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# EXPERIMENTS ON THE EFFECTS OF ATMOSPHERIC REFRACTION AND AIRPLANE ACCELERATIONS ON SONIC-BOOM GROUND-PRESSURE PATTERNS

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## SUMMARY

A special series of sonic-boom flight tests has been conducted with a fighter airplane in the altitude range from 33 500 to 52 200 feet (10 211 to 15 911 meters) at Mach numbers to 2.0 in an attempt to define better the lateral extent of the sonic-boom pressure pattern during steady supersonic flight and the superboom and multiple-boom regions during accelerated flight for quiescent atmospheric conditions. Ground-pressure measurements have been obtained for lateral distances up to about 35 miles (56 315 meters) to each side of the flight track during the steady-level flight conditions and for distances of about 23 miles (37 007 meters) along the flight track for the acceleration and low Mach number steady-level flights.

The lateral-spread phenomena appear to be fairly well understood and predictable for current and future supersonic airplanes. The highest overpressures are measured on the ground track and decrease with increasing lateral distance. Pressure buildups occur in the superboom region for longitudinal accelerations at constant altitude, and these are followed by a region of multiple booms wherein the pressures are of the order of magnitude predicted for comparative steady-level flight conditions.

In some instances where the shock waves are in proximity to the ground but do not intersect the ground (due to atmospheric refraction), disturbances are observed in the form of rumbles. These disturbances are believed to be the result of the acoustic phenomena associated with the extremity of the shock waves.

## INTRODUCTION

Minimization of community reaction to sonic booms resulting from supersonic airplanes, in particular the proposed commercial supersonic transport, requires a knowledge of the effects of airplane operation and the atmosphere on the ground exposure areas. Of significance are the pressure distributions associated with both the acceleration phase of the flight profile from transonic to supersonic speeds and the steady-level phase of flight at supersonic cruise speeds. Associated with each of these two phases of flight is the possibility of pressure enhancement as a result of the refraction effects of the atmosphere and focusing due to the accelerations of the airplane (refs. 1 to 7).

Theoretical methods (refs. 1 to 7) are available for application to the prediction of the ground pressures during airplane accelerated flight and for the lateral-spread pattern during steady-level flight. These analytical methods, some of which permit inclusion of atmospheric variation (i.e., temperature and wind gradients), have been verified to a certain extent with experimental studies in references 8 to 15. Little experimental information exists, however, in regard to detailed measurements of the sonic-boom ground pressures in the multiple-boom region due to acceleration and at the extremities of the lateral-spread pattern for steady-level flight conditions.

The purpose of this paper is to present the data from a special series of flight tests (some of which were previously reported briefly in ref. 16) with a fighter airplane in the altitude range from 33 500 to 52 200 feet (10 211 to 15 911 meters) at Mach numbers to 2.0. Sonic-boom measurements were obtained under closely controlled flight conditions for about 23 miles (37 007 meters) along the ground track for accelerated flight and low Mach number steady-level flight and for total lateral distances up to 65 miles (104 585 meters) for high Mach number steady-level flight conditions.

## SYMBOLS

The mile as a unit in this paper refers to the U.S. statute mile which is equivalent to 1609 meters.

$d$ lateral distance measured perpendicular to airplane ground track, miles (meters)

$K_r$ ground reflection factor

$M$ airplane Mach number

$\Delta p_o$ measured pressure rise across bow shock wave at ground level, pounds per foot$^2$ (newtons per meter$^2$)

$s$ distance, parallel to ground track, from plane perpendicular to ground and containing airplane to a point on the intersection of Mach cone and ground plane (as defined in fig. 10), feet (meters)

## APPARATUS AND METHODS

### Test Conditions

All flight tests in table I were made in the vicinity of Edwards Air Force Base, California. The area in which the measurements were taken was generally flat with only sparse vegetation and has an altitude of 2000 to 3600 ft (610 to 1097 m) above sea level. As can be seen from figure 1(a), no extreme variations in elevation existed in the immediate areas in which the ground measuring stations were located.

The ground instrumentation consisted of eight measuring stations positioned along a true north-south line extending about 65 miles (104 585 m) (fig. 1(a)). Each measuring station consisted of from two to four microphones positioned near ground level in an L-shaped array with an additional microphone elevated 20 ft (6.1 m) above the ground (fig. 1(b)). The choice of the location of each of the eight ground stations along the north-south line depended upon the particular objective of each flight. The open symbols of figure 1(a) represent alternate locations of some stations for the purpose of obtaining more complete measurements over a shorter distance for some tests. Accurate locations of all stations were established by means of standard surveying techniques.

### Test Airplanes

Two fighter airplanes of the same type were used in these tests, one with external wing tanks (airplane B) and one without external tanks (airplane A). (See fig. 2.) For the purpose of these tests the differences due to the external tanks were not believed to be significant. Airplanes B and A had an overall length of 54.5 ft (16.61 m) and empty gross weights of 14 217 and 13 770 lb (mass) (6449 and 6246 kg), respectively. The estimated weights of the airplane during the time of the sonic-boom passes are given in table I. Both airplanes were provided, maintained, and operated by NASA Flight Research Center personnel.

### Airplane Positioning

The airplanes were positioned over the test area by means of ground-control procedures with the aid of the Edwards Air Force Base radar tracking facility. For the lateral-spread tests and the "grazing" flight tests requiring steady-level flight conditions, the pilot was provided course corrections by the ground controller only to within about 20 miles (32 180 m) of the ground zero point (overhead of station for lateral spread and distance from first station approached for grazing tests, the actual distance being determined by the method given in ref. 10). No changes in airplane heading, speed, and altitude were given beyond this point so as to minimize possible effects of such changes on the sonic-boom ground-pressure patterns in the test area. In the case of the acceleration tests which were conducted from subsonic to supersonic speeds at constant altitudes, the airplane was directed on course and altitude prior to reaching a high subsonic Mach number. At the appropriate distance measured along the airplane ground track to the particular station at which the superboom was to be placed (according to fig. 11 of ref. 4), the pilot permitted maximum acceleration of the airplane.

It should be pointed out that the airplane began the acceleration from $M = 0.9$ rather than $M = 1.0$ so that the airplane engine would operate from military power to full afterburner smoothly rather than having the pilot attempt to modulate the afterburner to maintain $M = 1.0$.

Radar plotting-board overlays were obtained for all flights in addition to digital tape printouts at 1-second intervals. These data were used to provide information of the type shown in figure 3. The pilot was asked to read out his altitude, Mach number, heading, and fuel remaining onboard during each run.

In order to synchronize the tracking data and all eight ground-pressure measuring stations, a 1,000-cps tone was superimposed on the data records and radar plot at the time the aircraft passed over a specific measuring station (which depended upon the type of test conducted).

## Atmospheric Soundings

Rawinsonde observations from Edwards Air Force Base weather facility, which was located 8 miles (12 872 m) from the north-south ground-recording station line (fig. 1(a)), were taken within about 3 hr of the times of all flight tests. Measured values of temperature and pressure, along with the calculated speed-of-sound and humidity values and wind-velocity and direction values, were provided at 1000-ft (305 m) intervals to altitudes of 5000 ft (1524 m) or more in excess of the airplane test altitude. The sample data of atmospheric pressure, temperature, and speed of sound were obtained as a function of altitude on the same day at two different test times. (See fig. 4.) An inspection of all data records indicated that these curves were representative of those for the entire period of the test program. The 1962 U.S. Standard Atmosphere values are also shown for comparison. (See ref. 17.) In that all of the flights were conducted along an approximate north, south, east, or west heading, the wind velocities have been resolved into similar components and are presented in figure 5.

For altitudes up to the tropopause, the atmospheric pressure, temperature, and speed of sound were generally higher than those of the 1962 U.S. Standard Atmosphere. The wind profiles shown in figure 5 indicate that maximum wind-component velocities of about 0 to 72 fps (21.9 m/sec) were recorded for the test period.

Reported surface observations by the sonic-boom pressure measuring station operators indicated that most flights were conducted during times of quiescent conditions – that is, normal surface temperatures and low wind velocities.

## Pressure Instrumentation

The main components of the ground measuring systems used for sonic-boom pressures are the same as those described in more detail in reference 18. Each channel of the system used in the experiments consisted of a specially modified microphone, tuning unit, dc amplifier, and oscillograph recorder. The usable frequency range was from 0.02 to 5000 cps, and this range applies to all the data presented herein. The microphones have a dynamic range from about 70 to 150 dB. They were field-calibrated statically before each test by means of a pressure bellows and a sensitive manometer. Prior to field installation, frequency-response curves were measured for all microphone systems.

For ease of setup and consistency of measurements as a result of the various alternate locations of some of the eight measuring stations (fig. 1(a)), each microphone was shock-mounted 6 in. (0.153 m) above ground level with the sensitive element parallel to the reflecting surface. Previous measurements (ref. 12) indicate that this type of mounting arrangement results in only small differences in wave form compared to those obtained in the ground plane. Wind screens consisting of two layers of cheesecloth were employed to minimize effects of surface winds on the microphone readings and also to provide shade from the sun and protection from blowing sand particles.

Each of the eight stations of the present tests consisted of a microphone layout similar to those shown in figure 1(b). From three to four (with the exception of station 3 which consisted of two microphones 200 ft (60.96 m) apart) ground microphones were placed in an L-shaped array at each station with a spacing of 200 ft (60.96 m) between microphones. An additional microphone was positioned at the corner of each station L-shaped array 20 ft (6.1 m) above the ground to indicate shock-wave angle at ground level.

Prior to positioning for the research flights the ground-pressure measuring instruments at each of the eight measuring stations along the north-south array line were subject to calibration flights. All 24 microphones were shock-mounted in a reflection board within an area of less than 2 $ft^2$ (0.186 $m^2$) to check for repeatability and to determine the amount of variation inherent in the field use of these instruments.

Two passes were made over the microphone setup by the same fighter airplane at an altitude of about 37 000 ft (11 278 m) and a Mach number of about 1.5. As reported in references 12 and 18, the measured sonic-boom pressure signatures were nearly the same for all microphone channels and had the characteristic N-wave shape. The variations observed in the overpressure values which are primarily ascribed to instrument differences and calibration and reading errors were noted to be in the order of ±1 dB or about ±15 percent. Grouping of the microphones minimizes the possible variations in the sonic-boom signatures resulting from weather effects. (See refs. 12 and 18.)

## RESULTS AND DISCUSSION

Two main types of information were obtained in the present studies: detailed pressure time histories at several measuring points and the arrival times of the shock wave disturbances at those points. This type of information was obtained for the lateral-spread and grazing tests at steady-level flight conditions and also for the constant-altitude longitudinal acceleration tests from subsonic to supersonic speeds.

### Lateral Spread

References 10 to 13 and 15 present comparisons of experimental and calculated sonic-boom lateral-pressure distributions. The experimental results were usually limited to measurements on only one side of the ground track (refs. 10 and 13), measurements to one side of the track with observation to the other side of the ground track (ref. 11), or measurements on each side of the ground track but for relatively low flight altitudes (ref. 15). Reference 12 presented some measurements to each side of the ground track, but the data were obtained under atmospheric conditions which provided substantial variations in the peak ground overpressures.

The present tests were designed to provide simultaneous measurements on both sides of the ground track and for both quiescent and unstable conditions of the atmosphere. Particular emphasis was placed on obtaining measurements near the lateral extremity of the pattern in order to define better the pressure gradient and signature shapes in the region of cutoff due to atmospheric refraction.

Measured sonic-boom pressure signatures.- For the lateral-spread tests the eight measuring stations were positioned along the north-south array line (fig. 1(a)) at locations out to about 40 miles (64 360 m) and 25 miles (40 225 m) to each side of station 5, respectively. These measuring stations are designated by the solid circular points in figure 1(a) and are assigned station numbers 1 to 8. The fighter airplane was flown at steady conditions in a direction perpendicular to the station array along a ground track passing through station 5 at an altitude of 52 200 ft (15 911 m) above sea level at a Mach number of 2.0.

Figure 6 presents the measured bow-wave overpressures for the flight as obtained from each ground microphone of each of the eight measuring stations. Also shown in the figure are the theoretical variations of overpressure as a function of lateral distance to each side of the ground track and the calculated lateral cutoff distance due to refraction based on the methods of references 5 and 6 for the altitude, Mach number, and atmospheric conditions of the test. As theory predicts, the maximum overpressure occurs on the ground track and the pressures generally decrease with increasing lateral distance (the solid symbols at the approximate 40-mile (64 360 m) lateral station indicate no disturbances observed or measured). It is significant to note the lack of scatter in the data at any given measuring station (as compared, for example, with the results presented in fig. 11 of ref. 12). In this regard, it is of interest to examine the details of the sonic-boom pressure signatures measured at the various stations.

Figure 7 shows the sonic-boom pressure signatures as measured at station 5 by each of the four ground microphones located in the L-shaped array. Typical N-wave signatures were obtained with little variation in the peak bow overpressures at each of the microphone locations. Similar results were obtained at the other seven measuring stations – that is, the overpressure results from each of the microphones in a given station array were nearly the same. (See fig. 6.) Based on the experience of references 12 and 18 this would suggest the existence of quiescent atmospheric conditions.

Figure 8 presents typical sonic-boom signatures measured at the various station locations laterally to each side of the flight track. Similar waveforms were obtained for about the same distances to each side of the airplane ground track and the bow-shock overpressure decreases while the rise time increases (wave becomes more rounded) as the lateral cutoff is approached. Beyond this point, the signatures lose their identity and are observed as a rumbling noise.

In figure 8 no disturbances were observed at the furthermost lateral location (station 1); however, the fact that disturbances were observed at distances beyond the calculated lateral cutoff (at stations 2 and 8) led to more definitive studies which were conducted at altitudes of about 37 600 ft (11 460 m) and Mach numbers of about 1.5. For these tests, stations 1, 2, and 8 were relocated to positions A, B, and C. (See fig. 1(a).) The two fighter airplanes provided a total of four passes at a heading perpendicular to the north-south station array at various lateral distances of about 2, 4, 5, and 7 miles (3218, 6436, 8045, and 11 263 m) north of station 3. Such an arrangement of flight tracks and station locations, which was based on a knowledge of the calculated lateral cutoff for the nominal altitude and Mach number, permitted concentration of measuring stations in the vicinity of the cutoff region.

Figure 9(a) presents the measured bow-wave overpressures for the four flights, as represented by the different symbols, at each of the eight measuring stations along with representative sketches of the sonic-boom signatures measured at various lateral locations. Also shown in this figure is the theoretical variation of overpressure as a function of lateral distance to each side of the ground track and the calculated lateral cutoff distance due to atmospheric refraction based on the methods of references 5 and 6 for a nominal altitude of 37 600 ft (11 460 m) and Mach number 1.5 and for the atmospheric condition during the time of the tests.

The results obtained in figure 9(a) are similar to those of figure 6 and, in general, disturbances are observed about 15 miles beyond the calculated lateral cutoff distance. (Solid symbols indicate no booms measured or observed at recording station.) Some insight as to the nature of these phenomena can be obtained by examining the sketches of the pressure signatures shown in figure 9(a) which were measured at various lateral locations from the ground track. As is also shown in figure 8, definite shock-wave-type signatures with decreasing pressures and increasing rise times are measured with increasing lateral distance. The results are in agreement with those predicted by reference 19 which suggests that ground reflection effects may be at least partly responsible for the increase in rise time. Beyond the calculated lateral cutoff distance the signatures lose their identity and they are observed as rumbles. Such rumbles are believed to be the result of acoustic phenomena associated with the extremity of the shock wave. (These phenomena are discussed in some detail in ref. 20.)

Lateral-spread results presented in figure 9(b) were obtained in the same manner as those of figure 9(a), only during a day in which the atmosphere was known to be more active – that is, high surface winds, cloud cover, and overcast. Because of the malfunction of equipment, no rawinsonde data were obtained during the afternoon hours although a definite change was noted in the weather conditions between the weather soundings of figures 4 and 5 taken respectively in the early morning and at the time of the flights. The results presented are for two steady-level passes of the fighter aircraft at an altitude of about 37 200 ft (11 339 m) and Mach number about 1.4. (See table I, flight tests 18 and 19.) Separate symbols are shown for each of the two passes. The solid symbols represent no disturbances observed or measured. Also shown in the figure are the theoretical variations of overpressure as a function of lateral distance to each side of the ground track and the calculated lateral cutoff distance due to atmospheric refraction based on the methods of references 5 and 6. Also shown in the figure are sketches of the type of pressure signatures measured at the various recording stations.

The most significant features of the results of figure 9(b) are the shapes of the signatures and the shorter distances that disturbances were measured beyond the cutoff point (as compared with fig. 9(a), for example). The normally expected N-waves are distorted such that peaking or rounding off of the shapes result. Similar results were obtained during the studies of references 12, 18, and 21 and were attributed to atmospheric effects.

The amplitude of the observed signals beyond the calculated lateral cutoff, as shown in figure 9, did not vary in a systematic manner; that is, there was no well-defined decrease in amplitude with increasing lateral distance. Based on the observations of the station operators, the local surface weather conditions of the tests of figure 9(a) were noted to be quiescent in contrast to the generally more turbulent surface conditions of the tests of figure 9(b). The phenomena of disturbances beyond the lateral cutoff are believed to be very sensitive to local surface weather conditions.

Wave-front ground intersection.- Because each record of the measuring stations was synchronized in time with the airplane position, the relative arrival times of the shock waves could be determined. With the use of these arrival times as measured at each station, the measured ground speed of the airplane from radar tracking, and the shock wave propagation speed across each measuring station, the shape of the shock front was estimated. The results are presented in figure 10 for the steady flight of the fighter airplane at 52 200-ft (15 911 m) altitude and Mach number 2.0. Also shown are the theoretical intersections assuming a homogeneous atmosphere (no winds and uniform temperature) and also for the atmospheric conditions existing at the times of the tests. These calculations were obtained by the method of reference 5. The intersection of the ordinate and abscissa scales represent the overhead position of the airplane (over station 5, fig. 1(a)). The shock wave intersects the ground some 75 000 ft (22 860 m) behind the airplane and the pattern is nearly symmetrical about the ground-track line. In addition, a difference of the order of 1.5 to 5.0 miles exists between the measured wave-front ground intersection and the calculated values using the actual and homogeneous atmosphere, respectively. These results are in agreement with similar results presented in reference 10.

## Grazing Tests Along Ground Track

Theoretical considerations presented in reference 2 and further refined in reference 20 suggest the possibility of pressure buildups for conditions of steady-level flight at cutoff Mach number along the ground track of an airplane. The cutoff Mach number is defined as that Mach number for which the airplane speed is equal to the local propagation speed at the ground. For this condition, the shock wave just reaches the ground and is essentially normal to the ground. The reflection factor $K_r$, therefore, approaches 1.0 rather than 2.0. (See ref. 20.) This phenomenon, which has been referred to as grazing, results from atmospheric refraction and is a special case for which the lateral-spread pattern is zero. As suggested in reference 2, the cross-sectional area of the ray tube decreases and approaches zero. According to linear theory, the pressures tend to increase and approach infinity. Previous experimental studies aimed at obtaining this so-called graze condition did not result in measured overpressures greater than about 30 percent above those predicted for steady-level flight at the same altitude but at higher Mach numbers. (See ref. 14.)

In the present tests, five supersonic flights were conducted in an attempt to define better this grazing condition. These tests were conducted with a fighter airplane during the morning and afternoon of one day. Because of altitude restrictions on the day of the flights, three passes were conducted at an altitude of about 37 500 ft (11 430 m) at steady Mach numbers above, near, and below the calculated cutoff Mach number (based on theory assuming a standard atmosphere). The two other flights were made at an altitude of about 33 500 ft (10 211 m). The station arrangement for these tests, which were made along the north-south array, is shown in figure 1(a). Station 2 was positioned to location D, and the array included stations 3, D, 4, C, B, 5, A, and 6 reading north to south. The results of these tests are presented in figure 11 where the bow overpressures as measured at each station are plotted as a function of distance along the ground track. Figure 11(a) is for the tests at about 37 500 ft (11 430 m), and figure 11(b) for the tests at an altitude of about 33 500 ft (10 211 m). Also shown in the figure are the types of disturbances observed for each Mach number. The solid symbols represent a no-boom condition. The dashes across each figure are the calculated overpressure for steady flight at Mach number 1.25 at a nominal altitude of 37 500 ft (11 430 m) and 33 500 ft (10 211 m) with a ground reflection coefficient $K_r$ of 1.0 and 2.0, respectively.

Although some scatter exists in the values at and between each measuring station due in large part to atmospheric variations, the data fall in general between the two calculated values. This result suggests that there might be a tendency for pressure buildups due to grazing but because of the relatively low reflection factor for this condition the resulting ground overpressure values are of the same order of magnitude as those predicted for steady-level flight at higher Mach numbers. Also, for Mach numbers well above grazing, definite shock-type signatures were observed, and for a Mach number condition well below grazing, no booms were observed. At Mach numbers just slightly below grazing, the signatures observed are believed to be acoustic in nature as previously discussed for the lateral cutoff phenomena.

## Longitudinal Acceleration

An extensive series of ground-pressure measurements has been made for longitudinal airplane accelerations in an attempt to define better the superboom and multiple-boom regions along the airplane ground track. These tests were conducted during the morning and afternoon of one day along the same north-south station line used for the previously discussed grazing tests. Five passes were made at a constant altitude of about 37 200 ft (11 339 m) with the airplane accelerating from about Mach number 0.9 to 1.5. In these tests it was planned to position the airplane at the beginning of its accelerated run such that the superboom would fall in the vicinity of measuring station 5. (See fig. 1(a).) Based on a knowledge of the estimated acceleration rate of the airplane at the various gross weights, which were estimated for each of the acceleration passes, and assuming standard atmospheric conditions, the distance measured along the north-south ground track from station 5 to the point at which the airplane began accelerating was determined with the aid of figure 11 of reference 4. The results from the five individual accelerated flights (flights 13 to 17) are shown in figure 12 along with tracings of sample signatures.

Plotted in figure 12 are the peak positive overpressures for each measured signature at the respective station locations indicated at the top of the figure. The circular symbols represent the bow-wave overpressure associated with the first N-wave to arrive. Likewise, the square symbols represent the bow-wave overpressure of the second N-wave to arrive where multiple signatures are observed. The diamond symbols represent the peak pressures associated with signatures other than N-wave type signatures. For cases represented by the circles and squares, booms were observed; for the case represented by the diamonds, rumbles were observed.

The data of figures 12(a), (b), and (c) have the gross features of the results from longitudinal accelerations previously obtained. (See, for example, refs. 7, 9, and 18.) For instance, single N-wave signatures having relatively high peak values are observed in a very localized region, followed by multiple signatures of lower peak values.

The data of figures 12(d) and (e), however, do not exhibit the orderly pattern just described. These latter data were obtained at times for which the surface weather conditions were judged to be markedly different than for the times of figures 12(a), (b), and (c). A gusty wind condition developed rapidly between the times of the flights of figures 12(c) and (d).

Further insight into the longitudinal acceleration phenomena can be obtained by examination of the results of figure 13, in which the measured data points of flights 13, 14, and 15 (shown in figs. 12(a), (b), and (c)) are combined. The data at the zero position represent the so-called superboom condition where pressure buildups occur. The data for the three separate flights were normalized by plotting the highest measured overpressure values at this zero position. The direction of the airplane is from left to right, as indicated by the sketches at the top along with corresponding tracings of measured signatures. The data points in the figure represent peak overpressures as defined in the sketch. The low-value points to the left of the figure represent noise and are observed as rumbles. The high value points near the center of the figure correspond to measurements that are very close to the focus point and, thus, represent what are conventionally described as superbooms. To the right of the focus point are two distinct sets of measurements which relate to the region of multiple booms. For convenience in illustrating the trends of the data, solid and dashed lines are faired through the data points. The data points that cluster about the solid curve relate to the first signature to arrive and this eventually develops into the steady-state signature. The data points that cluster about the dashed curve relate to the second signature to arrive. These values generally decrease as distance increases, and eventually this second wave ceases to exist (approximately 20 miles (32 180 m) down the ground tracks) because of the refraction effects of the atmosphere.

The highest overpressures are measured in a very localized region. These values are as high as 2.5 times the maximum value observed in the multiple-boom region and are thus in general agreement with the measured results for lower altitude tests of references 7 and 18. The main multiple-boom overpressure values are of the same order of magnitude as those predicted for comparable steady-state flight conditions. (See fig. 9(a).) Based on the experience with longitudinal acceleration flights at constant altitude presented in figures 12 and 13, wherein use was made of the theoretical curves of figure 11 of reference 4, it is believed that the superboom can be placed at a position on the ground to within about ±5 miles (8045 m) of the desired location provided such information as flight path, altitude, and acceleration rate of the airplane is available.

## CONCLUSIONS

Sonic-boom ground-pressure measurements have been obtained from a special series of flights of fighter airplanes in an attempt to define better the effects of airplane operation and atmospheric refraction effects on the ground-exposure patterns. Based on the results obtained, the following conclusions are presented:

1. As predicted by theory, the sonic-boom pressures were highest on the track and generally decreased with increasing lateral distance out to the point of cutoff due to atmospheric refraction effects.

2. For distances up to the calculated lateral cutoff distance, N-type signatures were generally observed. Beyond the calculated lateral cutoff distance, the signatures lost their identity, and disturbances in the form of rumbles were observed at distances up to about 15 miles (24 135 m) in excess of the calculated lateral cutoff distance.

3. These disturbances or rumbles were believed to be the result of acoustic phenomena associated with the extremities of the shock waves.

4. There was a suggestion of pressure buildups due to the grazing condition during the test at cutoff Mach number along the ground track. However, because of the relatively low ground reflection factor for this condition the resulting ground overpressure values were of the same order of magnitude as those predicted for steady-level flight at higher Mach numbers.

5. For the conditions of Mach number and altitude above cutoff, definite shock-wave signatures were observed whereas for conditions of Mach number and altitude less than

cutoff the signatures lose their characteristic shape. Acoustic disturbances similar to those observed at the extremities of the lateral-spread pattern were observed.

6. Pressure buildups during acceleration from subsonic to supersonic speeds were measured in the very localized superboom region, and these buildups were noted to be up to about 2.5 times the pressures measured in the accompanying multiple-boom region.

7. The multiple-boom region covered a distance of about 20 miles (32 180 m) along the airplane ground track and was characterized by two N-waves producing four booms. The highest pressures were associated with the first N-wave to arrive in each case, and these were of the same order of magnitude as would be predicted for similar steady-level flight conditions.

8. The location of the superboom and multiple-boom regions were predictable to within ±5 miles (8045 m), provided the airplane flight profile and acceleration rate were known.

9. For the acceleration studies, disturbances in the form of rumbles were observed for large distances along the airplane ground track prior to the intersection of the shock waves with the ground. These rumbles were also believed to be the result of acoustic disturbances similar to those observed at the extremities of the lateral-spread pattern and for the cutoff Mach number flights.

Langley Research Center,
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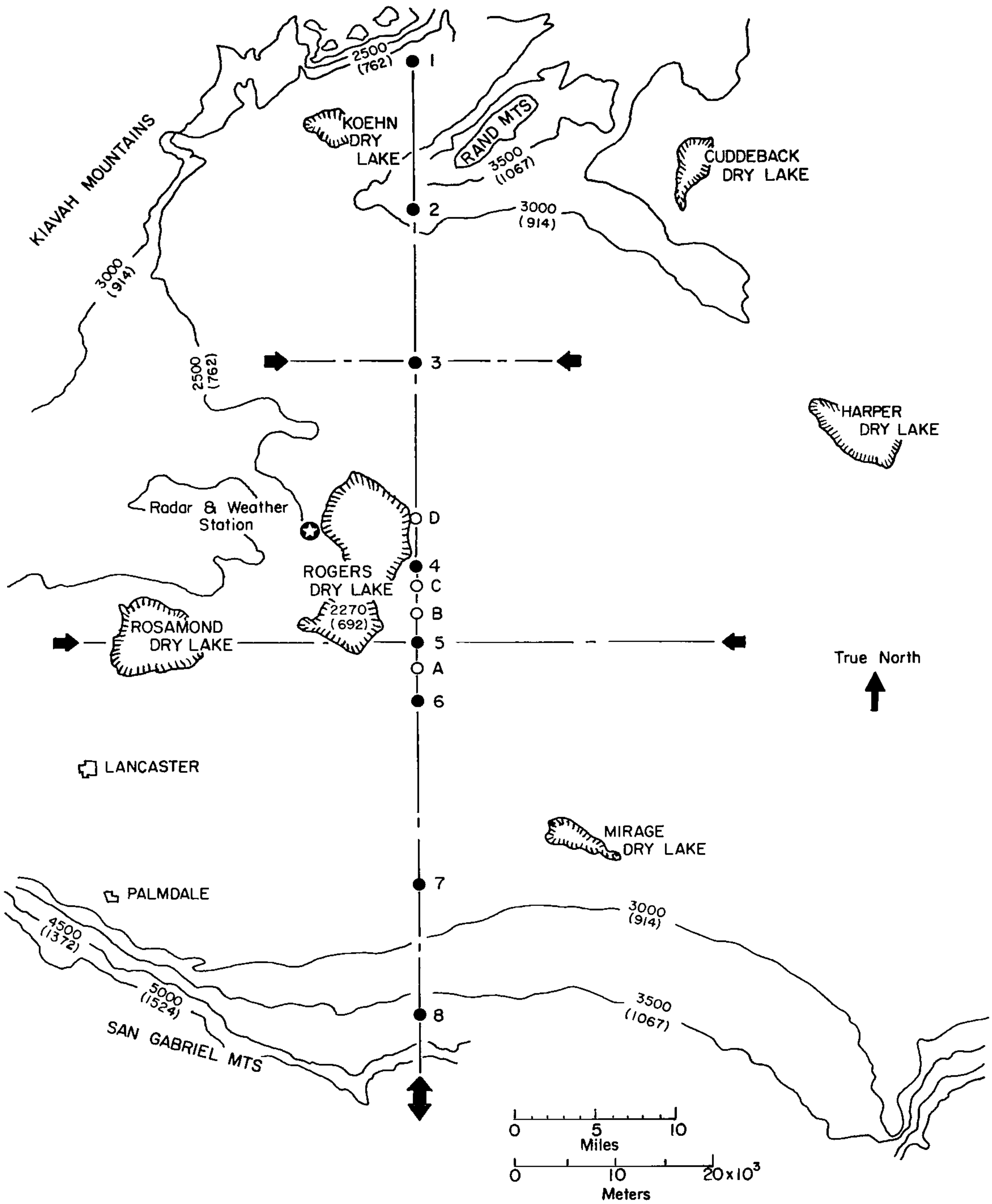
TABLE I.- LOG OF SONIC-BOOM TEST FLIGHTS

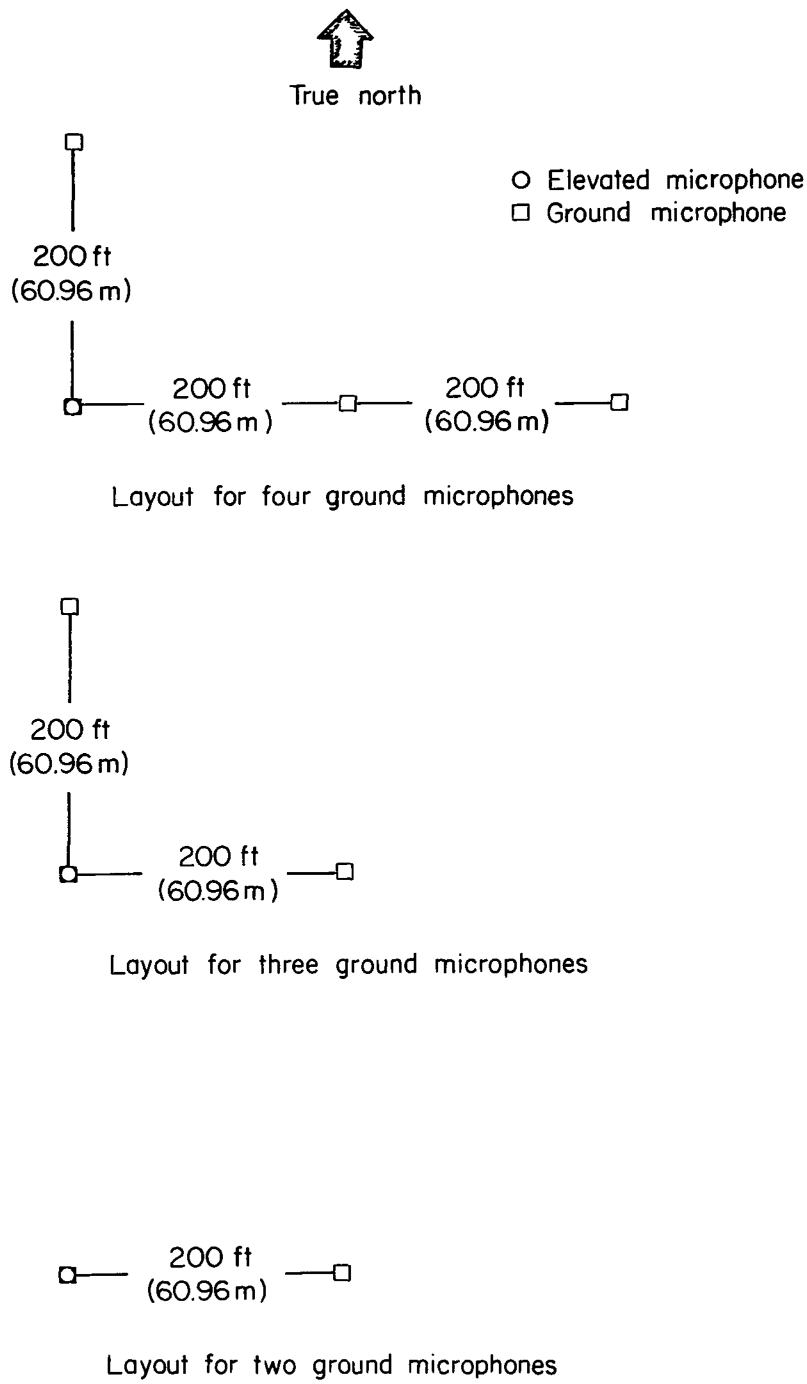
| Flight test | Date | Time of day, hr | Airplane (a) | Mach number | Altitude (mean sea level) | | Airplane gross weight at time of pass | | Airplane true heading, deg | Lateral displacement over main station | | Purpose of flight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | ft | m | lb (mass) | kg | | ft | m | |
| 1 | 10- 7-64 | 1008 | A | 1.43 | 37 000 | 11 278 | 17 370 | 7879 | 261 | 1 000 N | 305 N | Microphone calibration |
| 2 | 10- 7-64 | 1017 | A | 1.59 | 37 300 | 11 369 | 15 570 | 7062 | 083 | 2 100 S | 640 S | Microphone calibration |
| 3 | 10- 8-64 | 1033 | B | 2.00 | 52 200 | 15 911 | 16 517 | 7492 | 269 | 600 N | 183 N | Lateral spread |
| 4 | 10- 9-64 | 1007 | A | 1.52 | 37 700 | 11 491 | 17 220 | 7811 | 268 | 10 000 S | 3 048 S | Lateral spread |
| 5 | 10- 9-64 | 1019 | A | 1.49 | 37 500 | 11 430 | 15 470 | 7017 | 091 | 18 500 N | 5 639 N | Lateral spread |
| 6 | 10- 9-64 | 1039 | B | 1.52 | 37 600 | 11 460 | 18 017 | 8172 | 272 | 23 300 N | 7 102 N | Lateral spread |
| 7 | 10- 9-64 | 1056 | B | 1.51 | 37 600 | 11 460 | 16 017 | 7265 | 090 | 34 500 N | 10 516 N | Lateral spread |
| 8 | 10-12-64 | 0859 | B | 1.27 | 37 400 | 11 400 | 19 217 | 8717 | 181 | 20 000 W | 6 096 W | Steady-level grazing |
| 9 | 10-12-64 | 0916 | B | 1.21 | 37 600 | 11 460 | 17 217 | 7809 | 182 | 9 200 W | 2 804 W | Steady-level grazing |
| 10 | 10-12-64 | 0931 | B | 1.16 | 37 500 | 11 430 | 15 417 | 6993 | 182 | 2 250 W | 686 W | Steady-level grazing |
| 11 | 10-12-64 | 1042 | B | 1.23 | 33 600 | 10 241 | 19 417 | 8807 | 181 | 5 650 W | 1 722 W | Steady-level grazing |
| 12 | 10-12-64 | 1055 | B | 1.17 | 33 500 | 10 211 | 17 417 | 7900 | 181 | 1 000 E | 305 E | Steady-level grazing |
| 13 | 10-13-64 | 1012 | B | 0.9 to 1.49 | 37 300 | 11 369 | 18 717 | 8490 | 002 | 0 | 0 | Longitudinal acceleration |
| 14 | 10-13-64 | 1028 | B | 0.9 to 1.53 | 37 300 | 11 369 | 16 717 | 7583 | 359 | 1 500 E | 457 E | Longitudinal acceleration |
| 15 | 10-13-64 | 1424 | B | 0.9 to 1.37 | 37 000 | 11 278 | 19 417 | 8807 | 359 | 2 250 E | 686 E | Longitudinal acceleration |
| 16 | 10-13-64 | 1441 | B | 0.9 to 1.52 | 36 900 | 11 247 | 17 517 | 7946 | 358 | 5 400 W | 1 646 W | Longitudinal acceleration |
| 17 | 10-13-64 | 1456 | B | 0.9 to 1.65 | 37 100 | 11 308 | 15 717 | 7129 | 358 | 1 000 W | 305 W | Longitudinal acceleration |
| 18 | 10-14-64 | 1350 | B | 1.35 | 37 000 | 11 278 | 19 217 | 8717 | 270 | 5 200 S | 1 585 S | Lateral spread |
| 19 | 10-14-64 | 1405 | B | 1.50 | 37 300 | 11 369 | 16 617 | 7537 | 089 | 5 700 S | 1 737 S | Lateral spread |

[a]Airplane A: without tip tanks; empty weight, 13 770 lb (mass) (6246 kg).
Airplane B: with tip tanks; empty weight, 14 217 lb (mass) (6449 kg).




(a) General layout. Open symbols represent alternate microphone locations; arrows indicate various flight tracks used for tests; all altitudes are given in ft (m).

Figure 1.- Arrangement of test facilities and equipment.




(b) Typical station microphone arrangement.

Figure 1.- Concluded.

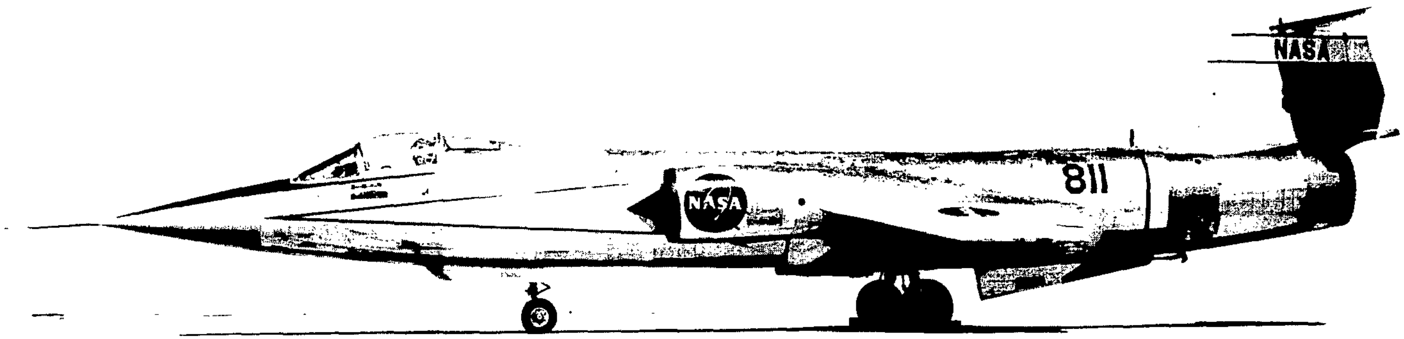



Figure 2.- Photograph of airplane of type used for tests.

E-13016

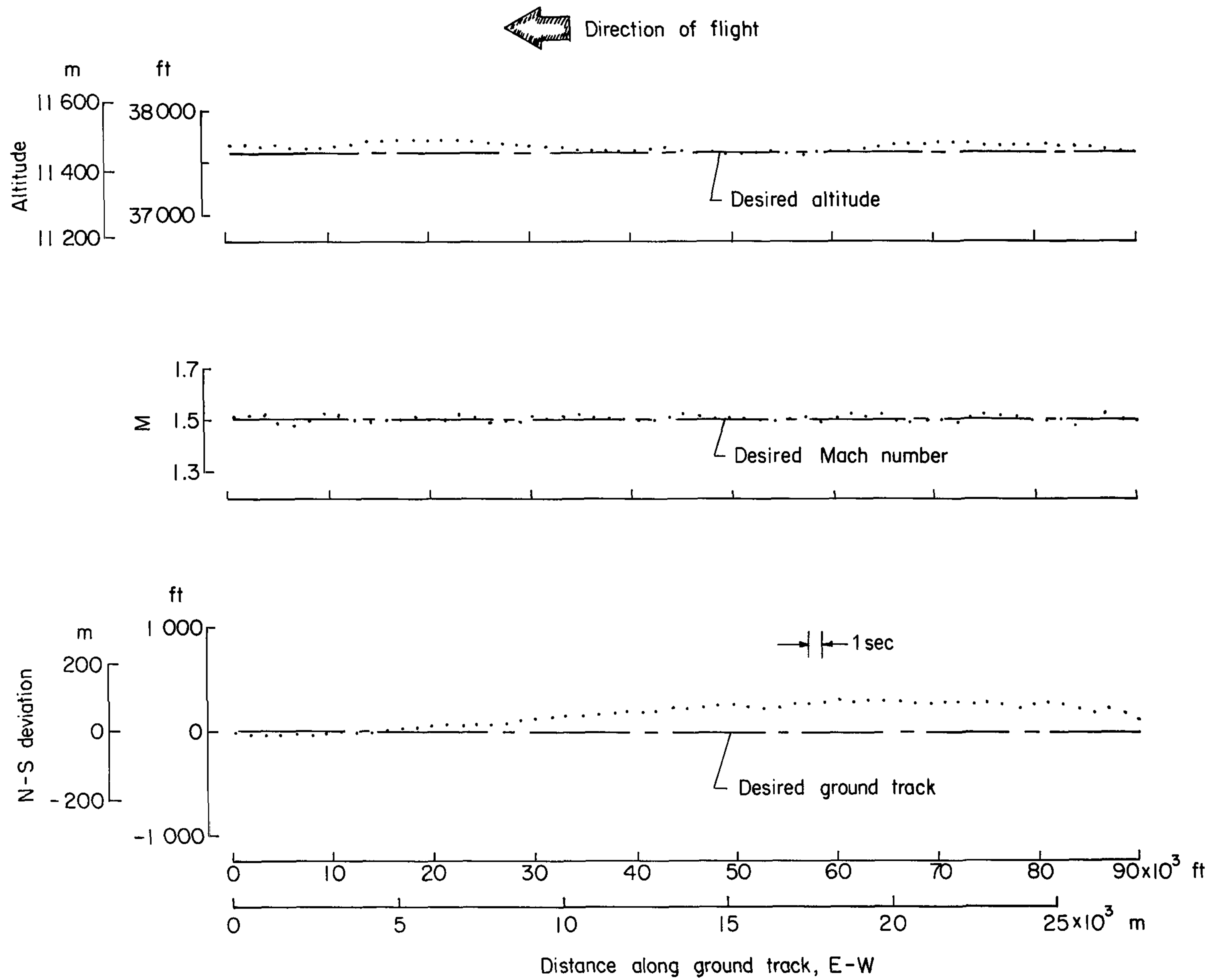



Figure 3.- Typical altitude, Mach number, and plan position of airplane from radar data. Flight 7.

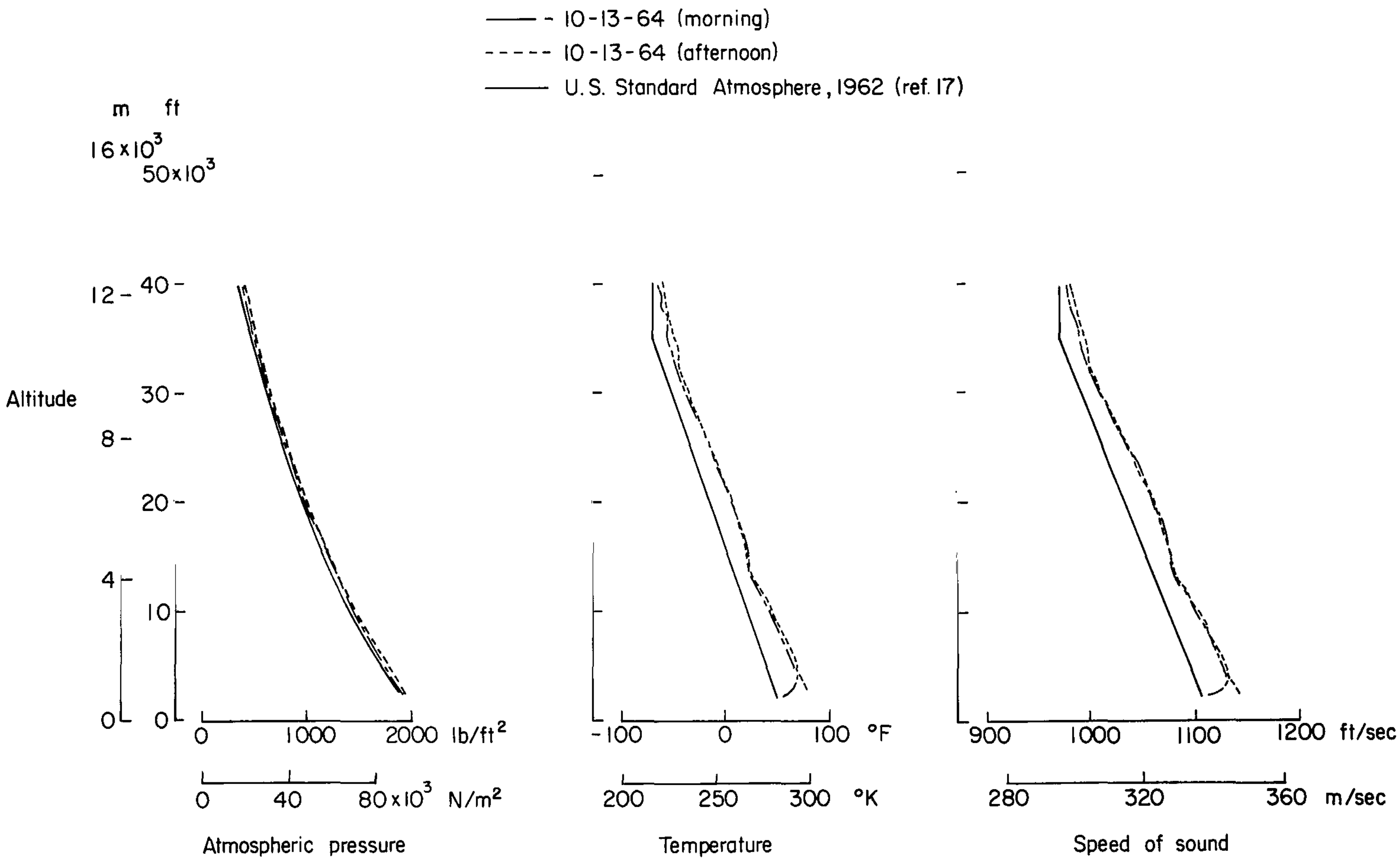



Figure 4.- Results from atmospheric soundings taken during test flights.

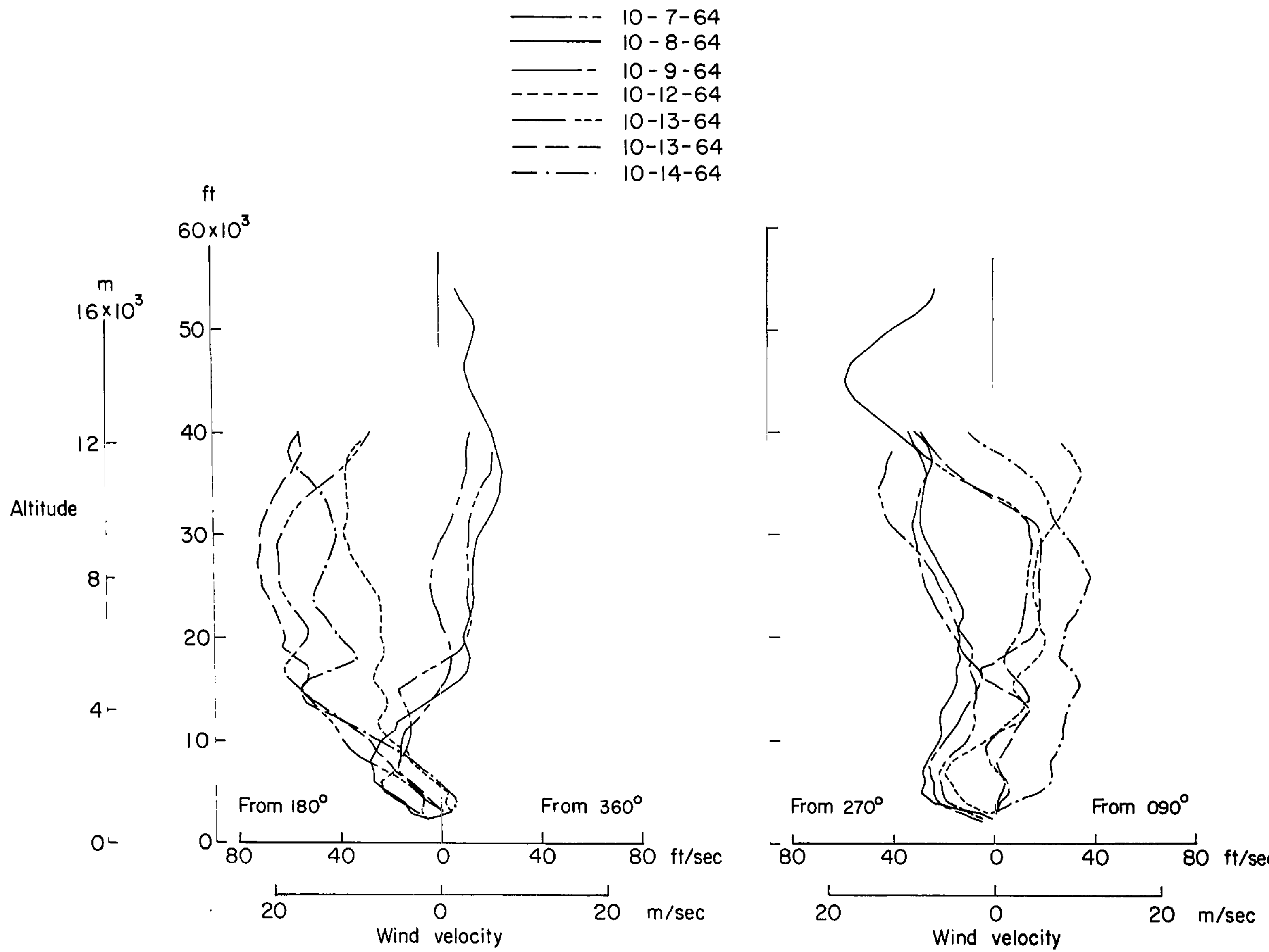



Figure 5.- Wind data obtained from atmospheric soundings taken during flight tests.

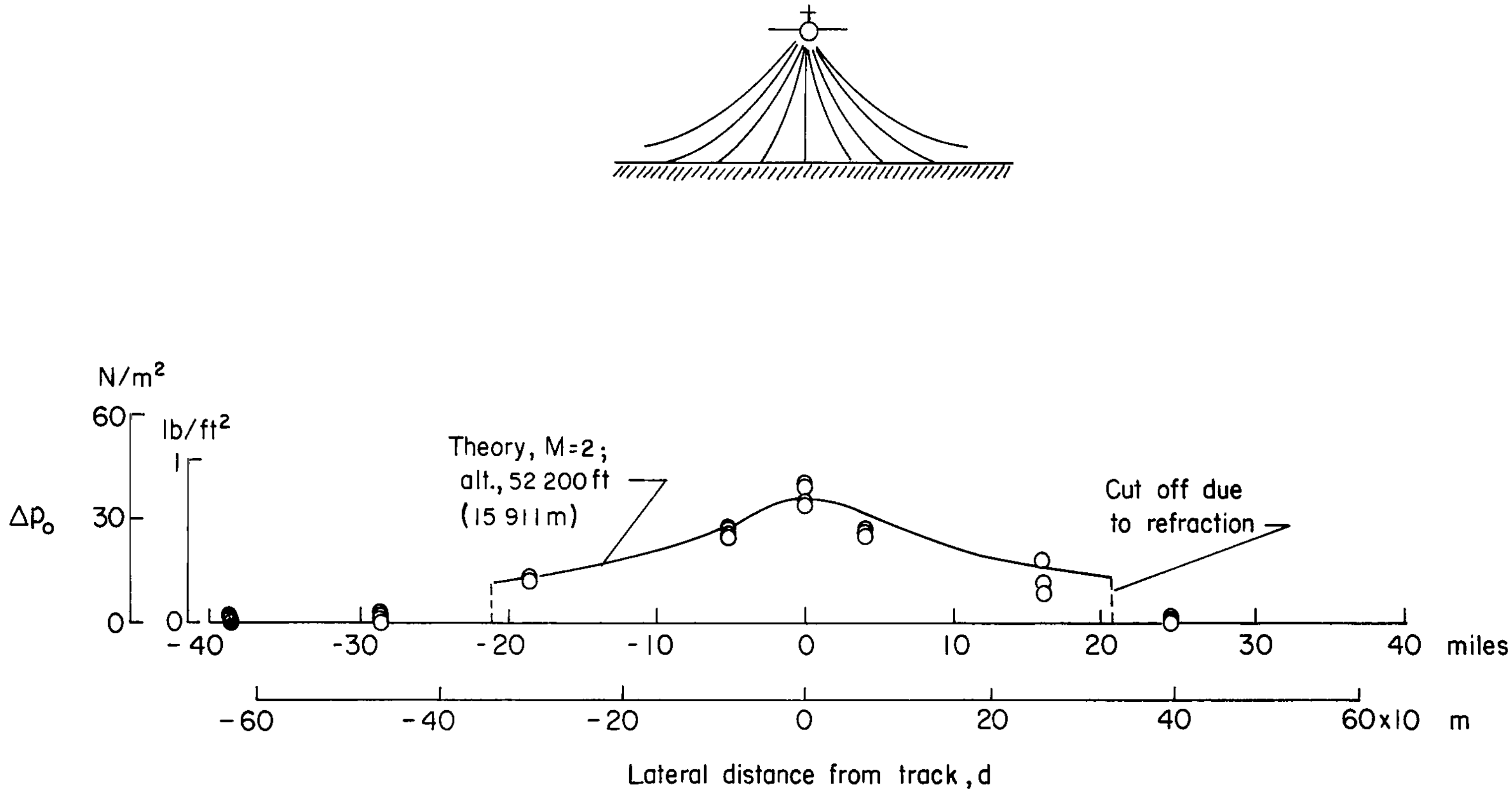
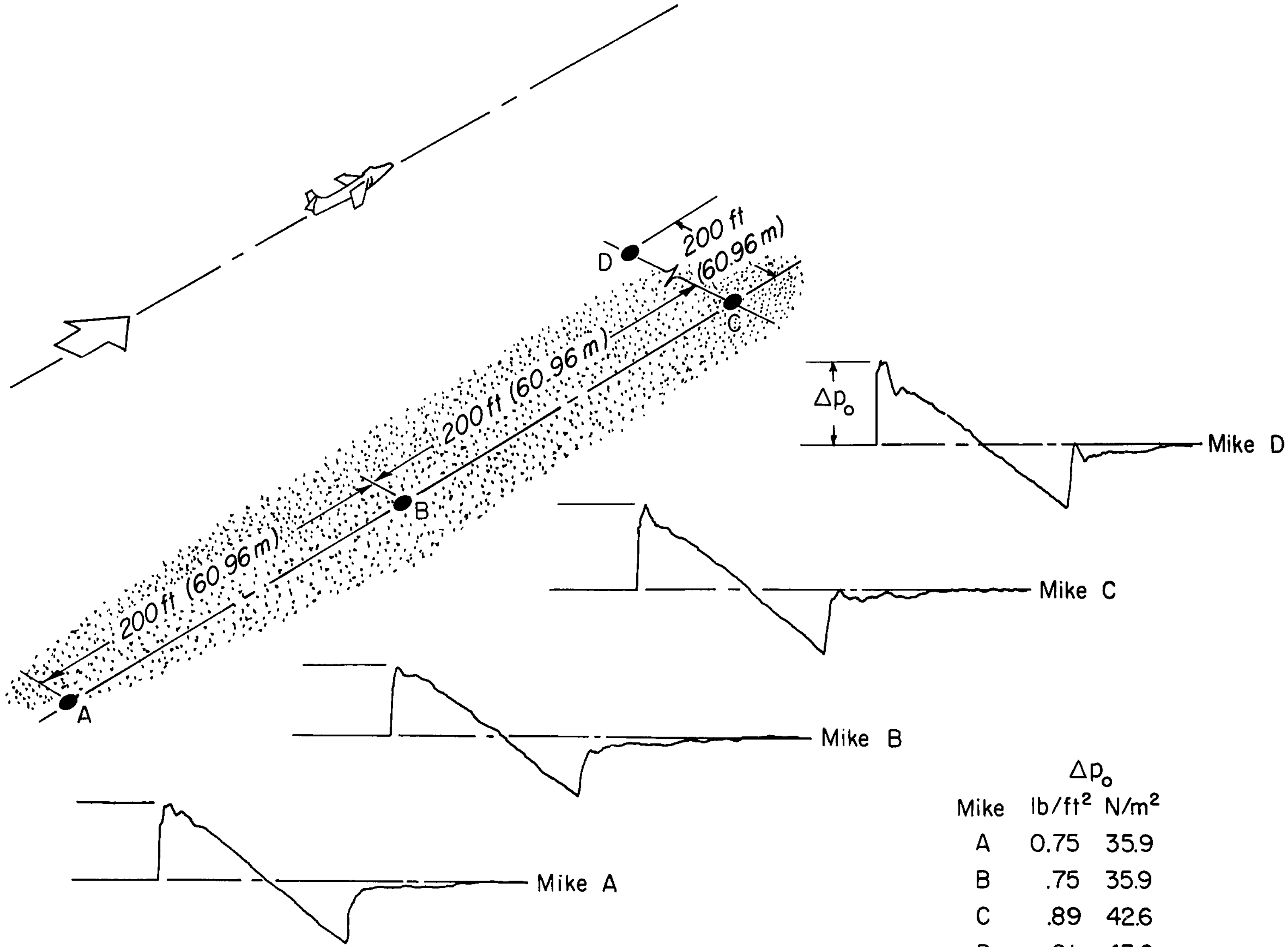
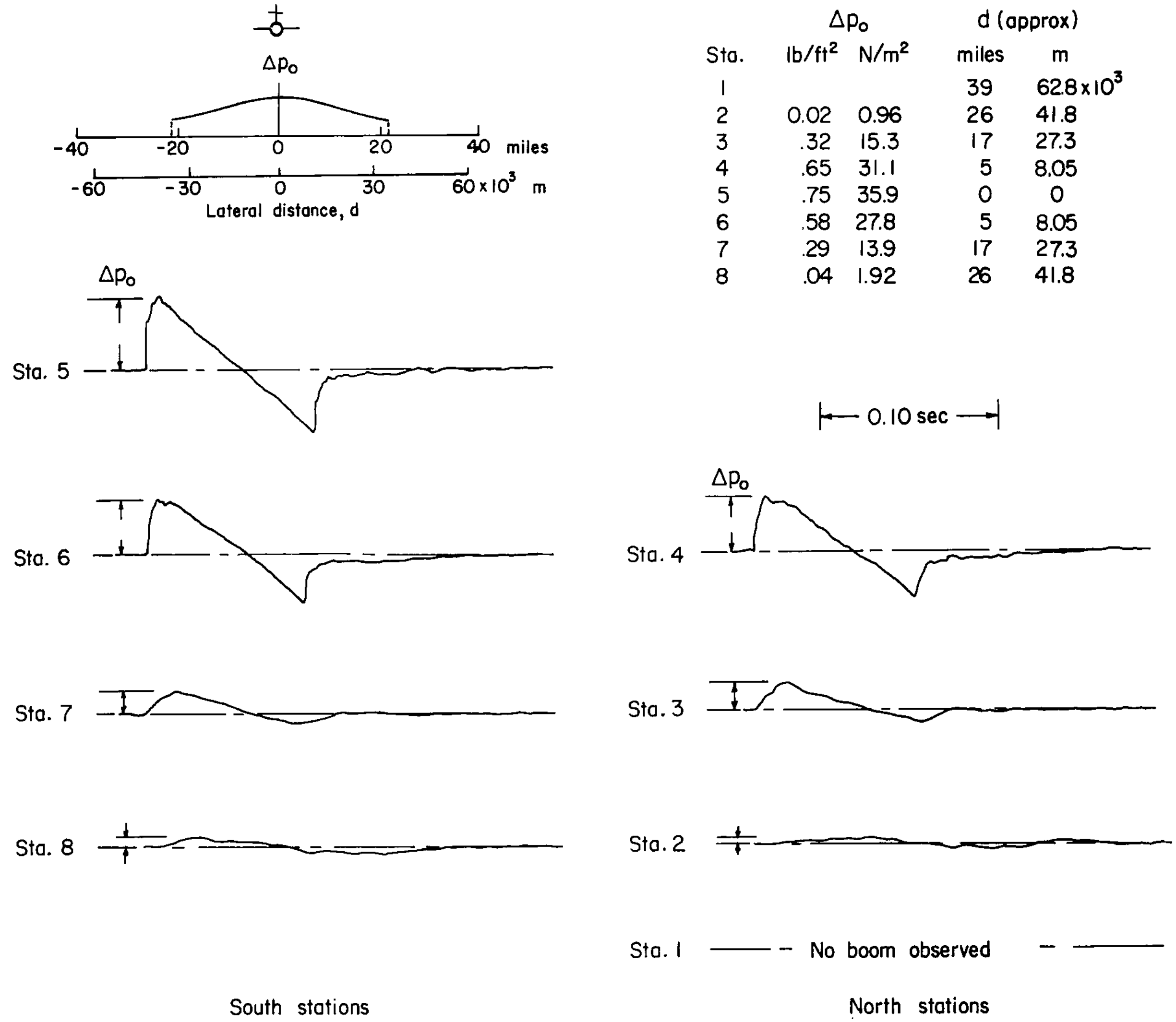



Figure 6.- Measured sonic-boom ground overpressures at several measuring stations at different distances to each side of the airplane ground track. Flight 3; solid symbols indicate no disturbance observed or measured.



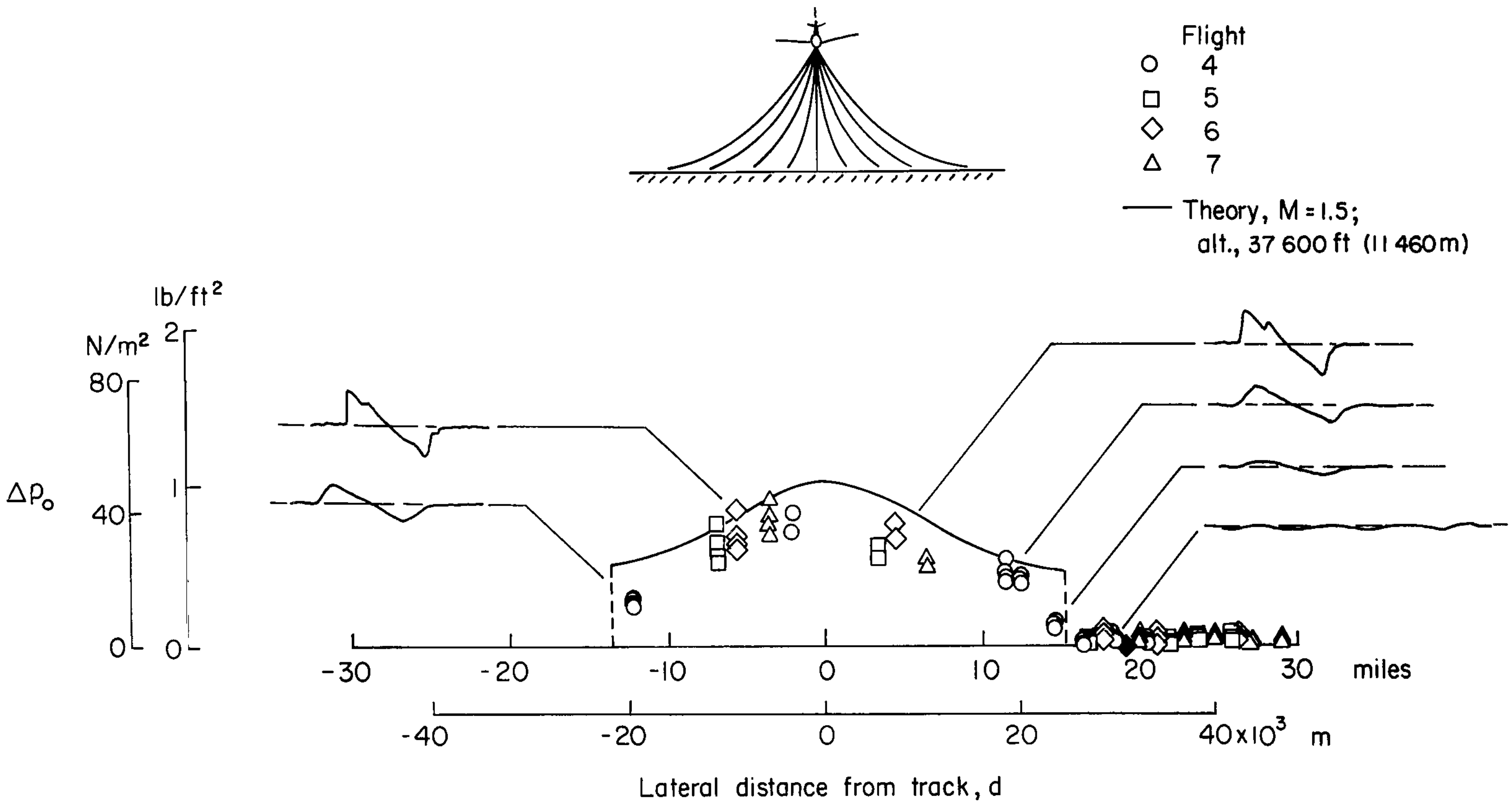

| Mike | $\Delta p_o$, lb/ft$^2$ | $\Delta p_o$, N/m$^2$ |
|---|---|---|
| A | 0.75 | 35.9 |
| B | .75 | 35.9 |
| C | .89 | 42.6 |
| D | .91 | 43.6 |

Figure 7.- Measured sonic-boom pressure signatures at several points along the ground track of a fighter airplane in steady-level flight at 52 200 ft (15 911 m) and M = 2.00. Station 5 of flight 3.



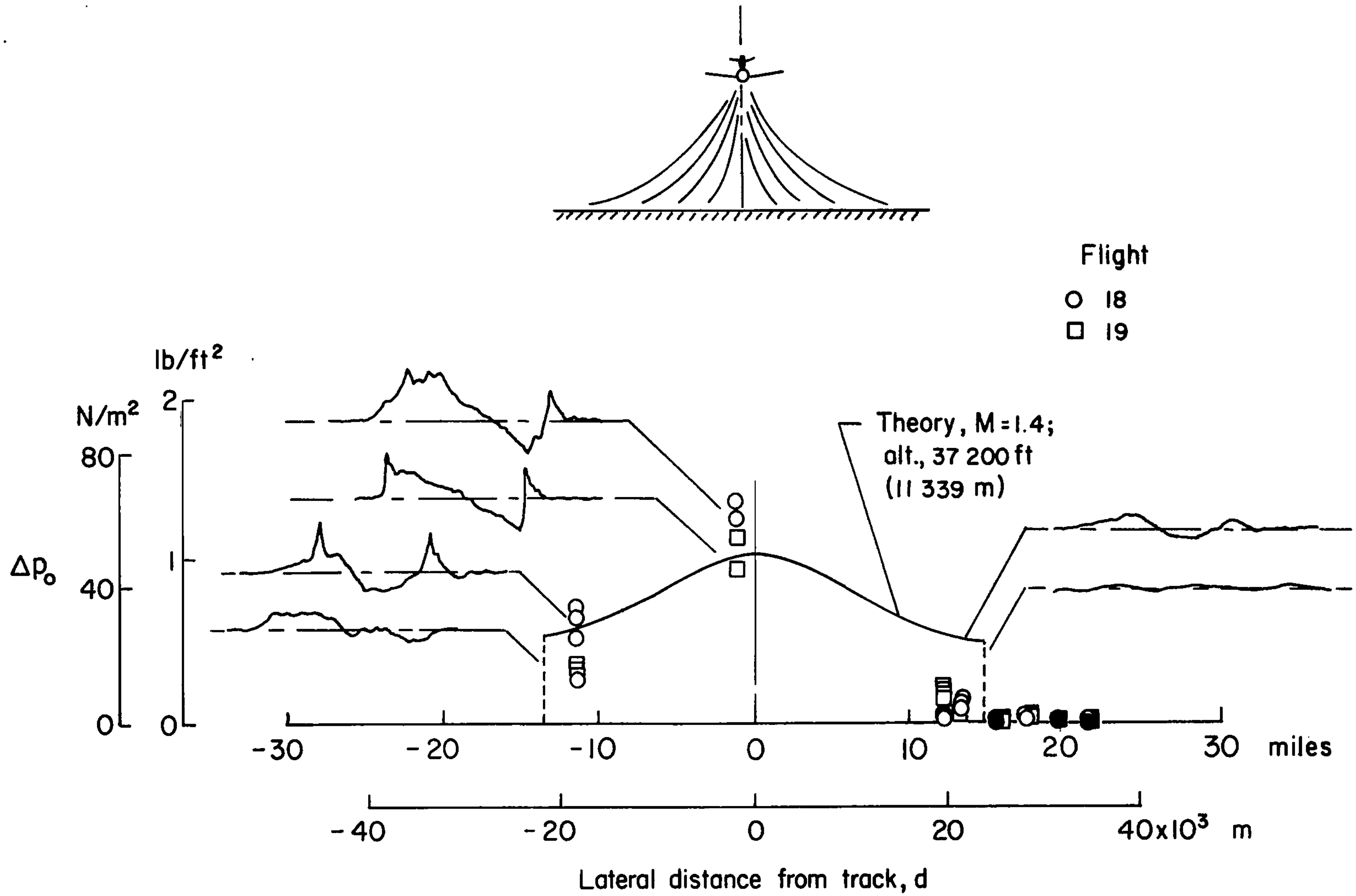

| Sta. | $\Delta p_o$ lb/ft$^2$ | $\Delta p_o$ N/m$^2$ | d (approx) miles | d (approx) m |
|---|---|---|---|---|
| 1 | | | 39 | $62.8 \times 10^3$ |
| 2 | 0.02 | 0.96 | 26 | 41.8 |
| 3 | .32 | 15.3 | 17 | 27.3 |
| 4 | .65 | 31.1 | 5 | 8.05 |
| 5 | .75 | 35.9 | 0 | 0 |
| 6 | .58 | 27.8 | 5 | 8.05 |
| 7 | .29 | 13.9 | 17 | 27.3 |
| 8 | .04 | 1.92 | 26 | 41.8 |

Figure 8.- Measured sonic-boom ground-pressure signatures at several measuring stations at different distances to each side of the aircraft ground track. Airplane in steady-level flight at 52 200 ft (15 911 m) and M = 2.00; flight 3.




(a) Four flights at an altitude of approximately 37 600 ft (11 460 m) and M = 1.5; flights 4 to 7.

Figure 9.- Measured sonic-boom overpressures at ground level as a function of lateral distance for fighter airplanes in steady-level flight. Solid symbols indicate no disturbance observed or measured.




(b) Two flights at an altitude of approximately 37 200 ft (11 339 m) and $M \approx 1.4$; flights 18 and 19.

Figure 9.- Concluded.

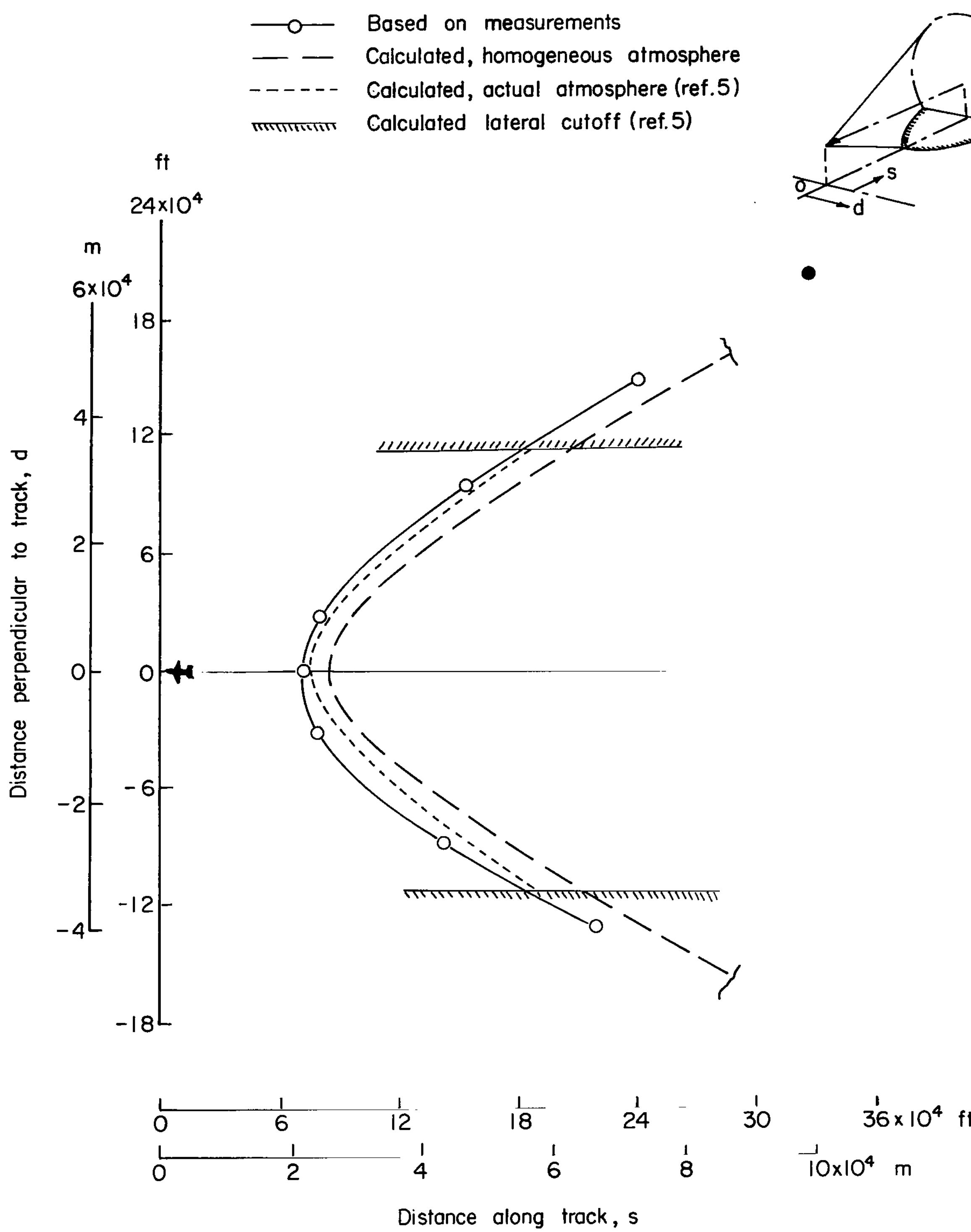



Figure 10.- Comparison of measured and calculated bow-shock wave ground intersection patterns for fighter airplane in steady-level flight at 52 200 ft (15 911 m) and M = 2.00. Flight 3; solid symbol indicates no disturbances observed or measured.

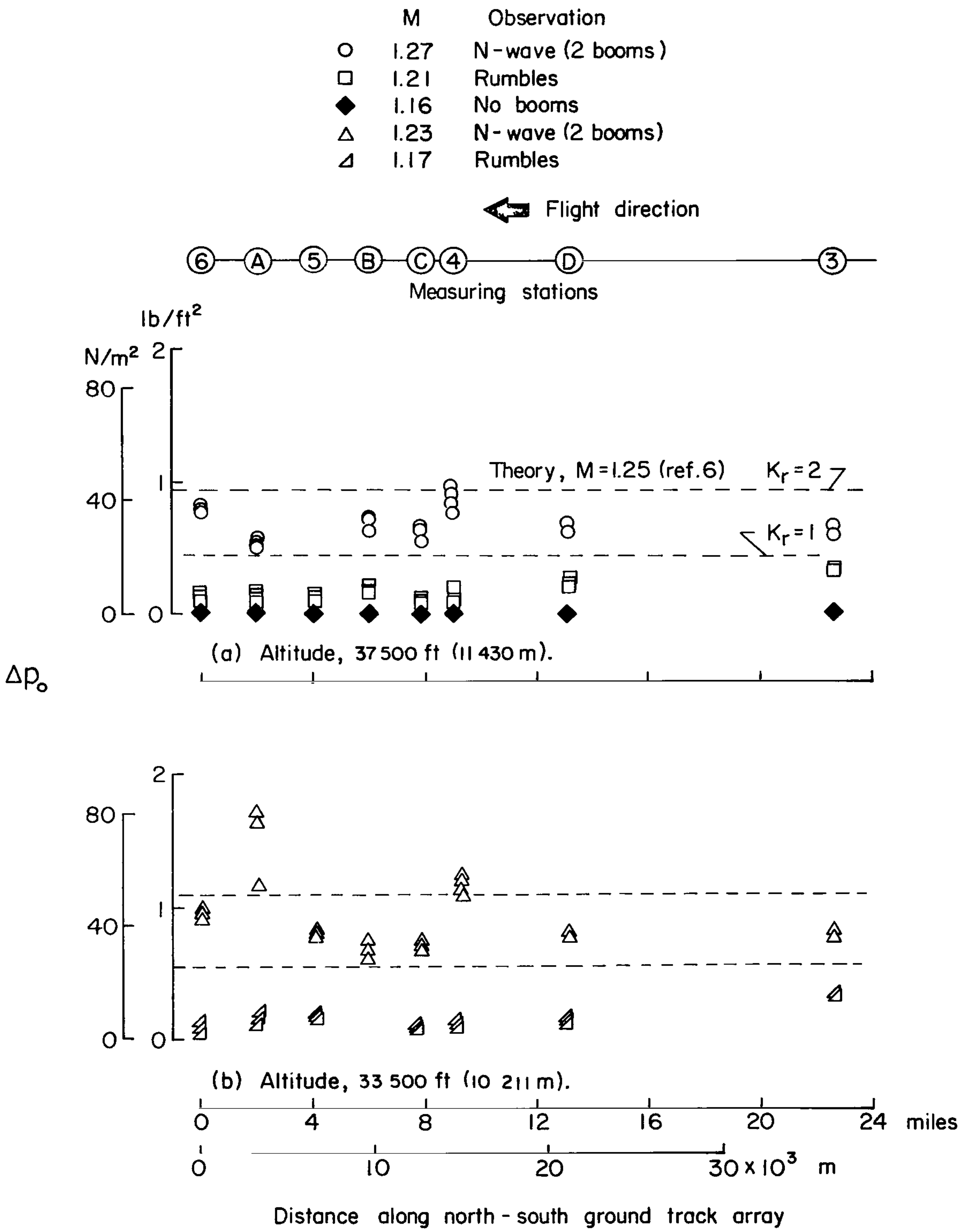



Figure 11.- Sonic-boom pressure measurements along the ground track of a fighter airplane in steady-level flight at various Mach numbers.

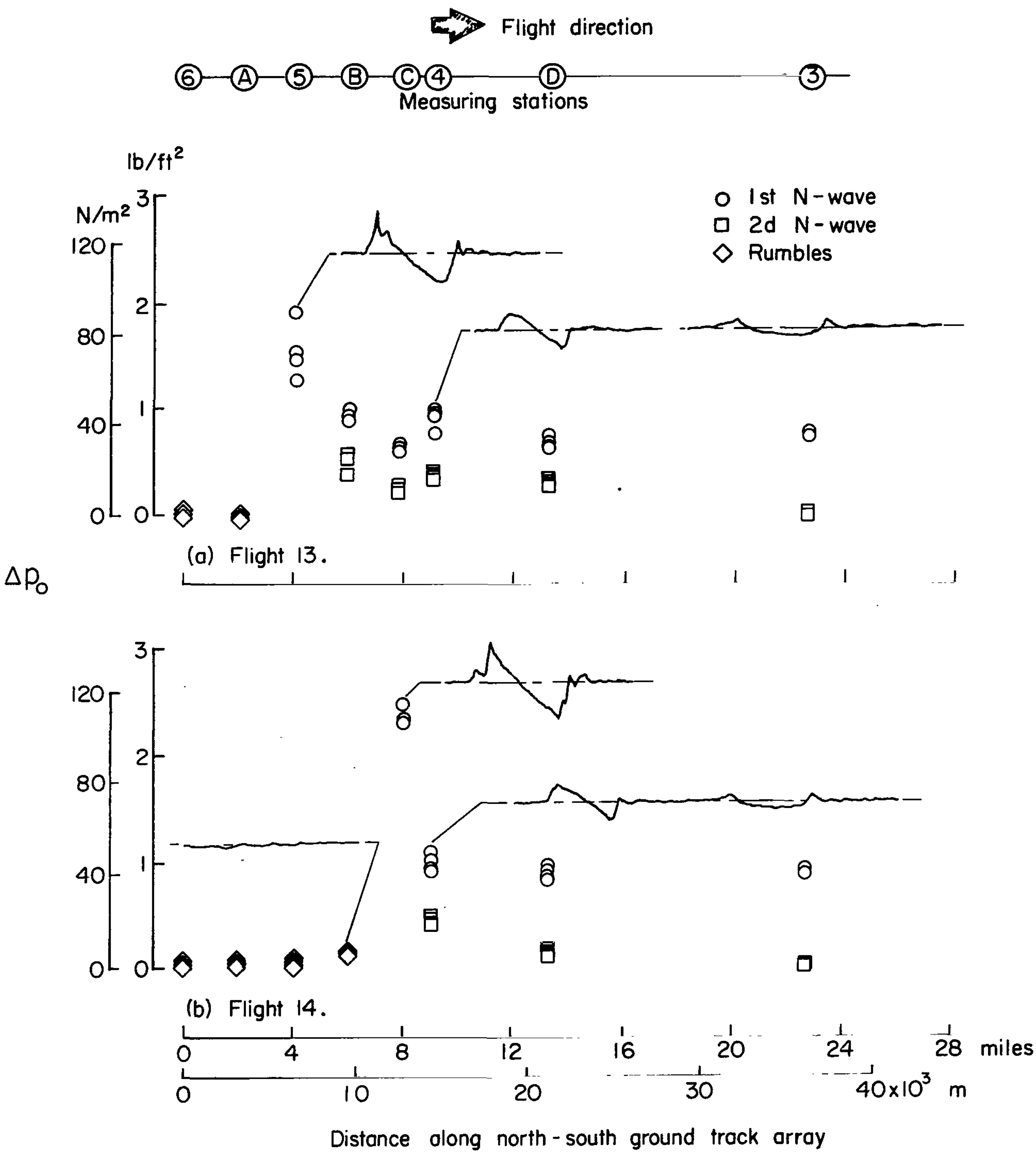



Figure 12.- Measured sonic-boom overpressures at various locations along the ground track of fighter airplane for five longitudinal acceleration passes at $M \approx 0.9$ to 1.5 at constant altitude of 37 200 ft (11 339 m).

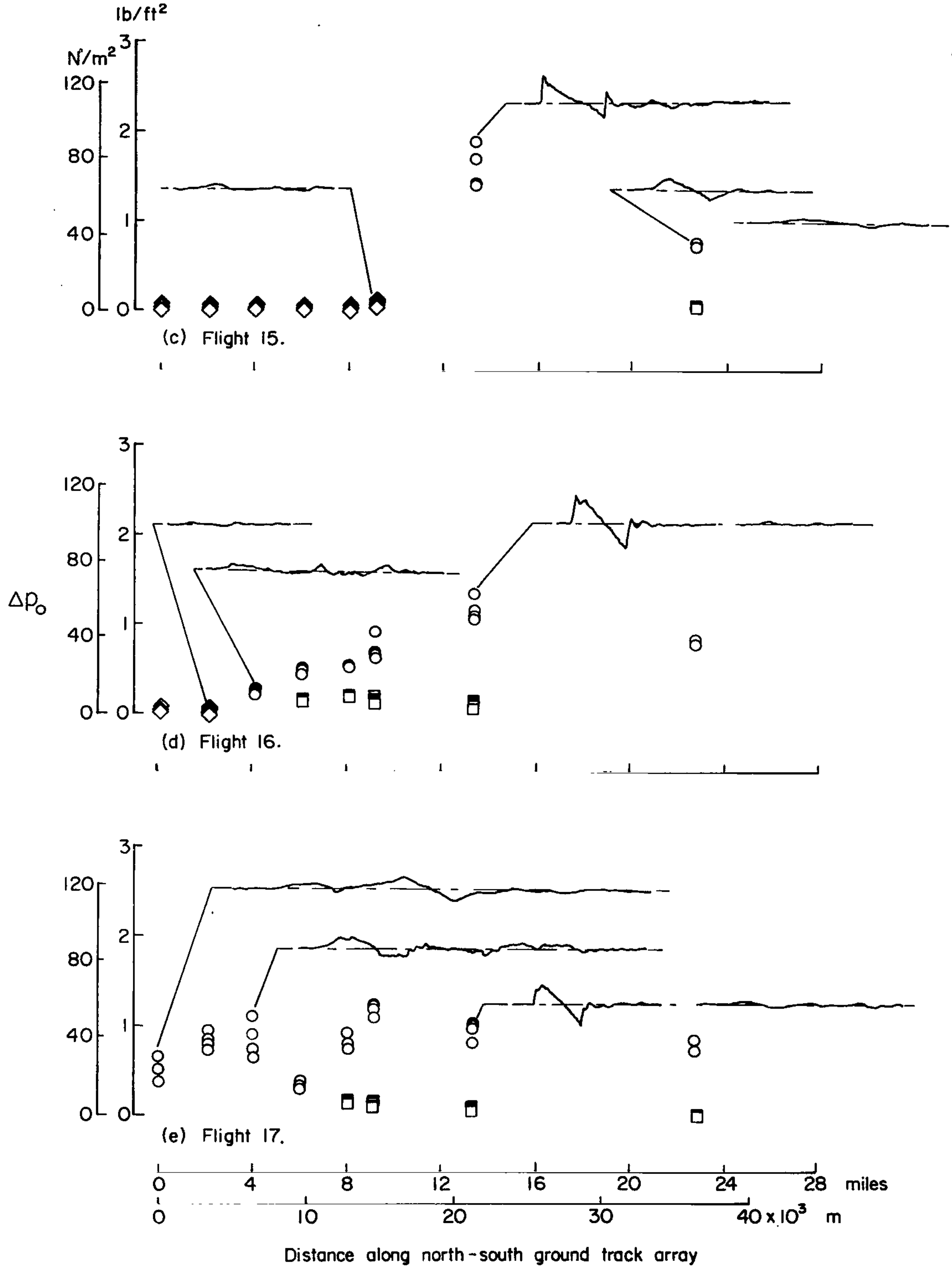



Figure 12.- Concluded.

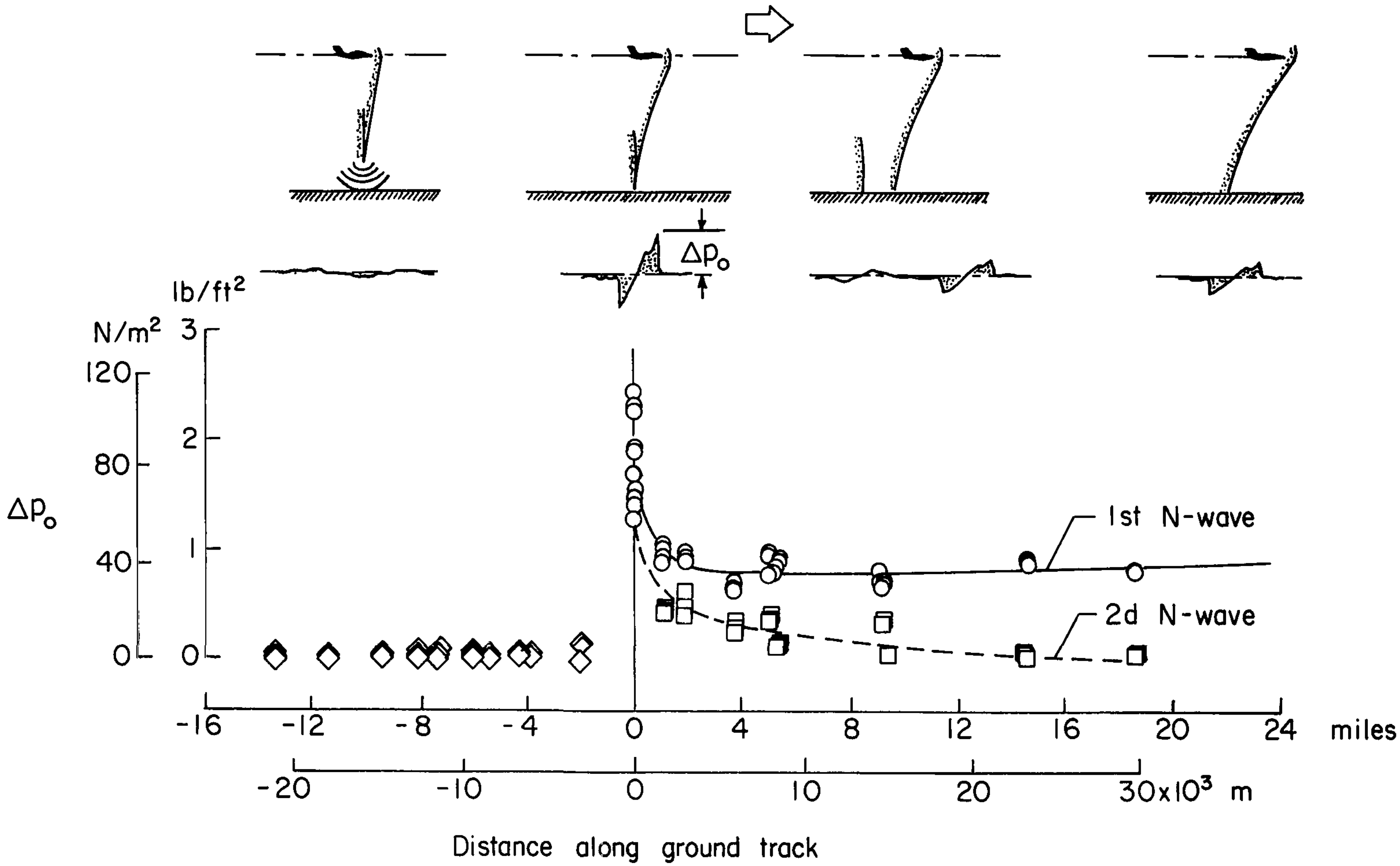



Figure 13.- Normalized plot of measured sonic-boom overpressures at various locations along the ground track of a fighter airplane for three longitudinal acceleration passes at $M \approx 0.9$ to 1.5 at constant alitude of 37 200 ft (11 339 m). Data of flights 13, 14, and 15 normalized to given position along ground track.

NASA-Langley, 1966 L-4567

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