Report No. 3947

Analysis of Recorded Sounds Relating to the Assassination of President John F. Kennedy

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Select Committee on Assassinations

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FOREWORD

On May 12, 1978, the House Select Committee on Assassinations asked Bolt Beranek and Newman Inc. (BBN) to conduct a preliminary review of the following material:

- Tape recordings reportedly made of the sounds in Dealey Plaza around 12:30 pm on November 22, 1963
- Transcripts of the testimony of earwitnesses who were in the Plaza at that same time.

The purpose of this review was to determine which, if any, of this material constituted potential evidence with respect to the gunfire associated with the assassination of President John F. Kennedy.

The review established that (1) only two of the recordings constituted potential evidence and (2) a statistical analysis of the earwitness testimony could reveal whether the concept of one rifle is consistent with these individual accounts.

The two tapes found to be made of the events surrounding the assassination were records from Channels 1 and 2 of the Dallas Police Department's (DPD) radio dispatching system. The Channel 1 tape contains a continuous record of the sounds transmitted between 12:28 and 12:34 pm over a DPD motorcycle radio stationed in Dealey Plaza. The Channel 2 tape is an intermittent recording of additional radio traffic – in particular, communications between the Chief of the Dallas Police Department, who occupied the car immediately preceding the Presidential limousine in the motorcade, and the Channel 2 Dispatcher at DPD headquarters.

An initial analysis of a portion of the Channel 1 tape did not rule out the possibility that the recording contained the sounds of gunfire. The House Committee therefore authorized BBN to conduct studies both of the DPD tapes and of the earwitness testimony. This report describes the results of an analysis of the tapes. The study of earwitness testimony is reported under separate cover.*

*Green, D.M., "Analysis of Earwitness Reports Relating to the Assassination of President John F. Kennedy," BBN Rep. 4034, January 1979.

ACKNOWLEDGMENT

The authors gratefully acknowledge the fine contributions made to this study by Joseph F. Colaruotolo, Daniel N. Kalikow, Nancy M. McMahon, Theodore L. Rhyne, and Leo A. Sledjeski.

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1. INTRODUCTION AND SUMMARY

The House Select Committee on Assassinations authorized Bolt Beranek and Newman Inc. (BBN) to study two tape recordings made by the Dallas Police Department (DPD) on November 22, 1963 on Channels 1 and 2 of the DPD's radio dispatching system. Channel 1 is the channel ordinarily used to handle DPD radio traffic, and this channel is recorded continuously on a Dictabelt recorder. Channel 2, an auxiliary channel generally used to handle the additional radio traffic necessitated by special events, is recorded intermittently on a Gray Audograph recorder, as actuated by voice communications and time annotation. Frequent time annotations – usually at 1-minute intervals – are made by the radio dispatchers handling each of these channels.

On November 22, 1963, during the time of President Kennedy's assassination, the radio of a DPD motorcycle, which may have been in the motorcade, was stuck in the transmitting mode on Channel 1 for approximately 5 minutes. During this time, the Chief of the Dallas Police Department, whose car immediately preceded the President's limousine in the motorcade, transmitted several messages concerning the progress of the motorcade over Channel 2. Channel 2 had been designated for use by DPD officers in the motorcade on November 22, 1963. Therefore, if the Channel 1 recording were to contain sounds of gunfire associated with the assassination, then at least one of the motorcycle radios used in the motorcade must have been incorrectly switched to Channel 1. Voice transmissions on both tapes were monitored for the call numbers of the 18 motorcycle officers in the motorcade. Six of the officers were heard to transmit on Channel 2; three on Channel 1.* The other nine did not make any transmissions, so it cannot be determined which channel their radios were set for.

*These three transmissions were made at about 2:10 pm, 4:39 pm, and 5:22 pm, all later times than the assassination.

1.1 Initial Analysis

The questions to be addressed in the analysis of these tapes were:

- Does the 5-minute segment recorded on Channel 1 contain the sound of gunfire?
- If so, how many shots were recorded and from what location (or locations) did the shots originate?

To begin with, if gunfire had been recorded on Channel 1, the analysis of that tape could be expected to reveal patterns of transient waveforms that would be generally characteristic of the shock wave produced by the bullet, of the loud and impulsive noise of the muzzle blast, and of echoes of each. It could further be expected that the major components of the shock wave would appear in the 1-kHz to 3.2-kHz frequency band.

The initial analysis of the Channel 1 tape therefore consisted of filtering and recording the entire 5-minute segment through each of two filters designed to reveal the presence of any transient impulsive waveform patterns that might be masked by the repetitive loud noise of the motorcycle. The first was a bandpass filter that filtered out all sounds not contained within the frequency range extending from 1 kHz to 3.2 kHz. This range was known to contain the principal frequency components of the shock wave produced by the bullet and to contain relatively few components of motorcycle noise. The second filter was an adaptive Widrow LMS filter, which studies the repetitive nature of noise, estimates what it will be a short time later, and subtracts these noise components out, leaving transient events not anticipated by the filter.

The recorded outputs from both filters for the full 5 minutes were compared, examined, and plotted on a scale where 5 in. equals 1/10 sec. These plots revealed five impulse patterns introduced by a source other than the motorcycle. Upon closer examination, all but one of these patterns were sufficiently similar to have had the same source, and the impulses contained in these patterns appeared to have shapes similar to the expected characteristics of a shock wave and of a muzzle blast. The remaining pattern was sufficiently different in amplitude and duration as to have been caused by a different source.

The hypothesis to be tested, then, was that these four impulse patterns were caused by gunfire. Initially, this hypothesis was subjected to five simple, but necessary, screening tests:

1. Time of occurrence
2. Uniqueness of patterns
3. Time span between patterns
4. Shape of impulses within the patterns
5. Amplitude of impulses.

Should the hypothesis then pass these tests, a sixth, more rigorous, test would be applied. This final test would require an acoustical reconstruction of the circumstances of the original gunfire in Dealey Plaza to reveal the relative times that muzzle blast and shock wave impulses, together with their echoes, would arrive at microphones located where the motorcycle radio might have been.

1.2 Screening Tests

The five screening tests were designed to determine whether the characteristics of the four impulse patterns corresponded both to other evidence and to the characteristics of actual gunfire.

1. *Did the impulse patterns occur at the same time the shots were actually fired? Yes.*

Stopwatch timing and examination of both tapes placed the time of the shot and the time of onset of the first pattern of waveforms within 35 sec of each other. The margin of acceptable time difference was 60 sec, since the two time clocks used by the two dispatchers were synchronized to within just 1 minute.

2. *Were these impulse patterns unique? Yes.*

Examination of the entire 5-minute segment did not reveal sufficiently similar impulse patterns elsewhere on the tape to discount gunfire as the source of these four patterns.

3. *Did the time span between the patterns correspond to other evidence of intervals between shots? Yes.*

The intervals between the onset times of the four impulse patterns on the DPD tape with the frames on the Zapruder film showing bullet impact were compared. According to the Zapruder film, the time span between the earliest and the latest gunfire-like events recorded on Channel 1 had to be no less than 5.6 sec. The span between onset times of the first and the fourth patterns was 8.3 sec.

4. *Did the shape of the impulse patterns resemble those generated by actual rifle fire? Yes.*

Tape recordings of test shots made with a Mannlicher-Carcano rifle were put through electrical circuits that mimicked those through which the 5-minute segment had been recorded. The shape of the impulse patterns on the Channel 1 tape approximates those produced by the test shots.

5. *Did the range of amplitude (loudness) of the impulse patterns resemble that of the echo patterns produced by the test shots? Yes.*

Processing the echo patterns of the test shots through a radio receiver like that used in the DPD recording system showed similar compression of the range of amplitude of recorded signals with respect to the range of the signals fed into the receiver.

The answers to these five questions neither proved nor disproved the possibility that the four impulse patterns on the Channel 1 tape had been caused by gunfire. A more rigorous analysis was required to determine with some confidence whether or not these patterns had been caused by gunfire.

1.3 Further Analysis

The gunfire and the potential motorcycle radio positions on November 22, 1963 were acoustically reconstructed on August 20, 1978 in Dealey Plaza. The sounds were subsequently processed into echo patterns, each one representing the unique "fingerprint" of gunfire sounds as heard at one location when a weapon is fired from one place to one target. The Channel 1 recording made at the time of the assassination had been similarly processed into sound impulse patterns. However, the

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Channel 1 impulse patterns were like badly smudged "fingerprints," because of the extremely noisy environment in which the original recording had been made.

The echo patterns were compared to the impulse patterns to see if any of the clear "fingerprints" obtained during the reconstruction matched any of the smudged "fingerprints" on the Channel 1 recording. The matching process was a binary correlation detector – a simple but powerful signal-detection scheme that is conducted mathematically.

Several echo patterns from the acoustical reconstruction matched sufficiently well with the four impulse patterns that we were able to place the motorcycle behind the Presidential limousine, at distances varying from 120 ft to 160 ft.

The correlation detector indicated that four shots may have been fired, as follows:

1. time 0.0 sec – one shot from the Texas School Book Depository (TSBD) aimed between the limousine positions seen in frames 160 and 313 of the Zapruder film
2. time 1.6 sec – one shot from the TSBD aimed near the limousine position seen in frame 313
3. time 7.8 sec – one shot from behind the fence on the knoll aimed near the limousine position seen in frame 313
4. time 8.3 sec – one shot from the TSBD aimed between the limousine position seen in frame 313 and the triple underpass.

1.4 Conclusions Based on Results of the Acoustical Reconstruction

The conclusions drawn from the results of the matches obtained by our analysis were presented at the public hearing before the committee on September 11, 1978. Essentially, we had concluded that the motorcycle had indeed been in the motorcade and that possibly four shots had been fired at President Kennedy. The reason that our findings with respect to the four shots were stated in terms of probabilities is as follows.

The correlation detector produced several false alarms that could be identified as such. These false alarms are spurious matches caused by uncertainty of the exact motorcycle position with respect to the known positions of microphones used in the reconstruction test. Therefore, some of the correlations that indicated the four shots must also be suspected as false alarms. This uncertainty introduced by the suspected false alarms can be expressed as a set of probabilities on the possible true outcomes. These probabilities were calculated from the judgment that each match has a 50% probability of being a false alarm and from the assumption that each match is an independent observation. Thus, the individual probabilities that the shots occurred at each of the four times are:

Shot 1. 88% based on three matches

Shot 2. 88% based on three matches

Shot 3. 50% based on one match

Shot 4. 75% based on two matches.

The probability that the four possible shots found by the correlation detector include at least two correct detections is high, about 96%. The probability that there are three correct detections is lower, about 75%. The probability that all four are correct is only about 29%. The combined probability that there are three correct detections, and that the third (knoll) shot is among them is about 47%.

1.5 Independent Analytical Extension of the Reconstruction Test

The Committee sought to have the uncertainty in the test results reduced, particularly with respect to the 50% probability of the third (knoll) shot. Professor Mark Weiss and Mr. Ernest Aschkenasy of Queens College were authorized by the Committee to conduct an analytical extension of our acoustical reconstruction test. They first identified the objects in Dealey Plaza that caused each echo that appeared in the echo pattern we had found to indicate the possible third (knoll) shot. Next, they calculated how this echo pattern would be modified for receivers in the neighborhood of the microphone from which the echo pattern was obtained. Finally, they were able to show that 10 echoes of 12 in one of their calculated echo patterns matched with 10 sound impulses of 14 on the DPD tape recording — each one to an accuracy of $\pm$ 1 ms. The first of the 10 matching impulses was found to occur 7.6 sec after the first impulse indicating the first shot.

We examined the results of this independent study and judged both the technique and the parameters they used to be correct in every detail. We further concluded that the odds were only about 1 in 20 that their very precise match could have been achieved by chance — i.e., if the 14 sound impulses on the DPD tape were all noise and did not include echoes from a knoll gunshot. For this reason, we conclude that there is a 95% probability that there was a gunshot fired from the knoll at about 7.6 sec after the first one.

1.6 Findings

The results of our analysis of the tape-recorded evidence, together with the independent analysis of the echo-pattern match with the third (knoll) shot, permit the following findings:

1. The recorded sounds on Channel 1 of the Dallas Police radio dispatch system probably include the sounds of four gunshots fired in Dealey Plaza at about 12:30 pm on November 22, 1963.

2. The recorded gunshot sounds were sensed and transmitted by a police radio mounted on a motorcycle in the motorcade and positioned at distances ranging from 120 ft to 160 ft behind the Presidential limousine.

3. The first probable shot was fired at about 12:30:47 from the TSBD. The motorcycle position was then on Houston St. having only about 3 sec earlier slowed in preparation for the left turn onto Elm St. No shock wave indicating a supersonic projectile is seen as a precursor to the sounds of the muzzle blast, and none is expected, owing to the position of the motorcycle with respect to the expected trajectory of the bullet. Therefore, no conclusion can be drawn about whether this first acoustic disturbance was due to a rifle or to a sound impulse as loud as the report of a rifle. However, the sound did originate in the vicinity of the sixth floor of the TSBD.

4. The second probable shot was fired about 1.6 sec after the first one, also from the TSBD. At this time the motorcycle was just at the corner of Houston and Elm. Again, no shock wave is seen as a precursor to the sounds of the muzzle, and, again, none is expected.

5. The third probable shot was fired about 7.6 sec* after the first one, and it was fired from behind the fence upon the "grassy knoll." At this time, the motorcycle was proceeding westward on Elm St. about 80 ft west of the intersection with Houston St. An apparent shock wave is seen as a precursor to the sounds of the muzzle blast. Inasmuch as a supersonic projectile would show such a precursor when the motorcycle is in this position, the third shot is probably from a rifle.

6. The fourth probable shot was fired about 8.3 sec after the first one, and it was fired from the TSBD. The motorcycle was on Elm St. about 90 ft west of the intersection with Houston St. An apparent shock wave is seen as a precursor to the sounds of the muzzle blast. Since the trajectory of the bullet would have been over the motorcycle, such a precursor would be expected for a rifle shot. Therefore, the fourth shot is probably from a rifle.

7. Additional police radio transmissions are intermittently recorded on the tape during and after the last two probable shots. These transmissions contribute a few electrical impulses to the noise background in which the impulses of gunfire are set. However, these noise impulses are too few in number to have a material effect on the accuracy by which the echo patterns of the acoustical reconstruction match the impulse patterns on the DPD tape.

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*This time was obtained from the independent study of Weiss and Aschkenasy, and it differs by about 0.2 sec from the time obtained by our correlation detector.

These findings were presented at public hearing before the Committee on December 29, 1978. At that hearing, Officer H.B. McLain of the DPD testified that he had been riding his motorcycle on the left-hand side of Houston St., approaching Elm St. when he heard a single shot. After the hearing, he said that he remembered that he had turned on his siren shortly after the assassination and moved with the motorcade to the hospital. However, the appearance of McLain in photographs taken in Dealey Plaza just after the assassination suggests he did not leave the area with the motorcade. Unless McLain turned on his own siren, the absence of the siren sound on the tape is consistent with McLain's behavior as documented in photographs and it may have been his motorcycle.

Section 2 of this report describes the acoustical nature of gunfire — i.e., what could be expected after appropriate filtering of the Channel 1 tape, if it did indeed contain the sound of gunfire. Section 3 reports the procedures used to process the tape and the results of this processing. Section 4 describes the five screening tests, and Sec. 5 reports the results of the acoustical reconstruction of gunfire in Dealey Plaza. Section 6 discusses additional relevant sounds on the Channel 1 recording. Finally, Sec. 7 describes our review of an independent analysis of the match between our acoustical reconstruction and the sounds of the probable third shot.

2. NATURE OF RADIO-TRANSMITTED SOUNDS OF GUNFIRE

2.1 Overview

The discharge of a rifle creates two sources of impulsive sound – the sound of the muzzle blast and the sound of the shock wave shed from the supersonic bullet as it travels at a speed greater than the speed of sound. Figure 1 illustrates the difference in how these two impulsive sounds travel through the air. The shock wave, for example, has a direct path of travel that resembles a cone, while the sound of the muzzle blast spreads spherically from the source.

In addition to traveling at different speeds and in different ways, these impulsive sounds travel over several different paths before arriving at a receiver – in this case, a microphone. Figure 2 illustrates these paths. The first sound impulses to arrive travel in a straight line from the source to the microphone; this sound path is called the direct (D) path. It includes reflections (D_2) from impulses traveling the direct path and striking the ground very near the microphone. Later sound impulses arrive at the microphone after first reflecting from large surfaces, such as building facades and the ground; these sound paths are called reflected (R) paths. Even later sound impulses arrive at the microphone after first diffracting from the corners of buildings and the edges of other large objects; these sound paths are called diffracted (T, M, L) paths. A weaker set of sound impulses, arriving at the microphone just after the direct arrival, are scattered first by small objects such as poles, people, and automobiles. After striking these scattering objects, these weaker sound impulses arrive at the microphone over the scattered (S, P) paths. Finally, reflections

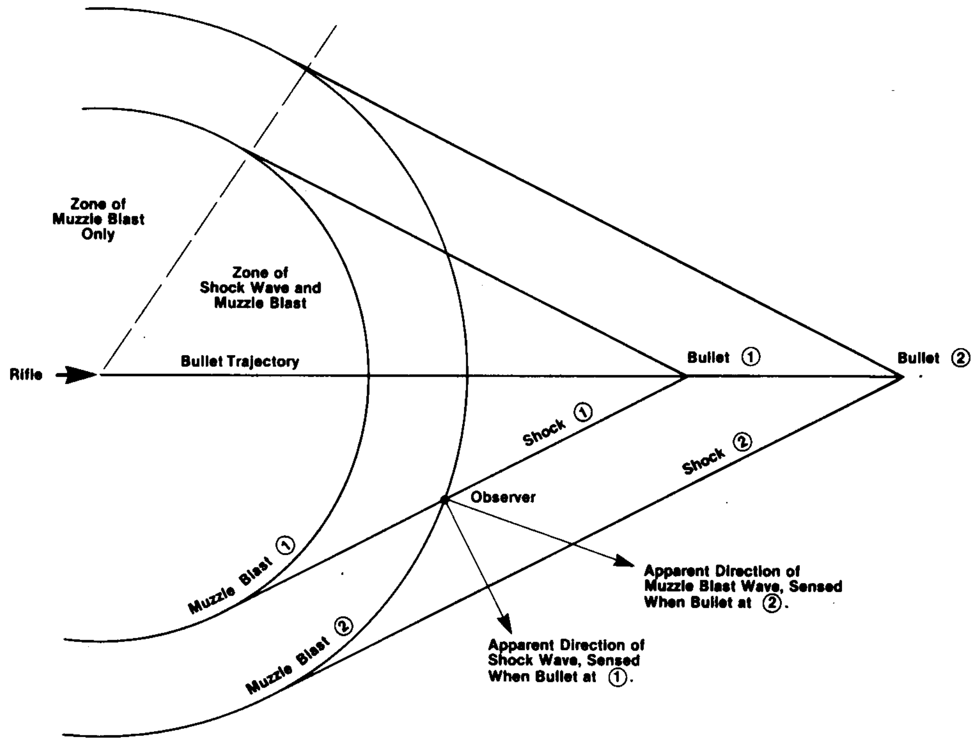


FIG. 1. LOCI OF MUZZLE BLAST AND SHOCK WAVES AT TWO TIMES AFTER FIRING OF BULLET.

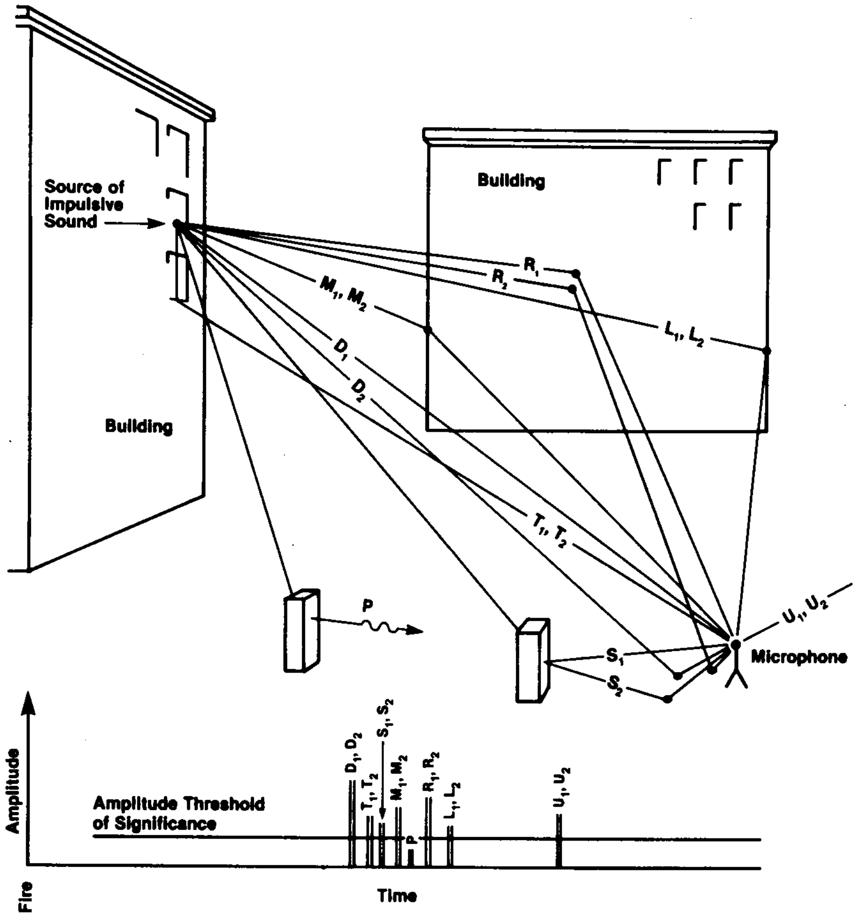


FIG. 2. ECHO PATTERNS CAUSED BY DIRECT, REFLECTED, DIFFRACTED, AND SCATTERED IMPULSIVE SOUNDS IN AN URBAN ENVIRONMENT.

from distant objects (U) arrive over various reflected paths, but these signals appear much later than those arriving by all the previously described paths.

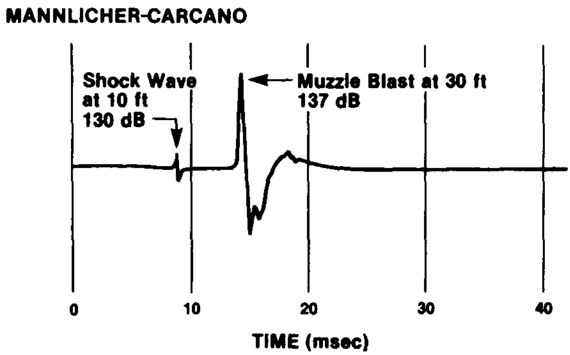
All sound impulses arriving at the microphone that are loud enough to be heard over the environmental noise would be transmitted over the radio connected to the microphone. In this case, the environmental noise consisted primarily of the very loud, repetitive noise made by the engine of a moving motorcycle. This noise was found to be only about 10 dB lower than the loudest gunfire impulse recorded. Thus, only the very loudest gunfire sound impulses would actually be detectable above the engine noise.

The loudest sound impulses from gunfire are considerably louder than the loudness of speech, for which the radio was designed to operate. These loud impulses overdrive the radio circuitry. Because of the limiting circuits in the radio transmitter, very loud sounds are recorded in distorted fashion and appear as much weaker signals than they really are. In fact, despite the difference in loudness of signals traveling over the several paths illustrated in Fig. 2, each is recorded as having about the same amplitude.

After the sounds that were picked up at the microphone had been transmitted to the DPD radio receiver, the output of the receiver was recorded on a Dictabelt recorder. The circuitry of the receiver and the characteristics of the recorder also affected the transmitted signals. The recorded loudness of the sounds transmitted from the motorcycle radio with the stuck microphone were additionally affected somewhat by simultaneous transmissions from other officers in the motorcade. An FM radio receiver, such as the one in DPD headquarters, receives best from the transmitting radio having the strongest transmitted signal and can accommodate at the same time all receivers whose transmitted signal strengths differ by less than the receiver capture ratio.

Thus, the effects of severe environmental noise, of the limiting circuitry of the radio transmitter, of simultaneous radio transmissions, and of the recording characteristics of a Dictabelt recorder were such that any waveforms that would emerge from an analysis of the tape would be severely distorted. What these waveforms would look like without such distortion is illustrated in Fig. 3.

The waveforms shown in the upper portion of this figure were produced by a Mannlicher-Carcano with Western Cartridge Co. ammunition and picked up by a microphone positioned 30 ft from the muzzle and 10 ft to one side of the bullet's trajectory. The muzzle-blast waveform reveals a peak pressure impulse having a sound pressure level of 137 dB re $2\times10^{-5}N/m^2$. For comparison, Fig. 3 also shows the corresponding waveforms for an M-1 rifle. Despite the differences in loudness (amplitude) from one weapon to the other, the shock wave and the muzzle blast can be seen to have characteristic shapes. Sounds processed from the Channel 1 tape could be expected to contain these shapes, but in distorted fashion. The shapes could be expected to be compressed in amplitude and to be accompanied by indications of overdriving of the radio circuits. They would also be accompanied by waveforms produced by the arrival of sound echoes from several sources, as described in the rest of this section.



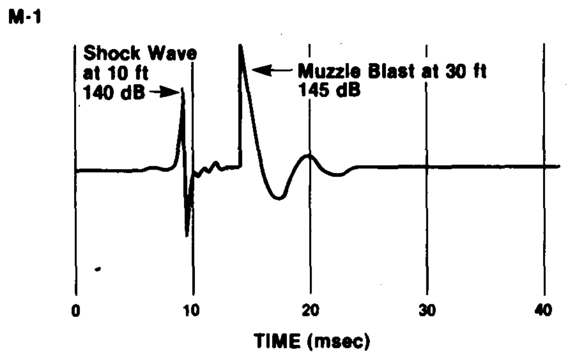


FIG. 3. MUZZLE BLAST AND SHOCK WAVEFORMS FOR MANNLICHER-CARCANO AND M-1 RIFLES.

2.2 Propagation Over the Direct Path

The distance from the muzzle in the TSBD to the nearest possible location of the motorcycle microphone is 60 ft and to the farthest possible location (at Houston and Main) is 260 ft. Loss in amplitude of the sound of the muzzle blast over the direct path is due principally to the spherical spreading of the sound as it travels outward from the source of gunfire. This weakening (attenuation) is accounted for by the quantity 20 log(D/30), where D is the length, in ft, of the path of travel. The estimated loudness of the muzzle blast at the nearest possibly motorcycle location is 137 - 20 log(60/30), which is equal to 131 dB re $2\times10^{-5}N/m^2$. The estimated loudness of the muzzle blast at the farthest possible location is equal to 118 dB re $2\times10^{-5}N/m^2$.

Thus, both the muzzle blasts and the shock waves would be received over the direct path with sound pressure levels greater than the approximately 100-dB limiting sound pressure levels of the motorcycle radio. The result would be both an indication of overdriving the system and a compression of the recorded amplitude.

2.3 Propagation Over Reflected Paths

Ground reflections will always occur from below the microphone at the specular reflection point. Since the path length of the reflected path is only a few feet longer than for the direct path, the amplitude of ground-reflected sounds will nearly equal the amplitude of sounds arriving over the direct path.

Building reflections occur only when a building facade includes a specular reflection point for the source and microphone. This condition is met by the buildings on Houston St. for microphones located on Houston near Main St., and it is also met by the Post Office Annex for microphones located on Elm St. The path length for these reflections is the total distance from the source to the specular reflection point and then to the microphone. For microphones on Elm, the path length for reflections off the Post Office is about 1100 ft. The amplitude of such echoes is, therefore, estimated to be $137 - 20 \log(1100/30) = 106$ dB re 2×10^{-5}N/m^2 – still loud enough to cause limiting by the radio.

All reflected sounds, regardless of the reflecting surface, arrive at the microphone T seconds later than sounds traveling the direct path. T can be expressed as the ratio $\Delta D/c$, where ΔD is the difference between path lengths in ft, and c is the speed of sound in ft/sec. At 65°F, c is 1123 ft/sec, and at 90°F, c is 1150 ft/sec. Sounds reflected from the Post Office occur about (1100-100)/1100, or about 0.9 sec later than the direct sounds.

2.4 Propagation Over Diffracted Paths

The amplitude of sound diffracted by a corner of a building can be estimated as follows.* The ratio of diffracted sound pressure P_d to direct sound pressure P_0 can be written as:

$$\frac{P_d}{P_0} = \frac{|F|}{\sqrt{6\pi k r_0}} \sqrt{\frac{\xi^2+1-{}^2\xi\cos\theta}{\xi(\xi+1)}} \quad ,$$

*See J.J. Bowman, T.B.A. Senior, P.L.E. Uslenghi, *Electromagnetic and Acoustic Scattering by Simple Shapes*, North-Holland Publishing Company, Amsterdam, 1969 (p. 274).

where $\xi = r/r_0$, the distances from the corner to the source and from the corner to the microphone, respectively. The angle between arriving and diffracted rays of sound is θ, and k is the acoustic wavenumber. The function $|F|$ is a number generally between 1 and 2.

There are many corners that can cause diffractions. The corner of the Records Building is typical. The amplitude of a sound impulse diffracted from its corner and received at Houston and Elm would be about 30 dB lower than that of an impulse arriving directly from the source. Since the amplitude of the direct-path sound of the muzzle blast near Houston and Elm is about 131 dB re $2\times10^{-5}N/m^2$, the amplitude of the diffracted impulse will be about 101 dB re $2\times10^{-5}N/m^2$, still loud enough to be somewhat limited by the radio and to be quite audible.

The total path lengths of diffracted sounds vary continuously between limits set by the direct path length and by the longest reflected path length. Thus, diffracted sounds should occur between the time of the direct arrival and the time of the arrival of the reflection from the Post Office.

2.5 Propagation Over Scattered Paths

Objects small enough so that $kd \approx 2$, where d is the nominal diameter of the object, will scatter sound in all directions. Substantial energy in the muzzle blast impulse is contained at frequencies near 500 Hz, where $k = 2.8\ ft^{-1}$. Thus, objects having a diameter of about 1 ft satisfy the scattering requirement. Such objects could be light poles, people, and motorcycles.

The loudness of scattered sound diminishes rapidly with increased distance from the scattering object. For this reason, only sounds scattered from objects fairly close to the microphone would be loud enough to be recorded.

Scattered sounds loud enough to be picked up by the microphone would arrive just following strong direct, reflected, and diffracted sounds. These scattered arrivals tend to increase the apparent time interval in which the primary signals arrive.

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3. RESULTS OF EXAMINING AND PROCESSING THE DPD CHANNEL 1 TAPE

The first tape we received on May 12 from the Committee had a very scratchy overlay of needle noise, indicating that it was a very poor or multiple-generation dub of a recording. In July, the Committee gave us an electromagnetic tape recording that was identified as an original dub made by the DPD, as well as the original Dictabelt record. We then made our own dub on magnetic tape from the original Dictabelt record and compared our dub with that reportedly made by the DPD. We digitized both dubbed tapes - ours and that made by the DPD, plotted the outputs of the digitizing process, and found them to be virtually identical. In this way, we determined that the Dictabelt record was really the source of the data on the DPD-dubbed tape that we were using for analysis.

On the DPD Channel 1 tape, there is an interval of about 5-minute duration, beginning a little after 12:28 pm, in which the radio traffic on this channel is disrupted by a continuous transmission by some remote transmitter, presumably because its transmit button was stuck in the "on" position. As described in Appendix A, we input this entire interval into a digital computer, for subsequent detailed listening, viewing, and processing. This section describes the results of that examination.

3.1 The Unprocessed Waveform Data

First, we made a high-resolution graphical plot of the waveform of this signal, at a scale of 5 in. per 1/10 sec, for detailed visual examination. The plot of the entire interval comprises a roll of paper 12 in. wide by 234 ft long. Reductions of excerpts of this plot are reproduced in Fig. 4. In this figure and in the following discussion, time is noted in seconds from the beginning of the interval.

The first region to be noted in Fig. 4 is the area around 131 sec. This region is typical of the high level of motorcycle noise that characterizes the first 2 minutes of the data.

In the region of 132 to 133 sec, we can see the amplitude of the noise slowly drop. Later, when we discover the trajectory of the motorcycle as a by-product of detecting the sounds of shots, we find that the motorcycle was approaching the corner of Houston and Elm Sts. at this time. Therefore, this diminution of motorcycle noise is probably due to the slowing necessary to negotiate the 120° left turn at the corner.

At about 135.6 sec, we note a single large impulse of relatively long duration. Because of its length and because the region following this impulse is largely free of other impulses, such as the echoes normally associated with loud impulsive sounds, we feel that it is unlikely that this impulse represents the sound of gunfire.

The regions around 137.3 to 138.7 and 139.2 to 140.5 sec are notable for a number of brief, loud impulses. These impulse patterns, the first to appear in the data up to this time, were judged as potentially representing gunfire.

The region from 144.8 to 147.2 sec, which does not appear in Fig. 4, also contains a large number of impulses of similar character. Because this region is about twice as long as the

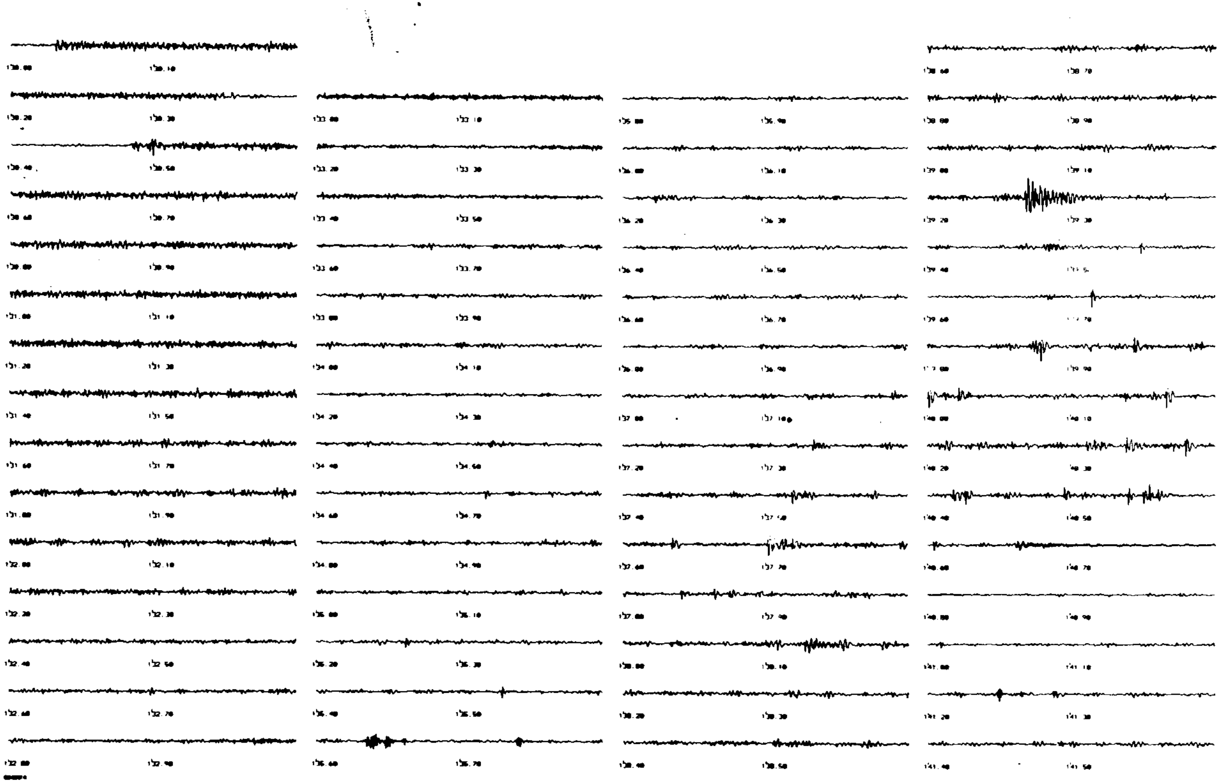

FIG. 4. WAVEFORMS RECORDED FROM CHANNEL 1 TRANSMITTER WITH STUCK MICROPHONE.

preceding ones, it was identified as possibly representing two separate impulse patterns, and, therefore, as potentially containing the sounds of two shots.

3.2 Spectrographic Analysis

Another way of portraying acoustical data is in the form of a spectrogram, in which the short-term spectrum of the signal is displayed as a function of time. Two example spectrograms from the region 141 to 148 sec are shown in Fig. 5. In this figure, time runs from left to right across the figure, and frequency from bottom to top. The energy at a given time and frequency is depicted by the blackness of the paper at that point.

The region from 141 to 144 sec is only noise. Just after 144 sec, a single loud click occurs, followed by a region of very faint speech (faint diagonal and horizontal smudges that change rapidly), clicks (thin vertical lines), and keying heterodynes (steady horizontal bars). The analysis into characteristic frequency components performed by the spectrograph permits us to recognize these events in a way not possible in the waveform patterns.

3.3 The Filtered Waveform Data

To be sure that the 137- to 147-sec region of the transmission contained the only transients of potential importance with respect to gunfire, we attempted to remove the effect of the motorcycle engine noise to see if it was obscuring other transients. For this purpose, we implemented on a high-speed digital computer a noise-canceling filter program that adapts to and subsequently cancels sound components that appear to

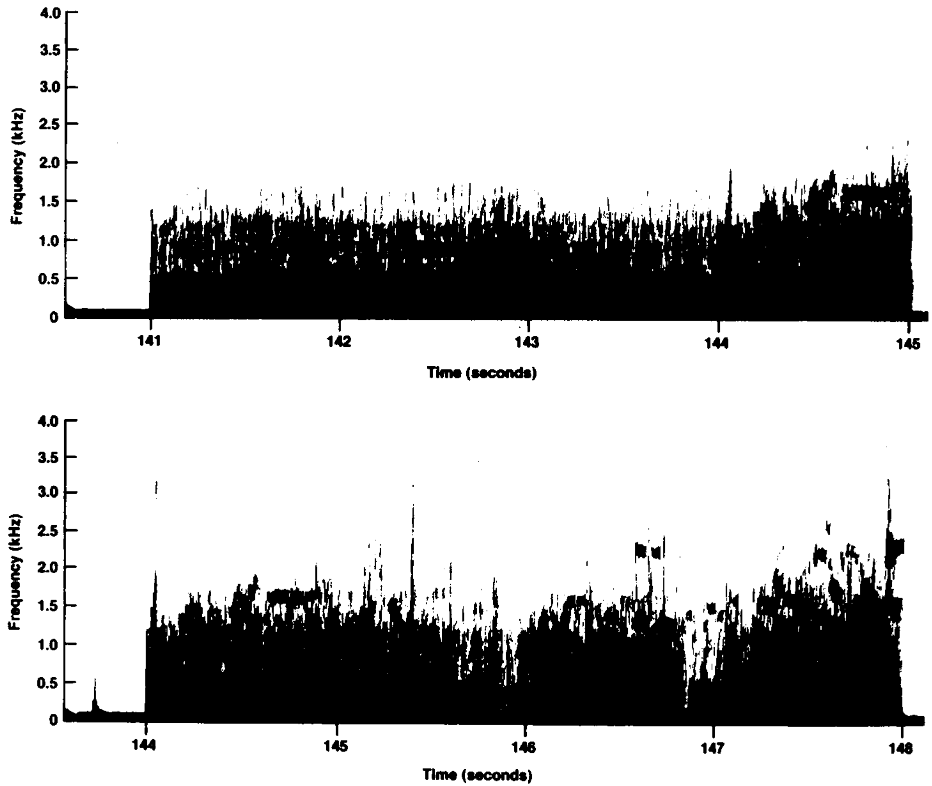

FIG. 5. SPECTROGRAMS FROM WAVEFORMS RECORDED FROM CHANNEL 1 TRANSMITTER WITH STUCK MICROPHONE.

be nonrandom (in this case, the periodic noise of the engine). This filtering algorithm is described in Appendix A. It was tested on a high-fidelity recording of motorcycle engine noise and was found to be very effective in removing it.

The adaptive filtering algorithm, when applied to the entire 5-minute segment of transmission, was not so éffective. Figures 6 and 7 show the effect of filtering the waveform from 130 to 150 sec (overlapping the period for which the unprocessed waveform is shown in Fig. 4). The adaptive filtering removed hum and some low-frequency noise components, but the overall effect was not dramatic. Evidently, the distortions introduced by the radio transmitter, the original Dictabelt recording system, and the subsequent multiple playings of the Dictabelt had added nonrandom noise components that the adapative filter was unable to remove.

Appendix A also describes other signal-processing techniques that were applied to these data in attempts to remove the motorcycle noise and to detect and track motorcycle engine speed. The results in both cases were negative.

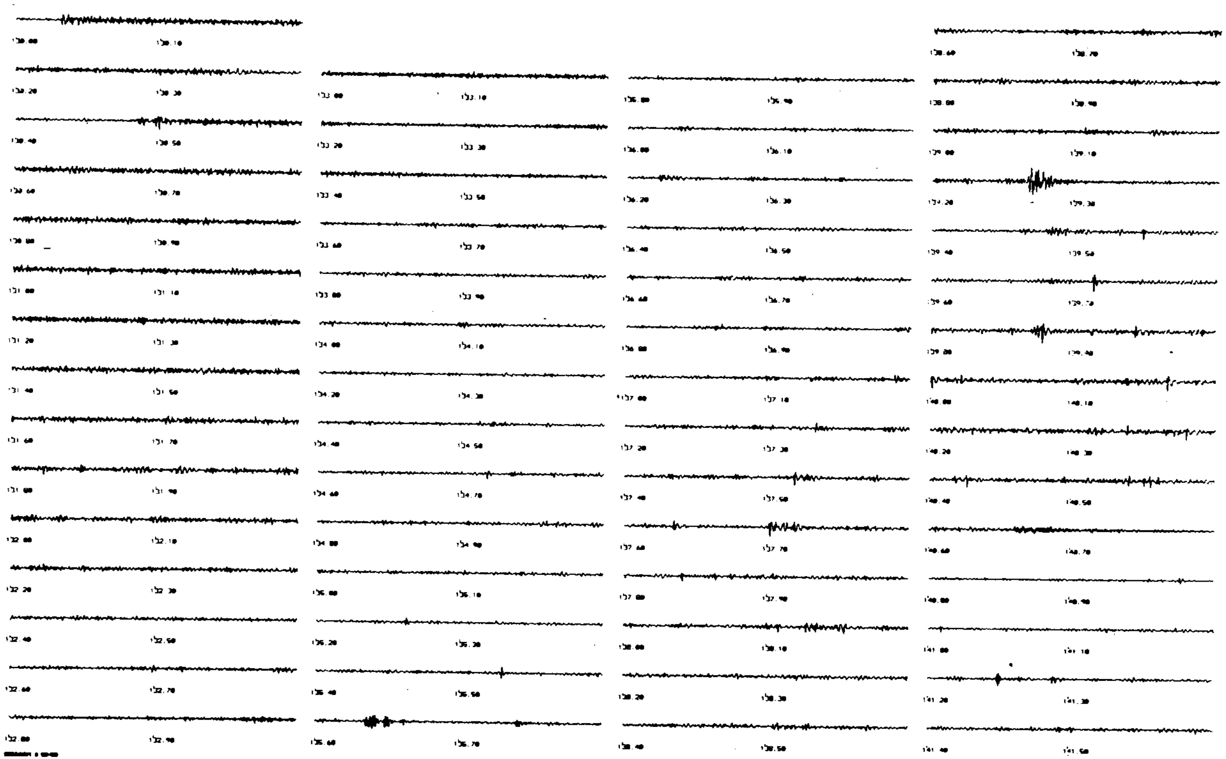

FIG. 6. ADAPTIVE FILTERED WAVEFORMS RECORDED FROM CHANNEL 1 TRANSMITTER WITH STUCK MICROPHONE (130 to 141 sec).

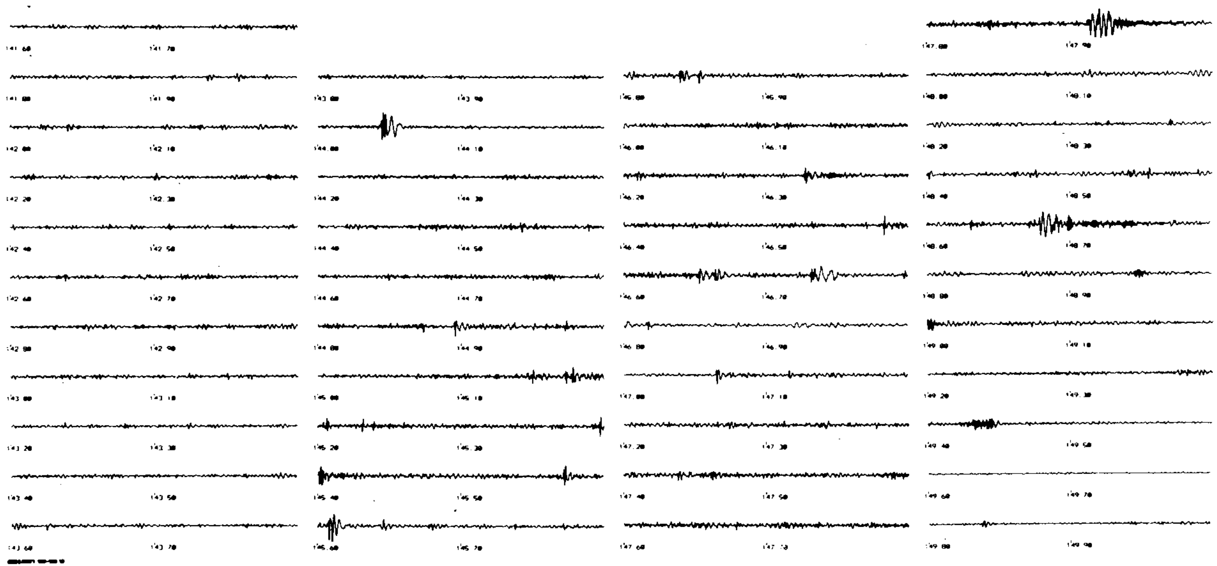

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FIG. 7. ADAPTIVE FILTERED WAVEFORMS RECORDED FROM CHANNEL 1 TRANSMITTER WITH STUCK MICROPHONE (141 to 150 sec).

4. SCREENING TESTS

As described in Sec. 1, the four impulse patterns on the DPD tape were subjected to five simple but necessary screening tests. If the patterns did not pass any of these simple tests, then they could safely be assumed to have been caused by something other than gunfire. If they were to pass these tests, they could not be assumed to be gunfire, but further analysis would be warranted. Essentially, the screening tests were designed to answer the following questions:

1. Did the impulse patterns occur at the same time as the assassination?
2. Were the patterns unique? In other words, were they caused by the same source, and did they appear only at this time and nowhere else on the tape?
3. Did the time intervals between the impulse patterns match that of other evidence of gunfire?
4. Did the shape of the impulses resemble the shape of impulses of recorded gunfire?
5. Was the amplitude of the impulses similar to that of recorded gunfire?

This section of the report describes how these questions were answered.

4.1 Time of Occurrence

To determine the time of day when the impulse patterns were recorded on Channel 1, we examined the Channel 1 and the Channel 2 tapes. It is usual DPD practice for the Dispatchers on both channels to make frequent time annotations. In doing so, they refer to two different clocks, which are synchronized at the beginning of each month and which are read out in full minutes only. An FBI study concluded that, towards the end of the month, the clocks could differ by as much as 1 minute. The allowable difference in the timing of events on Channels 1 and 2, therefore, was 60 sec.

The Channel 1 segment was a continuous recording that had no time annotations during the period of stuck transmission, but time annotations preceded and followed this period. The Channel 2 segment was an intermittent recording with frequent time annotations throughout. A stopwatch was used to time the events on both channels.

Figure 8 illustrates the results of stopwatch timing of the Gray Audograph record of Channel 2 events. Time annotations made by the Channel 2 Dispatcher are plotted against time on the stopwatch for the interval extending from 12:22 pm to 12:40 pm. Lines representing the least-square error fit are drawn through the time annotations. Note that the clock used by the Dispatcher is read out only in full minutes, and occasionally there is more than one annotation for the same minute.

For the events occurring before 12:30 pm on the Channel 2 tape, the slope of the least-square error fit is only 0.4, indicating intermittent operation of the recorder, which stops recording when there are no voice transmissions. At about 12:30 pm, the voice traffic picked up, and the Gray Audograph began recording continuously, as indicated by a least-square error fit slope of 1.0.

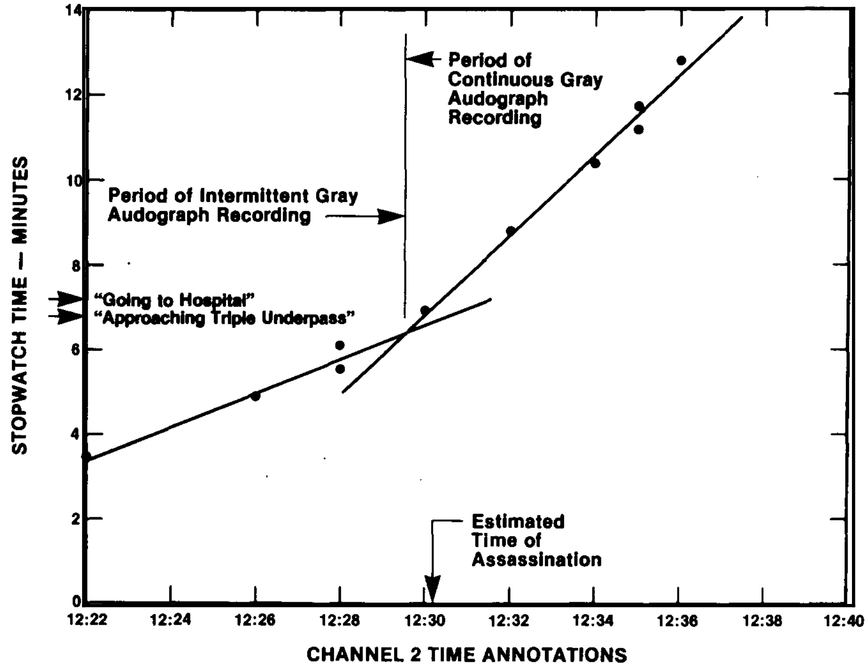

FIG. 8. LEAST-SQUARE ERROR FITS TO CHANNEL 2 DISPATCHER'S TIME ANNOTATIONS SHOWING TIMES OF DPD CHIEF'S RADIO TRANSMISSIONS.

The stopwatch time of two successive transmissions from Chief Curry are noted at the left of the illustration between the period extending from 6 minutes to 8 minutes. In the first, he notes that the motorcade is "approaching the triple underpass." After the Dispatcher notes the time as being 12:30, the Chief announces, "We are going to the hospital, officers." The assassination must have occurred sometime between Chief Curry's two voice transmissions. Since the slope of the least-square error fit changes at about 12:30, it is impossible to determine precisely the time on the Channel 2 clock when the assassination occurred. The best estimate is 12:30:12 pm.

Figure 9 illustrates the results of stopwatch timing of the Dictabelt record of the events on Channel 1. Here, the slope of the least-square error fit is 0.95, indicating that the recorder was running 5% too slow and, therefore, was compressing time slightly.* The fact that the slope does not change over the course of the entire segment shows that the recorder operated continuously.

The onset of the first impulse pattern, or gunfire-like event, on Channel 1 occurred at 12:30:47, Channel 1 time. Thus, the events on Channels 1 and 2 occurred within 35 sec of each other, well within the time difference allowable for this screening test.

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*Frequency analysis of the power hum on the tape recording also indicated that the recorder had been about 5% slow. Since the hum could have been added when the tape was recorded from the dictabelt, this is not a reliable indication of the original recording speed.

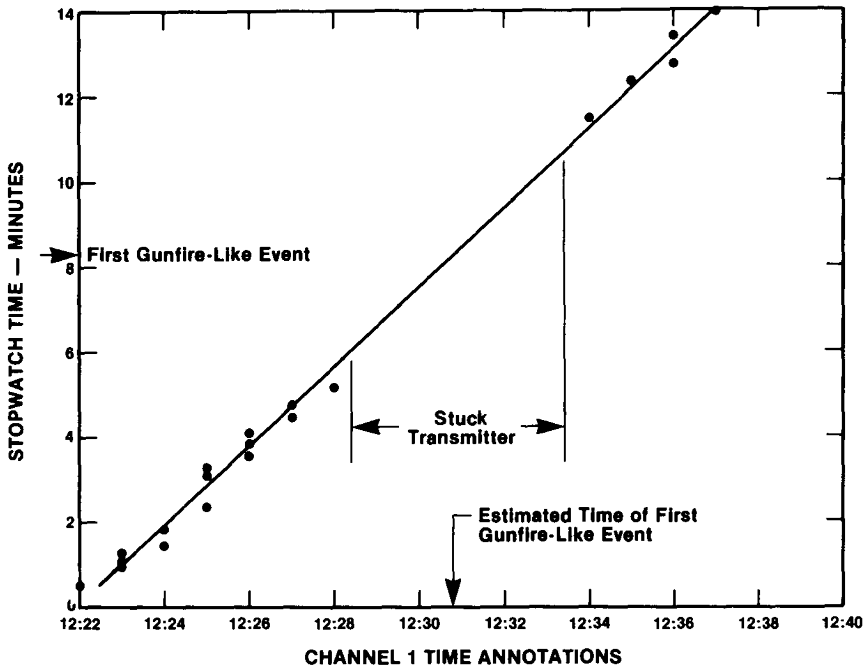

FIG. 9. LEAST-SQUARE ERROR FIT TO CHANNEL 1 DISPATCHER'S TIME ANNOTATIONS SHOWING TIME OF FIRST SET OF GUNFIRE-LIKE EVENTS.

4.2 Uniqueness of the Impulse Patterns

If impulse patterns similar to those occurring at the time of the assassination were to be found anywhere else during the 5-minute recording of stuck transmission, then the patterns could safely be assumed to have been caused by something other than gunfire. Thus, we examined processed waveforms for the entire segment of stuck transmission, looking for impulse patterns similar to those already identified. During the course of this examination, only one other pattern was found. It began about 30 sec áfter the other four patterns and was comprised mostly of impulses apparently caused by radios keying in, attempting to transmit. This sequence, which lasted for approximately 4 sec, did not resemble the earlier impulse patterns well enough to have been caused by the same source.

4.3 Time Span of the Impulse Patterns

If the impulse patterns were caused by the gunfire of the assassination, the time span they occupy would have to be at least as long as the evidence of time between bullet impacts as seen on the Zapruder film. On that film, bullet impact is judged to occur before frame 210 and again at frame 313, an interval of 103 frames. Since Zapruder's camera was judged to be operating at 18.3 frames per sec, the time span between these two events is 5.6 sec. The time span between the onset of the first impulse pattern and the onset of the fourth impulse pattern on the Channel 1 tape is 7.9 sec. When corrected for the fact that the tape recorder was running about 5% too slowly, the real time span is 8.3 sec.

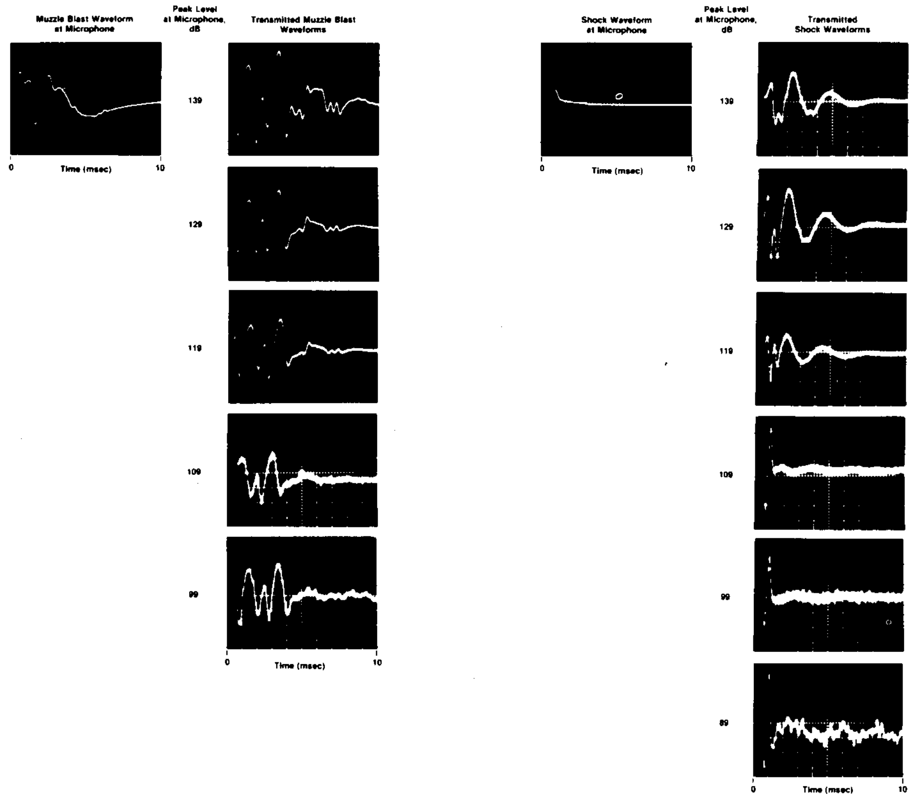

FIG. 10. MUZZLE-BLAST AND SHOCK WAVEFORMS TRANSMITTED BY A POLICE RADIO SIMILAR TO THE ONE USED BY DPD MOTORCYCLES FOR SEVERAL DIFFERENT LOUDNESSES.

4.4 Shape of Impulses

If the impulse patterns recorded on the DPD tape were gunfire, the shape of the waveforms would have been distorted by the limiting circuitry of the radio transmitter. Figure 10 shows the nature of these distortions. At the left of the figure is a muzzle-blast waveform obtained from the test firing of a Mannlicher-Carcano rifle. This waveform has a double peak showing the direct arrival of the muzzle blast with a strong ground reflection immediately following. A tape recording of these impulses was fed through a transmitting and recording system similar to that used by the DPD. The characteristics of both these systems are discussed in Appendix B.

The series of five photographs of transmitted muzzle-blast waveforms shows the effect of the system's circuitry on impulse shapes — essentially, the louder the input signal, the greater the distortion. For example, the top photograph shows how the loudest signals, those arriving over the direct path, would be recorded. The signal that was input at 109 dB is a good example of what the reflection from a large and distant surface, such as the Post Office, would look like. Similar analysis of the shock-wave impulse at the right of the figure illustrates how the simple N-wave of the bullet is severely distorted when the input signal greatly exceeds the 100-dB limiting circuitry of the transmitter.

Comparison of these waveforms with the impulse patterns obtained from the DPD tape showed sufficient similarity that the possiblity that the impulse patterns were caused by gunfire could not be ruled out.

4.5 Amplitude of Impulses

Another characteristic of the waveforms that would have been affected by the circuitry of the radio transmitter if the input signal was as loud as gunfire was their amplitude. The recorded amplitudes of the sounds would be compressed in such a way that strong signals would appear to be weaker than they actually were, and weak signals in the same pattern would, therefore, appear stronger. As can be seen in Fig. 11, this compression is greatest for very loud signals, especially those with high-frequency content. For example, although all the signals were compressed, the amplitude compression of muzzle-blast waveforms above 100 dB was in every case less than that of the shock waves that are of higher frequency.

When the peak-to-peak difference in amplitude between two signals was 30 dB, they were recorded as having only a 20-dB difference (muzzle blast) or only a 10-dB difference (shock wave). As the amplitude of the input signal decreased, the difference in peak-to-peak level became more noticeable. This analysis gave us greater insight into the characteristics of the sounds originally recorded on the DPD tape. The signals on that tape also appeared to be compressed in amplitude, indicating that the sounds, as originally picked up at the motorcycle microphone, may have been loud enough to have been caused by gunfire.

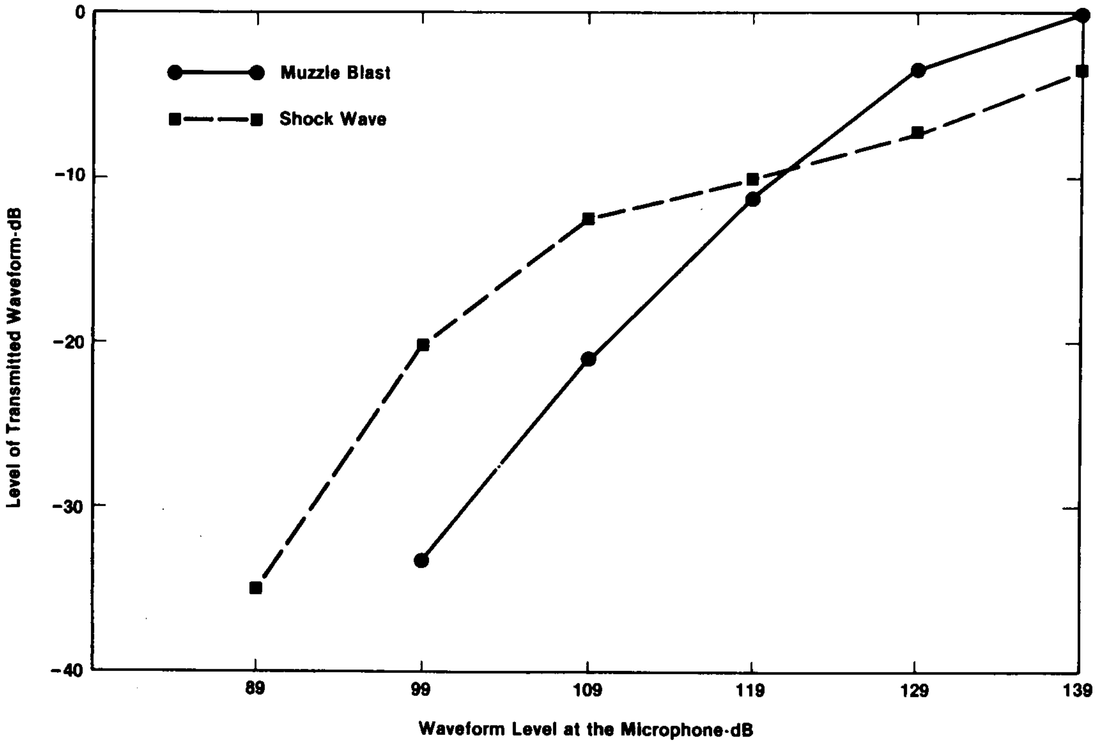

FIG. 11. LEVEL OF TRANSMITTED WAVEFORMS AS A FUNCTION OF WAVEFORM LEVEL AT THE MICROPHONE.

5. ACOUSTICAL RECONSTRUCTION IN DEALEY PLAZA

Because the five screening tests described in Sec. 4 had failed to disprove the possibility of gunfire having been recorded on the Channel 1 tape, a more rigorous test was required. The objective of the acoustical reconstruction, therefore, was to obtain several "acoustical fingerprints" of the sound of gunfire in Dealey Plaza to compare with the impulse patterns found on the Channel 1 tape. If any of the "fingerprints" matched, then the reconstruction would result in determining both the timing of the shots and the locations of the weapon and the target for each shot. Only those weapon and target locations indicated by available testimony were to be tested.

5.1 Nature of the Test

The most powerful test for the presence of weak signals that have many known features, but that are not clearly detectable because of background noise, is the correlation detection test. There are six distinct steps required to conduct this test.

Step 1: Obtain acoustical measurements, called test patterns, of the signals to be detected.

These test patterns are uniquely determined by weapon-target-microphone locations for each shot. There were 12 combinations of weapon-target locations, and they are listed in Table I. There were 36 microphone locations (3 arrays of 12 microphones), which, along with the four target locations, are illustrated in Fig. 12. Thus, 432 (12 × 36) unique test patterns were obtained. Six of these are illustrated in Fig. 13, where the logarithm of sound-pressure amplitude is displayed as a function of time, on a scale 16 in. to 1 sec.

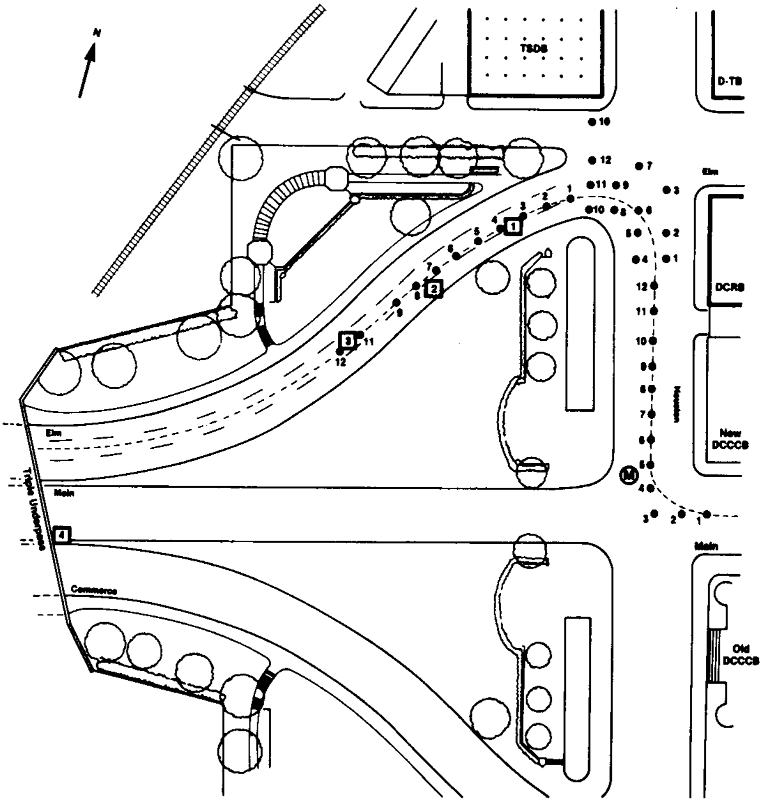

FIG. 12. MICROPHONE LOCATIONS AT DEALEY PLAZA.

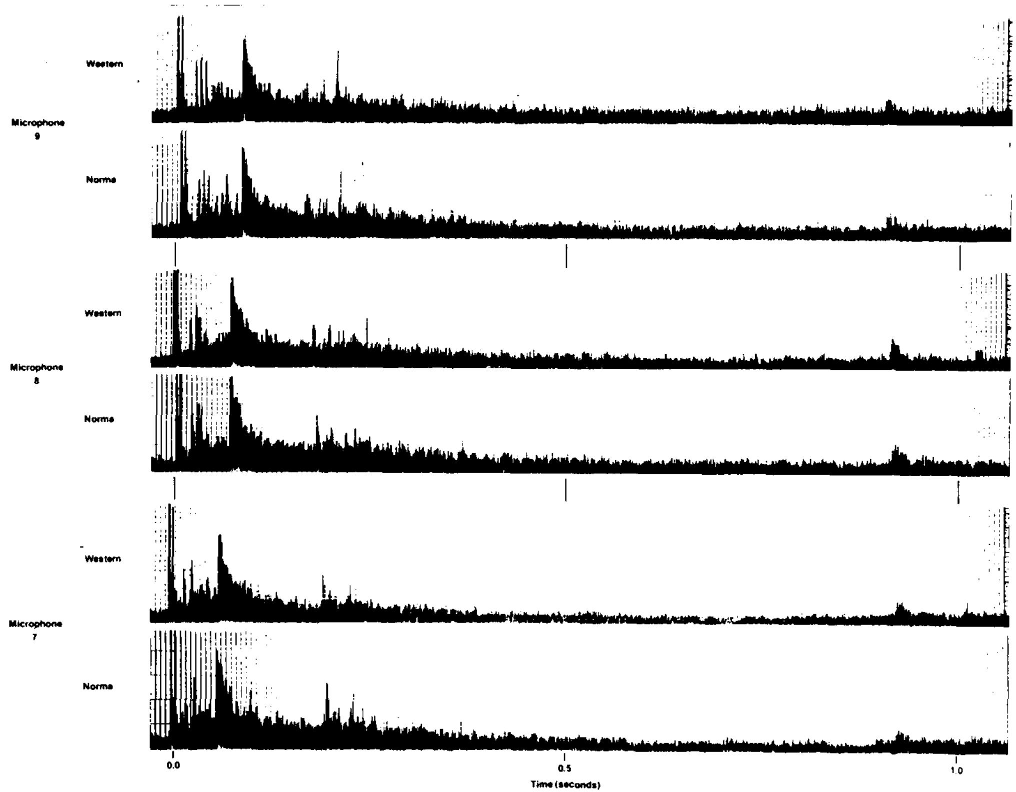

FIG. 13. COMPARISON OF TEST ECHO PATTERNS PRODUCED BY BOTH WESTERN AND NORMA AMMUNITION FIRED FROM TSBD (MUZZLE WITHDRAWN) AT TARGET NO. 3 AND RECEIVED AT ARRAY 3, MICROPHONES 7, 8, AND 9.

TABLE I. SEQUENCE OF TEST SHOTS

Weapon Location	Target 1	Target 2	Target 3	Target 4
TSBD (Muzzle in plane of window)	Shot 1	Shot 3	Shot 6	Shot 10
TSBD (Muzzle 2 ft inside plane of window)	Shot 2	Shot 4	Shot 7	Shot 11
Knoll (Rifle)		Shot 5	Shot 8	Shot 12
Knoll (Pistol)			Shot 9	

Step 2: Process the 432 unique test patterns into a like number of unique echo patterns or "fingerprints."

Since the radio receiver compresses the amplitude of loud gunfire sounds into a narrow range of amplitudes, for comparison with the compressed impulse patterns, test-shot echoes that differ greatly in loudness must be compressed so as to differ only slightly in loudness after transmission by the radio. To achieve this compression, we selected only those echoes in a pattern having sufficient loudness to render them distinct from their neighboring weaker echoes.

This echo selection process is illustrated in Figs. 14 through 17, for test patterns of individual shots as recorded by three adjacent microphones. For each of these figures, the geometry of the test shot – i.e., the weapon-target microphone location sequence – can be reconstructed by referring to Fig. 12. As can be seen from that figure, 12 microphones were placed in 3 successive arrays along the route of the motorcade, beginning at the right of the figure at the corner of Houston and Main. The outputs of the microphones were recorded on channels having the same numbers as the microphones. Thus, the echo patterns in Fig. 14 represent the sound of gunfire made by a Mannlicher-Carcano rifle, withdrawn 2 ft within the plane of the TSBD window, fired at the target located closest to the TSBD, and picked up by microphones 4, 5, and 6 located on Houston St. before the turn onto Elm.

In each of these four figures, 14 through 17, very loud echoes were selected from the echo patterns recorded by the three adjacent microphones. Those echoes judged to have been caused by some feature in Dealey Plaza – e.g., direct arrivals of shock wave and muzzle blast, ground and building reflections, etc. – were identified by dots that are connected by nearly vertical lines. The reason the lines are not vertical is that the microphones were far enough apart to receive the same sound at different times. When Fig. 14 is again used as an example, the slope of the vertical lines at the left of the figure indicates that microphone 6 was closest to the weapon location and was, therefore, the first microphone to pick up sound arriving by the direct path and by other short paths. The slope of the lines at the right of the figure indicates that microphone 4 was closest to a major reflecting surface, such as the Post Office, and was the first to pick up those echoes.

From the four groups of echo patterns shown in Figs. 14 through 17, we selected as "fingerprint" material the following number of echoes: 15, 14, 9, and 10. Again, selection of these echoes was based on their strength and on an understanding of how all the echoes would be compressed in amplitude by the limiting circuitry of the DPD dispatching system. The same procedure was used to select echo patterns from each of the 432 test patterns. Each echo pattern consisted of dots placed at

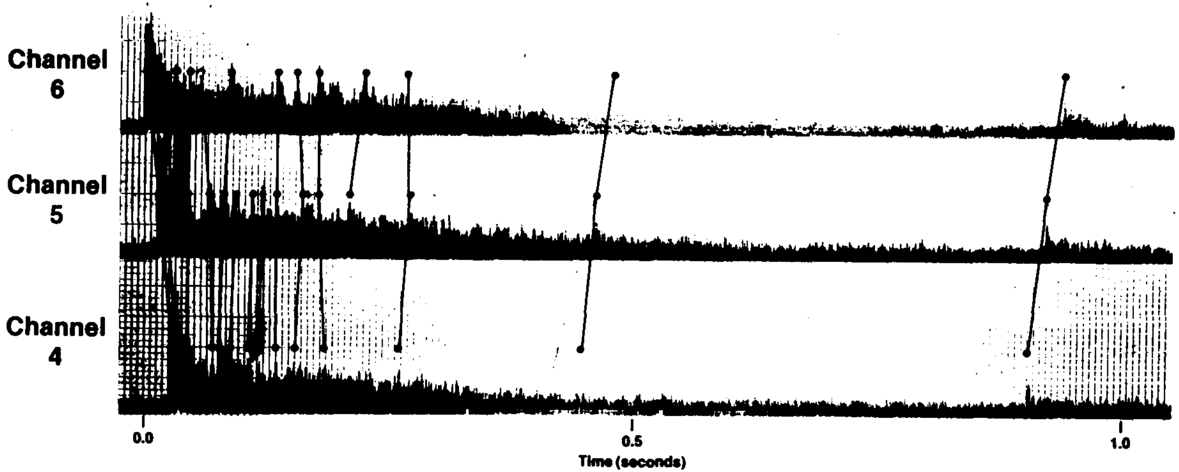

FIG. 14. ECHO PATTERN FOR SHOT 2 (TSBD, MUZZLE WITHDRAWN, TARGET NO. 1) RECEIVED AT ARRAY 2, MICROPHONES 4, 5, AND 6.

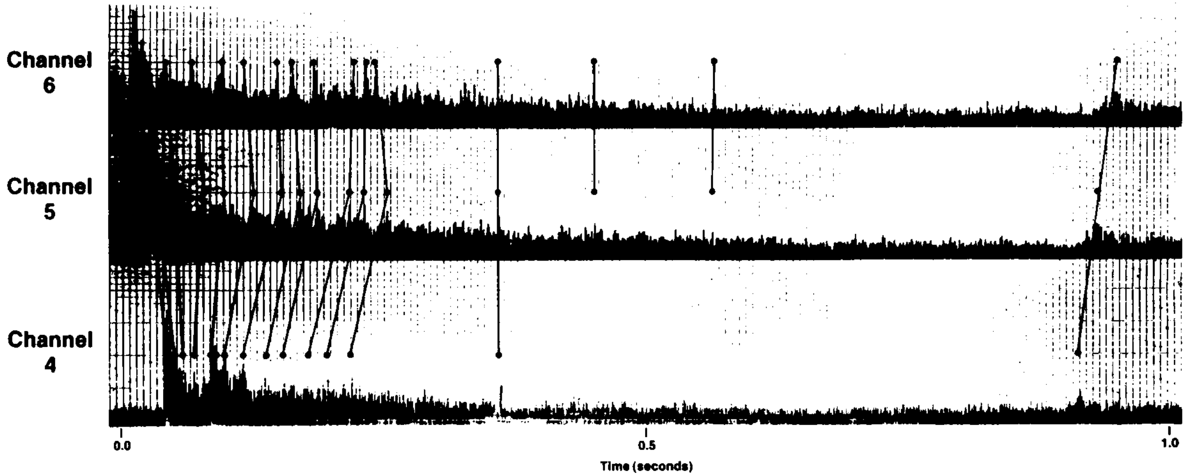

FIG. 15. ECHO PATTERN FOR SHOT 7 (TSBD, MUZZLE WITHDRAWN, TARGET NO. 3) RECEIVED AT ARRAY 2, MICROPHONES 4, 5, AND 6.

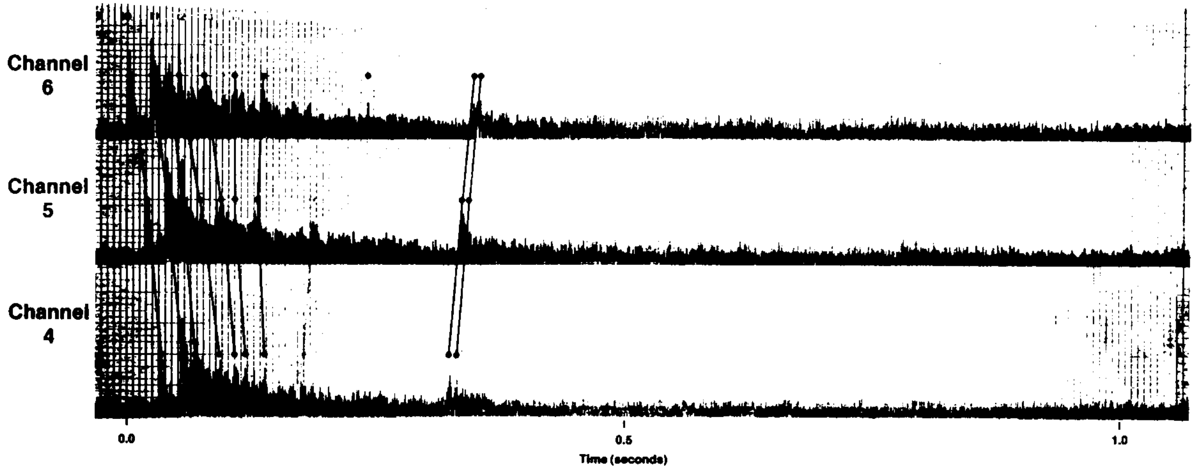

FIG. 16. ECHO PATTERN FOR SHOT 8 (KNOLL, TARGET NO. 3) RECEIVED AT ARRAY 3, MICROPHONES 4, 5, AND 6.

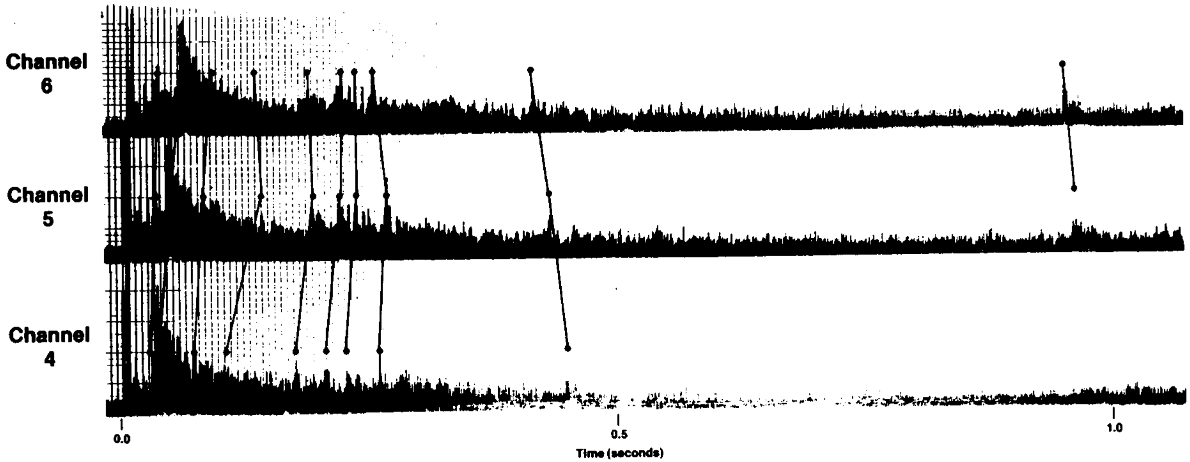

FIG. 17. ECHO PATTERN FOR SHOT 6 (TSBD, MUZZLE EXPOSED, TARGET NO. 3) RECEIVED AT ARRAY 3, MICROPHONES 4, 5, AND 6.

the time of each echo on a scale of 16 in. per sec, and there was an average number of 12 echoes on each echo pattern. Most echo patterns were of about 1-sec duration, or 16 in. long.

Step 3: Process into impulse patterns the segment of the DPD tape recording that passed all five screening tests.

The amplitude of the sounds on each segment was displayed in dB as a function of time, with each second of data occupying 16 in. of the display. The tape segment was subdivided for convenience into six separate segments of about 1-sec duration, each segment containing numerous sound impulses.* About 4 sec of data were discarded, because there were no impulses occurring within them. All impulses louder than a threshold value were selected as members of the impulse pattern. This process is illustrated in Fig. 18, where 17 impulses were selected in a 1.2-sec-long segment of the DPD tape that begins at 137 sec from onset of the stuck microphone.

Above each numbered impulse in Fig. 18 is a pair of vertical lines separated from the time of impulse by 6 msec. The 12 msec between this pair of lines represents a window in which an echo from an echo pattern recorded during the reconstruction might acceptably occur. The reason for establishing such an acceptance window for the comparison between impulse and echo patterns is that the precise motorcycle position and, therefore, its position relative to the actual test microphone locations, was not known. This subject is addressed further in Sec. 5.2.

Three other impulse patterns are illustrated in Figs. 19 through 21. These correspond to DPD tape segments that begin at 139, 145, and 145.5 sec, and they contain 15, 11, and 8

*These segments included the four impulse patterns that passed the screening tests, with the fourth pattern divided into two segments, and one pattern that did not pass the tests.

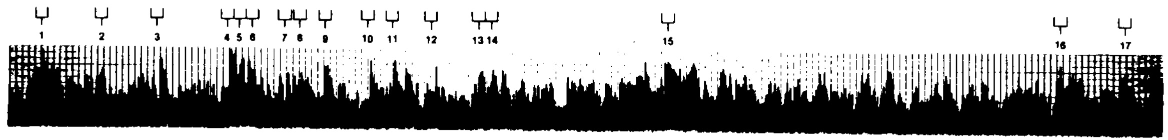

FIG. 18. IMPULSE PATTERN FROM STUCK-TRANSMITTER RECORDING BEGINNING AT TIME 137 SEC.

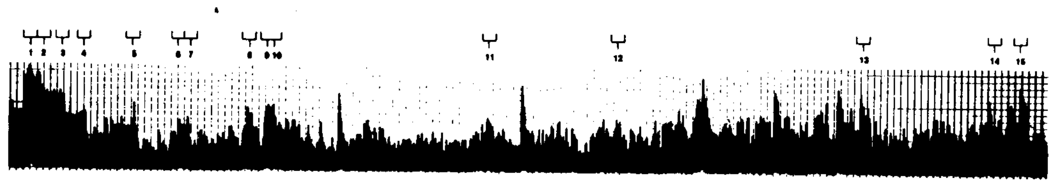

FIG. 19. IMPULSE PATTERN FROM STUCK-TRANSMITTER RECORDING BEGINNING AT TIME 139 SEC.

FIG. 20. IMPULSE PATTERN FROM STUCK-TRANSMITTER RECORDING BEGINNING AT TIME 145 SEC.

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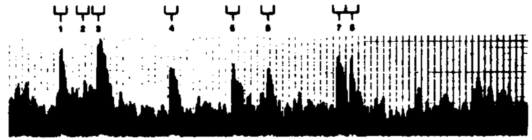

FIG. 21. IMPULSE PATTERN FROM STUCK-TRANSMITTER RECORDING BEGINNING AT TIME 145.5 SEC.

impulses, respectively. The two impulse patterns not illustrated contained 4 and 8 impulses, so that all six of the 1-sec segments averaged 10.5 impulses each.

Step 4: Correlate each of the 432 echo patterns with each of the six impulse patterns for a total of 2592 separate correlation coefficients.

The process of correlation, which obtains the measure of goodness of match between an echo pattern and an impulse pattern, is the essence of the correlation detector. The process is carried out by sliding the impulse pattern along the echo pattern until the maximum number of echoes occurs within the acceptable windows of corresponding impulses. This maximum number is called the number of matches. The correlation coefficient is the number of matches divided by the square root of the product of the number of echoes and the number of impulses; i.e.,

$$\text{correlation coefficient} = \frac{\text{No. of Matches}}{\sqrt{\text{No. of Echoes} \times \text{No. of Impulses}}} .$$

If there is an equal number of echoes and impulses, and if they all match when the two patterns are positioned at one relative time, then the match is perfect and the value of the correlation coefficient is unity (1.0). If there are extraneous impulses or echoes, such as may be caused by noise on the DPD tape or by an echo-acceptance threshold too low for the reconstructed sounds, then the match cannot be perfect and the correlation coefficient will be less than unity. If the echo pattern is not at all similar to the impulse pattern, there will be only one or two matches, and the correlation coefficient will be only a little larger than zero.

The correlation coefficients for all 2592 matches were calculated by determining the maximum correlation coefficient possible for each, after sliding each pair of echo patterns and impulse patterns relative to one another. The time of the first impulse on the impulse pattern was noted with respect to the instant that the microphone button became stuck.

Step 5: Select all correlation coefficients having values greater than the detection threshold value.

The detection threshold concept is necessary because we have observed that noise and experimental uncertainty tend to prevent any perfect correlations (unity value of the correlation coefficient). Whenever an echo pattern matches sufficiently well with an impulse pattern to produce a correlation coefficient higher than the threshold value, that echo pattern is said to pass the detection test. There are two possible meanings to be assigned to each passing of the test. First, if the impulse pattern was truly caused by gunfire, the passing is called a detection. Second, if the impulse pattern was *not* caused by gunfire – but rather by any other event capable of introducing noise in the radio – then the passing is called a false alarm.

Since impulse patterns that are truly caused by gunfire and mixed with radio noise cannot be expected to correlate perfectly with the test patterns, the detection threshold must be set low enough to ensure that no detections are missed. But the lower the detection threshold is set, the more false alarms that can be expected to occur. The analysis described in Appendix C indicated that random noise on one 1-sec segment of the DPD tape having about 12 impulses per sec will cause fewer than 3.3 false alarms out of 432 echo patterns, provided the detection threshold is 0.6. This rate of false alarms was judged acceptable and was considered necessary to prevent misses.

Step 6: Eliminate from the set of detections and false alarms the false alarms that can be identified.

Since false alarms are caused by noise (unexplainable events), they may occur with echo patterns that represent weapon, target, and microphone positions that are obviously disjoint from actual detections and from false alarms that mimic actual detections. These events can be correctly identified as false alarms and eliminated from further consideration. Only independent (non-DPD tape) evidence can be used to identify those false alarms that may be mimicking detections.

5.2 Problems To Be Solved by the Acoustical Reconstruction Test

The acoustical reconstruction test had to be conducted in a safe and timely manner. Therefore, all conceivable weapon, target, and microphone locations could not be reconstructed. Five problems arising from this fact, and their solutions, are discussed here.

1. *Where in the motorcade was the motorcycle during the time span of the assassination, assuming that it was in the motorcade?*

The motorcycle would need to be within the confines of Dealey Plaza in order to pick up the sound of gunfire. From the corner of Main St. and Houston St. to the position of the President's limousine at the time the President's head wound was inflicted is a distance of about 460 ft. Since the pavement widens greatly at the corner of Houston and Elm, about 150 ft needed to be covered twice, for a total linear distance of 610 ft. It was judged that there would be time from sunrise until noon to conduct four complete firing sequences. One of these would need to be a repeat to test for the similarity of two types of ammunition. Only 12 microphones could be used simultaneously, because of the need to keep 2 channels of a 14-channel tape recorder in reserve for annotation. Therefore, 36 microphone positions would have to cover a distance of 610 ft. Also, the streets in Dealey Plaza are about 40 ft wide, meaning that a motorcycle would likely be no more than about 18 ft from the center of a street. For these reasons, the microphones were spaced 18 ft apart, as illustrated in Fig. 12.

Because of the spacing of the microphones and lack of knowledge of the precise position of the motorcycle within the motorcade, it was judged that the motorcycle would, in the worst case, have been no more than 18 ft away from a microphone location. The most likely separations were accounted for in Sec. 5.1, Step 3, by the establishing of a ±6-msec acceptance window for matching echo and impulse patterns.

2. *Is live ammunition necessary in the acoustical reconstruction, and does the type of weapon and ammunition make a difference?*

In Sec. 2, we described how the shock waves generated by rifle bullets would be sufficiently loud at some microphone positions to become a significant part of an echo pattern. The speed of the bullet is important, because it determines the difference in time between perception of the shock waves and perception of the muzzle-blast waves. Therefore, it would be best to use the same type of rifle and the same type of ammunition in the reconstruction as was used in the assassination. Evidence dictated use of a Mannlicher-Carcano rifle from the sixth floor of the TSBD, firing Western Cartridge Co. ammunition. The Committee supplied a similar rifle, but only 15 WCC rounds. It was necessary to use Norma ammunition for the first three sequences of rifle fire, while the fourth sequence was a duplicate of the third, with the exception of substituting WCC rounds for Norma rounds. No significant difference due to the type of ammunition was observed, as can be seen in Fig. 13.

Gunfire from behind the fence on the knoll had been alleged by some, although there was no evidence to indicate what type of weapon or ammunition might have been used. The greatest difference between echo patterns caused by two different weapons occurs whenever one fires a supersonic projectile and the other a subsonic one. For this reason, a Mannlicher-Carcano was used to produce the supersonic projectile and a 38-caliber pistol was used to produce the subsonic projectile. Since the knoll-to-target distances were only about 100 ft, it was not necessary to obtain great accuracy in matching test weapons with alleged assassination weapons in this case.

3. *Where should the targets be located?*

Photographic evidence indicated that shots struck the President when his limousine was at the locations indicated approximately in Zapruder frames 200 and 313. Also, evidence indicated that a bullet may have struck the curb on the south side of Main St., near the triple underpass. Finally, our initial investigation of the tape indicated a shot may have been fired when the limousine was near frame 160. For these reasons, four targets were selected, and their positions are marked on Fig. 12.

4. *Had any significant physical changes been made in Dealey Plaza?*

An important factor to be considered was the change over 15 years in the physical, and therefore acoustical, characteristics of Dealey Plaza. The absence of the crowd and cars was judged insignificant, because reflections of sound from these sources would constitute sufficiently weaker signals than those that would be selected for analysis. Thus, only two changes of importance had taken place: the introduction of the Hyatt Regency building a couple of blocks away as a possible reflector of sound and the absence of the building formerly located at the southeast corner of Commerce and Houston Sts.

Travel time for a sound wave to reach the Hyatt Regency and be reflected back to the microphone was estimated at 2 sec. Since the four impulse patterns had durations of no more than 1.1 sec each, the echo from the Hyatt Regency would not distort the data.

The sound waves that originally hit the missing building would have been diffracted by the corner of the building itself, with much of the sound energy being scattered. The reflected signal from this building would, therefore, have been sufficiently weak to have been swamped by the very strong reflection coming off the Post Office Building located at the southwest corner of the same streets.

For the purposes of reconstruction, therefore, Dealey Plaza was judged to have the same acoustical characteristics in 1978 that it had in 1963. However, when the test was being set up, we found that to shoot from the TSBD at Target No. 2, it was necessary to shoot between two overhead signboards on a sign above Elm St. that was not there during the assassination. This sign could not be moved. The secondary echoes generated by the projectile shock waves impinging on these two signs apparently reduced the correlation coefficients for matches with test shots at this target, for only three were ever found to exceed the detection threshold, and these were identified as false alarms.

5. How could the listening tests be accommodated?

The experts used by Dr. Green* to determine how earwitness accounts of the sounds of gunfire might be explained needed to hear each of the various test shots from at least four different locations. This requirement was met by our use of four identical sequences of test shots.

5.3 Results of the Acoustical Reconstruction Test

Of the 2592 maximum correlation coefficients determined by correlating the 432 echo patterns with the impulse patterns on six tape segments, 15 correlation coefficients exceeded the detection threshold value of 0.6. The time and weapon-target-microphone locations for each of these coefficients are listed in Table II. Inspection of the table shows that no correlations exceeded the threshold value for the two segments beginning at 136.20 sec and 146.30 sec after the time the microphone button became stuck. Fourteen of the 15 correlations that did exceed the

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*See footnote, p. iv.

TABLE II. LIST OF ALL 15 CORRELATIONS BETWEEN IMPULSE PATTERNS OCCURRING IN SIX SEGMENTS OF THE DPD RECORD AND ECHO PATTERNS FROM 432 TEST SHOTS (2592 SEPARATE CORRELATIONS) HAVING A CORRELATION COEFFICIENT HIGHER THAN 0.5.

Beginning Time of First Impulse on Tape Segment§	Microphone Array and (Channel Number)	Rifle Location	Target Location	Correlation Coefficient**
136.20 sec	No Correlations Higher Than			0.5
137.70 sec	2 (5)	TSBD*	1	0.8
"	2 (5)	TSBD*	3	0.7
"	2 (6)	TSBD	3	0.8
"	2 (6)	KNOLL	4	0.7
139.27 sec	2 (6)	TSBD*	3	0.8
"	2 (6)	TSBD	3	0.6
"	2 (10)	TSBD	3	0.6
140.32 sec	2 (11)	TSBD*	3	0.6
139.27 sec	3 (5)	KNOLL	2	0.6
145.15 sec	3 (4)	KNOLL	3	0.8
"	3 (7)	TSBD*	2	0.7
"	3 (8)	TSBD	3	0.7
145.61 sec	3 (5)	TSBD	3	0.8
"	3 (6)	TSBD	4	0.8
"	3 (8)	TSBD*	2	0.7
146.30 sec	No Correlations Higher Than			0.5

§These times are tape times, and they are about 5% smaller than true time because the tape-recording process was about 5% slow.

*Indicates Muzzle Withdrawn 2 ft from Plane of Window.

$$^{**}\text{Correlation Coefficient} = \frac{\text{Number of Echoes Matched with Impulses}}{\sqrt{\text{Number of Echoes X Number of Impulses}}} \leq 1.0$$

threshold value occurred at four different instants of time, those beginning at 137.70 sec, 139.27 sec, 145.15 sec, and 145.61 sec. This result shows the possibility of four shots having been fired, each at one of the four times listed. The fifteenth correlation value to exceed the detection threshold occurred at 140.32 sec after the time the microphone button became stuck. This lone correlation will be identified as a false alarm in the next section and, therefore, does not indicate the possibility of a fifth shot. These times are all about 5% too small, because the tape-recording process was found to be about 5% slow (see Sec. 4.1).

5.4 Conclusions about the Acoustical Reconstruction Test

It becomes clear upon examination of the weapon, target, and microphone locations for the several echo patterns that passed the correlation detection test at each of the four different times, that some are inconsistent with each other. Thus, some or perhaps all represent false alarms. Deciding which are false alarms was greatly facilitated by plotting the microphone locations for each of the 15 echo patterns against the time on the DPD tape when it correlated highly. This plot appears in Fig. 22, where zero on the time scale is taken to be the time on the DPD tape where high correlations were first detected. Zero on the distance scale is taken at the point where the Hughes film* shows a motorcycle to be, just as the Presidential

*Frames from the film taken by Robert Hughes, an amateur photographer, were introduced as evidence at the December 29 Hearing. This film was taken from the left-hand edge of Houston St., near Main St. With the camera pointed north up Houston St., the limousine is seen just disappearing around the corner after a left turn onto Elm St. A few frames later a motorcycle passes through the field of view, moving from right to left, proceeding north on Houston St.

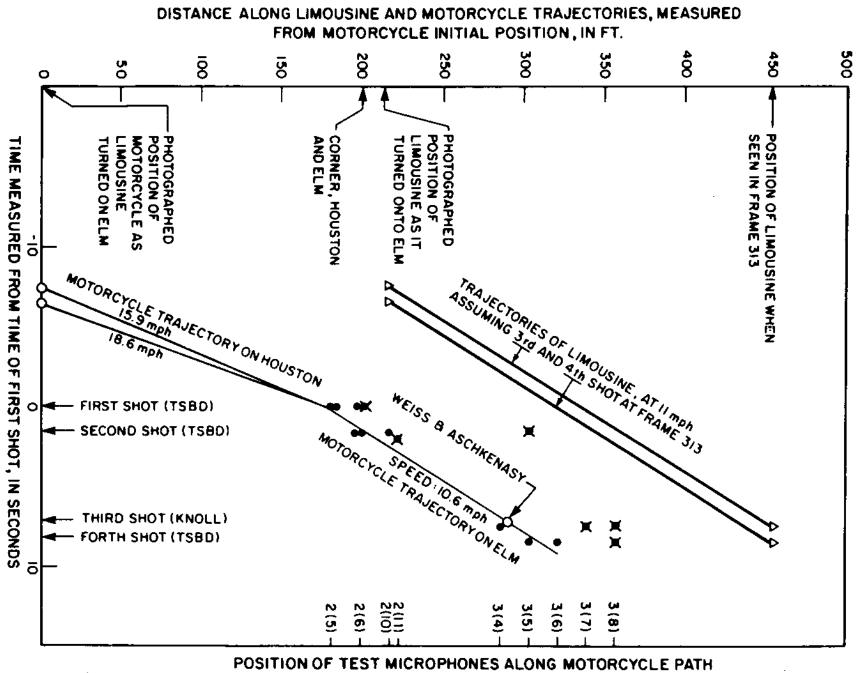

FIG. 22. MICROPHONE POSITIONS ALONG MOTORCYCLE ROUTE WHERE HIGH CORRELATIONS WERE OBTAINED, AS A FUNCTION OF TIME. ESTIMATED TRAJECTORIES OF MOTORCYCLE AND OF THE PRESIDENTIAL LIMOUSINE ARE SHOWN FROM THEIR POSITIONS INDICATED BY THE HUGHES FILM AT THE TIME THE LIMOUSINE TURNED DOWN ELM ST.

limousine is seen to disappear around the corner from Houston St. onto Elm St. This motorcycle position is marked M in Fig. 12. Distance is measured in feet from this point along the motorcade route.

Even a brief glance at Fig. 22 shows that the microphone locations that correspond to correlations at the three times after the first impulse tend to progress uniformly forward along the motorcade route. This conclusion can be quantified statistically by the chi-square test. If the motorcycle were not moving through Dealey Plaza at the time of the assassination, the distance along the motorcade route would be a meaningless coordinate, and the microphone locations for the correlations that exceed the detection threshold would occur at random. When the chart in Fig. 22 is partitioned into a 2 × 2 table by separating time at 5 sec and distance at 250 ft, we find 1, 6, 8, and 0 correlations in the four sections reading from left to right, top to bottom. But the expected number of correlations to be found in these four sections, if the correlations occurred at random, are 4.2, 2.8, 4.8, 3.2. The value of chi-square for the observed and expected values is equal to 11.4. There is only 1 degree of freedom in this 2 × 2 table, and the probability that this large value of chi-square could occur at random is less than 1%. Therefore, there is little doubt that the distance coordinate is meaningful, and we conclude that the motorcycle was moving through Dealey Plaza and did, in fact, detect the sounds of gunfire.

Looking at the information in Table II and in Fig. 22, we can determine that at least 6 of the 15 correlations above the detection thresholds are false alarms. These six false alarms are indicated in Fig. 22 with an X drawn over them, and they are:

1. The fourth entry in Table II that occurred at 137.70 sec is a false alarm, because it represents a rifle shot fired from the knoll at Target 4 near the triple underpass at a time when the limousine was near the position seen in frame 171. Thus, this shot was fired in a direction opposite to that of the logical target.

2. The entry in Table II that occurred at 140.32 sec is a false alarm, because it occurred only 1.05 sec later than earlier correlations also obtained from the TSBD. The rifle cannot be fired that rapidly. Since there are three correlations plausibly indicating the earlier shot, the one occurring 1.05 sec later must be a false alarm.

3. The fourth entry in Table II that occurred at 139.27 sec is a false alarm, because the motorcycle would have had to travel 130 ft in 1.6 sec (55 mph) to gain that position.

4,5,6. The second and third entries at 145.15 sec and the third entry at 145.61 sec are false alarms, because the motorcycle would have had to travel at 16 mph to gain the indicated position of only 70 ft behind the limousine at the time of the last shot. The motorcycle noise level (see Fig. 4) decreased by about 10 dB just 3 sec before the time of the first correlations, indicating a slowing to negotiate the 120° turn onto Elm St. The motorcycle noise level did not increase for the next 13 sec, so it could not have increased speed to 16 mph and maintained it.

There remain nine correlations that exceeded the detection threshold, and they occur at four different times:

Group 1. 137.70 sec – four correlations with test shots from the TSBD at Targets 1 and 3.*

Group 2. 139.27 sec – three correlations with test shots from the TSBD at Target 3.

Group 3. 145.15 sec – one correlation with a test shot from the knoll at Target 3.

Group 4. 145.61 sec – two correlations with test shots from the TSBD at Targets 3 and 4.

There is no other acoustical evidence that would help to determine which of the remaining nine correlations are false alarms, if any. Clearly, at least one of the first two groups of correlations and at least one of the second two groups of correlations must contain detections, because the order found in the data would not likely have occurred by chance. The probability that two detections have been achieved and that one is near 138 sec and the other near 145 sec is at least 95%.

However, the expected number of false alarms to be found when testing four different impulse patterns is 13 (see Appendix C), and only six have been found. Therefore, it is not unreasonable to expect that there are seven more, although that would be the largest number possible since at least two of the remaining nine are probably detections. The best that can be safely assumed is that each of the nine remaining correlations is equally likely to represent a detection or a false alarm.

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*Possibly because of the presence of an overhead sign that interfered with test shots at Target 2, no correlations were found with that target.

On the basis of this judgment and the assumption that each of the 15 events are independent, the probabilities of several different outcomes can be calculated.

The probability that at least two shots have been detected is 96%, the probability that at least three shots have been detected is 75%, and the probability that four shots have been detected is 29%. The individual probabilities that shots occurred at each of the four times at which correlations exceeded threshold are 88%, 88%, 50%, and 75%, listed in order of increasing time. The combined probability that there were three shots and that the third (knoll) shot was one of them is 47%.

Our correlation detector that located the origin of gunfire also located the position of the radio that transmitted the gunfire sounds. It is important to show that the motorcycle trajectory determined by the detections is compatible with independent evidence about a motorcycle trajectory. The necessary independent evidence to show this compatibility is partially obtained from the positions of the Presidential limousine and a motorcycle shown in the movie taken by Hughes (see footnote on p. 62). This movie shows the limousine just turning onto Elm St. just before a motorcycle passes that has turned onto Houston St. from Main St. We estimate that the motorcycle was at point M (Fig. 12) at that sighting. We estimate that the limousine was at the position of microphone 2(9) (Fig. 12) at that sighting, 215 ft north on Houston St.

The position of the limousine at the instant of the President's head wound is shown in Fig. 22 at two different times, assuming that either the third or the fourth shot struck. Photogrammetric determination of the limousine speed on Elm St. was about 11 mph. The limousine's positions at times before the head wound is shown by the two parallel lines projected backward, having a slope equal to 11 mph. The two times at which the limousine position is equal to its assumed position when the motorcycle was at point M are shown in Fig. 22. We find that these times were either 6.5 sec or 7.2 sec before the first shot was fired. The motorcycle position at either one of these two times was 180 ft away from its position when the first shot was fired, according to the results of our correlation detector. Therefore, its average speed north on Houston St. would be either 15.9 mph or 18.6 mph, depending upon whether the third or fourth shot caused the head wound. These two trajectories are shown in Fig. 22 also.

A precise motorcycle location at the time of the third shot, calculated by Weiss and Aschkenasy, was found to be 5 ft southwest of microphone position 3(4). This location is marked in Fig. 22. The straight line that passes through this point, and best fits the eight other microphone locations that produced echo patterns indicating the other three shots, is plotted in Fig. 22. This line is the estimated motorcycle trajectory on Elm St., and it indicates an average speed of 10.6 mph.

The complete motorcycle trajectory shows that the motorcycle traveled north on Houston St. at about 17 mph. It slowed to about 10 mph at a point about 40 ft south of the corner at Elm St., and then continued west on Elm St. at about 10 mph. This single diminution of speed is compatible with the single diminution of motorcycle noise about 3 sec before the first shot is heard (see Fig. 6). We conclude that the motorcycle trajectory determined by the gunfire detections is compatible both with the positions of a motorcycle shown in the Hughes film and with the loudness of the motorcycle noise as transmitted to the Dispatcher.

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6. ADDITIONAL RELEVANT SOUNDS ON THE DPD CHANNEL 1 TAPE

In an attempt to gain as much acoustical evidence as possible, the Channel 1 tape was examined for other relevant sounds. These other sounds consisted primarily of the tolling of a bell, the noise of sirens, and voice and other transmissions.

6.1 Bell

The toll of a bell can be heard faintly at about 152.5 sec. It was hoped that the location of the bell, and therefore of the radio transmitter, could be obtained by acoustically identifying the bell.

The energy spectrum of the 1/3-sec segment containing the bell sound is shown in Fig. 23. Several peaks evident in the spectrum are harmonically related. The fundamental frequency of this series of spectral peaks is 210 Hz. The spectral peaks are marked according to the usual nomenclature used to describe overtones of a carillon bell. The fundamental tone is called the hum note. The second harmonic, called the strike note, is at the nominal pitch of the bell – in this case, 420 Hz. The third harmonic is a fifth above the strike note. Higher harmonics are strong at 1050 Hz and 1470 Hz. The minor third above the strike note is strong, and this fact is characteristic of carillon bells.

The tape-recording system was found to be about 5% slow, when the time annotations were measured with a stopwatch (see Fig. 9). Therefore, the apparent pitch of the tone would have a frequency of (1.05) (420) = 441 Hz.

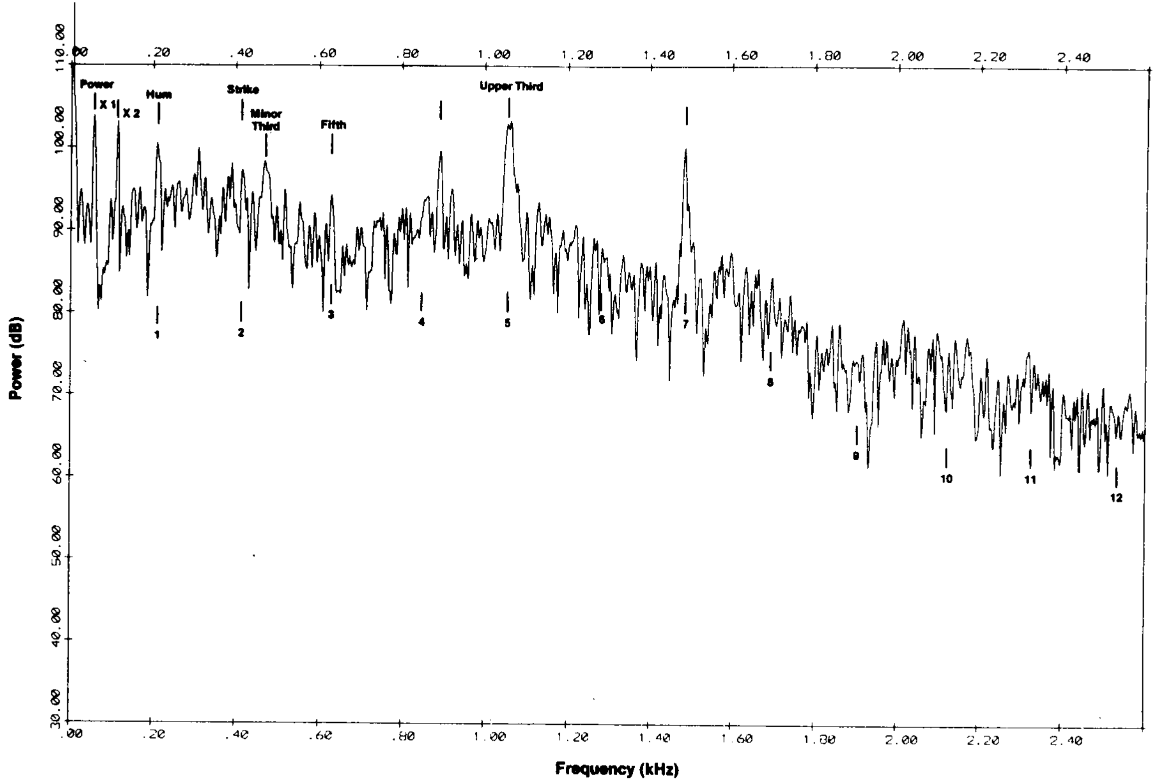

FIG. 23. ENERGY SPECTRUM OF TAPE SEGMENT CONTAINING THE SOUND OF A BELL.

Careful investigation by the Committee staff did not discover any such bell within earshot of Dealey Plaza. During the acoustical reconstruction tests in Dealey Plaza, the sounds of railroad locomotive bells were recorded and subsequently analyzed. These sounds bore no similarity to the carillon-like sounds of the original recording.

We concluded that the bell sound on the Channel 1 tape recording must contain sounds from at least one transmitter not in Dealey Plaza at a time near 152.5 sec.

6.2 Sirens

The region from 263 to 300 sec of the stuck transmission contains the sounds of a number of sirens. The effect is not that of a microphone being carried on a vehicle with a wailing siren, but rather of many vehicles with sirens coming and going around the microphone.

6.3 Voice and Other Remote Transmissions

Starting just after 264 sec, a voice transmission says, "Anybody know where 56 is?" The quality of this voice is such that it sounds as if it may have been picked up by the open microphone of the stuck transmitter, rather than having come from a second transmitter on the same channel, but it is impossible to tell for sure.

In many other cases, there are brief voice signals from other remote transmitters. Sometimes these signals are too faint to be understood (such as the voice signal shown in the spectrograms in Fig. 5), sometimes they are loud but very distorted, and sometimes they are quite intelligible. These competing transmissions are often, but not always, accompanied by heterodynes, which are tones caused by slight differences in frequency among the competing transmitters. Many times these remote transmissions are very brief (around 0.1 sec) "beeps" with no voice, signifying attempts to make one's desire to use the channel known. This beeping is common practice on a shared radio channel.

7. REVIEW OF AN INDEPENDENT ANALYSIS OF THE POSSIBLE THIRD SHOT

Owing to the uncertainty about the possible third shot found in our study, the Committee sought an independent analysis. Professor Mark Weiss and Mr. Ernest Aschkenasy of Queens College conceived of an analytical extension to our work that could determine with more certainty whether or not the match between one echo pattern from our acoustical reconstruction with one impulse pattern on the DPD tape indicated a third shot. At a meeting on October 24, we contributed to the design of this analytical work.

Their analysis was conducted as follows. First, they made a graph of the waveform of the echo pattern we recorded on microphone 3(4), when a rifle was fired from the knoll at target no. 3 (see Table II). From this graph, they identified the 22 loudest individual echoes within the pattern. Then, they identified the 22 echo-producing objects within Dealey Plaza by noting which objects corresponded to observed echo delay times – i.e., by identifying rifle-to-object-to-microphone sound paths that would account for the times each of the 22 echoes were received by microphone 3(4).

Next, they analytically moved the position of microphone 3(4) several times by calculating for each time what the echo pattern would have looked like if that microphone used in the acoustical reconstruction had been located in these other positions. After a time, they found that a position about 5 ft southwest of the actual location of microphone 3(4) represented the true location of the motorcycle at the instant the muzzle blast would have been received by its radio. Then they calculated the delay times for each of the 22 echoes received at that point as it moved down Elm St. at 11 mph. The resulting series of echoes was found to match with the sound impulses on the DPD tape beginning at about 144.9 sec (see Table II).

Weiss and Aschkenasy found that 12 of the 22 echoes were loud enough to exceed a threshold that they felt excluded most of the weak echoes that would not be audible in the DPD tape. They found that 10 of these 12 echoes occurred within ±1 msec of the occurrences of 10 of the 14 impulses on the DPD tape that were loud enough to exceed a threshold. The value of the correlation coefficient that represents this match is 0.77. This value exceeds the threshold value of 0.60 for which we accept a correlation as possibly indicating a shot.

The probability that a false alarm will be produced by the correlation scheme used by Weiss and Aschkenasy is much lower than it is by our correlation scheme, because in our analysis we counted echoes that occurred within ±6 msec of the occurrence of impulses on the DPD tape. We were required to count echoes occurring within this larger time interval, because of our initial uncertainty of the true motorcycle location.

We computed the probability that Weiss and Aschkenasy could have obtained by chance their good match between their calculated echo pattern and the impulse pattern on the DPD tape. We observed that they obtained 10 matches, to a precision of ±1 msec, out of 12 test echoes, with 14 impulses in a 320 msec time span. We note, however, that the 12 test echoes were contained in two time intervals of 90-msec total duration. These two intervals were separated by a span of about 230 msec in which no echoes appeared. Because an echo was counted if it occurred within a 2-msec time window, there were 45 possible windows in which echoes may occur. Since one of the 10 occurrences can always be matched simply by adjusting the origin of the time scale, there are only 9 independent occurrences. The probability of obtaining by chance 9 or more out of 12 echoes occurring within any specific 14 time windows out of a possible 45 is equal to 3.13×10^{-4}. This probability of obtaining by chance as good a match as was obtained on a single try is given by the hypergeometric probability function. However, they were required to try not once, but about 180 times. This is because the motorcycle could have been anywhere in a 40-ft by 18-ft rectangular space. Since a significantly different pattern would be calculated by them for each different 2-ft by 2-ft square, they were required to examine about 180 different patterns. The probability of obtaining just one match by chance in any of 180 independent tries is equal to 5.3×10^{-2}, or about 5%. Therefore, the probability that they obtained their match because the two matched patterns were due to the same source (gunfire from the knoll) is about 95%.

APPENDIX A. COMPUTER SIGNAL PROCESSING

Many of the analyses of the acoustic data were performed on digital computers. In this appendix, we describe these processing methods.

A.1 Digitizing

When played from a magnetic tape, sound is in the form of a continuous electrical signal. For it to be amenable to processing by a digital computer, its voltage must be sampled, or read, at frequent intervals. The voltage must then be expressed as a digital quantity. The sampling rate must be sufficiently rapid to preserve the high-frequency components of the signal; sampling rates of 10,000 times per sec and 20,000 times per sec were used in this work. The signal must then be digitized with an analog-to-digital converter; the resulting series of numbers is stored on a computer disk-file.

A.2 Interactive Playback and Display

Once the signals have been digitized, waveforms can be graphically plotted on a computer display; the signals may also be reconverted to sound by a digital-to-analog converter. Interactive signal display, editing, and playback programs make it possible to display any time interval of the signal and to convert it back to a sound signal for listening. This interactive process of observing portions of the signal waveform and simultaneously listening to it is very valuable.

A.3 Plotting

In addition to showing portions of the signal waveform on the computer display, we also used the computer and a graphical plotter to make pen-and-paper drawings of the signal waveforms. These high resolution plots, usually made with a scale of 5 in. per 1/10 sec, provide a permanent record of the signal. Examples of these plots are shown in Sec. 3 of this report.

A.4 Signal Enhancement

Computations performed on the digitized signal can produce filtered versions and other representations of the signals. Digital signal processing can accomplish the same kinds of filtering that can be performed in the analog domain, and it can accomplish new kinds of filtering that are impossible by conventional means. Several different kinds of signal processing were performed on the data.

Enhancement by Adaptive Noise-Canceling Filter

An adaptive noise-canceling filter differs from fixed filters in that it automatically adjusts its signal-processing characteristics by means of an algorithm that allows it to predict certain noise components. The particular filtering process* used for the Channel 1 tape allows the filter to separate periodic components of the noise from random components. Periodic components are those elements of an input signal that repeat at regular intervals — for example, the ticks of a clock and a 60-Hz powerline voltage hum.

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*Widrow, B., Glover, J.R., Jr., McCool, J.M., Kaunitz, J., Williams, C.S., Hearn, R.H., Zeidler, J.R., Dong, E., Jr., and Goodlin, R.C., "Adaptive Noise Cancelling: Principles and Applications," *Proc. IEEE* 63, 1692-1716 (December 1975).

One property of periodic components is that, given sufficient past history, they can be predicted; indeed, a perfectly periodic signal can be predicted perfectly. The filter "learns" from the past history of the signal, estimates the signal for the next time period, and subtracts its estimate from the input. What is left are those portions of the signal that the filter cannot estimate – i.e., the random components.

A time delay was inserted into the processing system, just ahead of the adaptive filter, to assist in controlling the separation of periodic and random components. Random components having a time duration less than that of the time delay pass through essentially unaffected by the filter. These random components form the primary output of the filter. A second output was the periodic component that was being subtracted out; this subtracted information was also saved in digital form on disk. Examination of this subtracted signal, by aural and visual means, yields considerable insight into filter performance. Several test signals were fed into the filter to verify proper operation and to adjust the various filter parameters. The filter performed very well on the various test signals.

On the DPD Channel 1 tape, anticipated periodic and undesirable interferences included components of motorcycle cylinder firing, powerline hum, heterodyne "squeals," and occasional speech. Sections of this tape were played into the filter with a wide range of filter parameter values. Filter action was monitored by listening to both the primary and the secondary outputs. The filter removed residual powerline hum, some speech, and heterodyne "squeals" of time duration longer than that of the time delay. However, it accomplished little with respect to what had been believed to be motorcycle noise. We therefore performed an autocorrelation analysis, as described below.

Autocorrelation Analysis of Motorcycle Engine Noise

Our interpretation of the sounds on the Channel 1 tape would have been made much easier if we had had some knowledge of the movements of the motorcycle carrying the microphone. For example, if we had had information on when the motorcycle was moving steadily (along a straight street), slowing down and possibly shifting gears to turn a corner, or stopping, we might have been able to infer whether these movements were consistent with travel into or through Dealy Plaza. However, we did not have this information. Thus, to determine the engine speed with greater accuracy than is possible from engine loudness, we wrote a computer program that would compute the short-time autocorrelation function of the motorcycle noise signal. This function assesses the similarity of a signal with itself shifted in time; if the signal is periodic, this similarity will peak when the signal is shifted by one period.

This autocorrelation analysis program was applied to the stuck transmission period on the Channel 1 tape. The results showed no periodicity that we could attribute to motorcycle engine firing. As a test case, this program was also applied to a high-fidelity recording of motorcycle engine noise, and it clearly showed the known periodicity of the test signal. Although our failure to detect the motorcycle engine periodicity is puzzling, it is consistent with our inability to perceive the engine firing clearly when we are listening to the tape, and it is also somewhat consistent with the failure of the adaptive noise-canceling filter to filter out a coherent motorcycle engine sound signal.

Enhancement by Spectral Subtraction

A third method applied to enhance the Channel 1 signals was the subtraction of a noise spectrum estimate. This method is currently under development at BBN, under U.S. Government sponsorship, for the enhancement of speech signals in the presence of stationary flat-spectrum additive noise.* It is similar to, but somewhat more general than, the INTEL enhancement method developed by Weiss *et al.*† We could not tell whether this method would be effective with nonstationary non-flat-spectrum noise, but since the program was already available, we tried it.

In this method, the signal is converted by a Discrete Fourier Transform to a magnitude spectrum and a phase spectrum. A previously computed estimated noise spectrum is subtracted from the magnitude spectrum; the altered magnitude spectrum is then recombined with the phase spectrum converted back to a waveform by an Inverse Discrete Fourier Transform. Several parameter settings for this filtering method were used with a portion of the Channel 1 tape. None were successful in reducing the motorcycle noise without introducing noise transients attributable to the filtering process.

*Berouti, M., Schwartz, R., and Makhoul, J., "Enhancement of Speech Corrupted by Acoustic Noise," IEEE Int. Conf. on Acoustics, Speech, and Signal Processing, Washington, DC, April 2-4, 1979.

†Weiss, M.R., Aschkenasy, E., and Parsons, T.W., "Study and Development of the INTEL Technique for Improving Speech Intelligibility," Nicolet Scientific Corp., Report RADC-TR-75-108, 1975.

APPENDIX B. RADIO TRANSMISSION OF GUNFIRE SIGNALS

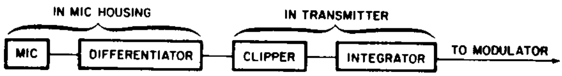
The 1963 DPD Channel 1 radio link and recording system contained the following components: microphones, radio transmitters, an RCA Fleetline radio receiver (Model C9F350), and a Dictabelt recorder. Radio systems such as this are designed to carry speech signals and therefore incorporate signal modifiers to optimize the dynamic range and bandwidth of the system with respect to voice transmissions. Since these signal modifiers are usually incorporated in the transmitter, rather than in the receiver or the recording device, we focused our efforts to simulate the radio link on the transmitter/microphone combination.

Among the radio transmitters in use by the DPD in 1963, House Committee researchers found that five different models were used on motorcycles. These were

- Motorola Model FMT-41
- Motorola Model T-31BAT
- Motorola Model U-41GGT
- Motorola Model T-41GGT
- General Electric Model MT-13-N.

At the time of this study, it was very difficult to find manuals for these models and even more difficult to obtain access to a working unit. With the manuals we were able to find and with assistance from Motorola factory personnel, we discovered that the microphone used with the T-31BAT would have been Motorola NMN 6006A and that microphones used with the other Motorola transmitters would have had similar characteristics; i.e., they would have been dynamic cardioid types with internal preamplifiers. We have no information about the GE radio model and its microphone. We eventually located a T-31BAT owned by the Boston Metropolitan District Commission Police Department. The MDC kindly made this radio and a GE Model ER51A receiver available to us.

The basic scheme used in this and other Motorola radio transmitter/microphone systems of the same vintage is sketched below. This type of circuit limits the slope of the audio



signal rather than its amplitude. Therefore, it will limit high-frequency signals more than low-frequency signals, as shown in Fig. 11 of this report. The frequency response of the system rolls off at 36 dB/octave above 3 kHz and at 6 dB/octave below 2.3 kHz. The signal, in effect, is differentiated and low-pass filtered. The smoothed, calculated frequency response of the system is plotted in Fig. B.1.

Our procedure for obtaining the data shown in Figs. 10 and 11 was to play tape recordings of gunfire, made anechoic by time gating, through a circuit designed to simulate the frequency response and amplitude-limiting characteristics of the Motorola 6006A microphone into a second tape recorder. We then took the second tape to the MDC Police radio shop. There, we played this tape through a variable attenuator (to control the level of the signal being put into the transmitter), through the Motorola

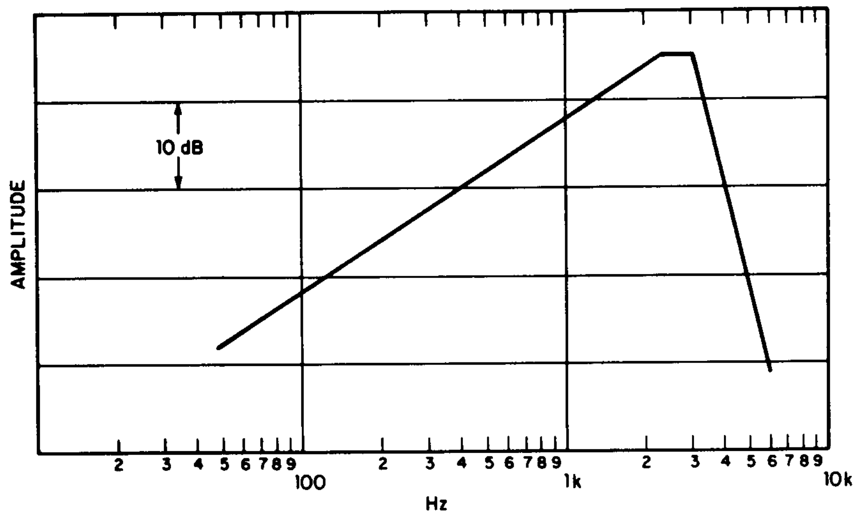


FIG. B.1. TRANSMITTER/MICROPHONE SYSTEM FREQUENCY RESPONSE.

transmitter, through the GE receiver, and onto another tape recorder. This third tape recording was played back into an oscilloscope and photographed producing the waveforms shown in Fig. 10. Peak-to-peak amplitudes of these waveforms were measured and plotted to produce Fig. 11.

In addition to having had similar effects on the waveforms recorded on Channel 1, the DPD recording shows evidence of a time constant in the 0.1 to 1.0 sec range. This AGC does not occur in any of the Motorola transmitters. It could, therefore, have been caused by the GE transmitter, by the receiver, or by the recorder.

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APPENDIX C. ANALYSIS OF FALSE ALARMS IN THE CORRELATION DETECTION TEST

The process of binary correlation that was used to detect gunfire echo patterns among the impulse patterns on the DPD tape can, like any other detector, produce false alarms. This analysis determines the number of false alarms to be expected from random noise impulses on the DPD tape.

Each echo pattern contains an average of $M = 12$ echoes in a 1/2-sec span. But, we consider each echo to have a $\pm$6-msec acceptance window to account for echo time differences introduced by not knowing the motorcycle position relative to the test microphone positions. Therefore, there are about $N = 40$ different time slots in which the 12 echoes may exist.

Each impulse pattern contains some number of impulses ranging from $n = 8$ to $n = 17$, also in a 1/2-sec span.

The matching process seeks to find the number of impulses, i, that lie within the acceptance windows of the echoes that comprise the echo pattern. If the impulses are caused by a random noise source, then the number of matches, i, is what would be expected from random sampling n times a population of N that contains M echoes. The probability of getting i matches at random is given by the hypergeometric probability distribution $p(N, M, n, i)$.

The correlation coefficient is defined to be equal to $i/\sqrt{Mn}$. The probability of obtaining a correlation coefficient equal to 0.6 or greater was calculated for $N = 40$, $M = 12$, and $n = 8, 10, 12, 13, 14, 17$. The results for the six successive values of n were: 4.8×10^{-3}, 6.0×10^{-3}, 8.5×10^{-3}, 1.0×10^{-2}, 1.2×10^{-2}, 1.5×10^{-2}.

For an impulse pattern having 10 impulses (n=10), there are expected $(6.0\times10^{-3}\times432) = 2.6$ false alarms, because there are 432 echo patterns to correlate with. There were four impulse patterns that were correlated with all 432 echo patterns, and they had n = 8, 10, 12, 17 impulses on them. The total number of false alarms to be expected works out to 13.

This number was judged to be acceptably small, so the detection threshold value was set at 0.6.