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# METHODOLOGY FOR DETERMINING, ISOLATING AND CORRECTING RUNWAY ROUGHNESS

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DEPARTMENT OF TRANSPORTATION ★ UNITED STATES OF AMERICA



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Final Report





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16. Abstract

A method to determine the roughness of runway profiles in terms of aircraft response is presented. The aircraft response is specified in terms of pilot-station vertical accelerations, which are determined from computer simulation. Corrections to the profiles are then made to reduce the aircraft response.

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## SECTION I
## INTRODUCTION

### 1. BACKGROUND

Until recently the determination of runway roughness and the effects of roughness on aircraft have been entirely qualitative. Thus, there exists a need for quantitative methods to determine, isolate, and correct runway surface roughness.

### 2. OBJECTIVES

The objectives of this study of runway roughness were (1) to determine the relationship between roughness, in terms of the elevation profile, and aircraft response to the profile; (2) to isolate segments of the runway that might be considered rough; and (3) to outline a procedure to reduce overall roughness.

### 3. APPROACH

Several factors must be considered in the determination of runway roughness. First is the runway itself. In this study the runway was represented by a runway centerline elevation profile. This profile consisted of elevations measured at 2-foot increments along the length of the runway by a laser profilometer and stored on digital data tape. From the elevation profile a quantitative measure of roughness can be determined. Previous work in this area has suggested that the root mean square (rms) of the profile could be used as such a measure (reference 1). Elevation profiles are filtered to remove wavelengths longer than 400 feet; rms elevations are calculated; and these values are used

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1. Sonnenburg, Paul N., *Analysis of Airfield Runway Roughness Criteria*, FAA-RD-75-110, U.S. Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Washington, D.C., November 1976.

to describe overall roughness. Next, the aircraft must be considered. The importance of roughness is in the effect that it has upon aircraft response. The computer code TAXI (reference 2), which simulates an aircraft traveling over a runway profile, was developed to study the dynamic response of a moving aircraft to a runway profile. The elevation profile, the aircraft response data, and the TAXI Code were used in this study to evaluate roughness and to suggest a procedure to reduce roughness.

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2. Gerardi, A. G., and Lohwasser, A. K., *Computer Program for the Prediction of Aircraft Response to Runway Roughness*, AFWL-TR-73-109, Vol. I & II, Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico, September 1973 and April 1974.

# SECTION II

## DETERMINING RELATIONSHIP BETWEEN ELEVATION PROFILE AND AIRCRAFT RESPONSE

In the study of runway roughness it is necessary to establish, if possible, a direct correlation between roughness (irregularities) in the profile and aircraft response. Root mean square elevation has been suggested as a measure of runway profile roughness (reference 1); the rms vertical acceleration at the pilot station was chosen as the measure of aircraft response. Root mean square accelerations were generated with the TAXI Code by taxiing an aircraft over a runway profile at a constant speed of 100 feet per second. Fifteen runway profiles were used to generate pilot-station acceleration profiles for the 727 aircraft. The elevation and acceleration profiles generated were filtered, and then rms values were calculated.

Early in the analysis the elevation profiles were filtered to eliminate all wavelengths greater than 400 feet. This procedure was predicated on the state-of-the-art at the time reference 1 was in preparation. The prevailing thought at that time was that rms acceleration (ordinate) versus rms elevation (abscissa) would plot such that high rms elevations would lead to high rms accelerations. It would then be a simple matter to evaluate the roughness of a runway; i.e., simply project the rms acceleration from such a graph. Unfortunately, such was not the case. Plots of this type showed low correlation and could not be used as a roughness evaluation tool. However, in the attempt to use this technique, the elevation profiles had been filtered at several levels to eliminate wavelengths greater than 400, 200, 150, 100, or 75 feet. It was subsequently found that by filtering all wavelengths greater than 150 feet from the profile before calculating the rms elevation, acceptable plots of the type suggested could be developed. Upon reflection this seems appropriate; i.e., acceleration should not correlate with elevation but rather with the rate of change of elevation. The effect of such severe filtering (removal of wavelengths less than 400 feet) is that the rms elevation approaches the rms slope gradient and this leads to better correlations. In spite of this, however, such an approach is not useful from a repair point of view since it only indicates that the pavement is rough, not what degree of roughness could possibly be removed from the pavement through repair techniques.

Because the rms values showed no correlation, an attempt was made to define the range of wavelengths in the elevation profile which would affect the vertical acceleration. Accordingly, five elevation profiles which represented a range of roughness were filtered as before, except that several different cutoff wavelengths were used. These filtered profiles were then used to generate rms accelerations for several different aircraft. The rms accelerations for each aircraft were normalized to the maximum value for the roughest runway in order to examine the effects of cutoff wavelengths and relative roughness on the rms acceleration. Plots of rms acceleration versus cutoff wavelengths (figures 1 through 4) show that wavelengths less than 200 feet contribute most to the response of all aircraft considered. It is apparent that wavelengths greater than 200 feet have very little effect on the aircraft response. Because these wavelengths contribute to the rms elevation but not to the roughness in terms of aircraft response, their removal should improve the roughness estimation.

With this information, another attempt was made to correlate rms elevation with rms acceleration. Figure 5 is a plot of the relationship between the rms of 15 elevation profiles which were filtered to remove wavelengths greater than 200 feet and the rms of pilot-station vertical accelerations in a 727 aircraft. A fair correlation exists between rms elevation and rms acceleration, but there is still significant scatter of the data. As noted, the slope of the elevation profile should be a significant factor in runway roughness. Also, the nature of the coupling between the runway profile and the aircraft (reference 2) suggests that the elevation slope is more directly related to roughness in terms of aircraft response. Figure 6 shows a very good correlation when the rms elevation is replaced by the rms change in elevation.

When determining runway roughness in terms of aircraft response, the characteristics of the aircraft as it travels along the runway have a marked effect on the roughness profile. To obtain a better understanding of the relationship between the roughness profile and the type of aircraft and aircraft taxi speed, TAXI runs were made with a DC-8 aircraft traveling at various speeds on Albuquerque Runway 17 (ABQ RN17). Figure 7 shows rms pilot-station acceleration, which was used as the measure of roughness, versus aircraft taxi speed. At low speeds the energy transmitted by runway roughness to the aircraft can be partially absorbed by the landing gear, but at higher speeds the code predicts decreases in the energy transmitted because of aircraft lift. These characteristics are apparent in figure 7; i.e., a sharp increase in roughness at taxi speeds above 75 feet per second and a decrease at speeds in excess of 150 feet per second. The overall roughness is greatest at the intermediate speeds and the variation with speed is small. A reasonable estimate of the speed at which the overall roughness is maximum is one-half the takeoff velocity (145 feet per second for the DC-8 aircraft).

Along with the overall roughness (runway rms value), the roughness profile is a major factor in determining and isolating runway roughness. The aircraft response is a function of the nose-gear-to-main-gear separation, the rate of change of elevation, the elevation, and the aircraft taxi speed. This is shown in figures 8 through 11 for the DC-8 aircraft taxiing at speeds of 75, 100, 125, and 150 feet per second on ABQ RN17. Roughness is presented as the rms pilot-station acceleration for a 100-foot segment of the runway profile.

In comparing the roughness profiles for the various speeds, it can be seen that the general trends are similar. Individual segments (100-foot sections), however, show significant differences in roughness, depending on the aircraft speed. Looking at the maximum segment rms acceleration as a function of velocity (figure 12), one can see that the maximum rms acceleration is also likely to occur at a velocity near 145 feet per second for the DC-8. The position on the runway profile and absolute magnitude of the maximum rms acceleration are more likely a complicated function of aircraft speed and characteristics and runway profile characteristics and seems to be a quantity which could not be readily determined without running TAXI tests at several velocities.

In general, tests made for profile correction (section III) reveal that corrections of those segments of the runway for which rms accelerations exceed the mean of all segments will not only reduce roughness in those regions, but will reduce the roughness for all areas to some extent, irrespective of velocity. Therefore, any reasonable aircraft velocity could be used to determine and isolate roughness, but the results of this study suggest that a speed of one-half the takeoff speed is a most reasonable value. Also, it seems that study of the effects of speed on roughness for the corrected runway profile can be informative and very easily conducted.

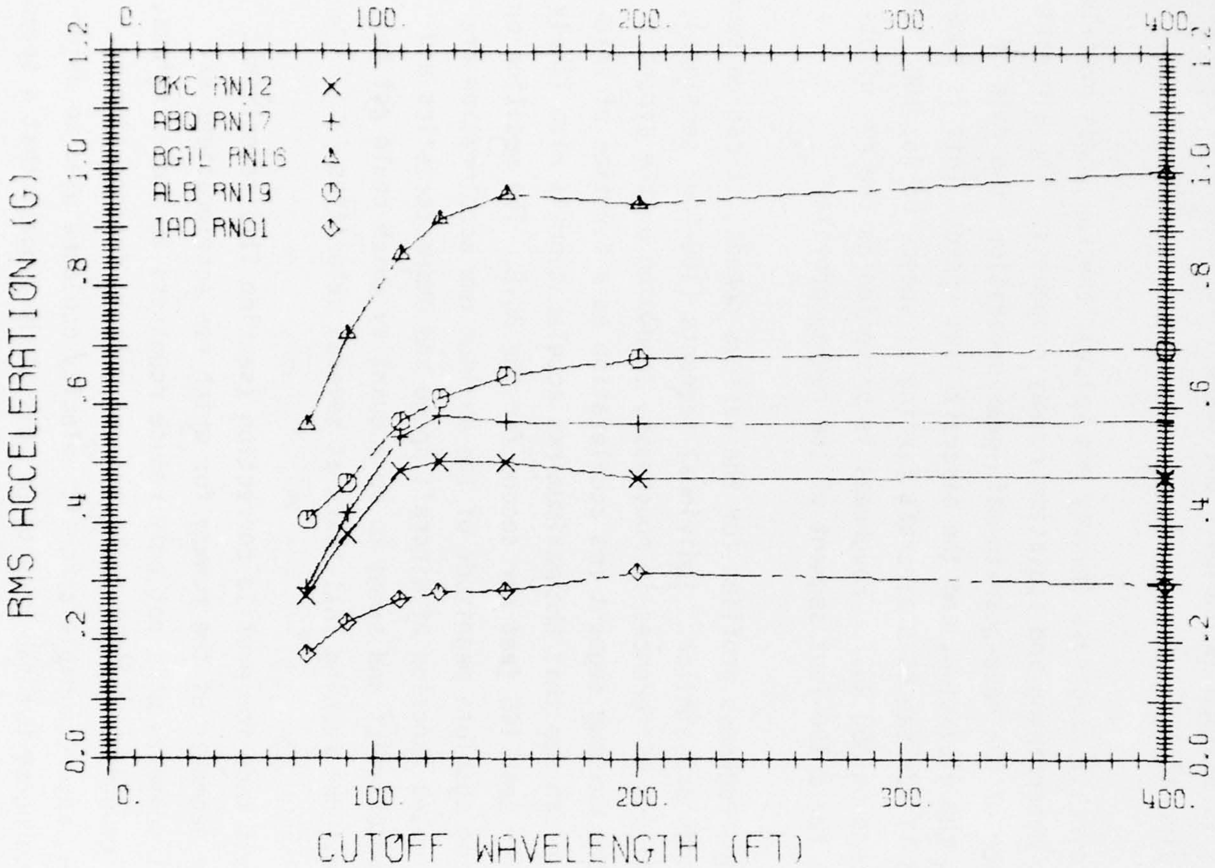


Figure 1. Root Mean Square Pilot-Station Acceleration Versus Cutoff Wavelength (727 Aircraft)

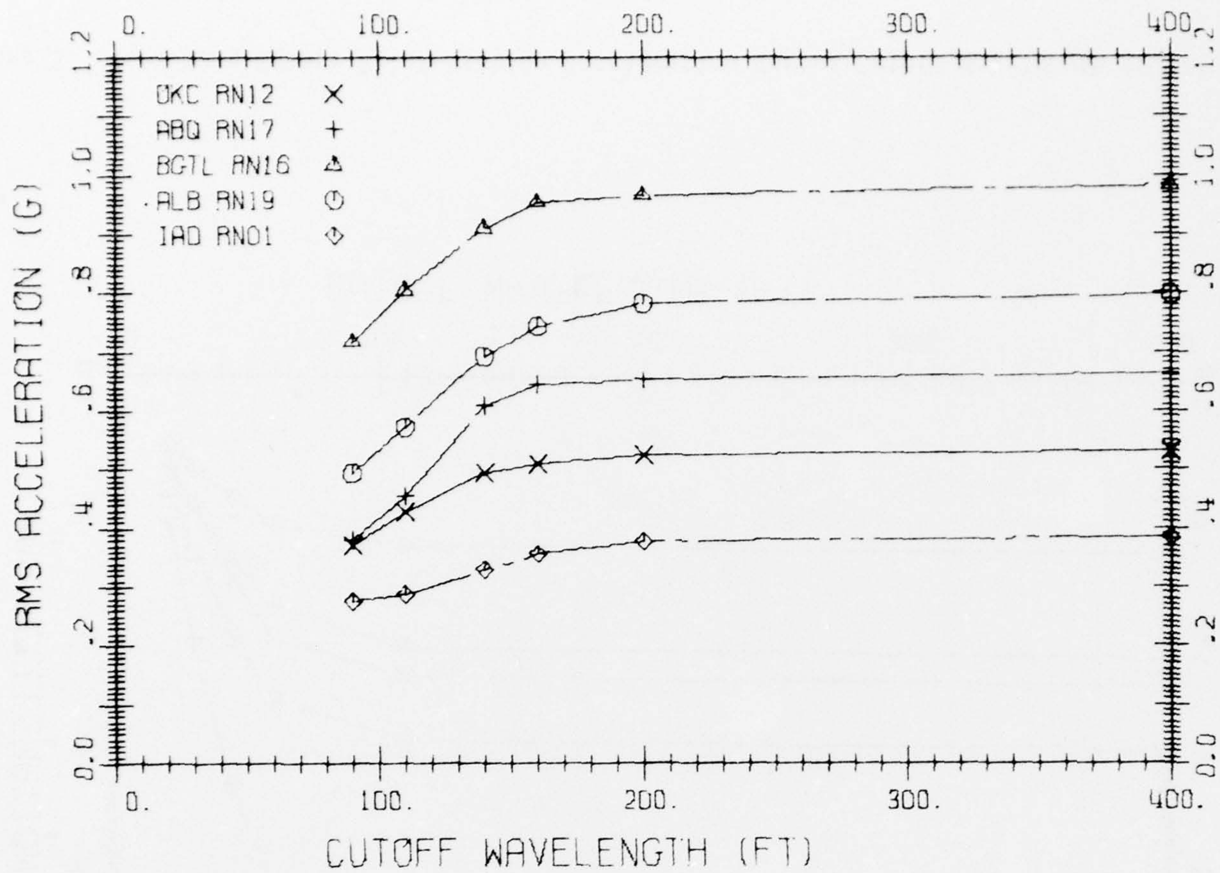


Figure 2. Root Mean Square Pilot-Station Acceleration Versus Cutoff Wavelength (DC-10 Aircraft)

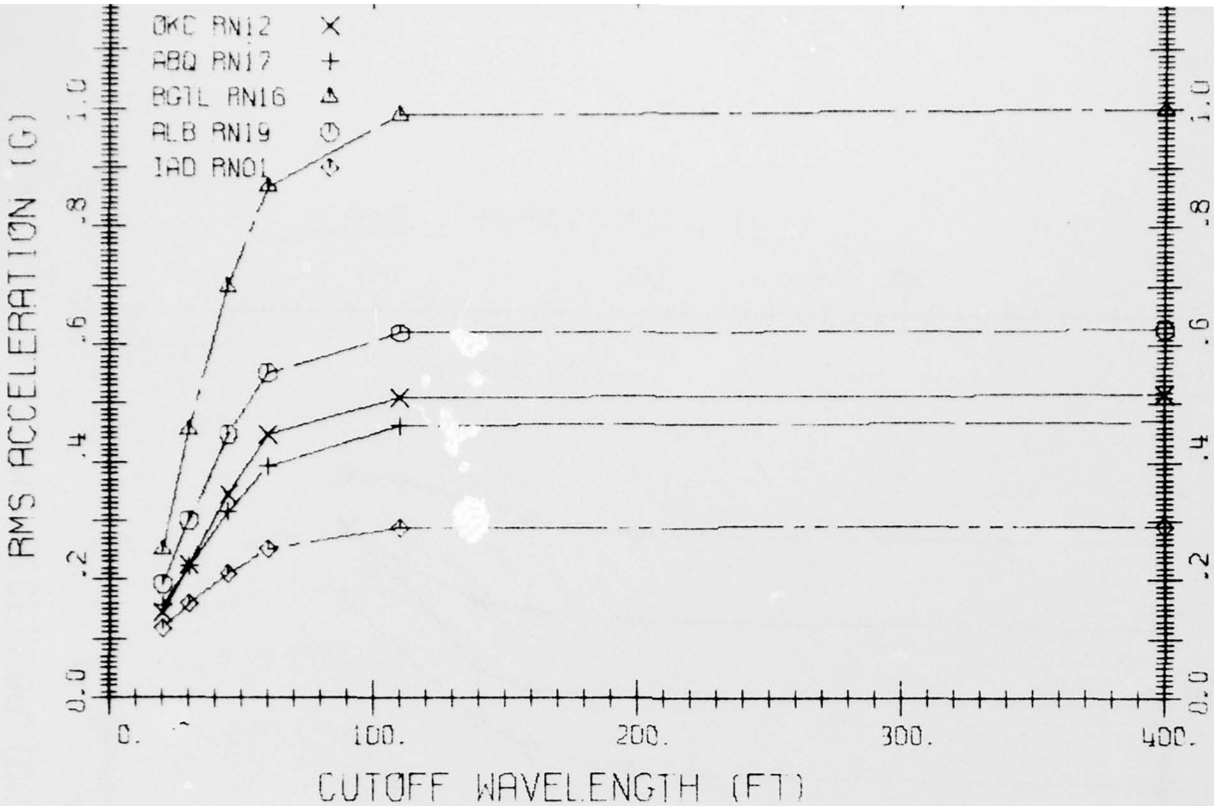


Figure 3. Root Mean Square Pilot-Station Acceleration Versus Cutoff Wavelength (F-111 Aircraft)

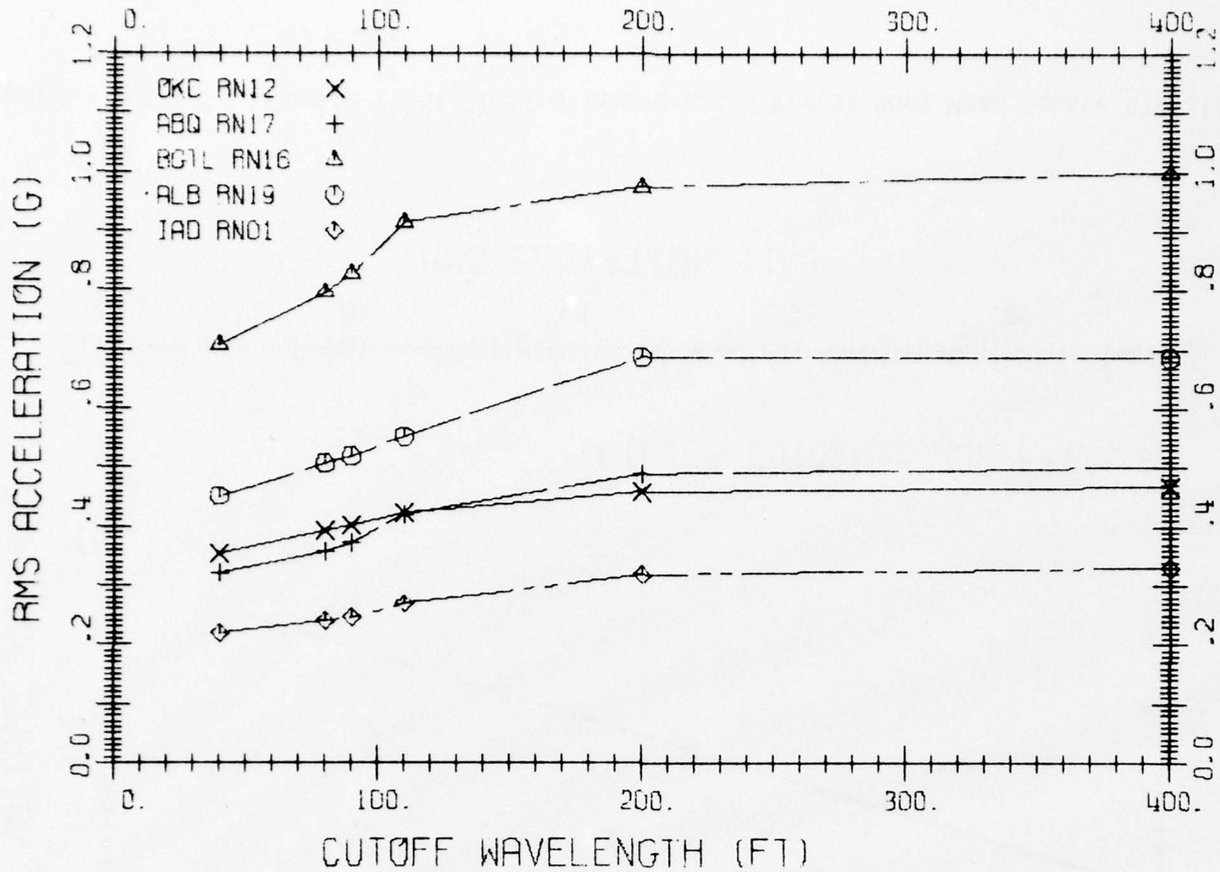


Figure 4. Root Mean Square Pilot-Station Acceleration Versus Cutoff Wavelength (KC-135 Aircraft)

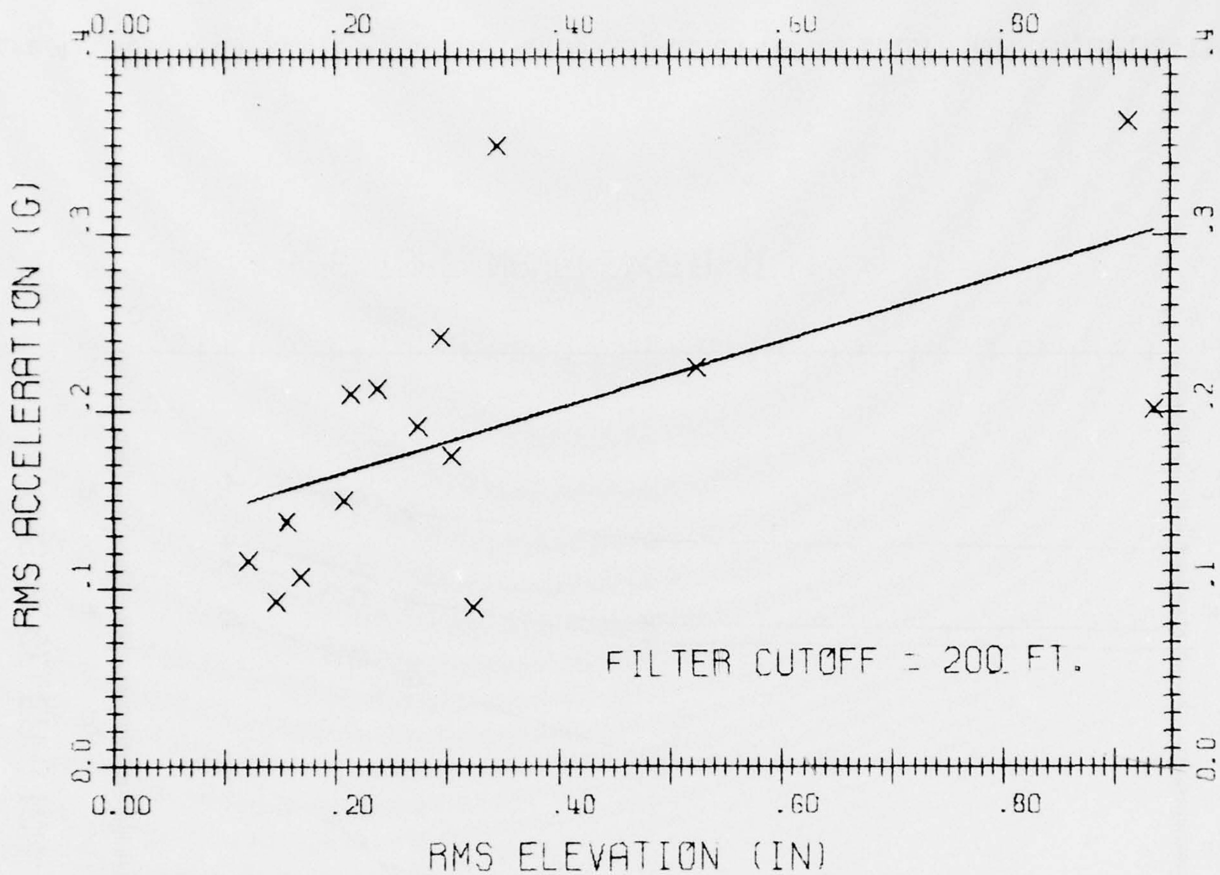


Figure 5. Root Mean Square Pilot-Station Acceleration Versus Root Mean Square Elevation

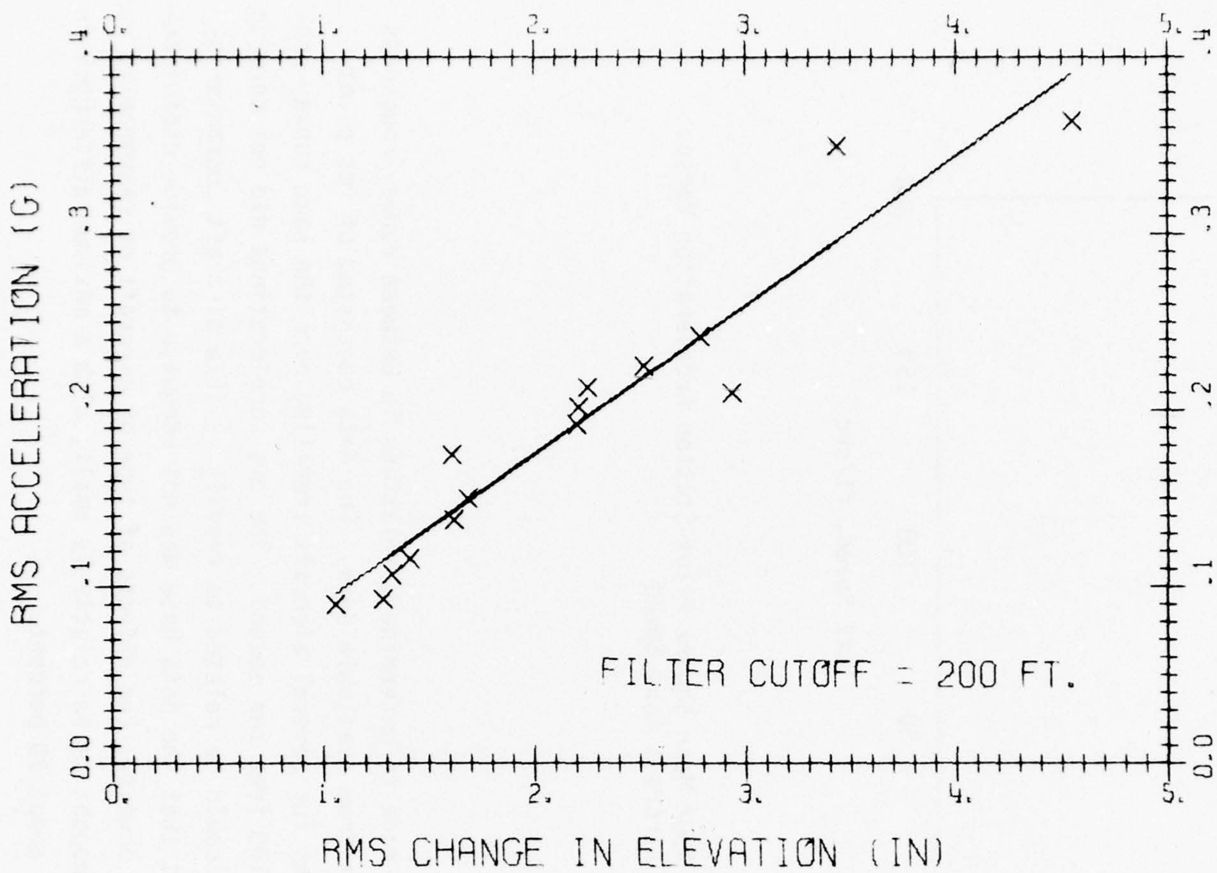


Figure 6. Root Mean Square Pilot-Station Acceleration Versus Change in Elevation

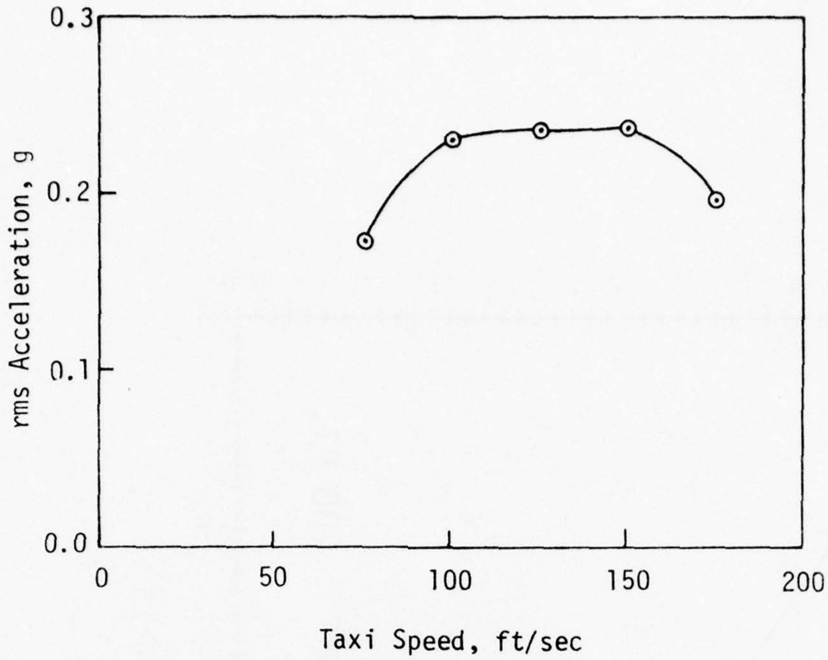


Figure 7. Root Mean Square Pilot-Station Acceleration Versus Aircraft Taxi Speed

An attempt was made to determine a relationship between runway roughness and type of aircraft from available data. The data consisted of rms pilot-station accelerations for several aircraft traveling over the same runway profile at a speed of 100 feet per second. The rms accelerations did not seem to follow a trend that could be related to readily visible aircraft characteristics and it was felt that the data base was not adequate to provide useful results. In general, however, the effects of type of aircraft on response to runway roughness are thought to be relatively small, with a maximum difference in overall response of about 20 percent.

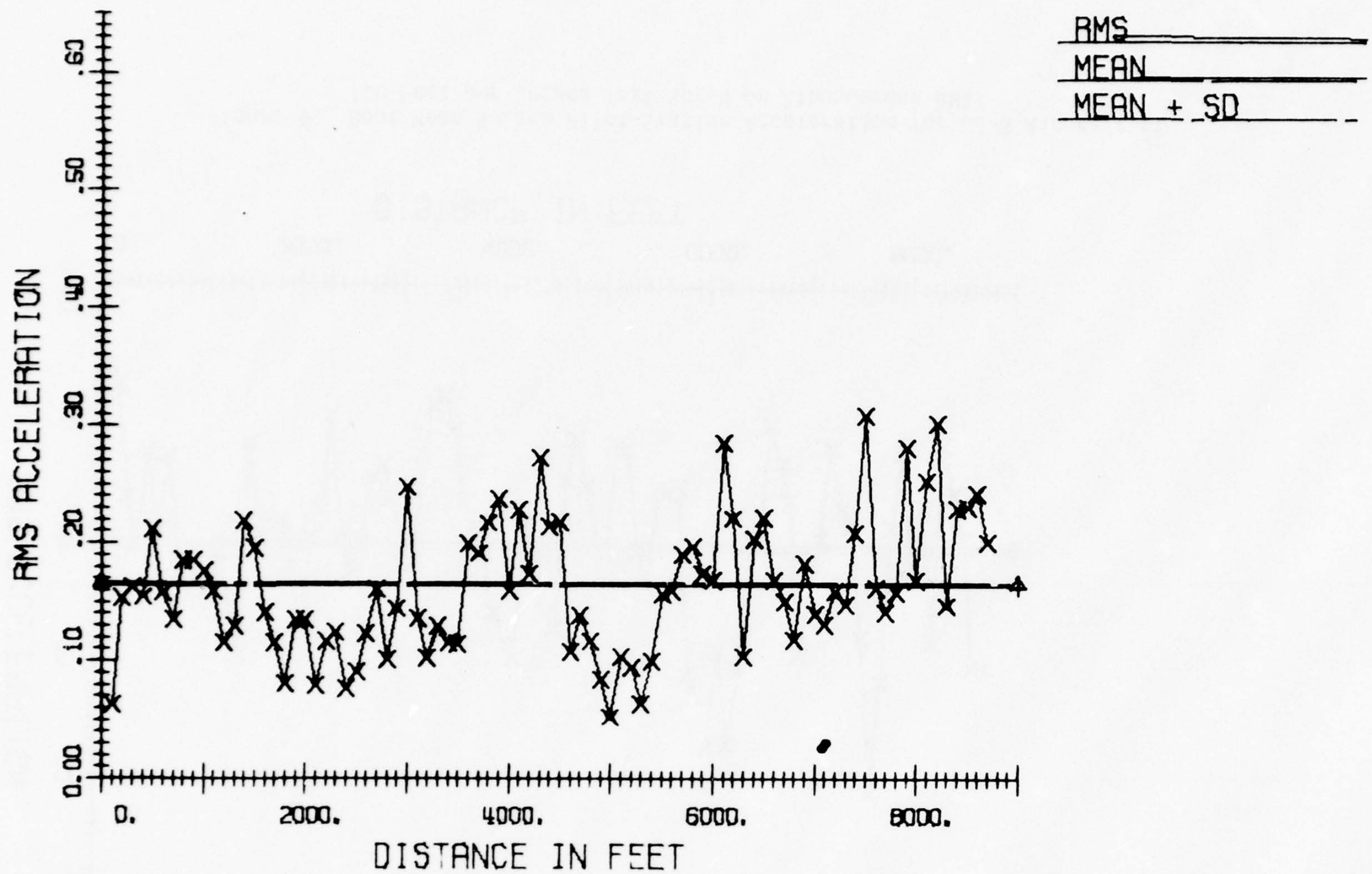


Figure 8. Root Mean Square Pilot-Station Acceleration for DC-8 Aircraft at 75 Feet per Second Taxi Speed on Albuquerque RN17

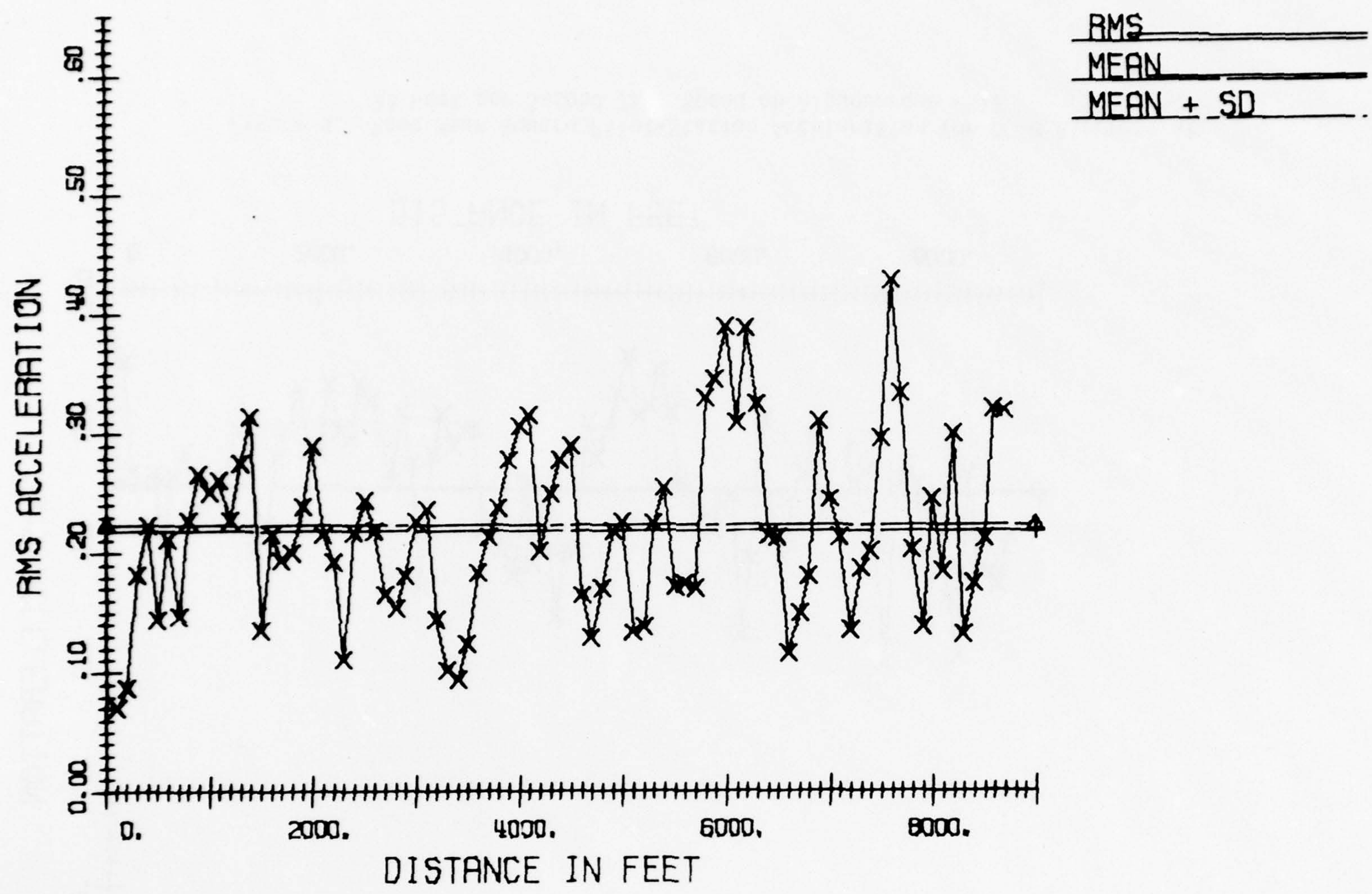


Figure 9. Root Mean Square Pilot-Station Acceleration for DC-8 Aircraft at 100 Feet per Second Taxi Speed on Albuquerque RN17

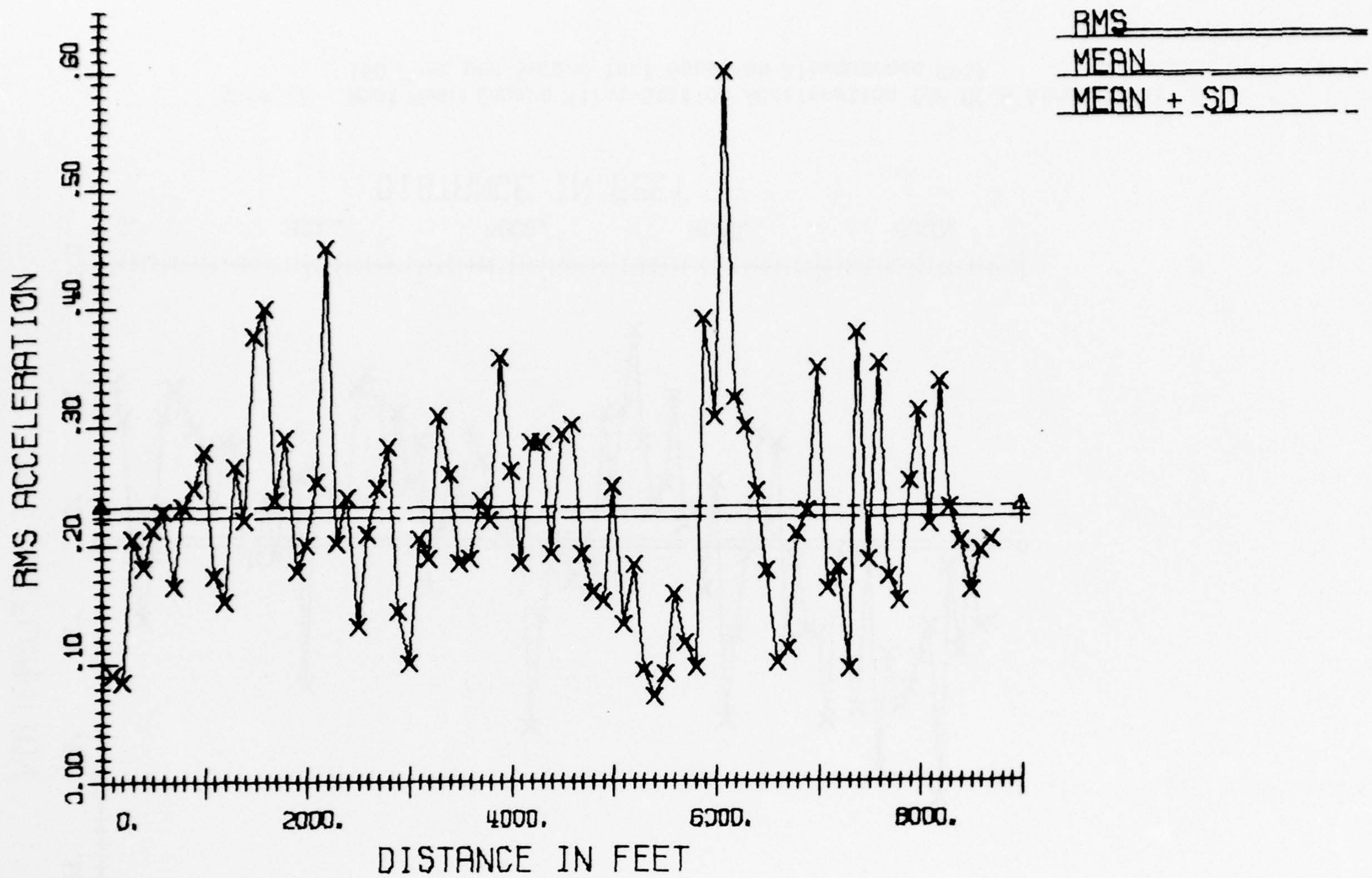


Figure 10. Root Mean Square Pilot-Station Acceleration for DC-8 Aircraft at 125 Feet per Second Taxi Speed on Albuquerque RN17

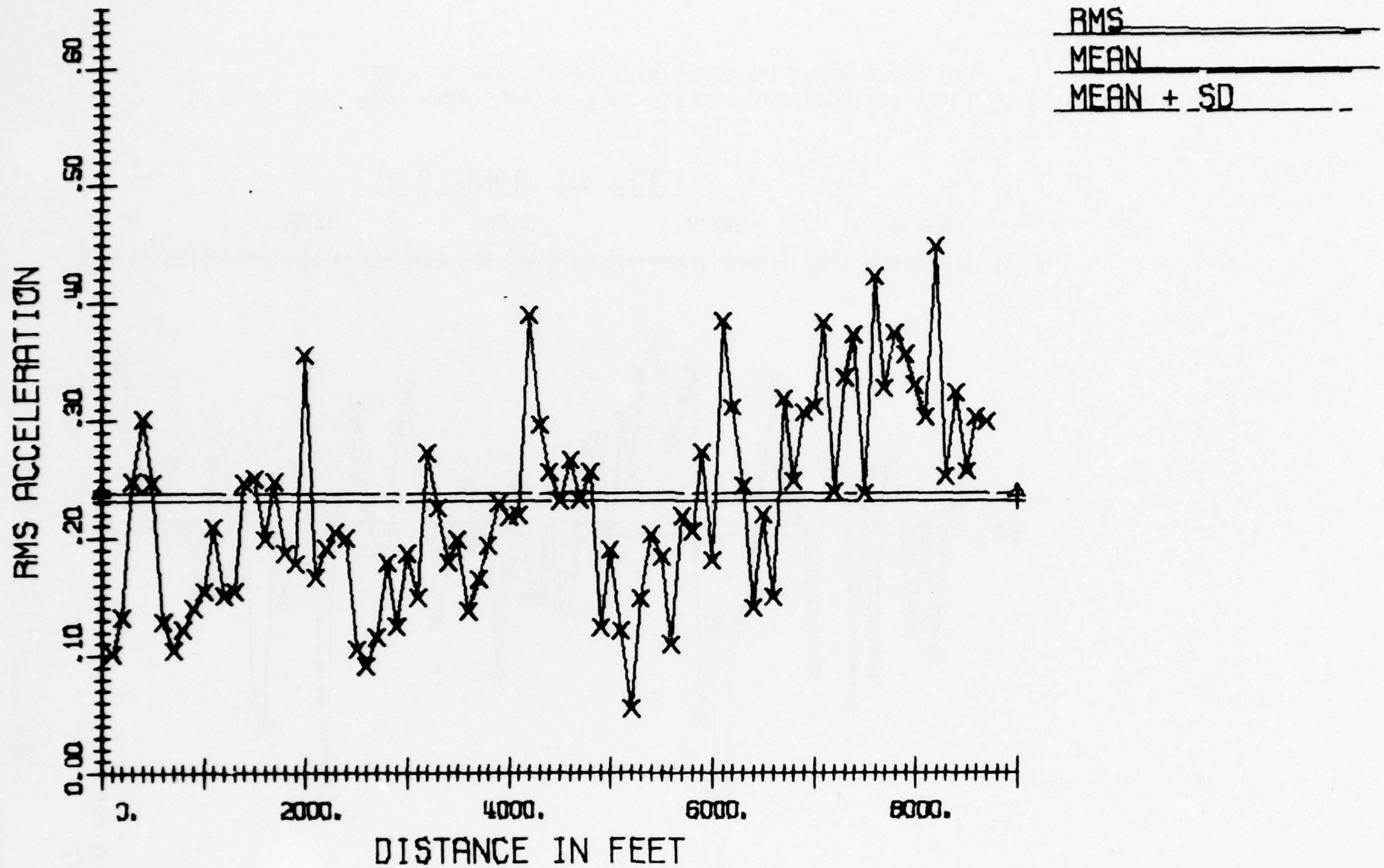


Figure 11. Root Mean Square Pilot-Station Acceleration for DC-8 Aircraft at 150 Feet per Second Taxi Speed on Albuquerque RN17

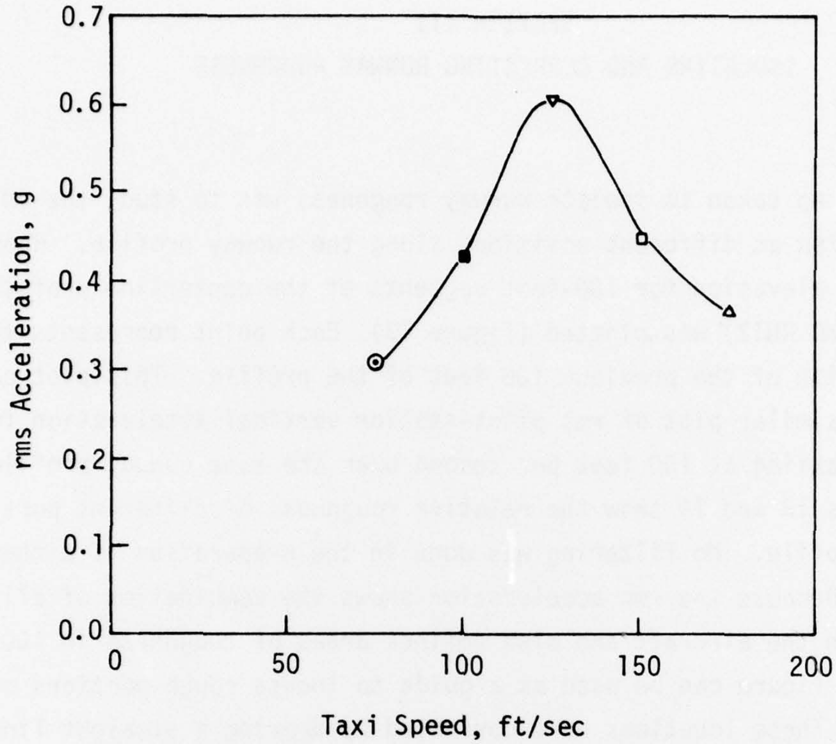


Figure 12. Maximum Root Mean Square Pilot-Station Acceleration for 100-Foot Segment Versus Aircraft Taxi Speed

## SECTION III
## ISOLATING AND CORRECTING RUNWAY ROUGHNESS

The first step taken to isolate runway roughness was to study the rms change in elevation at different positions along the runway profile. Root mean square change in elevation for 100-foot segments of the centerline profile at Oklahoma City (OKC RN12) was plotted (figure 13). Each point represents the rms change in elevation of the previous 100 feet of the profile. This plot can be compared with a similar plot of rms pilot-station vertical acceleration for the DC-10 aircraft taxiing at 100 feet per second over the same runway profile (figure 14). Figures 13 and 14 show the relative roughness of different portions of the runway profile. No filtering was done in the preparation of either of these figures. Because the rms acceleration shows the combination of all the runway effects on the aircraft and also defines areas of roughness in 100-foot increments, this figure can be used as a guide to locate rough portions of the runway profile. These locations were corrected by drawing a straight line between the endpoints of each segment which had a response above the mean response of the entire profile. Profile plots were then made of each segment which had been corrected (figures 15 and 16). A second set of corrections was then made using straight-line segments or vertical curves when necessary to correct roughness. Figure 17 is an example of the type of correction in which a vertical curve was fitted into the profile. Table 1 contains the corrected segments for runway RN12 at Oklahoma City.

The corrected profile was then used in the TAXI Code to check the aircraft response (figure 18). The vertical scale is magnified to present more clearly the changes in rms acceleration. Comparison of this response and the original profile response (figure 14) shows that the overall rms response dropped from 0.168 to 0.098 g and that the maximum rms response for a 100-foot segment was at the same level as the rms response of the uncorrected profile.

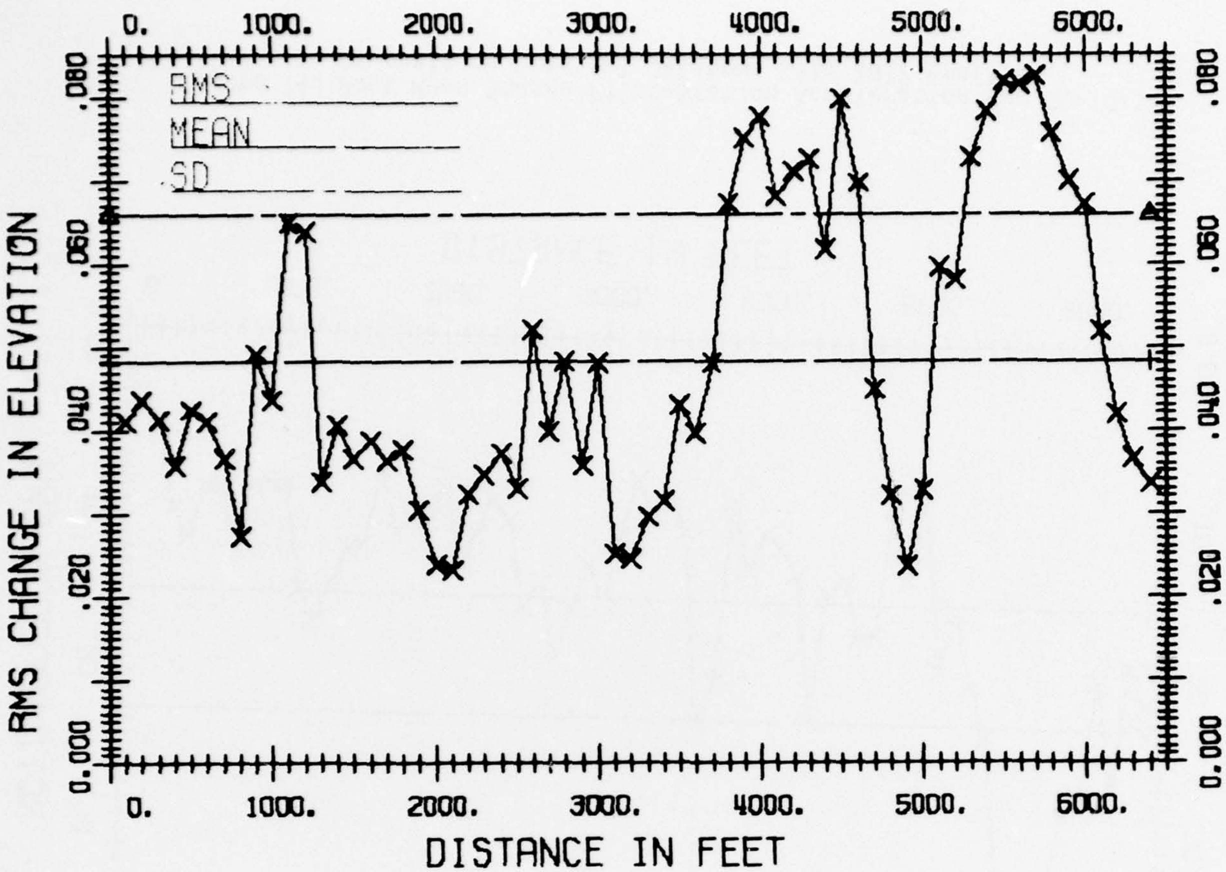


Figure 13. Root Mean Square Change in Elevation on Oklahoma City RN12

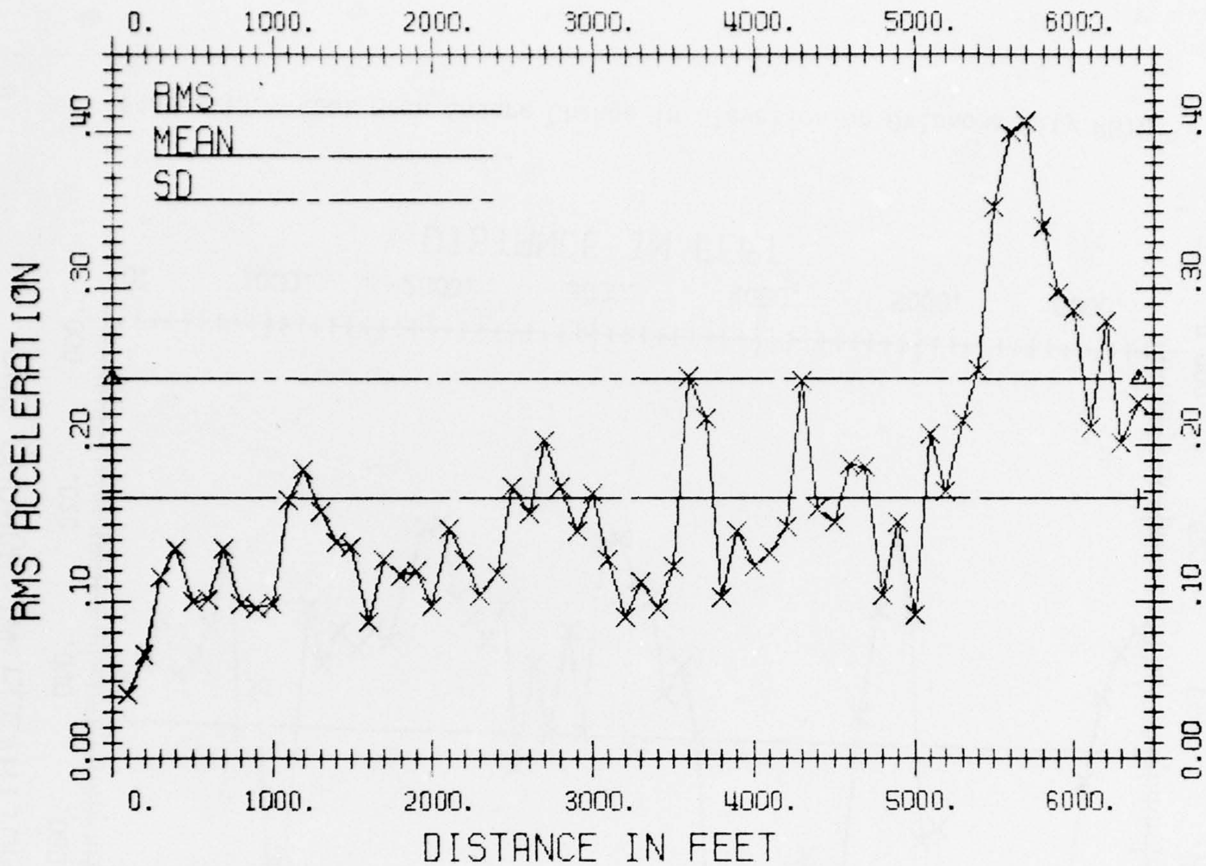


Figure 14. Root Mean Square Pilot-Station Acceleration for DC-10 Aircraft on Original Oklahoma City RN12 Profile

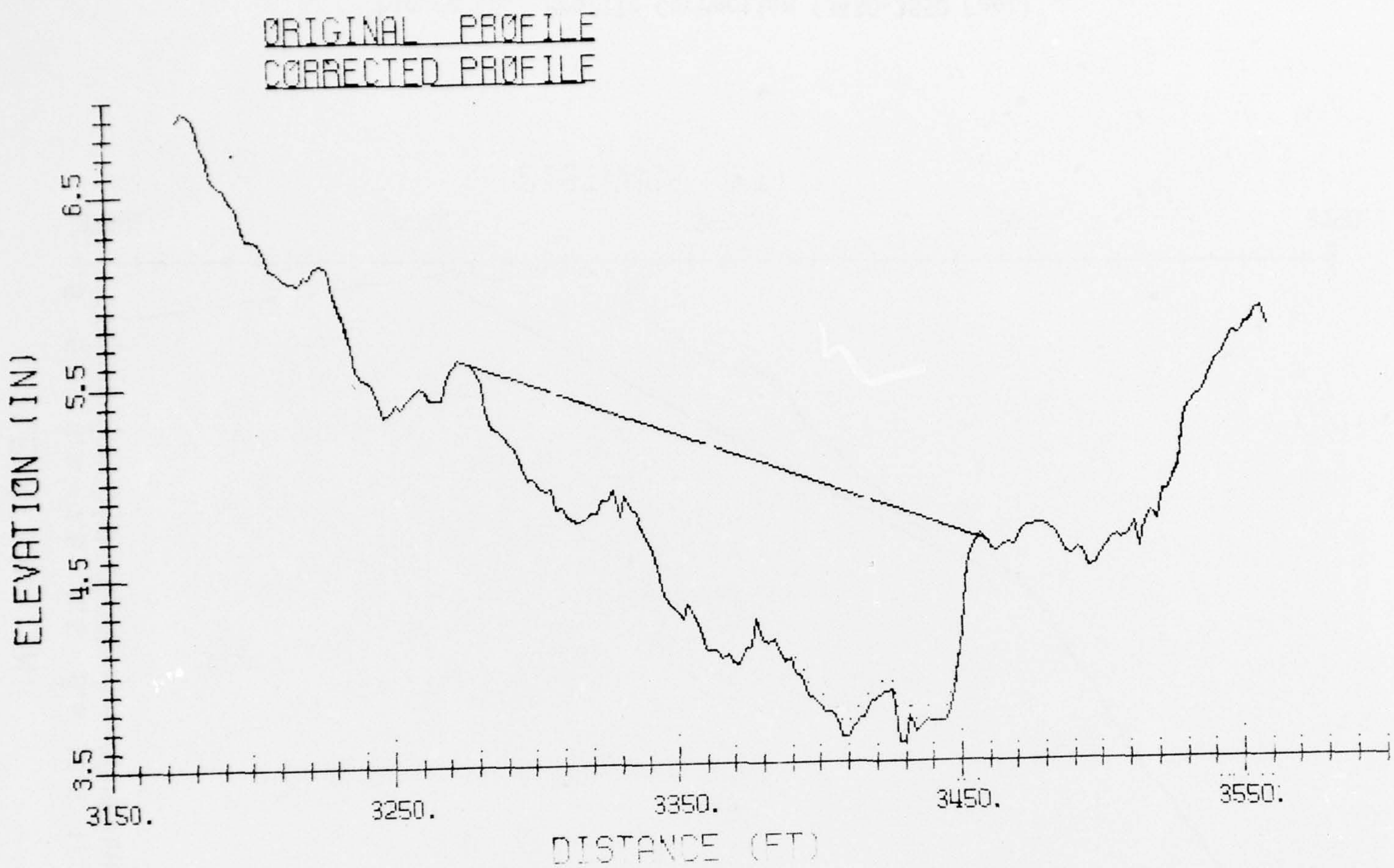


Figure 15. Profile Correction (3350-3450 Feet)

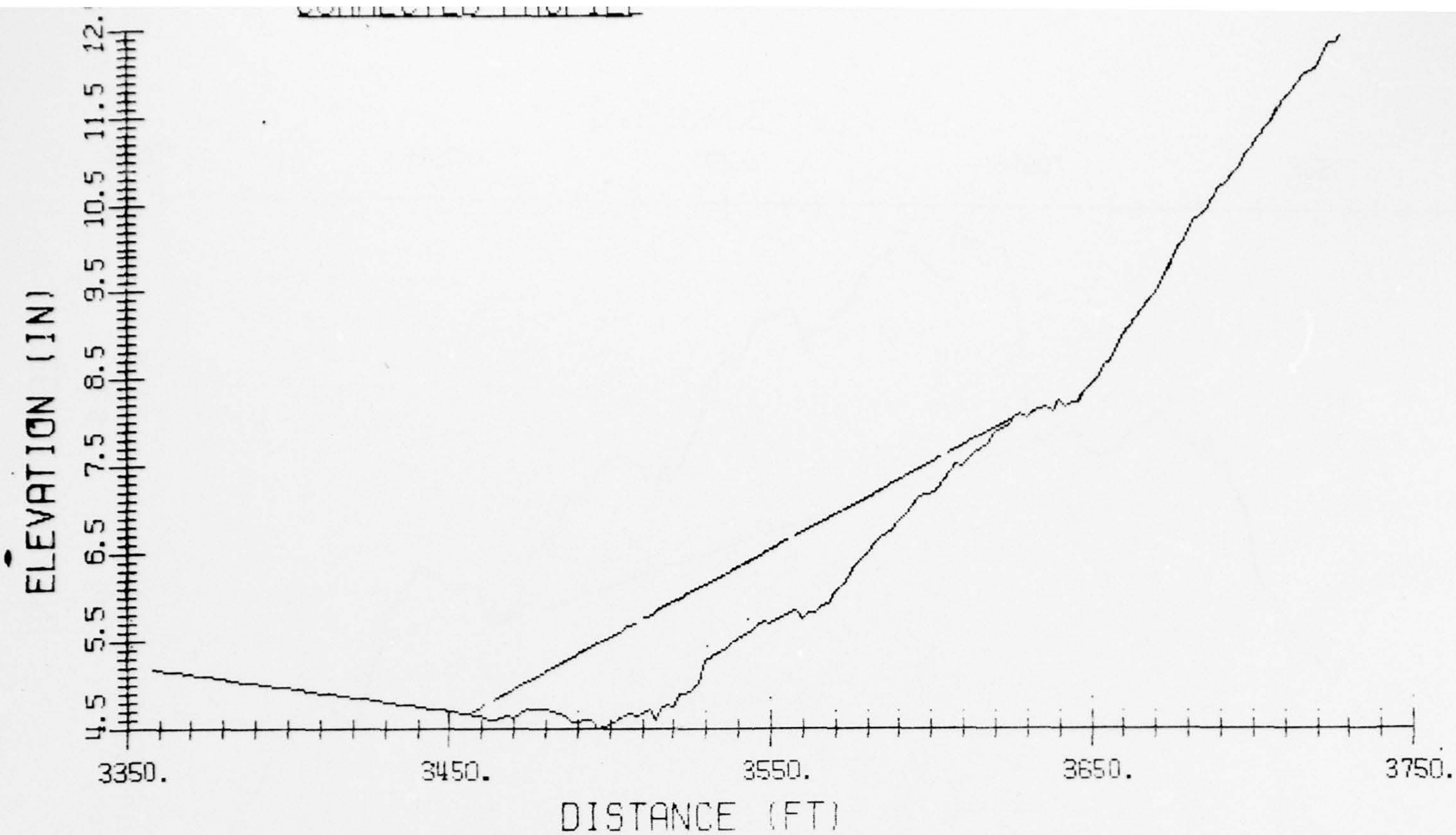


Figure 16. Profile Correction (3450-3550 Feet)

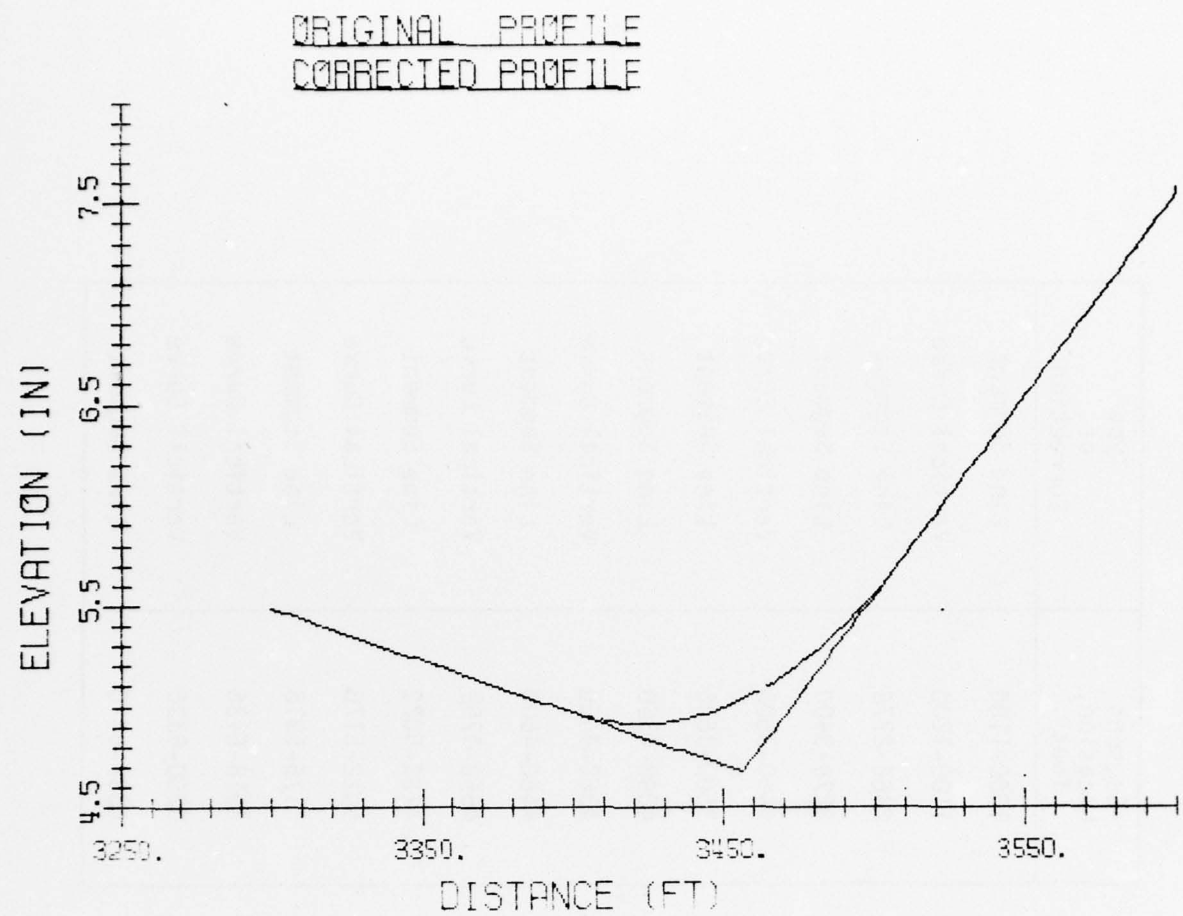


Figure 17. Profile Correction (3400-3500 Feet)

TABLE 1. CORRECTED RUNWAY SEGMENTS FOR OKLAHOMA CITY RN12

| Segment Location, feet | Type of Correction |
|---|---|
| 1000-1100 | Line Segment |
| 1100-1200 | Vertical Curve |
| 2466-2776 | Line Segment |
| 3276-3400 | Line Segment |
| 3400-3500 | Vertical Curve |
| 3500-3626 | Line Segment |
| 4090-4360 | Line Segment |
| 4360-4460 | Vertical Curve |
| 4460-4600 | Line Segment |
| 4650-4758 | Vertical Curve |
| 4758-5022 | Line Segment |
| 5022-5176 | Vertical Curve |
| 5176-5918 | Line Segment |
| 5918-6136 | Vertical Curve |
| 6200-6336 | Vertical Curve |
| 6336-6420 | Line Segment |

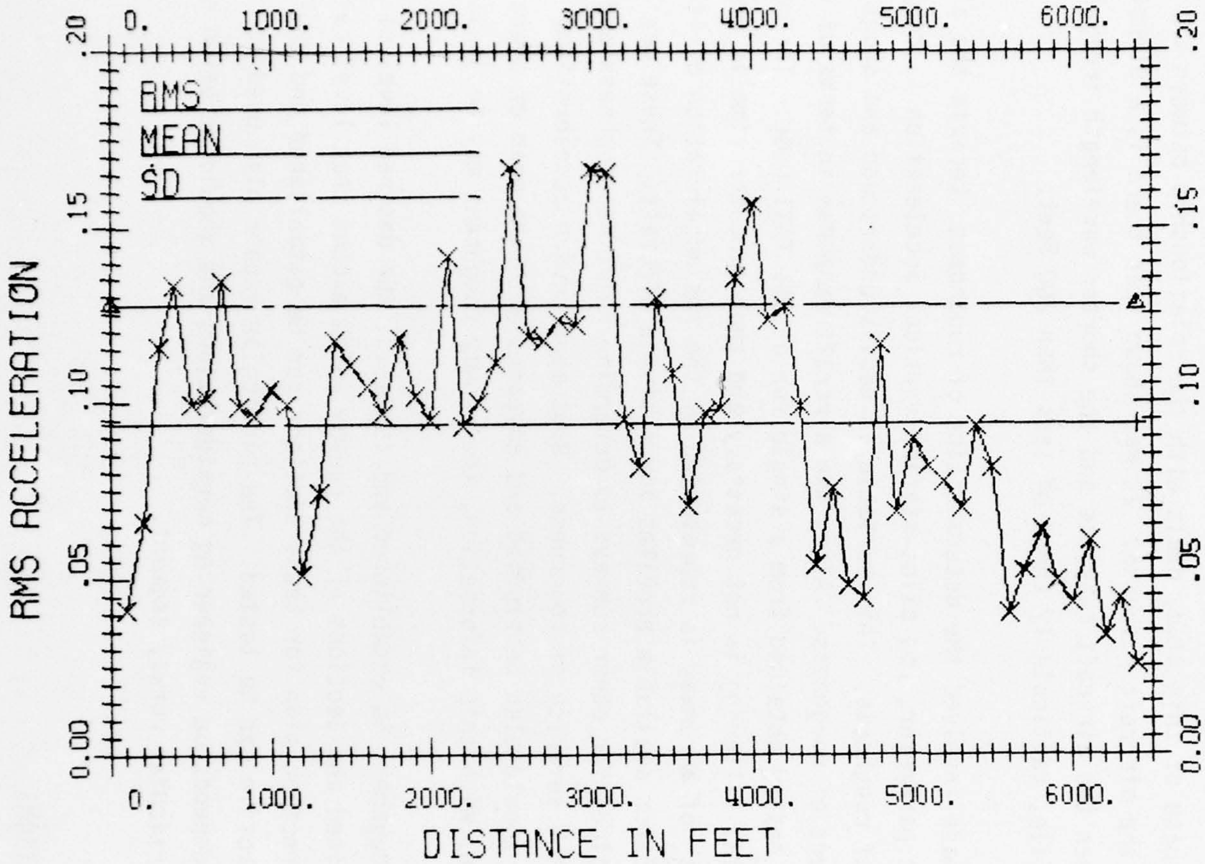


Figure 18. Root Mean Square Pilot-Station Acceleration for DC-10 Aircraft on Corrected Oklahoma City RN12 Profile

# SECTION IV
# CONCLUSIONS AND RECOMMENDATIONS

## 1. CONCLUSIONS

The first phase of this study dealt with the relationship between the runway profile and the aircraft response. It was shown that there is a direct relationship between the aircraft response and the shorter wavelength irregularities in the profile, particularly those of less than 200 feet.

The next phase involved the determination of roughness. Because the aircraft is the important parameter, rms pilot-station vertical acceleration is considered the measure of roughness. This variable is easily understood and shows clearly the effect of roughness. Also, the aircraft response in terms of rms acceleration is easily obtained from a single run of the TAXI Code. The mathematics of digital filtering is not necessary and thus computer time is reduced. Overall roughness of a runway is represented by the rms acceleration of its centerline and other available profiles for a single aircraft. These may be compared with values for other runways to determine relative roughness and to help determine the severity of roughness. Root mean square accelerations for runway segments should also be studied and compared with the mean or overall rms acceleration. With this information, the runway roughness may be isolated.

Once the roughness is established and isolated, the desired level of roughness may be defined and sections of the runway which exceed that level can be studied. A correction plan for those sections can be established and the corrected runway profile can be tested. The particular repair plan used for a runway segment depends on engineering considerations and should be based on a study of the particular runway segment.

## 2. RECOMMENDATIONS

Profiles of an existing runway should be used with the TAXI Code to determine the degree of roughness of a runway, isolate rough areas, and test repairs planned for the runway.

TABLE 2. RELATIVE RUNWAY ROUGHNESS FOR DC-10 AIRCRAFT

| Runway | rms Acceleration |
|---|---|
| BGTL RN16 | 0.296 |
| ALB RN19 | 0.280 |
| JFK RN13R | 0.196 |
| OKC RN35R | 0.180 |
| OKC RN12 | 0.162 |
| ABQ RN17 | 0.159 |
| ORD RN22L | 0.150 |
| CVS RN03 | 0.117 |
| DFW RN17 | 0.116 |

The first step in the isolation and correction of runway roughness is to define the relative roughness of the runway and determine where it occurs. By running a particular aircraft over runway profiles, vertical accelerations may be obtained and rms values may be calculated for sections of the profiles as well as the mean or overall rms values. For example, table 2 lists several runways and their relative roughness in terms of rms pilot-station vertical acceleration. Runways with rms acceleration values between 0.10 and 0.15 are relatively smooth; those with values greater than 0.20 are considered rough. By studying these values the roughness can be isolated and a determination of the amount of correction necessary in terms of a reduction in rms acceleration can be made. This determination depends on engineering considerations as well as the severity of roughness. With data of the type shown in figure 1, the user must determine the desired rms acceleration. Once the desired level of rms acceleration is defined a repair plan must be established for those sections of the runway which have excessive rms levels. This can be best accomplished by determining and evaluating a corrected elevation profile for the centerline of the runway. This is an iterative procedure and cannot be accomplished exclusively on the computer; engineering judgment relative to profile correction is a vital part of the process. This will certainly include such factors as construction alternates and project economics. Off-centerline as well as centerline profiles should be checked to ensure the feasibility of the applied corrections. When the corrected profiles are established they may be checked with the TAXI Code to confirm that the rms accelerations are acceptable.

The segment length used in this research for calculating rms accelerations was 100 feet, but other lengths may be used depending on the length of the shortest correction distance. Segment lengths less than 50 feet, however, are not recommended.