NPOA Report No. 91-4
March 1992

N-96-01
II-A-728

HMMH Report No. 290940.02

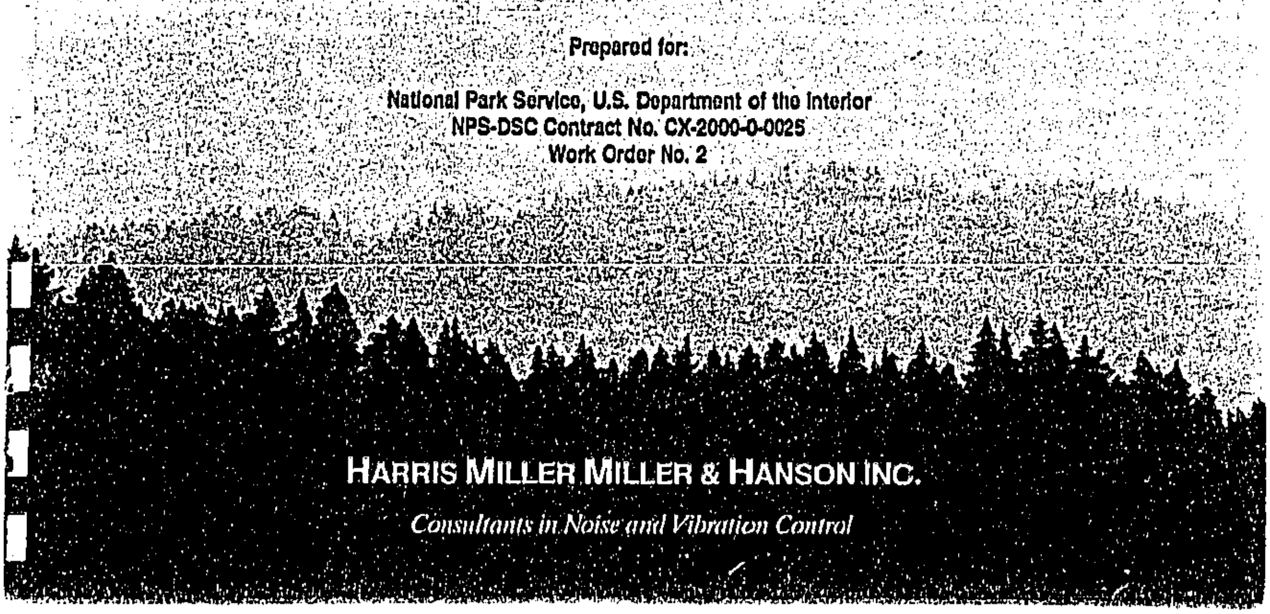
AIRCRAFT OVERFLIGHT STUDY

Effect of Aircraft Altitude Upon Sound Levels at the Ground

Grant S. Anderson, Richard D. Horonjeff

Prepared for:

National Park Service, U.S. Department of the Interior
NPS-DSC Contract No. CX-2000-0-0025
Work Order No. 2



HARRIS MILLER MILLER & HANSON INC.

Consultants in Noise and Vibration Control

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FOREWORD

This report was prepared by Harris Miller Miller & Hanson Inc. under Work Order No. 2 of National Park Service Contract CX-2000-0-0025: Comprehensive Aircraft Management Studies, Various National Park Service Areas -- administered by the Department of Interior, National Park Service.

EXECUTIVE SUMMARY

Background and overview. Section 1(a) of Public Law 100-91 requires the Secretary of the Interior, acting through the Director of the National Park Service, to "conduct a study to determine the proper minimum altitude which should be maintained by aircraft when flying over units of the National Park System."

As part of that study, the technical acoustical literature was reviewed to determine the effects of altitude on aircraft sound levels on the ground. This report summarizes that literature review. And based upon that literature review, this report discusses the potential acoustical effectiveness of using altitude as a mitigation measure for any adverse effects of aircraft sound within the National Park System.

To avoid confusion and to conform to common word usage, this report uses "height" instead of "altitude" to denote "height above the ground." In addition, because the total slant distance -- height combined with horizontal range -- is fundamental to the sound level on the ground, this report focuses upon the effect of total slant distance, rather than height alone, upon sound levels on the ground. Where necessary, a distinction is made between the height component and the horizontal component of total slant distance.

It is common knowledge that sound levels "drop off" with slant distance from a source of sound. This report discusses that drop off with distance. It is not so commonly known at what rate sound levels drop off as distance increases, nor that this drop-off rate depends upon a host of complicating factors. This report is primarily concerned with the drop-off rate of sound with slant distance, and with the various complicating factors that determine the drop-off rate.

Specifically, this report begins with the "baseline relationship" for the effect of slant distance upon sound levels. This baseline relationship is called "sound divergence." The report then discusses the factors that complicate this baseline relationship. These complicating factors consist of:

- "atmospheric absorption," which depends upon humidity, temperature, and atmospheric pressure -- plus strongly upon the aircraft's sound spectrum (frequency components),
- attenuation due to intervening hills and heavily wooded areas,
- "ground attenuation," which depends upon the type of ground and its proximity to the sound path -- as well as the aircraft's sound spectrum, the wind direction/speed, and vertical temperature gradients, and

- the particular "acoustical descriptor" that is of concern as the aircraft flies by. As an aircraft flies by, its sound level first increases as the aircraft approaches, then reaches a maximum, and then decreases as the aircraft recedes into the distance. Several acoustical descriptors are commonly used to describe this flyby's entire sound-level history. Each of these acoustical descriptors is a different measure of the aircraft's sound during the flyby. Each can serve a different purpose in assessing the acoustical effects of the flyby. And each depends somewhat differently upon slant distance.

Finally, this report concludes with a summary of the effect of aircraft altitude upon sound levels on the ground, taking all these complicating factors into account. Included in this summary is a discussion of the potential acoustical effectiveness of using altitude as a mitigation measure for any adverse effects of aircraft sound within the National Park System.

General findings. The literature review resulted in the following general findings concerning the effect of aircraft slant distance on sound levels on the ground:

- Due to "sound divergence," sound levels decrease 6 decibels for every doubling of slant distance from any source of sound, including aircraft.

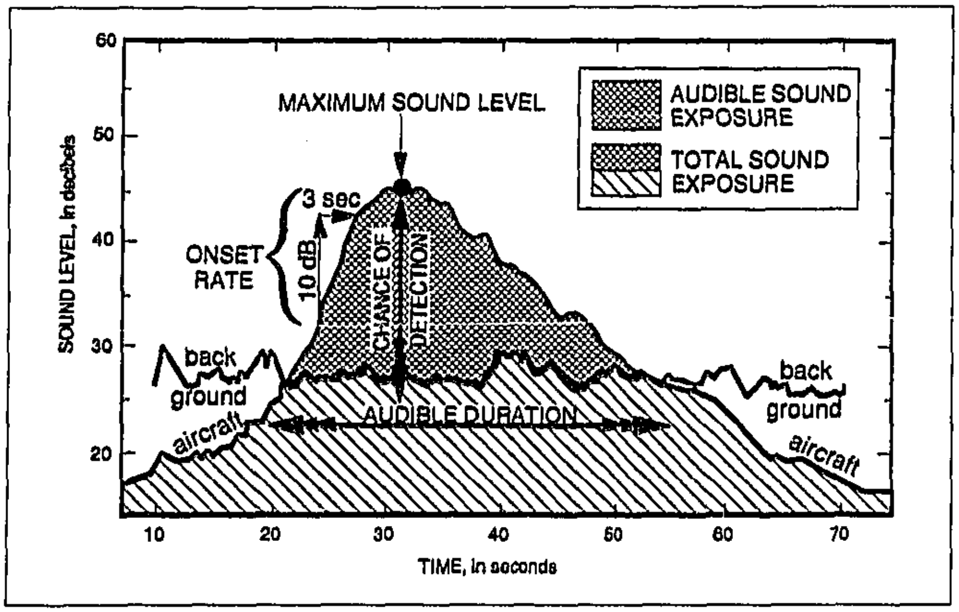
  A 6-decibel reduction is a moderate-to-substantial one -- equivalent to decreasing one's voice effort from "loud" to "raised," or from "raised" to "normal" -- or equivalent to facing directly away from a listener instead of directly towards the listener. A 6-decibel reduction is easily sensed by people, even when they are not being attentive to the sound. Two such reductions, for a total reduction of 12 decibels, are equivalent to shutting a window to outdoor sounds.
- Due to "atmospheric absorption," sound levels decrease with slant distance an additional amount of approximately 1-to-2 decibels every 1000 feet.
- Taking both sound divergence and atmospheric absorption into account, stepped increases in slant distance reduce sound levels in steps as well, but with "diminishing returns." The sound-level steps become ever smaller with increasing distance.
- If an aircraft flies by at a relatively large horizontal range, and if the aircraft height is low enough so that hills or heavily wooded areas interrupt the sound path throughout the aircraft's flyby, then these hills will further reduce the aircraft's sound level on the ground. In general, aircraft sound levels are reduced greatly (15-to-25 decibels) by intervening hills, and are reduced substantially (10-to-15 decibels) by intervening heavily wooded areas.

  This sound-level reduction generally occurs at relatively low aircraft heights, but only at relatively large horizontal ranges. Contrary to all trends discussed above, increasing aircraft height in this situation causes an *increase* in sound level to distant listeners/microphones -- as the aircraft emerges into direct view. Once the aircraft rises high enough so that the hills and wooded areas no longer intervene, however, this effect is finished and the sound level then decreases as usual with increasing aircraft height.

- In a manner analogous to intervening hills, "acoustically soft" terrain (grassland or other ground that contains root structure, plowed or aerated earth, snow, or other "fissured" ground) reduces sound levels when sound paths "graze" across such terrain. This reduction can be as large as 10-to-15 decibels when the elevation angle of the aircraft, above the horizontal, is very small.

  In this case, increasing the aircraft height causes an *increase* in sound level to distant listeners/microphones -- as the aircraft rises above the ground's influence. Once the aircraft rises high enough, however, this effect is finished and the sound level then decreases as usual with increasing aircraft height.

More specific details. As an aircraft flies by, its sound level first increases as the aircraft approaches, then reaches a maximum, and then decreases as the aircraft recedes into the distance. The following figure shows this varying sound level during a representative flyby:



Different acoustical descriptors can be used to describe this entire flyby. Several descriptors of potential concern to the Park Service are shown in an approximate manner in the figure. See the main text and appendices for definitions and further explanation of these descriptors. Each of these descriptors is a different measure of the aircraft's sound during the flyby.

The effect of aircraft height upon these acoustical descriptors depends upon the location of the flight track relative to the listener/microphone on the ground. Three situations are of importance:

- when the flight track is directly overhead, or nearly so,
- when the flight track is to the side, laterally displaced from the listener /microphone, with the sound grazing across relatively flat ground, and
- when the flight track is "below" the listener/microphone, directly visible in an immediately adjacent valley, gorge, or canyon.

Flight track overhead. When the flight track is directly overhead, or nearly so, then the sound levels at the listener/microphone reduce in value as aircraft height increases. The following table shows the approximate effect of increased slant distance upon the acoustical descriptors that are of potential importance to the National Park Service:

APPROXIMATE CHANGES IN SOUND LEVELS
DUE TO 1000-FOOT INCREASES IN SLANT DISTANCE TO THE FLIGHT TRACK

INCREASE IN SLANT DISTANCE TO FLIGHT TRACK	DECREASE IN MAXIMUM SOUND LEVEL	DECREASE IN ONSET RATE	DECREASE IN TOTAL SOUND EXPOSURE	DECREASE IN AUDIBLE SOUND EXPOSURE	DECREASE IN CHANCE OF DETECTION	CHANGE IN AUDIBLE DURATION
from 125 ft to 1,000 ft	24 dB	28 dB/sec	14 dB	14 dB	0 %	+10 sec
then to 2,000 ft	8 dB	3 dB/sec	6 dB	6 dB	0 %	+7 sec
then to 3,000 ft	5 dB	1 dB/sec	5 dB	5 dB	0 %	+7 sec
then to 4,000 ft	4 dB	1 dB/sec	3 dB	3 dB	0 %	+4 sec
then to 5,000 ft	4 dB	1 dB/sec	2 dB	2 dB	0 %	+2 sec
then to 6,000 ft	3 dB	0 dB/sec	2 dB	2 dB	0 %	0 sec
then to 7,000 ft	3 dB	0 dB/sec	2 dB	2 dB	0 %	0 sec
then to 8,000 ft	2 dB	0 dB/sec	2 dB	2 dB	0 %	−1 sec
then to 9,000 ft	2 dB	0 dB/sec	2 dB	2 dB	0 %	−2 sec
then to 10,000 ft	2 dB	0 dB/sec	2 dB	2 dB	1 %	−2 sec
then to 11,000 ft	2 dB	0 dB/sec	2 dB	2 dB	10 %	−2 sec
then to 12,000 ft	2 dB	0 dB/sec	2 dB	4 dB	40 %	−4 sec
then to 13,000 ft	2 dB	0 dB/sec	1 dB	7 dB	25 %	−6 sec
then to 14,000 ft	2 dB	0 dB/sec	1 dB	11 dB	10 %	−12 sec
then to 15,000 ft	2 dB	0 dB/sec	1 dB	17 dB	4 %	−15 sec
then to 16,000 ft	2 dB	0 dB/sec	1 dB	25 dB	1 %	−22 sec

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for 'moderate' background sound levels. See text for other conditions.

2. The tabulated acoustical descriptors are defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

For the first three acoustical descriptors in the table (Maximum Sound Level, Onset Rate, and Total Sound Exposure), 1000-foot stepped increases in slant distance reduce the acoustical descriptors in steps, as well, but with "diminishing returns." The situation is more complex for the last three descriptors in the table (Audible Sound Exposure, Chance of Detection, and Audible Duration), which depend upon aircraft audibility above the non-aircraft background sounds. For the Audible Sound Exposure, the steps first decrease in the normal manner, but then they become quite large at the bottom of the table. This "transition to inaudibility" at the bottom of the table also causes the tabulated pattern for the Chance of Detection and the Audible Duration.

In the table, the transition to inaudibility occurs at a slant distance around 10,000-to-15,000 feet. However, this transition to inaudibility would occur at different slant distances for commercial jets at other speeds, and for other aircraft, and for other amounts of background sound. Even in a single location within a park, note that background sound levels often vary significantly from day to day, hour to hour, and even moment to moment -- often influenced strongly by time-varying wind speed. In short, the transition to inaudibility is real, but occurs at a slant distance highly dependent upon local wind and upon aircraft flight conditions.

Flight track to the side over relatively flat ground. The situation is more complex when the flight track is to the side, laterally displaced from the listener/microphone, with the sound grazing across relatively flat ground. The table is a starting point for this situation, as well. In addition, however, when the aircraft appears at low elevation angles with the horizontal, "acoustically soft" ground may attenuate the aircraft sound even further than shown in the table, or it may be further attenuated by intervening hills or heavily wooded areas.

In these situations, the amount of further attenuation depends upon the elevation angle of the aircraft above the acoustically soft ground, or upon the blockage in the sound path by the hills or heavily wooded areas. In turn, these depend upon the aircraft's height above the ground. Increasing the aircraft height in these situations causes an *increase* in sound level -- as the aircraft rises above the ground's influence, or the hill's influence, or the wooded-area's influence. Once the aircraft rises high enough, however, this effect is finished and the sound level then decreases with increasing aircraft height, as shown in the table.

Flight track "below" -- directly visible in an immediately adjacent valley, gorge, or canyon. When the flight track is "below" the listener/microphone, directly visible in an immediately adjacent valley, gorge, or canyon, the situation differs in two respects. First, even though the flight track is to the side, as described in the previous section, the sound does not graze across flat ground nor is it blocked by intervening hills or heavily wooded areas. For this reason, the sound is not attenuated further than shown in the table. In other words, such a flight track produces the same changes due to 1000-foot increases in slant distance as does a flight track overhead. Of importance only is the slant distance to the flight track.

Second, some aircraft direct different amounts of sound upwards and sideways, compared to downwards. These differences in source "directivity" result in a different sound level upwards/sideways than downwards, for the same slant distance to the flight track. With this relative orientation between the flight track and the listener/microphone held constant, however, the pattern of dependence of sound level upon slant distance is similar to that shown in the table above.

The potential acoustical effectiveness of altitude as a mitigation measure. The table above shows, at large slant distances, that sound-level reductions converge to small values (tend toward zero) for each 1,000-foot increase in slant distance. In other words, 1000-foot stepped increases in slant distance reduce sound levels in steps as well, but with "diminishing returns." The sound-level steps become ever smaller with increasing slant distance.

For this reason, the enforcement of minimum altitudes above units of the National Park System has potential acoustical effectiveness only when the aircraft presently fly relatively low above these units. Slant-distance increases from 125 feet to 1,000 feet, for example, would produce very large reductions in sound level (15-to-25 decibels or so). Increases from 1,000 feet to 2,000 feet would produce smaller reductions, still moderate to substantial. Increases from 10,000 feet to 11,000 feet, on the other hand, would produce only very small reductions in sound level (around 2 decibels), and so would have little potential for effective mitigation.

In other words, moderate-to-substantial benefits (4-to-10 decibels or so) require an approximate doubling of the slant distance between the aircraft and the listener/microphone. Where existing slant distances are small, their doubling may come easily, depending upon non-acoustical circumstances. On the other hand, where existing distances are large, their doubling is essentially impossible. Where existing slant distances are intermediate, their doubling becomes more and more difficult the greater their initial value. Doubling them may or may not be practicable for non-acoustical reasons.

If altitude restrictions are attempted as a mitigation measure above units of the National Park Service, care must be taken to avoid the loss of soft-ground attenuation, or of attenuation due to hills or heavily wooded areas. Where aircraft now fly low, these attenuations may now accrue to points on the ground at large horizontal ranges from the aircraft flight track. Requiring aircraft to fly higher in such situations might actually increase sound levels far from the flight tracks -- as the aircraft are forced higher, into direct view or out of the ground's acoustical influence.

Several acoustical descriptors of aircraft sound reduce nearly to zero at specific slant distances -- distances at which an aircraft becomes essentially inaudible. In the table above, this transition to inaudibility occurs at a slant distance of approximately 10,000-to-15,000 feet. This transition to inaudibility depends strongly, however, upon the "moderate" background sound levels used to compute this table. To a first approximation, transition to inaudibility would occur at approximately 4,000-to-5,000 feet in the presence of "strong" surf sound in a National Seashore, and at approximately 20,000-to-30,000 feet in areas with background sound levels close to the threshold of human hearing. Moreover, inaudibility would occur at lesser distances for quieter aircraft and larger distances for louder ones.

In brief, we do not recommend any particular "inaudibility" distance as a minimum altitude restriction above units of the National Park Service, for two reasons: (1) because inaudibility depends strongly upon background sound levels, which are difficult to predict and which vary significantly from day to day, hour to hour, and even moment to moment, and (2) because inaudibility depends strongly, as well, upon the type of aircraft and its speed.

Aircraft sound also reduces with increased horizontal range, because increases in horizontal range cause corresponding increases in slant distance. In addition, as horizontal range increases, the chance of obtaining further attenuation improves, if the sound grazes over acoustically soft ground or is interrupted by hills or heavily wooded areas. For this reason, when aircraft fly low, relocating flight tracks to increase the horizontal range to sound-sensitive areas within parks is a potentially effective mitigation measure.

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FIGURES

TABLES

Chapter 1. BACKGROUND AND OVERVIEW

Section 1(a) of Public Law 100-91 requires the Secretary of the Interior, acting through the Director of the National Park Service, to "conduct a study to determine the proper minimum altitude which should be maintained by aircraft when flying over units of the National Park System."

As part of that study, the technical acoustical literature was reviewed to determine the effects of altitude on aircraft sound levels on the ground. The study's literature review included a search of existing scientific literature that relates to (1) the most common aircraft types flying over units of the National Park System, and (2) the "acoustical descriptors" (measures) of aircraft sound that are most relevant to the park situation.

This report summarizes that literature review, discussing sound divergence, atmospheric absorption, attenuation due to intervening hills and heavily wooded areas, soft-ground attenuation, and the acoustical descriptors that are of potential concern to the Park Service as the aircraft flies by.

Finally, this report concludes with a summary of the effect of aircraft altitude upon sound levels on the ground, taking all these factors into account. Included in this summary is a discussion of the potential acoustical effectiveness of using altitude as a mitigation measure for any adverse effects of aircraft sound within the National Park System.

Chapter 2. PRELIMINARY REMARKS CONCERNING THE WORDS: ALTITUDE, HEIGHT, HORIZONTAL RANGE, AND TOTAL SLANT DISTANCE

2.1 Altitude and height

The word "altitude" is not used often in this report. Its use is clouded by two conflicting meanings: (1) height above the ground, and (2) height above sea level. Only the first meaning is important here: height above the ground. Therefore, to avoid confusion and to conform to common word usage, this report uses "height" instead of "altitude" to denote "height above the ground."

2.2 Height, horizontal range, and total slant distance

As an aircraft flies past a listener/microphone, its sound level there depends upon its flight track's *total distance* from the listener/microphone. And this distance depends upon both the aircraft's height above the ground and its horizontal range to the listener/microphone. In this report, this total distance is called a "slant distance" to emphasize its two components: height and horizontal range.

Because the total slant distance -- height combined with horizontal range -- is fundamental to the sound level on the ground at the listener/microphone, this report focuses upon the effect of total slant distance, rather than height alone, upon aircraft sound levels on the ground. Where necessary, a distinction is made between the height component and the horizontal-range component of total slant distance.

Chapter 3. THE "BASELINE RELATIONSHIP" OF THE EFFECT OF SLANT DISTANCE UPON SOUND LEVELS

As sound propagates outward from its source, the waves of sound "diverge" to fill more and more space as they progress outward [Anderson, 1992] [Delany, 1978] [Embleton, 1982] [Pierce, 1981] [Piercy, 1977, 1991]. Because they fill ever more space, the sound waves become ever more diluted as they diverge. This dilution of sound with distance is the "baseline relationship" for the effect of slant distance upon aircraft sound levels. It is technically called "sound divergence."

Due to sound divergence, sound levels decrease 6 decibels for every doubling of slant distance from the source of sound, here an aircraft.[1] For example, if the sound level were 94 decibels at a distance of 125 feet from the aircraft, it would reduce to 88 decibels (94 minus 6) at a distance of 250 feet, then to 82 decibels (88 minus 6) at 500 feet, then to 76 decibels (82 minus 6) at 1,000 feet -- and so on. Table 1 shows this distance-doubling behavior.

Table 1. Sound-level Reduction Due to Divergence Only: Double-distance Steps

SLANT DISTANCE	DISTANCE STEP	SOUND LEVEL	SOUND-LEVEL STEP
125 feet	------------	94 dB	------------
250 feet	125-foot increase	88 dB	down 6 dB
500 feet	250-foot increase	82 dB	down 6 dB
1,000 feet	500-foot increase	76 dB	down 6 dB
2,000 feet	1,000-foot increase	70 dB	down 6 dB
4,000 feet	2,000-foot increase	64 dB	down 6 dB
8,000 feet	4,000-foot increase	58 dB	down 6 dB
16,000 feet	8,000-foot increase	52 dB	down 6 dB

NOTE: Tabulated sound levels are based upon theory rather than upon actual aircraft measurements -- theory applied to an aircraft producing 94 decibels at 125 feet. Sound-level steps, however, apply to all aircraft types at all speeds.

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[1] A 6-decibel reduction is a moderate-to-substantial one -- equivalent to decreasing one's voice effort from "loud" to "raised," or from "raised" to "normal" -- or equivalent to facing directly away from a listener instead of directly towards the listener. A 6-decibel reduction is easily sensed by people, even when they are not being attentive to the sound. Two such reductions, for a total reduction of 12 decibels, are equivalent to shutting a window to outdoor sounds.

As is apparent from this table, larger distance steps are needed at larger slant distances, to achieve the same 6 decibels of reduction for each double-distance step. Another view of this same relationship appears in Table 2, this time for *equal* distance steps -- initially 125 feet, then 1000 feet below the dashed line.

Table 2. Sound-level Reduction Due to Divergence Only: Equal-distance Steps

SLANT DISTANCE	DISTANCE STEP	SOUND LEVEL	SOUND-LEVEL STEP
125 feet	————	94.0 dB	————
250 feet	125-foot increase	88.0 dB	down 6.0 dB
375 feet	125-foot increase	84.5 dB	down 3.5 dB
500 feet	125-foot increase	82.0 dB	down 2.5 dB
625 feet	125-foot increase	80.0 dB	down 2.0 dB
750 feet	125-foot increase	78.4 dB	down 1.6 dB
875 feet	125-foot increase	77.1 dB	down 1.3 dB
1,000 feet	125-foot increase	75.9 dB	down 1.2 dB
1,000 feet	————	75.9 dB	————
2,000 feet	1,000-foot increase	69.9 dB	down 6.0 dB
3,000 feet	1,000-foot increase	66.4 dB	down 3.5 dB
4,000 feet	1,000-foot increase	63.9 dB	down 2.5 dB
5,000 feet	1,000-foot increase	61.9 dB	down 2.0 dB
6,000 feet	1,000-foot increase	60.3 dB	down 1.6 dB
7,000 feet	1,000-foot increase	59.0 dB	down 1.3 dB
8,000 feet	1,000-foot increase	57.8 dB	down 1.2 dB
9,000 feet	1,000-foot increase	56.8 dB	down 1.0 dB
10,000 feet	1,000-foot increase	55.9 dB	down 0.9 dB
11,000 feet	1,000-foot increase	55.1 dB	down 0.8 dB
12,000 feet	1,000-foot increase	54.3 dB	down 0.8 dB
13,000 feet	1,000-foot increase	53.6 dB	down 0.7 dB
14,000 feet	1,000-foot increase	53.0 dB	down 0.6 dB
15,000 feet	1,000-foot increase	52.4 dB	down 0.6 dB
16,000 feet	1,000-foot increase	51.8 dB	down 0.6 dB

NOTE: Tabulated sound levels are based upon theory rather than upon actual aircraft measurements -- theory applied to an aircraft producing 94 decibels at 125 feet. Sound-level steps, however, apply to all aircraft types at all speeds.

As Table 2 shows, equal distance steps do not produce equal sound-level steps.. Equal distance steps have less effect at larger slant distances than they have at smaller slant distances. Their effect gradually tapers off towards the bottom of the table.

This table illustrates a very fundamental result in acoustics. Stepped increases in slant distance do reduce sound levels in steps as well, but with "diminishing returns." The sound-level steps become ever smaller. If the table were extended above 16,000 feet, the sound-level steps would tend ever closer to 0 dB for each additional 1,000-foot increase in slant distance.

Divergence, as summarized in Table 2, constitutes the baseline situation for the effect of slant distance upon sound levels. The following sections discuss several complications that overlay this baseline situation. These complications change the table somewhat, but do not change the essential nature of the "diminishing returns" achieved with stepped increases in slant distance.

Chapter 4. COMPLICATION: ATMOSPHERIC ABSORPTION AND AIRCRAFT SOURCE SPECTRA

The first complication concerns atmospheric absorption: the actual absorption of sound energy during its passage through the atmosphere [Anderson, 1992] [Delany, 1978] [Embleton, 1982] [Pierce, 1981] [Piercy, 1977, 1991]. This absorption is caused mostly by so-called "vibrational relaxation" of oxygen and nitrogen molecules during sound passage through air. It depends upon humidity, temperature, and atmospheric pressure -- plus strongly upon the frequency of sound.

4.1 Dependance upon humidity, temperature, atmospheric pressure, and sound frequency

Several standard methods exist for computing atmospheric absorption at different frequencies, as a function of humidity, temperature, and atmospheric pressure [ANSI, 1978] [SAE, 1975]. The most widely used of these for computation of aircraft sound is the series of tables published by the Society of Automotive Engineers (SAE) expressly for aircraft-sound computation. At 70 percent relative humidity, 75 degrees Fahrenheit, and one atmosphere pressure, the SAE tables show the following amount of atmospheric absorption -- for each 1000 feet of distance:

Frequency (Hertz):	50	63	80	100	125	160	200	250	315	400	500	630	800	1,000
Absorption (dB): per 1000 feet	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.6	0.7	0.9	1.1	1.4	1.8

Frequency (Hertz):	1,250	1,600	2,000	2,500	3,150	4,000	5,000	6,300	8,000	10,000
Absorption (dB): per 1000 feet	2.2	2.9	3.6	4.6	5.9	7.6	8.7	11.0	14.9	20.6

In this tabulation, the unit of sound frequency is Hertz (cycles per second). Absorptions are tabulated for every "1/3-octave band," centered at the frequencies shown.[2]

As shown in this tabulation, atmospheric absorption at 4,000 Hertz (7.6 dB per 1000 feet) is thirty-eight times as great as that at 100 Hertz (0.2 dB per 1000 feet). At a distance of 10,000

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[2] Three of these 1/3-octave bands constitute an "octave" on the piano -- between the note C and the next C, one octave higher, for example. As the tabulation shows, frequency doubles in value for each octave increase -- that is, for every three of these 1/3-octave bands. The word "octave" derives from the eight white keys in each piano octave.

feet, the atmosphere absorbs only 2 decibels at 100 Hertz, but a much larger 76 decibels at 4,000 Hertz.

Because outdoor humidity and temperature vary considerably from moment to moment and place to place along typical sound paths, computations with the full set of SAE tables are not practicable, for lack of adequate input. The federally sanctioned computer programs require only approximate average conditions for satisfactory computation.[3]

Table 2 on page 4 above must be modified to account for atmospheric absorption. Its modification obviously depends upon sound frequency, in accordance with the frequency-dependent absorption values on the previous page. At a frequency of 100 Hertz, for example, atmospheric absorption has only a small influence, as shown in Table 3.

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[3] This report refers often to the data bases and computations of three particular computer programs, sanctioned by the federal government for the prediction of aircraft sound levels:

- Integrated Noise Model (INM) of the Federal Aviation Administration (FAA), which pertains to commercial fixed-wing aircraft [FAA, 1982],
- Heliport Noise Model (HNM) of the FAA, which pertains to commercial helicopters [FAA, 1988], and
- NOISEMAP of the U.S. Air Force (USAF), which pertains to military fixed-wing aircraft and helicopters, but which contains useful baseline data for commercial aircraft, as well [USAF, 1986].

Table 3. Standardized Sound-level Reduction Due to Divergence and Atmospheric Absorption: Frequency = 100 Hertz

SLANT DISTANCE	DISTANCE STEP	SOUND LEVEL	SOUND-LEVEL STEP
125 feet	――――――	94.0 dB	――――――
250 feet	125-foot increase	88.0 dB	down 6.0 dB
375 feet	125-foot increase	84.5 dB	down 3.5 dB
500 feet	125-foot increase	81.9 dB	down 2.6 dB
625 feet	125-foot increase	79.9 dB	down 2.0 dB
750 feet	125-foot increase	78.3 dB	down 1.6 dB
875 feet	125-foot increase	77.0 dB	down 1.3 dB
1,000 feet	125-foot increase	75.7 dB	down 1.3 dB
1,000 feet	――――――	75.7 dB	――――――
2,000 feet	1,000-foot increase	69.5 dB	down 6.2 dB
3,000 feet	1,000-foot increase	65.8 dB	down 3.7 dB
4,000 feet	1,000-foot increase	63.1 dB	down 2.7 dB
5,000 feet	1,000-foot increase	60.9 dB	down 2.2 dB
6,000 feet	1,000-foot increase	59.1 dB	down 1.8 dB
7,000 feet	1,000-foot increase	57.6 dB	down 1.5 dB
8,000 feet	1,000-foot increase	56.2 dB	down 1.4 dB
9,000 feet	1,000-foot increase	54.0 dB	down 1.2 dB
10,000 feet	1,000-foot increase	52.9 dB	down 1.1 dB
11,000 feet	1,000-foot increase	51.9 dB	down 1.0 dB
12,000 feet	1,000-foot increase	50.9 dB	down 1.0 dB
13,000 feet	1,000-foot increase	50.0 dB	down 0.9 dB
14,000 feet	1,000-foot increase	49.2 dB	down 0.8 dB
15,000 feet	1,000-foot increase	48.4 dB	down 0.8 dB
16,000 feet	1,000-foot increase	47.6 dB	down 0.8 dB

NOTE: Atmospheric absorption was computed from the SAE standard method [SAE, 1975], assuming air at 70 percent relative humidity, 75 degrees Fahrenheit, and 1 atmosphere pressure. It applies to all aircraft types at all speeds.

At a frequency of 4,000 Hertz, in contrast, atmospheric absorption has a much larger influence than at 100 Hertz, as shown in Table 4.

Table 4. Standardized Sound-level Reduction Due to Divergence and Atmospheric Absorption: Frequency = 4,000 Hertz

SLANT DISTANCE	DISTANCE STEP	SOUND LEVEL	SOUND-LEVEL STEP
125 feet	————	94.0 dB	————
250 feet	125-foot increase	87.0 dB	down 7.0 dB
375 feet	125-foot increase	82.6 dB	down 4.4 dB
500 feet	125-foot increase	78.9 dB	down 3.5 dB
625 feet	125-foot increase	76.2 dB	down 2.9 dB
750 feet	125-foot increase	73.6 dB	down 2.6 dB
875 feet	125-foot increase	71.5 dB	down 2.2 dB
1,000 feet	125-foot increase	69.2 dB	down 2.2 dB
1,000 feet	————	69.2 dB	————
2,000 feet	1,000-foot increase	55.6 dB	down 13.6 dB
3,000 feet	1,000-foot increase	44.5 dB	down 11.1 dB
4,000 feet	1,000-foot increase	34.4 dB	down 10.1 dB
5,000 feet	1,000-foot increase	24.8 dB	down 9.6 dB
6,000 feet	1,000-foot increase	25.6 dB	down 9.2 dB
7,000 feet	1,000-foot increase	6.7 dB	down 8.9 dB
8,000 feet	1,000-foot increase	−2.1 dB	down 8.8 dB
9,000 feet	1,000-foot increase	−10.7 dB	down 8.6 dB
10,000 feet	1,000-foot increase	−19.2 dB	down 8.5 dB
11,000 feet	1,000-foot increase	−27.6 dB	down 8.4 dB
12,000 feet	1,000-foot increase	−36.0 dB	down 8.4 dB
13,000 feet	1,000-foot increase	−44.3 dB	down 8.3 dB
14,000 feet	1,000-foot increase	−52.5 dB	down 8.2 dB
15,000 feet	1,000-foot increase	−60.7 dB	down 8.2 dB
16,000 feet	1,000-foot increase	−68.9 dB	down 8.2 dB

NOTE: Atmospheric absorption was computed from the SAE standard method [SAE, 1975], assuming air at 70 percent relative humidity, 75 degrees Fahrenheit, and 1 atmosphere pressure. It applies to all aircraft types at all speeds.

At this high frequency of 4,000 Hertz, the sound-level steps approach 8 decibels of reduction for each additional 1,000-foot increase in slant distance at the bottom of the table. As is obvious, the dependence upon frequency is dramatic. Note that the negative sound levels in this table are real sound levels, though much too faint to be heard.

In total, the net effect for any type of aircraft depends upon what frequencies predominate in that aircraft's sound spectrum, as discussed next.

4.2 Aircraft spectra in the "loudest" direction

Sound emissions from aircraft contain a whole spectrum of sound frequencies: from the deepest "tremors" around 50 Hertz, to the mid-frequency "roaring" around 200 Hertz, to the high-frequency "whooshing and hissing" around 1,000-to-2,000 Hertz and higher. A particular aircraft's sound spectrum depends upon its type and somewhat upon its speed. In addition, for a particular aircraft type and speed, the sound spectrum depends upon the direction of sound emission from the aircraft. This directional effect is called the aircraft's' "directivity."

Many aircraft spectra appear in the acoustical literature and in the data bases of the federally sanctioned computer programs. Figures 1 through 4 contain "loudest-direction" spectra that are representative of those aircraft that fly over units of the National Park System. Plotted horizontally in each of these figures is frequency, with units of Hertz. Plotted vertically is sound pressure level, the basic unit of sound.

Also plotted at the right of each figure are the "A-weighted sound levels" for these aircraft. Each A-weighted sound level is a single number that is computed from the corresponding spectrum of 1/3-octave-band sound pressure levels to the left in the figure. In effect, the A-weighted sound level "condenses" the spectral information into a single number. A-weighted sound levels are prescribed by many governmental agencies to assess environmental sound. They correlate closely with human judgements of annoyance. In practice, they are read directly on sound level meters, with the "weighting switch" set on "A" [Anderson, 1992].

The commercial jet spectra of Figure 1 are typical of jet airliners on intercity routes. "Stage 2" refers to older-generation aircraft; "Stage 3" refers to newer-generation, generally quieter aircraft. These spectra were measured during development of the data base for the NOISEMAP computer model of the U.S. Air Force, for military planes/engines similar to those in commercial service [USAF, 1991]. Measurements were generally made at distances of 1000 feet, for aircraft flying between 300 and 400 miles per hour, or during takeoff.

The military jet spectra of Figure 2 are typical of U.S. military aircraft flying along military training routes. These spectra were also measured during development of the data base for the NOISEMAP computer model of the U.S. Air Force [USAF, 1991]. Measurements were generally made at distances of 1000 feet, for aircraft flying between 300 and 400 miles per hour.

The helicopter spectra of Figure 3 are typical of helicopters used for air tours over National Parks, plus military helicopters that overfly National Parks. These spectra were measured during development of the data bases for both the NOISEMAP computer model of the U.S. Air Force [USAF, 1991] and the Heliport Noise Model of the Federal Aviation Administration [FAA, 1988] [Newman, 1984 (all citations)] [True, 1977]. Measurements were generally made at distances of 500 feet, for helicopters flying between 70 and 150 miles per hour.

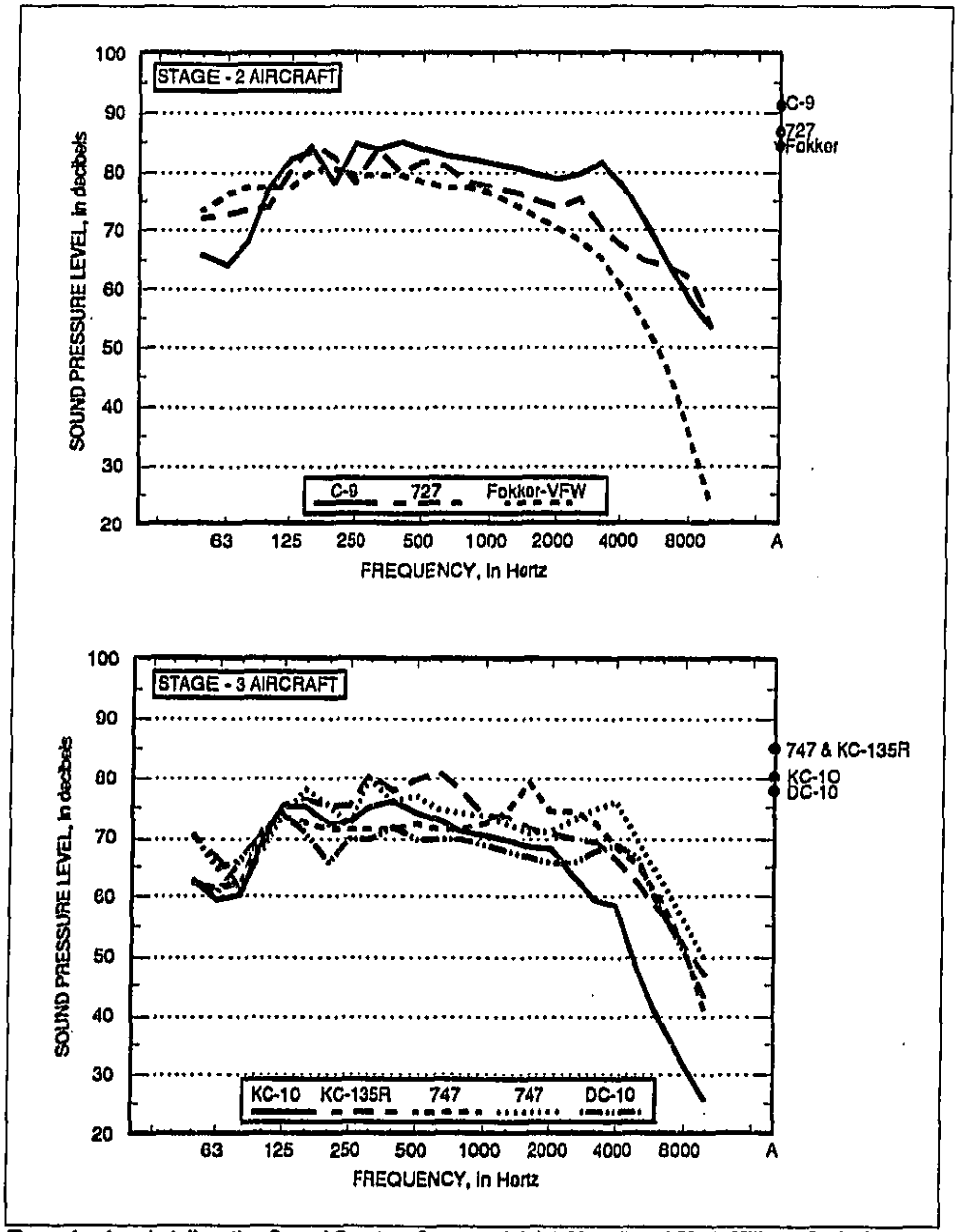

Figure 1. Loudest-direction Sound Spectra: Commercial Jet Aircraft and Their Military Equivalents

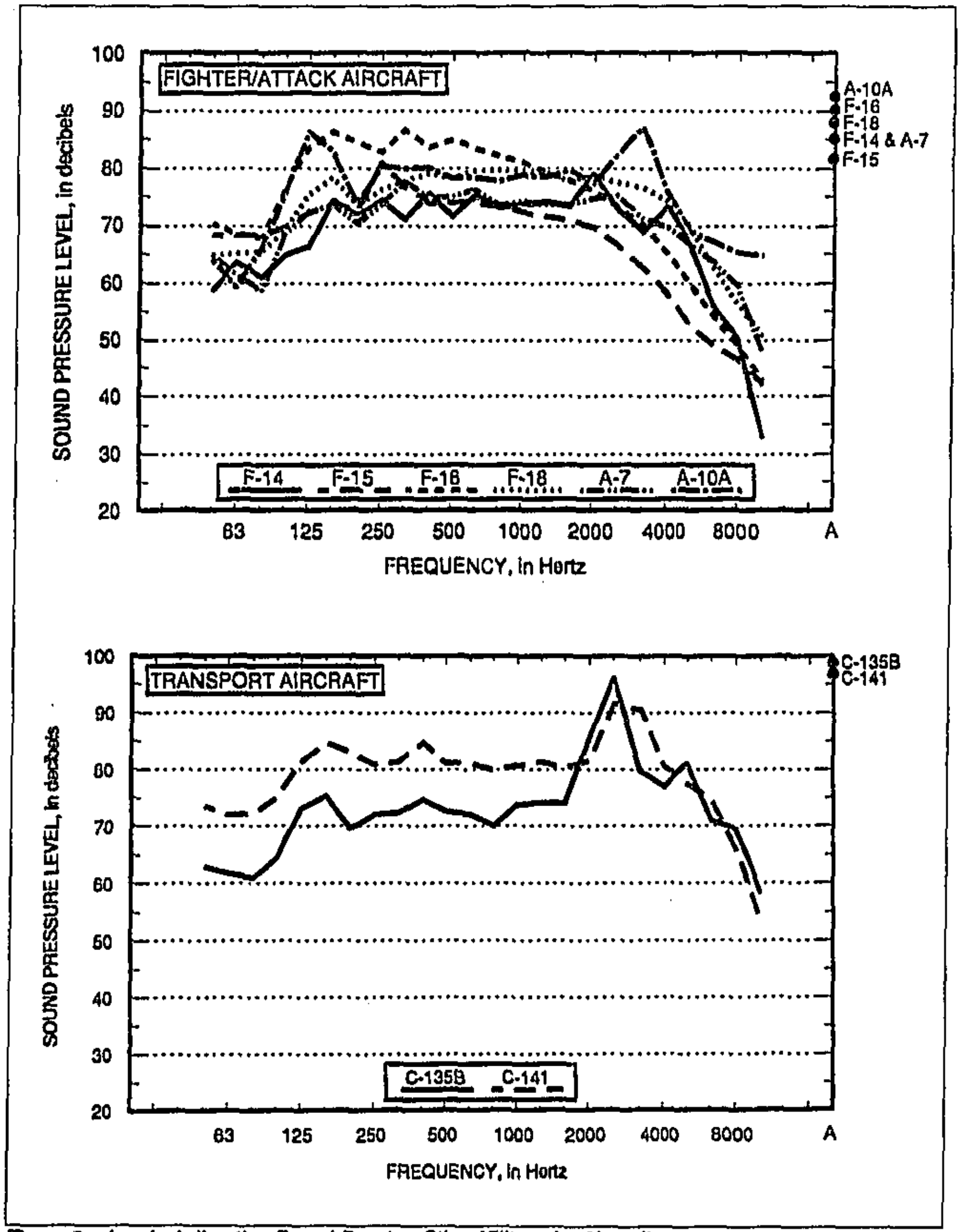

Figure 2. Loudest-direction Sound Spectra: Other Military Jet Aircraft

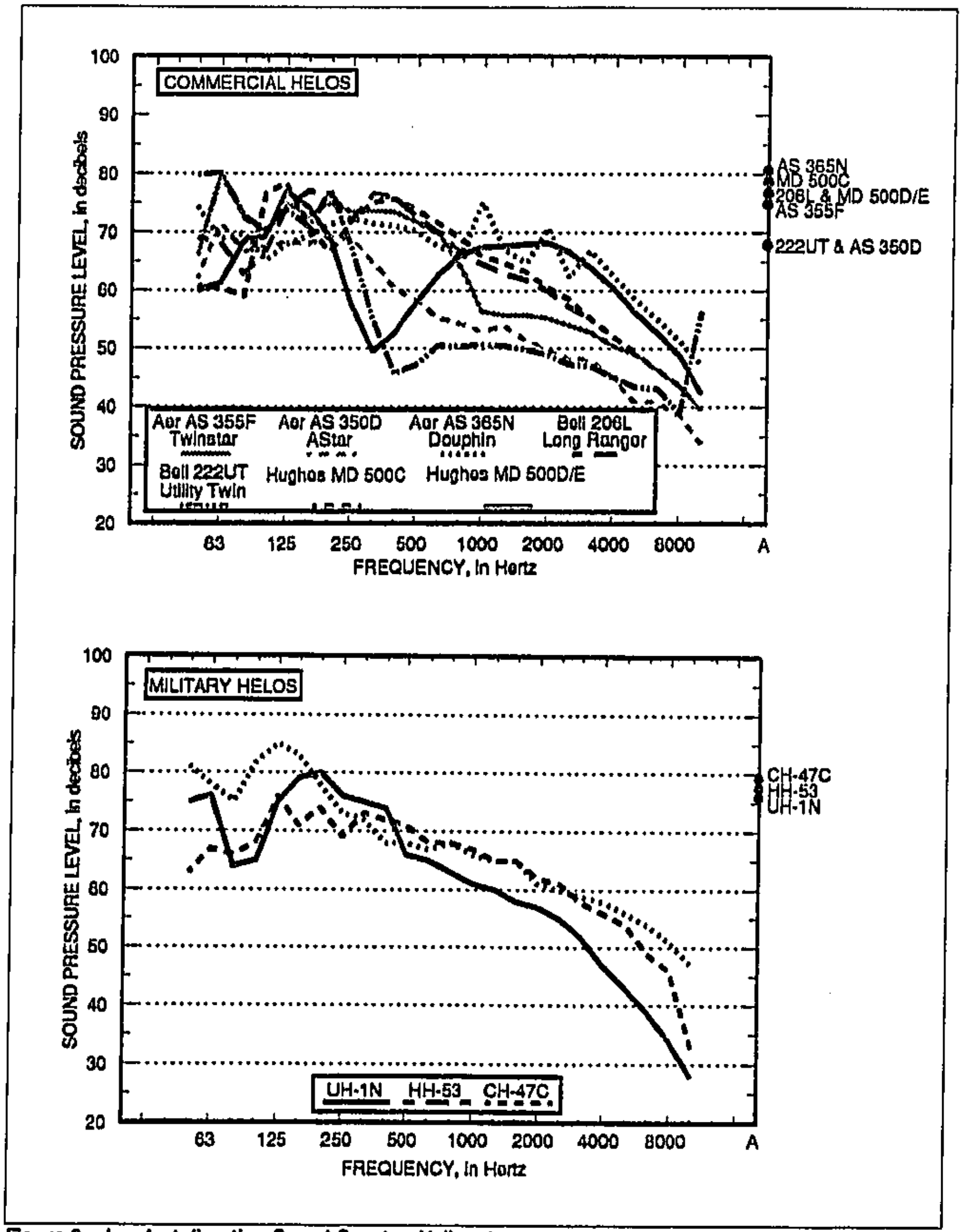

Figure 3. Loudest-direction Sound Spectra: Helicopters

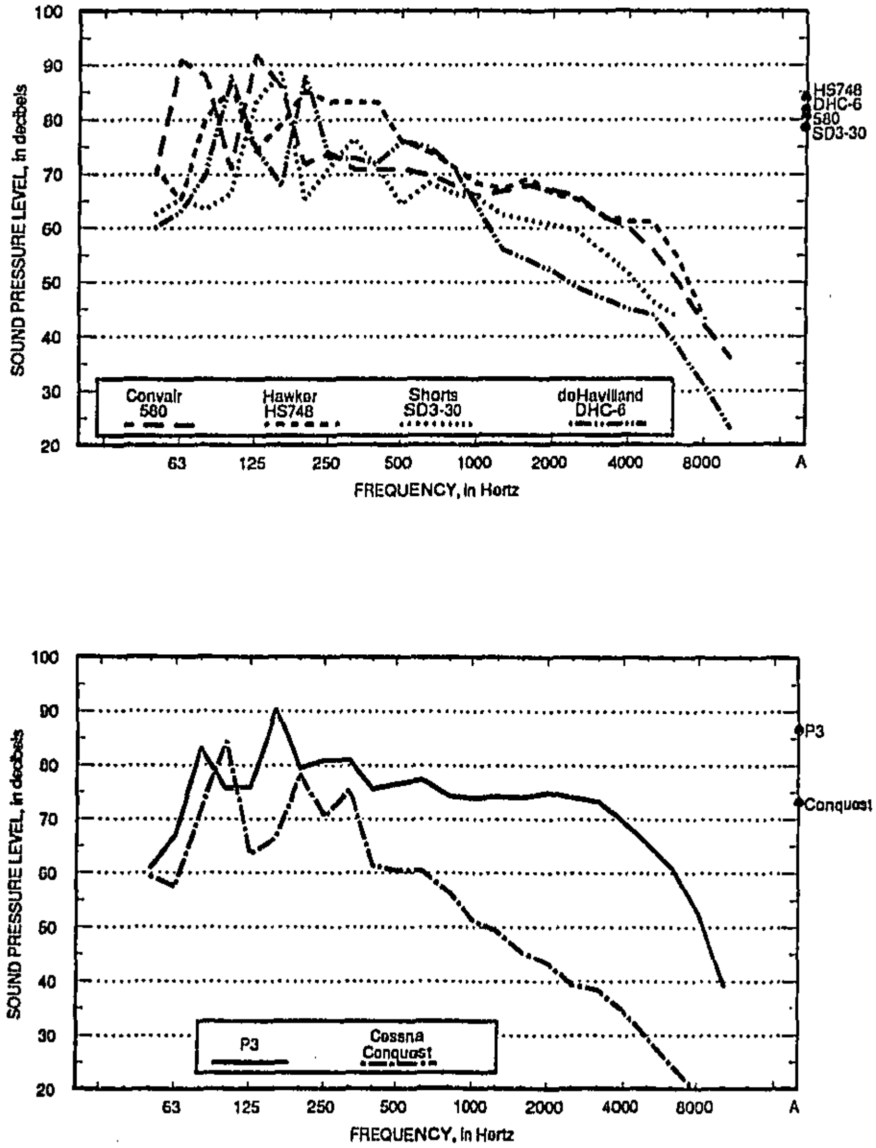

Figure 4. Loudest-direction Sound Spectra: Propeller Aircraft

The propeller-aircraft spectra of Figure 4 are typical of propeller aircraft used for air tours over National Parks. These spectra were also measured during development of the data base for the NOISEMAP computer model of the U.S. Air Force [USAF, 1991]. Measurements were generally made at distances of 1000 feet, for aircraft flying between 300 and 400 miles per hour, or during takeoff.

Of importance to atmospheric absorption is only the "shape" of an aircraft's spectrum -- roughly, the relative amounts of low-frequency and high-frequency sound energy emitted by the aircraft. The shapes of the spectra in Figures 1 through 4 depend only weakly upon the particular measurement conditions mentioned above. Measurements at closer range, for example, would shift a spectrum upwards on its graph but would not significantly change its shape.

4.3 Effect of atmospheric absorption on the maximum A-weighted sound level

The net result of atmospheric absorption is computed as follows. At any given distance from the aircraft, atmospheric absorption is subtracted from the aircraft's spectrum, separately in each 1/3-octave band. Then the sound pressure levels of each 1/3-octave band are combined into the A-weighted sound level for that distance. Table 5 results from such a computation.

Table 5. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Maximum Sound Level

SLANT DISTANCE	DISTANCE STEP	MAXIMUM SOUND LEVEL	MAXIMUM-SOUND-LEVEL STEP
125 feet	————————	94 dB	————————
250 feet	125-foot increase	87 dB	down 7 dB
375 feet	125-foot increase	82 dB	down 5 dB
500 feet	125-foot increase	79 dB	down 3 dB
625 feet	125-foot increase	76 dB	down 3 dB
750 feet	125-foot increase	74 dB	down 2 dB
875 feet	125-foot increase	72 dB	down 2 dB
1,000 feet	125-foot increase	70 dB	down 2 dB
1,000 feet	————————	70 dB	————————
2,000 feet	1,000-foot increase	62 dB	down 8 dB
3,000 feet	1,000-foot increase	57 dB	down 5 dB
4,000 feet	1,000-foot increase	53 dB	down 4 dB
5,000 feet	1,000-foot increase	49 dB	down 4 dB
6,000 feet	1,000-foot increase	46 dB	down 3 dB
7,000 feet	1,000-foot increase	43 dB	down 3 dB
8,000 feet	1,000-foot increase	41 dB	down 2 dB
9,000 feet	1,000-foot increase	39 dB	down 2 dB
10,000 feet	1,000-foot increase	37 dB	down 2 dB
11,000 feet	1,000-foot increase	35 dB	down 2 dB
12,000 feet	1,000-foot increase	33 dB	down 2 dB
13,000 feet	1,000-foot increase	31 dB	down 2 dB
14,000 feet	1,000-foot increase	29 dB	down 2 dB
15,000 feet	1,000-foot increase	27 dB	down 2 dB
16,000 feet	1,000-foot increase	25 dB	down 2 dB

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels.[4] See text on page 38 for other conditions.

2. The Maximum Sound Level is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

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[4] Many of the tables and figures in this report are specialized for commercial jet aircraft, rather than for military jets or for helicopters or for propeller aircraft. The concepts that the tables/figures illustrate are general, however, to all aircraft types. Commercial jet aircraft were chosen to illustrate these general concepts because existing literature is more complete for them than for other aircraft types. This relative completeness allowed computation of time histories for commercial jet aircraft without the need for independent research and/or extensive consolidation from data bases of the Federal Aviation Administration and the U.S. Air Force -- or from privately held data not in the open literature.

For the A-weighted sound level, which is a composite of all frequencies, the table shows sound-level steps converging at large distances to approximately 2 decibels for each 1,000-foot increase in distance -- compared to 0 decibels in Table 2 on page 4 above, which ignores atmospheric absorption.

4.4 Aircraft spectra and A-weighted sound levels in other directions

The sound spectra in the figures above pertain to the sound emitted in the "loudest" direction from the aircraft. They were measured at that point in time during a flyby when the aircraft registered its highest A-weighted sound level at the measurement microphone.

During a full flyby, the direction of sound emission towards the microphone constantly changes. Initially the microphone picks up sound emitted in the forward direction by the aircraft as it is approaching, and then sound emitted downwards or sideways when the aircraft is closest, and then sound emitted rearward when it is receding.

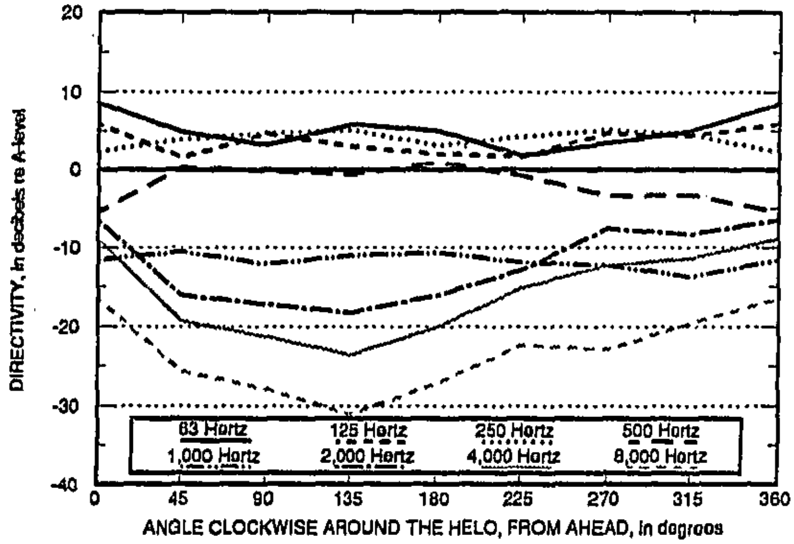
Many directivity patterns have been measured around aircraft on the ground -- during engine runups and at the start of takeoff, for example. Unfortunately, these directivity patterns of sound emission are not typical of aircraft in flight. The forward motion of the aircraft changes its sound emission significantly [Eldred, 1991]. Figures 5 through 7 contain several representative directivity patterns around helicopters in flight [Newman, 1984 (all citations)]. These directivities were measured are at a constant distance of 500 feet from the helicopter.

As the figures imply, in-flight helicopter spectra change significantly with direction. The figures also illustrate that various types of helicopters are significantly different in this respect.

In-flight directivity patterns for jet and propeller aircraft are not generally available in the open acoustical literature. Reliable data of this type are held privately, mostly by firms that test aircraft for FAA noise certification. Pursuing and analyzing such data bases is beyond the scope of this literature review.

When an aircraft spectrum changes with direction, so does its A-weighted sound level. Unlike spectra, A-weighted sound levels are often measured continuously during aircraft flyovers. Figure 8 shows A-weighted sound levels of representative aircraft, as functions of direction underneath (or around) the aircraft [Newman, 1980, 1984 (all citations)] [Pietrzko, 1988] [SAE, 1977] [True, 1977]. As is apparent from the figure, jet aircraft emit more sound toward their "rear quarter" than in other directions. Propeller aircraft emit less sound rearward. And helicopters vary significantly from model to model.

The federally sanctioned computer programs take source directivity into account in only the simplest manner. The Integrated Noise Model (INM) assumes no directivity for propeller aircraft and a so-called "dipole" directivity for jets, pointed sideways. NOISEMAP assumes no directivity for either aircraft type. The Heliport Noise Model (HNM) tabulates A-weighted sound levels in several directions for individual helicopters within its database.



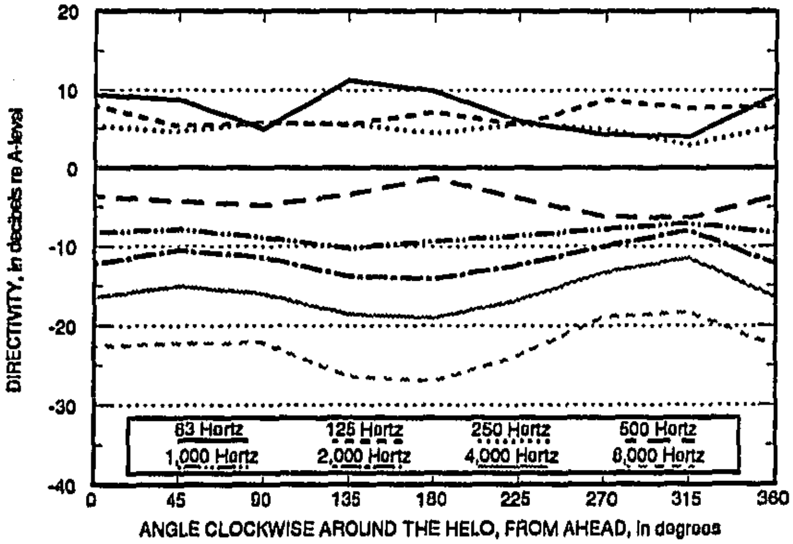
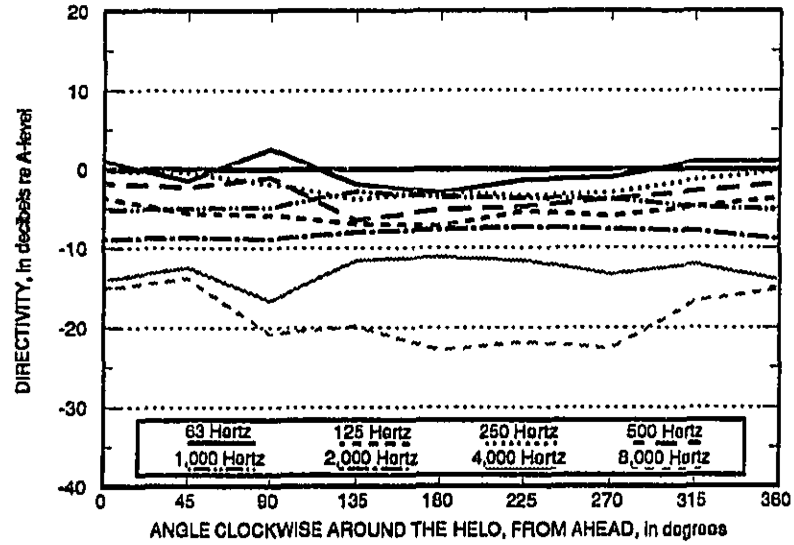


Figure 5. **Octave-band Directivities: Aerospatiale AS 355F Twinstar and AS 350D AStar Helicopters**



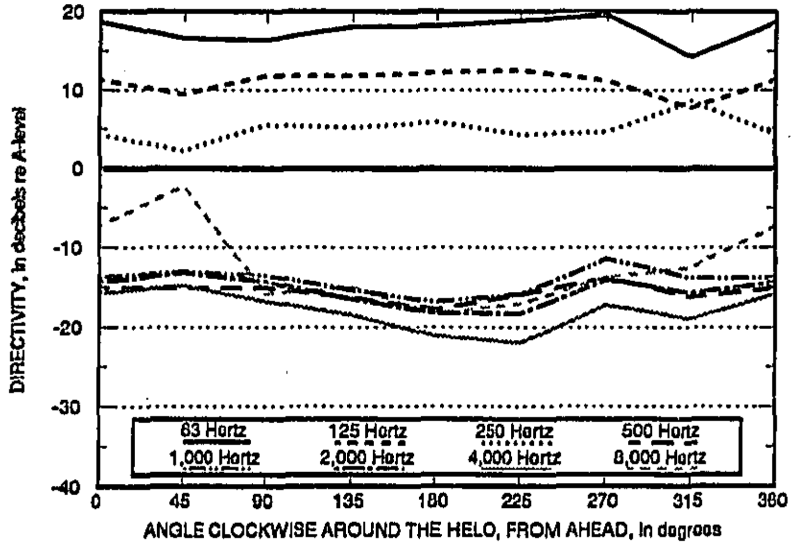


Figure 6. Octave-band Directivities: Aerospatiale SA 365N Dauphin 2 and Bell 222 Twin Jet Helicopters

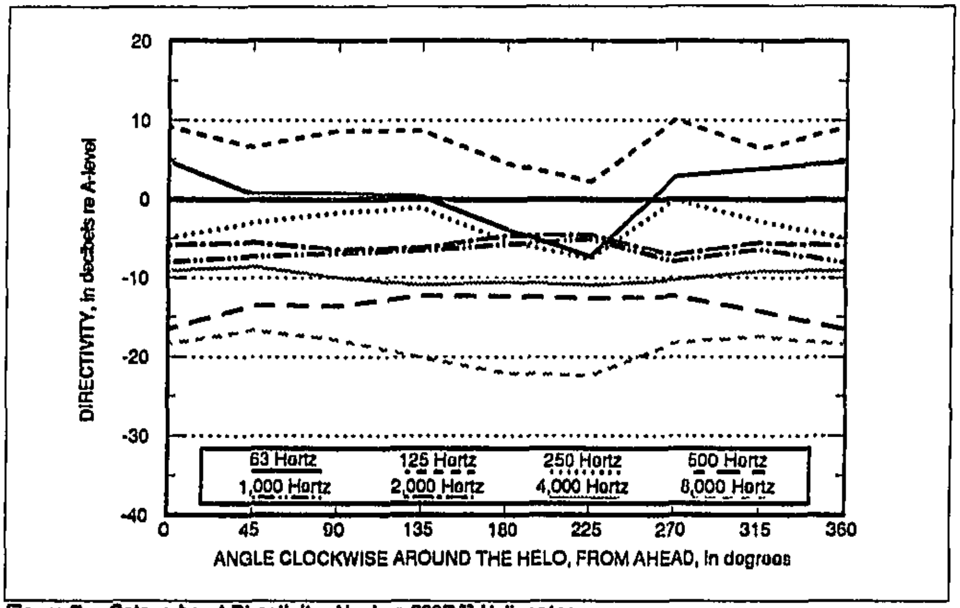


Figure 7. Octave-band Directivity: Hughes 500D/E Helicopter

None of these models incorporates the type of spectral dependency upon direction that is shown in Figures 5 through 7, above. In general, the "loudest" direction is the most important direction in assessing aircraft sound. For this reason, these federally sanctioned programs incorporate only the spectrum in this loudest direction.

4.5 Potential effects of atmospheric turbulence and focusing

During propagation between an aircraft and a particular location of concern on the ground, sound energy can be "scattered" somewhat by air turbulence. Such scattering results in a redirection of the sound energy originally headed towards the location of concern, through small scattering angles, to other nearby locations. It is generally believed that such scattering results in negligible attenuation of sound levels on the ground, for sources such as aircraft [Piercy, 1977]. In essence, sound originally headed towards a particular location, then scattered somewhat "aside," is replenished by sound originally headed "aside" and then scattered towards the location of concern.

Atmospheric "focusing" can also affect aircraft sound levels on the ground. Such focusing occurs when temperature and wind gradients bend (refract) sound waves along their propagation paths. Sometimes the sound waves are refracted so as to concentrate them at a particular location on the ground, like light is concentrating by a focusing magnifying glass. And sometimes sound waves are diluted, instead, by refraction away from the

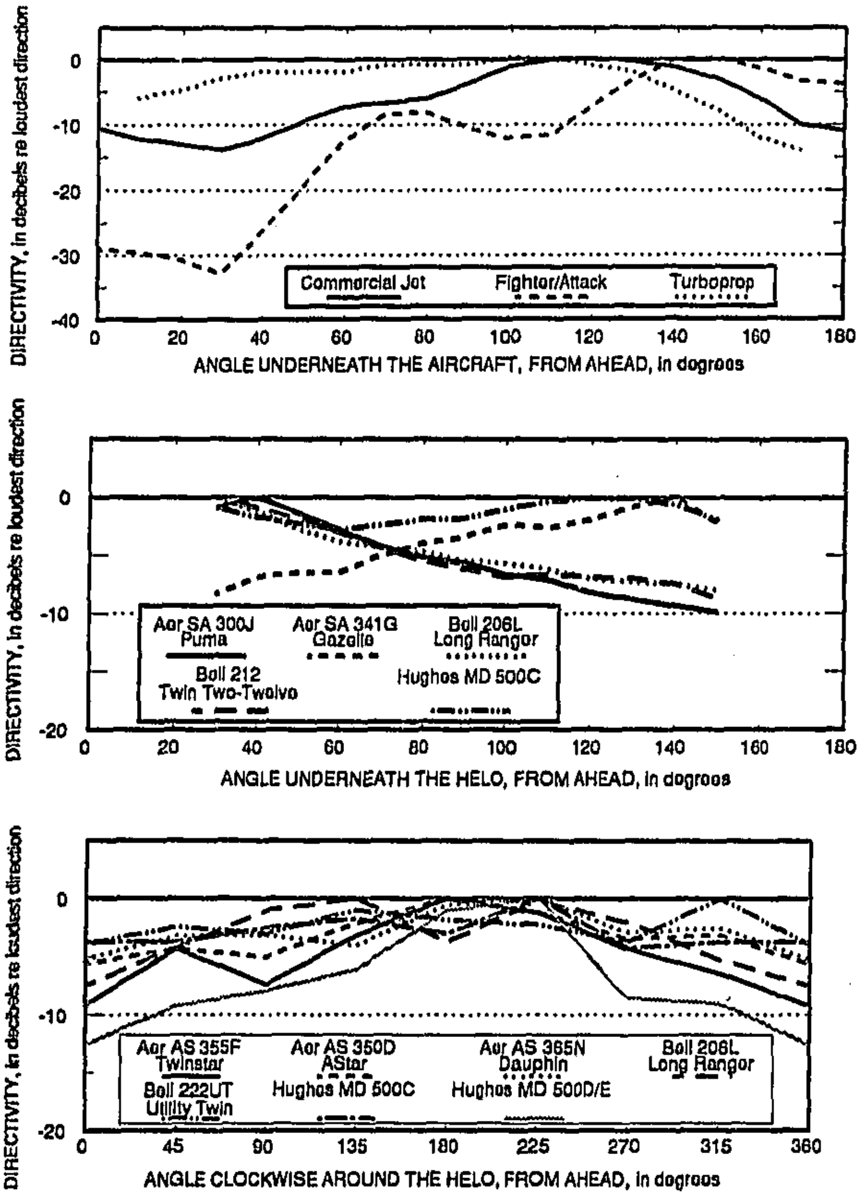


Figure 8. A-weighted Directivity of Representative Aircraft

particular location of concern. Atmospheric focusing can cause deviations from the average sound level on the ground by as much as ±20 decibels, but on the average these deviations will cancel out over time [Piercy, 1991].

Chapter 5. COMPLICATION: ATTENUATION DUE TO INTERVENING HILLS AND HEAVILY WOODED AREAS

5.1 Intervening hills

When an aircraft flies overhead, or nearly so, the maximum A-weighted sound level is not affected by hills, for none interrupt the sound path when the aircraft is closest. However, if an aircraft flies by at a relatively large horizontal range, and if the aircraft height is low enough so that hills interrupt the sound path throughout the aircraft's flyby, then these hills will reduce the aircraft's sound level at the listener/microphone. The hills act as a "barrier" to the sound, which must bend (diffract) over the interrupting hilltops or ridges. In doing so, the sound level is reduced by the hill's "barrier attenuation" [Anderson, 1992] [Berthelot, 1987 (both citations), 1988] [GIT, 1988] [Pierce, 1981] [Rasmussen, 1985].

The simple "thin-barrier" equations suffice in essentially all cases -- even for rounded, acoustically absorptive hills [Berthelot, 1987] [GIT, 1988]. Barrier attenuation depends only somewhat upon sound frequency, increasing approximately 1 decibel for each 1/3-octave increase in frequency.

In general, A-weighted sound levels of aircraft are reduced greatly by even moderately sized intervening hills. The more deeply the aircraft flies behind the hill, the more attenuation the hill provides. The amount of reduction depends upon how deeply the hill "shadows" the listener/microphone, which in turn depends upon the aircraft's height above the ground. Contrary to all trends discussed above, increasing the aircraft height in this situation causes an *increase* in sound level to distant listeners/microphones -- as the aircraft emerges into direct view. Once the aircraft rises high enough so that the hill no longer intervenes, however, this effect is finished and the sound level then decreases as usual with increasing aircraft height.

5.2 Intervening heavily wooded areas

Sufficiently dense and deep wooded areas provide attenuation when they intervene between aircraft and listener/microphone [Anderson, 1992] [Aylor, 1980] [Martens, 1985] [Price, 1988]. As with intervening hills, this situation generally occurs at relatively low aircraft heights, but at relatively large horizontal ranges.

Such attenuation is caused by sound scattering into the sky from trunks and limbs (middle frequencies) and leaves (very high frequencies). Sound *absorption* by leaves is generally not significant. For some types of trees, loss of leaves during the winter reduces wooded-area attenuation somewhat; for others it does not. In addition, some low-frequency attenuation results from ground reflections within the wooded area, where the roots of underbrush produce "acoustically soft" ground, discussed below.

The attenuation caused by heavy woods increases with the amount of wooded area passed through by the sound. At mid frequencies, this attenuation increases to a substantial 10-to-15 decibels for a passage of approximately 300-to-1000 feet, and then generally increases no further. To be certain of this attenuation, (1) the wooded area must be dense with trees and have sufficient underbrush to block direct view of the aircraft, and (2) the trees must generally extend above the sound path by 15 feet or more.

As in the case of intervening hills, increasing the aircraft height in this situation causes an *increase* in sound level to distant listeners/microphones -- as the aircraft emerges into direct view. Once the aircraft rises high enough so that the wooded area no longer intervenes, however, this effect is finished and the sound level then decreases as usual with increasing aircraft height.

Chapter 6. COMPLICATION: SOFT-GROUND ATTENUATION

"Acoustically soft" terrain can reduce sound levels even when it does not interrupt the sound path [Anderson, 1992] [Attenborough, 1988] [Chessell, 1977, 1978] [Pierce, 1981] [Thomasson, 1981] [Willshire, 1979]. Acoustically soft terrain consists of grassland or other ground that contains root structure, plowed or aerated earth, snow, or other "fissured" ground. Attenuation does not occur across "acoustically hard" ground such as asphalt, hard-packed earth, water, and water-soaked earth.

A sound path that grazes across acoustically soft terrain loses sound energy due to so-called soft-ground attenuation. Such grazing sound paths occur across relatively flat terrain, when the flight track is to the side, laterally displaced from the listener/microphone. They do not occur when the flight track is nearly overhead, nor when the aircraft is "below" the listener/microphone, directly visible in an immediately adjacent valley, gorge, or canyon.

In brief, soft-ground attenuation occurs because of the following. In addition to sound that arrives directly from the aircraft, sound also arrives after reflection from the ground. This ground-reflected sound combines with the direct, non-reflected sound to produce net attenuation. This attenuation is a function of frequency, often as much as 20-to-30 decibels in the mid frequencies.

6.1 Computation

The detailed computation of soft-ground attenuation is very complex, even across uniform, flat terrain. Expressly for aircraft sound, the Society of Automotive Engineers provides forty-eight pages of 1/3-octave-band graphs, plus four pages of associated tables, for the approximation of soft-ground attenuation over flat, acoustically soft ground [SAE, 1985c].

Simplifying these graphs/tables, while still retaining 1/3-octave bands in the resulting computation, would be a major undertaking. Instead, the federally sanctioned computer programs approximate soft-ground attenuation -- for A-weighted sound levels, only -- as shown in Figure 9 [Bishop, 1985] [SAE, 1981] [Speakman, 1989]. As the figure shows, the attenuation of A-weighted sound levels depends upon the elevation angle of the aircraft above the horizontal. For very distant aircraft this angle is small, the sound essentially "grazes" across the ground, and the resulting attenuation is large. For closer aircraft or aircraft higher above the ground, this angle is larger -- and so the soft-ground attenuation is less.

In summary, the amount of soft-ground attenuation depends upon the elevation angle, which in turn depends upon the aircraft's height above the ground. Increasing the aircraft

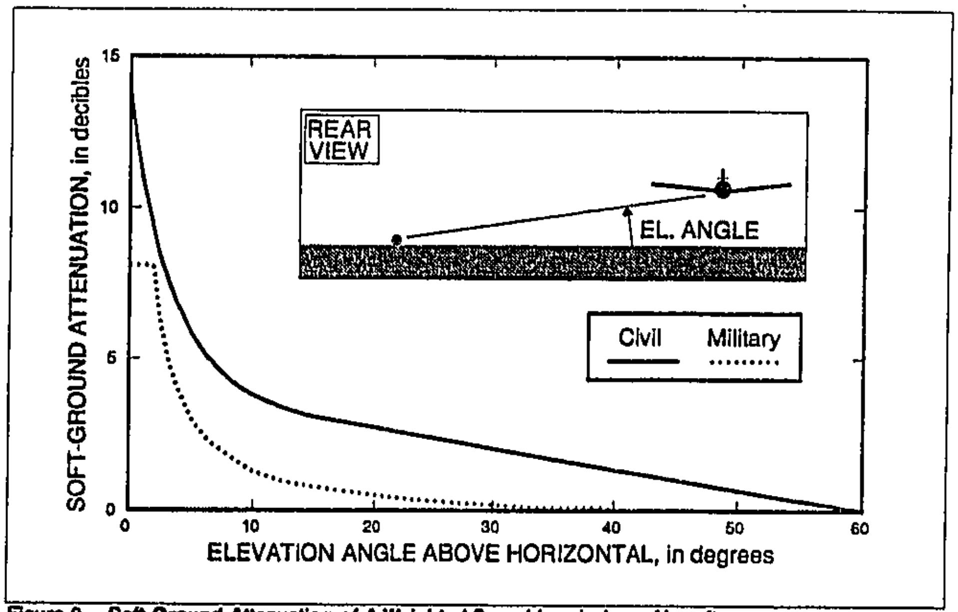


Figure 9. Soft-Ground Attenuation of A-Weighted Sound Levels from Aircraft

height above acoustically soft ground causes an *increase* in sound level to distant listeners/microphones -- as the aircraft rises above the ground's influence. Once the aircraft rises high enough, however, this effect is finished and the sound level then decreases as usual with increasing aircraft height.

6.2 A generalization to compute flyby time histories

Within the federally sanctioned computer programs, the elevation angle is measured at the aircraft's point of closest approach. The resulting soft-ground attenuation is called "lateral attenuation," for it is significant only when the flight track is displaced laterally from the listener/microphone by a significant amount. In other words, when the aircraft flies overhead, or nearly so, the maximum A-weighted sound level at the listener is not affected by soft-ground attenuation. However, when an aircraft flies by at a large horizontal range, in which case the elevation angle to the closest point on its flight path will be relatively small, then this soft-ground attenuation will significantly reduce the maximum sound level of the flyby.

The Society of Automotive Engineers recognizes that this same soft-ground attenuation might also apply, per the available evidence, at every moment during the aircraft flyby [SAE, 1981]. It is a changing quantity from moment to moment during the flyby -- as the elevation angle with the horizontal changes from moment to moment. When the aircraft is approaching from far away, its elevation angle is small and so its sound is attenuated by grazing over the ground. When it is at its closest point of approach, soft-ground attenuation may be zero if the aircraft passes overhead or it may be moderate-to-large if the flight track is laterally displaced, far to the side. When the aircraft recedes, again the elevation angle becomes less and the soft-ground attenuation increases.

Computation of a full sound-level history of the aircraft flyby, as a function of time, requires use of the soft-ground attenuation in this manner, throughout the full flyby.

6.3 Complications

The scientific literature contains much discussion about the many practical complications involved in predicting or measuring soft-ground attenuation over flat ground [Anderson, 1985] [Bishop, 1985] [Burkhard, 1960] [Chessell, 1977, 1978] [Daigle, 1983] [deJong, 1983] [Embleton, 1974, 1976] [Ingard, 1953, 1963] [Mueller, 1979] [Nyborg, 1955] [Pao, 1978] [Parkin, 1964, 1965] [Soom, 1981] [Thompson, 1972] [Willshire, 1979].

Undulating terrain can greatly complicate the combination of the direct and reflected sound paths. In addition, soft-ground attenuation is significantly affected by atmospheric turbulence. Furthermore, wind speed and temperature can both affect this soft-ground attenuation. In essence, vertical gradients of wind speed and temperature cause sound paths to bend (refract) either upwards or downwards, and thereby change the nature of the ground reflection by actually changing the angle of reflection.

In general, upward refraction occurs when sound propagates either upwind or at night during temperature inversions. This upward refraction results in increased lateral attenuation, due to the formation of so-called "sound shadows." In contrast, downward refraction may cause the loss or reduction of soft-ground attenuation -- as well as the reduction of attenuation due to hills and heavily wooded areas [Anderson, 1985, 1992] [Daigle, 1982] [Scholes, 1971]. Obviously, the effects of wind and temperature gradients are highly variable from day to day, hour to hour, and even moment to moment.

Chapter 7. COMPLICATION: THE ACOUSTICAL DESCRIPTOR

As an aircraft flies by, its sound level first increases as the aircraft approaches, then reaches a maximum, and then decreases as the aircraft recedes into the distance. Figure 10 shows this varying sound level during a representative flyby.

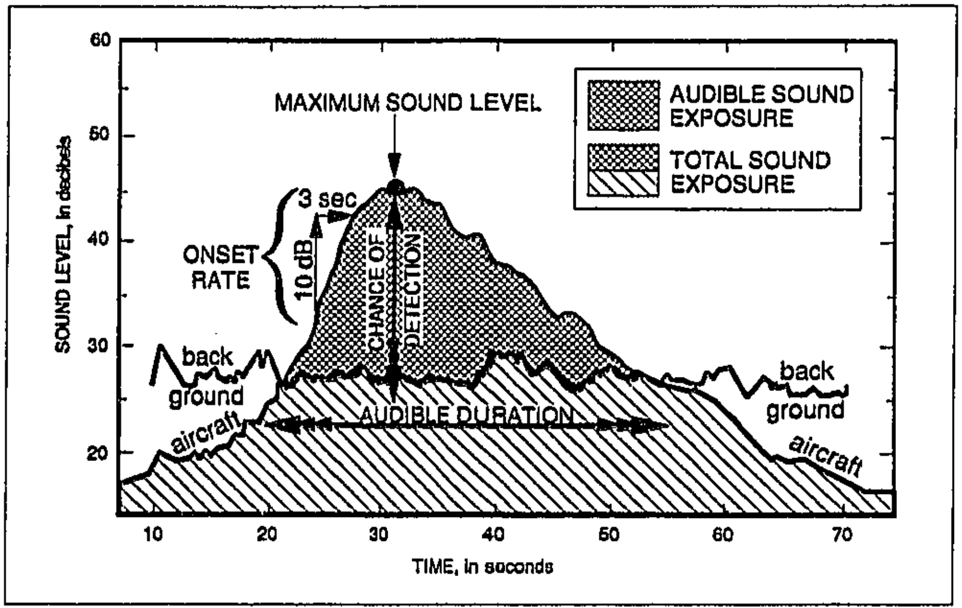


Figure 10. Sound-Level History of a Representative Aircraft Flyby

7.1 Acoustical descriptors of potential concern to the National Park Service

Different "acoustical descriptors" can be used to describe this entire flyby. Several descriptors of potential concern to the Park Service are shown in an approximate manner in the figure (and more precisely in the appendix on Technical Translations). The descriptors of potential concern to the Park Service are:

- **Maximum Sound Level, in dBA** -- the aircraft's maximum A-weighted sound level,

- **Onset Rate, in decibels per second** -- the maximum rate of increase in the aircraft's A-weighted sound level as it approaches,
- **Total Sound Exposure, in dB** -- the total sound exposure due to the aircraft,
- **Audible Sound Exposure, in dB** -- the audible portion (based upon the technical parameter d') of the total sound exposure due to the aircraft,
- **Chance of Detection, in percent** -- the chance that the aircraft can be detected by attentive listeners on the ground (also based upon d'), and
- **Audible Duration, in seconds** -- the audible duration (also based upon d') of the aircraft's flyover.

Each of these acoustical descriptors is a different measure of the aircraft's sound during the flyby. The discussions above focused upon the first of these acoustical descriptors: the maximum sound level during the flyby. This acoustical descriptor is most commonly associated with aircraft sound by the average person. Each of the other acoustical descriptors, however, can serve a different purpose in assessing the acoustical effects of the flyby -- depending upon circumstances of natural quiet, park-visitor activity, background sound level, aircraft type, aircraft mission, and other factors. And each of these other acoustical descriptors depends somewhat differently upon slant distance than does the maximum sound level.

7.2 Computation of these acoustical descriptors

To determine the dependence of each relevant acoustical descriptor upon slant distance and aircraft speed, it was necessary to synthesize an approximate computation procedure from the literature review (see Appendix B). In brief, this synthesis first approximates the full sound-level history of an aircraft flyover, separately for each 1/3-octave band from 50 to 10,000 Hertz. Then it computes each acoustical descriptor from these 1/3-octave sound-level histories, to approximate the acoustical descriptor's dependence upon slant distance and aircraft speed.

Figures 11 and 12 contain a set of 1/3-octave-band sound-level histories for a single flyby, along with the corresponding history for the composite A-weighted sound level, shown as a darker line in the top frame of Figure 11. As the two figures show, the A-weighted sound-level history peaks at a greater value than that of the 1/3-octave bands, essentially because it is a composite of these bands. In addition, the high-frequency histories drop precipitously relative to their maxima, as the aircraft approaches and recedes, because of atmospheric absorption. The same is not true for the low-frequency histories, which persist for a long time after the aircraft has passed. It is these low-frequency 1/3-octave bands that often cause aircraft to be audible long after they have passed by.

The rising/falling shapes of Figures 11 and 12 are representative of other aircraft, as well. At larger slant distances to the flight track, and also for slower aircraft speeds, the

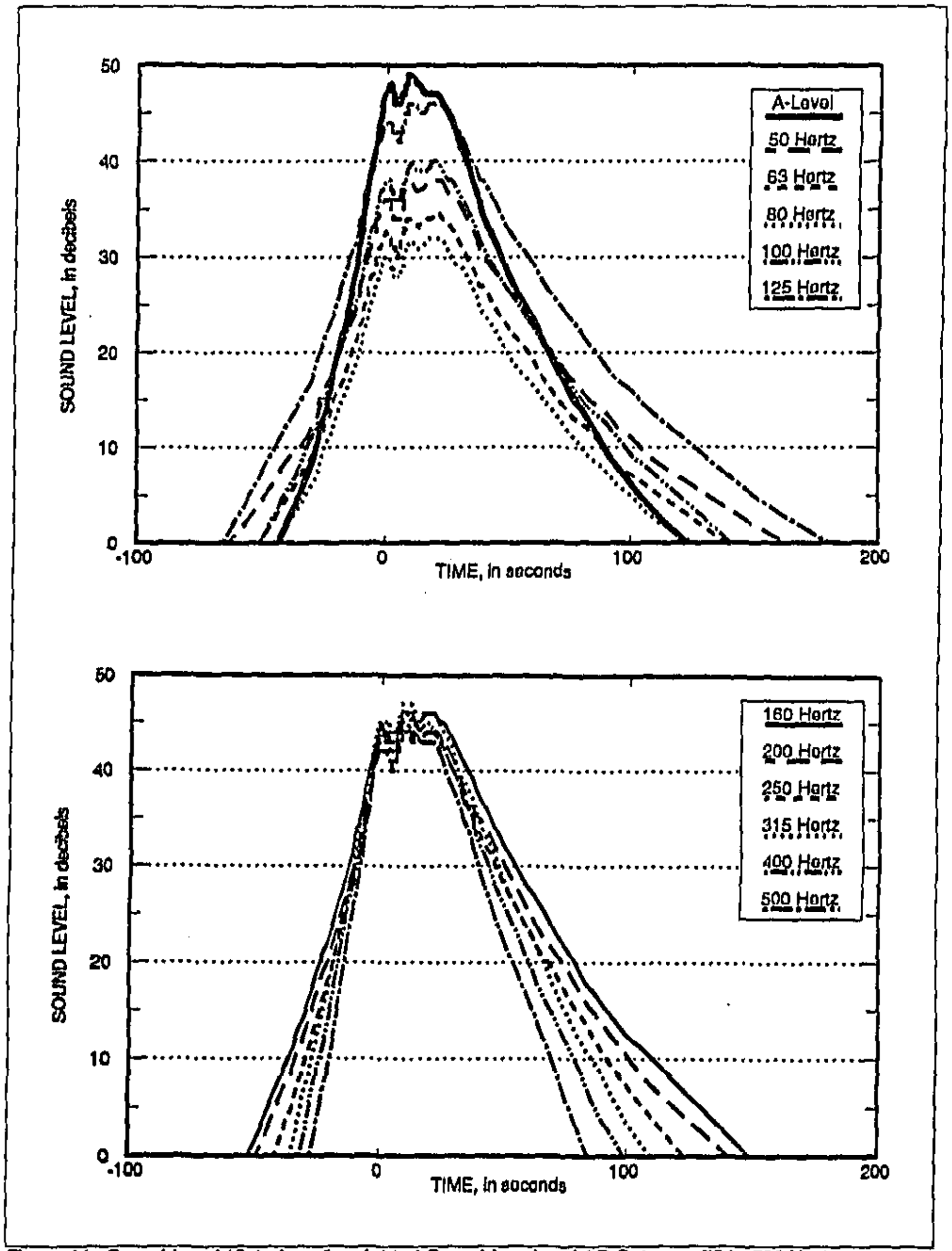


Figure 11. Sound-Level Histories: A-weighted Sound Level and 1/3 Octaves, 50 to 500 Hertz

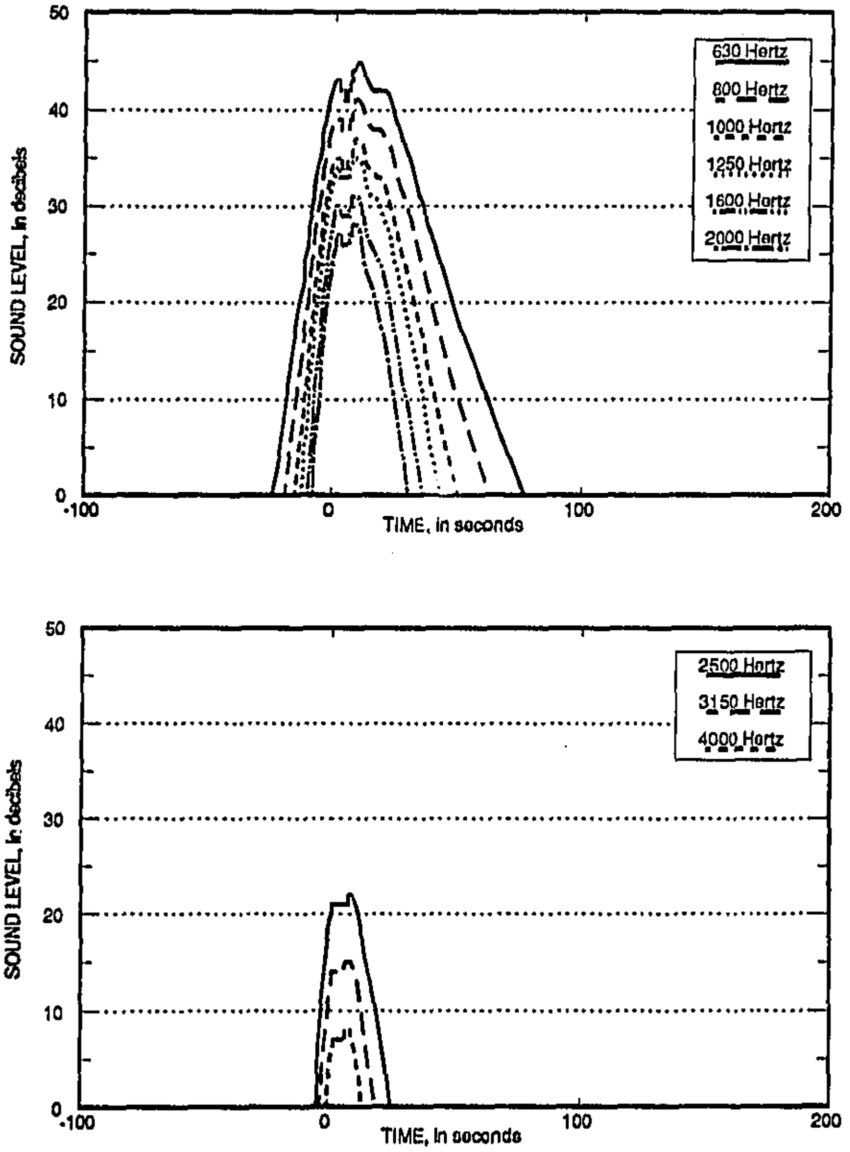


Figure 12. Sound-Level Histories: 1/3 Octaves, 630 to 4,000 Hertz

rising/falling slopes would be more gradual than shown in the figures.

Figure 13 shows how the A-weighted sound-level history depends upon aircraft speed, for all aircraft types (the figure's approaching/receding slopes would be less steep at larger slant distances to the flight track).

As shown in the figure, the maximum sound level is relatively independent of speed. Although theory indicates a *reduction* of sound output with increased speed for jet aircraft, this behavior has not been clearly found during actual measurements. As a result, the federally sanctioned computer programs show no speed dependence for the maximum sound levels of jets, nor for any of the aircraft types. Because the maximum sound level is essentially independent of speed, the chance of audibility is essentially independent of speed, as well.

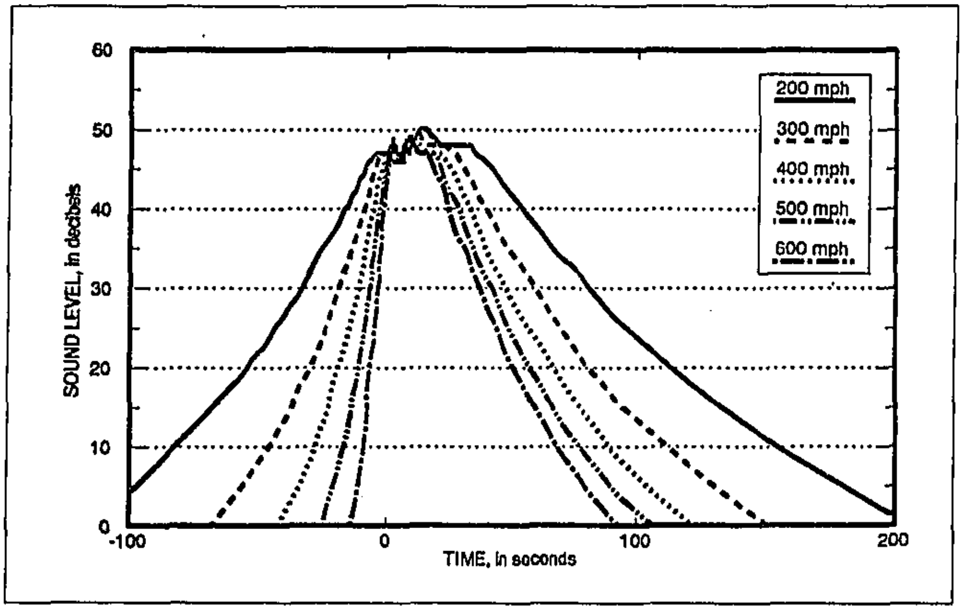


Figure 13. Representative Sound-Level Histories: Dependance upon Speed

As shown in the figure, the onset rate increases dramatically with increasing aircraft speed. On the other hand, the audible duration of the aircraft *decreases* with speed, because the aircraft passes by more quickly. Similarly, the area under the sound-level history curve, which represents the total sound exposure, decreases as well. This decrease agrees with the federally sanctioned computer programs, which are geared to computing this total sound exposure.

Figure 14 shows how the A-weighted sound-level history depends upon slant distance to the flight track, for all aircraft types (the figure's approaching/receding slopes would be less

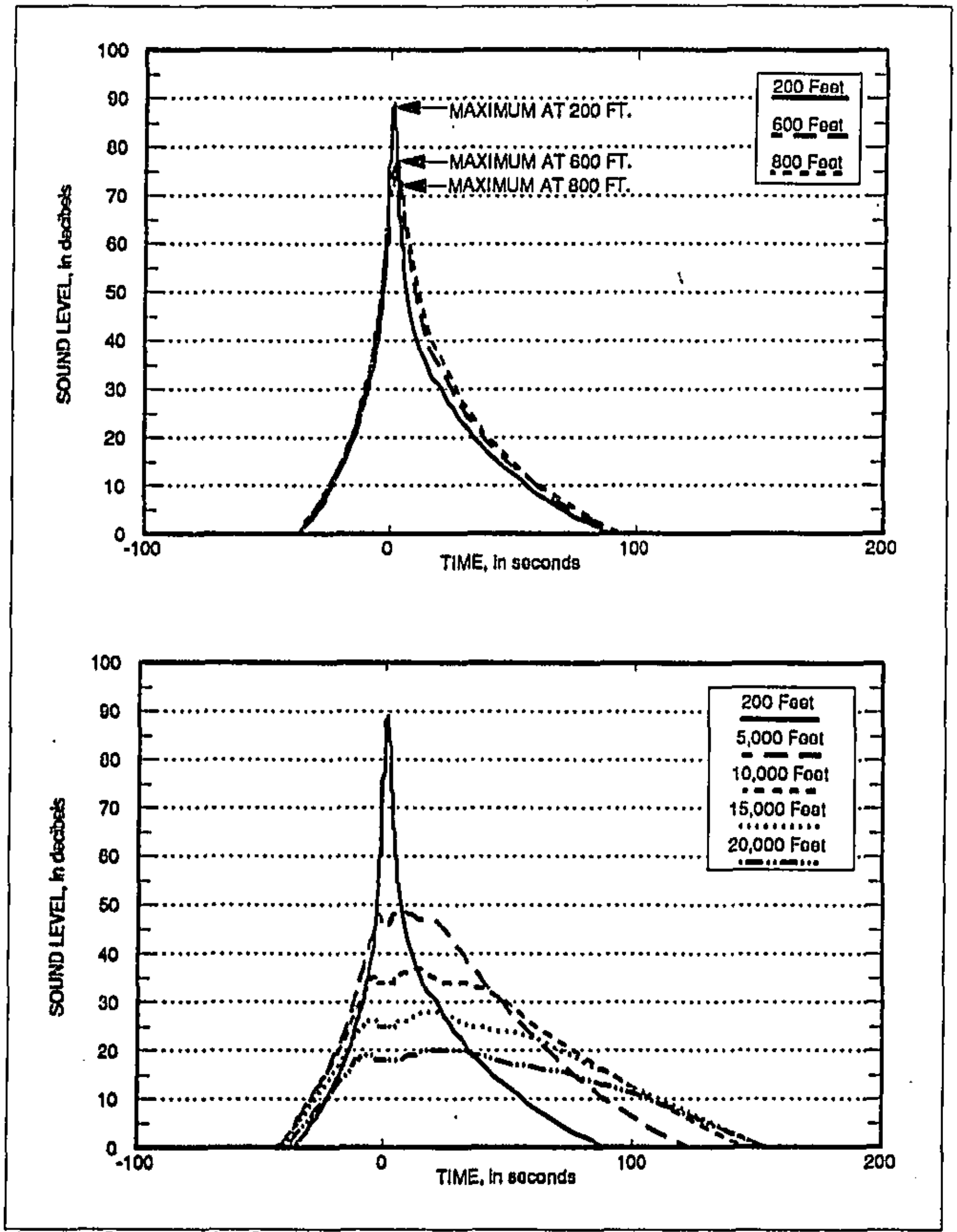


Figure 14. Representative Sound-Level Histories: Dependance upon Slant Distance to the Flight Track

steep for slower aircraft speeds). With increasing slant distance, the maximum sound level decreases abruptly at first. However, at the largest distances only several decibels of extra reduction in this maximum accrues for each additional 1,000 feet of distance. The area under the curve, which represents the total sound exposure, decreases less than the maximum, essentially because the slant distances during approach and after passby decrease far less than does the slant distance to the closest point of the flight track. In addition, the onset rate decreases substantially for greater slant distances.

At some particular slant distance, the aircraft sound no longer can be heard above the background sound, and so the three acoustical descriptors connected with audibility and computed with the technical parameter d' (Total Audible Exposure, Chance of Detection, and Audible Duration) reduce in value rather abruptly at some particular distance. This transition to inaudibility is computed by comparing sound-level histories -- aircraft with background -- in the complete set of 1/3-octave bands.

7.3 Effect of aircraft height on the width of its "acoustic trail"

Figure 15 illustrates the concept of an aircraft's "acoustic trail." The top half of the figure shows the rear view of an aircraft flying directly away from the viewer, along with noise contours (centered on the aircraft) and their intersection with the ground. The contour intersections with the ground trace out an acoustic trail along the aircraft's track. The width of this trail depends upon which contour is of interest. The narrowest trail shown is the 100-decibel one, which lies between the two locations, left and right of the aircraft's track, where the 100-decibel contour intersects the ground. The widest trail shown is the 65-decibel one.

As the aircraft rises higher above the ground in the bottom half of the figure, the 100-decibel trail shrinks to nothing -- as do the 95, the 90, and the 85-decibel trails as well). In general, acoustic trails shrink with increasing aircraft height, especially for listener/microphones close to the flight track -- that is, at small horizontal ranges from the flight track.

To illustrate this further, the top half of the figure includes a short slanted line between the aircraft and a close-in ground position. For this low-flying aircraft, the sound level at this position is 100 decibels. For the higher aircraft, it reduces to 84 decibels *at this same position on the ground.* This sound-level decrease is caused by the larger slant distance between this ground position and the aircraft, as shown in the figure.

In contrast, the 65-decibel trail width expands slightly as the aircraft rises higher above the ground. The sound level increases from 65 to 67 decibels for the ground position shown to the left in both portions of the figure. Two opposite mechanisms are at work at this large horizontal range from the flight track. First, the slant distance increases to this more-distant position, as well, but not proportionally as much as for the close-in position. The increasing slant distance causes a slight reduction in the sound level.

However, for this distant ground position, the aircraft's elevation angle above the horizontal increases dramatically with increasing aircraft height. And this increase in elevation angle

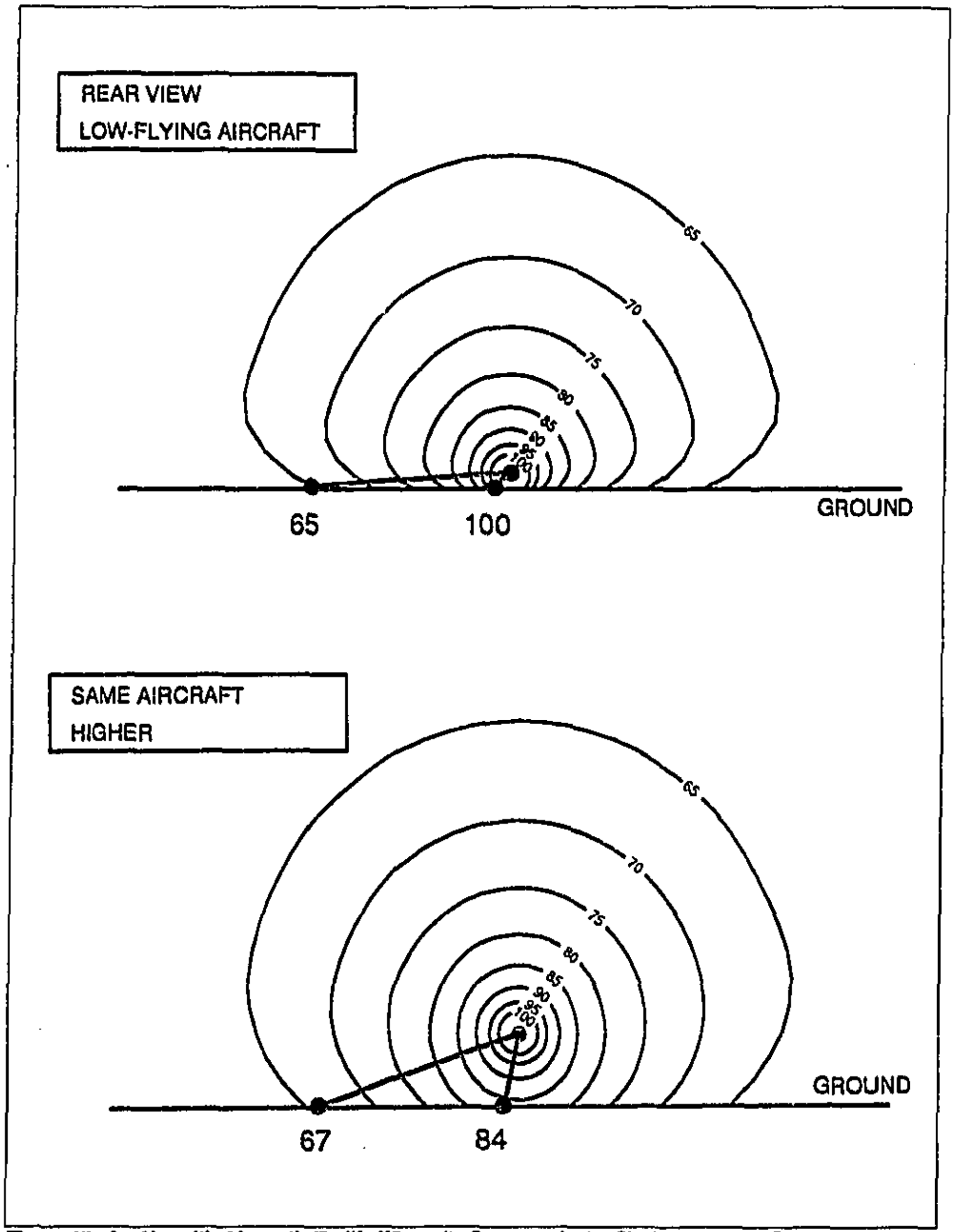


Figure 15. An Aircraft's "Acoustic Trail": Where Its Contours in the Sky Intersect the Ground

causes a sound-level increase as soft-ground attenuation is progressively lost with increasing aircraft height.

In general, acoustic trails narrow with increasing aircraft height when the aircraft's elevation angle is initially large -- meaning little or no soft-ground attenuation. Generally this occurs relatively close-in to the aircraft's flight track. In contrast, acoustic trails widen somewhat when the aircraft's elevation angle is initially very small -- meaning significant soft-ground attenuation that is lost as the aircraft rises higher. Generally this occurs at large horizontal ranges from the aircraft's flight track, when propagation initially grazes across acoustically soft ground.

The same widening of acoustic trails at larger horizontal ranges can occur over hills and wooded areas. This happens when the aircraft, upon rising in height, comes into direct view of remote ground locations that were blocked from view at the lower aircraft height.

Shown in Figure 16 is a "sound-ray skirt," extending downward from an aircraft. When the aircraft rises higher above the ground, this sound-ray skirt spreads over a wider area of the ground, as shown in the bottom half of the figure. And so it appears as if the acoustic trail widens. This is a common misconception about acoustic trails. This sound-ray skirt, which extends from the aircraft to the ground, does not represent a constant sound level. Instead, sound levels along the skirt continually reduce with distance from the aircraft, as shown in the bottom half of the figure: 100 to 95 to 90 to 85 to 80 decibels. Therefore, even though the skirt spreads more widely with increasing aircraft height, the sound levels on the ground behave as described above, in conjunction with the previous figure.

7.4 Sound-level tables for all relevant acoustical descriptors

For Maximum Sound Level, Table 5 on page 16 above, is repeated here as Table 6, followed by corresponding tables for the other acoustical descriptors: Onset Rate, Total Sound Exposure, Audible Sound Exposure, Chance of Detection, and Audible Duration.

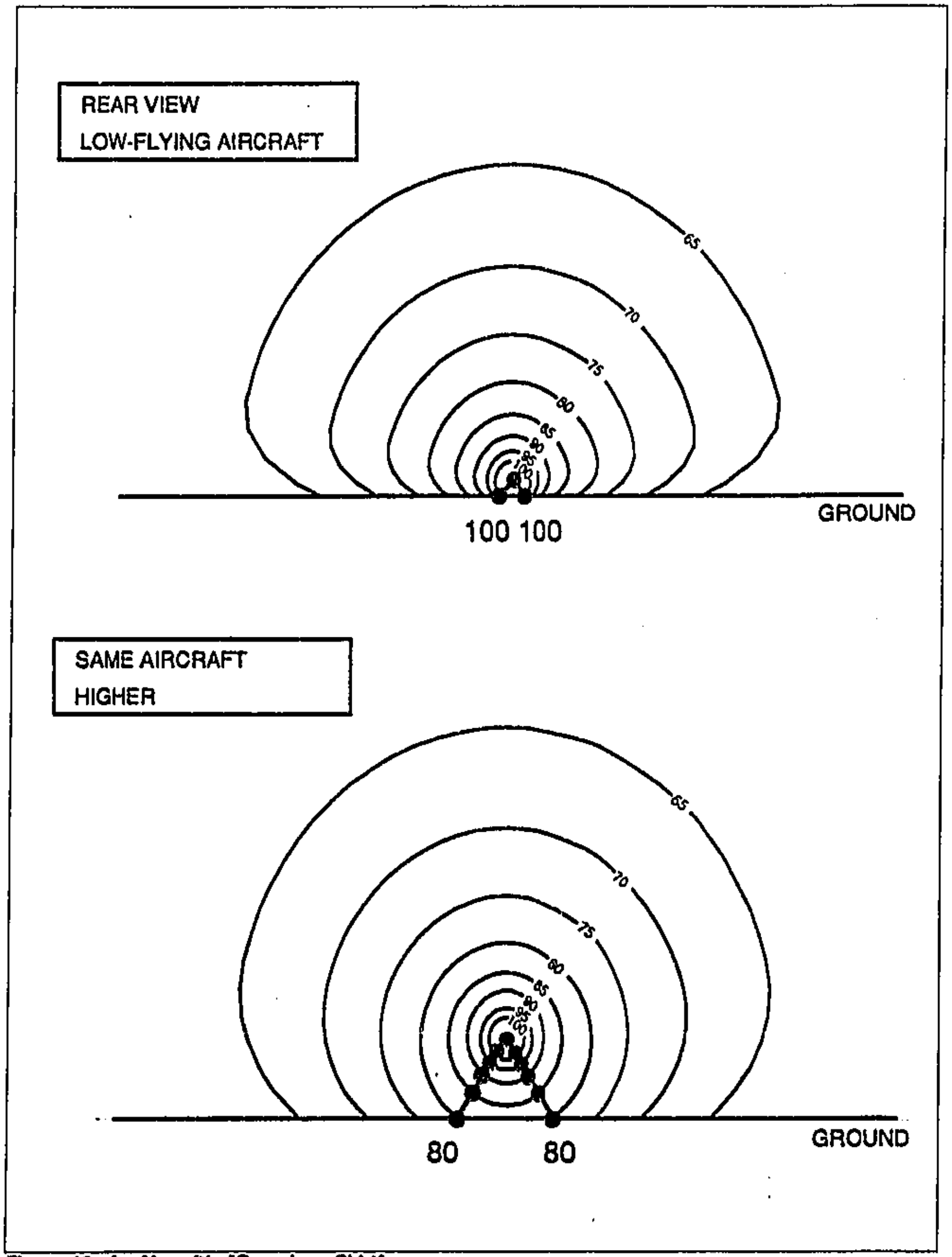


Figure 16. An Aircraft's "Sound-ray Skirt"

Table 6. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Maximum Sound Level

SLANT DISTANCE	DISTANCE STEP	MAXIMUM SOUND LEVEL	MAXIMUM-SOUND-LEVEL STEP
125 feet	--------------------	94 dBA	--------------------
250 feet	125-foot increase	87 dBA	down 7 dB
375 feet	125-foot increase	82 dBA	down 5 dB
500 feet	125-foot increase	79 dBA	down 3 dB
625 feet	125-foot increase	76 dBA	down 3 dB
750 feet	125-foot increase	74 dBA	down 2 dB
875 feet	125-foot increase	72 dBA	down 2 dB
1,000 feet	125-foot increase	70 dBA	down 2 dB
1,000 feet	--------------------	70 dBA	--------------------
2,000 feet	1,000-foot increase	62 dBA	down 8 dB
3,000 feet	1,000-foot increase	57 dBA	down 5 dB
4,000 feet	1,000-foot increase	53 dBA	down 4 dB
5,000 feet	1,000-foot increase	49 dBA	down 4 dB
6,000 feet	1,000-foot increase	46 dBA	down 3 dB
7,000 feet	1,000-foot increase	43 dBA	down 3 dB
8,000 feet	1,000-foot increase	41 dBA	down 2 dB
9,000 feet	1,000-foot increase	39 dBA	down 2 dB
10,000 feet	1,000-foot increase	37 dBA	down 2 dB
11,000 feet	1,000-foot increase	35 dBA	down 2 dB
12,000 feet	1,000-foot increase	33 dBA	down 2 dB
13,000 feet	1,000-foot increase	31 dBA	down 2 dB
14,000 feet	1,000-foot increase	29 dBA	down 2 dB
15,000 feet	1,000-foot increase	27 dBA	down 2 dB
16,000 feet	1,000-foot increase	25 dBA	down 2 dB

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.

2. The Maximum Sound Level is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As shown in Table 6 for the maximum sound level, the sound-level steps converge at large distances to approximately 2 decibels for each 1,000-foot increase in slant distance. In other words, at the largest slant distances only 2 decibels of extra benefit accrues for each additional 1,000 feet of distance. Although this amount is small, it is larger than the step size in Table 2 on page 4 above, which ignores atmospheric absorption.

Figures 1 through 4 above show moderate differences among sound spectral shapes for different aircraft types. These differences in sound spectral shapes cause moderate differences in the amount of atmospheric absorption that occurs between the aircraft and the ground. Less sound is absorbed at low frequencies than at high frequencies, as shown above. For this reason, atmospheric absorption will reduce the A-weighted sound level less for predominantly low-frequency aircraft types: propeller aircraft, helicopters, and some Stage-3 commercial jets. Tables similar to Table 6 for these aircraft types would show somewhat smaller sound-level steps.

Table 7. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Onset Rate

SLANT DISTANCE	DISTANCE STEP	ONSET RATE	ONSET-RATE STEP
125 feet	----------	35 dB/sec	----------
250 feet	125-foot increase	20 dB/sec	down 15 dB/sec
375 feet	125-foot increase	15 dB/sec	down 5 dB/sec
500 feet	125-foot increase	11 dB/sec	down 4 dB/sec
625 feet	125-foot increase	10 dB/sec	down 1 dB/sec
750 feet	125-foot increase	9 dB/sec	down 1 dB/sec
875 feet	125-foot increase	8 dB/sec	down 1 dB/sec
1,000 feet	125-foot increase	7 dB/sec	down 1 dB/sec
1,000 feet	----------	7 dB/sec	----------
2,000 feet	1,000-foot increase	4 dB/sec	down 3 dB/sec
3,000 feet	1,000-foot increase	3 dB/sec	down 1 dB/sec
4,000 feet	1,000-foot increase	2 dB/sec	down 1 dB/sec
5,000 feet	1,000-foot increase	2 dB/sec	down 1 dB/sec
6,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
7,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
8,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
9,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
10,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
11,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
12,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
13,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
14,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
15,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec
16,000 feet	1,000-foot increase	1 dB/sec	down 0 dB/sec

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.

2. The Onset Rate is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As shown in Table 7, the Onset-Rate steps converge at large distances to approximately 1 dB/sec for each 1,000-foot increase in distance. At large slant distances, the onset rate of

1 decibel per second is completely negligible, and so additional reduction is neither needed nor achievable.

Onset Rate depends primarily upon aircraft speed, mostly independent of aircraft type. For speeds less than 400 miles per hour, tabulated Onset Rates would be less than shown; for higher speeds, greater than shown.

Table 8. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Total Sound Exposure

SLANT DISTANCE	DISTANCE STEP	TOTAL SOUND EXPOSURE	TOTAL-SOUND-EXPOSURE STEP
125 feet	----------	98 dB	----------
250 feet	125-foot increase	94 dB	down 4 dB
375 feet	125-foot increase	91 dB	down 3 dB
500 feet	125-foot increase	89 dB	down 2 dB
625 feet	125-foot increase	87 dB	down 2 dB
750 feet	125-foot increase	86 dB	down 1 dB
875 feet	125-foot increase	85 dB	down 1 dB
1,000 feet	125-foot increase	84 dB	down 1 dB
1,000 feet	----------	84 dB	----------
2,000 feet	1,000-foot increase	78 dB	down 6 dB
3,000 feet	1,000-foot increase	73 dB	down 5 dB
4,000 feet	1,000-foot increase	70 dB	down 3 dB
5,000 feet	1,000-foot increase	68 dB	down 2 dB
6,000 feet	1,000-foot increase	66 dB	down 2 dB
7,000 feet	1,000-foot increase	64 dB	down 2 dB
8,000 feet	1,000-foot increase	62 dB	down 2 dB
9,000 feet	1,000-foot increase	60 dB	down 2 dB
10,000 feet	1,000-foot increase	58 dB	down 2 dB
11,000 feet	1,000-foot increase	56 dB	down 2 dB
12,000 feet	1,000-foot increase	54 dB	down 2 dB
13,000 feet	1,000-foot increase	53 dB	down 1 dB
14,000 feet	1,000-foot increase	52 dB	down 1 dB
15,000 feet	1,000-foot increase	51 dB	down 1 dB
16,000 feet	1,000-foot increase	50 dB	down 1 dB

NOTES:
1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.
2. The Total Sound Exposure is defined in the appendix on Technical Translations.
3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As shown in Table 8, for the Total Sound Exposure the steps converge at large slant distances to approximately 1 decibel for each 1,000-foot increase in distance. In other words, at the largest slant distances only 1 decibel of extra benefit accrues for each additional 1,000 feet of distance. This step size is even smaller than the 2-decibel step size for the maximum sound level. A similar convergence to 1 decibel each 1,000 feet would occur for all aircraft types, at all speeds.

Table 9. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Audible Sound Exposure

SLANT DISTANCE	DISTANCE STEP	AUDIBLE SOUND EXPOSURE	AUDIBLE-SOUND-EXPOSURE STEP
125 feet	----------	98 dB	----------
250 feet	125-foot increase	94 dB	down 4 dB
375 feet	125-foot increase	91 dB	down 3 dB
500 feet	125-foot increase	89 dB	down 2 dB
625 feet	125-foot increase	87 dB	down 2 dB
750 feet	125-foot increase	86 dB	down 1 dB
875 feet	125-foot increase	85 dB	down 1 dB
1,000 feet	125-foot increase	84 dB	down 1 dB
1,000 feet	----------	84 dB	----------
2,000 feet	1,000-foot increase	78 dB	down 6 dB
3,000 feet	1,000-foot increase	73 dB	down 5 dB
4,000 feet	1,000-foot increase	70 dB	down 3 dB
5,000 feet	1,000-foot increase	68 dB	down 2 dB
6,000 feet	1,000-foot increase	66 dB	down 2 dB
7,000 feet	1,000-foot increase	64 dB	down 2 dB
8,000 feet	1,000-foot increase	62 dB	down 2 dB
9,000 feet	1,000-foot increase	60 dB	down 2 dB
10,000 feet	1,000-foot increase	58 dB	down 2 dB
11,000 feet	1,000-foot increase	56 dB	down 2 dB
12,000 feet	1,000-foot increase	52 dB	down 4 dB
13,000 feet	1,000-foot increase	45 dB	down 7 dB
14,000 feet	1,000-foot increase	34 dB	down 11 dB
15,000 feet	1,000-foot increase	17 dB	down 17 dB
16,000 feet	1,000-foot increase	-8 dB	down 25 dB

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.

2. The Audible Sound Exposure is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As shown in Table 9, for the Audible Sound Exposure, the steps show a more interesting pattern. At first they decrease in the normal manner, from 6dB to 2dB each 1,000 feet, and then they become quite large around a slant distance of 13,000-to-15,000 feet. This "transition to inaudibility" occurs when the aircraft starts to become inaudible due to the natural background sounds in the environment.

Table 9 was computed for a "moderate" amount of background sound, measured at Shoshone Point in the Grand Canyon National Park. At this position, background sound was caused by moderate winds of 10-to-20 miles per hour [Dunholter, 1989]. Winds of this speed increase the background sound above what it is normally during calmer periods at this position in the park. The background sound has an A-weighted sound level of approximately 45 dBA.

Note that the aircraft begins to become inaudible in this 45-dBA background when the aircraft's maximum A-weighted sound level is only 30-to-35 dBA -- some 10-to-15 decibels lower than the background. Even though the aircraft's A-weighted sound level is lower than that of the background sound, the aircraft's sound pressure level around 100 Hertz is not; it is comparable to the background's sound pressure level in this frequency region. And for that reason the aircraft is still audible; its sound around 100 Hertz would signal its presence to an attentive listener.

This same rather abrupt reduction of the Audible Sound Exposure with distance would also occur for any other background spectra, but transitioning to inaudibility at some other slant distance. Even in a single location within a park, background sound levels often vary significantly from day to day, hour to hour, and even moment to moment -- often influenced strongly by time-varying wind speed. To a first approximation, background sound nearby ocean surf is some 10-to-15 decibels greater at all frequencies than the wind-induced background used for Table 9 [EPA, 1971]. Such surf-induced background sound would cause a transition to inaudibility to occur at a slant distance of approximately 5,000-to-10,000 feet, instead of the 10,000-to-15,000 feet shown in the table.

By contrast, the very quietest times in many National Parks measure below the threshold of human hearing -- approximately 20-to-30 decibels less at all frequencies than the wind-induced background sound above [CSTI, 1990] [Dunholter, 1989]. During such times of "near silence," the transition to inaudibility would occur at a slant distance of approximately 20,000-to-25,000 feet, instead of the 10,000-to-15,000 feet shown in the table.

One additional important point: These particular distances are for a typical Stage-2 commercial jet travelling around 400 miles per hour. They will differ for jets at other speeds, as well as for other aircraft, as a function of speed. In essence, different aircraft cause different sound levels at the ground, as a function of their speed, and therefore they will become inaudible at different slant distances.

Table 10. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Chance of Detection

SLANT DISTANCE	DISTANCE STEP	CHANCE OF DETECTION	CHANCE-OF-DETECTION STEP
125 feet	------------	100 %	------------
250 feet	125-foot increase	100 %	down 0 %
375 feet	125-foot increase	100 %	down 0 %
500 feet	125-foot increase	100 %	down 0 %
625 feet	125-foot increase	100 %	down 0 %
750 feet	125-foot increase	100 %	down 0 %
875 feet	125-foot increase	100 %	down 0 %
1,000 feet	125-foot increase	100 %	down 0 %
1,000 feet	------------	100 %	------------
2,000 feet	1,000-foot increase	100 %	down 0 %
3,000 feet	1,000-foot increase	100 %	down 0 %
4,000 feet	1,000-foot increase	100 %	down 0 %
5,000 feet	1,000-foot increase	100 %	down 0 %
6,000 feet	1,000-foot increase	100 %	down 0 %
7,000 feet	1,000-foot increase	100 %	down 0 %
8,000 feet	1,000-foot increase	100 %	down 0 %
9,000 feet	1,000-foot increase	100 %	down 0 %
10,000 feet	1,000-foot increase	99 %	down 1 %
11,000 feet	1,000-foot increase	80 %	down 19 %
12,000 feet	1,000-foot increase	40 %	down 40 %
13,000 feet	1,000-foot increase	15 %	down 25 %
14,000 feet	1,000-foot increase	5 %	down 10 %
15,000 feet	1,000-foot increase	1 %	down 4 %
16,000 feet	1,000-foot increase	0 %	down 1 %

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.

2. The Chance of Detection is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As Table 10 shows, the Chance of Detection is 100 percent for aircraft at small-to-moderate slant distances. Starting around 10,000 feet, however, the Chance of Detection starts to reduce to zero. This occurs hand in hand with the reduction in Audible Sound Exposure mentioned above, for the same reason. And again, the slant distance at which the Chance of Detection begins its reduction is highly variable, depending upon background sound levels, aircraft type, and aircraft speed.

Table 11. Sound-level Reduction Due to Divergence and Atmospheric Absorption: Audible Duration

SLANT DISTANCE	DISTANCE STEP	AUDIBLE DURATION	AUDIBLE-DURATION STEP
125 feet	----------	36 sec	----------
250 feet	125-foot increase	37 sec	up 1 sec
375 feet	125-foot increase	38 sec	up 1 sec
500 feet	125-foot increase	39 sec	up 1 sec
625 feet	125-foot increase	40 sec	up 1 sec
750 feet	125-foot increase	42 sec	up 2 sec
875 feet	125-foot increase	44 sec	up 2 sec
1,000 feet	125-foot increase	46 sec	up 2 sec
1,000 feet	----------	46 sec	----------
2,000 feet	1,000-foot increase	53 sec	up 7 sec
3,000 feet	1,000-foot increase	60 sec	up 7 sec
4,000 feet	1,000-foot increase	64 sec	up 4 sec
5,000 feet	1,000-foot increase	66 sec	up 2 sec
6,000 feet	1,000-foot increase	66 sec	no change
7,000 feet	1,000-foot increase	66 sec	no change
8,000 feet	1,000-foot increase	65 sec	down 1 sec
9,000 feet	1,000-foot increase	63 sec	down 2 sec
10,000 feet	1,000-foot increase	61 sec	down 2 sec
11,000 feet	1,000-foot increase	59 sec	down 2 sec
12,000 feet	1,000-foot increase	55 sec	down 4 sec
13,000 feet	1,000-foot increase	49 sec	down 6 sec
14,000 feet	1,000-foot increase	37 sec	down 12 sec
15,000 feet	1,000-foot increase	22 sec	down 15 sec
16,000 feet	1,000-foot increase	0 sec	down 22 sec

NOTES: 1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for 'moderate' background sound levels. See text for other conditions.

2. The Audible Duration is defined in the appendix on Technical Translations.

3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

As Table 11 shows, the Audible Duration shows an interesting pattern. At first it increases with increasing slant distance. This happens because the table is constructed for an aircraft that passes directly overhead. Increased slant distance in the table, therefore, means increased aircraft height above the ground. This increased height reduces the soft-ground attenuation when the aircraft is approaching from far away, when its elevation angle is small and so its sound is attenuated by grazing over the ground. This occurs as well when the aircraft recedes. With further increase in aircraft height, however, the aircraft rises out of the ground's influence and can be heard when further away, both approaching and receding.

In addition, starting around a slant distance of 10,000 feet, the aircraft begins to become less audible, as discussed above. When its audibility becomes essentially zero, around 16,000 feet, its Audible Duration reduces to zero, as well. This occurs hand in hand with the reduction in Audible Sound Exposure and the reduction in Chance of Detection, both mentioned above. And again, the slant distance at which Audible Duration begins its reduction towards zero is highly variable, depending upon background sound levels, aircraft type, and aircraft speed.

Chapter 8. SUMMARY OF THE EFFECT OF AIRCRAFT HEIGHT UPON SOUND LEVELS ON THE GROUND

The effect of aircraft height upon sound levels at the ground depends upon the location of the flight track relative to the listener/microphone. Three situations are of importance:

- when the flight track is directly overhead, or nearly so,
- when the flight track is to the side, laterally displaced from the listener/microphone, with the sound grazing across relatively flat ground, and
- when the flight track is "below" the listener/microphone, directly visible in an immediately adjacent valley, gorge, or canyon.

8.1 Flight track overhead

When the flight track is directly overhead, or nearly so, then the sound levels at the listener/microphone reduce in value as aircraft height increases. This reduction in sound levels is due to sound divergence and atmospheric absorption, which both cause sound levels to decrease with slant distance from the sound source.

Table 12 shows the approximate effect of increased slant distance upon six acoustical descriptors that are of potential importance to the National Park Service:

- **Maximum Sound Level, in dBA** -- the maximum A-weighted sound level during the aircraft flyover,

- **Onset Rate, in decibels per second** -- the maximum rate of increase in the A-weighted sound level as the aircraft approaches,

- **Total Sound Exposure, in dB** -- the total sound exposure during the flyover,

- **Audible Sound Exposure, in dB** -- the audible portion of the total sound exposure,

- **Chance of Detection, in percent** -- the chance that the aircraft can be detected by attentive listeners on the ground, and

- **Audible Duration, in seconds** -- the audible duration of the flyover.

Table 12. Approximate Changes In Sound Levels Due to 1000-foot Increases In Slant Distance to the Flight Track

INCREASE IN SLANT DISTANCE TO FLIGHT TRACK	DECREASE IN MAXIMUM SOUND LEVEL	DECREASE IN ONSET RATE	DECREASE IN TOTAL SOUND EXPOSURE	DECREASE IN AUDIBLE SOUND EXPOSURE	DECREASE IN CHANCE OF DETECTION	CHANGE IN AUDIBLE DURATION
from 125 ft to 1,000 ft	24 dB	28 dB/sec	14 dB	14 dB	0 %	+10 sec
then to 2,000 ft	8 dB	3 dB/sec	6 dB	6 dB	0 %	+7 sec
then to 3,000 ft	5 dB	1 dB/sec	5 dB	5 dB	0 %	+7 sec
then to 4,000 ft	4 dB	1 dB/sec	3 dB	3 dB	0 %	+4 sec
then to 5,000 ft	4 dB	1 dB/sec	2 dB	2 dB	0 %	+2 sec
then to 6,000 ft	3 dB	0 dB/sec	2 dB	2 dB	0 %	0 sec
then to 7,000 ft	3 dB	0 dB/sec	2 dB	2 dB	0 %	0 sec
then to 8,000 ft	2 dB	0 dB/sec	2 dB	2 dB	0 %	−1 sec
then to 9,000 ft	2 dB	0 dB/sec	2 dB	2 dB	0 %	−2 sec
then to 10,000 ft	2 dB	0 dB/sec	2 dB	2 dB	1 %	−2 sec
then to 11,000 ft	2 dB	0 dB/sec	2 dB	2 dB	19 %	−2 sec
then to 12,000 ft	2 dB	0 dB/sec	2 dB	4 dB	40 %	−4 sec
then to 13,000 ft	2 dB	0 dB/sec	1 dB	7 dB	25 %	−6 sec
then to 14,000 ft	2 dB	0 dB/sec	1 dB	11 dB	10 %	−12 sec
then to 15,000 ft	2 dB	0 dB/sec	1 dB	17 dB	4 %	−15 sec
then to 16,000 ft	2 dB	0 dB/sec	1 dB	25 dB	1 %	−22 sec

NOTES:
1. Table was computed for (1) a commercial Stage-2 jet aircraft travelling at 400 miles per hour and (2) for "moderate" background sound levels. See text for other conditions.
2. The tabulated acoustical descriptors are defined in the appendix on Technical Translations.
3. When a flight track is directly overhead, its slant distance equals the aircraft height above the ground.

The first column in the table shows slant-distance increases in steps of 1000 feet, except for the first step, which is slightly smaller. The remaining columns show the effect of these slant-distance increases on the six acoustical descriptors.

For the first three acoustical descriptors in the table (Maximum Sound Level, Onset Rate, and Total Sound Exposure), 1000-foot increases in slant distance reduce the acoustical descriptor's values. For example, a 1000-foot increase from 4,000 to 5,000 feet (1) reduces the Maximum Sound Level by 4 decibels, (2) reduces the Onset Rate by 1 decibel per second, and (3) reduces the Total Sound Exposure by 2 decibels.

For these three acoustical descriptors, the sound-level steps converge at large distances to small values for each 1,000-foot increase in slant distance. 1000-foot stepped increases in slant distance reduce the acoustical descriptors in steps, as well, but with "diminishing returns." The sound-level steps become ever smaller with increasing slant distance between aircraft and the listener/microphone.

The situation is more complex for the last three descriptors in the table (Audible Sound Exposure, Chance of Detection, and Audible Duration), which depend upon aircraft audibility above the non-aircraft background sounds. For the Audible Sound Exposure, the steps first decrease in the normal manner, but then they become quite large at the bottom of the table. This "transition to inaudibility" at the bottom of the table also causes the tabulated pattern for the Chance of Detection and the Audible Duration.

In the table, the transition to inaudibility occurs at a slant distance around 10,000-to-15,000 feet. However, this transition to inaudibility assumes a "moderate" amount of background sound, produced by a 10-to-20 mile-per-hour wind. This same transition to inaudibility would also occur for other background sound levels, but at some other slant distance. To a first approximation, it would occur around a slant distance of approximately 5,000-to-10,000 feet in the presence of strong surf sound, and at a slant distance of approximately 20,000-to-25,000 feet in areas with background sound levels close to the threshold of human hearing. Even in a single location within a park, note that background sound levels often vary significantly from day to day, hour to hour, and even moment to moment – often influenced strongly by time-varying wind speed.

In short, the transition to inaudibility is real, but occurs at a slant distance highly dependent upon local wind conditions and upon aircraft flight conditions. It would occur at different slant distances for commercial jets at other speeds, as well as for other aircraft. In essence, different aircraft cause different sound levels at the ground, as a function of their speed, and therefore they will become inaudible at different slant distances.

8.2 Flight track to the side over relatively flat ground

The situation is more complex when the flight track is to the side, laterally displaced from the listener/microphone, with the sound grazing across relatively flat ground. Table 12 is a starting point for this situation, as well. In addition, however, when the aircraft appears at low elevation angles with the horizontal, "acoustically soft" ground may attenuate the aircraft sound even further than shown in the table, or it may be further attenuated by intervening hills or heavily wooded areas.

In these situations, the amount of further attenuation depends upon the elevation angle of the aircraft above the acoustically soft ground, or upon the blockage in the sound path by the hills or heavily wooded areas. In turn, these depend upon the aircraft's height above the ground. Increasing the aircraft height in these situations causes an *increase* in sound level – as the aircraft rises above the ground's influence, or the hill's influence, or the wooded-area's influence. Once the aircraft rises high enough, however, this effect is finished and the sound level then decreases with increasing aircraft height, as shown in the table.

8.3 Flight track "below" -- directly visible in an immediately adjacent valley, gorge, or canyon

When the flight track is "below" the listener/microphone, directly visible in an immediately adjacent valley, gorge, or canyon, the situation differs in two respects. First, even though the flight track is to the side, as described in the previous section, the sound does not graze across flat ground nor is it blocked by intervening hills or heavily wooded areas. For this reason, the sound is not attenuated further than shown in Table 12. In other words, such a flight track produces the same changes due to 1000-foot increases in slant distance as does a flight track overhead. Of importance only is the slant distance to the flight track.

Second, some aircraft direct different amounts of sound upwards and sideways, compared to downwards. These differences in source "directivity" result in a different sound level upwards/sideways than downwards, for the same slant distance to the flight track. With this relative orientation between the flight track and the listener/microphone held constant, however, the pattern of dependence of sound level upon slant distance is similar to that shown in the table.

8.4 The potential acoustical effectiveness of altitude as a mitigation measure

Table 12 shows that sound-level reductions converge towards zero at large slant distances for each 1,000-foot increase in slant distance. In other words, 1000-foot stepped increases in slant distance reduce sound levels in steps as well, but with "diminishing returns." The sound-level steps become ever smaller with increasing slant distance.

For this reason, the enforcement of minimum altitudes above units of the National Park System has potential acoustical effectiveness only when the aircraft presently fly relatively low above these units. Slant-distance increases from 125 feet to 1,000 feet, for example, would produce very large reductions in sound level (15-to-25 decibels or so). Increases from 1,000 feet to 2,000 feet would produce smaller reductions, still moderate to substantial. Increases from 10,000 feet to 11,000 feet, on the other hand, would produce only very small reductions in sound level (around 2 decibels or so), and so would have little potential for effective mitigation.

In other words, moderate-to-substantial benefits (4-to-10 decibels or so) require an approximate doubling of the slant distance between the aircraft and the listener/microphone. Where existing slant distances are small, their doubling may come easily, depending upon non-acoustical circumstances. On the other hand, where existing slant distances are large, their doubling is essentially impossible. Where existing slant distances are intermediate, their doubling becomes more and more difficult the greater their initial value. Doubling them may or may not be practicable for non-acoustical reasons.

If altitude restrictions are attempted as a mitigation measure above units of the National Park Service, care must be taken to avoid the loss of soft-ground attenuation, or of attenuation due to hills or heavily wooded areas. Where aircraft now fly low, these attenuations may now accrue to points on the ground at large horizontal ranges from the aircraft's flight track. Requiring aircraft to fly higher in such situations might actually increase sound levels far from the flight tracks -- as the aircraft are forced higher, into direct view or out of the ground's acoustical influence.

Several acoustical descriptors of aircraft sound reduce to zero at specific slant distances -- distances at which the aircraft become essentially inaudible. This transition to inaudibility depends strongly, however, upon the "moderate" background sound levels used to compute this table, and is therefore very difficult to predict with precision or to rely upon for consistent effect. In addition, they vary with the type of aircraft and with its speed. For all these reasons, we do not recommend any "inaudibility" distance as a candidate for a minimum altitude restriction above units of the National Park Service.

Note that aircraft sound also reduces with increased horizontal range, because increases in horizontal range cause corresponding increases in slant distance. In addition, as horizontal range increases, the chance of obtaining further attenuation improves, as the sound grazes over acoustically soft ground or is interrupted by hills or heavily wooded areas. For this reason, relocating low-height flight tracks to increase the horizontal range to sound-sensitive areas within parks is a potentially effective mitigation measure.

Appendix A. TECHNICAL TRANSLATIONS OF SEVERAL NON-TECHNICAL TERMS USED IN THIS REPORT

In the tabulations and discussions of acoustical descriptors above, several non-technical terms were substituted for specialized terms common in the acoustical literature. The non-technical terms are thought to be more understandable by non-technical readers and by readers in technical professions other than acoustics, because the substituted terms are rooted in common English rather than in acoustical jargon.

For professionals in acoustics, this present section translates these non-technical terms into their technical counterparts. For clarity, non-technical terms are surrounded by quotation marks wherever they appear in this section.

Audibility. The term "audibility" is used above in a non-technical sense, as a substitute for signal detectability [Green, 1966]. As used above, an aircraft is considered "audible" (detectable above the concurrent background sound) if the aircraft's detectability index d' at any time during the aircraft's flyover is 2.32 or greater (equivalently, 10 log(d') is 3.65 dB or greater). This value of d' corresponds to a 50 percent chance of detection with a one percent chance of false alarms.

To compute "audibility" above, the set of d_i in each 1/3-octave band from 25 to 10,000 Hertz were combined into d' by the following equation:

$$d' = \sqrt{d_1^2 + d_2^2 + ... + d_n^2}$$

Audible duration. "Audible duration" is the time interval during which the aircraft's d' is 2.32 or greater (equivalently, 10 log(d') is 3.65 dB or greater.

Chance of detection. An aircraft's "chance of detection," is distributed in a Gaussian manner about 10 log(d') = 3.65 dB, with a standard deviation of 1 dB. In tabular form:

d'	10 log(d')	Chance of detection
1.16	0.65 dB	0.1 %
1.46	1.65 dB	2.3 %
1.84	2.65 dB	16.0 %
2.32	3.65 dB	50.0 %
2.92	4.65 dB	84.0 %
3.67	5.65 dB	97.7 %
4.62	6.65 dB	99.9 %

For use below, this "chance of detection" as a function of d' is denoted as Ch(d').

Total sound exposure. The term "total sound exposure" is used above as a substitute for the aircraft's Sound Exposure Level, SEL.

Audible sound exposure. "Audible sound exposure" $(SEL)_d$, is computed with the following energy-like equation:

$$10^{\left(\frac{(SEL)_d}{10}\right)} = \left[\frac{Ch(d')}{100\%}\right] 10^{\left(\frac{SEL}{10}\right)}$$

Note that when the chance of detection is 100 percent, the "audible sound exposure" equals the "total sound exposure" -- that is, SEL. However, as the chance of detection reduces from 100 towards 0 percent, then the "audible sound exposure" reduces as well, so that its associated energy-like term reduces to zero.

Appendix B. SYNTHESIS FOR THE SOUND-LEVEL HISTORY OF A JET AIRCRAFT FLYOVER

To determine the dependence of each relevant acoustical descriptor upon slant distance and aircraft speed, it was necessary to synthesize an approximate computation procedure from the literature review. In brief, this synthesis first approximates the full sound-level history of an aircraft flyover, separately for each 1/3-octave band from 50 to 10,000 Hertz. Then it computes each acoustical descriptor from these 1/3-octave sound-level histories, to approximate the acoustical descriptor's dependence upon slant distance and aircraft speed.

This appendix describes the resulting synthesis, for readers technically familiar with acoustics. The synthesis is not intended to be a rigorous computation method for aircraft 1/3-octave-band time histories, nor for their resulting acoustical descriptors. Development of such a method is beyond the scope of this literature review. Desired instead was a synthesis that approximates the general trends of the acoustical descriptors with increasing aircraft slant distance and varying aircraft speed -- as a basis for the illustrative figures and tables in the main body of this report.

The synthesis is specialized for commercial jet aircraft, rather than for military jets or for helicopters or for propeller aircraft. Commercial jet aircraft were chosen for the synthesis because existing literature is more complete for them than for other aircraft types. This relative completeness allowed a synthesis for commercial jet aircraft without the need for independent research and/or extensive consolidation from data bases of the Federal Aviation Administration and the U.S. Air Force -- or from privately held data not in the open literature.

The synthesis proceeds as follows:

Aircraft spectrum. We start the synthesis with the aircraft's 1/3-octave spectrum in the NOISEMAP data base. Within this data base, spectra are specific to individual aircraft types and apply (1) during a 1000-foot flyover, (2) at a reference speed, s_{ref}, particular to that aircraft type, and (3) at the moment in time during the flyover when the aircraft registers its highest A-weighted sound level at the receptor on the ground.

We denote the time of maximum A-weighted sound level at the receptor as $(t_{rec})_{ref}$. Note that the sound received at $(t_{rec})_{ref}$ is emitted by the aircraft at a slightly earlier time, $(t_{emm})_{ref}$, because the sound takes an amount of time $(t_{rec})_{ref} - (t_{emm})_{ref}$ to travel from aircraft to receptor.

Also included in the NOISEMAP data base is the angle of sound emission from the aircraft, θ_{ref}, that results in this highest A-weighted sound level at the receptor. θ_{ref} is measured from a zero angle "ahead" of the aircraft. For jets, θ_{ref} is generally towards the rear quarter of the aircraft.

Note that θ_{ref} is measured at time $(t_{emm})_{ref}$, when the reference sound is emitted from the aircraft, not at time $(t_{rec})_{ref}$ when it arrives at the receptor. Also note that θ_{ref} is not the angle of largest directivity; during the flyover, mechanisms in addition to directivity influence the sound on the ground (changing slant distance, changing air absorption, and so forth) and therefore directivity alone does not decide θ_{ref}.

The sound energy emitted in the reference direction θ_{ref} travels a reference slant distance

$$r_{ref} = \frac{1000\text{ ft}}{\sin(\theta_{ref})}$$

between aircraft and receptor.

Summary to this point in the synthesis. At this point in the synthesis, we have the aircraft spectrum for the following single reference condition: (1) time of sound emission, $(t_{emm})_{ref}$, measured at the aircraft, (2) aircraft height above the ground, h_{ref} = 1000 feet, (3) aircraft altitude above sea level, a_{ref}, equal to 1000 feet as well, (4) aircraft slant distance from the receptor, r_{ref}, (5) sound emission angle θ_{ref}, and (6) aircraft speed, s_{ref}.

Ultimately we wish to synthesize the sound-level history of the aircraft flyover at the aircraft's actual speed, s, and actual height above the ground, h. Before doing this, however, we need to synthesize the sound-level history for the reference speed, s_{ref}, and the reference height, h_{ref} = 1000 feet. This is necessary to reconcile the data-base's reference spectrum with both (1) the aircraft's A-weighted directivity from independent sources in the literature, and (2) the data base's value of Sound Exposure Level, SEL, for the reference conditions.

So next we need to synthesize the reference aircraft's full sound-level history in 1/3-octave bands (at height 1000 feet and s_{ref}), using the reference spectrum under the reference conditions. For times before and after $(t_{emm})_{ref}$, the following parameters vary relative to their reference values: (1) slant distance, $r(t_{emm})$, between aircraft and receptor, which affects the amount of sound divergence and atmospheric absorption, (2) angle of sound emission, $\theta(t_{emm})$, which affects the amount of sound emitted in accordance with the aircraft's directivity, and (3) lateral attenuation between aircraft and receptor, which depends upon the continually changing elevation angle to the aircraft.

Slant distance, $r(t_{emm})$. In a straightforward manner, we first determine the time-varying slant distance as the aircraft proceeds along its route. This slant distance bears the standard relationship between perpendicular distance (1000 feet) to the flight path, the aircraft speed s_{ref}, and time t_{emm} as measured at the aircraft. Without loss of generality, we set t_{emm} equal to zero when the aircraft is at its closest point of approach to the receptor.

Note that we initially use the time of sound emission, t_{emm}, in our synthesis, rather than the time of sound arrival at the receptor, t_{rec}. We do this because the amount of sound energy emitted per second by the aircraft depends upon the time scale at the aircraft and upon the emission angles measured at the aircraft. We will later convert to receptor time, t_{rec}, because that is the time scale for our desired time histories.

Divergence. Next we adjust each 1/3-octave band level by the additional amount of divergence at time t_{emm}, relative to the reference conditions. This adjustment equals

$$-20 \log \left[\frac{r(t_{emm})}{r_{ref}} \right]$$

This adjustment will be negative at times when the aircraft is further from the receptor than r_{ref}, and will be positive when closer. Note that the reference distance is the slant distance, r_{ref}, not the distance of closest approach, 1000 feet.

Atmospheric absorption. Next we adjust each 1/3-octave band level by the additional amount of atmospheric absorption at time t_{emm}, relative to the reference conditions. This adjustment differs for each frequency band, and is computed as that band's atmospheric absorption per foot of sound propagation, times the propagation distance in excess of r_{ref}. This adjustment will be negative at times when the aircraft is further from the receptor than r_{ref}, and will be positive when closer. Note again that the reference distance is the slant distance, r_{ref}, not the distance of closest approach, 1000 feet.

Lateral attenuation. When the aircraft is at a great distance from the receptor, either when approaching or when receding, its elevation angle above the horizontal is small. For this reason, we subtract the lateral attenuation from each 1/3-octave band level, to account for the soft-ground attenuation between aircraft and receptor. As the aircraft approaches the receptor, this lateral attenuation reduces to zero; it then increases again as the aircraft recedes. In this part of the synthesis, we are approximating to (1) relatively flat, acoustically absorptive ground and (2) an aircraft that flies directly overhead or nearly so.

Conversion from emission time to receptor time. At this point in the synthesis, we have the aircraft's sound-level history with time t_{emm} at the aircraft. Before we can adjust this sound-level history for directivity, we must convert the time axis to t_{rec} at the receptor.

Two mechanisms enter into this conversion. First, because the sound takes time to travel from aircraft to receptor, there is a continually changing offset between the two time scales. Mathematically, t_{rec} equals t_{emm} plus the amount of time it takes the sound to travel the slant distance, r.

Second, while the aircraft is approaching the receptor, the sound energy emitted during a time interval of one second (measured at the aircraft) actually arrives over a shorter time interval measured at the receptor, because of the motion of the aircraft towards the receptor. For example, if the aircraft were approaching the receptor at one half the speed of sound, one second's worth of emitted energy would arrive compressed into one-half second at the receptor. Therefore, the sound intensity at the receptor would be doubled -- that is, twice as much energy per second would enter the microphone as otherwise. Accordingly, the sound level is increased by this motion of source towards receptor. On the other hand, while the aircraft is receding from the receptor, the opposite happens: the sound level is decreased by the motion of source away from the receptor.

In total, the required adjustment in sound level equals

$$-10\log\left[1-\left(\frac{s_{ref}}{c}\right)\cos\theta\left(t_{emm}\right)\right]$$

During approach, this adjustment is positive and can be relatively large. For example, when the aircraft is still very far off and approaching, then θ nearly equals zero degrees. In this case, the adjustment equals +3 decibels for an aircraft travelling at half the speed of sound, c, and +6 decibels for one travelling at three-quarters the speed of sound. As the aircraft approaches closer, θ tends towards 90 degrees and the adjustment reduces slowly to zero at the aircraft's point of closest approach. As the aircraft recedes, θ transitions from 90 to 180 degrees and the adjustment therefore tends towards small negative values, minus 1-to-2 decibels.

Directivity. Concerning directivity, we begin with the typical jet directivity pattern from the literature, as shown in the main body of this report. This directivity pattern contains a lobe towards the rear quarter of the jet. We next must modify this directivity to be consistent with the reference conditions from the data base. Otherwise, our resulting sound-level history would not have its maximum A-weighted sound level at the proper θ_{ref}.

To modify the directivity pattern, we compute a full set of 1/3-octave-band time histories from the considerations above, and then compute the resulting A-weighted sound-level history. We then observe the angle at which this sound-level history becomes a maximum. This will generally not be equal to the reference angle θ_{ref}, because the directivity pattern from the literature is not precisely consistent with the data base. We therefore "re-aim" the major lobe of the directivity pattern somewhat, in as smooth a manner as possible, to turn the maximum A-weighted sound level to the data base's direction, θ_{ref}.

Reference SEL. We next must ensure consistency of the aircraft's sound-level history with the data base's value of the reference Sound Exposure Level, SEL_{ref}. To do this, we determine the SEL from the resulting A-weighted sound-level history in the standard manner, and calibrate the entire sound-level history in all frequency bands, thereby shifting it either up or down somewhat to produce the proper SEL_{ref}.

Summary to this point in the synthesis. At this point in the synthesis, we have synthesized the aircraft's 1/3-octave-band time histories at the receptor, consistent with the reference conditions in the data base. For the reference height (h_{ref} = 1000 feet) and reference speed, s_{ref}, these 1/3-octave time histories produce (1) the proper general shape of the aircraft's A-weighted directivity, re-aimed somewhat, (2) the proper reference SEL_{ref}, (3) a maximum A-weighted sound level at the proper angle θ_{ref}, and (4) the proper relative spectrum at θ_{ref}.

We have had to slightly compromise on producing the proper maximum A-weighted sound level, in order to calibrate the sound-level history to the proper SEL_{ref}. In addition, we have not been able to incorporate the aircraft's 1/3-octave directivities, for lack of adequate data in the open literature. Instead, we have considered them to be the same as the A-weighted directivities. Finally, we have not incorporated the Doppler effect, which shifts sound energy upwards in frequency upon the aircraft's approach and downward when it recedes.

Computation for actual flight conditions. Now that the computations are calibrated in this manner to the reference conditions, we proceed to synthesize the sound-level history for the aircraft's actual height, h, and speed, s. In addition, we must make one further adjustment for the aircraft's actual altitude, a, above sea level, which affects its sound emission.

To synthesize the 1/3-octave time histories for actual flight conditions, we repeat the above steps, except for the calibrations of directivity and SEL -- this time for the actual aircraft height above the ground and aircraft speed. We start with the data-base reference conditions and increase the perpendicular distance between flight path and receptor to the actual height above the ground. This results in an adjustment for both divergence and atmospheric absorption, as discussed above. Then we traverse the aircraft along its flight path, at its actual speed, to determine its 1/3-octave time histories in t_{emm} units, while taking into account changes in divergence, atmospheric absorption, and directivity. And finally we convert to time units, t_{rec}, at the receptor as discussed above.

Note that we make no explicit adjustment from the reference speed s_{ref} to the actual aircraft speed, s. Nevertheless, the computed SELs from the model will vary with speed in the proper manner,

$$-10\log\left[\frac{s}{s_{ref}}\right]$$

because the time histories will account for aircraft speed: the histories will be "shorter" along the time axis for faster aircraft and "longer" for slower aircraft.

Altitude-above-sea-level adjustment. One further adjustment is needed to complete the aircraft's time histories: an altitude-above-sea-level adjustment to account for reduced jet-aircraft emissions at the actual aircraft altitude, a. To make this adjustment, we subtract the following from each 1/3-octave band level [Galloway, 1981] [SAE, 1985 (both citations)]:

$$\mathrm{Adj}(a) = 105\log[1-(6.8756\times10^{-6})\,a] - 10\log[1-(6.648\times10^{-6})\,a]$$

This subtraction adjusts the aircraft's sound emission to aircraft altitudes above sea level different from 1000 feet. Note that the data base assumes that the ground is at sea level and correspondingly that the aircraft is 1000 feet above sea level during its reference flyover.

Computation of descriptors. The resulting synthesis produces 1/3-octave time histories during the aircraft flyover. We then can compute the acoustical descriptors of interest directly from these time histories, while taking into account the 1/3-octave-band spectrum of the background sound. These computations of acoustical descriptors are summarized in Appendix A.

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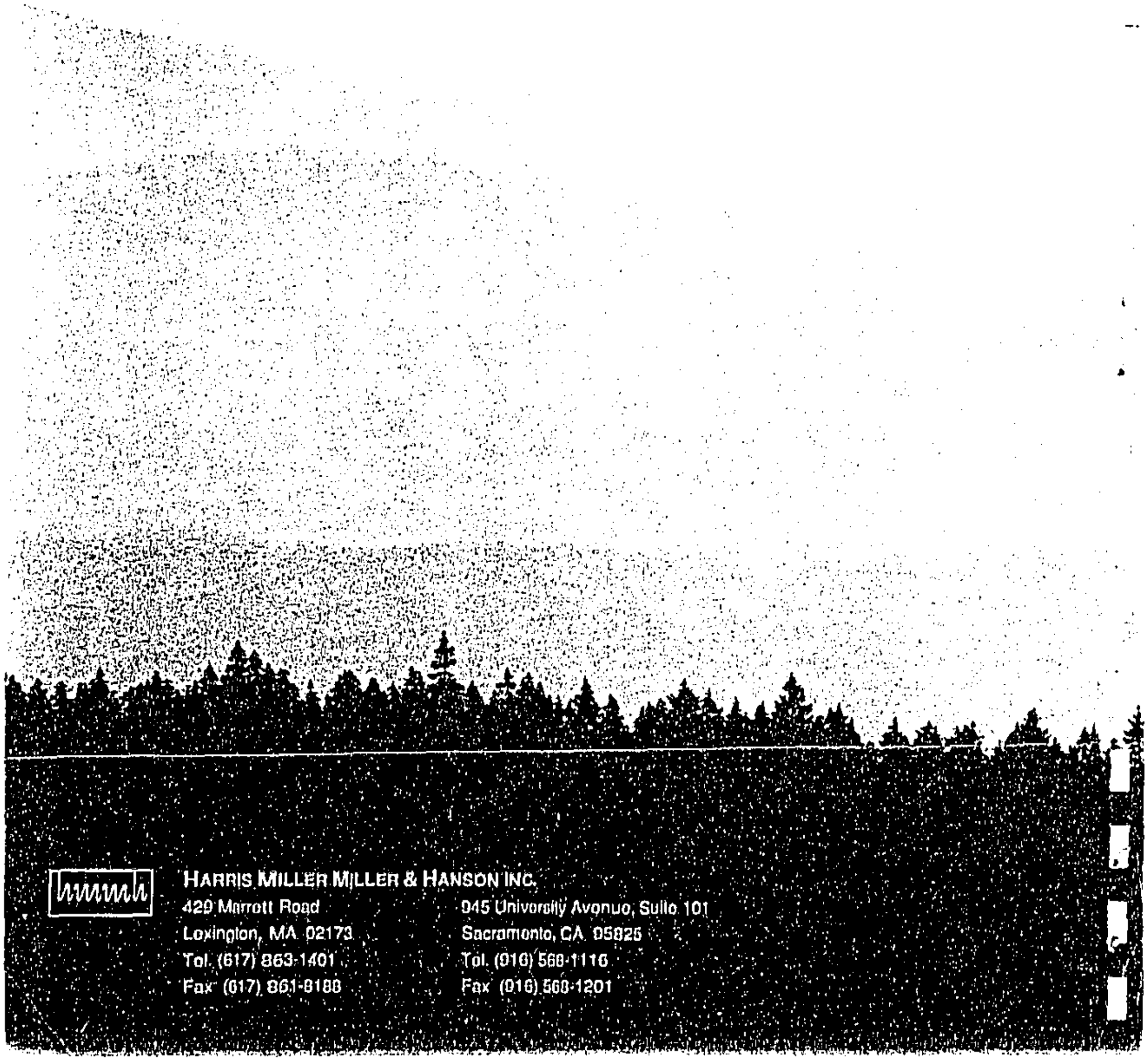

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