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CALCULATION OF SIDELINE NOISE LEVELS DURING TAKEOFF ROLL.(U)

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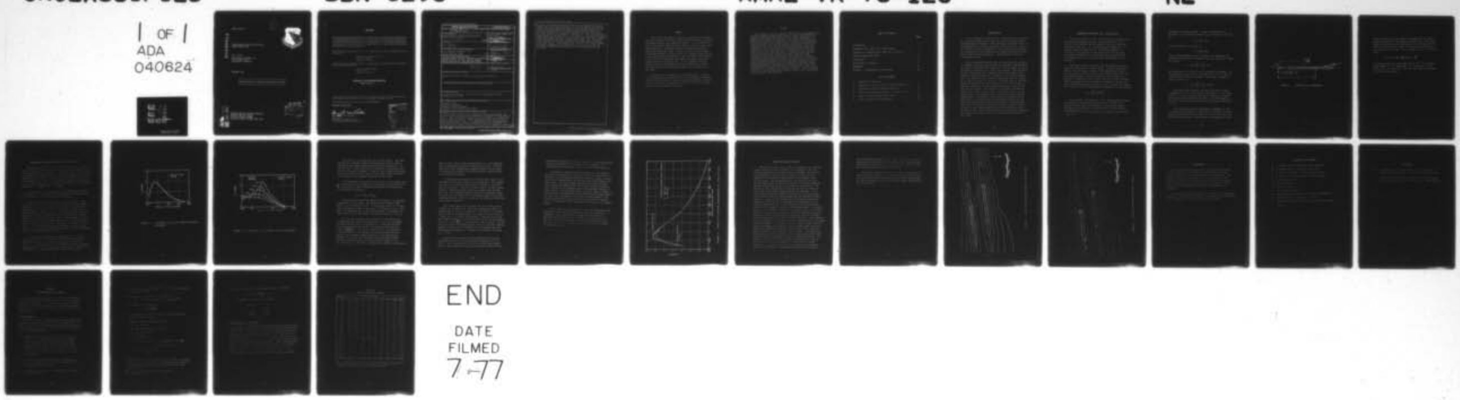

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# CALCULATION OF SIDELINE NOISE LEVELS DURING TAKEOFF ROLL

John F. Mills

Bolt Beranek and Newman Inc.
21120 Vanowen Street
Canoga Park, California

September 1976







AEROSPACE MEDICAL RESEARCH LABORATORY
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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AMRL-TR-76-123

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

**FOR THE COMMANDER**

HENNING E. VON GIERKE
Director
Biodynamics and Bionics Division
Aerospace Medical Research Laboratory

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This report discusses an improved analytical approach for computing the sideline noise generated by aircraft during takeoff roll. The relationship accounts for the effects of acceleration on the typical shape of noise radiation pattern from a static full-power ground runup. This simplified model is suitable for hand calculations or direct implementation into NOISEMAP, the computerized procedure used by the Air Force to generate contours

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)* of equal noise exposure about airbases resulting from aircraft flight and ground runup operations. For the Boeing 707-300 aircraft, the new, simplified model yielded results within 0.5 dB of those obtained with more complex computational procedures involving the effects of forward speed on the jet noise output. An F-104 takeoff roll example is included as a test case and to demonstrate the validity of the new model for engine types ranging from afterburning turbojet to low bypass ratio turbofan. Recent noise measurements by Bolt Beranek and Newman, Inc. at several civil airports showed good agreement with the values predicted using this model. Accordingly, this takeoff roll noise algorithm has been incorporated into NOISEMAP 3.4 and will be used for all future airbase noise exposure contour predictions by the Air Force.

SUMMARY

This report discusses an analytical approach to determine the noise levels at various locations resulting from an aircraft accelerating along the runway for takeoff. A time history of the noise event is constructed by means of moving a noise source past observers at different sideline distances distributed behind and along the runway. Based on this, a relationship is obtained between the noise level at a constant speed and the noise level during acceleration. Also included is an analysis of the effects of gradually increasing the power during the initial part of the ground roll. It is concluded that the effects of this non-instantaneous power addition are small, and that there is no substantial benefit in including it in the model.

A procedure is presented for incorporating the results of the study into a computer model. The procedure is intended for use with NOISEMAP, a computer program developed by BBN for the U. S. Air Force, designed to calculate the noise exposure resulting from aircraft operations.

## PREFACE

This report is one of a series describing the contractual and in-house research program undertaken by the Aerospace Medical Research Laboratory under Project/Task 723104, Measurement and Prediction of Noise Environments of Air Force Operations, to develop a procedure for predicting the community noise exposure resulting from aircraft operations. Other reports previously published under this research program include: AMRL-TR-73-105, "Community Noise Exposure Resulting From Aircraft Operations: Application Guide for Predictive Procedure"; AMRL-TR-73-106, "Community Noise Exposure Resulting From Aircraft Operations: Technical Review"; AMRL-TR-73-107, "Community Noise Exposure Resulting From Aircraft Operations: Acquisition and Analysis of Aircraft Noise and Performance Data"; AMRL-TR-73-108, "Community Noise Exposure Resulting From Aircraft Operations: Computer Program Operator's Manual"; AMRL-TR-73-109, "Community Noise Exposure Resulting From Aircraft Operations: Computer Program Description"; AMRL-TR-73-108, Appendix "Community Noise Exposure Resulting From Aircraft Operations: NOISEMAP Program Operator's Manual"; AMRL-TR-73-108, "Addendum For Version 3.3 of NOISEMAP". Technical monitor for this effort was Mr. Jerry Speakman of the Biodynamic Environment Branch. Partial funding for this effort was provided by the Air Force Civil Engineering Center, Tyndall AFB, Florida.

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# INTRODUCTION

The calculation of noise levels at some point on the ground as a result of flight operations can be made using relatively straightforward procedures. Data obtained from flight tests can be extrapolated to various distances, and adjusted for speed. The effects of sound propagation at low angles above the ground are accounted for by considering the excess attenuation occurring in this mode of propagation. Interpolation is used for intermediate angles.

These procedures work well for the case where the aircraft is airborne; however, the situation is much more complex during the takeoff roll, where the aircraft is accelerating, and where the power is applied over a finite time period. This situation has been accounted for in computations of noise exposure by adding a correction which is a maximum at the start of takeoff roll, and reduces as the aircraft accelerates down the runway. For a typical takeoff, an offset of 4 dB was added to the sound levels at the start of roll, relative to the lift-off point. This was reduced to 0.5 dB half-way through the takeoff roll, and zero at liftoff. This results in a constant increase in noise levels at all points along a line perpendicular to the flight path. The magnitude was derived from limited sideline measurements. In practice, this should be a variable value. Application of the empirical relationships obtained from the data also gives rise to some inconsistencies in dealing with operations of the same aircraft at different weights, and also results in zero noise exposure in the area behind the start of takeoff roll, which is an area actually receiving an appreciable exposure because of the directional characteristics of jet noise.

## PROCEDURES FOR NOISE LEVEL CALCULATIONS

The noise level at a point on the ground at a particular time can be determined from the relative position of the aircraft and observer, and the shape of the noise radiation pattern at that time. By considering the movement of the aircraft past the observer, it is therefore possible to construct a time history of the noise level from the time that power is applied to the time when the noise level has once again fallen to a low level following passage of the aircraft.

There are a number of effects on the radiation pattern which are a function of forward speed. The most significant effects are the change in shape of the directivity pattern and the change in noise level as the relative velocity of the jet exhaust varies. For the purposes of this study, the effects of forward velocity on the shape of the noise pattern have been ignored, and the pattern is assumed to be that of a static full-power runup. The noise level is assumed to change as a function of the forward speed according to the relationship:

$$\Delta \text{ dB} = \left( \frac{V_j - V_A}{V_j} \right)^6 \quad *$$

For the basic investigation of the sideline noise levels, the aircraft acceleration is assumed to be uniform. The simplified model used in calculating aircraft performance (Reference 1) is employed to determine the takeoff distance

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* Definitions of the symbols used are provided at the end of the text.

and speed for civil aircraft. Using the terminology of Reference 1, the takeoff distance, $S_o$, see Figure 1, is given by

$$S_o = C_1 W^2 \text{ feet}$$

and the speed at $S_o$ is given by

$$V = C_2\sqrt{W} \text{ knots}$$

These relationships are used to develop the expression for distance from the start of takeoff roll as a function of time, as follows:

$$D = \frac{1}{4} \times \frac{C_2^{\,2}}{C_1} \times \frac{K^2}{W} \times T^2$$

The distance D is in feet, W is in thousands of pounds, T is in seconds from the start of takeoff roll, and K = 1.688, to convert knots to feet per second. Similarly, the speed at time T is given by

$$V = \frac{1}{2} \times \frac{C_2^{\,2}}{C_1} \times \frac{K}{W} \times T \text{ knots}$$

The noise level patterns used were derived from data acquired as part of a USAF project (Reference 2). The runup pattern of a C-141 aircraft was used to simulate the noise characteristics of the Boeing 707-300. The TF 33 engine of the C-141 is an uprated version of the JT3D which powers the 707-300.

The runup patterns were processed by NOISEMAP 3.2 with the appropriate operational information to generate a grid of A-weighted noise levels to a scale of 1 inch = 400 feet with 200 feet grid spacing. Time patterns were generated at one-

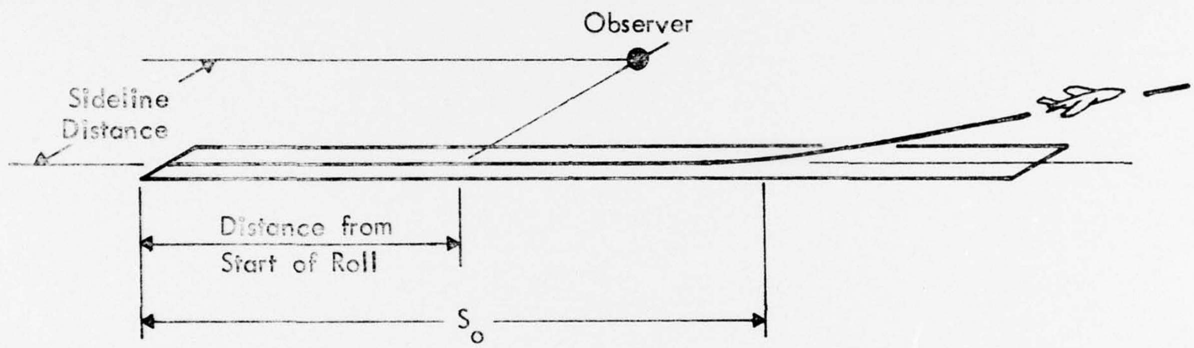


FIGURE 1. TAKEOFF ROLL GEOMETRY

second intervals for five sideline distances and at various positions relative to the start of takeoff roll. The values between grid points were interpolated, and then adjusted for forward velocity at that time. The resulting time history was summed over the upper 10 dB of signal, using the relationship:

$$SEL = 10 \log_{10} \sum \text{antilog}_{10} \frac{dB}{10}$$

A reference value was calculated for the case of a constant speed segment of the flight path, at a speed equal to the speed at $S_o$. The values at other positions were all related to this reference value.

## VARIATION OF SIDELINE NOISE LEVEL WITH POSITION

The calculations outlined in Section II were made in detail for a Boeing 707-300 operated at a takeoff weight of 265,205 lbs. and in less detail for an F-104. The weight of the 707 was chosen to generate a climb speed of 160 knots. The corresponding takeoff distance $S_o$ is 4779 feet. These values were derived from data in the referenced EPA report. For the Boeing 707-300, the value of $C_1$ is .0728, thus $S_o = .0728\ (256.205)^2 = 4779$ feet. $C_2$ is 9.996 thus speed $= 9.996\sqrt{256.205} = 160$ knots.

For convenience, all noise levels are related to the value at 160 knots. The difference in noise levels is referred to as $\Delta_6$, to conform with previously-used terminology.

Figure 2 shows the variation of $\Delta_6$ as a function of the position of an observer along a line 1000 feet from the runway centerline. (Note that this variation assumes no change of power settings throughout the run. The values include duration effects and the reduction in thrust as forward speed increases.) This indicated that the maximum noise level occurs at a point behind the start of roll with a value of approximately + 9.5 dB relative to the 160 Kt constant speed value. At further distances behind the start of roll, the noise level falls off quite rapidly. At a position close to the aircraft liftoff, the $\Delta_6$ value is zero, and halfway between the start of roll and liftoff, the value is approximately + 2.5 dB.

At other sideline distances, the variation of $\Delta_6$ has a similar form, but with different maximum values occurring in different positions. The comparative values are shown in Figure 3. The maximum value of $\Delta_6$ is greater at close distances and occurrs at a point closer to the start of roll. This can be attributed to the directional nature of the noise source.

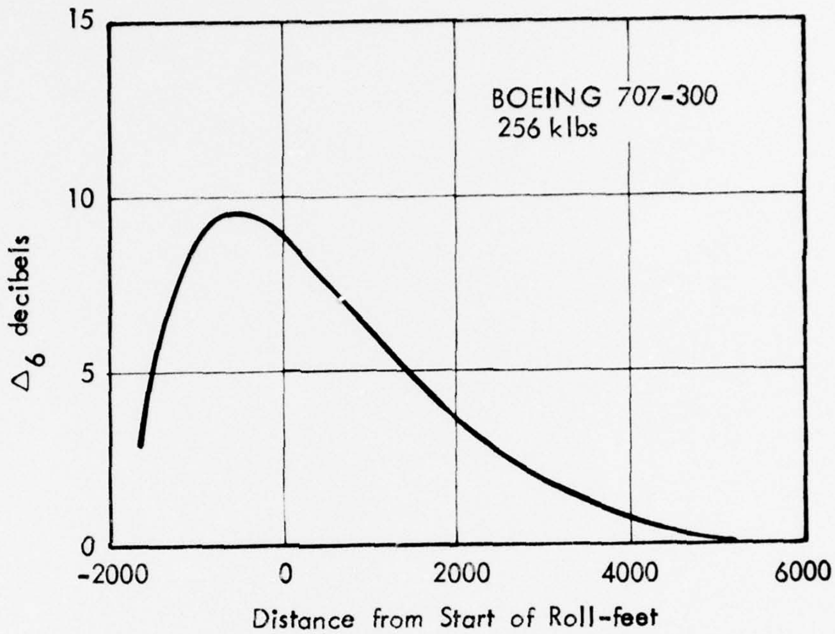


FIGURE 2. VARIATION OF $\Delta_6$ FOR 1000 FT SIDELINE DISTANCE

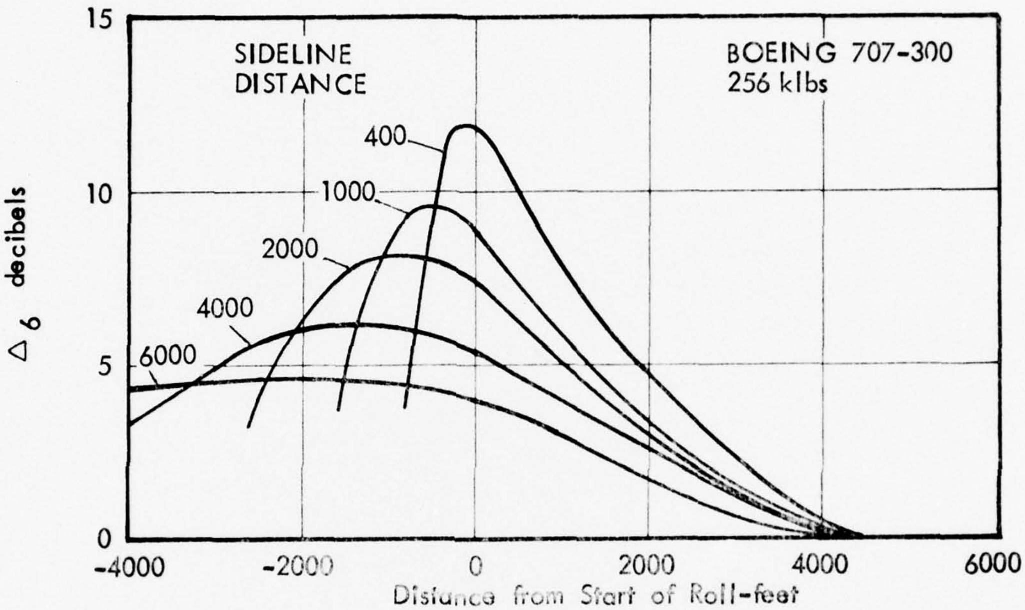


FIGURE 3. VARIATION OF $\Delta_6$ WITH SIDELINE DISTANCE

The value of $\Delta_6$ varies with the aircraft weight. The same aircraft at a heavier weight accelerates more slowly, with a correspondingly higher duration during the initial part of the takeoff roll. Also, more runway is required to accelerate, and the lift-off speed is higher. Using the same simplifying assumptions as before, the noise level at any given location and time is a function of the aircraft position at that time.

The adjustment for duration is a function of the speed, which at any given position during the acceleration is proportional to $\sqrt{W}$. From this, it may be deduced that during the takeoff roll, the adjustment is given by

$$\Delta_6 = 5 \log_{10} W/W_{ref}$$

The duration of the noise signal at distance $S_o$ is inversely proportional to the speed. The speed is proportional to $\sqrt{W}$. Thus at $S_o$, the value of $\Delta_6$ is $- 5 \log W/W_{ref}$, which is of equal value and opposite sign to the value at the start of roll. This simplified analysis ignores the small changes in instantaneous noise levels due to the change in relative velocity of the jet.

The test the analysis, the procedure of calculating and integrating noise levels was repeated for a 707 at its maximum certified takeoff weight of 333,600 lbs. Using the relationships derived above, the value of $\Delta_6$ should be increased by $5 \log_{10} \frac{333.600}{256.205} = 0.6$ dB at the start of roll, and reduced by 0.6 dB at liftoff. The changes obtained by a point-by-point analysis were slightly higher than the 0.6 dB predicted due primarily to the use of a simplified duration change model, and neglecting the effects of forward speed changes on the jet noise output. The error in ignoring this effect is relatively small, and in view of other uncertainties, it is recommended that the simplified duration model should be used. Results from future test programs may suggest changes in this model. A step-by-step procedure for calculating the required offset is provided in Appendix A.

In applying these results to other aircraft types, it is necessary to take into account other parameters. For example, the values of $\Delta_6$ derived above are all related to the noise level at 160 knots. Thus if the noise data to be used corresponds to a different speed, then an allowance must be made for this. As an example and test case, the analytical values of $\Delta_6$ for an F-104 takeoff were calculated based on the relationships derived for the 707, and also by moving a runup noise source past an observer.

The liftoff speed for this aircraft is 200 knots with a takeoff roll of 3000 feet. Thus the acceleration, which is proportional to $V^2/S_o$, is $(200/160)^2 \times 4779/3000 = 2.49$ times that of the 707, corresponding to a change in the $\Delta_6$ value of $- 5\log 2.49 = -2.0$ dB for acceleration. Relative to the 200 knot liftoff speed, the total difference in the $\Delta_6$ value would be $-2.0 + 10 \log \frac{200}{160} = -1.0$ relative to the 707 value. To test this, the value of integrated noise level at 1000 feet sideline distance at the start of takeoff roll was computed with the afterburner runup pattern. Relative to 200 knots, this gave $\Delta_6 = 7.5$ dB.

Using the above analysis, the predicted value is that calculated for the 707, 8.9 dB, with an offset of -1.0, to give 7.9 dB, compared with 7.5 dB by the other more complex method. This agreement is good, particularly in view of the considerable difference in engine types, i. e., an afterburning turbojet as opposed to a low bypass ratio turbofan, with corresponding differences in noise radiation characteristics.

In practice, during normal operations of civil aircraft, the power is applied as the aircraft starts its takeoff roll. The result is a varying acceleration and noise output, and full power is not reached until the aircraft has an appreciable forward speed. The noise levels resulting from this operation were computed by assuming that the thrust increases uniformly over a period of ten seconds, with a corresponding changes in noise output. The resulting values of $\Delta_6$ are shown in Figure 4. The position of the maximum value is displaced by approximately 200 feet, and the magnitude is reduced by approximately 1 dB. At positions beyond about 500 feet from the start of takeoff roll, the values are indistinguishable from those of the simpler model.

At the present time, there is no complete measurement data available to make detailed comparison with the information presented. Some limited data acquired for the purposes of defining adjustments during the takeoff roll were compared, and show reasonable agreement. Additional measurements under carefully controlled conditions would be required to validate or refine the model.

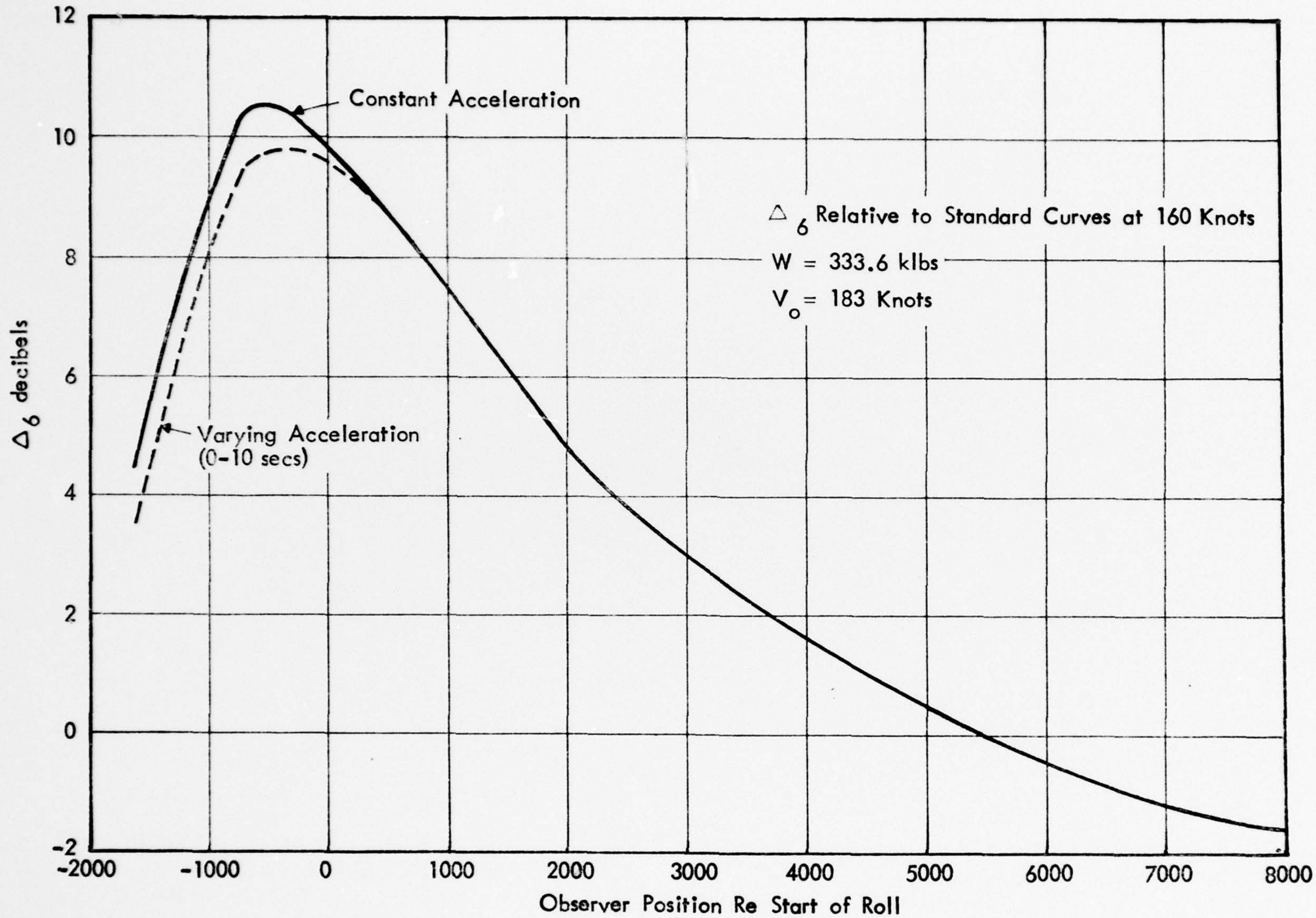


FIGURE 4. EFFECT OF VARYING ACCELERATION AT START OF ROLL

## COMPUTER SIMULATION MODEL

This section deals with a means of generating the required offset values in a form compatible with NOISEMAP. With the existing computation procedures used by NOISEMAP, the value of $\Delta_6$ specified at a given distance along the flight track is applied at all distances perpendicular to the flight track at that point. Two exceptions occur, one which is used for curved flight paths to take into account the variable duration, and the other which occurs at the start of takeoff roll. The former is of no significance in this study, but the effect of the latter on the noise contour pattern is important. It is clear that for correct simulation the value of $\Delta_6$ should vary with distance from the runway centerline, and therefore simply adding a $\Delta_6$ value at this point will not accurately model the contours. Therefore, it is necessary to superimpose on the contour generated by the flight operation a noise pattern with which it will combine to generate the required shape. An examination of the required contour shape indicates that it has a form similar to a ground runup pattern, which is specified in terms of noise levels at various angles and distances from the aircraft, in this case assumed to be at the runway threshold. The procedure used in calculating the contours to be superimposed was to determine the values generated by flight operations along a given line and then to determine the noise levels to be added along the line to generate the required contours. This was done for a number of angles from 0° to 180° from the aircraft nose. For simplicity, the contours behind the aircraft were closed using circular arcs. Several cuts were necessary to obtain the desired results. The fixed source "runup" pattern was then normalized with respect to the ground-to-ground propagation values used for flight operations. Thus a pattern can be developed for any aircraft by adding the offsets to the ground-to-ground noise values at the corresponding distance. The offset values and a means of applying them are discussed in the Appendix. Figures 5 and 6 show typical contour sets, one generated using the model and the other without the fixed "runup" source.

The effect of using the model derived here depends on the size of the noise contours. The major effect is to increase the noise levels abeam of and behind the runway, particularly at further distances, where the simplified model underpredicts the noise levels.

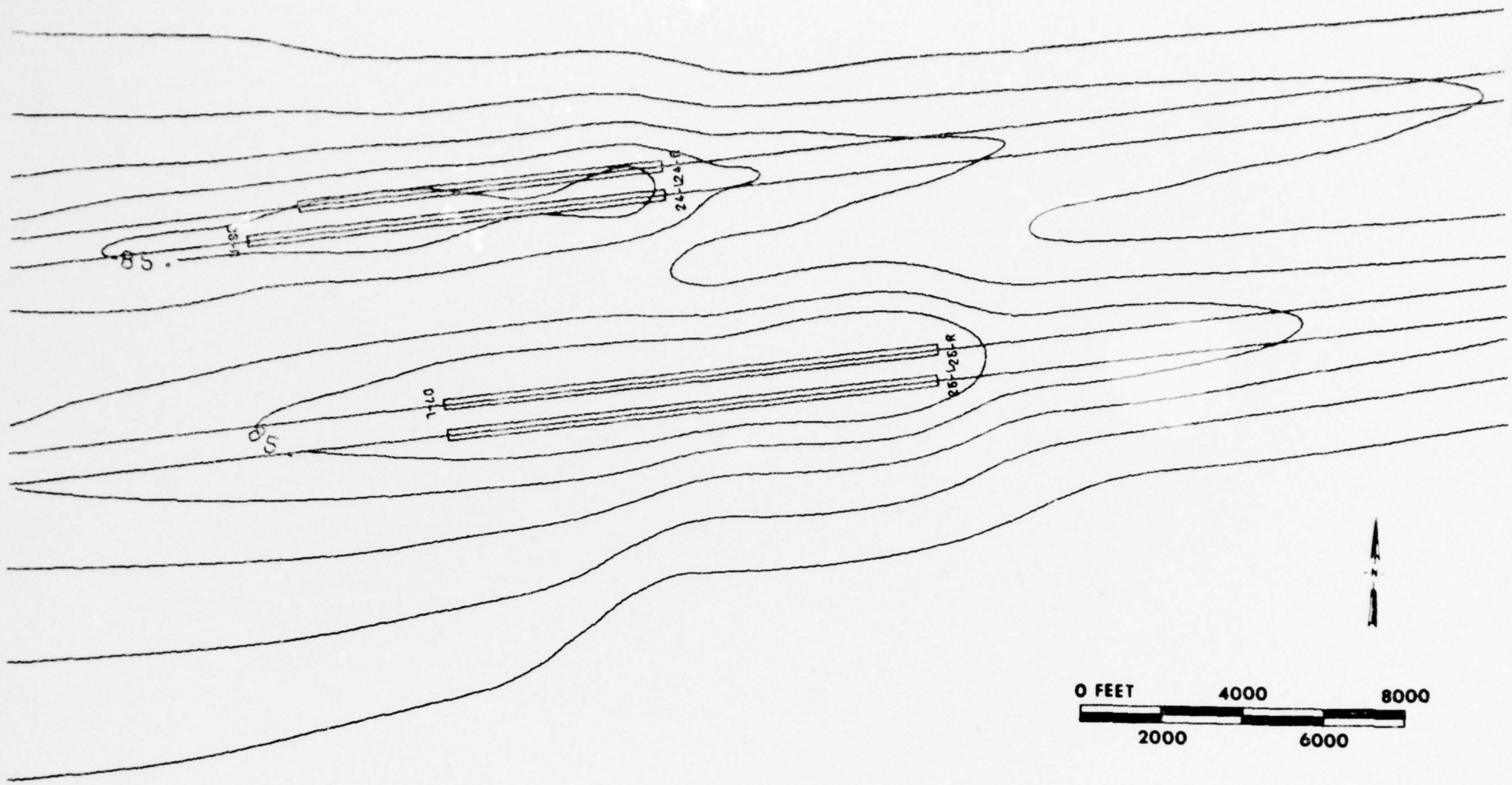


FIGURE 5. NOISE CONTOURS WITHOUT FIXED SOURCE

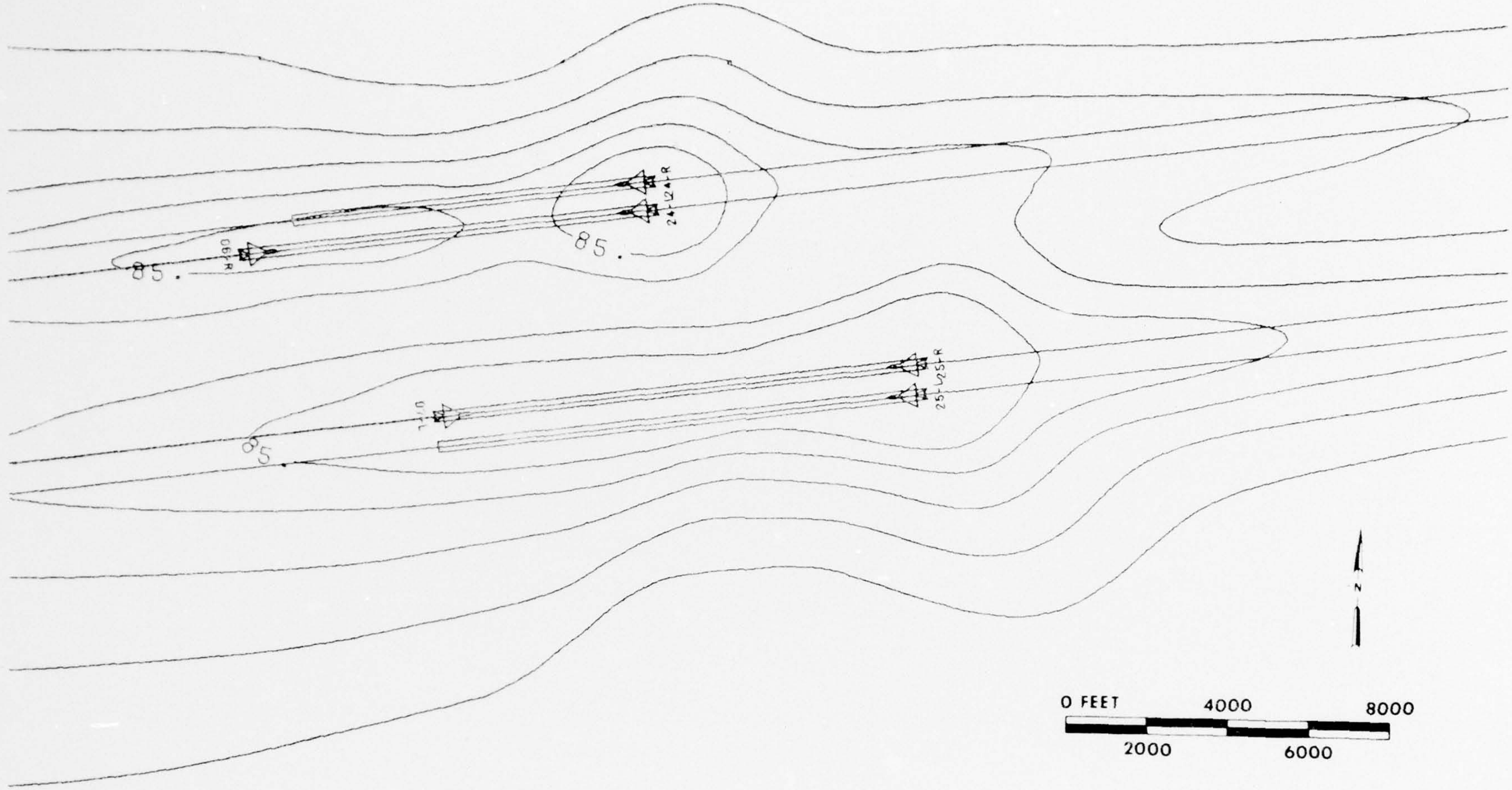


FIGURE 6. NOISE CONTOURS WITH FIXED SOURCE

## CONCLUSIONS

The procedures developed during this study permit a more accurate simulation than previously available of the noise levels occurring as an aircraft starts its takeoff roll. The method is general and applicable to all jet aircraft types. A number of factors can influence the accuracy of the simulation, and if there are procedures (such as extended runups on the runway before takeoff), then special consideration is required.

The offsets provided in Table A-1 are based on a theoretical analysis. For further refinements of the data, it will be necessary to undertake a controlled measurement program.

## DEFINITIONS OF SYMBOLS

| | |
|---|---|
| $C_1$ | A constant used to calculate takeoff distance. |
| $C_2$ | A constant used to calculate climb speed. |
| $f$ | A value proportional to aircraft acceleration. |
| $k$ | A constant to convert knots to feet per second. |
| SEL | Sound Exposure Level. |
| $S_o$ | Takeoff distance. |
| $V_A$ | Aircraft velocity. |
| $V_j$ | Jet exhaust velocity. |
| $V_2$ | Minimum safe climb speed with one engine inoperative. |
| W | Aircraft weight in thousants of pounds. |
| $\Delta_6$ | An adjustment to SEL to account for thrust and duration changes. |

## REFERENCES


1. "Data Base for Predicting Noise from Civil Aircraft: Flight Profile Prediction". BBN Report 2746, Nov. 1976.

2. "Community Noise Exposure Resulting from Aircraft Operations: Acoustic Data on Military Aircraft". AMRL-TR-73-110.

## APPENDIX

## IMPLEMENTATION OF THE MODEL

This appendix describes how to calculate adjustments to inflight noise data to simulate the noise levels occurring during the takeoff roll. In essence, it consists of superimposing on the flight operation an artificially-generated runup pattern, each with the correct offsets, to obtain the desired result.

### FLIGHT OPERATION

The noise profiles (ground-to-ground and air-to-ground) and altitude profiles are specified in the normal way. A special $\Delta_6$ profile is required, with specified values at the start of takeoff roll and at the liftoff point. Following is a step-by-step procedure:

(1) Determine the effective distance from the start of takeoff roll to liftoff $S_o$, in feet. Note that if there is an acceleration phase during the initial climb immediately after takeoff, the steady climb segment should be projected back to zero altitude, and the intercept point used to determine $S_o$. This is compatible with the profiles currently in use for civil aircraft.

(2) Determine the initial climb speed at distance $S_o$ in knots. For convenience, this can be called $V_2 + 10$, as is used for civil aircraft.

(3) Determine $V_{ref}$, the speed corresponding to the noise profile to be used.

(4) Calculate the value $\frac{(V_2 + 10)^2}{S_o} = f.$* This is proportional to the acceleration.

(5) Calculate $\Delta_6$ at the start of takeoff roll

$$= 5 \log_{10} 5.357/f + 10 \log V_{ref}/160.^{**}$$

(6) Calculate $\Delta_6$ at distance $S_o$

$$= 10 \log \frac{V_{ref}}{(V_2+10)}$$

(7) If required, calculate $\Delta_6$ values at further distances from the start of roll.

Example: F-104 afterburner takeoff

(a) $S_o = 3000$ feet

(b) Initial speed at $S_o = 200$ knots

(c) $V_{ref} = 240$ knots

(d) $f = \frac{200^2}{3000} = 13.33$

(e) $\Delta_6$ at start of roll $= 5 \log \frac{5.357}{13.33} + 10 \log \frac{240}{160}$

$$= -2.0 + 1.8 = 0.2$$

(f) $\Delta_6$ at $S_o = 10 \log \frac{240}{200}$

$$= +0.8$$

---

* $V_2 + 10$ is used here for convenience to indicate the initial climb speed. This terminology is consistent with transport type aircraft, however there is no equivalent for other aircraft types.

**For the 707 used as the basis for the model, $f = 160^2/4779 = 5.357$.

(8) Speed at 16,000 feet from brake release is 300 knots.

$$\Delta_6 = 10 \log \frac{240}{300} = - 1.0$$

The required $\Delta_6$ profile is as follows:

| Distance | $\Delta_6$ |
|---|---|
| 0 | - 0.2 |
| 3,000 | + 0.8 |
| 16,000 | - 1.0 |

etc.

IMPLEMENTATION OF THE MODEL

In order to simulate the takeoff roll noise in calculations using NOISEMAP, an artificially-generated stationary noise source must be added. In practice, this may be treated in exactly the same manner as a ground runup, with the aircraft at the end of the runway, headed in the direction of flight. Table A-1 lists the required offsets to be applied to the ground-to-ground flight data, as a function of angle and distance. These offsets should be used to generate the stationary noise source. In addition, a value of $\Delta_6$ should also be applied, equal to that for the flight operation at the start of the takeoff roll. For each flight operation, a runup duration of one second is required.

TABLE A-1

OFFSETS FOR RUNUP PROFILE

| Distance feet | Offsets in dB 0° | 20° | 35° | 50° | 70° | 90° | 110° | 130° | 180° |
|---|---|---|---|---|---|---|---|---|---|
| 200 | 17.6 | 17.6 | 14.8 | 14.0 | 11.8 | 12.2 | 12.1 | 14.6 | 14.6 |
| 250 | 17.5 | 17.5 | 14.7 | 13.7 | 11.6 | 12.0 | 12.1 | 14.5 | 14.5 |
| 315 | 17.4 | 17.4 | 14.4 | 13.3 | 11.3 | 11.8 | 12.0 | 14.3 | 14.3 |
| 400 | 17.1 | 17.1 | 14.1 | 12.8 | 10.8 | 11.4 | 11.8 | 14.0 | 14.0 |
| 500 | 16.8 | 16.8 | 13.6 | 12.1 | 10.3 | 10.9 | 11.4 | 13.5 | 13.5 |
| 630 | 16.4 | 16.4 | 13.0 | 11.4 | 9.7 | 10.4 | 11.1 | 13.0 | 13.0 |
| 800 | 15.5 | 15.5 | 12.0 | 10.2 | 8.6 | 9.4 | 10.3 | 12.1 | 12.1 |
| 1000 | 15.1 | 15.1 | 11.4 | 9.3 | 7.9 | 8.8 | 9.9 | 11.6 | 11.6 |
| 1250 | 14.4 | 14.4 | 11.7 | 8.3 | 7.0 | 8.0 | 9.4 | 10.6 | 10.9 |
| 1600 | 13.4 | 13.4 | 9.7 | 6.9 | 5.9 | 7.1 | 8.7 | 10.1 | 10.1 |
| 2000 | 12.2 | 12.2 | 8.4 | 5.2 | 4.5 | 5.9 | 7.8 | 9.0 | 9.0 |
| 2500 | 11.0 | 11.0 | 7.1 | 3.5 | 3.4 | 4.9 | 7.1 | 8.2 | 8.2 |
| 3150 | 9.2 | 9.2 | 5.2 | 1.2 | 2.0 | 3.8 | 6.4 | 7.2 | 7.2 |
| 4000 | 6.1 | 6.1 | 2.7 | -2.2 | 0.6 | 2.8 | 5.3 | 6.4 | 6.4 |
| 5000 | -* | -* | -2.6 | -19.4 | -0.3 | 2.7 | 5.6 | 6.5 | 6.5 |
| 6300 | - | - | -* | -* | -2.0 | 2.4 | 5.6 | 6.2 | 6.2 |
| 8000 | - | - | - | - | -5.4 | 1.7 | 5.4 | 5.8 | 5.8 |
| 10000 | - | - | - | - | -* | 1.2 | 5.3 | 5.5 | 5.5 |
| 12500 | - | - | - | - | - | 0.5 | 5.2 | 5.0 | 5.0 |
| 16000 | - | - | - | - | - | -0.2 | 5.1 | 4.6 | 4.6 |
| 20000 | - | - | - | - | - | -0.5 | 5.3 | 4.5 | 4.5 |
| 25000 | - | - | - | - | - | -0.6 | 5.6 | 4.4 | 4.4 |

*No contributions from the artificial runup profile are required beyond this distance. Values should be 0, -1, -2, etc. to prevent error messages in the NOISEMAP program.