BBN Report No. 8257

STUDY OF THE LEVELS, ANNOYANCE AND POTENTIAL MITIGATION OF BACKBLAST NOISE AT SAN FRANCISCO INTERNATIONAL AIRPORT

KARL PEARSONS, SANFORD FIDELL, LAURA SILVATI,
MATTHEW SNEDDON, AND RICHARD HOWE

19 January 2000

Prepared by:

BBN TECHNOLOGIES
A Unit of GTE Internetworking
21128 Vanowen Street
Canoga Park, California 91303-2853

Prepared for:

CITY AND COUNTY OF SAN FRANCISCO
Noise Abatement Office
San Francisco International Airport
P.O. Box 8097
San Francisco, California 94128

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENTS

This report was prepared under contract between San Francisco International Airport (SFO) and BBN Technologies. Mr. Wayne Bryant of SFO's Noise Abatement Office oversaw the conduct of this study, in consultation with Messrs. David Carbone, Roger Chinn, Walter Gilfillan, and Pat Kelly. Information and text contained in Section 5 are based upon measurements and analyses performed by Messrs. Stephen Martin and Ronald Brown, under subcontract between BBN Technologies and Wyle Laboratories.

The authors are grateful to the staff of SFO's Noise Abatement Office, and to the staff of the Airport/Community Roundtable for providing background information; to Mr. Mark Hinds for permission to include in this report information developed under the sponsorship of the City of Richfield, MN; to Mss. Mary Westheimer and Elizabeth Fujimoto for assistance in data collection; to Mr. Daniel Flynn for making his house available for data recordings; and to the test subjects for their diligent participation in the annoyance judgment study.

1 INTRODUCTION AND SUMMARY OF FINDINGS

This report describes the initial phase of a study of the levels, annoyance and potential mitigation of aircraft departure ("backblast") noise at San Francisco International Airport (SFO). The effort reported here was intended to quantify low-frequency aircraft noise levels and complaint densities in specific neighborhoods, and to determine the relative annoyance of backblast and overflight noise. Information of this sort is needed to develop recommendations for potential treatments of residences to mitigate low-frequency aircraft noise impacts.

This report contains information derived from (1) an analysis of noise complaints from residential areas behind Runways 01 L/R; (2) field measurements of low-frequency aircraft noise; and (3) a laboratory study of the annoyance of low-frequency aircraft noise. These findings are expected to help define design measures for a subsequent low-frequency noise mitigation demonstration.

The major conclusions that may be drawn from this study include the following:

- Backblast noise is a readily measurable concentration of low-frequency noise created by individual aircraft departures in areas behind Runways 01L/R at SFO.

- The density of aircraft noise complaints in residential areas to the southwest of Runways 01L/R is greatest in two areas of Millbrae, Burlingame, and Hillsborough located roughly two miles from the start of takeoff roll.

- Although these two areas lie well outside of SFO's 65 dB CNEL contour, their locations are consistent with high noise levels associated with the directivity of jet engine exhaust noise.

- Meteorological conditions may be responsible for inducing considerable variability (at least ± 5 dB) in low-frequency aircraft departure noise level and duration in areas of Millbrae, Burlingame, and Hillsborough. Therefore, reliable prediction of times of day and seasons of the year when backblast noise is likely to be particularly high in level requires very detailed information about atmospheric conditions.

- C-weighted sound levels of individual aircraft departures measured in these two areas often exceed 80 dB, and can occasionally reach levels in the high 90 dB range, depending on aircraft type and other factors.

- Low-frequency sound levels corresponding to these C-weighted levels vary from about 70 to 90 dB in the one-third octave bands from 25 to 80 Hz.

- Instances of backblast noise associated with individual departures can be of unusually long duration with respect to typical aircraft overflight noise.

- When judged equally annoying, longer-duration, backblast-like sounds are lower in level than shorter-duration sounds by 3 dB per doubling of duration throughout the range of durations from 15-120 seconds. This finding confirms the need to keep in mind a 10 log (duration) correction in planning measures intended to mitigate the annoyance of backblast noise.

- The annoyance of backblast is heightened by its duration and potentially by the production of rattle in homes.

- When judged equally annoying, the maximum A-weighted sound levels of backblast noises lasting two minutes or more are 5 to 7 dB lower than those of typical aircraft overflights.

2 BACKGROUND AND LITERATURE REVIEW

2.1 REVIEW OF STUDIES OF BACKBLAST NOISE AT SFO

SFO and the cities of Burlingame, Hillsborough, and Millbrae have longstanding concerns with low-frequency noise created by aircraft departures from Runways 01 L/R at SFO. Prior studies of low-frequency aircraft noise at SFO have focused on physical measurements of A- and C-weighted noise levels behind Runways 01 L/R (Caltrans, 1984; Connor, 1986; Kesterson, Vondemkamp, and Connor, 1987), and on secondary analyses and interpretations of these measurements (HMMH, 1996b). According to Gilfillan (1999), formal concern about low-frequency aircraft noise in communities near SFO can be traced to the 1970s. Chapter V of a Joint Action Plan developed under a 1980 Joint Land Use Study contained a list of unresolved issues, of which one was "What alternatives to the A-weighted decibel scale could be used to measure the effects of low-frequency noise events?"

A set of low-frequency noise measurements was an initial step taken by Caltrans to address this issue in 1984 (Caltrans, 1984). This data set, presented to the Airport/Community Roundtable in four volumes without evaluation, narrative of findings, or conclusions, was reviewed by the Roundtable's consultant in 1985. Nighttime B-727 operations on Runways 01 L/R were identified as a prominent source of low-frequency aircraft noise in the community. As part of a 1986 settlement agreement arising from noise nuisance litigation, SFO agreed to conduct and report a set of "full spectrum" (including low-frequency) aircraft noise measurements in neighborhoods behind Runways 01L/R.

Measurements made by Tracor at several of SFO's permanent noise monitoring stations in 1986 and 1987 (Connor, 1986; Kesterson, Vondemkamp, and Connor, 1987) were analyzed to assess how the low-frequency content of aircraft departure noise affected the accuracy of aircraft noise measurements behind Runways 01L/R, and the appropriateness of A-weighted (as opposed to C-weighted) measurements for characterizing aircraft departure noise. Tracor concluded that "The sound of some aircraft departures from Runways 1L and 1R has a character distinct from that of ordinary aircraft noise in that it has relatively more low-frequency content and longer duration." Tracor also noted that B-727 and B-737 departures were the predominant source of aircraft noise in areas behind Runways 01L/R, and that CNEL values in the area behind Runways 01L/R were adequately measured.

A Memorandum of Understanding concerning aircraft noise mitigation, based on the Environmental Impact Report of SFO's 1992 Airport Master Plan, was adopted in 1993. One item identified in the Joint Work Plan (Item C.3.(c)) of this document addressed the reduction of backblast noise. When Caltrans included the Roundtable Work Plan as a condition of SFO's 1993 noise variance, conduct of a demonstration house project became one condition of this variance.

SFO and the Roundtable commissioned another review of the 1986/87 Tracor information. Completed in 1996 (HMMH, 1996b), this review identified a C-weighted single-event noise descriptor (a maximum C-weighted sound level of 80 dB) as a reasonable criterion for identifying aircraft departure noise with vibration-producing potential. Arrangements for the conduct of the current project began in 1996, when SFO issued a Request for Proposals to establish the location of a demonstration house and plans for empirical study of low-frequency noise mitigation measures.

2.2 RECENT STUDIES OF LOW-FREQUENCY AIRCRAFT NOISE EFFECTS ELSEWHERE

Recent studies of the effects of low-frequency aircraft noise (not necessarily associated with start of takeoff roll noise) in the United States have been conducted near airports in Baltimore, Boston, and Minneapolis.

2.2.1 Study of Low-Frequency Takeoff Noise at Baltimore-Washington International Airport (BWI)

Miller, Reindel, Senzig, and Horonjeff (1998) report measurements of aircraft departure sound levels in single family detached housing located about half a mile from the end of a busy departure runway at BWI. The homes in question were within BWI's 65 dB DNL aircraft noise contour. They also report an analysis of a single resident's annoyance ratings of a limited number of aircraft departures. Shade (1997) conducted analyses of low-frequency noise reduction improvements in two houses exposed to start of takeoff roll noise on BWI's Runway 28 that were treated to increase C-weighted noise reduction. These measurements and analyses, complemented by an "Engineer's Report" for residential sound insulation, provided the documentary basis for a decision by FAA to participate in funding sound insulation treatments beyond those required to produce a 5 dB A-weighted improvement in noise reduction.

2.2.2 Measurements of Low-Frequency Noise Emissions of Stage II and Stage III Aircraft at Logan International Airport (BOS)

Horonjeff and Thompson (1996) describe a study focused on measurement and analysis of "low-frequency rumble produced by jet aircraft operations at Boston's Logan International Airport." Their analyses indicate (*inter alia*) little difference in the very low-frequency (below 40 Hz) noise emissions of Stage II and Stage III aircraft, and no reduction in thrust reverser noise for a Stage III aircraft fleet *vs*. a Stage II fleet. Horonjeff and Thompson also noted that even unusually thorough acoustic treatments of homes (*i.e.*, super-insulation of a single room-within-a-room) failed to yield an increase in noise reduction of more than 8 to 9 decibels at frequencies below 100 Hz.

2.2.3 Study of Annoyance of Low-Frequency Noise near Los Angeles International Airport

Fidell, Silvati, Pearsons, Lind, and Howe (1999) describe a social survey of the annoyance of rattle and vibration associated with runway sideline noise.[1] Interviews were completed with 644 respondents living in households with LFSL[2] values between 60 and 95 dB in a neighborhood immediately south of Los Angeles International Airport.

Figures 1 through 3 summarize major findings of this study. Figure 1 shows how often respondents noticed rattle produced by aircraft operations. Figure 2 identifies the sources of rattling sounds in the respondents' homes. Figure 3 compares the percentage of respondents who noticed rattle, were annoyed in any degree by rattle, and were highly annoyed by rattle, as a function of outdoor low-frequency sound levels.

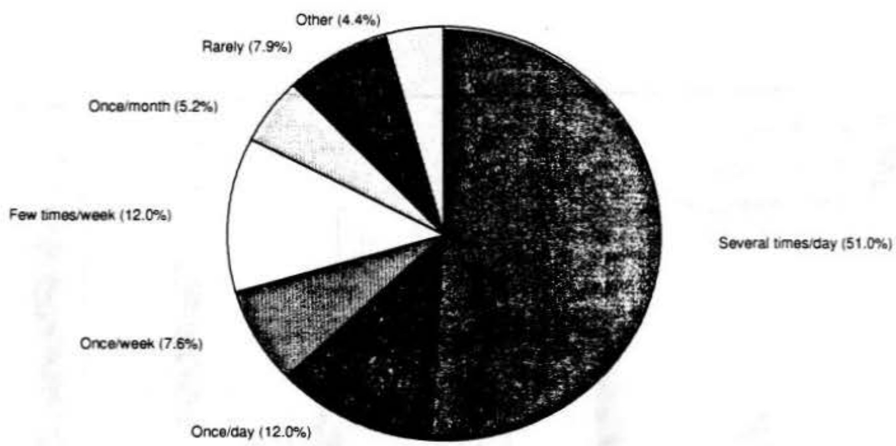


Figure 1 Frequency of notice of rattling sounds in respondents' homes.

[1] Noise created along runway sidelines has proportionally more low-frequency content than noise produced by overflights, but differs in character from backblast noise in ways discussed in Section 3.

[2] LFSL is the abbreviation for Low-Frequency Sound Level, a descriptor of low-frequency aircraft noise described by Fidell, Silvati, Pearsons Lind and Howe (1999). LFSL is a single-event noise metric that sums the maximum one-third octave band sound levels from 25 to 80 Hz, inclusive, that occur during the course of an individual aircraft passby.

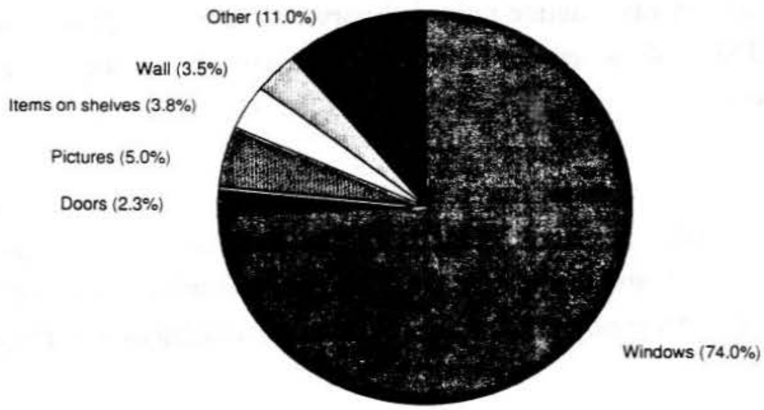


Figure 2 Identification of sources of rattling noises in respondents' homes.

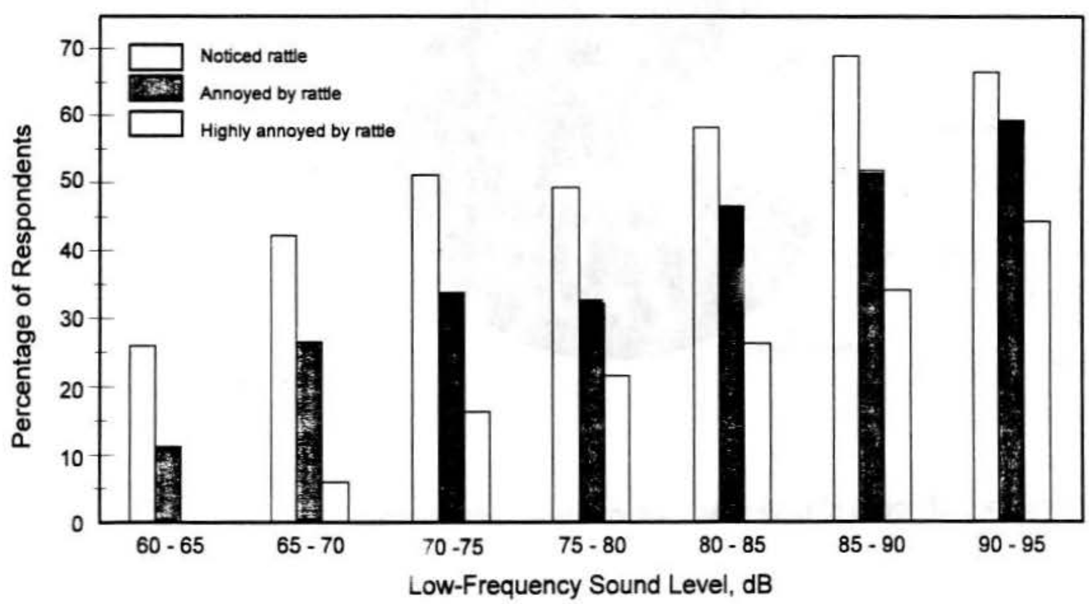


Figure 3 Comparison of percentages of respondents noticing rattle, annoyed in any degree by rattle, and highly annoyed by rattle associated with low-frequency noise

2.2.4 Study of Annoyance of Low-Frequency Noise near Wold-Chamberlain Field in Minneapolis (MSP)

Fidell, Silvati, and Pearsons (1999) have recently completed a social survey of the annoyance of rattle and vibration due to low-frequency aircraft noise in the vicinity of MSP.[3] The major goal of the study was to document the prevalence of annoyance due to aircraft noise-induced rattle among residents exposed to runway sideline noise at MSP. It was found that the prevalence of annoyance due to aircraft noise-induced rattle was similar to that described above at LAX for similar low-frequency sound levels; that similar objects were cited as sources of rattle in the two studies; and that the frequencies of occurrence of rattle were comparable among respondents to the MSP and LAX surveys. Figure 4 displays the prevalence of annoyance among respondents living in households with similar LFSL values at both LAX and MSP.

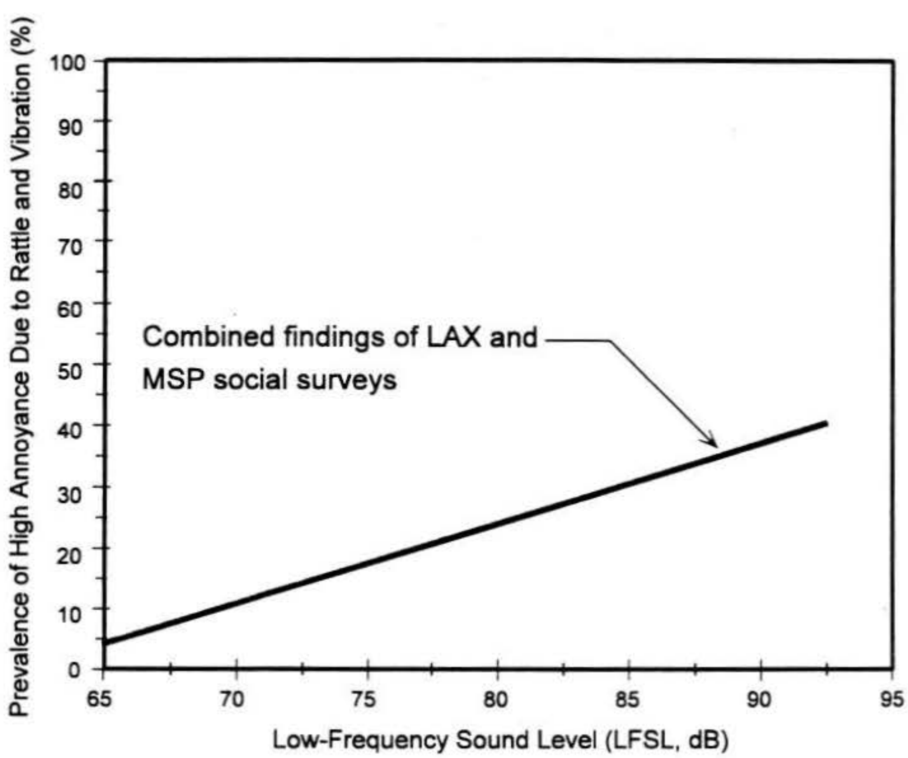


Figure 4 Relationship between LFSL values and the prevalence of a consequential degree of annoyance in combined findings of LAX and MSP social surveys.

[3] This study was conducted as part of an extensive set of measurements and analyses stemming from an agreement between the City of Richfield, MN and the Metropolitan Airports Commission. The findings of the study described here are not those of the entire process.

3 TECHNICAL DISCUSSION

This section contains a general discussion of the nature of low-frequency aircraft noise. The reader's attention is directed to the Glossary for definitions of terms.

3.1 GENERAL CHARACTERISTICS OF AIRCRAFT NOISE AS HEARD NEAR AIRPORTS

The character of aircraft noise heard in communities near airports varies considerably with location relative to runways in sound level, frequency content, onset and decay rates, duration, and distinctiveness. Table 1 summarizes the general characteristics of overflight, sideline, and departure noise. Figure 5 illustrates the areas in which these types of aircraft noise predominate. In addition to differences between the noise emissions of different aircraft types, factors that affect the character of aircraft noise as heard in different locations include the flight regime and directivity of aircraft noise emissions, the geometry of the aircraft's flight path with respect to an observer, the slant range between the aircraft and the observer, and the path(s) by which aircraft noise reaches the observer.

Table 1 Summary of general characteristics of overflight, sideline, and departure noise. (Specific location with respect to runway influences all characteristics.)

	TYPE OF AIRCRAFT NOISE		
Factor	**Overflight**	**Sideline**	**Departure**
Frequency content	Broadband, dominated by mid frequencies	Greater low-frequency content than overflights	Little or no high-frequency content
Duration	15 - 30 seconds	30 - 60 seconds	60 - 120 seconds
Onset rate	5- 15 dB/second	5 - 15 dB/second	Relatively slow
Decay rate	5 - 15 dB/second	Strong function of distance	Very slow decay rate
Time history	Roughly symmetric "haystack", usually with clear 10 dB-down points	Often skewed toward greater duration after peak	Multiple peaks common; 10 dB-down points may be difficult to discern
Maximum level	Generally greatest	Intermediate	Generally lowest

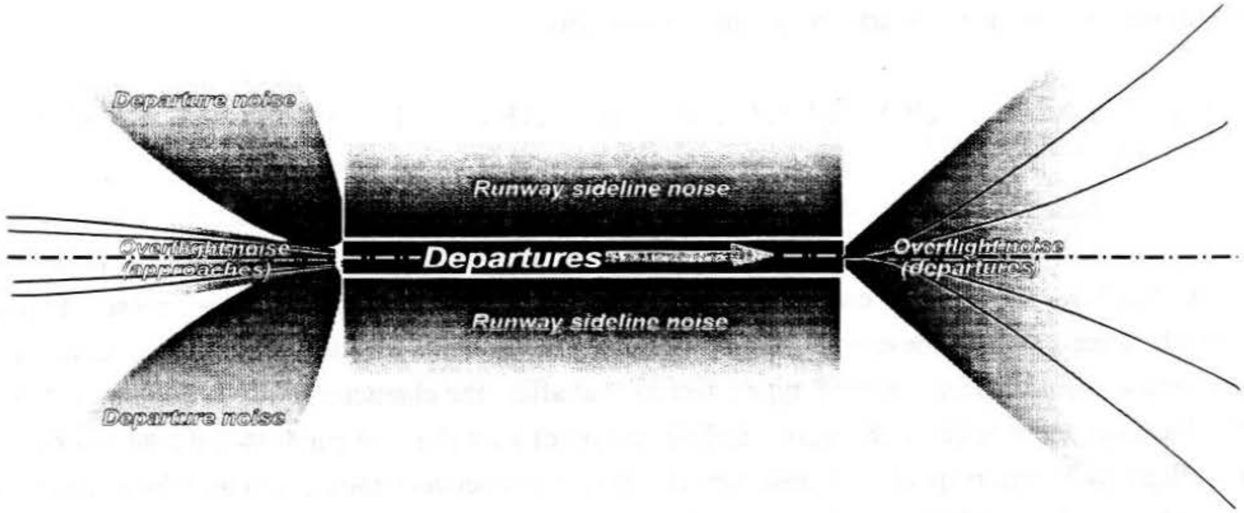


Figure 5 Identification of areas near runways in which sideline, departure, and overflight noise predominate.

3.2 CHARACTERISTICS OF AIRCRAFT DEPARTURE NOISE

Figure 6 shows the time history of an aircraft departure from Runway 01R at SFO of the sort that produces prominent low-frequency noise, as measured at a point 1.5 km behind the start of takeoff roll. The passage of time is represented from left to right on the horizontal axis, while A- and C-weighted sound levels are shown on the vertical axis. As the aircraft begins its takeoff roll, its sound level rises from the ambient noise level (roughly 50 dB A-weighted/62 dB C-weighted) to an initial maximum value (about 75 dB A-weighted/nearly 90 dB C-weighted) after about 20 seconds. As the aircraft's takeoff roll continues, its level slowly declines until about a minute after the start of takeoff roll. After the aircraft becomes airborne, its sound level gradually increases in level to a second peak at about a minute and forty five seconds after the start of takeoff roll, after which it gradually reverts to the ambient level.

Figure 7 illustrates the distribution in frequency of the acoustic energy of the overflight on the same time scale as Figure 6. Rather than expressing sound levels in A-weighted or C-weighted units as in Figure 6, the vertical axis of Figure 7 shows sound levels in individual one-third octave bands. Reds, oranges and yellows represent higher sound levels, while blues and greens represent lower sound levels. Thus, the brightest red and yellow colors, marking the highest sound levels at frequencies in bands from about 63 to 200 Hz, occur both at the time of the initial and second peaks in Figure 6.

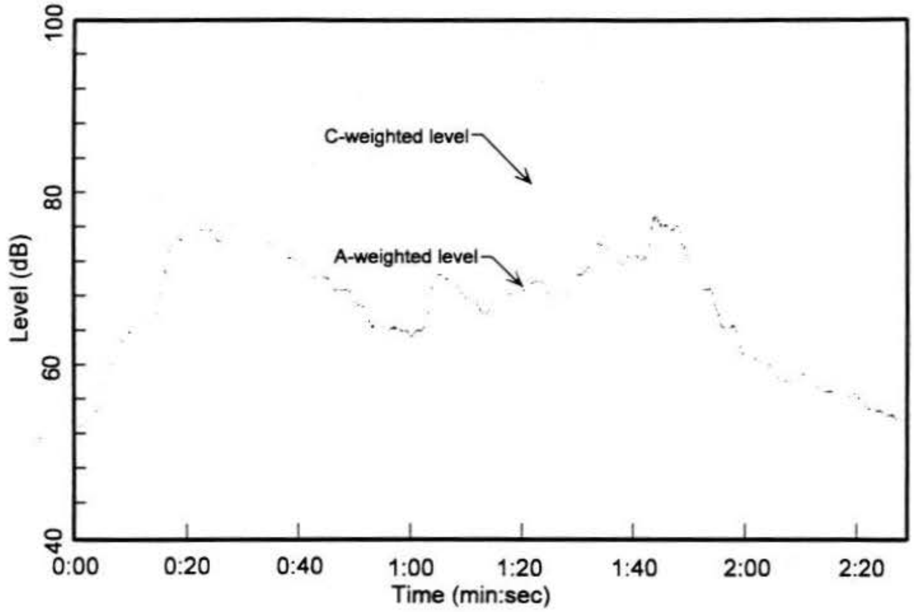


Figure 6 A- and C-weighted time histories of aircraft departure as heard approximately 1.5 km behind SFO Runway 01R.

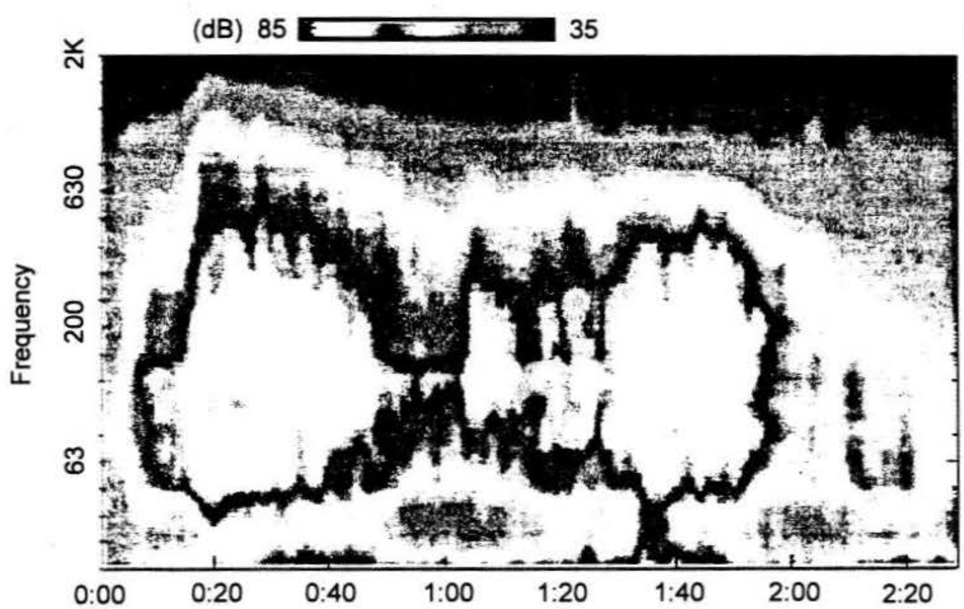


Figure 7 Spectrogram of aircraft departure at a point approximately 1.5 km behind San Francisco International Airport Runway 01R.

4 COMPLAINT ANALYSIS

Digital files containing information about telephone calls received by SFO's noise complaint telephone service for the years 1992 through 1998 were made available by SFO for analysis. These files were processed to yield monthly statistics for numbers of complainants and numbers of complaints per complainant. The latitude and longitude of each complainant's street address were also established. Figure 8 is a summary of geographic complaint patterns for Millbrae, Burlingame and Hillsborough. The figure was prepared from combined monthly numbers of complaints and of complainants. Data for each month of the year were aggregated over the entire time period (1992-1998), as shown in Table 2.

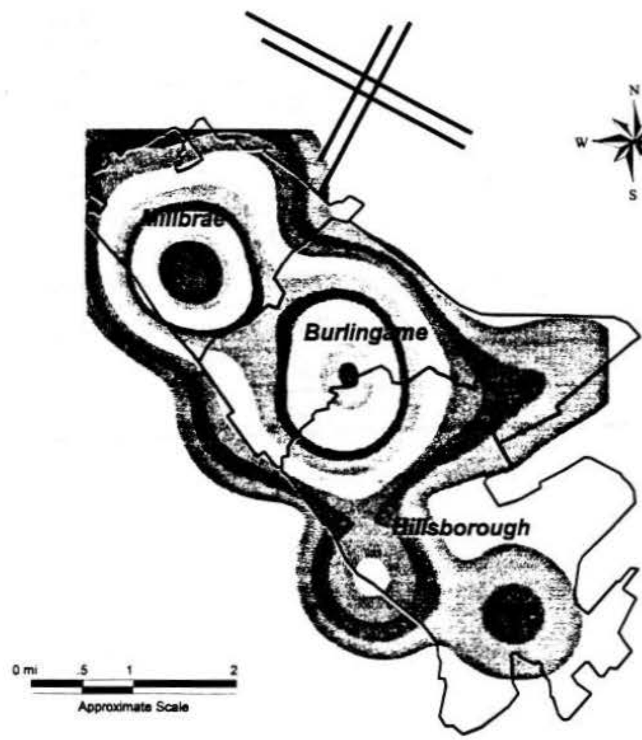


Figure 8 Aircraft noise complaint density for the Millbrae/Burlingame/Hillsborough areas, 1992-1998.

The color coding in Figure 8 represents complaint densities over the entire time period. The yellow, orange, and red areas encompass values from a low of 896 complaints to a high of 1,344 complaints per square mile. The greens and lighter blues represent a low of 448 complaints to a high of less than 896 complaints per square mile. The darker blue and magenta represent areas with ranges of complaints from 2 through 448 complaints per square mile.

Two concentrations of complaints are readily apparent, located approximately 45° to the side of the extended centerline of Runways 01L/R. These locations correspond closely to the lobes of the directivity pattern of jet engine exhaust noise of aircraft departing on Runways 01 L/R. Although the relative numbers of complaints in each lobe vary somewhat from month to month, the gross geographic pattern of complaints remains consistent in Millbrae, Burlingame and Hillsborough through all seasons of the year.

Table 2 Summary of aggregated complaint data.

MONTH	NUMBER OF YEARS	NUMBER OF COMPLAINTS	NUMBER OF COMPLAINANTS
January	6	2,436	804
February	6	2,629	803
March	6	2,695	814
April	6	2,106	639
May	6	2,609	776
June	5	2,004	721
July	5	1,897	637
August	6	2,361	854
September	7	2,782	906
October	7	3,005	971
November	6	1,944	605
December	6	2,278	789

5 FIELD MEASUREMENTS OF BACKBLAST NOISE

This section describes field measurements made by Wyle Laboratories.

5.1 SCHEDULE OF FIELD MEASUREMENTS

Two sets of acoustic measurements were made in an area southwest of SFO. The first set of measurements was made between 8 and 11 June, 1999, while the second set was made from 23 to 27 August, 1999. A- and C-weighted sound level event data and hourly interval noise level measurements were collected at six measurement sites during the two periods. Broadband noise levels were recorded at four of the sites.

The field instrumentation included Larson·Davis LD820, LD 870, and LD700 integrating sound level meters, and Tascam and Sony digital audio tape recorders. The sound level meters met the requirements for Type I sound level meters as defined in ANSI S1.4, 1983 except for three Type II LD700 instruments used during the first measurements to monitor C-weighted sound level event data and hourly noise levels.

5.2 MEASUREMENT SITES

Two primary sites were selected near the centroid of areas where large numbers of complaints had been received by the airport. These two sites were designated as sites 3A and 3B. Other sites were chosen along a line between the primary sites and the south end of Runway 01. Two of these locations were selected near the runway, while the other two sites were selected near the midpoint of the line between the runway and the primary site. The locations are identified on the map of Figure 9 as sites 1A, 1B, 2A, 2B, 3A, and 3B. The site locations are also listed in Table 3. The locations of sites 1B and 3A were moved a short distance during the second measurement period, as homeowners at sites 1B and 3A were not available during the second period.

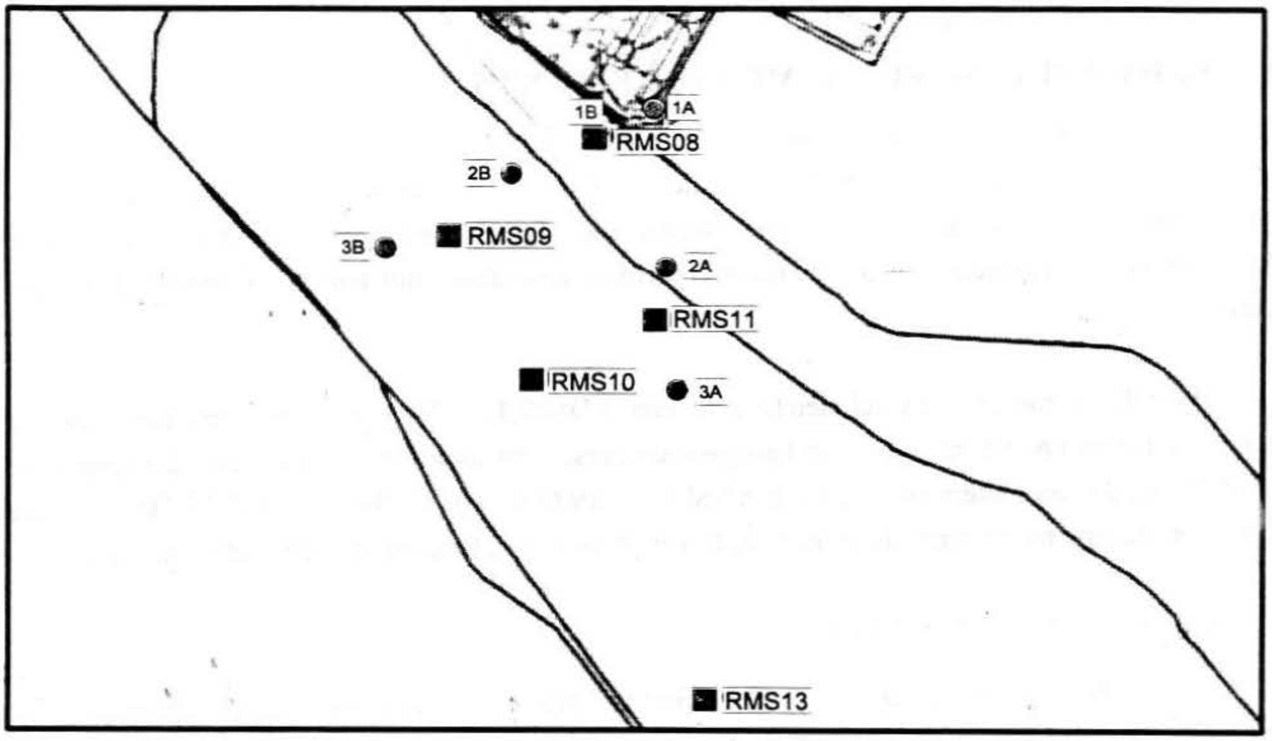


Figure 9 Locations of sites at which measurements were made from 8-11 June and from 23-27 August 1999, and of SFO's nearby remote noise monitoring sites.

Table 3 Addresses of measurement sites.

SITE	ADDRESS	LATITUDE	LONGITUDE
1A	San Francisco International Airport	37° 38.729' N	122° 22.767' W
1B	191 Aviador, Millbrae (first measurement period) 307 Roblar, Millbrae (second measurement period)	37° 36.163' N 37° 36.186' N	122° 23.073' W 122° 23.096' W
2A	1128 Hamilton, Burlingame	37° 35.527' N	122° 22.527' W
2B	254 La Cruz, Millbrae	37° 35.996' N	122° 23.617' W
3A	2116 Hillside, Burlingame (first measurement period) 2114 Hillside, Burlingame (second measurement period)	37° 34.995' N 37° 34.970' N	122° 22.560' W 122° 22.560' W
3B	1177 Hillcrest, Millbrae	37° 35.627' N	122° 24.294' W

5.3 MEASUREMENT PROCEDURES

Microphones with windscreens were mounted on tripods at a height of 4 feet. Associated instrumentation was placed in nearby environmental enclosures. Microphones were positioned more than 6 feet from building facades, and in most cases at distances greater than 10 feet. Noise level thresholds for event data were set approximately 5 dB above ambient levels.

A signal splitter placed at the output of the microphone preamplifier routed the signal to the integrating sound level meter and to the input of the digital audio tape recorder, as shown in Figure 10. The sound level meter was calibrated and the 114 dB calibrator signal was recorded at the beginning of the digital tape. The recorded calibration signal was used during the analysis to provide the spectrum analyzer with a reference for normalizing the recorded data to the proper sensitivity and to yield absolute sound levels. All of the instrumentation systems were battery powered except at the primary measurement sites (3A and 3B), where electrical power was available from the residences.

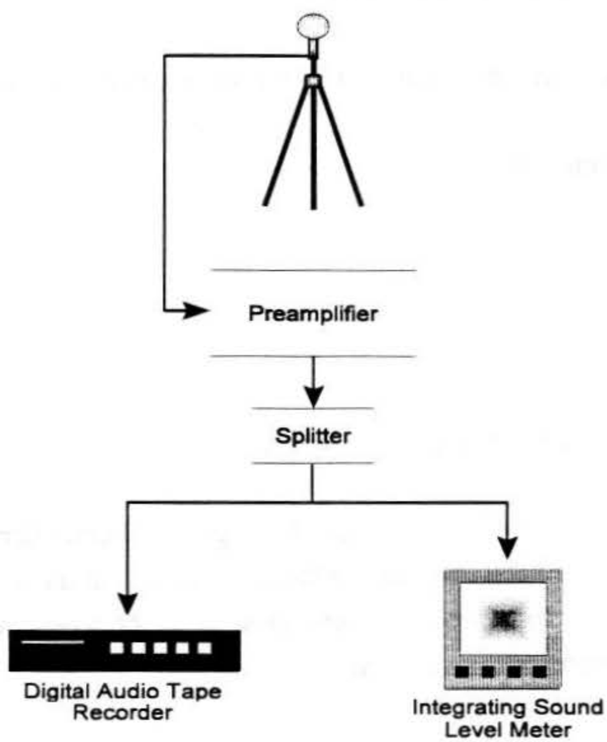


Figure 10 Schematic of field measurement instrumentation.

5.4 NATURE OF MEASUREMENTS MADE

5.4.1 Sound Level Measurements

One of the sound level meters at each site was configured to store A-weighted sound level events and hourly interval data, while another meter stored C-weighted sound level events and hourly interval data. The noise level measurements were compared to background noise levels and to aircraft noise levels obtained from analysis of the recorded data and information collected by airport noise monitoring stations.

The event information collected included the following:

- Date and time
- Maximum level
- Sound Exposure Level (SEL)
- Duration (for time above the threshold)

The following parameters were stored and analyzed for each of the hourly interval data:

- Date and hour of the day
- Hourly L_{eq}
- Maximum level
- Statistical levels (L_1, L_{10}, L_{33}, L_{50}, L_{90}, and L_{99})

The noise event data collected at various sites for a given aircraft departure operation were not precisely synchronized, since most of the instruments store the time that the sound level of an event first crosses the noise level threshold. Differences of several seconds between the time of the same event recorded at different sites were therefore anticipated.

5.4.2 Broadband Recordings

Broadband recordings were made at sites 1A, 1B, 3A, and 3B on one Sony TCD-D100 and three Tascam DA-P1 digital audio tape (DAT) recorders. The recordings were approximately 2 hours in duration. The tape recorders located at the four sites were started as close as possible to the same time to acquire simultaneous data.

5.5 SUPPLEMENTARY INFORMATION

The intent of the measurement program was to estimate spectral levels of aircraft operations at the primary measurement sites. Supplementary information from the airport noise monitoring system and complaint data were used to help identify aircraft events for analysis and to permit comparisons with A-weighted aircraft noise levels. The times and locations of complaints were used to review measured data for possible events. Upper air soundings from the National Weather Service in Oakland were also collected.

5.5.1 San Francisco International Airport Noise Monitoring System and Complaint Data

SFO's airport noise monitoring system includes five remote monitoring sites (RMS) near the current measurement locations: RMS-8, 9, 10, 11 and 13. Aircraft noise data measured at each RMS were associated with airport operations and complaint data to aid in verifying the sources of noise events. The airport operations data for the August visit may be found in Table 6 of this report.

5.5.2 Weather Information

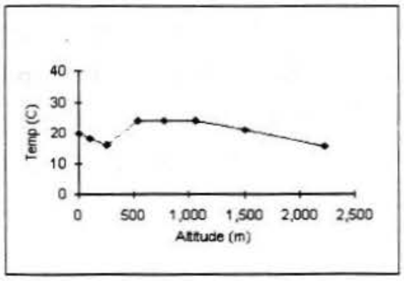
A temperature profile for the first 2,000 m of the atmosphere at a location in Oakland was plotted for two times of each day of the study. It is not clear how closely these profiles predict temperature gradients between the western threshold of Runways 01L/R and the measurement sites. The Oakland data nonetheless illustrate a wide range of temperature profile conditions, as shown for the August measurements in Figure 11. During some time periods, temperature decreased with altitude in the usual manner. At other times, temperature increased with altitude (a temperature "inversion"). Temperature (as well as wind) gradients can dramatically influence long-range sound propagation, since sound refracted back to the earth can produce increased sound levels at extended distances from the source.

5.6 DATA ANALYSIS

The field measurements were analyzed to determine the levels of selected (unambiguously identifiable, relatively high level) aircraft noise events. Most of the analysis was conducted on the data obtained at the primary sites, 3A and 3B.

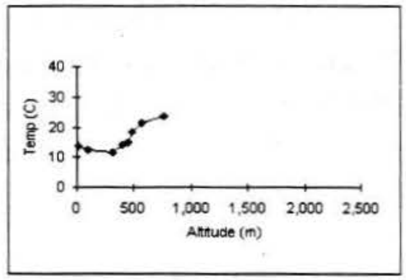
August 23, 1999
1700

Alt. (m)	T (C)
5	20.0
99	18.4
254	16.0
531	24.4
773	24.4
1,061	24.4
1,510	21.2
2,224	15.6



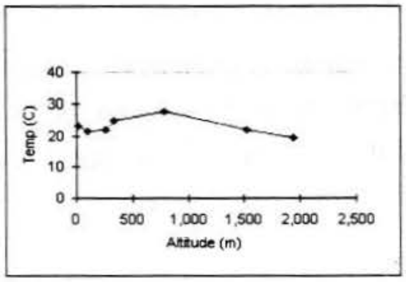
August 24, 1999
0500

Alt. (m)	T (C)
7	14.0
99	12.8
320	11.6
398	14.2
442	15.2
486	18.6
568	21.6
763	23.8



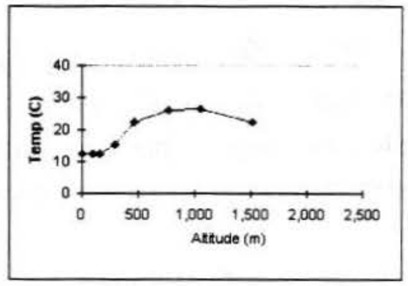
August 24, 1999
1700

Alt. (m)	T (C)
8	23.2
94	21.4
261	22.0
332	25.0
779	27.8
1,519	21.8
1,934	19.2



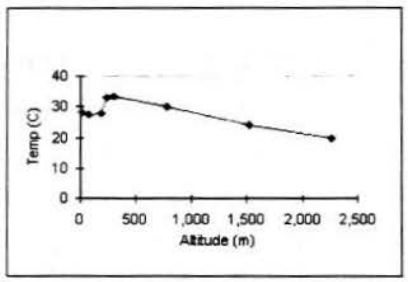
August 25, 1999
0500

Alt. (m)	T (C)
4	12.4
96	12.4
164	12.4
292	15.6
461	22.4
768	26.2
1,048	26.6
1,508	22.4



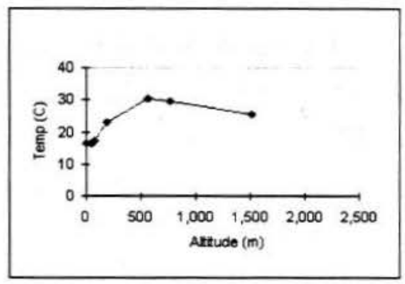
August 25, 1999
1700

Alt. (m)	T (C)
7	28.6
77	27.6
184	28.0
238	33.0
294	33.6
775	30.2
1,520	24.0
2,263	19.6



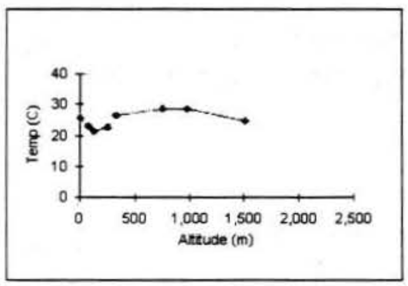
August 26, 1999
0500

Alt. (m)	T (C)
3	16.4
54	16.6
71	17.4
184	23.0
559	30.6
759	29.6
1,508	25.6



August 26, 1999
1700

Alt. (m)	T (C)
3	25.6
72	23.4
124	21.6
257	22.6
329	26.8
759	28.8
982	28.8
1,506	25.0



August 27, 1999
0500

Alt. (m)	T (C)
2	19.4
79	19.2
167	25.0
256	26.4
764	23.8
888	24.6
1,501	20.6

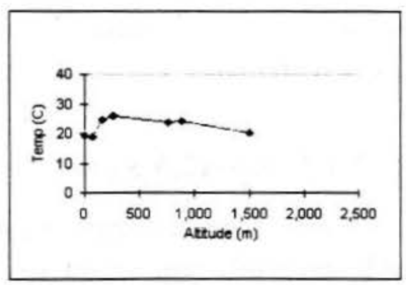


Figure 11 Atmospheric temperature profiles observed in Oakland during the 23-27 August, 1999 measurement period.

5.6.1 Sound Level Measurements

A- and C-weighted noise event levels stored in each sound level meter were downloaded in the field to laptop computers. These data, which provided nearly continuous 24-hour monitoring of noise events, were used to verify noise event levels recorded on digital audio tape.

Some of the sound level meters were additionally set to record A-weighted interval data. These interval data were analyzed to estimate daily CNEL values for sites 3A and 3B during the second measurement period, as shown in Table 4. The data measured at RMS 9 and 11 are shown in the table for comparison.

Table 4 24 hour A-weighted CNEL values during the August measurement period.

SITE	24 AUGUST 1999	25 AUGUST 1999
3A	57.9 dB	58.2 dB
3B	54.0	59.5
RMS 9	58.5	63.2
RMS 11	57.3	62.7

A subset of the C-weighted sound level meter data was analyzed to estimate the distributions of high level aircraft noise events at the various sites. The measurements were made synchronously at all sites between 16:30 and 21:16 on 25 August, 1999. Figures 12, 13 and 14 show cumulative distributions of these noise levels. Each point represents the cumulative percentage of measurements (shown on the ordinate) that reached the corresponding sound level (on the abscissa) in excess of thresholds set at 90 dB at sites 1A and 1B, 75 dB at site 2B, and 70 dB at sites 2A, 3A and 3B. These cumulative distributions of C-weighted maximum aircraft event levels are included to illustrate the distribution of the maximum event levels in August. Each of the figures illustrates typical distribution curves, while Figure 12 indicates the expected decay in level as sound propagates from site 1A to site 3A. In Figure 13, the curve for site 2B crosses over the curve for site 3B, possibly due to some shielding at site 2B. Figure 14 compares this distribution for sites 3A and 3B, showing greater sound levels at site 3B, possibly due to a higher elevation.

Note that the median (50th centile) C-weighted sound levels of aircraft departure noise at the more remote sites 2A and 3A were in the high 70 dB range. In other words, roughly half of the aircraft departures during this four hour period produced C-weighted sound levels in excess of 78 dB. About ten percent of the aircraft departures in the same time period produced C-weighted sound levels in the high 80 dB range at these sites, and a small percentage of departures produced noise levels on the order of 90 dB.

Figures 13 and 14 show a very similar pattern of findings for sites 1B, 2B, 3A and 3B.

5.6.2 Broadband Recordings

Field recordings were reduced to time history strip charts as a visual indication of times of occurrence of unambiguous aircraft noise events. Figure 15 shows one example of such a chart for noise events at sites 3A and 3B between 21:25 and 21:40 on 24 August, 1999. Selected noise events were auditioned to verify that they were due to aircraft noise, and analyzed on a Larson·Davis 2900 spectrum analyzer to determine the frequency spectra of the event. One-third octave band levels were obtained at half second intervals over a 30-second time period that encompassed the maximum sound level. These spectra were imported into spreadsheets, from which A- and C-weighted levels were computed. These data were compared to the event data measured by the sound level meters and airport noise monitoring system.

The unambiguous high level aircraft events recorded during the surveys are summarized in Tables 5 and 6. The events shown in the tables were selected because each was appreciably greater in level than the ambient noise level, and because the events could be associated with events registered by sound level meters and the airport noise monitoring system. The tables combine the measurements made by the sound level meters, the broadband data analysis, and the supplementary airport noise monitoring system data.

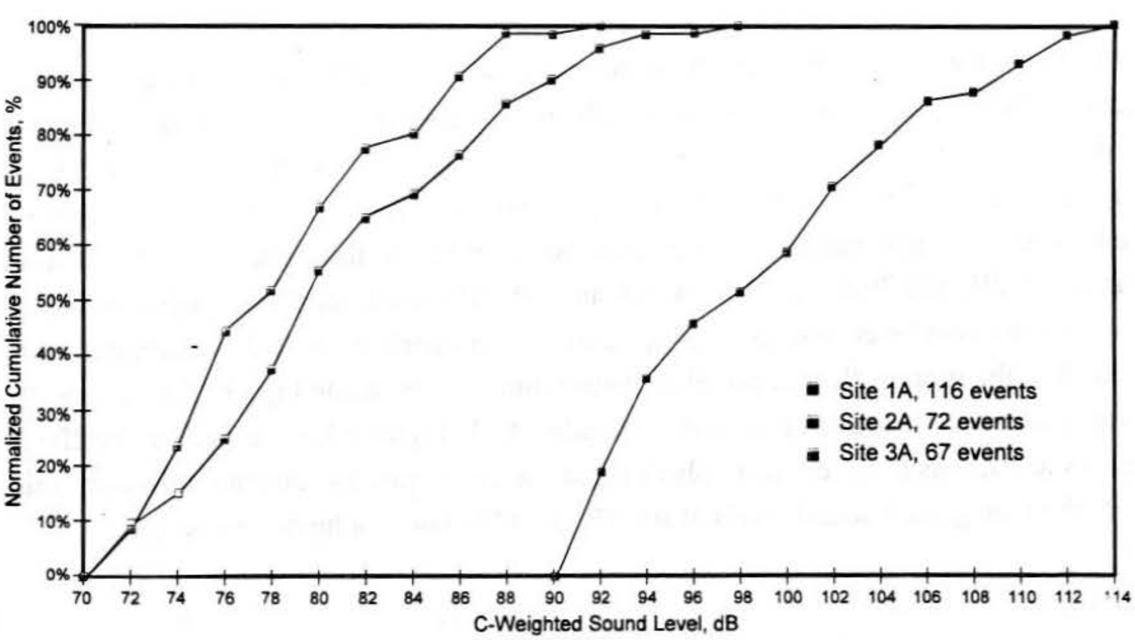


Figure 12 Cumulative distribution of greatest aircraft noise levels measured on 25 August, 1999, 16:30 to 21:16, sites 1A, 2A and 3A.

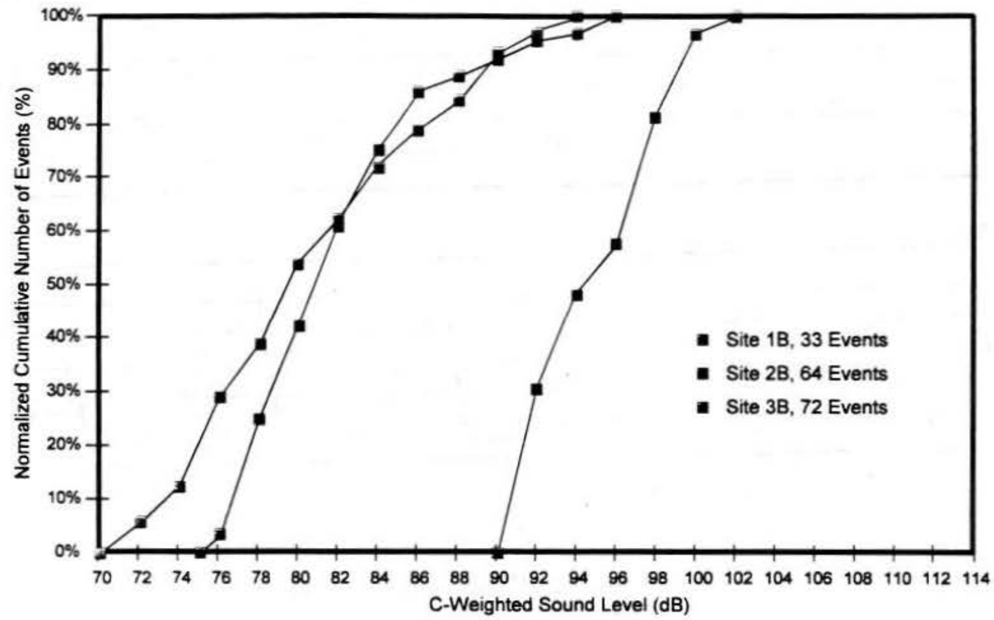


Figure 13 Cumulative distribution of maximum event levels on 25 August, 1999, 16:30 to 21:16, sites 1B, 2B and 3B.

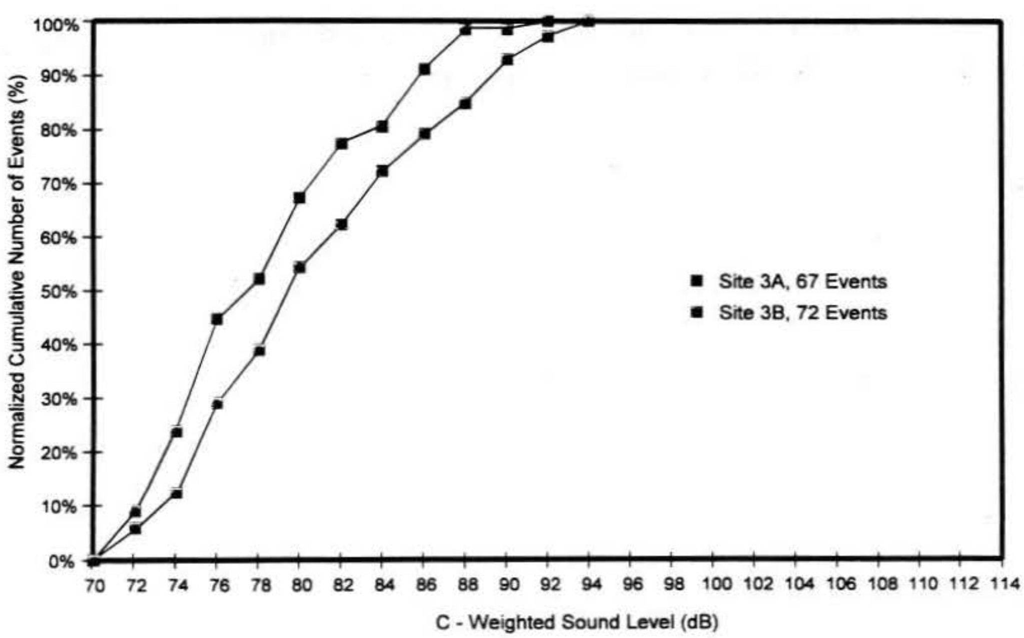


Figure 14 Cumulative distribution of maximum event levels on 25 August, 1999, 16:30 to 21:16, sites 3A and 3B.

Site 3A

Site 3B

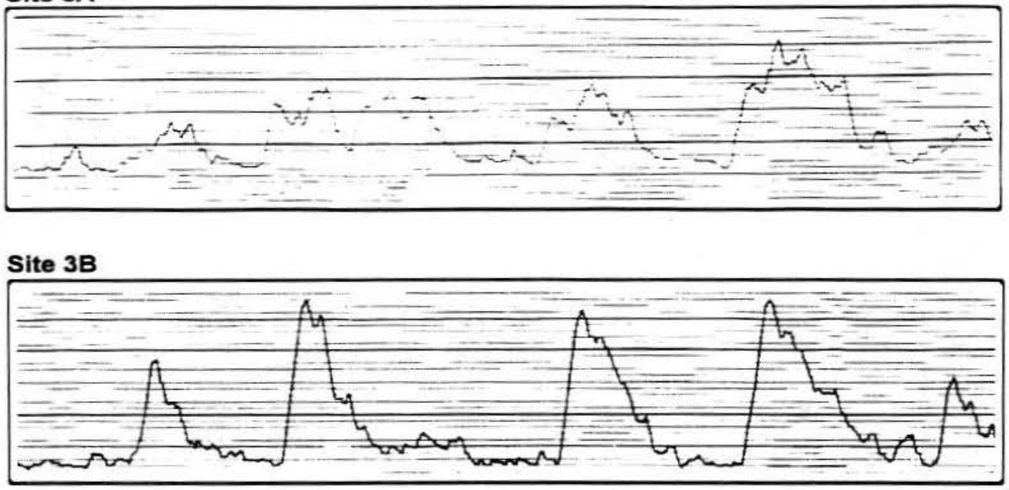


Figure 15 Time history strip chart for 24 August, 1999, 21:25 to 21:40.

Tables 5 and 6 show that measured aircraft noise levels were characteristically higher in level at site 3B than at site 3A, and that the higher levels were measured during the second set of measurements. The latter measurements are similar to those made earlier for purposes of collecting samples of backblast sounds for use in the laboratory study described in the following section.

The three August aircraft noise events plotted in Figures 16 through 21 show the range of one-third octave band levels measured during the second measurement period.

Table 5 Summary of measured aircraft noise levels, from 8 through 10 June, 1999.

	Site 1A		Site 2A		Site 3A		Site 1B		Site 2B		Site 3B		RMS 08	RMS 09	RMS 10	RMS 11	Aircraft Operation			
	L_{max}		L_{max}		L_{max}		L_{max}		L_{max}		L_{max}		L_{max}	L_{max}	L_{max}	L_{max}				
Time	C-Wtd	A-Wtd	C-Wtd	A-Wtd	C-Wtd	A-Wtd	C-Wtd	A-Wtd	C-Wtd	A-Wtd	C-Wtd	A-Wtd	A-Wtd	A-Wtd	A-Wtd	A-Wtd	Oper	Rwy.	Airline	A/C Type
8 June 1999																				
2126	113.3	99.5	NA	65	75.6	NA	89.1	72	NA	NA	84.1	NA	66.2	NA	NA		D	01R	UAL2458	B733
2138	112.3	93		60.5	82.3		88.8			58.5	88.5		76.5				D	01L	SKW5303	E120
Average	112.8	96.3	NA	62.8	79.0	NA	89.0	72.0	NA	58.5	86.3	NA								
9 June 1999																				
1910	101.1		76.9	60	76.2		86	73.5			75.8		75.4	70.3	70.6				ROA2735	MD83
2127	110	97.5	74.2	59.5	72.2		89.9			59.5	87		61.8			63.1			ASA387	MD80
2138	110.1	97	84	68	77		87.1			54.5	82.2		63.3						UAL1286	DC10
2151	110.2	91.5	76.7		72.8		85.5			53	80		66.2						COA150	B752
2200	105.1	88	73.1		73.7		81.9			62	77.4					64.1			UAL2272	B735
2209	108.8	93.5	76.3		73.1		85.1			58	77.3								UAL2071	B735
2223	107.1	89.5	73.1	61.5	77.1		85.9			56.5	81.5		66.6						USA72	B752
2233	108.5	99.5	73.6	60	74.8		87.1			56.5	81.5		69.3			61.4			COA9920	MD80
2257	110.7	91.5	73	58.5	72.9		88.6			65	74.8		63.1						USA96	B752
Average	108.0	93.5	75.7	61.3	74.4	NA	86.3	73.5	NA	58.1	79.7	NA								
10 June 1999																				
1108		101.5	79.4	71	68.6			73.5			84								UAL1694	B722
1155		93.5	74.1	63	74.6			95			85.2								AWE804	B732
1205		90.5	79.8	63.5	72						82								ROA2729	MD83
Average	NA	95.2	77.8	65.8	71.7	NA	NA	84.3	NA	NA	83.7	NA								
Two day Average	108.8	94.3	76.2	62.8	74.5	NA	86.8	78.5	NA	58.2	81.5	NA								

Table 6 Summary of measured aircraft noise levels, 24-25 August, 1999.

	Site 3A			Site 3B			RMS 08	RMS 09	RMS 11	Aircraft Operation			
	L_{max}			L_{max}			L_{max}	L_{max}	L_{max}				
Time	C-Wtd	A-Wtd	C - A	C-Wtd	A-Wtd	C - A	A-Wtd	A-Wtd	A-Wtd	Oper	Rwy.	Airline	A/C Type
24 Aug 1999													
2113	NA	NA		90.6	76.3	14.3		88.2	82.2	D	01L	CC1312	B722
2123	81.8	70.0	11.8	99.0	80.0	19.0			61.8	D	28R	DAL1985	B763
2128	77.8	65.9	11.9	99.3	80.6	18.7		75.1		D	01R	ASA387	MD80
2135	82.5	64.4	18.1	96.9	77.3	19.6	71.9	77.2		D	01L	SWR109	MD11
2157	80.0	NA		90.5	71.5	19.0	64.8		61.0	A	28L	UAL2137	B733
2205	78.0	60.1	17.9	86.5	68.9	17.6	68.1			D	01R	DAL212	B763
2213	79.5	NA		88.8	69.9	18.9		66.9		D	01R	USA72	B752
2226	75.0	NA		85.4	64.1	21.3			61.8	A	28R	COA1543	B752
2228	76.0	NA		84.1	65.8	18.3			61.9	A	28L	UAL8105	B752
2231	75.5	NA		83.0	66.5	16.5	70.4		57.7	D	01R	AAL18	B752
Average	78.5	65.1	14.9	80.4	72.1	18.3							
25 Aug 1999													
1126	78.6	63.9	14.7	85.4	68.9	16.5			58.2	D	01L	UAL1972	B735
1136	80.6	64.3	16.3	86.5	71.0	15.5			58.2	A	U/K	UAL288	B752
1210	74.1	59.0	15.1	80.5	63.4	17.1			66.1	D	01L	MEP921	MD80
1613	75.9	58.1	17.8	80.9	61.2	19.7			60.0	D	01L	ROA2777	MD90
1615	87.8	68.3	19.5	92.3	83.5	8.8			67.7	D	U/K	N911HB	DA50
1630	86.5	66.8	19.7	88.5	70.1	18.4		67.5	73.4	D	01R	AZA625	B763
1635	85.5	67.9	17.6	93.4	73.1	20.3		73.5	69.3	D	01L	SKW5039	E120
1655	88.2	71.9	16.3	94.2	77.5	16.7		83.9		D	01L	UAL1458	B722
1703	80.6	64.1	16.5	92.8	73.4	19.4	77.0		63.6	D	U/K	SKW5452	E120
1717	85.0	66.5	18.5	92.2	70.7	21.5		73.1	74.2	D	01L	ROA2745	MD83
1719	91.6	76.7	14.9	90.8	77.9	12.9		78.9	81.6	D	01L	CDN514	B732
1743	77.0	60.3	16.7	85.5	62.7	23.1	78.5	64.1		D	01L	AAL492	MD80
Average	82.6	65.7	17.0	88.6	71.1	17.5							
Two-day average	80.7	65.5	16.5	89.5	71.6	17.9							

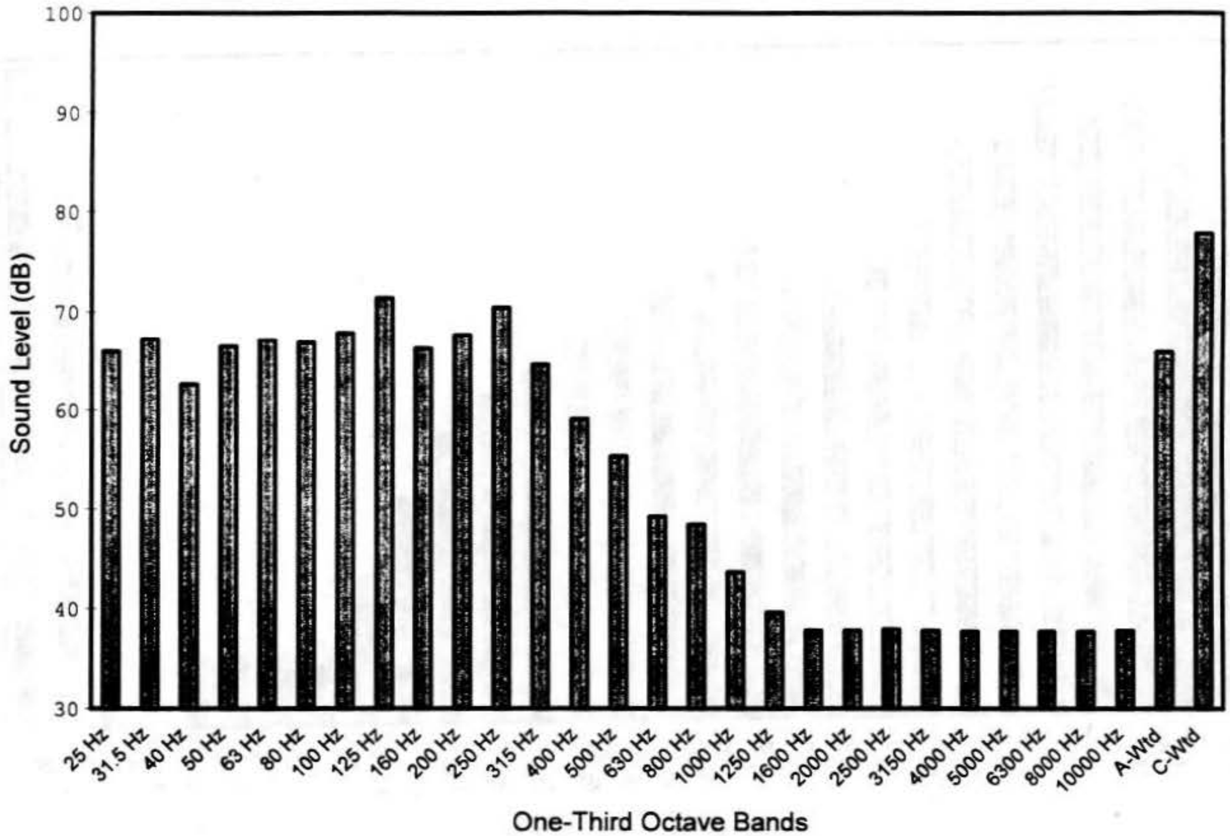


Figure 16 Maximum aircraft noise spectrum of MD-80 measured at Site 3A, 24 August, 1999, at 21:28.

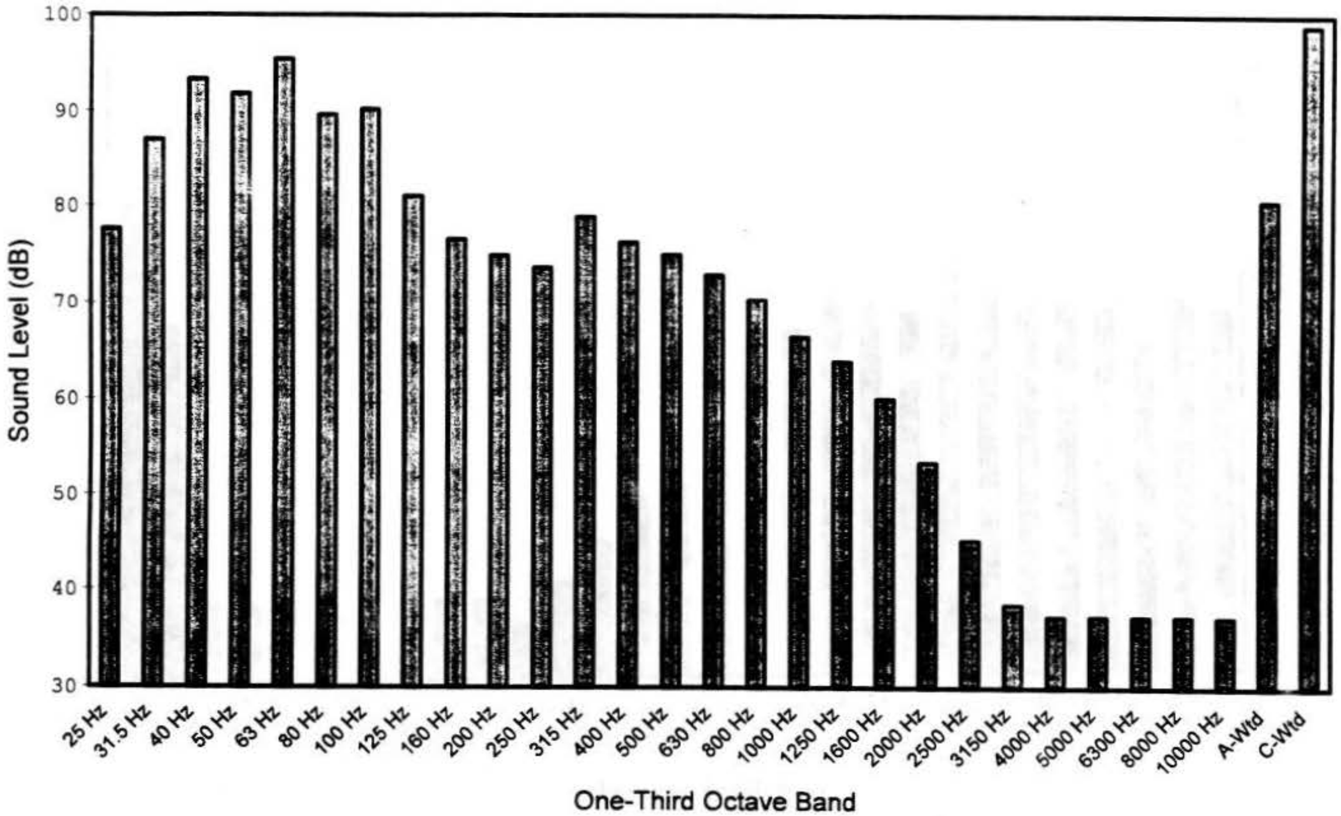


Figure 17 Maximum aircraft noise spectrum of MD-80 measured at Site 3B, 24 August, 1999, at 21:28.

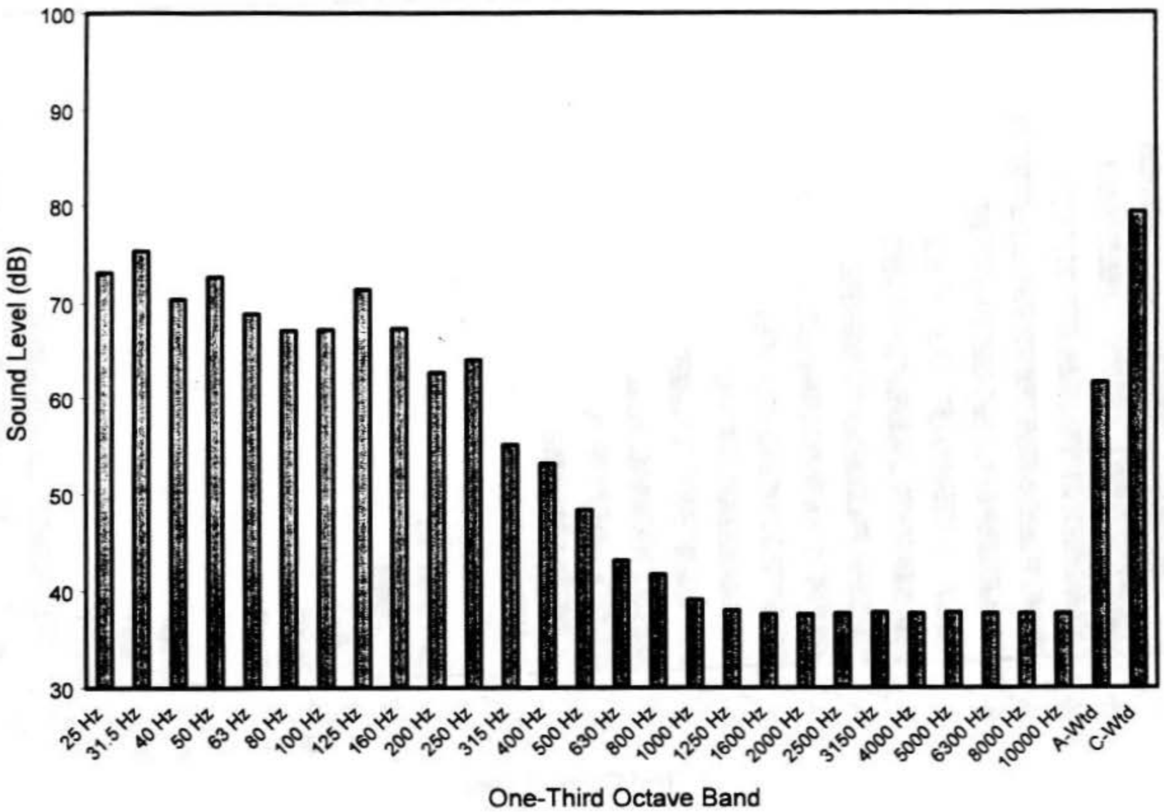


Figure 18 Maximum aircraft noise spectrum of B-757-200 measured at Site 3A, 24 August, 1999, at 22:13.

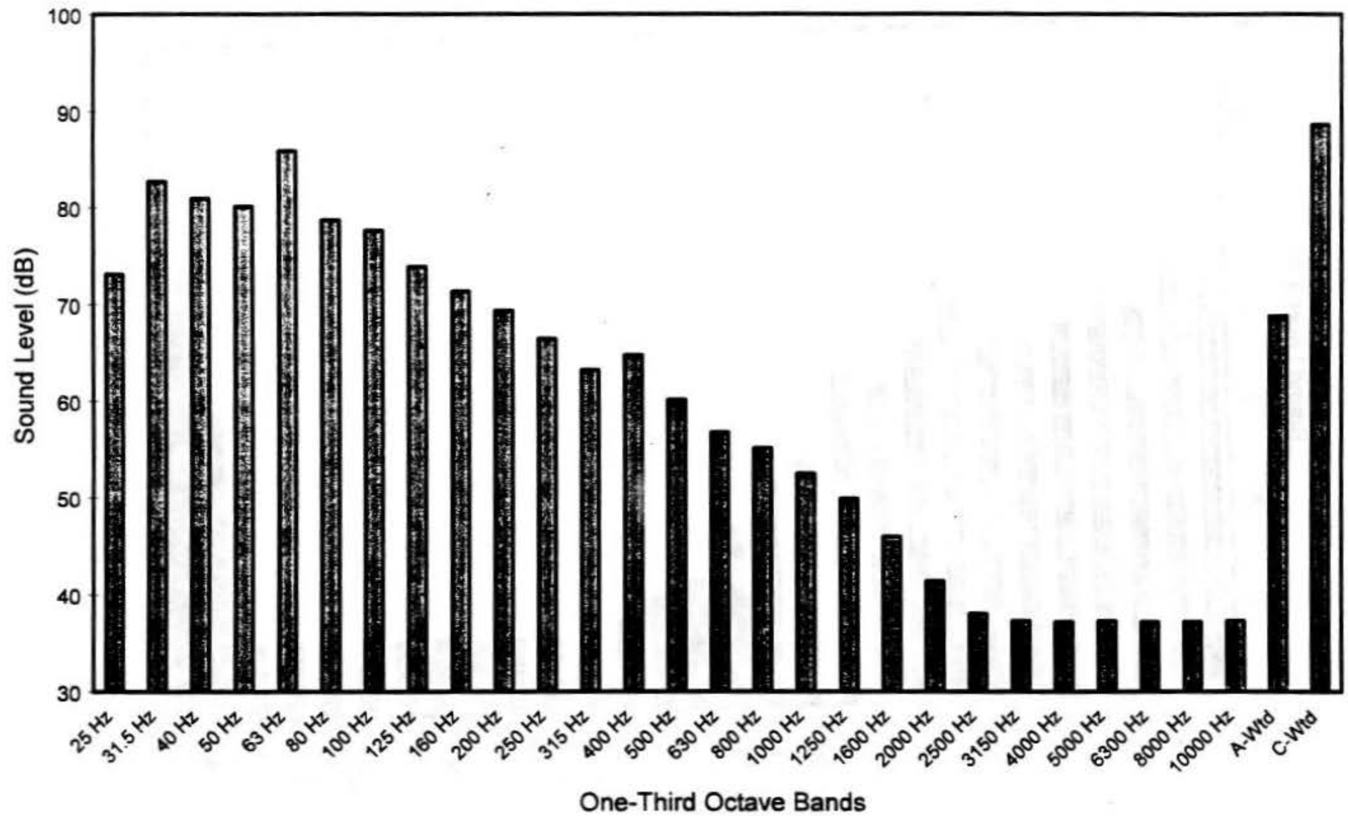


Figure 19 Maximum aircraft noise spectrum of B-757-200 measured at Site 3B, 24 August, 1999, at 22:13.

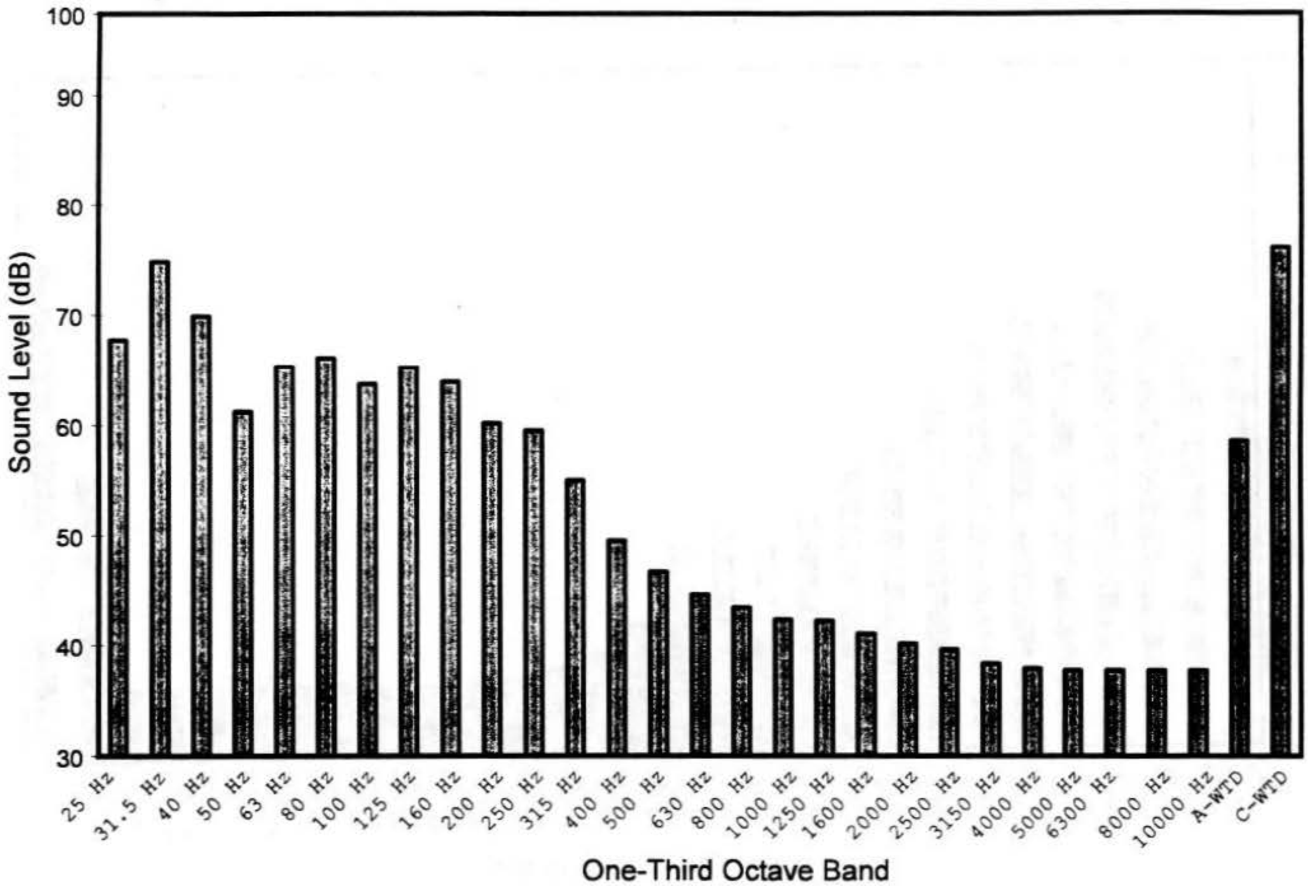


Figure 20 Maximum aircraft noise spectrum of MD-90 measured at Site 3A, 25 August, 1999, at 16:13.

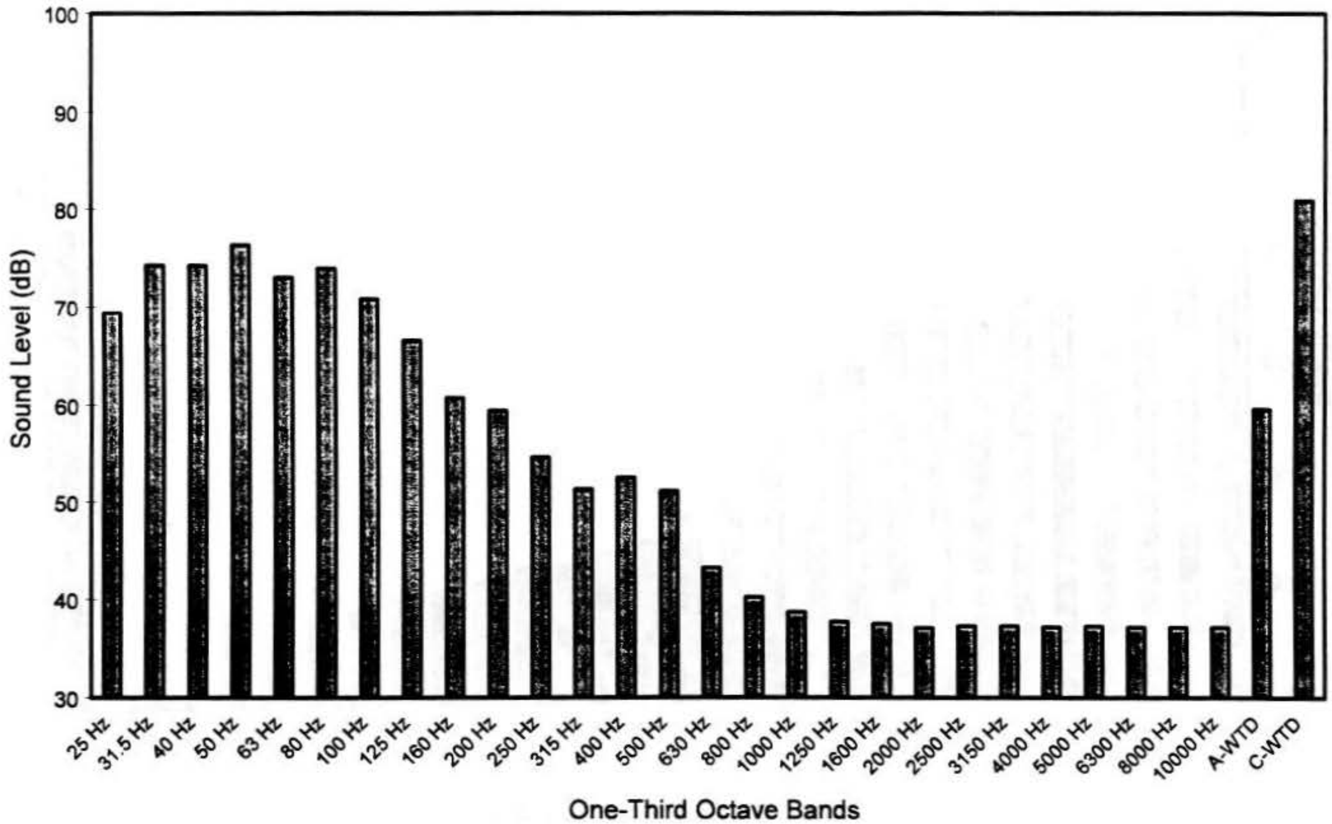


Figure 21 Maximum aircraft noise spectrum of MD-90 measured at Site 3B, 25 August, 1999, at 16:13.

5.7 DISCUSSION OF FIELD MEASUREMENTS

5.7.1 Effect of Atmospheric and Terrain Conditions

While much is known of near-ground sound propagation, it is impossible to effectively account for all the different conditions that prevail at any given time period. The usual approach to modeling aircraft noise levels in the community is to assume an annual average temperature and relative humidity, flat terrain with ground attenuation of sound at the ground plane, and a generalized model of lateral attenuation for angles of sound propagation referenced to the ground plane between 0° and 45°. The most recent release of FAA's aircraft noise modeling computer program (INM) takes account of some (but not all) of the effects of elevation changes due to hills and valleys.

However, other propagation effects can cause common aircraft operations at the airport to produce unusually high noise levels elsewhere. These unusual noise conditions may sometimes be due to temperature inversion conditions. They can combine with local terrain and wind effects to cause apparent amplification and/or focusing of noise in specific geographical areas. Figure 22 illustrates the effect of downward refraction (bending) of sound waves that would otherwise propagate away from the ground. Such downward refraction can increase noise levels at locations where they would otherwise occur at lower levels, giving a false impression of unusual aircraft operations.

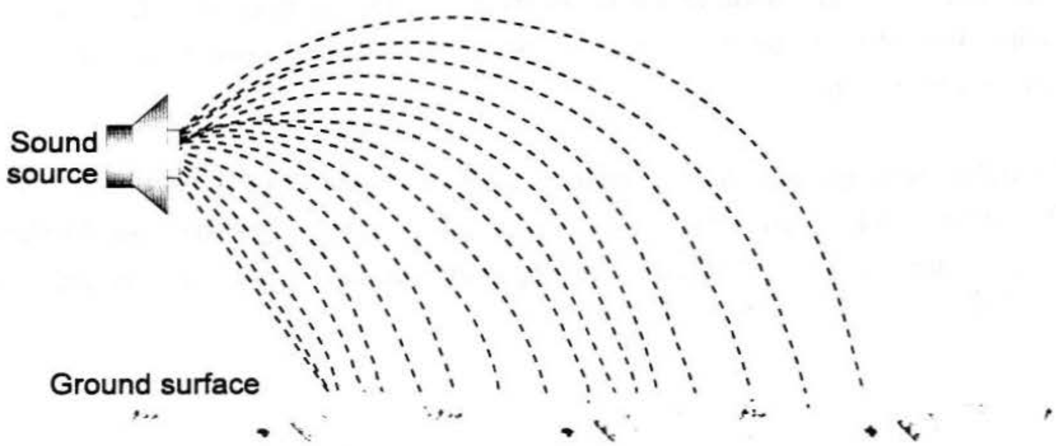


Figure 22 Illustration of downward refraction (bending) of sound waves caused by unusual temperature or wind gradients in the local atmosphere.

The seasonal distribution of complaints, and the noise measurements made during June and August 1999, suggest that such atmospheric conditions might effect low-frequency noise levels to the southwest of Runways 01 L/R. The prevalence of complaints in winter and spring months is consistent with the likelihood of temperature inversion conditions. The occurrence and magnitude of downward refractive atmospheric conditions are difficult to predict, however, without continuous knowledge of wind and temperature gradients in the direction of noise propagation.

5.7.2 Differences in Maximum Noise Event Levels During Two Measurement Periods

The June measurements show some distinctive differences in the maximum level of noise events at sites that are approximately the same distance from the airport. The average difference between maximum C-weighted event levels at sites 3A and 3B is approximately 6 dB. Site 3B is at an elevation of approximately 375 feet whereas site 3A is at an elevation of approximately 75 feet.

The average noise levels measured on 10 June at site 3B were higher than those measured on 9 June. Although this difference could be due to a stronger temperature inversion on the 10^{th} of June, which might have focused sound at the more elevated site 3B, such an effect cannot be calculated from the limited weather data available.

The aircraft noise levels measured during the second measurement period generally exceeded those measured during the first survey. The highest level C-weighted event recorded during the first visit was 88.5 dB. The maximum levels of the aircraft noise events measured at site 3B during the second survey varied from 72.5 to 99.3 dB (C-weighted) and 55.7 to 80.6 dB (A-weighted). The higher level events occurred during the late afternoon and early evening, the time period when the strongest temperature inversion conditions often occur. C-weighted noise levels exceeded A-weighted noise levels by as much as 20 dB for the same event.

The highest level noise events occurring between 16:30 and 18:00 on 25 August, 1999 were Stage II aircraft. The distribution of aircraft types is summarized in Table 7. Of the Stage III aircraft operations listed in Table 7, the MD-80 aircraft type departing from Runway 01 produced the highest noise levels at sites 3A and 3B.

Table 7 Aircraft types identified on 25 August, 1999 between 16:30 and 18:00.

AIRCRAFT TYPE	NUMBER OF EVENTS
B-727	3
B-737	11
B-747	1
B-757	1
B-767	4
A320	1
MD-80	4

It appears from Table 6 and Figures 16 through 21 that the low-frequency content of the aircraft noise at site 3B is higher than that at site 3A. Comparison of similar data on 24 and 25 August shows the average C-weighted levels for site 3B to be higher than those at site 3A by 1.9 dB and 6.0 dB, respectively, while the A-weighted level differences for the two days are 7.0 and 5.4 dB. The weather inversion data do not indicate a significant difference for these days. The overall average C-weighted difference is 8.8 dB while the A-weighted difference is 6.1 dB. Calculating the value of the C-weighted level minus the A-weighted level ("C minus A") gives a rough indication of the low-frequency content of the noise. The C minus A level for the two days measured 16.5 dB at site 3A and 17.9 dB at site 3B, indicating strong low-frequency content of the noise.

5.8 SUMMARY OF FIELD MEASUREMENTS

High levels of C-weighted aircraft noise levels are present in each of the areas of complaints. Higher level aircraft noise events generally occurred in the late afternoon and early evening. These levels can vary over the course of the year by as much as 10 dB. The highest C-weighted noise levels measured in the high complaint areas during the measurement periods were within the range of 95 to 100 dB. The C-weighted noise levels of some noise events were about 20 dB higher than their A-weighted equivalents. The average difference between A- and C-weighted levels of the significant events over the two-day period in August was 16.5 dB and 17.9 dB for sites 3A and 3B, respectively. These differences do not necessarily affect long-term CNEL values.

Occasional occurrences of unusually high levels of low-frequency aircraft noise may be due to specific atmospheric conditions, such as temperature inversions, rather than to changes in aircraft type or operating conditions. The specific areas affected by low-frequency aircraft noise may therefore vary in an unpredictable manner.

6 LABORATORY STUDY OF ANNOYANCE

This section describes judgments of the annoyance of recorded aircraft departure and related sounds made under highly controlled conditions.

6.1 METHOD

An empirical study of the effects of varying duration and low-frequency content of aircraft noise on annoyance was conducted in a laboratory setting. Sounds heard by test participants were selected to test hypotheses about the relative annoyance of aircraft overflight and backblast noise of varying duration and low-frequency content.

6.1.1 Description of Test Environment and Procedures

All annoyance judgments were made in a low-frequency test facility that permitted controlled generation of signals at sound pressure levels as great as 136 dB at infrasonic frequencies. Figure 23 is a schematic representation of the test facility. Figure 24 is an interior view of the drive modules that created the test signals. Figure 25 is a photograph of the area in which subjects were seated.

Subjects entered the low-frequency facility with the experimenter prior to the start of testing on their first day of participation to familiarize themselves with the environment and listen to typical signals. They were encouraged to discuss the nature of their participation and to seek clarification of any matters that they might not have fully understood prior to granting written informed consent for participation in the study.

One subject at a time was seated in a chair inside the test facility facing a curtain hung in front of a full-scale plaster wall, behind which the low-frequency drive modules were mounted. These drive modules produced the low-frequency (below 100 Hz) portion of the signals. Two high-quality loudspeakers installed just behind the curtain reproduced the high-frequency (above 100 Hz) portion of the signals. An intercom and a video camera permitted an experimenter located in a nearby control room to communicate with and view subjects at all times. Four test sessions lasting approximately 25 minutes each were conducted daily.[4] Subjects were required to leave the test facility between testing sessions. A subject's participation spanned three days. Instructions to subjects may be found in Appendix A.

---

[4] Since subjects were not forced to respond within a fixed duration response interval, the pace of data collection varied slightly from session to session.

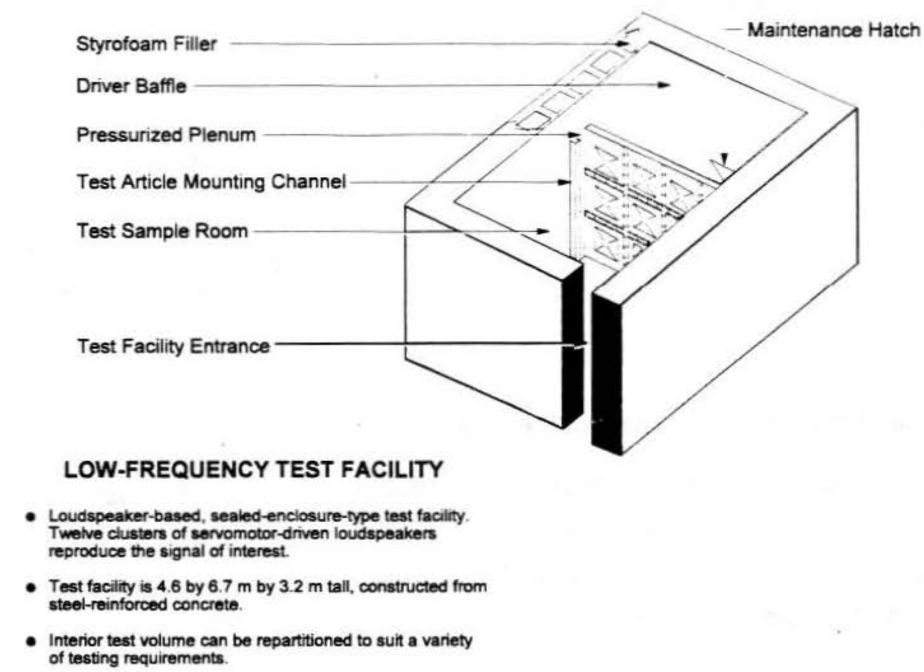


Figure 23 Schematic representation of low-frequency test facility.

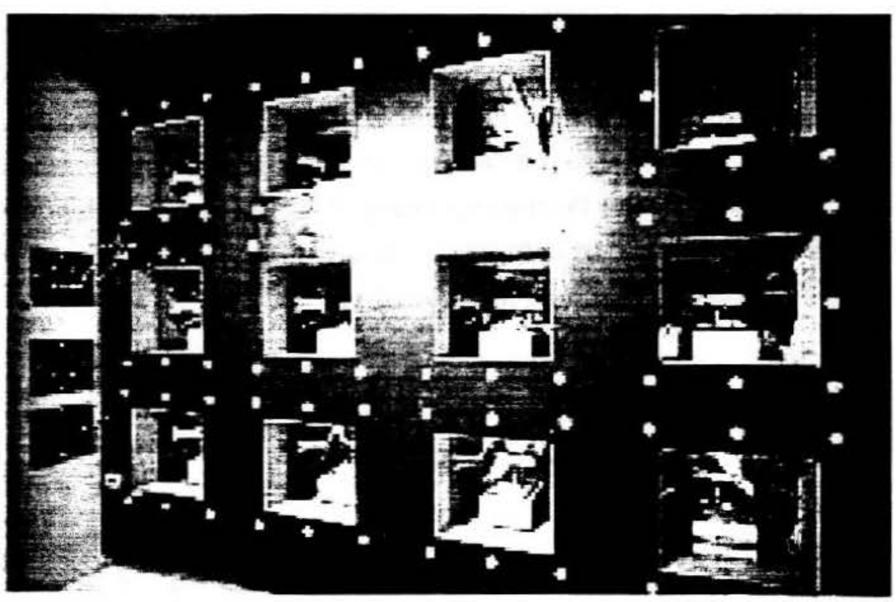


Figure 24 Interior view of low-frequency test facility.

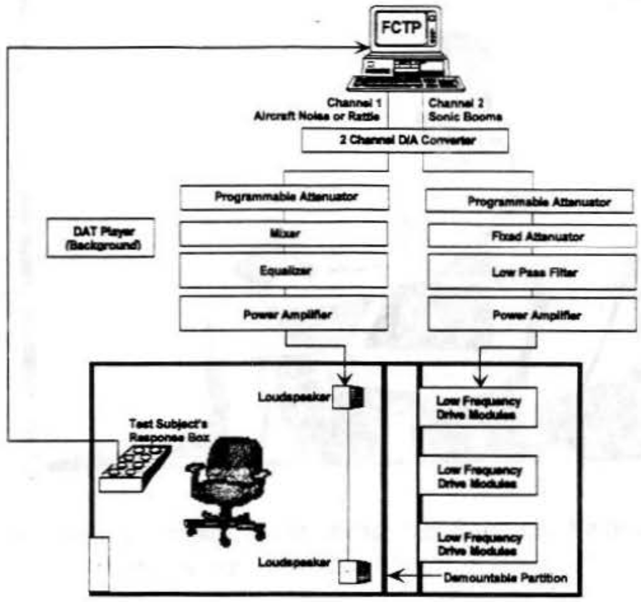
Figure 25 Interior view of low-frequency test facility test subject chamber, showing seated test participant holding response box used to record subjective judgments.

6.1.2 Solicitation of Annoyance Judgments

Direct judgments of the relative annoyance of pairs of test signals were solicited in an adaptive paired comparison experimental design. Subjects were instructed to judge whether the first or second signal presentation of each trial was the more annoying. Ten such trials were presented for each signal pair. The durations of the signal presentation intervals were determined by the durations of the signals themselves. The duration of the response interval was determined by a subject's response latency.

Signal generation and presentation, as well as all other aspects of data collection, were under real-time computer control. Figure 26 diagrams the signal generation and presentation hardware. A maximum likelihood estimation algorithm described by Green (1990, 1995) and by Zhou and Green (1995) adaptively controlled signal presentation levels in real time, on the basis of test participants' ongoing decisions. The underlying psychometric function was assumed to be a cumulative Gaussian with a standard deviation of 10 dB. The value of the estimated point on the psychometric function was 50%. This is the point of subjective equality of annoyance, at which individual subjects rated the comparison (variable level signal) more annoying 50% of the time and the standard (fixed level) signal more annoying 50% of the time.

The point of subjective equality of annoyance was approached by a binary search algorithm. Step sizes between trials ranged from a maximum of 40 dB to a minimum of 2.5 dB. The maximum permissible signal presentation level was approximately 110 dB. The spectra of the presented noises are shown in Figures 27 and 28. Ten trials were administered for each determination of the relative annoyance of signal pairs, sufficient to yield a standard deviation of the threshold estimate of approximately 4 dB. The order of presentation of the fixed and variable signals was randomized on a trialwise basis. The order of presentation of signal pairs was independently randomized and fully interleaved, so that subjects were unable to predict which signal pair would be heard next.



Low-Frequency Test Facility

Figure 26 Illustration of instrumentation controlling administration of test conditions in the low-frequency test facility.

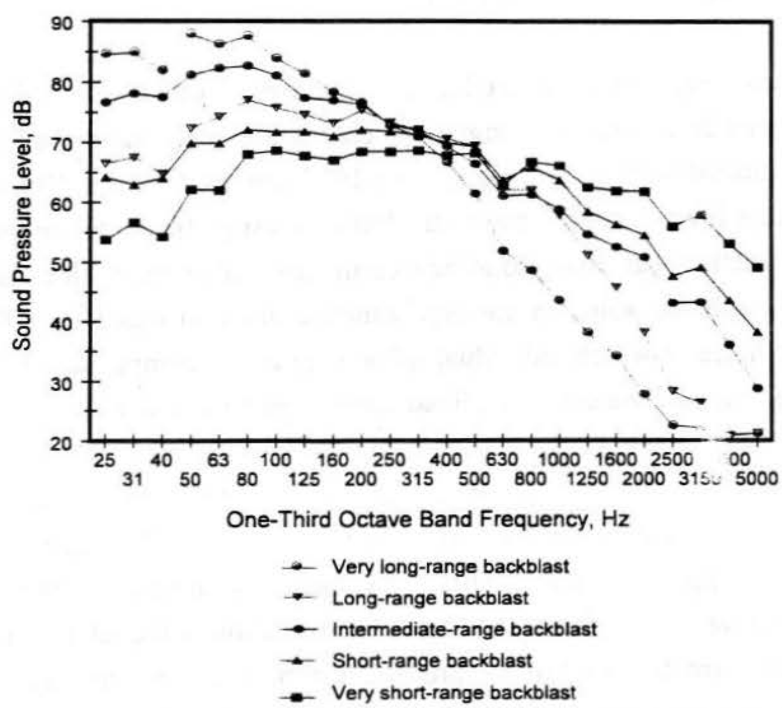


Figure 27 Spectral plots of the synthetic signals included in the low-frequency study.

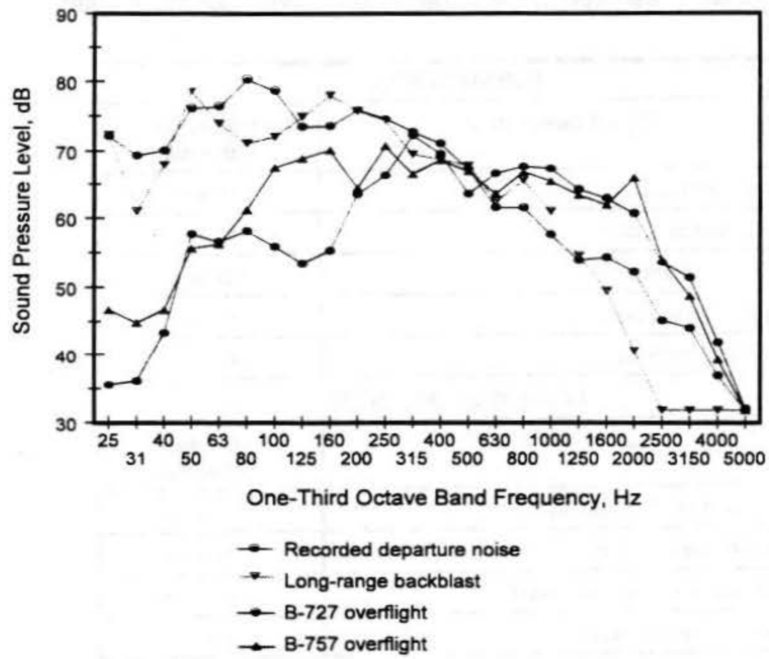


Figure 28 Spectral plots of the recorded signals used in the low-frequency study.

A long-duration digital recording of shaped Gaussian noise was reproduced at all times that subjects were present in the test facility. The A-level of the background noise at the subject's head position was approximately 41 dB.

6.1.3 Description of Test Signals and Presentation Levels

The experiment was conducted in two parts. The first part of the study examined the effects of varying durations of test signals on annoyance, while the second part examined the effects of varying low-frequency content of test signals on annoyance. Table 8 summarizes the fixed and variable level signals presented in the two parts of the experiment. Prior to the start of data collection, SFO-area residents auditioned samples of backblast noise recorded at several sites near their homes in the test chamber.

Table 9 summarizes the eight signal pairs presented in the duration study. Fixed level signals were always presented at the levels shown in the table. Table 10 summarizes the 12 signals pairs presented in the low-frequency portion of the experiment.

Table 8 Summary of signals presented in the duration and low-frequency studies.

DURATION STUDY	
Signal Description	**A-Weighted Signal Duration**
Simulated backblast	15 sec
Simulated backblast	40 sec
Simulated backblast	120 sec
Recorded backblast	15 sec
Recorded backblast	40 sec
LOW-FREQUENCY STUDY	
Signal Description	**Simulated/ Recorded**
Very long-range backblast	Simulated
Long-range backblast	Simulated
Intermediate-range backblast	Simulated
Short-range backblast	Simulated
Runway threshold noise	Simulated
Departure noise	Recorded
Long-range backblast	Recorded
B-727 overflight	Recorded
B-757 overflight	Recorded

Table 9 Summary of fixed and variable level signals presented in the duration study.

Fixed Level Signal	A-Weighted Presentation Level (dB)	Variable Level Signal
15 seconds of recorded backblast	75	15 seconds of recorded backblast
		40 seconds of recorded backblast
15 seconds of simulated backblast	75	15 seconds of simulated backblast
		40 seconds of simulated backblast
		120 seconds of simulated backblast
		40 seconds of recorded backblast
40 seconds of simulated backblast	70	40 second of recorded backblast
		120 seconds of simulated backblast

Table 10 Summary of signal pairs presented in low-frequency study.

SIGNAL PAIR ID	FIXED LEVEL SIGNALS		VARIABLE LEVEL SIGNALS
	Description	Level	Description
1	Simulated Intermediate-range backblast	75	Simulated very long-range backblast
2	Simulated Intermediate-range backblast	75	Simulated long-range backblast
3	Simulated Intermediate-range backblast	75	Simulated long-range backblast
4	Simulated Intermediate-range backblast	75	Simulated intermediate-range backblast
5	Simulated Intermediate-range backblast	75	Simulated short-range backblast
6	Simulated Intermediate-range backblast	75	Simulated runway threshold noise
7	Recorded departure noise	75	Simulated intermediate-range backblast
8	Intermediate-range backblast	75	Recorded long-range backblast
9	Intermediate-range backblast	75	Recorded B-727 overflight
10	Intermediate-range backblast	75	Recorded B-757 overflight
11	Simulated short-range backblast	75	Simulated long-range backblast
12	Simulated runway threshold noise	75	Simulated very long-range backblast

6.1.4 Subjects

Subjects were audiometrically screened to within 20 dB of normal hearing (audiometric zero) over the frequency range of 100 to 6,000 Hz prior to testing. All subjects were retested at the end of their third day. No substantive changes in hearing were observed upon completion of the judgment tests.

A total of twenty-nine test subjects judged the relative annoyance of the test signals. Twenty-eight of the participants completed all three days of planned testing, while one (a woman) completed the duration study only. Thirteen of the test participants who participated in the study were women ranging in age from 18 to 47, while sixteen were men ranging in age from 18 to 50. The average age of female participants was 26 years, while the average age of male participants was 25 years.

6.2 RESULTS

This section summarizes data collection, reliability analyses, and analyses of paired comparison judgments. The basic unit of analysis was the sound level of a variable level signal on the final signal pair presentation (assumed to be equal in annoyance to a fixed level signal.

6.2.1 Data Collection and Processing

The eight signal pairs presented ten times to each of 29 subjects yielded a total of 2,320 paired comparison judgments in the duration study. These eight determinations of subjective equality of the signal pairs produced 232 data points.

The twelve signal pairs presented ten times to each of 28 subjects yielded a total of 3,360 paired comparison judgments in the low-frequency study. These twelve determinations of subjective equality between the signal pairs produced 336 data points.

6.2.2 Reliability of Adjusted Signal Levels

6.2.2.1 Comparisons of signal versus itself

One paired comparison was administered for initial screening purposes, and to quantify the reliability of annoyance judgments. Subjects unable to judge the variable level signal to be equal in annoyance to that of the same signal presented 7 dB or more higher or lower in level were not permitted to participate in the study. Only two potential test subjects were unable to do so. Figure 29 shows the levels of the variable level signal when judged to be equal in annoyance to itself signal for each test subject. The level of the fixed signal was always 75 dB, whereas the mean level of the variable level signal at the point of subjective

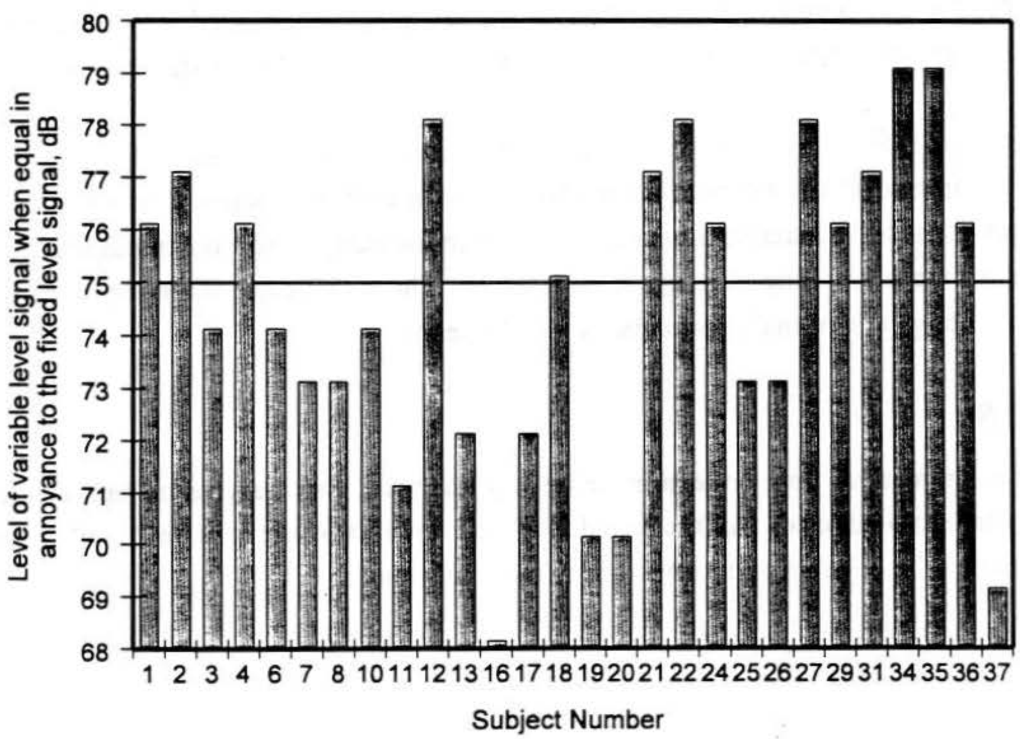


Figure 29 Levels of variable level signal when judged to be equally annoying to the fixed level signal for 28 test subjects.

equality was 74.5 dB. Most subjects were able to judge the variable level signal to be equally annoying when it was within 4 dB of the same signal in this initial paired comparison.

6.2.2.2 Test-Retest Reliability

For reliability purposes, the long-range backblast signal was compared to the intermediate-range backblast signal twice in the low-frequency study. Figure 30 shows the levels of the long-range backblast signal when judged to be equal in annoyance to the intermediate-range backblast signal for all test subjects. Although the spread of the resulting levels is slightly greater in the second comparison, the overall means do not differ.

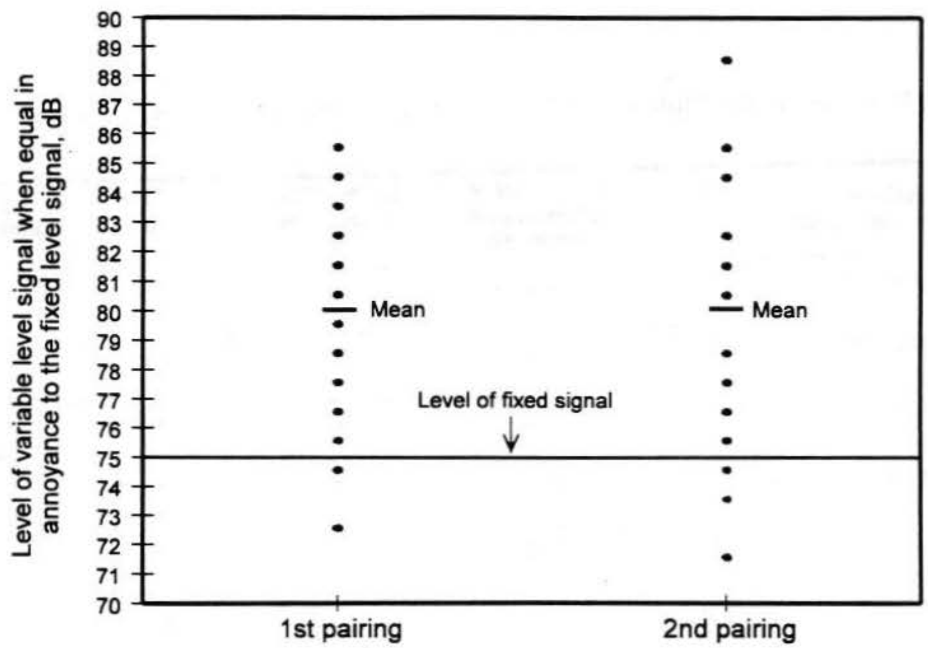


Figure 30 Level of long-range backblast signal when judged to be equally annoying to the intermediate-range backblast signal in repeated pairings.

6.2.3 Results of Duration Study

Table 11 contains summary statistics (of maximum A-weighted levels) of eight paired comparisons tested in the duration study. The second column contains the number of subjects whose resulting variable signal levels were within three standard deviations of the mean for each comparison and hence included in further analyses. The third column of the table contains the average level of the variable level signal when judged to be equal in annoyance to the fixed level signals. The fourth column contains the levels of the fixed level signals in each comparison. The fifth column contains the average differences between the variable and fixed level signals when judged to be equally annoying. The sixth column, which contains 10 times the log of the ratios of durations (variable duration/fixed duration) of the signal pairs, shows predicted decibel differences in noise levels of the variable and fixed level signals, in accordance with the "equal energy" theory. Table 12 presents summary statistics in sound exposure level (SEL) for the same comparisons.

Table 11 Summary statistics (of maximum A-weighted levels) of eight paired comparisons in duration study.

Description of Comparison (Variable Level *vs* Fixed Level Signal)	N	Mean Level of Variable Level Signal, dB	Level of Fixed Level Signal, dB	Mean Difference	10 Log Ratio of Durations, dB
15 sec simulated *vs* 15 sec simulated backblast *	27	74.5	75	-0.5	0
40 sec simulated *vs* 15 sec simulated backblast *	27	68.7	75	-6.3	-4.3
120 sec simulated *vs* 15 sec simulated backblast *	27	66.8	75	-8.2	-9.0
40 sec recorded *vs* 15 sec simulated backblast	28	67.7	75	-7.3	-4.3
120 sec simulated *vs* 40 sec simulated backblast	28	68.2	70	-1.8	-4.8
40 sec recorded *vs* 40 sec simulated backblast	28	66.4	70	-3.6	0
15 sec recorded *vs* 15 sec recorded backblast	28	76.1	75	1.1	0
40 sec recorded *vs* 15 sec recorded backblast	28	66.6	75	-8.4	-4.3

* Indicates that comparison was included in analysis of variance

Table 12 Summary statistics (of SEL) of eight paired comparisons in duration study.

Description of Comparison (Variable Level *vs* Fixed Level Signal)	N	Mean Level of Variable Level Signal, dB	Level of Fixed Level Signal, dB	Mean Difference
15 sec simulated *vs* 15 sec simulated backblast	27	82.5	82.1	0.4
40 sec simulated *vs* 15 sec simulated backblast	27	82.4	82.1	0.3
120 sec simulated *vs* 15 sec simulated backblast	27	83.7	82.1	1.6
40 sec recorded *vs* 15 sec simulated backblast	28	79.9	82.1	-2.2
120 sec simulated *vs* 40 sec simulated backblast	28	85.2	83.3	1.9
40 sec recorded *vs* 40 sec simulated backblast	28	78.9	83.3	-4.4
15 sec recorded *vs* 15 sec recorded backblast	28	82.5	81.6	0.9
40 sec recorded *vs* 15 sec recorded backblast	28	79.0	81.6	-2.6

Figure 31 displays the A-weighted sound levels of the variable level signals when judged to be equal in annoyance to the fixed level signals for all eight comparisons in the duration study. (Many overlapping judgments are obscured by the plotting symbols.) The heavy horizontal lines mark the levels of the fixed signals, while the solid triangles indicate the mean levels of the variable signals for each comparison. If the mean of the variable level signal is lower than the fixed level signal, then the fixed signal would be more annoying at equal levels. If the mean of the variable signal is higher than that of the fixed signal, then the variable level signal would be more annoying at equal levels.

Three comparisons (marked with asterisks in Table 11) were subjected to a repeated measures analysis of variance (ANOVA) to investigate the effects of varying signal duration on subjects' judgments of annoyance. The durations of the variable level signals for these three comparisons were 15 seconds, 40 seconds, and 2 minutes, whereas the duration of the fixed level signal was always 15 seconds. The signals were identical in their spectral contents and differed only in duration. Data from two subjects were dropped from this analysis since their resultant annoyance judgments were more than three standard deviations from the mean in at least one of the three comparisons. Hence, data from 27 subjects were included in this analysis.

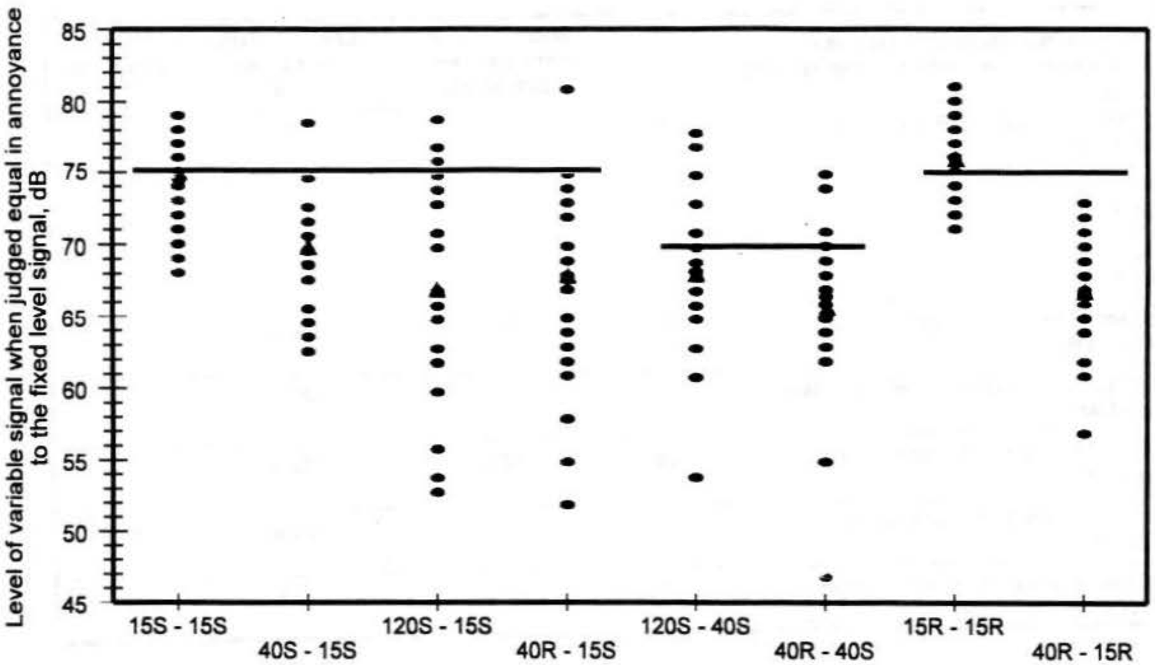


Figure 31 Level of variable level signal when judged to be equally annoying to the fixed level signals for all comparisons in the duration study. Mean values of the variable level signal are plotted as solid red triangles. Dark horizontal lines indicate fixed signal levels.

Table 13 shows the results of the ANOVA. A statistically significant effect of duration was found (with $F_{(2,52)} = 20.8$, $p < .001$). Mean levels of the three variable signals at the points of equal annoyance are shown in Figure 32. Increasing the duration of the variable level signal from 15 to 40 seconds produced an increase of 5.8 dB in the level of the variable signal at the point of subjective equality. A further increase in the duration of the variable signal to 120 seconds yielded an increase of 7.7 dB in the level of the variable signal at the point of subjective equality.

Table 13 Summary of analysis of variance results for effects of duration on annoyance.

SOURCE	SS	df	MS	F	p
Duration	863.5	2	431.8	20.8	<.001
Error	1,079.3	52	20.8		

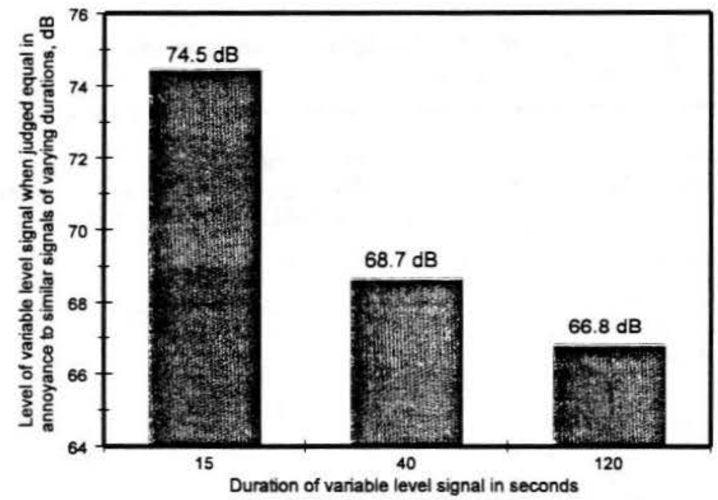


Figure 32 Mean levels of variable signals of varying durations when judged equally annoying to a similar fixed level signal of 15 seconds in duration.

6.2.4 Results of Low-Frequency Study

Table 14 summarizes the results of twelve paired comparisons tested in the low-frequency study in A-weighted levels. The second column contains the number of subjects whose resulting variable signal levels were within three standard deviations of the mean for each comparison and hence included in further analyses. The third column of the table contains the average level of the variable level signal when judged to be equal in annoyance to the fixed level signals. The fourth column contains the levels of the fixed level signals in each comparison. The fifth column contains the average differences between the variable and fixed level signals at the point of subjective equality.

Figure 33 shows the levels of the variable level signals when judged equal in annoyance to the intermediate-range backblast signal. The red bar indicates the level of the fixed level signal. The center comparison (of the blue shaded bars) is the intermediate-range signal versus itself (with a mean of 74.7 dB). The level of the very long-range backblast signal as well as the level of the runway threshold noise signal were within 1 dB of the level of the intermediate-range backblast signal at the point of equal annoyance. The level of the intermediate-range backblast signal was 5 dB lower than the long-range backblast signal at the point of equal annoyance. The level of the intermediate-range backblast signal was 3 dB lower than the short-range backblast signal at the point of equal annoyance.

Table 14 Summary statistics (of maximum A-weighted levels) of annoyance judgments for 12 paired comparisons in low-frequency study.

DESCRIPTION OF COMPARISON (VARIABLE LEVEL *vs* FIXED LEVEL SIGNAL)	N	MEAN LEVEL OF VARIABLE LEVEL SIGNAL, dB	LEVEL OF FIXED LEVEL SIGNAL, dB	DIFFERENCE
simulated very long-range backblast *vs* simulated intermediate-range backblast	28	74.1	75	-0.9
simulated long-range backblast *vs* simulated intermediate-range backblast	28	80.1	75	5.1
simulated long-range backblast *vs* simulated intermediate-range backblast	28	80.0	75	5.0
simulated intermediate-range backblast *vs* simulated intermediate-range backblast	28	74.7	75	-0.3
simulated short-range backblast *vs* simulated intermediate-range backblast	28	78.0	75	3.0
simulated runway threshold noise *vs* simulated intermediate-range backblast	28	75.4	75	0.4
simulated long-range backblast *vs* simulated short-range backblast	27	78.5	75	3.5
simulated very long-range backblast *vs* runway threshold noise	28	75.5	75	0.5
recorded long-range backblast *vs* simulated intermediate-range backblast	28	75.6	75	0.6
recorded B727 overflight *vs* simulated intermediate-range backblast	28	72.7	75	-2.3
recorded B757 overflight *vs* simulated intermediate-range backblast	27	71.7	75	-3.3
simulated intermediate-range backblast *vs* recorded departure noise	28	70.3	75	-4.7

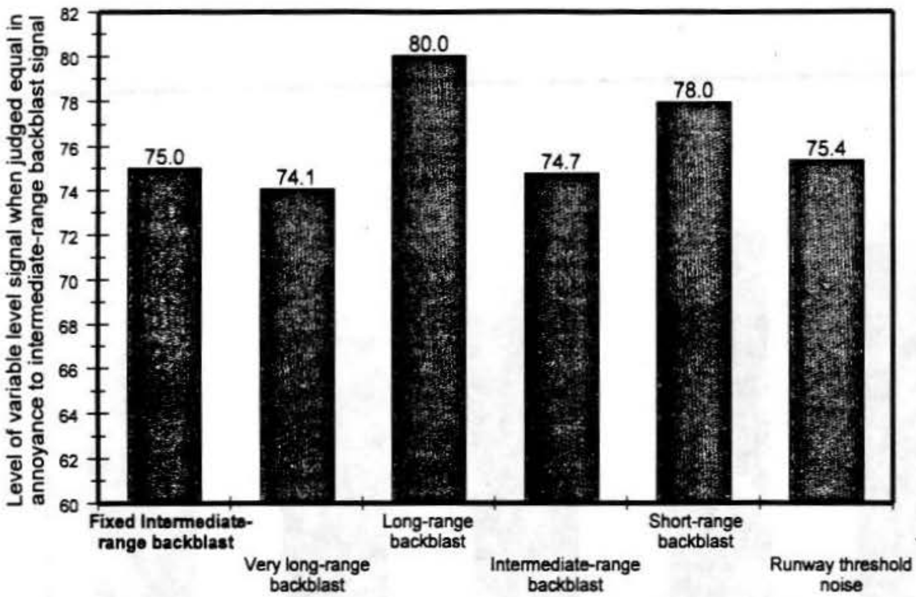


Figure 33 Mean levels of five signals with varying spectral content when judged to be equal in annoyance to the intermediate-range backblast signal. The red bar indicates the level of the fixed level signal.

Figure 34 compares the annoyance of simulated intermediate-range backblast noise and recorded flyover and backblast noise at short and long ranges. In all but the long-range backblast noise case, the recorded signals were lower in maximum A-level than the simulated signals at the point of equal annoyance. Aircraft flyover noise recordings were 2-3 dB lower and the short-range backblast signal was 5 dB lower than the simulated medium-range backblast signal at judged equal annoyance. The maximum A-level of the recorded long-range backblast signal was comparable (0.5 dB higher) than the simulated intermediate-range backblast signal. However, as shown in Figure 33, the simulated long-range backblast signal was 5 dB higher than the simulated intermediate-range backblast at the point of subjective equality. Thus the recorded long-range backblast signal would be about 4. 5 dB lower in level than the simulated backblast signal when judged to be equal in annoyance. In general, recorded signals are lower in maximum A-level than simulated backblast signals.

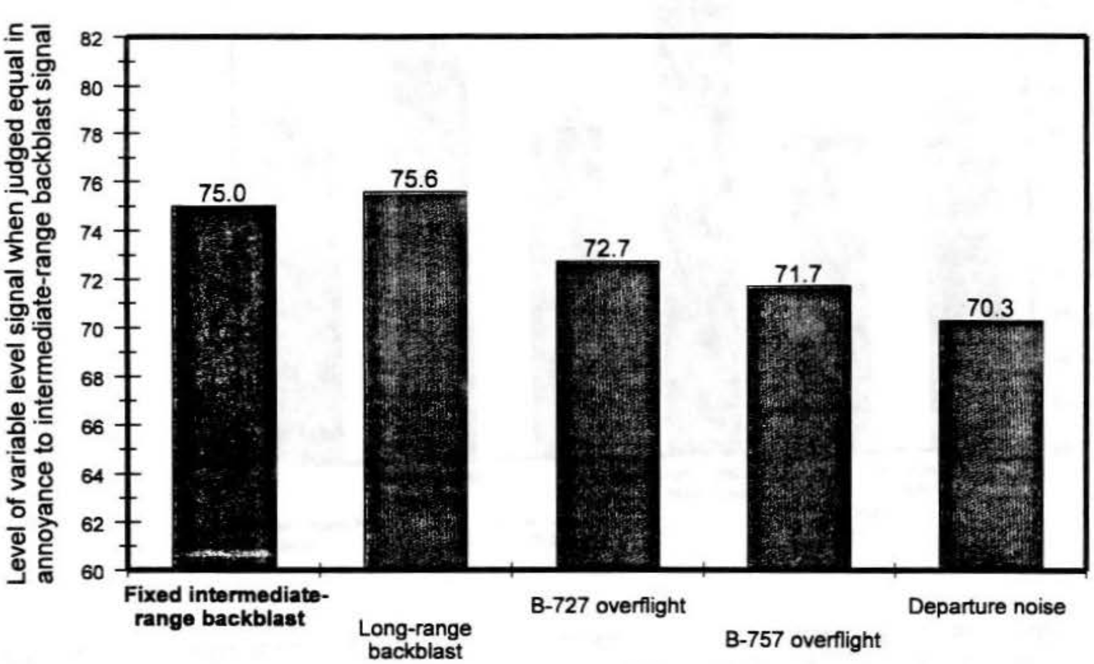


Figure 34 Mean level of recorded long-range backblast, B727, B757, and departure noise signals when judged equal in annoyance to the intermediate-range backblast signal. The red bar indicates the level of the fixed level signal.

6.3 DISCUSSION OF FINDINGS OF DURATION STUDY

The data show that sounds of longer duration must be lower in level to be judged equal in annoyance to sounds of shorter duration. Figure 35 suggests that the amount of increase is related to the amount of energy in the signal, at a rate of 3 dB for every doubling of duration. The red regression line through the data points and the blue line representing 3 dB per doubling are in close agreement.

Figure 36 illustrates a similar conclusion with a nearly horizontal regression line through the data points using SEL as a metric. (SEL takes account of duration of the signal as well as its maximum level.) It was noted when field recordings were made of the signals for the judgment tests that durations of two minutes were not uncommon for backblast noise. This was further confirmed by field measurements of duration associated with noise levels tabulated at locations 3A and 3B in Table 5 on Page 25. If durations of 15 seconds are assumed for typical aircraft flyover noises under the departure flight path near an airport, then all other things being equal, the backblast noise would have to be 9 dB lower than the shorter-duration flyover signal to be judged equally annoying.

Correcting for duration differences by expressing paired comparison judgments in units of SEL, recorded backblast sounds were judged between 2.2 and 4.4 dB more annoying than synthesized backblast sounds.

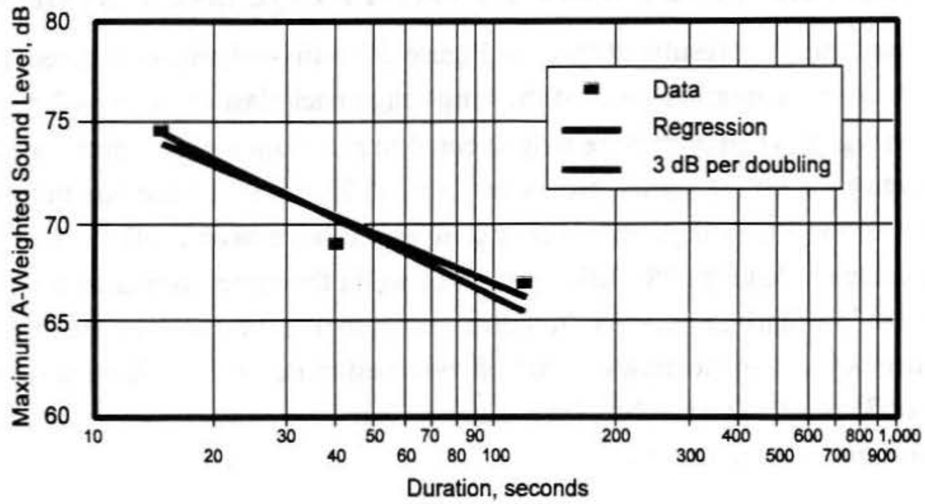


Figure 35 Signal level at judged equal annoyance, maximum A-weighted sound level *vs.* log duration.

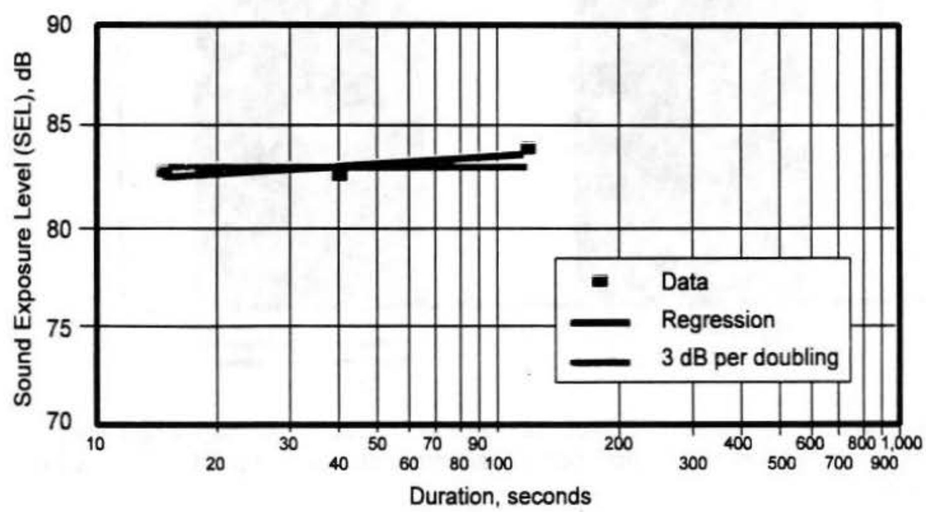


Figure 36 Signal level at judged equal annoyance, SEL *vs.* log duration.

6.4 DISCUSSION OF FINDINGS OF LOW-FREQUENCY STUDY

Figure 38 combines the results shown in Figure 37 with judgments derived from Figure 33. Figure 33 shows that the maximum A-level of the long-range backblast signal was 2 dB higher than the short-range backblast signal when both were judged equal in annoyance to the intermediate-range signal. Thus, if the short-range backblast signal had been fixed at 75 dB (the case for the results shown in Figure 37), the level of the long-range backblast signal would have been 2 dB higher (77 dB) at equal annoyance. This is comparable to the 78.5 dB result obtained for the direct comparison shown in Figure 37 (replotted in Figure 38). Similarly, Figure 38 shows the results for the level of the very long-range backblast signal when equal in annoyance to the runway threshold noise estimated at 73.7 dB do not differ greatly from the observed value of 75.5 dB. The results of these comparisons are another indication of the consistency and reliability of the annoyance judgments.

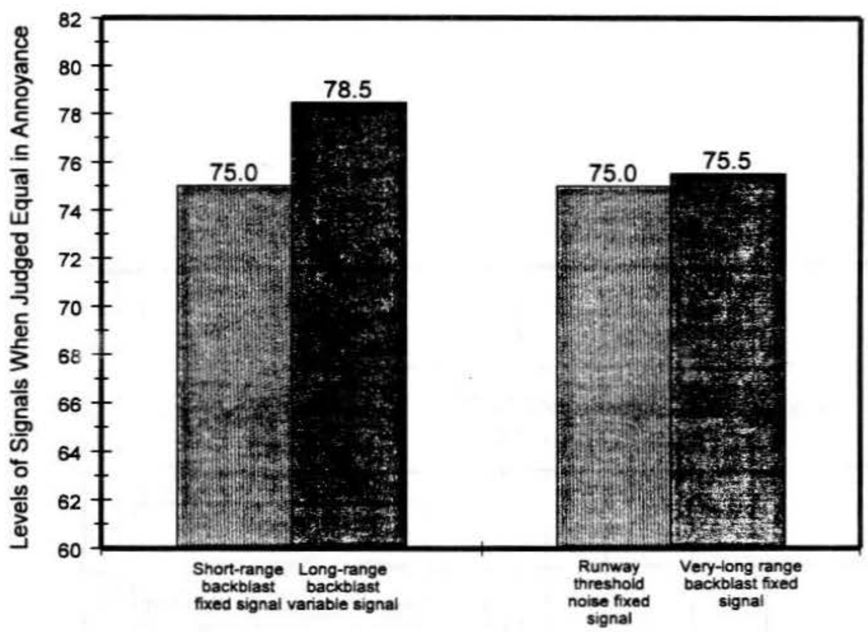


Figure 37 Mean levels of long-range and very long-range backblast signals when judged to be equal in annoyance to the fixed level short-range backblast signal and the fixed runway threshold noise, respectively.

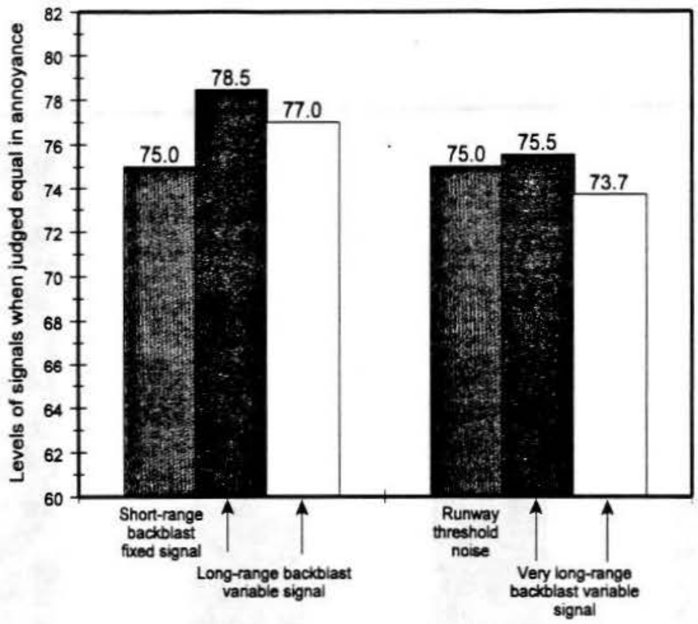


Figure 38 Mean levels of long-range and very long-range backblast signals when judged to be equal in annoyance to the fixed level short-range backblast signal and the fixed runway threshold noise, respectively. (Data represented by yellow bars were derived from data in Figure 33.)

6.4.1 Findings of Related Laboratory Study of Annoyance of Low-Frequency Noise and Rattle

A similar study (Pearsons, Fidell, Silvati, and Howe, 1999) employing identical trial procedures and some of the same test sounds documented the effect of rattle on the annoyance of low-frequency aircraft noise. The same backblast signal as compared to sideline noise was presented for annoyance judgments to 28 subjects, with and without rattle sounds. Figure 39 shows that the addition of minor amounts of rattling sounds notably increased the annoyance of the backblast signal.

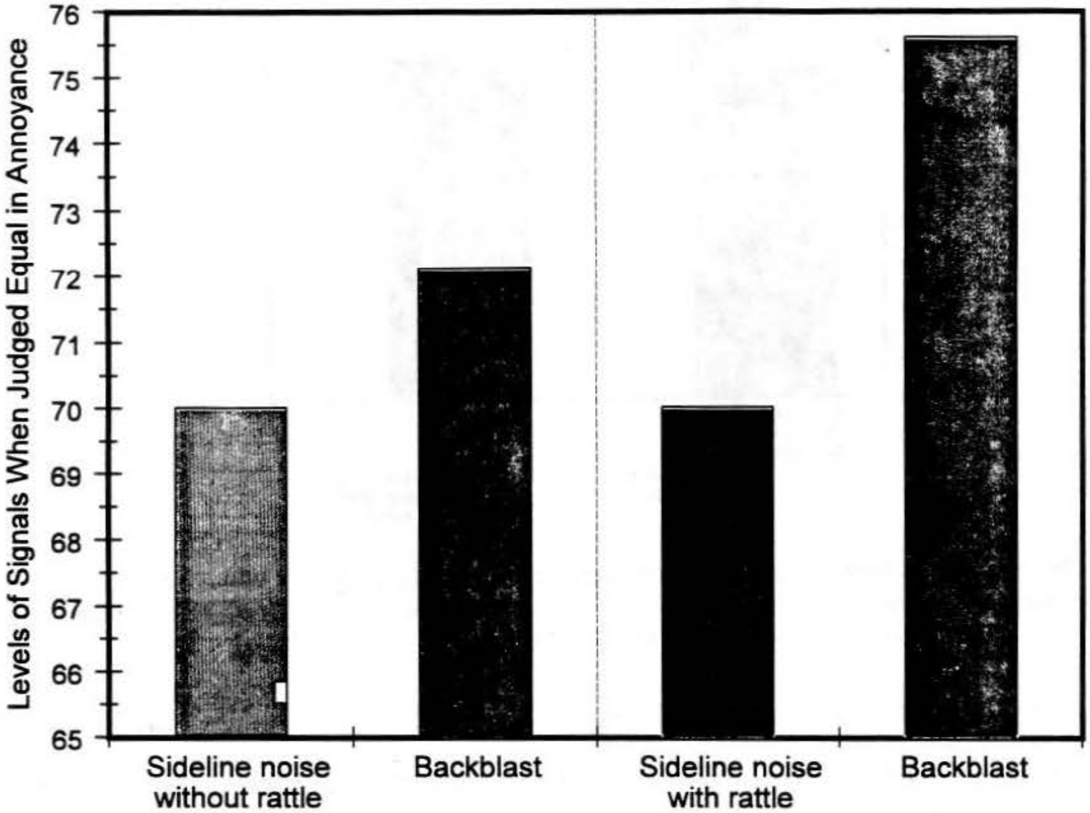


Figure 39 Effect of rattle on annoyance judgment of sideline noise.

7 CONCLUSIONS

The major conclusions that may be drawn from this study include the following:

- Backblast noise is a readily measurable concentration of low-frequency noise created by individual aircraft departures in areas behind Runways 01L/R at SFO.

- The density of aircraft noise complaints in residential areas to the southwest of Runways 01L/R is greatest in two areas of Millbrae, Burlingame, and Hillsborough located roughly two miles from the start of takeoff roll.

- Although these two areas lie well outside of SFO's 65 dB CNEL contour, their locations are consistent with high noise levels associated with the directivity of jet engine exhaust noise.

- Meteorological conditions may be responsible for inducing considerable variability (at least ± 5 dB) in low-frequency aircraft departure noise level and duration in areas of Millbrae, Burlingame, and Hillsborough. Therefore, reliable prediction of times of day and seasons of the year when backblast noise is likely to be particularly high in level requires very detailed information about atmospheric conditions.

- C-weighted sound levels of individual aircraft departures measured in these two areas often exceed 80 dB, and can occasionally reach levels in the high 90 dB range, depending on aircraft type and other factors.

- Low-frequency sound levels corresponding to these C-weighted levels vary from about 70 to 90 dB in the one-third octave bands from 25 to 80 Hz.

- Instances of backblast noise associated with individual departures can be of unusually long duration with respect to typical aircraft overflight noise.

- When judged equally annoying, longer-duration, backblast-like sounds are lower in level than shorter-duration sounds by 3 dB per doubling of duration throughout the range of durations from 15-120 seconds. This finding confirms the need to keep in mind a 10 log (duration) correction in planning measures intended to mitigate the annoyance of backblast noise.

- The annoyance of backblast is heightened by its duration and potentially by the production of rattle in homes.

- When judged equally annoying, the maximum A-weighted sound levels of backblast noises lasting two minutes or more are 5 to 7 dB lower than those of typical aircraft overflights.

8 REFERENCES

Berglund, B., Hassmén, P., and Job, R.F.S. (1996). "Sources and effects of low-frequency noise," *J. Acoust. Soc. Am.*, *99*(5), 2985-3002.

Blazier, W. (1991) "Noise Control Criteria for Heating, Ventilating, and Air-Conditioning Systems," Chapter 43 of Harris, C. (ed.), Third Edition, Handbook of Acoustical Measurements and Noise Control, McGraw-Hill, Inc., New York.

Broner, N. (1978). "The effects of low-frequency noise on people — a review," *J. Sound and Vib.*, *58*(4), 483-500.

Brown, D., and Sutherland, L.C. (1992), "Evaluation of Outdoor-to-Indoor Response to Minimized Sonic Booms," NASA Contractor Report 189643, Langley Research Center, Hampton, VA.

Caltrans Division of Aeronautics (1984). "Monitoring data, aircraft noise frequency analysis, San Francisco International Airport."

Connor, W. (1986). "Investigation of aircraft departure noise in community areas behind runways 1L and 1R at San Francisco International Airport," Tracor Applied Sciences Document T86-01-9521U, Austin, TX.

FAA Engineer's Report (1998) "Residential Sound Insulation at Baltimore/Washington International Airport," AIP 3-24-0005-39.

Federal Interagency Committee on Noise (FICON) (1992). Final Report: Airport Noise Assessment Methodologies and Metrics, Washington, D.C.

Fidell, S., Silvati, L., Pearsons, K., Lind, S., and Howe, R. (1999). "Field study of the annoyance of low-frequency runway sideline noise," *J. Acoust. Soc. Am.*, in press.

Fidell, S., Silvati, L., Pearsons, K., (1999). "Field study of the annoyance of aircraft noise-induced rattle and vibration at MSP," *J. Acoust. Soc. Am.*, in press.

Gilfillan, W. (1999). "Fast Track Item III.B — Backblast noise insulation pilot project; Initial findings," Memorandum prepared for 7 April 1999 meeting of Airport/Community Roundtable.

Green, D. M. (1990). "Stimulus selection in adaptive psychophysical procedures," *J. Acoust. Soc. Am.*, *87*(6), pp. 2662-2674.

Green, D. M. (1995). "Maximum likelihood procedures and the inattentive observer," *J. Acoust. Soc. Am.*, *97*(6), pp. 3749-3760.

Horonjeff, R.D. and Thompson (1996). "Logan Low-Frequency Noise Study," HMMH Report 293810.04.

Harris Miller Miller & Hanson (1996b). "Development of Single Event Noise Metrics for Use in Identifying Aircraft Operations for Possible Mitigation," HMMH Report 294090.

Hubbard, H. (1982). "Noise Induced House Vibrations and Human Perception," *Noise Control Engineering Journal*, *19*(2), pp. 49-55.

Kesterson, J., Vondemkamp, M., and Connor, W. (1987). "Investigation of low-frequency noise from departures on runways 1L and 1R at San Francisco International Airport," Tracor Project 076-439(-01), Austin, TX.

Lind, S., Pearsons, K., and Fidell, S. (1997). "An Analysis of Anticipated Low-Frequency Aircraft Noise in Richfield Due to Operation of a Proposed North-South Runway at MSP," BBN Report 8196.

Miller, Reindel, Senzig and Horonjeff (1998). "Study of Low-Frequency Takeoff Noise at Baltimore-Washington International Airport," HMMH Report 294730.300/293100.09.

Passchier-Vermeer, W. (1998). "Vibrations in the living environment: Factors related to vibration perception and annoyance," TNO Prevention and Health Report 98.022, Leiden, The Netherlands.

Passchier-Vermeer, W., and Zeichart, K. (1998). "Vibrations in the living environment: Relationships between vibration annoyance and vibration metrics," TNO Prevention and Health Report 98.022, Leiden, The Netherlands.

Pearsons, K., Fidell, S., Silvati, L., and Howe, R. (1999). BBN Contribution to Richfield-MAC Low Frequency Noise Expert Panel.

Shade, N. T. (1997). "Final Report: BWI Low-Frequency Noise Analysis for Allwood Neighborhood," Acoustical Design Collaborative Project 96.01, Falls Church, VA.

Sutherland, L. (1982) "Low-frequency response of structures," Wyle Research Report WR 22-18.

Sutherland, L., Sharp, B., and Mantey, R., (1983). "Preliminary evaluation of low-frequency noise and vibration reduction retrofit concepts for woodframe structures," Wyle Research Report WR 83-26.

Zhou, B., and Green, D. M. (1995). "Reliability of pure-tone thresholds at high frequencies," *J. Acoust. Soc. Am.*, *98*(2:1), pp. 828-836.

Zwicker, E. (1977). "Procedure for calculating loudness of temporally variable sounds," *J. Acoust. Soc. Am.*, *62*, pp. 675-682.

9 GLOSSARY

Definitions of formal acoustic quantities correspond to those of *American National Standard S1.1-1994 Acoustical Terminology*. Other terms, abbreviations, and symbols are defined in the sense in which they are used in this report.

A-weighted sound level: A single number index of a broadband sound that has been subjected to the A-weighting network (*q.v.*).

A-weighting network: A frequency-equalizing function intended to approximate the sensitivity of the human hearing to sounds of moderate sound pressure level.

C-weighted sound exposure level: Sound exposure level, as defined below, where C-weighted sound pressure is used instead of A-weighted sound pressure. Unit, decibel; abbreviation, CSEL; symbol, L_{CE}.

day average sound level: Time-average sound level between 0700 and 2200 hours. Unit, decibel (dB); abbreviation, DL; symbol, L_d. Note: Day average sound level in decibels is related to the corresponding day sound exposure level, L_{Ed}, according to:

$$L_d = L_{Ed} - 10 \log(54000/1)$$

where 54,000 is the number of seconds in a 15-hour day.

day-night average sound level: Twenty-four hour average sound level for a given day, after addition of 10 decibels to levels from 0000 to 0700 hours and from 2200 (10 p.m.) to 2400 hours. Unit, decibel (dB); abbreviation, DNL; symbol, L_{dn}. Note: Day-night average sound level in decibels is related to the corresponding day-night sound exposure level, L_{Edn}, according to:

$$L_{dn} = L_{Edn} - 10 \log(86400/1)$$

where 86,400 is the number of seconds in a 24-hour day. A-frequency weighting is understood, unless another frequency weighting is specified explicitly.

departure noise: A general descriptive term for noise created by aircraft operations on a departure runway.

energy average. Colloquial term for time-mean-square average of a series of sound signals.

energy summation. Colloquial term loosely used to indicate addition of non-coherent sound signals by the sum of the squares of their sound pressures or sound exposures.

instantaneous sound pressure: Total instantaneous pressure at a point in a medium minus the static pressure at that point. Unit, pascal (Pa); symbol, p.

maximum sound level; maximum frequency-weighted sound pressure level: Greatest fast (125 ms) A-weighted sound level within a stated time interval. Alternatively, slow (1000 ms) time-weighting and C-frequency-weighting may be specified. Unit, decibel (dB); abbreviation, MXFA; symbol, L_{AFmx} (or C and S).

night average sound level: Time-average sound level between 0000 and 0700 hours and 2200 and 2400 hours. Unit, decibel (dB); abbreviation, NL; symbol, L_{n}. Note: Night average sound level in decibels is related to the corresponding night sound exposure level, $L_{E\mathrm{n}}$, according to:

$$L_{\mathrm{n}} = L_{E\mathrm{n}} - 10 \log(32400/1)$$

where 32,400 is the number of seconds in a 9-hour night.

one-hour average sound level: Time-average sound level during a time period of one hour. Unit, decibel (dB); abbreviation, 1HL; symbol, $L_{1\mathrm{h}}$. Note: One-hour average sound level in decibels is related to the corresponding one-hour sound exposure level, $L_{E1\mathrm{h}}$, according to:

$$L_{1\mathrm{h}} = L_{E1\mathrm{h}} - 10 \log(3600/1)$$

where 3600 is the number of seconds in one hour, 1 s is the reference duration for sound exposure, and sound exposure E is in pascal-squared seconds.

NOTE – Procedures for computing perceived noise level are stated in Federal Aviation Regulation Part 36, *Noise Standards: Aircraft Type and Airworthiness Certification*, Appendix B, and in International Civil Aviation Organization Annex 16, Volume 1, *Aircraft Noise*, Third Edition, July 1993.

sound exposure: Time integral of squared, instantaneous frequency-weighted sound pressure over a stated time interval or event. Unit: pascal-squared second; symbol, E. Note: If frequency weighting is not specified, A-frequency weighting is understood. If other than A-frequency weighting is used, such as C-frequency weighting, an appropriate subscript should be added to the symbol; e.g., E_{C}.

Duration of integration is implicitly included in the time integral and need not be reported explicitly. For the sound exposure measured over a specified time interval such as one hour, a 15-hour day, or a 9-hour night, the duration should be indicated by the abbreviation or letter symbol, for example, one-hour sound exposure (1HSE or E_{1h}) for a particular hour; day sound exposure (DSE or E_d) from 0700 to 2200 hours; and night sound exposure (NSE or E_n) from 0000 to 0700 hours plus from 2200 to 2400 hours.

Day-night sound exposure (DNSE or E_{dn}) for a 24-hour day is the sum of the day sound exposure and 10 times the night sound exposure. Unless otherwise stated, the normal unit for sound exposure is the pascal-squared second.

sound level; weighted sound pressure level: Ten times the logarithm to the base ten of the ratio of A-weighted squared sound pressure to the squared reference sound pressure of 20 μPa, the squared sound pressure being obtained with fast (F) (125 ms) exponentially weighted time-averaging. Alternatively, slow (S) (1000 ms) exponentially weighted time-averaging may be specified; also C-frequency weighting. Unit, decibel (dB); symbol L_A, L_C. Note: In symbols, A-weighted sound level $L_{A\tau}(t)$ at running time t is:

$$L_{A\tau}(t) = 10 \log \left\{ \left[(1/\tau) \int_{-\infty}^{t} p_A^2(\xi)\, e^{-(t-\xi)/\tau}\, d\xi \right] / p_0^2 \right\}$$

where τ is the exponential time constant in seconds, ξ is a dummy variable of integration, $p_A^2(\xi)$ is the squared, instantaneous, time-varying, A-weighted sound pressure in pascals, and p_0 is the reference sound pressure of 20 μPa. Division by time constant τ yields the running time average of the exponential-time-weighted, squared sound-pressure signal. Initiation of the running time average from some time in the past is indicated by $-\infty$ for the beginning of the integral. ANSI S1.4-1983, *American National Standard Specification for Sound Level Meters*, gives standard frequency weightings A and C and standard exponential time weightings fast (F) and slow (S).

sound pressure; effective sound pressure: Root-mean-square instantaneous sound pressure at a point, during a given time interval. Unit, pascal (Pa). Note: In the case of periodic sound pressures, the interval is an integral number of periods or an interval that is long compared with a period. In the case of nonperiodic sound pressures, the interval should be long enough to make the measured sound pressure essentially independent of small changes in the duration of the interval.

sound pressure level: Ten times the logarithm to the base ten of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 μPa. Unit, decibel (dB); abbreviation, SPL; symbol, L_p.

time-average sound level; time-interval equivalent continuous sound level; time-interval equivalent continuous A-weighted sound pressure level; equivalent continuous sound level: Ten times the logarithm to the base ten of the ratio of time-mean-square instantaneous A-weighted sound pressure, during a stated time interval T, to the square of the standard reference sound pressure. Unit, decibel (dB); respective abbreviations, TAV and TEQ; respective symbols, L_{AT} and L_{aeqT}. Note: A frequency weighting other than the standard A-weighting may be employed if specified explicitly. The frequency weighting that is essentially constant between limits specified by a manufacturer is called flat.

In symbols, time-average (time-interval equivalent continuous) A-weighted sound level in decibels is:

$$L_{AT} = 10 \log\left\{\left[(1/T)\int_o^T p_A^2(t)\,dt\right]/p_0^2\right\}$$
$$= L_{AeqT}$$

where p_A^2 is the squared instantaneous A-weighted sound pressure signal, a function of elapsed time t; in gases reference sound pressure $p_0 = 20\ \mu$Pa; T is a stated time interval. In principle, the sound pressure signal is not exponentially time-weighted, either before or after squaring.

APPENDIX A INSTRUCTIONS TO TEST SUBJECTS

What you will hear during a listening session

You will hear many pairs of sounds during the course of three listening sessions. Your job will always be the same: to listen carefully to each sound of a pair of sounds, and then to push either the first or the second button on the response box to tell us which of the two sounds was more annoying.

> ***In making your decision about which of the pair of sounds was more annoying, you should assume that each sound occurs 20 to 30 times a day in your home. Think about which of the two sounds you would not want to hear in your home 20 to 30 times a day and select that sound.***

When to Make Your Judgment

You must wait until the second sound of each pair ends before you decide which of the pair of sounds was more annoying. During the first session, some of the sounds will last much longer than others, and you may be comparing the annoyance of relatively short sounds and longer sounds. When deciding which of a pair of sounds is more annoying, you must be patient, and take into consideration your overall annoyance throughout the entire sound, not just how loud the two sounds were at one time or another.

> ***Remember: The computer will not let you judge the annoyance of a pair of sounds until you have heard both sounds completely. Please be patient, listen carefully to all of both sounds, and wait until the second sound ends before responding.***

Trial Sequence

The experimenter will show you into the room where the experiment will take place. You should sit down and pick up the response box. You will be using this box to record your answers during the study.

1. When you first start a listening session, the display on the response box will ask if you are ready to begin. The left button on the display will indicate "Yes" and the right button will indicate "No." Press the "Yes" button when you are ready to begin.

2. Next, the display will indicate "Experiment in Progress" and "Listen now for noise [1]." You will then see the lefthand light and hear the first noise.

3. Then the display will indicate "Listen now for noise [2]" and you will see the right-hand light and hear the second noise.

4. Once the second noise has finished playing the screen will say "Which noise was more annoying?" and you will see on the display, "Interval 1" with an arrow pointing to the left button and "Interval 2" with an arrow pointing to the right button. Push the button corresponding to the noise that you think was more annoying. Once you have done that, the next pair of sounds will be presented.

5. ***Your judgments of annoyance for each pair of sounds should be based only on the current pair of sounds and not on any pair heard previously***. You will hear many pairs of sounds in an unpredictable order, so you must judge the relative annoyance of only the two sounds that you have just heard.

Each listening session will last about two hours, but there will be opportunities to take a five minute break every thirty minutes or so. Each listening session consists of four or more experiments. When an experiment has been completed, the display on the black box will say "You have finished Experiment [number]." An OK button will be displayed with this message. You should click the OK button to begin the next experiment.

On your first day, the experimenter will show you how the study works and will sit with you in the testing room while you hear some of the test sounds. The sound levels that you will hear during the listening session will never be louder than the sounds that you hear during this initial training session. Once the actual experiment begins, the experimenter will not be in the testing room with you, but will be able to see and hear you on a TV monitor.

Just talk at any time you have a question or want to contact the experimenter. If you feel uncomfortable at any time in the testing room and you do not wish to continue, just stop pressing the buttons on the black box and the sounds will stop. You may then leave the room, or tell the experimenter that you want to stop, and the experimenter will open the door of the testing room so that you can leave.