is then computed as follows:

$$LA_{ADJ\ (INM)} = G(l_{seg})\ 7(\$) / 13.86 \quad \text{(dB)}$$

3.6.2 NOISEMAP Aircraft

If the MODEL_TYPE in the NOIS_GRP.DBF database file is categorized as NOISEMAP, computation of the lateral attenuation adjustment depends upon the elevation angle, \$. If the elevation angle is less then 2 degrees, the adjustment has a ground-to-ground component only. If the elevation angle is greater than or equal to 2 degrees, it has both a ground-to-ground and an air-to-ground component. In the latter case, the two components are computed separately and then combined.

The ground-to-ground component of the lateral attenuation adjustment is computed as follows:*

$$G(l_{seg}) = \begin{cases} 15.09\,[\,1 - e^{-0.00274\ lseg}\,] & \text{for } 0 < l_{seg} \# 401 \text{ m (1316 ft)} \quad \text{(dB)} \\ 10.06 & \text{for } l_{seg} > 401 \text{ m (1316 ft)} \quad \text{(dB)} \end{cases}$$

where,

l_{seg} sideline distance in the horizontal plane from the observer to the ground-projection of CPA (m).

The air-to-ground component of the lateral attenuation adjustment is computed as follows:

$$7(\$) = \begin{cases} (\,21.056 / \$) - 0.468 & \text{for } 2 \# \$ \# 45 \text{ degrees} \quad \text{(dB)} \\ 0 & \text{for } 45 < \$ \# 90 \text{ degrees} \quad \text{(dB)} \end{cases}$$

* The ground-to-ground component of the lateral attenuation adjustment actually computed by the NOISEMAP program is dependent upon the one-third octave-band frequency characteristics of the noise source. Due to this fact, small differences are expected when comparing INM and NOISEMAP results directly, especially in the immediate vicinity of the airport runways.

The overall lateral attenuation adjustment, LA_{ADJ}, which takes into account both the ground-to-ground component, $G(l_{seg})$, and the air-to-ground component, 7($), is then computed as follows:

$$LA_{ADJ\ (NOISEMAP)} = G(l_{seg})\ 7(\$) / 10.06 \qquad \text{(dB)}$$

3.7 Ground-Based Directivity Adjustment (DIR_{ADJ})

For the special case of computing noise behind the start-of-takeoff ground roll, as well as for computing metrics associated with runup operations, a field-measurement-based directivity adjustment is employed. This directivity adjustment is expressed as a function of azimuth angle, θ_1, defined as the angle formed by the flight-path segment and the connecting segment from the observer to the start of the flight-path segment, i.e., CPA.[15]

To account for the effect of slight variations in the heading of the aircraft just prior to takeoff ground roll, among other effects, a directivity smoothing adjustment, computed as a function of slant range from the observer location to the aircraft, is also applied.[21]

The azimuth angle, θ_1, used in computing the directivity adjustment is given by:

$$\theta_1 = \cos^{-1}(q / r_1) \qquad \text{(degrees)}$$

where,

- q — relative distance between points $\mathbf{P}_1$, and $\mathbf{P}_S$ (ft). By definition, the value of q is less than 0 (see Figure 3-5);
- r_1 — SLR_{seg}, the slant range from the observer to CPA on the flight-path segment (ft).

Since the value of q is less than zero, and the value of SLR_{seg} is greater than zero, then the value of θ_1 is always greater than 90 degrees. The directivity adjustment, DIR_{ADJ} is computed as a function of azimuth angle, as follows:

When θ_1 is between 90 and 148.4 degrees, DIR_{ADJ} is given by:

$$DIR_{ADJ} = 51.44 - 1.553\,\theta_1 + 0.015147\,\theta_1^{\,2} - 0.000047173\,\theta_1^{\,3} \qquad \text{(dB)}$$

When θ_1 is between 148.4 and 180 degrees, DIR_{ADJ} is given by:

$$DIR_{ADJ} = 339.18 - 2.5802\,\theta_1 - 0.0045545\,\theta_1^{\,2} + 0.000044193\,\theta_1^{\,3} \qquad \text{(dB)}$$

The directivity adjustment, DIR_{ADJ}, is then modified by a smoothing equation that is computed as a function of slant range from the observer location to CPA on the flight-path segment, SLR_{seg}. The smoothing function is activated when SLR_{seg} is greater than 2500 ft. The function, which reduces the directivity effect in dB by a factor of 50 percent, per doubling of distance, is given by:

$$DIR_{ADJ} = DIR_{ADJ}\,(\,2500 / SLR_{seg}\,) \qquad \text{for } SLR_{seg} > 2500 \text{ ft} \qquad \text{(dB)}$$

3.8 Computation of Exposure-Based Noise Level Metrics

This section discusses separately the computation of exposure-based noise level metrics for flight operations (Section 3.8.1), as well as for runup operations (Section 3.8.2). To obtain the total noise exposure at an observer location, the contributions from both flight operations and runup operations are combined.

For the computation of exposure-based metrics at multiple observers in a regular grid, including the base regular grid used in a single-metric and multi-metric contour analysis, the methodology described in Sections 3.1 through 3.8 is repeated iteratively. If the terrain elevation enhancement is not invoked, the step of computing the acoustic impedance adjustment for each observer iteration is skipped (Section 3.3). It is not necessary to repeat this step if the terrain elevation enhancement is inactive because the observer's elevation, temperature, and pressure are the same as at the airport.

3.8.1 Flight Operations

For the exposure-based noise metrics, the **sound exposure ratio** due to a single flight-path segment of a flight operation, denoted by the symbol $E/E_o(seg)$, is computed as follows:

$$E/E_o(seg) = 10^{[\,L_{P,d} + AI_{ADJ} + NF_{ADJ} + AS_{ADJ} - LA_{ADJ} + DIR_{ADJ}\,] / 10}$$

where,

- $L_{P,d}$ unadjusted, L_{AE} or L_{EPN}, in dB, resulting from the noise interpolation process (see Section 3.2);
- AI_{ADJ} acoustic impedance adjustment, in dB (see Section 3.3);
- NF_{ADJ} noise fraction adjustment, in dB (see Section 3.4);
- AS_{ADJ} airspeed adjustment, in dB (see Section 3.5);
- LA_{ADJ} lateral attenuation adjustment, in dB (see Section 3.6); and
- DIR_{ADJ} directivity adjustment, in dB, which is applied only if the flight-path segment is part of takeoff ground roll (see Section 3.7).

Each flight in the study case has associated with it a given number of operations for the day, evening, and night-time periods. Also, depending upon the user-specified metric, each time period may have a weighting factor, i.e., penalty, associated with it. The weighting factors for the standard exposure-based metrics, along with their associated time-averaging constants (Avg_{const}), which are discussed later in this section, are summarized in Table 3-2. INM 5.1 users also have the option to define their own weighting factors and averaging constants through the use of a user-specified exposure-based metric.

Table 3-2: Weighting Factors and Time-Averaging Constants for the Standard Exposure-Based Metrics

Metric	W_{day}	W_{eve}	W_{night}	Avg_{const}	$10 \log_{10}[Avg_{const}]$ (dB)
L_{AE}	1	1	1	1	0
L_{dn}	1	1	10	86400	49.37
L_{den}	1	3*	10	86400	49.37
L_{Aeq24h}	1	1	1	86400	49.37
L_d	1	1	0	54000	47.32
L_n	0	0	1	32400	45.11
L_{EPN}	1	1	1	1	0
L_{NEF}	1	1	16.67	630957345	88.0**
L_{WECPN}	1	3*	10	8640***	39.37

* In accordance with the technical definition, a 5 dB penalty is added to evening operations when computing the L_{den} noise metric. The 5 dB penalty, expressed in terms of a weighting factor, is equivalent to 3.16, not 3. However, in Title 21, Subchapter 6, §5001 of California state law a factor of 3 is used. Since the state of California is the primary user of the L_{den} metric, it was decided that INM would be consistent with state law, rather than the traditional technical definition. The evening weighting factor in the L_{WECPN} metric was changed to 3 for consistency. It is anticipated that this subtle difference will be of no practical consequence in the computations.

** The 88.0 dB value is an arbitrarily-chosen scaling constant inherent in the definition of the L_{NEF} metric. A 24-hour period is used to compute the metric.

*** The 8640 value represents the number of contiguous, 10-second intervals in a 24-hour period. Unlike L_{AE}, which is normalized to a duration of 1 second, L_{EPN} is normalized to a duration of 10 seconds.

The number of operations associated with each time period, coupled with the weighting factors, is used to compute the weighted sound exposure ratio, denoted by the symbol $E/E_o(wtseg)$, for a single flight-path segment and operation.

$$E/E_o(wtseg) = [\, W_{day}\, N_{day} + W_{eve}\, N_{eve} + W_{night}\, N_{night} \,]\ E/E_o(seg)$$

where,

N_{day}	number of user-specified operations between 0700 and 1900 hours local time;
N_{eve}	number of user-specified operations between 1900 and 2200 hours local time;
N_{night}	number of user-specified operations between 2200 and 0700 hours local time;
W_{day}	day-time weighting factor, either standard or user-defined (see Table 3-2 for the standard weighting factors associated with a particular exposure-based noise level metric);
W_{eve}	evening weighting factor, either standard or user-defined (see Table 3-2 for the standard weighting factors associated with a particular exposure-based noise level metric);
W_{night}	night-time weighting factor, either standard or user-defined (see Table 3-2 for the standard weighting factors associated with a particular exposure-based noise level metric); and
$E/E_o(seg)$	sound exposure ratio at an observer location due to a single flight-path segment of a flight operation.

The weighted sound exposure ratio, associated with each flight-path segment of a flight operation is computed iteratively and preserved.

The weighted sound exposure ratio due to an entire flight operation is then obtained by summing the ratios associated with each segment in the flight. The weighted sound exposure ratio for the entire flight operation, $E/E_o(wtflt)$, is computed as follows:

$$E/E_o(wtflt) = \sum_{I=1}^{n_{seg}} E/E_o(wtseg)_I$$

where n_{seg} is the number of segments in the three-dimensional flight path.

The weighted sound exposure ratio for each flight operation in the airport case is then computed iteratively and preserved.

The weighted sound exposure ratio for all flight operations in the entire study case is then obtained by summing the ratios associated with each operation. The weighted sound exposure ratio for all flight operations in the study case, $E/E_o(wtarpt)$, is computed as follows:

$$E/E_o(wtarpt) = \sum_{I=1}^{n_{flt}} E/E_o(wtflt)_i$$

where n_{flt} is the number of flight operations in the study case.

The **mean-square sound-pressure ratio** associated with a specific exposure-based noise level metric is computed by dividing the weighted sound exposure ratio for the related base metric, $E/E_0(wtarpt)$, by a time-averaging constant (Avg_{const}), either standard or user-specified. The time-averaging constants for the standard exposure-based metrics were summarized in Table 3-2. Note that two of the exposure-base metrics, L_{AE} and L_{EPN}, are true sound exposure levels, and they are not divided by a time-averaging constant (or, equivalently, divided by 1).

The average or equivalent mean-square sound-pressure ratio, p^2/p_0^2, associated with an exposure-based metric, is given by:

$$p^2/p_o^2 = E/E_o(wtarpt) / Avg_{const}$$

The final step in the process is to convert p^2/p_o^2 to its equivalent dB value. The dB value for a user-specified, exposure-based metric due to all flight operations in an airport case is computed as follows:

$$L_{exp} = 10 \log_{10}[\ p^2/p_o^2\ ] \qquad \text{(dB)}$$

L_{exp} is equivalent to either a standard exposure-based noise level metric or to a user-specified exposure-based metric, depending upon the specific weighting factors and time-averaging constants selected.

In addition to the above calculations, the single-event, unweighted sound exposure level, $L_{exp}(flt)$, for each flight operation is also computed iteratively and saved for use in the time-above calculation (see Section 3.10.1).

$$L_{exp}(flt) = 10 \log_{10}[\ \sum_{I=1}^{n_{seg}} E/E_o(seg)_I\ ] \qquad \text{(dB)}$$

3.8.2 Runup Operations

For the exposure-based noise metrics, the mean-square sound-pressure ratio due to a single runup operation, denoted by the symbol $p^2/p_o^2(rnup)$, is computed as follows:

$$p^2/p_o^2(\text{rnup}) = 10^{[\,L_{P,d} + AI_{ADJ} - LA_{ADJ} + DIR_{ADJ}\,]\,/\,10}$$

where,

$L_{P,d}$ unadjusted, L_{ASmx} or L_{PNTSmx}, in dB, resulting from the noise interpolation process (see Section 3.2);

DIR_{ADJ} directivity adjustment, in dB (see Section 3.7);

and all other variables are defined in Section 3.8.1 above.

As is the case with flight operations, each runup in the study case has associated with it a given number of operations for the day, evening, and night-time periods. Also, depending upon the user-specified metric, each time period may have a weighting factor, i.e., penalty, associated with it. The main difference in computing an exposure-based metric for a flight operation as compared with a runup operation, is that the runup also has associated with it a time duration.

The number of operations associated with each time period, coupled with the weighting factors and the duration, are used to compute the weighted sound exposure ratio, denoted by the symbol $E/E_o(\text{wtrnup})$, for a single runup operation.

$$E/E_o(\text{wtrnup}) = [\, W_{day}\, N_{day} + W_{eve}\, N_{eve} + W_{night}\, N_{night} \,]\ (t/t_o)\ \ p^2/p_o^2(\text{rnup})$$

where,

t runup duration (seconds),

t_o 1 second for L_{ASmx}, or 10 seconds for L_{PNTSmx},

and all other variables are defined in Section 3.8.1 above.

All subsequent steps required for computing exposure-based noise levels for runup operations are identical to those described in Section 3.8.1 for a flight operation. Specifically, the weighted sound exposure ratio for each runup operation is computed iteratively and preserved. Each ratio is then arithmetically summed for all runup operations in the airport case, a time averaging constant is applied and the ratio is converted to a dB value.

3.9 Computation of Maximum Noise Level Metrics

This section discusses separately the computation of maximum noise level metrics for flight operations (Section 3.9.1), as well as for runup operations (Section 3.9.2) . To obtain the maximum noise level at an observer location, the contribution from both flight operations and runup operations are considered.

For the computation of maximum noise level metrics at multiple observers in a regular grid, including the base regular grid used in a single-metric and multi-metric contour analysis, the methodology described in Sections 3.1 through 3.7, as well as that described in Section 3.9, is repeated iteratively. If the terrain elevation enhancement is not invoked, the step of computing the acoustic impedance adjustment for each observer iteration is skipped (Section 3.3). It is not necessary to repeat this step if the terrain elevation enhancement is inactive because the observer's elevation, temperature, and pressure are the same as at the airport.

3.9.1 Flight Operations

The maximum noise level due to a single flight-path segment, denoted by the symbol $L_{max}(seg)$, is computed as follows:

$$L_{max}(seg) = L_{P,d} + AI_{ADJ} - LA_{ADJ} + DIR_{ADJ} \qquad \text{(dB)}$$

where,

- $L_{P,d}$ unadjusted, L_{ASmx} or L_{PNTS}, in dB, resulting from the noise interpolation process (see Section 3.2);
- AI_{ADJ} acoustic impedance adjustment, in dB (see Section 3.3);
- LA_{ADJ} lateral attenuation adjustment, in dB (see Section 3.6);
- DIR_{ADJ} directivity adjustment, in dB, which is applied only if the flight-path segment is part of takeoff ground roll (see Section 3.7).

The maximum noise level associated with each flight-path segment in a flight operation is computed iteratively and preserved.

The maximum noise level associated with each flight operation, $L_{max}(flt)$, is then determined by performing a flight-segment by flight-segment comparison of $L_{max}(seg)$ values, and preserving the largest value associated with each flight. $L_{max}(flt)$ is computed as follows:

$$L_{max}(flt) = \underset{I=1}{\overset{n_{seg}}{\mathrm{Max}}}[\, L_{max}(seg)_I \,]$$

where n_{seg} is the number of segments in the three-dimensional flight path.

The maximum noise level associated with each flight operation in the airport case is then computed iteratively and preserved.

The $L_{max}(flt)$ values are then grouped according to the time period within which they occur, day, evening, or night.

The maximum noise level associated with each time period is preserved as follows:

$$L_{max}(flt)_{(day,eve,night)} = \operatorname*{Max}_{I=1}^{n_{flt}}[\, L_{max}(flt)_I \,]$$

where n_{flt} is the number of flight operations in the study case for a given time period.

Given three L_{max}(flt) values, one for each time period, day, evening and night, the INM 5.1 user is given the option to select a time period, either day, evening, or night, or any combination thereof, for which the maximum noise level is to be determined.

$$L_{max} = \mathrm{Max}[\, L_{max}(flt)_{day}\, W_{day},\, L_{max}(flt)_{eve}\, W_{eve},\, L_{max}(flt)_{night}\, W_{night}) \,]$$

where,

Max[ ]	function that returns the maximum of x noise level values;
$L_{max}(flt)_{day}$	maximum noise level for the time period between 0700 and 1900 hours local time;
$L_{max}(flt)_{eve}$	maximum noise level for the time period between 1900 and 2200 hours local time;
$L_{max}(flt)_{night}$	maximum noise level for the time period between 2200 and 0700 hours local time;
W_{day}	day-time weighting factor, either zero or unity, depending on whether that time period should be considered by the Max function;
W_{eve}	evening weighting factor, either zero or unity, depending on whether that time period should be considered by the Max function;
W_{night}	night-time weighting factor, either zero or unity, depending on whether that time period should be considered by the Max function.

L_{max} is equivalent to either the maximum A-weighted sound level, with slow-scale exponential weighting characteristics (L_{ASmx}), or the tone-corrected maximum perceived noise level, with slow-scale exponential weighting characteristics (L_{PNTSmx}). L_{max} is expressed in dB.

3.9.2 Runup Operations

The maximum noise level due to a single runup operation, denoted by the symbol L_{max}(rnup), is computed as follows:

$$L_{max}(rnup) = L_{P,d} + AI_{ADJ} - LA_{ADJ} + DIR_{ADJ} \qquad \text{(dB)}$$

where DIR_{ADJ} is the directivity adjustment, in dB (see Section 3.7); and all other variables are defined in Section 3.9.1 above.

As is the case with flight operations, the maximum noise level associated with each runup operation is computed iteratively and preserved.

All subsequent steps required for computing maximum noise levels for runup operations are identical to those described in Section 3.9.1 for a flight operation. Specifically, the L_{max}(rnup) values are grouped according to the time period within which they occur, the maximum value for each time period is determined, and the specific time period, or combination of periods is selected for determining the maximum level associated with runup operations.

3.10 Computation of Time-Above Metrics

This section discusses separately the computation of the time above a noise level threshold for flight operations (Section 3.10.1), as well as for runup operations (Section 3.10.2). To obtain the time above at an observer location, the contribution from both flight operations and runup operations are combined.

For the computation of time-above at multiple observers in a regular grid, including the base regular grid used in a single-metric and multi-metric contour analysis, the methodology described in Sections 3.1 through 3.7, as well as that described in Section 3.10, is repeated iteratively. If the terrain elevation enhancement is not invoked, the step of computing the acoustic impedance adjustment for each observer iteration is skipped (Section 3.3). It is not necessary to repeat this step if the terrain elevation enhancement is inactive because the observer's elevation, temperature, and pressure are the same as at the airport.

An important assumption inherent in time-above computations is that operations do not overlap in time, i.e., user-specified operations occur in a serial fashion. However, if a case airport has multiple parallel runways with operations occurring simultaneously, this assumption is invalid, and the computed time-above metric will be larger than at the airport. In such instances the burden is on the user to define operations in terms of an equivalent number of serial, or back-to-back operations, as compared with average-annual day operations.

See Appendix E for a derivation of the general equation used for the time-above metrics in INM 5.1.

3.10.1 Flight Operations

The time-above metric due to a single flight operation is equal to the following:

$$TA(flt) = (4/\beta)\, t_o\, 10^{(L_{exp} - L_{max})/10}\, (10^{(L_{max} - L_x)/20} - 1)^{1/2} \;/\; 60 \qquad \text{(minutes)}$$

where,

t_o constant value of 1 second for L_{AE}, or 10 seconds for L_{EPN}.

L_{exp} sound exposure level, either L_{AE} or L_{EPN}, for a given aircraft and observer/flight-path pair (dB);

L_{max} maximum noise level, either L_{ASmx} or L_{PNTSmx}, for a given aircraft and observer/flight-path pair (dB);

L_x user-specified noise-level threshold, expressed in either A-weighted sound level or tone-corrected perceived noise level (dB).

Each flight in the study case has associated with it a set number of operations for the day, evening, and night-time periods, along with weighting factors. In the case of the TA metric, the weighting factors act as binary switches, allowing the user to select/deselect specific time periods over which to compute TA. The number of operations associated with each time period, coupled with the weighting factors, are used to compute the weighted time-above value associated with a specific flight operation, TA(wtflt).

$$TA(wtflt) = [\, W_{day}\, N_{day} + W_{eve}\, N_{eve} + W_{night}\, N_{night} \,]\, TA(flt) \qquad \text{(minutes)}$$

where,

N_{day} number of user-specified operations between 0700 and 1900 hours local time;

N_{eve} number of user-specified operations between 1900 and 2200 hours local time;

N_{night} number of user-specified operations between 2200 and 0700 hours local time;

W_{day} day-time weighting factor, either zero or unity, depending on whether that time period should be considered;

W_{eve} evening weighting factor, either zero or unity, depending on whether that time period should be considered;

W_{night} night-time weighting factor, either zero or unity, depending on whether that time period should be considered.

The weighted TA for each flight operation in the study case is computed iteratively and preserved.

The time-above metric for all flight operations in the entire study case is then obtained by summing the TA(wtflt) values associated with each operation. The time above for all flight operations in the study case, TA, is computed as follows:

$$TA = \sum_{I=1}^{n_{flt}} TA(wtflt)_I \qquad \text{(minutes)}$$

where n_{flt} is the number of flight operations in the airport case.

TA is equivalent to either the time above an A-weighted sound level (TAL_A), or the time above a tone-corrected perceived noise level (TAL_{PNT}), depending on the metric family selected, either the A-weighted or the tone-corrected perceived. TA is expressed in minutes.

3.10.2 Runup Operations

The time-above metric due to a single runup operation is simply the portion of the runup time during which the user-specified noise level threshold is exceeded by the runup noise. The time-above for a runup operation is computed as follows:

$$TA(rnup) = \begin{cases} t & \text{when } L_{max} > L_x \\ 0 & \text{when } L_{max} \leq L_x \end{cases}$$

where t is the duration of the runup (minutes), and all other variables are defined in Section 3.10.1 above.

All subsequent steps required for computing time above for runup operations are identical to those described in Section 3.10.1 for a flight operation. Specifically, the weighted TA for each runup operation is computed iteratively and preserved. Each TA value is then arithmetically summed for all runup operations in the study case.

3.11 Single-Metric vs. Multi-Metric Computations

The difference between single-metric and multi-metric contour computations is relatively subtle. Specifically, the weighting factors (W_{day}, W_{eve}, W_{night}) and the time-averaging constants in the case of exposure-based noise level metrics (Avg_{const}) are applied during different steps of the computation process for single-metric as compared with multi-metric contour computations.

3.11.1 Single-Metric

For single-metric contour computations, the weighting factors and time averaging constants are known prior to computations. As such, they are considered in the step-by-step computation processes described in Sections 3.8 through 3.10.

3.11.2 Multi-Metric

For multi-metric contour computations, the weighting factors and time-averaging constants are not known prior to computations, and as such, not considered in the initial computations described in Sections 3.8 through 3.10. Instead, computations are performed independently within each time period, day, evening and night, and once complete, the INM 5.1 user is given the capability to apply the weighting factors and time-averaging constants after the bulk of the computations are done.

The primary advantage of the multi-metric mode is that it gives a user the flexibility to choose several metrics within a particular noise family for computations, either the A-weighted or the perceived noise family, without having to re-run the majority of the computations. In other words, once a multi-metric contour computation within the A-weighted family of metrics completed, a user has the ability to display the noise level contours for any one or all of the metrics within the A-weighted family.

However, there are two disadvantages to multi-metric contour computations: (1) the initial set of bulk computations tend to be a bit slower as compared with those for the single-metric computations, primarily because the single-metric computations have an additional time-saving feature which is discussed in detail in Section 4.2, i.e., the low/high contour cutoff test; and (2) there are some inherent differences associated with this method when computing other than exposure-based noise level contours. These differences have to do with the way **noise significance** testing is done, and they are described in Chapter 4.

4 RECURSIVELY-SUBDIVIDED IRREGULAR GRID DEVELOPMENT

As discussed earlier in Chapter 1, INM 5.1 computes the noise level or time-above in the vicinity of an airport, and presents the results in either one of two formats: (1) the noise-level or time-above for a regular grid of observers; or (2) a plot of contours of user-specified noise level or time-above. The basic methodology presented in Chapter 3 describes the computation of noise level or time-above at a single user-specified observer, or at an evenly-spaced, regular grid of observers, including the 17-by-17-point regular grid of observers used in the development of the recursively-subdivided irregular grid, required for a contour analysis. The development of the recursively-subdivided irregular grid requires additional discussion.

In performing a contour analysis, INM 5.1 computes noise-level or time-above values for each observer location in a base, 17-by-17 point regular grid, using the methodology described in Chapter 3. The program then uses the regular grid and information about the user-specified flight operations to create a recursively-subdivided irregular grid of observers. The density of the irregular grid is a function of the user-specified contour accuracy.

The recursively-subdivided irregular grid information is then used to develop noise-level or time-above contours using the United States Air Force's (USAF) NMPLOT Version 3.04 computer program.[22] In NMPLOT, a contour is constructed by (1) computing the Delaunay Triangulation of the grid points, (2) finding a rough contour by drawing straight contour segments through each triangle in the triangulation, and (3) smoothing the rough contour by using cubic splines under tension.*

NMPLOT is an integral component of the USAF's NOISEMAP suite of programs which is used to predict noise in the vicinity of airports dominated primarily by military operations.[3] To a certain extent, NMPLOT has become the standard contouring program in the transportation-related noise modeling industry. In addition to INM and NOISEMAP, NMPLOT is also used to compute sound level contours for the Federal Highway Administration's Traffic Noise Model (FHWA TNM®), which is used for predicting noise in the vicinity of highways and for designing highway noise barriers.[23]

* A detailed description of the NMPLOT algorithms eventually will be published in a technical manual for NMPLOT Version 4.0. For general information about NMPLOT, contact Wasmer Consulting via the Wide World Web at

"http://www.wasmerconsulting.com/nmplot.htm". The NMPLOT manual will be available for downloading from this site once the manual becomes available.

4.1 Determination of Noise/Time Significant Flight Operations

Following the development of the 17-by-17 point regular grid, the first step in the process of developing the recursively-subdivided grid is to determine which flight operations in a study case are noise-significant or time-significant at each observer location in the regular grid. The purpose of determining significant flight operations is to help reduce the run-time associated with an INM contour computation.

There are two separate tests performed by INM 5.1 to determine if a flight operation is noise-significant, a **relative noise-level/time test**, and a flight **track proximity test**. These tests are performed for each observer location making up the base, 17-by-17-point regular grid. The significance information is then used to guide the process of sub-dividing the base grid to improve contour precision.

4.1.1 Relative Noise-Level/Time Test

In the relative noise-level/time test, all flight operations in an input case are sorted, high-to-low, on the basis of their relative noise/time contribution to an observer location in the regular grid.

- If the user specifies that a single-metric contour analysis be performed, the sorted list takes into account the weighted operations associated with the specific metric.

- If the user specifies that a specific group, or family of metrics, either the A-weighted sound level or tone-corrected perceived noise-level family, be computed, the sorted list does not take into account weighted operations, since they are not yet known. Instead, three sorted lists are developed for operations occurring in the three time periods (day, evening, and night).

The total noise/time value at an observer location is computed by summing the sound exposure ratios or time-above values due to all airport operations.

A "running" noise value is also computed from the sorted list of flights beginning with the flight having the largest contribution to the noise/time, and proceeding through the ordered list. The running noise/time value is continually compared with the total noise/time value at the observer location. When the running value exceeds 97 percent of the total noise/time value, the running value is considered "complete", and all subsequent flights in the sorted list are deemed <u>noise-insignificant</u>.

In the case of the exposure-based and time-above metrics, the 97 percent criterion guarantees that the noise level is within 0.1 dB of the total, and that the time-above is within 3 percent of the total, i.e., relative to the total noise/time computed using all flights. This process is also performed for maximum noise level metrics, but it results in extra steps because there is only one maximum at an observer, not an ordered list of maxima. However, it has no effect on the accuracy of the computations.

4.1.2 Track-Proximity Test

Additionally, a track proximity test is used on all flights that are noise-insignificant. The flight-track proximity test uses the diagonal distance between points (e.g., the distance between points A and I in Figure 4-1) in the base, 17-by-17-point regular grid as an acceptance criterion for the test. If a flight track is within the diagonal distance of the regular grid point being tested, then all flight operations on that track are re-instated as noise/time-significant. In INM 5.0 and latter versions, the diagonal distance is a dynamic function of the user-defined case analysis window.

4.2 Grid Development

To generate the recursively-subdivided grid in INM 5.1, the 17-by-17 point regular grid is split into 64 grid working areas, each containing nine observer locations. The distance between observers is a function of the user-defined case analysis window (e.g., for a window that is 100,000-by-100,000 ft, the distance between adjacent points is 6250 ft, or approximately one nautical mile, i.e., 100000 / (17 – 1).

4.2.1 Low/High Contour Cutoff Splitting Test

To speed up the grid-development process for single-metric contour analyses, a **low/high cutoff contour test** is performed for all 64 working areas in the 17-by-17 point regular grid.

This test determines if <u>all</u> nine noise-level or time-above values within a given working area are sufficiently below/above the user-requested minimum/maximum contour levels. If this is the case, then further computations are unnecessary, and splitting of the working area is not performed. Similar to the above two noise significance tests, the primary purpose of this test is to improve runtime.

4.2.2 Tolerance and Refinement Splitting Tests

The splitting test used to develop the recursively subdivided irregular grid begins with a comparison of known values at regular grid-point observers in the nine-point working area, and linearly interpolated values at the same observers.

If the interpolated values are within a certain, user-specified tolerance of the known values, or the user-specified refinement level has been achieved, then no splitting is performed.

! The user-specified tolerance or accuracy is a value, expressed in dB or minutes, greater than 0.0. The default tolerance value in INM 5.1 is 1.0 (dB or minutes).

! The refinement level is a user-specified integer between 4 and 18, where 4 represents one level of subdivision of the 17-by-17 point base grid, and each subsequent refinement level represents an additional level of subdivision. The default refinement level in INM is 6, i.e., three levels of subdivision.

If the user specifies that a single-metric contour analysis be performed, the comparison between linearly interpolated values and known values takes into account the weighted operations associated with the specific metric.

If the user requests that a multi-metric contour analysis be performed, the comparison does not take into account weighted operations, since they are not yet known. In fact, the comparison is first performed for three temporary base grids, each representing the noise/time associated with the day, evening and night time periods separately. If the tests performed on any of the three temporary base grids warrant a split in a given working area, then the split is performed in a permanent version of the base grid. The splitting of the base grid in the case of multi-metric contour computations is established using the sound exposure metrics in each family, either L_{AE} or L_{EPN}, since the specific user-desired metric is not known at the time of the test.

Due to the difference between splitting tests, it is possible that a single-metric contour analysis, as compared with a multi-metric analysis, will yield slightly different maximum-level and time-above contours for identical input cases. In such instances, the contours generated by the single-metric analysis may be more accurate.

For the example nine-point working area shown in Figure 4-1 (points A through I), splitting proceeds in the following manner:

Point B value is determined through linear interpolation of the values at Points A and C;
Point E value is determined through linear interpolation of the values at Points A and I;
Point D value is determined through linear interpolation of the values at Points A and G.

The difference between the linearly interpolated values at points B, E, and D, and the known values at each of these points is then computed. If any of the absolute differences are greater than the user-specified tolerance, then the rectangle formed by points A, B, E, and D is subdivided, and points V, W, X, Y, and Z are created (note that point V is halfway between points A and B, point W is halfway between points A and D, etc).

The noise-level or time-above at points V, W, X, Y and Z is then computed using the methodology of Chapter 3, taking into account only the noise-significant flight operations associated with the closest regular grid points. For example, since point V is exactly halfway in between points A and B, the noise-significant flights associated with both points are used in the computation.

The above process continues iteratively until either the user-specified tolerance level or refinement level is achieved.

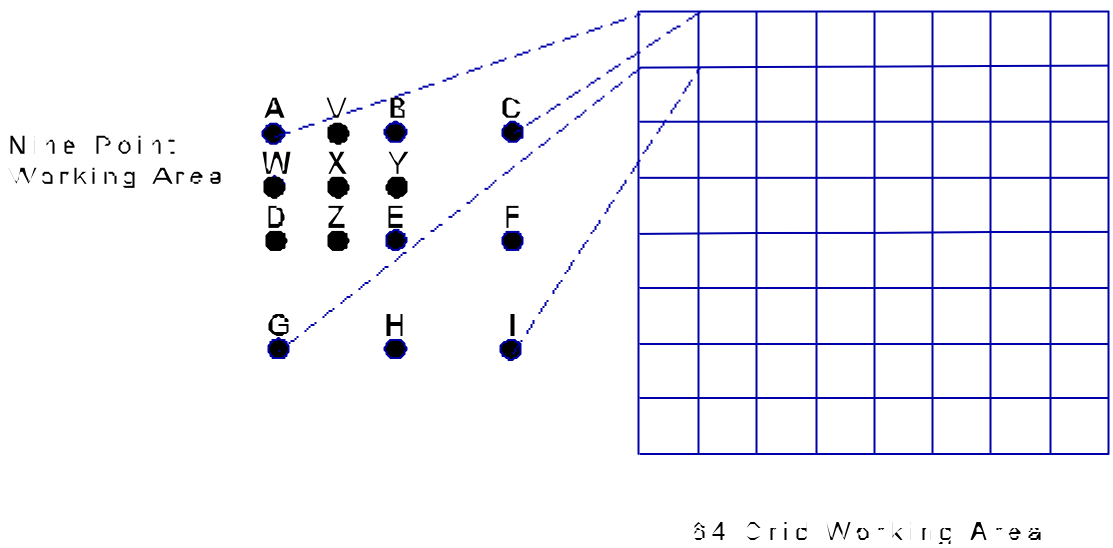

Figure 4-1: Grid Area Used for the Generation of Contours

When the single-metric process is complete for all 64 working areas, the point locations and associated noise-level or time-above values are saved in a pair of binary files, GRID and CONTOUR. These files are further processed to produce the binary file, NMPLOT.GRD. This file is used by the NMPLOT 3.04 computer program for contour generation.

Appendix A: EXAMPLE FLIGHT PATH FILE

The following example file shows data that are passed from the flight path calculation module to the noise calculation 5.1 FLIGHT.PTH file.

```
HEADER (study and case static data)

  case_id            = F:\INM5\EXAMPLES\TEST411\BASECASE
  aprt_lat           = 143533.00  (airport latitude, sec north)
  aprt_long          = -270882.00 (airport longitude, sec west)
  aprt_elev          = 0.00       (airport elevation, ft)
  aprt_temp          = 59.00      (airport temperature, F)
  aprt_press         = 29.92      (airport pressure, in-Hg)
  ta_thresh          = 85.00      (time-above threshold, dB)
  rs_refine          = 6          (refinement parameter)
  rs_toler           = 1.00       (tolerance parameter, dB)
  run_type           = S          (case run type = single-metric)
  metric_id          = DNL        (noise metric to compute)
  fq_type            = A          (noise family = A-weighted)
  metric_type        = E          (metric type = exposure)
  metric_weight      = 1.00, 1.00, 10.00  (day, evening, night ops)
  metric_time        = 49.37      (10 log( T/1s), dB)
  min_level          = 55.0       (minimum contour cutoff, dB)
  max_level          = 85.0       (maximum contour cutoff, dB)
  do_contour_grid    = 1          (yes)
  do_standard_grids  = 1          (yes)
  do_detailed_grids  = 1          (yes)
  do_metric          = 0, 0, 0, 0, 0, 1, 1, 1, 0, 0, 0, 0, 0 (CNEL=no DNL=no etc.)
  do_terrain         = 0          (no)
  terrain_file       =            (none)
  numb_noise         = 110        (number of noise curves)
  numb_acft          = 80         (number of flight+runup operations)
  numb_grid          = 3          (number of grids)
  numb_pop_pts       = 0          (number of population points)
  numb_loc_pts       = 0          (number of locations points)

NOISE (index, thrust, type, 10 SEL & EPNL values, 10 LAMAX & PNLTM values)

  0   3000.0 N  96.6  92.8  89.8  86.8  81.8  75.4  71.0  65.6  59.2  52.2
                96.9  90.2  85.6  80.6  72.8  64.3  58.1  51.2  43.3  34.8
  1   6000.0 N 101.8  98.0  95.1  92.0  87.0  80.9  76.2  70.8  64.4  57.4
               101.1  94.4  89.8  84.8  77.0  68.5  62.3  55.4  47.5  39.0
  2   8000.0 N 106.3 102.6  99.7  96.7  91.7  85.7  81.1  75.8  69.6  62.8
               106.1  99.4  94.8  89.8  82.0  73.6  67.5  60.6  52.9  44.6
  3  10000.0 N 111.0 107.2 104.5 101.5  96.6  90.6  86.1  81.0  74.9  68.3
               111.2 104.5  99.9  95.0  87.2  78.8  72.8  66.1  58.5  50.5
  4  12000.0 N 115.8 112.1 109.4 106.5 101.6  95.8  91.3  86.2  80.4  74.1
               116.6 109.9 105.3 100.4  92.5  84.3  78.4  71.7  64.4  56.6
```

```
  5  14000.0 N 121.1 117.4 114.8 112.0 107.1 101.4  97.0  92.1  86.4  80.4
               122.1 115.4 110.8 106.0  98.1  89.9  84.1  77.6  70.4  62.9

(... and so on for more noise indexes)

AIRCRAFT OPERATIONS (runup and flight operation data)

0 (runup/flight operation index)
  acft_id     = 747200    (aircraft identifier)
  eng_type    = J         (engine type = jet)
  owner_cat   = C         (user category = commercial)
  op_type     = R         (operation type = runup)
  numb_ops    = 10.0000, 0.0000, 0.0000  (day, evening, night)
  frst_a_nois = 24        (first A-weighted index, above in table)
  numb_a_nois = 5         (number of A-weighted noise curves)
  frst_p_nois = 29        (first perceived-weighted index)
  numb_p_nois = 5         (number of perceived noise curves)
  model_type  = I         (attenuation model type, I=INM N=Noisemap)
  runup_id    = R1        (runup identifier)
  point       = 0.0, 0.0  (runup pad x,y location, ft)
  heading     = 93.0      (deg ccw from north)
  thrust      = 41996.5   (corrected net pounds per engine)
  duration    = 1.0       (runup duration, sec)
1
  acft_id     = 727Q15
  eng_type    = J
  owner_cat   = C
  op_type     = A  (approach)
  numb_ops    = 19.6000, 0.0000, 2.8000
  frst_a_nois = 0
  numb_a_nois = 6
  frst_p_nois = 6
  numb_p_nois = 6
  model_type  = I
  flt_path    = A-U3-09R-TR9 (0)  (path id = optype+profile+runway+track+(sub))
  numb_segs   = 21                (number of flight path segments)
  0 (flight path segment index)
    start  = -126404.5, -13175.6, 6000.0  (starting x,y,z point, ft)
    unit   = 0.9834, 0.1754, -0.0454      (unit vector)
    length = 6758.2                       (segment length, ft)
    speed  = 273.5, -11.8                 (speed, and change in speed, kt)
    thrust = 809.2, 187.3                 (thrust, and change in thrust, lb)
    thrset = N                            (thrust setting type N=normal A=afterburn)
  1
    start  = -119758.2, -11989.8, 5692.9
    unit   = 0.9834, 0.1754, -0.0454
    length = 6758.2
    speed  = 261.7, -11.8
    thrust = 996.5, 187.3
    thrset = N
  2
    start  = -113111.9, -10804.1, 5385.8
```

```
    unit   = 0.9834, 0.1754, -0.0454
    length = 6758.2
    speed  = 249.9, -11.8
    thrust = 1183.9, 187.3
    thrset = N
  3
    start  = -106465.6, -9618.4, 5078.7
    unit   = 0.9834, 0.1754, -0.0454
    length = 6758.2
    speed  = 238.1, -11.8
    thrust = 1371.2, 187.3
    thrset = N

(... and so on for more path segments and flight operations)

GRIDS (grid definitions)

0 (grid index)
  grid_id   = CNR
  grid_type = C                (contouring window grid)
  origin    = -50000, -50000  (lower-left corner x,y point, ft)
  angle     = 0.0              (angle of I-axis from X-axis, deg cw)
  delta_i,j = 100000, 100000  (distances between grid points, ft)
  numb_i,j  = 2, 2             (number of points in I and J directions)
    0  x,y  = -50000, -50000  (list of x,y points in the grid, ft)
    1  x,y  = -50000, 50000
    2  x,y  = 50000, -50000
    3  x,y  = 50000, 50000
1
  grid_id   = D01
  grid_type = D (detailed grid)
  origin    = 11000, 3000
  angle     = 0.0
  delta_i,j = 0, 0
  numb_i,j  = 1, 1
    0  x,y  = 11000, 3000
2
  grid_id   = S01
  grid_type = S (standard grid)
  origin    = -3000, 1500
  angle     = 0.0
  delta_i,j = 1000, 700
  numb_i,j  = 2, 3
    0  x,y  = -3000, 1500
    1  x,y  = -3000, 2200
    2  x,y  = -3000, 2900
    3  x,y  = -2000, 1500
    4  x,y  = -2000, 2200
    5  x,y  = -2000, 2900

POPULATION POINTS
   (x,y list goes here)
```

```
LOCATION POINTS
   (x,y list goes here)
```

Appendix B: CLOSEST POINT OF APPROACH AND SLANT RANGE PARAMETERS

This Appendix describes the method utilized by INM 5.1 to compute: (1) the closest point of approach on a flight-path segment, or an extended flight-path segment, to an observer; and (2) the slant range from an observer location to the closest point of approach.

Figures B-1 through B-3 present, respectively, the observer/flight-segment geometry for the three general INM cases: (1) the observer is behind the flight-path segment; (2) the observer is astride the flight-path segment; and (3) the observer is ahead of the flight-path segment. The variables shown in these figures are defined as follows:

P The observer point.

$\mathbf{P}_1$ The start-point of the flight-path segment.

$\mathbf{P}_2$ The end-point of the flight-path segment.

$\mathbf{P}_S$ PCPA, the point on the flight-path segment, or the extended flight-path segment, which is the perpendicular closest point of approach to the observer. The specific definition depends on the position of the observer relative to the flight-path segment.

$\mathbf{P}_1\mathbf{P}_2$ The vector from the start of the flight-path segment to the end of the flight-path segment. It has a minimum length of 10 ft.

$\mathbf{P}_1\mathbf{P}$ The vector from the start of the flight-path segment to the observer. It has a minimum length of 1 ft.

$\mathbf{P}_2\mathbf{P}$ The vector from the end of the flight segment to the observer. It has a minimum length of 1 ft.

$\mathbf{P}_S\mathbf{P}$ The perpendicular vector from the observer to PCPA on the flight-path segment, or the extended flight-path segment. It has a minimum length of 1 ft.

SLR_{pth} $*\mathbf{P}_S\mathbf{P}*$, the length of the perpendicular vector from the observer to PCPA on the flight-path segment, or the extended flight-path segment. It has a minimum value of 1 ft.

L The length of the flight-path segment (ft). It has a minimum value of 10 ft.

CPA The point on the flight-path segment, not the extended flight-path segment, which is the closest point of approach to the observer. The specific definition depends on the position of the observer relative to the flight-path segment.

SLR_{seg} The length of the vector from the observer to CPA on the flight-path segment, not the extended flight-path segment. It has a minimum value of 1 ft.

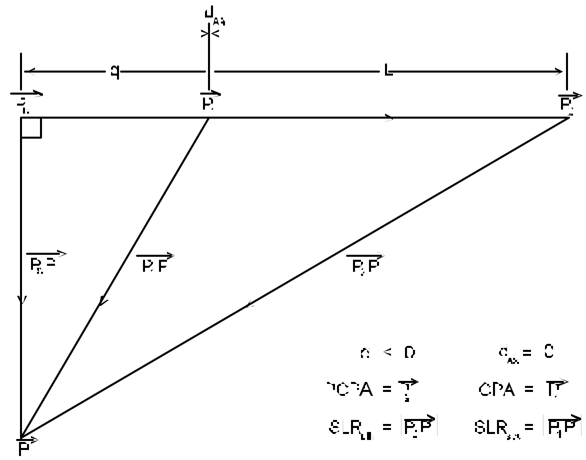

Figure B-1: The Closest Point of Approach and Slant Range for an Observer Behind a Segment

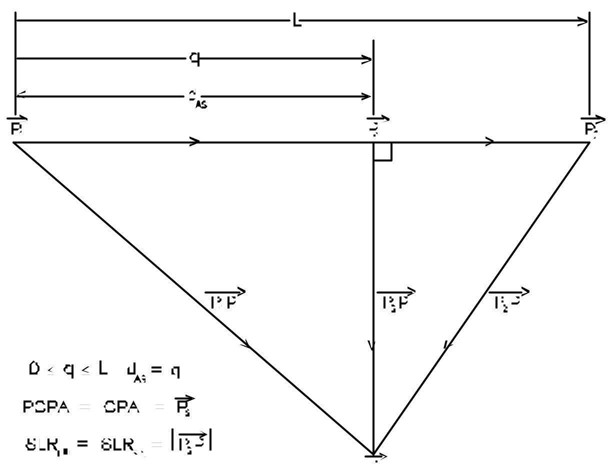

Figure B-2: The Closest Point of Approach and Slant Range for an Observer Astride a Segment

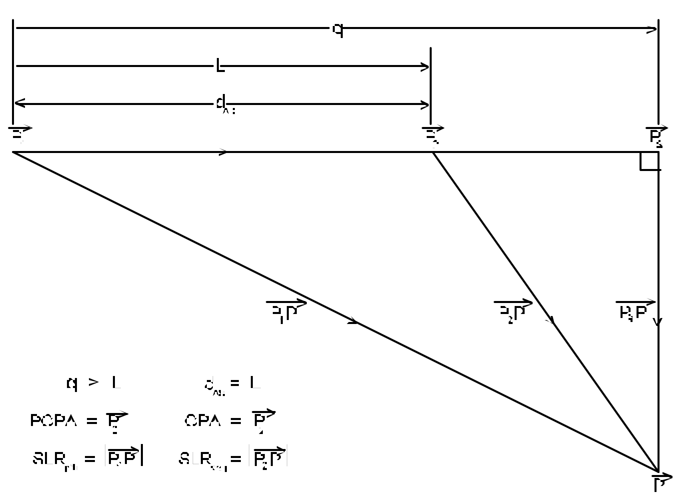

Figure B-3: The Closest Point of Approach and Slant Range for an Observer Ahead of a Segment

The components of the flight-segment unit vector, **u**, are derived from the components of the flight-segment vector, $\mathbf{P}_1\mathbf{P}_2$, and its length, $L = |\mathbf{P}_1\mathbf{P}_2|$, as follows:

$$\mathbf{u} = \mathbf{P}_1\mathbf{P}_2 / L$$

The relative distance value, q, is computed from the scalar product of two vectors, the vector $\mathbf{P}_1\mathbf{P}$, from the start of the flight-path segment to the observer, and the flight-segment unit vector, **u**, as computed above. q is computed as follows:

$$q = \mathbf{P}_1\mathbf{P} \cdot \mathbf{u}$$

q is the relative distance from point $\mathbf{P}_1$ at the start of the flight-path segment to point $\mathbf{P}_S$, the perpendicular closest point of approach (PCPA) on the flight-path segment, or the extended flight-path segment.

The value of q is directly related to the location of the PCPA. It also determines the location of the observer point, **P**, with respect to the flight-path segment. The three possible configurations of observer and flight-path segment, indicated by the value of q are as follows:

(1) If the value of q is negative, then the PCPA is located on the extended flight-path segment, prior to the start of the segment. The corresponding observer location, **P**, is behind the flight-path segment.

(2) If the value of q is zero or positive but not exceeding the length, L, of the flight-path segment, then the PCPA is located on the flight-path segment between its start and end. The corresponding observer location, **P**, is astride the flight-path segment.

(3) If the value of q is positive and exceeds the length, L, of the flight-path segment, then the PCPA is located on the extended flight-path segment, beyond the end of the segment. The corresponding observer location, **P**, is ahead of the flight-path segment.

For each of the three configurations of the observer relative to the flight-path segment, the following five variables are computed:

(1) The distance along the flight-path segment, d_{AS}, from the start of the segment at point $\mathbf{P}_1$ to CPA. Depending on the value of q, i.e., the relative geometry between the observer and the flight-path segment, d_{AS} takes on the following values:

$$d_{AS} = \begin{cases} 0 & q < 0, \quad \text{observer behind segment} \\ q = |\mathbf{P}_1\ \mathbf{P}_S| & 0 \le q \le L, \quad \text{observer astride segment} \\ L & q > L, \quad \text{observer ahead of segment} \end{cases}$$

d_{AS} is computed using the value of q and the unit step function, u(t), as follows:

$$d_{AS} = q\,u(q) - (q-L)\,u(q-L)$$

where u(t) is the unit step function having the following property:

$$u(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq 0 \end{cases}$$

(2) The closest point of approach, CPA, on the flight-path segment, but not the extended flight-path segment. Depending on the value of q, i.e., the relative geometry between the observer location and the flight-path segment, CPA takes on the following values:

$$\mathrm{CPA} = \begin{cases} \mathbf{P}_1 & q < 0, & \text{observer behind segment} \\ \mathbf{P}_S = \mathbf{P}_1 + q\,(\mathbf{P}_1\mathbf{P}_2 / L) & 0 \leq q \leq L, & \text{observer astride segment} \\ \mathbf{P}_2 & q > L, & \text{observer ahead of segment} \end{cases}$$

CPA is computed using the value of d_{AS}, computed above, as follows:

$$\mathrm{CPA} = \mathbf{P}_1 + d_{AS}\,(\mathbf{P}_1\mathbf{P}_2 / L)$$

(3) The slant range, SLR_{seg}, which is the length of the vector from the observer location, **P**, to CPA. Depending on the value of q, i.e., the relative geometry between the observer and the flight-path segment, SLR_{seg} takes on the following values:

$$SLR_{seg} = \begin{cases} |\mathbf{P}_1\mathbf{P}| = r_1 & q < 0 & \text{observer behind segment} \\ |\mathbf{P}_S\mathbf{P}| = (r_1^2 - q^2)^{1/2} & 0 \leq q \leq L & \text{observer astride segment} \\ |\mathbf{P}_2\mathbf{P}| = r_2 & q > L & \text{observer ahead of segment} \end{cases}$$

SLR_{seg} is computed using the value of q and the unit step function, u(t), as follows:

$$SLR_{seg} = \{ r_1^2 [\, 1 - u(q) \,] + [\, r_1^2 - q^2 \,] [\, u(q) - u(q-L) \,] + r_2^2 \; [\, u(q-L) \,] \}^{1/2}$$

$$SLR_{seg} = \{ r_1^2 - q^2 u(q) + [r_2^2 - (r_1^2 - q^2)]\, u(q-L) \}^{1/2}$$

SLR_{seg} has a minimum value of 1 ft.

(4) The perpendicular closest point of approach, PCPA, on the flight-path segment, or the extended flight-path segment, is computed as follows:

$$\mathrm{PCPA} = \mathbf{P}_S = \mathbf{P}_1 + q\,(\mathbf{P}_1\mathbf{P}_2 / L)$$

(5) The slant range, SLR_{pth}, the length of the perpendicular vector from the observer location, **P**, to PCPA, is computed as follows:

$SLR_{pth} = *\mathbf{P}_S\mathbf{P}* = (r_1^2 - q^2)^{½}$

SLR_{pth} has a minimum value of 1 ft.

The variables d_{AS}, CPA, SLR_{seg}, PCPA, and SLR_{pth}, are summarized below for the three general configurations of an observer and a flight-path segment:

(1) The observer is behind the flight-path segment, $q < 0$:

$$d_{AS} = q\, u(q) - (q-L)\, u(q-L) = 0$$

$$CPA = \mathbf{P}_1 + d_{AS} (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_1$$

$$SLR_{seg} = Max\{ r_1^2 - q^2 u(q) + [r_2^2 - (r_1^2 - q^2)]\, u(q- L) \}^{½},\ 1) = Max(r_1, 1)$$

$$PCPA = \mathbf{P}_1 + q (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_S$$

$$SLR_{pth} = Max(*\mathbf{P}_S\mathbf{P}*, 1) = Max(\{ r_1^2 - q^2 \}^{½},\ 1)$$

(2) The observer is astride the flight-path segment, $0 \# q \# L$:

$$d_{AS} = q\, u(q) - (q - L)\, u(q - L) = q$$

$$CPA = \mathbf{P}_1 + d_{AS} (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_1 + q (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_S$$

$$SLR_{seg} = Max(\{ r_1^2 - q^2 u(q) + [r_2^2 - (r_1^2 - q^2)]\, u(q - L) \}^{½},\ 1) = Max(\{ r_1^2 - q^2 \}^{½},\ 1)$$

$$PCPA = \mathbf{P}_1 + q (\mathbf{P}_1\mathbf{P}_2 / L) = CPA = \mathbf{P}_S$$

$$SLR_{pth} = Max(*\mathbf{P}_S\mathbf{P}*, 1) = SLR_{seg} = Max(\{ r_1^2 - q^2 \}^{½},\ 1)$$

(3) The observer is ahead of the flight-path segment, $q > L$:

$$d_{AS} = q\, u(q) - (q - L)\, u(q - L) = L$$

$$CPA = \mathbf{P}_1 + d_{AS} (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_2$$

$$SLR_{seg} = Max(\{ r_1^2 - q^2 u(q) + [r_2^2 - (r_1^2 - q^2)]\, u(q - L) \}^{½},\ 1) = Max(r_2, 1)$$

$$PCPA = \mathbf{P}_1 + q (\mathbf{P}_1\mathbf{P}_2 / L) = \mathbf{P}_S$$

$$SLR_{pth} = Max(*\mathbf{P}_S\mathbf{P}*, 1) = Max(\{ r_1^2 - q^2 \}^{½}, 1)$$

Appendix C: ACOUSTIC IMPEDANCE ADJUSTMENT

The vast majority of the noise level data in the INM database were derived from data originally measured during aircraft noise certification tests conducted in accordance with Federal Aviation Regulation, Part 36, "Noise Standards: Aircraft Type and Airworthiness Certification" (FAR Part 36).[12] Section 36.5(c)(1) of FAR Part 36 states that the noise measurements must be corrected to the following [homogeneous] noise certification reference atmospheric conditions:

(i) Sea level pressure of 2116 psf (76 cm mercury).
(ii) Ambient temperature of 77 degrees Fahrenheit (25 degrees Celsius).
(iii) Relative Humidity of 70 percent.
(iv) Zero wind.

The concept of acoustic impedance (denoted by the symbol Dc) is used in INM to effectively correct the reference-day NPD data to the off-reference, non-sea level conditions associated with the user-specified case airport.

Acoustic impedance, which is a function of temperature, atmospheric pressure, and indirectly altitude for the purposes of INM computations, is defined as the product of the density of a medium (in this case air) and the speed of sound in that medium. Noise level data originally measured at reference-day, sea-level conditions can be corrected to any airport-specific temperature and pressure by adjusting for the deviation in acoustic impedance of air at the airport from a reference-day impedance of 409.81 newton-seconds/m^3. An acoustic impedance of 409.81 newton-seconds/m^3 corresponds to reference atmospheric conditions as defined by FAR Part 36.

Harris[5] and Beranek[6] both contain empirical curves which present the acoustic impedance adjustment as a function of temperature and atmospheric pressure (see Figures C-1 and C-2). These curves can be used to obtain a general sense for the magnitude and direction of the adjustment. However they are not appropriate for correcting INM NPD data since the curves are referenced to an acoustic impedance of 406 and 400 newton-seconds/m^3, respectively, not the 409.81 newton-seconds/m^3 associated with reference-day conditions.

In most practical acoustic computations, the effect of varying acoustic impedance can be neglected. As can he seen from Figures C-1 and C-2, the adjustment is relatively small (usually less than a few tenths of a dB) unless there is a significant variation in temperature and atmospheric pressure relative to reference-day conditions.

However, since INM is used worldwide, and several international, as well as a few national airports are located thousands of feet above mean sea level, there are instances where the adjustment can be fairly substantial. As an example, take Denver International Airport, which is at an elevation of approximately 5000 ft: assuming a temperature of 70°F and an atmospheric pressure of 29.92 in-Hg, an acoustic impedance adjustment of −0.77 dB is required to correct the NPD data to airport conditions.

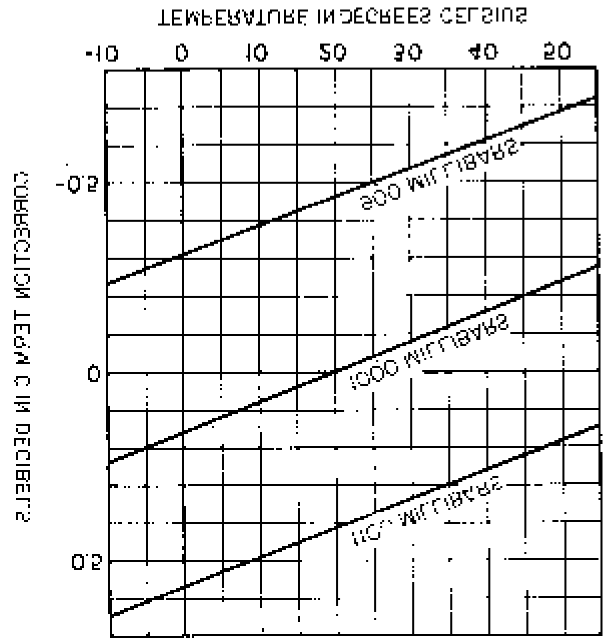

Figure C-1: Acoustic Impedance Adjustment re. 406 newton-second/m^3

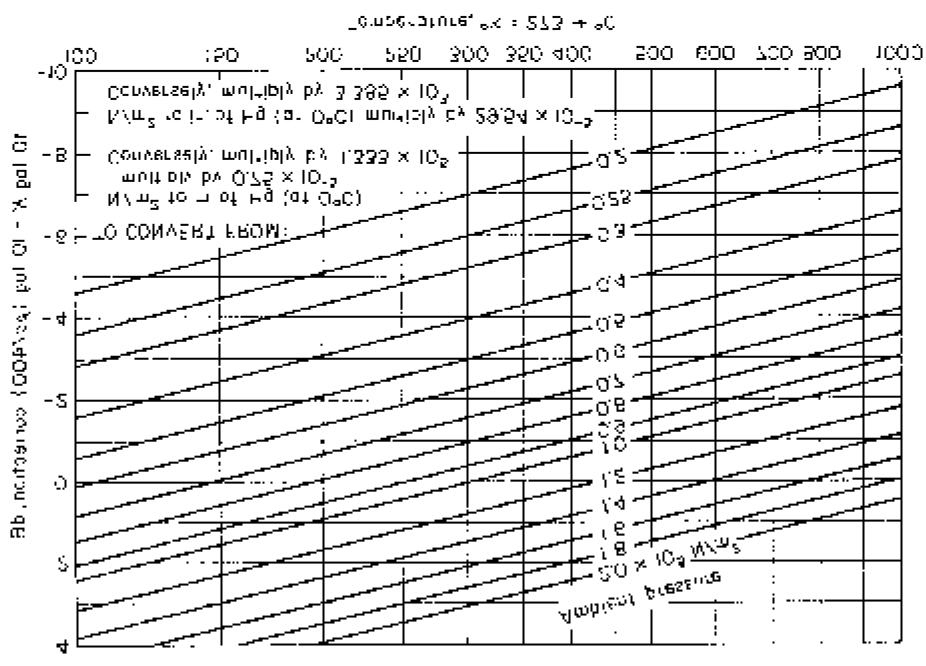

Figure C-2: Acoustic Impedance Adjustment re. 400 newton-second/m^3

To compute the acoustic impedance adjustment to be added to INM NPD data, the following equation is used:

$$AI_{ADJ} = 10 \log_{10}[\, Dc / 409.81 \,] \qquad \text{(dB)}$$

where,

$$Dc = 416.86 \, [\, * / 2^{1/2} \,]$$

$$* = [\, (518.67 - 0.003566 \, A) / 518.67 \,]^{5.256} + [\, P - 29.92 \,] / 29.92$$

$$2 = [\, 459.67 + T - 0.003566 \, (A - E) \,] / 518.67$$

The variables in the above equations are defined as follows:

AI_{ADJ}	acoustic impedance adjustment to be added to noise level data in the INM NPD database (dB);
Dc	acoustic impedance at observer altitude and pressure (newton-seconds/m^3);
*	ratio of atmospheric pressure at observer altitude to standard-day pressure at sea level, with an adjustment term added to take into account non-standard pressure;
A	observer altitude MSL (ft);
P	airport pressure MSL (in-Hg);
2	ratio of airport temperature to standard-day temperature at sea level;
T	airport temperature (°F);
E	airport elevation MSL (ft).

The aforementioned Harris and Beranek references concisely explain the above adjustment in their text, which relate sound intensity and sound pressure. In a free field for plane waves or spherical waves, the sound pressure and particle velocity are in phase, and the magnitude of the intensity (power per unit area), in the direction of propagation of the sound waves, is related to the mean-square sound pressure by the following equation:

$$I = p^2 / Dc$$

where,

I	sound intensity (power per unit area);
p^2	mean-square sound pressure;
Dc	acoustic impedance of the propagation medium.

Two sound intensities at a given distance from a given acoustical power source, one measured under actual conditions (no subscript), and the other measured under reference-day conditions (“ref” subscript), are equal:

$$p^2 / Dc \;=\; p^2_{ref} / Dc_{ref}$$

Therefore, by rearranging the above equation and dividing by a constant $p_o = 20\ \mu Pa$:

$$p^2 / p_o^2 \;=\; (p^2_{ref} / p_o^2)\, (Dc / Dc_{ref})$$

This equation can be converted to its equivalent dB relationship as follows:

$$10 \log_{10}[\, p^2 / p_o^2 \,] \;=\; 10 \log_{10}[\, p^2_{ref} / p_o^2 \,] \;+\; 10 \log_{10}[\, Dc / Dc_{ref} \,]$$

$$L \;=\; L_{ref} \;+\; 10 \log_{10}[\, Dc / Dc_{ref} \,] \qquad \text{(dB)}$$

where, in general terms as it relates to INM:

L	corrected NPD dB level;
L_{ref}	NPD dB level in the INM database for reference-day conditions;
$10 \log_{10}[\, Dc / Dc_{ref} \,]$	acoustic impedance adjustment, AI_{ADJ}.

Appendix D: DERIVATION OF NOISE FRACTION EQUATION FOR EXPOSURE-BASED METRICS

This Appendix presents a derivation of the noise fraction algorithm, which is used by INM 5.1 to compute the fraction of exposure associated with a finite aircraft flight-path segment. It is based upon a fourth-power, 90-degree dipole model of sound radiation, and is used exclusively for the computation of exposure-based noise-level metrics.

The following derivation of the noise fraction algorithm assumes that the aircraft proceeds along a straight flight path, parallel to the ground, and of infinite length. It also assumes that the observer, located at point **P**, is at a perpendicular distance, s, from the flight path. The geometry for this situation is shown in Figure D-1.

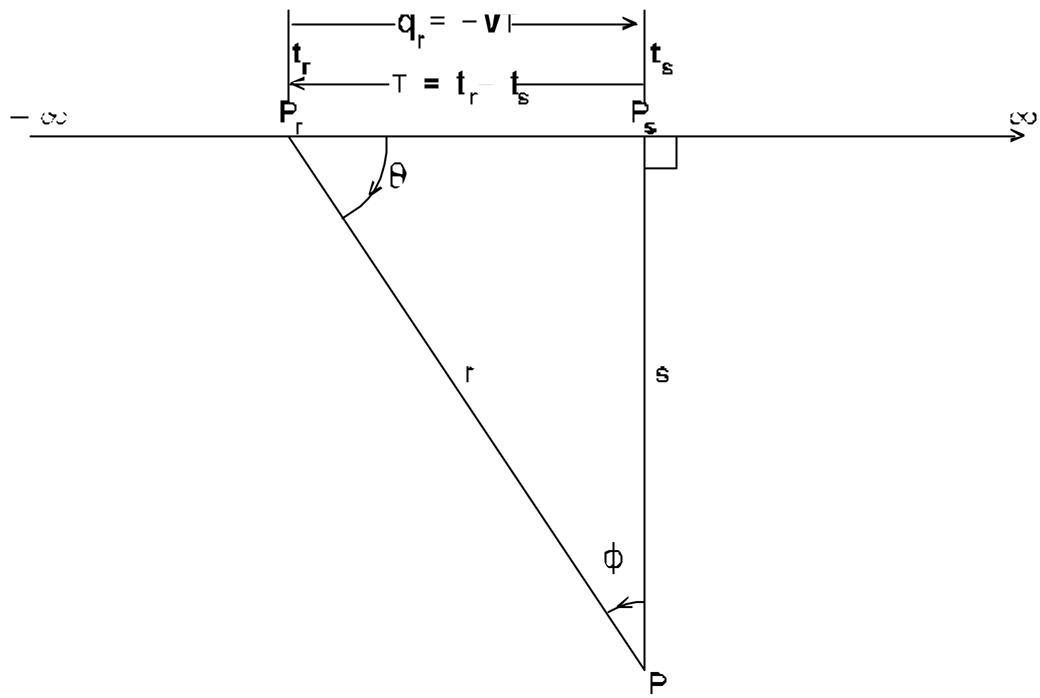

Figure D-1: Observer/Flight-Path Geometry

where,

r distance from the observer at point **P**, to the aircraft at point $\mathbf{P}_r$ (ft);

s perpendicular distance from the observer at point **P**, to PCPA at point $\mathbf{P}_S$ (ft);

q_r relative distance along the flight path from the aircraft at point $\mathbf{P}_r$, to PCPA at point $\mathbf{P}_S$ (ft);

v true airspeed of the aircraft (ft/sec);

t_r time at which the aircraft is located at point $\mathbf{P}_r$ (seconds);

t_s time at which the aircraft is located at PCPA, point $\mathbf{P}_s$ (seconds);

J time difference, t_r minus t_s (seconds);

2 angle formed by the flight path and a connecting segment from the observer at point **P**, to point $\mathbf{P}_r$;

p_r sound pressure generated by the aircraft at point $\mathbf{P}_r$;

p_s sound pressure generated by the aircraft at point $\mathbf{P}_s$.

The relative distance along the flight path, q_r, from point $\mathbf{P}_r$ to point $\mathbf{P}_s$ is computed from the scalar product of two vectors: $\mathbf{P}_r\mathbf{P}$, from the aircraft to the observer; and the unit vector, **u**, in the direction of the flight path. q_r is computed as follows:

$$q_r \; = \; \mathbf{P}_r\mathbf{P} \,@\, \mathbf{u} \; = \; \mathbf{P}_r\mathbf{P} \,@\, \mathbf{P}_r\mathbf{P}_s \,/\, *\mathbf{P}_r\mathbf{P}_s*$$

The value of q_r is positive if the aircraft, at point $\mathbf{P}_r$, is located prior to PCPA, while the value of q_r is negative if the aircraft is beyond PCPA.

The relative distance, q_r, between Points $\mathbf{P}_r$ and $\mathbf{P}_s$ on the flight path can also be expressed in terms of the true airspeed of the aircraft, v, and the time, J, required for the aircraft to move from point $\mathbf{P}_r$ to $\mathbf{P}_s$. Ordinarily, the distance q_r would simply be the product of the speed, v, and the time, J. However, this is not possible since J is negative, and the distance, q_r, has by definition a positive value when the aircraft is located before PCPA. Therefore, the distance q_r is computed, in terms of speed and time, as follows:

$$q_r \; = \; - \, v \, J$$

The exact noise fraction algorithm is derived from a fourth-power, 90-degree dipole time history model. In this model, p_r^2 is the mean-square sound pressure at the observer due to the aircraft, located at point $\mathbf{P}_r$; and p_s^2 is the mean-square sound pressure at the observer due to the aircraft, located at PCPA, point $\mathbf{P}_s$. The mean-square pressure, p_r^2, at the observer is expressed in terms of the mean-square pressure, p_s^2, at the observer, using the following equation:

$$p_r^2 \; = \; p_s^2 \,(s^2 / r^2)\, \sin^2 2$$

In this equation, the mean-square sound pressure for and airplane flying along a straight path is determined by r^2 spherical spreading loss, and by a sine-squared function that accounts for a variety of physical phenomena. These phenomena include frequency attenuation, which is accentuated in front of the airplane due to Doppler shift, and sound refraction away from the hot gases behind the airplane. The purpose of the sine-square term is to shape the skirts of the associated time-history curve to best fit empirical data.[15]

From the geometry in Figure D-1, the value of the perpendicular distance, s, expressed in terms of the distance, r, and the angle, 2, is given by:

$$s = r \sin 2$$

therefore,

$$p_r^2 = p_s^2 \sin^4 2 \ .$$

Two reference points on the flight path, $\mathbf{P}_1$ and $\mathbf{P}_2$, are chosen (see Figure D-2). These reference points, arbitrarily located before and after the observer, define a segment of the flight path, having a length, L. To determine the fraction of noise associated with this segment, the noise exposure for the segment is computed, and then compared to the noise exposure for the entire flight path.

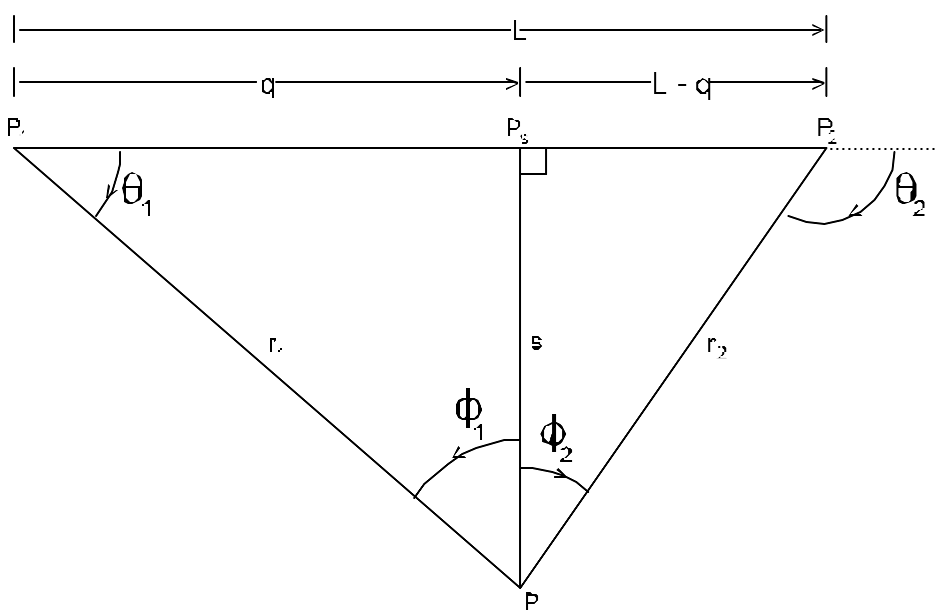

Figure D-2: Geometry for Generalized Noise Fraction Equation

The total sound exposure for the flight-path segment, E_{12}, defined by points $\mathbf{P}_1$ and $\mathbf{P}_2$, is the integral over time, τ, of the mean-square sound pressure p_r. E_{12} is computed as follows:

$$E_{12} = \int_{\tau_1}^{\tau_2} p_r^2 \, d\tau$$

From Figure D-1, E_{12} can be derived in terms of the angle, θ, using the relationship between the distance, q_r, the time, τ, and θ. The distance, q_r, as defined above, is computed using speed and time, as follows:

$$q_r = -v\,\tau$$

The perpendicular distance, s, is computed using q_r and θ, as follows:

$$s = q_r \tan\theta = -v\,\tau \tan\theta$$

The time, τ, is computed using s and the angle θ, as follows:

$$\tau = -(s / v) \cot\theta$$

$$d\tau = s\, d\theta / (v \sin^2\theta)$$

Assuming the speed along the flight-path segment, v, is constant, the total sound exposure associated with the segment defined by Points $\mathbf{P}_1$ and $\mathbf{P}_2$, in Figure D-2, is computed as follows:

$$E_{12} = \int_{\tau_1}^{\tau_2} p_r^2 \, d\tau$$

$$E_{12} = \int_{\theta_1}^{\theta_2} p_s^2 \sin^4\theta \,(s\, d\theta) / (v \sin^2\theta)$$

$$E_{12} = p_s^2 (s/v) \int_{\theta_1}^{\theta_2} \sin^2\theta \, d\theta$$

$$E_{12} = p_s^2 (s / 2v) \left[\theta_2 - \theta_1 + \sin(\theta_1 - \theta_2) \cos(\theta_1 + \theta_2) \right]$$

For an infinitely long flight path, with limits of $\theta = 0$ to π radians, E is computed as follows:

$$E = \pi \, (p_s^2 \, s / 2v).$$

Therefore, the noise fraction associated with the finite flight-path segment is computed by dividing E_{12} for the finite segment, by E for the infinite flight path, resulting in the following:

$$F_{12} = (1/\pi) \, [\, \theta_2 - \theta_1 + \sin(\theta_1 - \theta_2) \cos(\theta_1 + \theta_2) \,]$$

$$F_{12} = (1/\pi) \, (\, \theta_2 - \theta_1 + \sin\theta_1 \cos\theta_1 - \sin\theta_2 \cos\theta_2 \,)$$

where,

- θ_1 angle defined by: (1) the flight-path segment; and (2) a connecting segment from the observer to the start of the flight-path segment;
- θ_2 angle defined by: (1) the extended flight-path segment; and (2) a connecting segment from the observer to the end of the flight-path segment.

The above noise fraction, F_{12}, is the generalized noise fraction equation, expressed in terms of the angles θ_1 and θ_2, while in Section 3.4, F_{12} is presented in terms of the angles ϕ_1 and ϕ_2. To obtain the noise fraction in terms of the angles ϕ_1 and ϕ_2, Figures D-3 through D-5 are used to develop geometric relationships between the two sets of angles.

Figures D-3 through D-5 present the observer/flight-segment geometry for the three general INM cases: (1) the observer is behind the flight-path segment ($q < 0$); (2) the observer is astride the flight-path segment ($0 \le q \le L$); and (3) the observer is ahead of the flight-path segment ($q > L$).

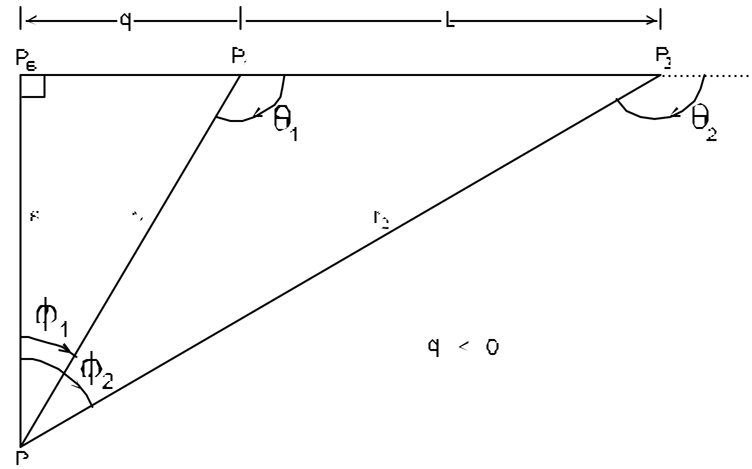

Figure D-3: Geometry for the Noise Fraction of an Observer Behind a Flight-Path Segment

In the case where the observer is behind the flight-path segment, PCPA is located on the extended flight-path segment at point $\mathbf{P}_s$ (see Figure D-3). The following relationships between the angles 2 and N are derived:

$$N_1 = 2_1 - B/2$$

$$2_1 = B/2 + N_1$$

$$N_2 = 2_2 - B/2$$

$$2_2 = B/2 + N_2$$

Substituting in the above relationships, the equation for the noise fraction, F_{12}, expressed in terms of the angle N, is given by the following:

$$F_{12} = (1/B)\,[2_2 - 2_1 + \sin(2_1 - 2_2)\cos(2_1 + 2_2)\,]$$

$$F_{12} = (1/B)\,[N_2 - N_1 - \sin(N_1 - N_2)\cos(N_1 + N_2)]$$

$$F_{12} = (1/B)\,(\,N_2 - N_1 + \sin N_2 \cos N_2 - \sin N_1 \cos N_1\,)$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment, i.e., CPA;

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment.

The angles N_1 and N_2 are defined as follows:

$$N_1 = \sin^{-1} * q / r_1 * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1} * (L-q) / r_2 * \qquad \text{(radians)}$$

In the case where the <u>observer is astride the flight-path segment</u>, PCPA is located on the flight-path segment at point $\mathbf{P}_s$ (see Figure D-4). The following relationships between the angles 2 and N are derived:

$$N_1 = B/2 - 2_1$$

$$2_1 = B/2 - N_1$$

$$N_2 = 2_2 - B/2$$

$$2_2 = B/2 + N_2$$

Substituting in the above relationships, the equation for the noise fraction, F_{12}, expressed in terms of the angle N, is given by the following:

$$F_{12} = (1/B)\,[\,2_2 - 2_1 + \sin(2_1 - 2_2)\cos(2_1 + 2_2)\,]$$

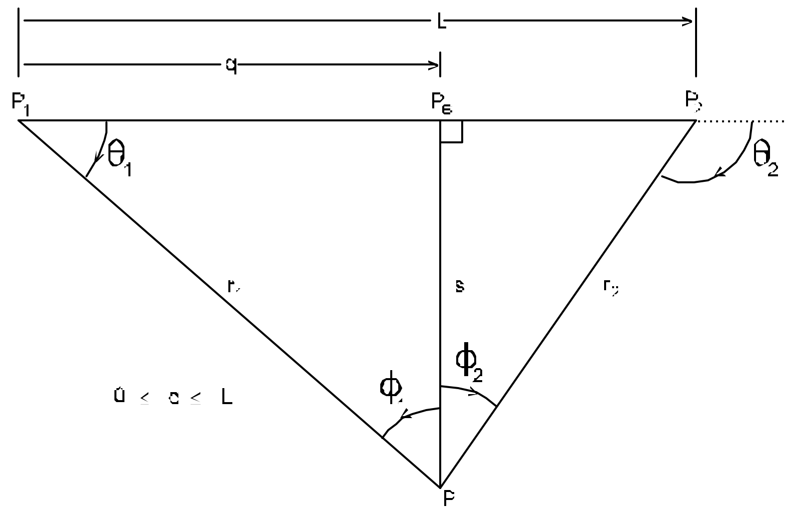

Figure D-4: Geometry for the Noise Fraction of an Observer Astride a Flight-Path Segment

$$F_{12} = (1/B)\,[\,N_1 + N_2 + \sin(N_1 + N_2)\cos(N_2 - N_1)\,]$$

$$F_{12} = (1/B)\,(\,N_1 + N_2 + \sin N_1 \cos N_1 + \sin N_2 \cos N_2\,)$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment;

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment.

The angles N_1 and N_2 are defined as follows:

$$N_1 = \sin^{-1} * q / r_1 * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1} * (L-q) / r_2 * \qquad \text{(radians)}$$

In the case where the observer is ahead of the flight-path segment, PCPA is located on the extended flight-path segment at point $\mathbf{P}_s$ (see Figure D-5). The following relationships between the angles 2 and N are derived:

$$N_1 = B/2 - 2_1$$

$$2_1 = B/2 - N_1$$

$$N_2 = B/2 - 2_2$$

$$2_2 = B/2 - N_2$$

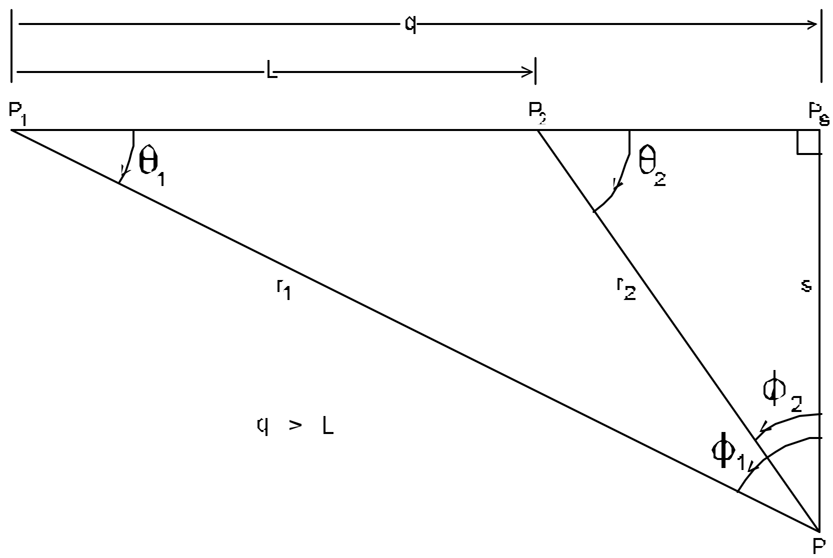

Figure D-5: Geometry for the Noise Fraction of an Observer Ahead of a Flight-Path Segment

Substituting in the above relationships, the equation for the noise fraction, F_{12}, expressed in terms of the angle N, is given by the following:

$$F_{12} = (1/B)\,[2_2 - 2_1 + \sin(2_1 - 2_2)\cos(2_1 + 2_2)\,]$$

$$F_{12} = (1/B)\,[N_1 - N_2 - \sin(N_2 - N_1)\cos(N_2 + N_1)\,]$$

$$F_{12} = (1/B)\,(N_1 - N_2 + \sin N_1 \cos N_1 - \sin N_2 \cos N_2)$$

where,

N_1 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the start of the flight-path segment;

N_2 angle defined by: (1) the segment connecting the observer to PCPA on the extended flight-path segment; and (2) the segment connecting the observer to the end of the flight-path segment, i.e., CPA.

The angles N_1 and N_2 are defined as follows:

$$N_1 = \sin^{-1} * q / r_1 * \qquad \text{(radians)}$$

$$N_2 = \sin^{-1} * (q-L) / r_2 * \qquad \text{(radians)}$$

Appendix E: DERIVATION OF TIME-ABOVE EQUATION

This Appendix presents a derivation of the time-above algorithm, which is used by INM 5.1 to compute the time, in minutes, that a user-specified noise-level threshold is exceeded at a given observer location. Like the noise fraction equation used in INM for exposure-based metrics, it is based on a fourth-power, 90-degree dipole model of sound radiation.

The following derivation of the time-above algorithm assumes that the aircraft proceeds along a straight flight path, parallel to the ground, and of infinite length. It also assumes that the observer, located at point **P**, is at a perpendicular distance, s, from the flight path. The geometry for this situation is shown in Figure E-1.

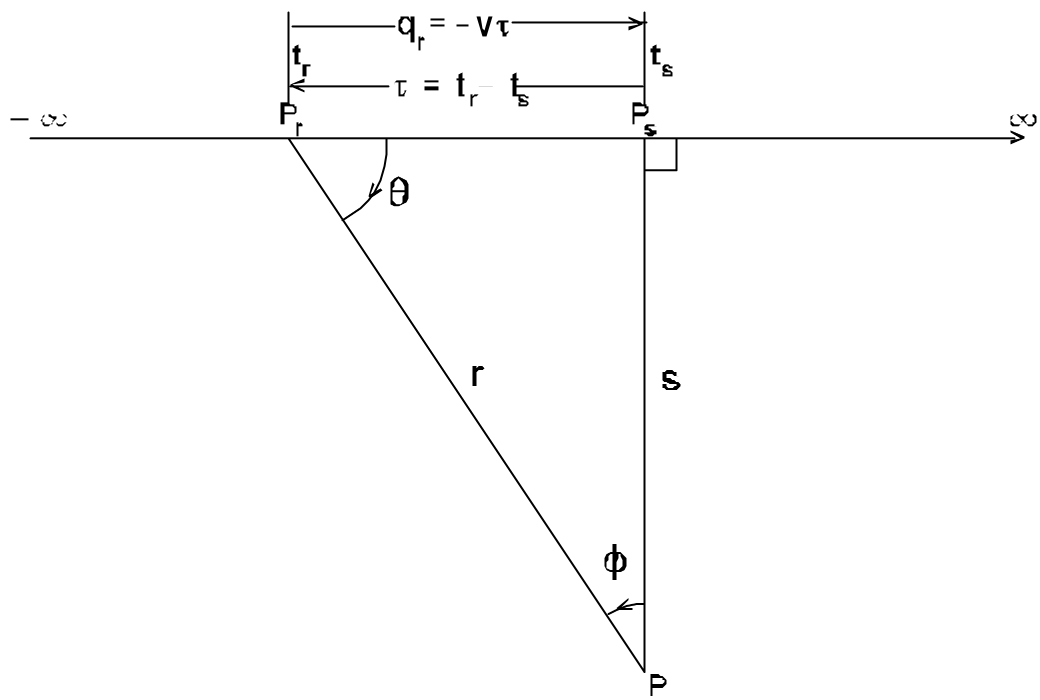

Figure E-1: Observer/Flight-Path Geometry

where,

r — distance from the observer at point **P**, to the aircraft at point $\mathbf{P}_r$ (ft);

s — perpendicular distance from the observer at point **P**, to PCPA at point $\mathbf{P}_s$ (ft);

q_r — relative distance along the flight path from the aircraft at point $\mathbf{P}_r$, to PCPA at point $\mathbf{P}_s$ (ft);

v true airspeed of the aircraft (ft/sec);

t_r time at which the aircraft is located at point $\mathbf{P}_r$ (seconds);

t_s time at which the aircraft is located at PCPA, point $\mathbf{P}_s$ (seconds);

τ the time difference, t_r minus t_s (seconds);

θ angle formed by the flight path and a connecting segment from the observer at point $\mathbf{P}$, to point $\mathbf{P}_r$;

p_r sound pressure generated by the aircraft at point $\mathbf{P}_r$; and

p_s sound pressure generated by the aircraft at point $\mathbf{P}_s$.

The relative distance along the flight path, q_r, from point $\mathbf{P}_r$ to point $\mathbf{P}_s$ is computed from the scalar product of two vectors: $\mathbf{P}_r\mathbf{P}$, from the aircraft to the observer; and the unit vector, $\mathbf{u}$, in the direction of the flight path. q_r is computed as follows:

$$q_r = \mathbf{P}_r\mathbf{P} \cdot \mathbf{u}$$

$$q_r = \mathbf{P}_r\mathbf{P} \cdot \mathbf{P}_r\mathbf{P}_s \,/\, |\mathbf{P}_r\mathbf{P}_s|$$

The value of q_r is positive if the aircraft, at point $\mathbf{P}_r$, is located prior to PCPA, while the value of q_r is negative if the aircraft is located beyond PCPA.

The relative distance, q_r, between points $\mathbf{P}_r$ and $\mathbf{P}_s$ on the flight path can also be expressed in terms of the true airspeed of the aircraft, v, and the time, τ, required for the aircraft to move from point $\mathbf{P}_r$ to $\mathbf{P}_s$. Ordinarily, the distance q_r would simply be the product of the speed, v, and the time, τ. However, this is not possible since τ is negative, and the distance, q_r, has by definition a positive value when the aircraft is located before PCPA. Therefore, the distance q_r is computed, in terms of speed and time, as follows:

$$q_r = -v\,\tau$$

The time-above algorithm, similar to the noise fraction algorithm, is derived from a 4th-power, 90-degree dipole time history model. In this model, p_r^2 is the mean-square sound pressure at the observer due to the aircraft, located at point $\mathbf{P}_r$; and p_s^2 is the mean-square sound pressure at the observer due to the aircraft, located at PCPA, point $\mathbf{P}_s$. The mean-square pressure, p_r^2, at the observer is expressed in terms of the mean-square pressure, p_s^2, at the observer, through the following equation:

$$p_r^2 = p_s^2 \,(s^2 / r^2)\, \sin^2\theta$$

As was discussed in Appendix D, this equation accounts for a variety of physical phenomena which effect aircraft noise generation, and represents a best fit to empirical time-history data.

From the geometry in Figure E-1, the value of the distance, r, expressed in terms of the perpendicular distance, s, and the distance, q_r, is given by:

$$r^2 = s^2 + q_r^2$$

$$r^2 = s^2 + (-v\tau)^2$$

Also,

$$\sin\theta = s / r$$

Therefore, the mean-squared pressure ratio, p_r^2/p_s^2, is given by:

$$p_r^2/p_s^2 = (s^2 / r^2) \sin^2\theta$$

$$p_r^2/p_s^2 = s^4 / r^4$$

$$p_r^2/p_s^2 = s^4 / [s^2 + (v\tau)^2]^2$$

$$p_r^2/p_s^2 = 1 / [1 + (v\tau/s)^2]^2$$

The sound exposure over the entire flight path, E, is computed as follows:

$$E = \int_{-\infty}^{\infty} p_r^2 \, d\tau = p_s^2 \int_{-\infty}^{\infty} (p_r^2 / p_s^2) \, d\tau$$

$$E = p_s^2 \int_{-\infty}^{\infty} d\tau / [1 + (v\tau/s)^2]^2$$

$$E = (2s/v) \, p_s^2 \int_{0}^{\infty} d(v\tau/s) / [1 + (v\tau/s)^2]^2$$

$$E = (½ \pi s/v) \, p_s^2$$

The effective time duration of the event, Δt_e, is defined as the factor (½ π s/v), which multiplies p_s^2. Thus, the mean-squared pressure ratio, p_r^2/p_s^2, can be written in terms of the effective time duration:

$$p_r^2/p_s^2 = 1 / [1 + (½ \pi \tau / \Delta t_e)^2]^2$$

The sound exposure level that is associated with the flight path is defined as follows:

$$L_{exp} = 10 \log_{10}[E / E_o] \qquad \text{(dB)}$$

$$L_{exp} = 10 \log_{10}[(p_s^2 \Delta t_e) / (p_o^2 t_o)] \qquad (p_o = 20 \ \mu\text{Pa}, t_o = 1\text{s or } 10\text{s})$$

$$L_{exp} = 10 \log_{10} (p_s/p_o)^2 + 10 \log_{10} ()\, t_e/t_o)$$

$$L_{exp} = L_{max} + 10 \log_{10} ()\, t_e/t_o)$$

Therefore, the effective time, $)\, t_e$, can be computed in terms of the sound exposure level and the maximum noise level by:

$$)\, t_e = t_o\, 10^{\,(Lexp\ -\ Lmax)/10}$$

where,

t_o constant value of 1 second for L_{AE}, or 10 seconds for L_{EPN};

L_{exp} sound exposure level, either L_{AE} or L_{EPN}, for a given aircraft and observer/flight-path pair (dB);

L_{max} maximum noise level, either L_{ASmx} or L_{PNTSmx}, for a given aircraft and observer/flight-path pair (dB).

From Figure E-2, the following definitions apply:

p_x root-mean-square pressure due to the aircraft at point $\mathbf{P}_X$;

L_x user-specified noise-level threshold;

q_x relative distance along the flight path from point $\mathbf{P}_X$ to point $\mathbf{P}_S$, i.e, the point on the flight path assumed to be associated with the maximum noise level;

J magnitude of the time difference between time t_x and time t_s.

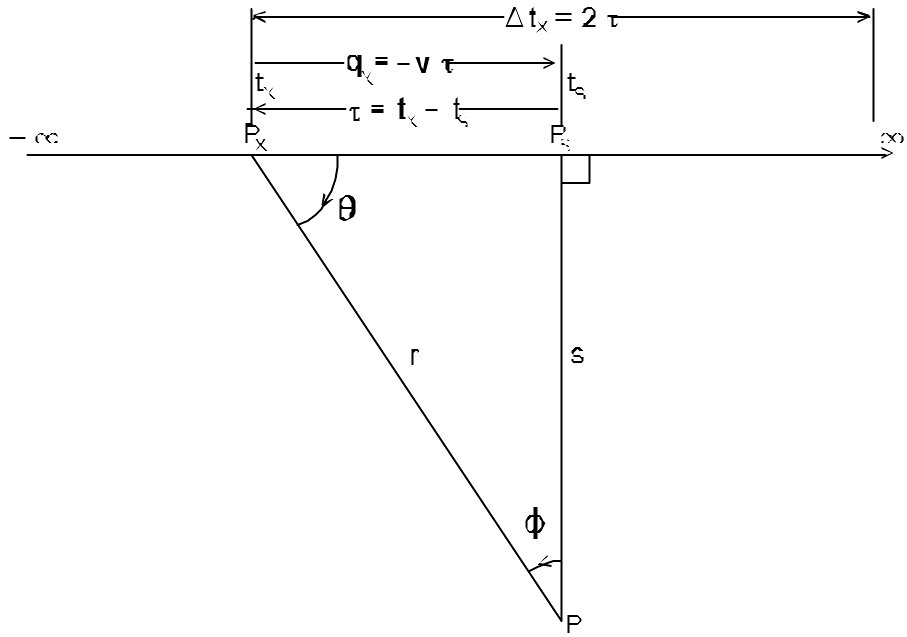

Figure E-2: Time-Above for an Observer Opposite a Flight Path

The time, $)t_x$, during which the noise level at any point on the flight path exceeds the noise-level threshold, L_x, is the time required to move twice the distance, q_x, from point P_X to point P_S, or twice the value of J; thus:

$$J =)t_x / 2$$

From above, the mean-squared pressure ratio at any point $\mathbf{P}_r$ on the flight path, using the 90-degree-dipole time-history model is given as:

$$p_r^2/p_s^2 = 1 / [\ 1 + (\ ½\ B\ J\ /\ )t_e)^2\ ]^2$$

The mean-squared pressure ratio at the noise-level threshold point, $\mathbf{P}_X$, is then computed by substituting p_x for p_r and $)t_x /2$ for J into the equation, resulting in:

$$p_x^2/p_s^2 = 1 / [\ 1 + (\ ¼\ B\ )t_x\ /\ )t_e)^2\ ]^2$$

After solving for the time-above, $)t_x$, the following equation is obtained:

$$)t_x = (4/B)\ )t_e\ (\ p_s/p_x - 1\ )^{½}$$

Since the following definitions apply, $L_{max} = 20 \log_{10}[p_s /p_o]$ and $L_x = 20 \log_{10}[p_x /p_o]$, the root-mean-squared pressure ratio can be written as:

$$p_s/p_x = 10^{(\ Lmax\ -\ Lx\ )\ /\ 20}$$

Therefore,

$$) t_x = (4/B) \;) t_e (10^{(Lmax - Lx)/20} - 1)^{½} \qquad (L_x < L_{max})$$

Since the effective time is $) t_e = t_o \, 10^{(Lexp - Lmax)/10}$, the time-above a user-specified noise level in minutes, $) t_{x,min}$, is computed as follows:

$$) t_{x,min} = (4/B) \, t_o \, 10^{(Lexp - Lmax)/10} (10^{(Lmax - Lx)/20} - 1)^{½} / 60 \qquad \text{(minutes)}$$

where,

t_o constant value of 1 second for L_{AE}, or 10 seconds for L_{EPN}.

L_{exp} sound exposure level, either L_{AE} or L_{EPN}, for a given aircraft and observer/flight-path pair (dB);

L_{max} maximum noise level, either L_{ASmx} or L_{PNTSmx}, for a given aircraft and observer/flight-path pair (dB);

L_x user-specified noise-level threshold, expressed in either A-weighted sound level or tone-corrected perceived noise level (dB).

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