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A Technical Evaluation of the Rockville-Indianapolis Microwave Link

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by

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A TECHNICAL EVALUATION OF THE ROCKVILLE-INDIANAPOLIS MICROWAVE LINK

SUMMARY

This report describes a series of tests to evaluate wide-band microwave link equipment for remoting radar data for air traffic control purposes. Tests were conducted from July 1, 1956, to July 1, 1957. The tests indicate the electrical characteristics of the link were satisfactory for remoting radar data used for air traffic control purposes. From the standpoint of reliability, however, the link was not adequate for air traffic control purposes.

INTRODUCTION

The microwave equipment used for these tests was manufactured by Motorola, Inc., and leased by the CAA Technical Development Center (TDC) from the Indiana Bell Telephone Co. It was installed early in 1956, to transmit radar data from an Air Defense Command CPS-6B radar at Rockville, Indiana, to TDC at Weir Cook Municipal Airport, Indianapolis, Indiana. The total length of the link is approximately 60 miles. The microwave link installation was sponsored originally by the Air Navigation Development Board to provide a radar environment for the Airways Operations Evaluation Center at TDC and for the purpose of conducting a technical evaluation of a wide-band radar remoting system. This equipment is the commercial equivalent of the Motorola MRR-3 system. In addition to the terminal equipment at Rockville and Indianapolis, there are two repeater stations located at Lena and Montclair, Indiana. Figure 1 shows a diagram of the system. The Rockville and TDC terminals are shown in Fig. 2

EQUIPMENT DESCRIPTION

Four data channels are provided in the microwave system to remote long-range search video, beacon video, three combined vertical beam videos, azimuth information, and trigger and range marks. Data are transmitted in one direction only on two radio-frequency (r-f) channels between 7,100 and 7,400 Mc. The two r-f carriers utilize a common antenna at Rockville and also at TDC. The repeaters consist of one antenna for receiving both carriers and one for transmitting both carriers. Each r-f channel is capable of transmitting a video signal containing frequencies as high as 5 Mc. Channel A carries search video (designated as Video 1), azimuth, and trigger information. Both the trigger and search video inputs to the link equipment are positive signals. Within the equipment the search video is inverted, the negative search video and positive trigger then are mixed and filtered to occupy a video bandwidth from 0 to 2.5 Mc. Azimuth information modulates three subcarriers at 3.5, 4.0, and 4.5 Mc and uses the remaining 2.5- to 5.0-Mc portion of Channel A.

Beacon video is carried on radio-frequency Channel B The positive beacon input video is inverted and coupled to a low-pass filter The high-frequency cutoff of the filter is 2.5 Mc. Positive range marks also are fed to the same low-pass filter. The combined beacon and range marks, designated as Video 2, occupy the 0- to 2.5-Mc portion of Channel B. Video 3, which contains the combined video of 3 vertical beam radars, modulates a 5-Mc carrier. This modulated signal is filtered to remove its upper sideband The output contains frequencies from 2.5 to 5 0 Mc. By mixing Video 2, range marks, and Video 3, a bi-polar video signal containing frequency components from 0 to 5 Mc is produced which occupies radio frequency Channel B.

Each of the two 5-Mc video channels are amplified and used to frequency-modulate two separate klystrons. The two r-f channels are fed through a common waveguide to the antenna system. At the TDC end of the link the signals are detected, demodulated, and separated into three videos, trigger, range marks, and rotational data.

PERFORMANCE TESTS

An ideal microwave link transmission system will furnish output radar data identical to the input data If the link changes the amplitude relationships, distorts pulse shapes, adds noise, or introduces cross-talk between channels, then the input is not reproduced faithfully at the output. The tests described below were conducted to determine the degree of change between input and output signals and also whether these differences can be tolerated in air traffic control (ATC) applications

Amplitude Linearity

To determine the amplitude linearity of the system, a one-microsecond pulse was applied to the input of each channel and varied in amplitude from 0.1 to 5.0 volts. Input and output readings were recorded simultaneously. Test results obtained are plotted in Fig 3 Prior to these measurements, the entire link was adjusted for 2 5 to 3.0 volts output with a 2.0-volt input signal The curves for Video 1 and Video 2 are similar, but somewhat different than Video 3. Perhaps this is because Video 1 and Video 2 each are inverted and each occupy the 0- to 2.5-Mc portion of their respective channels, whereas, Video 3 modulates a 5-Mc subcarrier and occupies the 2 5- to 5-Mc region of its channel. The differences, however, are not too significant and the amplitude linearity is considered satisfactory for the normal range of input signals from 0 to 3 volts Beyond this range the linearity is poor. Signals larger than 3 volts appear very much larger at the Video 3 output and smaller at Video 1 and Video 2 outputs.

High-Frequency Response.

Each radar is designed with a pulse width and bandwidth that provide optimum signal-to-noise ratio consistent with other performance requirements. The frequency response of the link system must be such that it will not alter materially the bandwidth of the data to be remoted. To determine this, a series of tests was devised to measure both high- and low-frequency response.

The rise time of a pulse at the output of the link is related to the high-frequency response of the system and can be expressed as

$$R_L = R_O^2 - R_{IN}^2 \qquad (1)$$

where
R_L = rise time of the link,
R_{IN} = rise time of the input pulse, and
R_O = rise time of the output pulse.

In this test a pulse with a rise time of 0.04 microsecond was introduced into each video channel. Measurements of the pulse outputs of Videos 1, 2, and 3 showed rise times of 0 15, 0.2, and 0.25 microsecond, respectively. See Figs. 4A, 4B, and 4C Using equation (1), this corre-ponds to rise times of the 3 video channels of approximately 0.14, 0.2, and 0.25 microsecond, respectively. An approximate relationship between rise time and bandwidth is[1]

$$\text{bandwidth} = \frac{0\ 35}{\text{rise time}}$$

This gives bandwidths of 2.5, 1.8, and 1.4 Mc, respectively, for Videos 1, 2, and 3. These values are approximate since they are true only for gradual decrease in amplitude with frequency, and in this case the decrease in amplitude with frequency is quite rapid. Nevertheless, it seems that the bandwidth is less than the 2 5-Mc design objective. For remoting long-range radars using pulse widths of 2 microseconds or longer, the bandwidth of the link is more than adequate

In addition to high-frequency measurements of the three video channels, measurements also were made of the bandwidth of r-f Channel B. A test pulse with an 0.04-microsecond rise time was applied to the input of Channel B and its rise time, R_O, of 0 08 microsecond was observed, See Fig. 4D. Using equation (1), the rise time, R_L, of Channel B is 0.07 microsecond for a bandpass of approximately 5 Mc.

Low-Frequency Response.

Low-frequency measurements were made by applying long video pulses to the link inputs, such as those caused by precipitation or ground clutter, and measuring their deterioration at the outputs. A pulse 200 microseconds wide followed 5 microseconds later by a 1-microsecond pulse was applied as a test signal to each input. The input test pulses had a "flat top" or near zero droop. The output pulse in the case of Video 1 had a 40 per cent droop. Video 2 had an 18 per cent droop, and Video 3 had a 10 per cent droop. In all cases no attenuation of the 1-microsecond pulse following the long pulse could

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[1] F. E. Therman and J. M. Pettit, "Electronics Measurements," McGraw-Hill Book Co., Inc., 1952, p. 327.

be detected. Although these measurements indicate some loss in low-frequency response, it was concluded that the response obtained is satisfactory for ATC applications.

Resolution.

Each radar has an inherent range resolution determined by its pulse width and over-all bandwidth As part of the bandwidth measurements of the link, a specific test concerning the ability to resolve two closely spaced pulses was made Test signals with variable pulse widths and spacing were used to measure link resolution. Two test pulses, each 1-microsecond wide with a 0.25-microsecond rise time, were applied to each video input. Pulse spacing of the test signals was reduced while observing the link output. When the trailing edge of the first output pulse just met the leading edge of the second output pulse, it was noted that a similar condition existed at the input terminals The link, therefore, had not stretched the leading pulse nor appreciably altered the rise time of the trailing pulse. The output noise level during these tests was about 0.2 volt. The link output then was connected to an SPA-8 radar indicator. Two-microsecond spacing from the trailing edge of the first pulse to the leading edge of the second pulse was required to resolve these targets on this radar indicator. These observations were made at a range of approximately 5 miles with the indicator adjusted for a maximum range of 10 miles It was concluded that the link had acceptable resolution for ATC purposes

Internal Noise

Thermal Noise.

The noise level of the link was observed on many occasions during the evaluation period. When the link was operating normally, and with unity gain from input to output (2 volts), the output noise level of the 3 video channels varied from 0.1 to 0.2 volt (peak), a 26-db to 20-db signal-to-noise ratio. This noise level is that contributed by the link only. It was determined by shorting the link input terminals.

Since the link is frequency-modulated, the amplitude of the output is directly related to frequency deviation. If the deviation of any path is lower than normal, the output signal is correspondingly lower. Noise, however, is not related to frequency deviation but rather to the gain and bandwidth of the system. Any aging of components and tubes associated with the klystron modulation amplifier which causes the frequency deviation to decrease causes the output signal level to drop. A gain adjustment to restore the output signal level increases link noise level also and decreases the signal-to-noise ratio of the system It is easy in daily operation to assume mistakenly the higher noise level in the output is part of the radar input signal, whereas, in reality, it may be caused by a malfunctioning of the link

Due to noise generated by the link, the output video differs from the input. In the absence of an input signal there is constant output noise of approximately 0.2 volt. This noise is inherent in the link and is related to path loss, bandwidth, and gain. A more detailed investigation of this noise was not made, however, remoting noise, like radar system noise, obviously will reduce the maximum range of the radar

Hum.

A local condition at the receiving terminal at Indianapolis occasionally caused a large amount of 60-cycle-per-second (cps) hum to appear on all outputs. This condition was partially corrected by providing a good ground for the terminal equipment and by providing an auxiliary distribution amplifier for each of the three outputs. Certain hum was found in the link itself, but this was not objectionable when the hum balance potentiometers on the modulation amplifiers of each transmitter were adjusted properly.

Interference.

The transmitting terminal is located several hundred feet from the radar and from VHF/UHF communications transmitters. No interference from these services was noted. The link repeaters at Lena and Montclair, Indiana, are at American Telephone and Telegraph Co. sites where other microwave systems also are repeated. No interference from these sources was noted. At the receiving terminal, a number of potential interfering sources exist. One ASR-2 radar antenna is located ten feet above the link receiving reflector on the same tower. Another ASR-2 radar is located approximately 1/4-mile distant and one FPS-8 radar system also is 1/4-mile from the link equipment. The ASR-2 radars operate in the 2,700 - 2,900-Mc band and the FPS-8 radar operates in the 1,280 - 1,350-Mc band. Interference encountered from the ASR-2 1/4-mile distant measured 0.5-volt on the video output terminals. This interference was entering the demodulation equipment directly. Completely shielding the microwave terminal building with aluminum-backed paper reduced this interference to an acceptable level of less than 0.05 volt.

The FPS-8 radar located 1/4-mile from the receiving terminal radiates one megawatt peak power. This radar initially produced objectionable interference at the link video output terminals. With the radar antenna aimed at the link terminal, interference of 2 volts could be found in the link output. The position of anyone inside the equipment building influenced the amplitude of the interference. With the receiver disconnected or turned off the interference was still present, however, disconnecting the balun amplifiers[2] reduced the interference greatly. Shields were fabricated for the balun amplifiers. With these shields in place the interference was reduced but still present. The building walls and ceiling previously had been shielded with aluminum-backed paper. This shield had become defective mainly due to tearing around the door. Repairing this shield reduced the interference to less than 0.1-volt on all 3 video output terminals, which is comparable to the system noise and is acceptable.

Interchannel Cross-Talk.

Tests were conducted to determine the amount of cross-talk that exists between the various channels of the link. For these tests a 1-microsecond, 2.5-volt pulse was applied to Video 1, while another pulse was applied to Video 2 and a third pulse to Video 3. These 3 pulses were spaced 3 microseconds apart so that they could be observed more easily. The

[2] Balun amplifiers have a balanced input and an unbalanced output.

pulse amplitudes applied to Video 2 and Video 3 were increased to 20 volts. At the input of Video 1, 0.05 volt of interference, caused by the inputs to Video 2 and Video 3, was observed This same level of interference also was observed at the output of Video 1, however, the normal noise level in the output of Video 1 (approximately 0.2 volt) tended to obscure it Since the input levels normally are 3 volts or less, it was concluded that interchannel cross-talk is not a significant factor.

BEACON TRANSMISSION CAPABILITY

The air traffic control radar beacon system (ATCRB) referred to in the following as a beacon, is intended to furnish the ATC system with identity of radar targets from beacon-equipped aircraft. It operates essentially as an interrogation from the ground and a coded reply from the aircraft. Proper ground decoding yields discrete aircraft identity within the limitations of the codes provided for the ATC function A protection circuit is provided in the beacon system to "kill" the output when an improper code is received. It can be assumed that in some instances the encoded replies will be remoted to the control location and then decoded. In the Rockville-Indianapolis microwave link, Video 2, with a nominal bandwidth of 2.5 Mc, is intended for the transmission of coded beacon signals The purpose of conducting tests on this channel was to determine whether a 2.5-Mc channel is sufficiently wide for satisfactory decoding In addition to these tests, a second set of decoding measurements was made in the laboratory to show decoding capabilities of the equipment where transmission bandwidth was not involved.

Each beacon signal or code consists of four pulses. Each pulse has a 0.45-microsecond width, a 0.1-microsecond rise time, and a 0.2-microsecond fall time. The positions of the 4 pulses are rigidly determined. There are 8 possible positions, 2 9 microseconds apart. Starting with the first position as 0, the pulses are spaced 0, 2.9, 5.8, 8.7, 11.6, 14.5, 17.4, and 20 3 microseconds The first and last (0- and 20 3-microsecond) pulses are the framing pulses and are always required in a code The remaining 2 pulses occupy 2 of the 6 middle positions. The code used for the tests was the No. 2 code, which contains the 0-, 2.9-, 11.6-, and 20.3-microsecond pulses. Setting the code selector switch to a given position connects crystal diodes to the proper taps on the delay line so that all four pulses will be coincident in time on the coincidence bus. The diodes normally are conducting, which keeps the coincidence bus close to ground potential. If positive pulses appear at all four taps simultaneously, all diodes will be cut off and the voltage on the bus will rise to the amplitude of the pulse for the duration of the pulse. This rise in voltage constitutes a pulse which is fed to the output terminal. A pulse appearing in any of the 4 remaining positions, namely, 5.8, 8.7, 14.5, and 17 4 microseconds corresponding to taps 2, 3, 5, and 6, would be applied to the killer bus and would cancel the pulse on the coincidence bus Tests were conducted to determine the effect, if any, that a remoting channel bandwidth of 2.5 Mc has on decoding and killing, and also the improvement, if any, when a 5-Mc wide channel is used

A Farnsworth code generator was set up in the laboratory and its output fed to the beacon input terminal of a Farnsworth decoder. With the code generator adjusted to generate code 2 and the selector on the decoder also set to code 2, a double pulse output of 2 volts was obtained. An additional pulse then was introduced at the 14.5-microsecond position. When this was done, the decoder output dropped to 0.1 volt. The 14.5-microsecond pulse then was advanced in 0.1-microsecond steps from 13.35 to 15.65 microseconds and the amplitude of the decoder output was recorded for each pulse position. These points are plotted in Fig. 5 and represent the decoding and killing action obtained in the laboratory with no degradation of the beacon pulses due to the transmission medium.

The code generator then was moved to the Rockville end of the microwave link and the decoder was connected to the TDC end of the link. Codes were fed into the beacon channel and the same test was repeated over the 2.5-Mc transmission channel. The results of this test also are shown on Fig. 5. The same test then was performed over a 5-Mc channel, which was obtained by bypassing the multiplexer at the Rockville terminal and the demultiplexer at the TDC terminal and occupying the entire bandwidth of Channel A. Since neither the multiplexer nor the demultiplexer was used, the beacon signals at the TDC end of the link appeared as 0.5-volt signals. These were amplified by a wide-band amplifier (10 Mc) to increase their amplitude to 2 volts for proper decoding.

In Fig. 5 the bench test curve is shown as a continuous line, the 2.5-Mc curve as a dotted line, and the 5-Mc curve as a dashed line. In later model decoders, the output is limited to 2 volts, and any level above 1.6 volts is considered a good decoded signal. Anything less than 0.4-volt is considered killed. During the laboratory test, the output was killed when the interfering pulse was within the 14.25- to 14.83-microsecond points on the curve. In the 2.5-Mc test it was killed when the pulse was within the 14.3- to 14.83-microsecond area. For the 5-Mc test it was killed from 14.3 to 14.90 microseconds.

For perfect decoding, that is, a pulse output of 2 volts, there should be a 2-volt pulse in each of the 4 proper taps on the delay line and no pulse in the other positions. For perfect killing there should be a 2-volt pulse on at least one of the other taps. If a pulse having a finite rise time is moved part way into a position, the canceling or killing will be imperfect and the double pulse output will have some value between 0 and 2 volts. Noise will cause a similar action. While a certain minimum voltage (0.2 volt) is clipped off, noise in excess of this amount, when added to part of a pulse, will cause partial killing and will decrease the decoding time. Figure 5 represents part of a cycle which repeats every 2.9 microseconds. On this basis, and considering a pulse amplitude equal to or greater than 1.6 volts as good decoding, the decoding time would be 65.5 per cent for the laboratory test, 62.9 per cent for the 2.5-Mc test, and 64.6 per cent for the 5-Mc test. This represents very little difference among the three tests.

From 14.75 to 15.00 microseconds, the bench and 2.5-Mc curves are very close together, and the 5-Mc wave deviates the most. From 14 to 14.25 microseconds, the bench and 5-Mc curves are close together, and the 2.5-Mc curve deviates the most. Originally it was thought that as the rise time of the pulses was lengthened by passing the codes through a system with lower high-frequency cutoff, the decoded killing curves would deviate more from the bench curve. From these tests, however, it would appear that there is little or no improvement in the 5-Mc video channel over the 2.5-Mc channel

The lack of improved performance with the wider band is attributed to the poor frequency response of the delay line which feeds the coincidence killer bus. Measurements made in the laboratory showed that a pulse at the delay line input having a 0 1-microsecond rise time and a 0.45-microsecond width appears at the delay line output with a 0.65-microsecond rise time and a 0.9-microsecond width. After being clipped in the decoder, the pulse has a 0.35-microsecond rise time and a 1.2-microsecond width.

RELIABILITY

The microwave link was first placed in operation during July 1956. It was operated continuously, except for outages, when they occurred. Standby equipments were not provided and contracted maintenance was provided by Indiana Bell Telephone Co on a 5-day-week basis from 8:00 a.m. until 5:00 p m. The following paragraphs describe equipment reliability after the first 30 days of operation during which there were numerous difficulties associated with the installation and initial adjustment.

During normal working hours, 8:30 a.m. to 5:00 p.m., failure to receive Rockville radar data could be noted by the personnel on duty, but this monitoring method did not separate radar outages from link outages. A test system was developed, therefore, to measure the total link outage time regardless of radar operation or time of day. By means of gating circuits, and a multipen Esterline-Angus recorder, all outputs of the link were sampled 300 times a second and the presence or absence of the test signal caused the recorder pens to indicate whether the system was or was not operating. If any of the three video channels failed, the corresponding pen would indicate failure. If r-f channel B failed, the two pens corresponding to Video 2 and Video 3 would indicate the condition The delay and gating circuits were timed by the Rockville radar system trigger, but, if the Rockville radar trigger was lost, the monitor generated its own test trigger. In this way the link performance could be monitored even though the radar was completely disabled. Continuous recordings of link outages were made from March 5 to June 24. The results are tabulated below:

Duration of test - 111 days, or 2,664 hours
Number of outages - 28
Number of days during which some part of link was inoperative - 32
Number of hours some part was inoperative - 230.4
Percentage of time some part of link was inoperative - 8.65

The 8.65 per cent mentioned above represents time lost when some channel of the link was completely out of service. It does not include many marginal periods when the azimuth or trigger was intermittent and when the noise level was high so that the radar information was unsatisfactory.

During the four-month period, the link was inoperative due mainly to klystron difficulties. The proper procedure for turning on the klystron oscillator in the transmitters and receivers includes turning on the beam current after a short warm-up period. In the event of a power failure, when the power is off for a time and then restored, this warm-up time is not provided. Under these conditions, the klystrons sometimes failed to oscillate, resulting in a link outage. Usually all that was required to resume operation was to turn the beam current off and then on again. Approximately 50 per cent of the outage time can be attributed to this sort of trouble. About 20 per cent was due to routine maintenance and adjustment. The remaining 30 per cent was caused by interference, trigger difficulties, and miscellaneous causes.

Corrective and preventive maintenance is difficult to perform by one man unless special test equipment is provided. If failures occur, or adjustments must be made that affect the frequency, power output, receiver sensitivity, or deviation of the system, it is necessary to have one man at the equipment to be adjusted and another at the next location to measure the effects of the adjustment. It would be highly desirable to develop test equipment that would make it possible for one man to adjust a repeater or terminal without assistance from a man farther down the chain Items of special test equipment required are. (1) microwave power and frequency meter, (2) microwave signal generator, (3) frequency deviation generator, and (4) deviation measurement device. Accurate deviation adjustments and measurements are important to keep the link noise at the lowest possible level. It should, of course, be possible to connect each of these instruments to the system without shutting it down, and it should be possible to make necessary tests on any channel without interference to the other channels.

To maintain the system efficiently, it is necessary to have a communication channel between its terminals and repeaters. Many of the adjustments required men located at two or more points in the system. Since the MRR-3 equipment did not have a built-in communication channel, sometimes referred to as an order wire, the telephone company provided a telephone system between the various stations in the link system. This was very helpful to the evaluation as well as to the maintenance of the system.

From the above experience, it is concluded that acceptable reliability requires a stand-by channel and a means of selecting this channel when it is required. Good maintenance standards and adequate test equipment are necessary to prevent prolonged periods of marginal performance. Maintenance personnel should be specialists on link equipment that is used to remote radar data. Since link performance can degrade the radar data seriously, agency-maintained equipment may be preferred over leased service in areas where radar remoting systems are not widely known or inadequate maintenance procedures are available.

CONCLUSIONS

The following conclusions were reached:

1. The microwave link has satisfactory frequency response, amplitude linearity, resolution, and cross-talk characteristics when operated properly.

2. Two sources of interference from nearby radars were noted. Interference from these sources was reduced to a negligible degree by employing standard shielding methods

3 Normally, the noise level was equal to or less than 0.2-volt (20 db signal-to-noise ratio). Regular checking and adjustment of the link was required to maintain this value Careful engineering of the system to keep path loss to a minimum will make future maintenance less critical and daily performance more satisfactory.

4. The 2.5-Mc beacon channel is satisfactory for transmission of codes to present-day beacon decoders which employ limited bandwidth delay lines. Improved decoders probably will dictate wider band video channels for transmission of beacon signals in the future.

5. Special test equipment is required to provide continuously acceptable performance with a minimum maintenance crew.

6. Skilled technicians and good preventive maintenance schedules are required to prevent prolonged periods of marginal performance.

7 Acceptable reliability requires dual-channel equipments and a remote means of selecting channels when required.

8. An order wire service is required to facilitate maintenance and adjustment of the equipment.

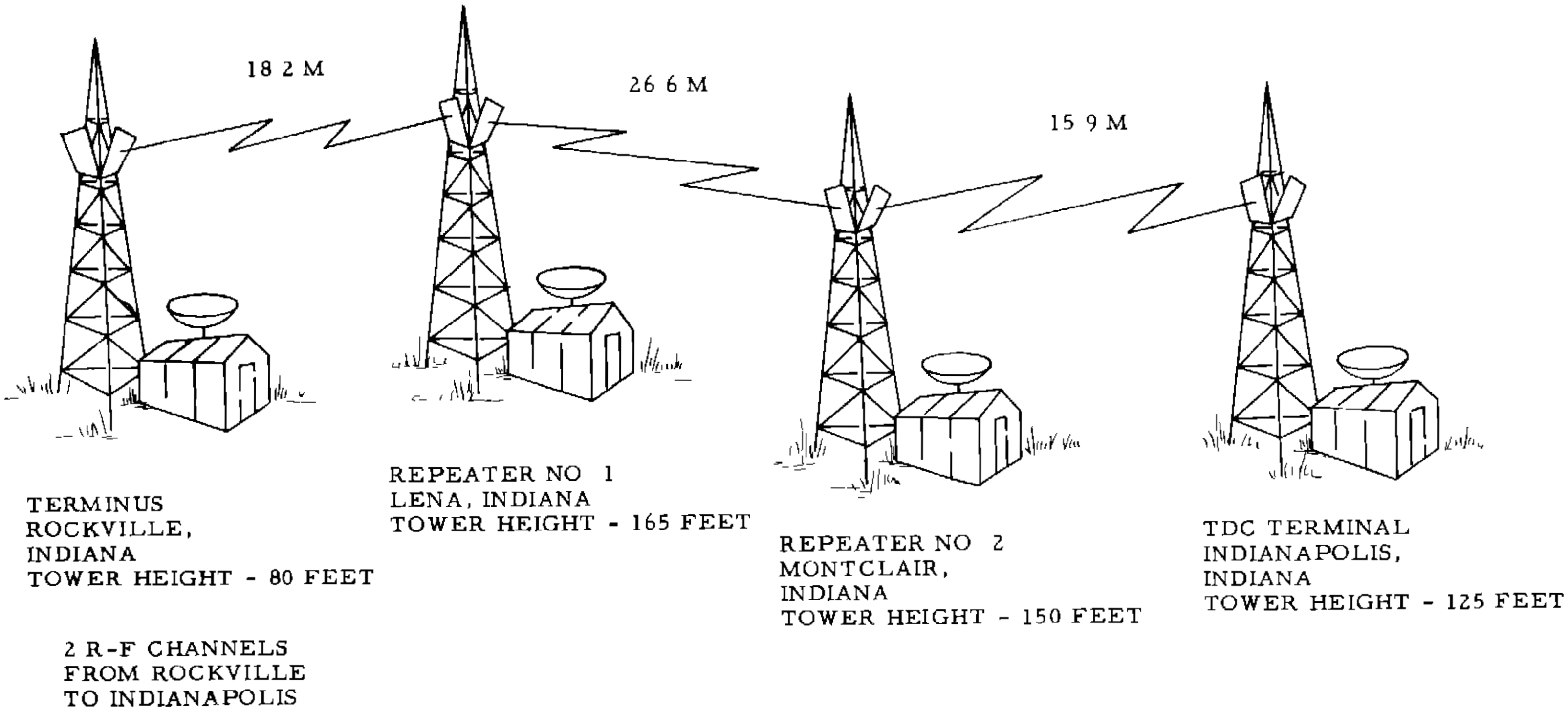
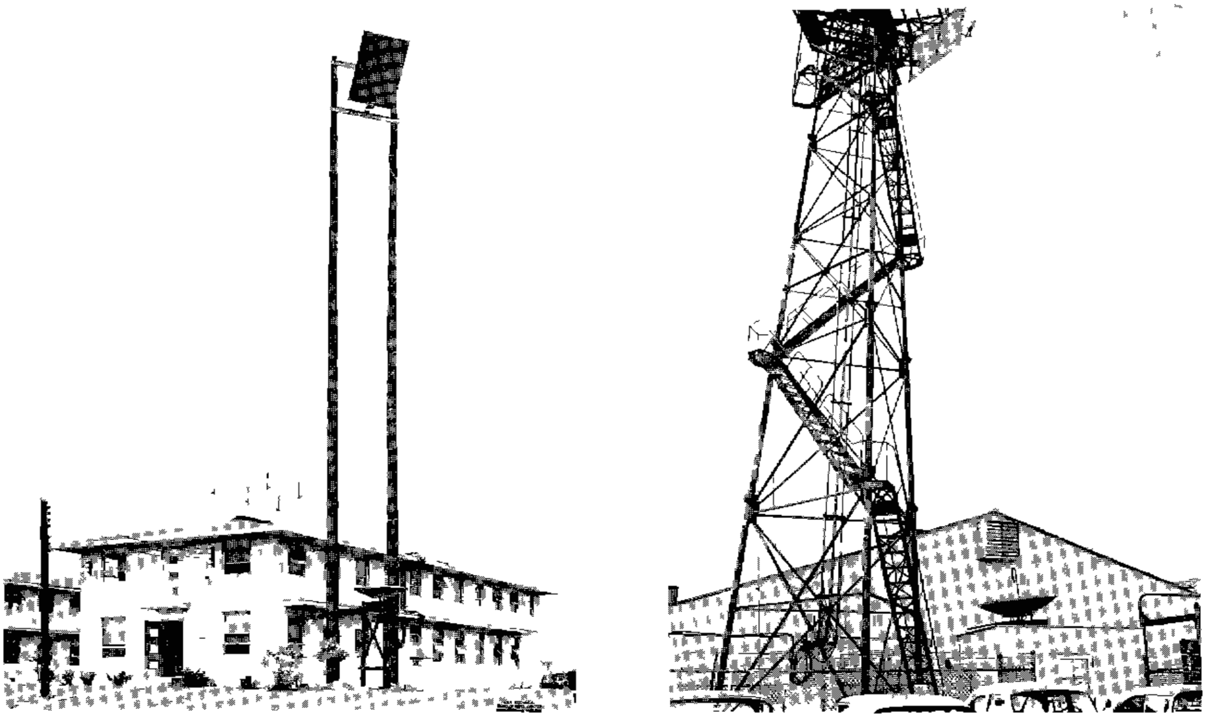
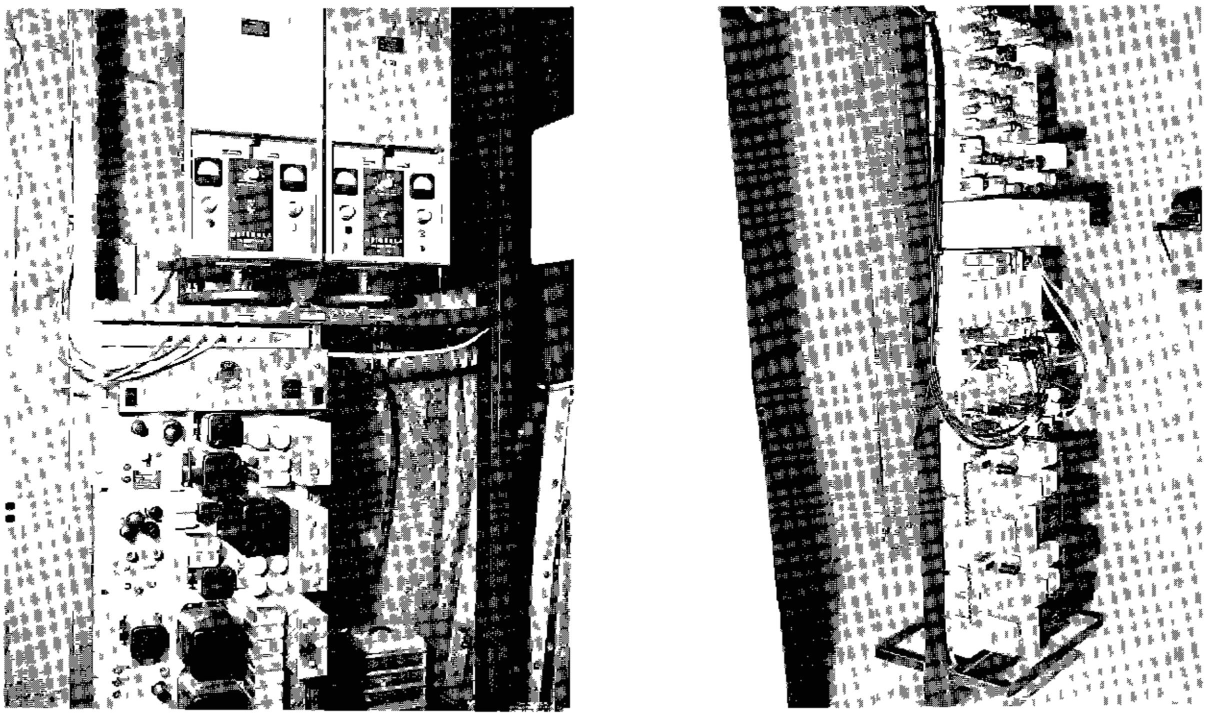


FIG 1 AOEC MICROWAVE LINK BETWEEN ROCKVILLE, INDIANA, AND INDIANAPOLIS, INDIANA



ROCKVILLE TERMINAL

INDIANAPOLIS TERMINAL



INDIANAPOLIS RF EQUIPMENT RACK

INDIANAPOLIS DEMODULATION EQUIPMENT RACK

FIG 2 PHOTOGRAPHS OF ROCKVILLE AND TDC TERMINALS AND INDIANAPOLIS TERMINAL EQUIPMENT

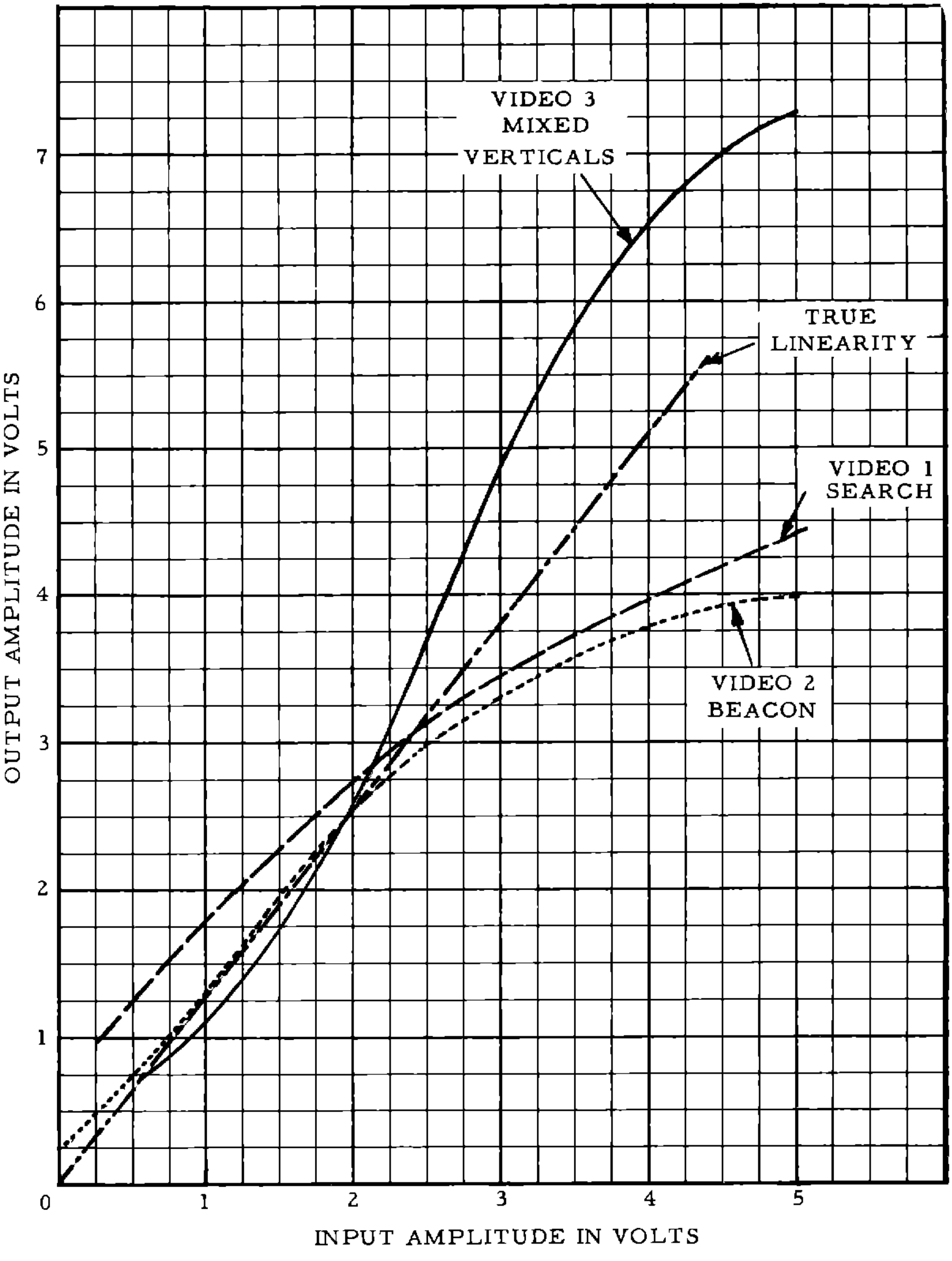


FIG 3 OUTPUT OF VIDEOS 1, 2, AND 3 VERSUS INPUT

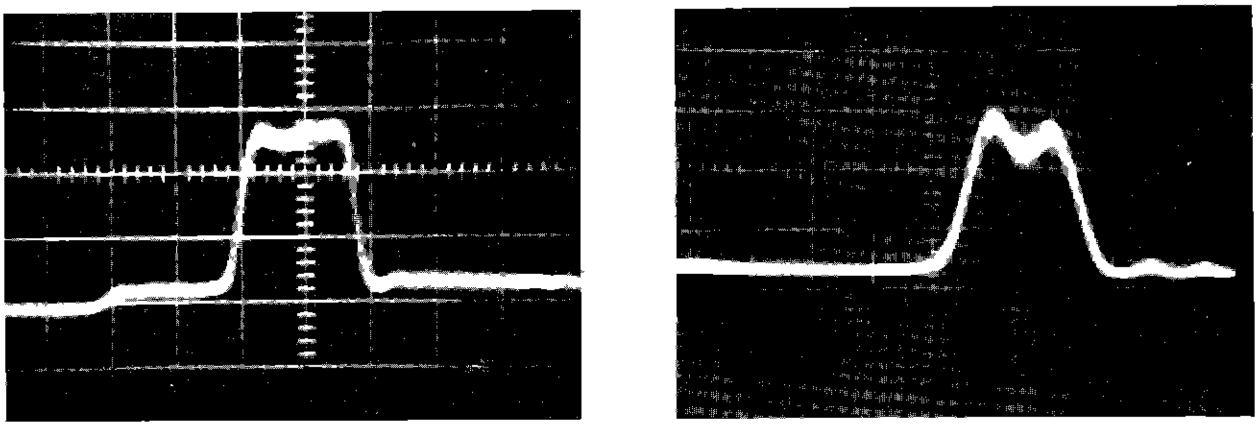


FIG 4A VIDEO 1 OUTPUT
0 5 MICROSECONDS/CM
0 5 VOLTS/CM
PULSE AMPLITUDE 1 3 VOLTS
NOISE AMPLITUDE 0 1 VOLTS
R_O = 15 MICROSECOND

FIG 4B VIDEO 2 OUTPUT
0 5 MICROSECONDS/CM
0 5 VOLTS/CM
PULSE AMPLITUDE 1 4 VOLTS
NOISE AMPLITUDE 0 1 VOLTS
R_O = 2 MICROSECOND

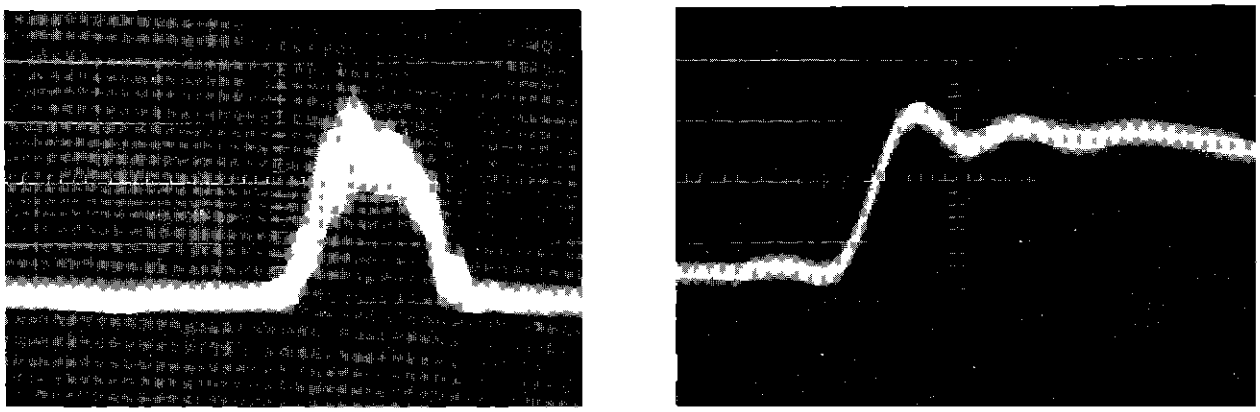


FIG 4C VIDEO 3 OUTPUT
0 5 MICROSECONDS/CM
0 5 VOLTS/CM
PULSE AMPLITUDE 1 2 VOLTS
NOISE AMPLITUDE 0 2 VOLTS
R_O = 25 MICROSECOND

FIG 4D CHANNEL B OUTPUT
5 MEGACYCLES WIDE
0 1 MICROSECONDS/CM
0 2 VOLTS/CM
R_O = 08 MICROSECOND

FIG 4 MICROWAVE LINK HIGH-FREQUENCY RESPONSE PHOTOGRAPHS

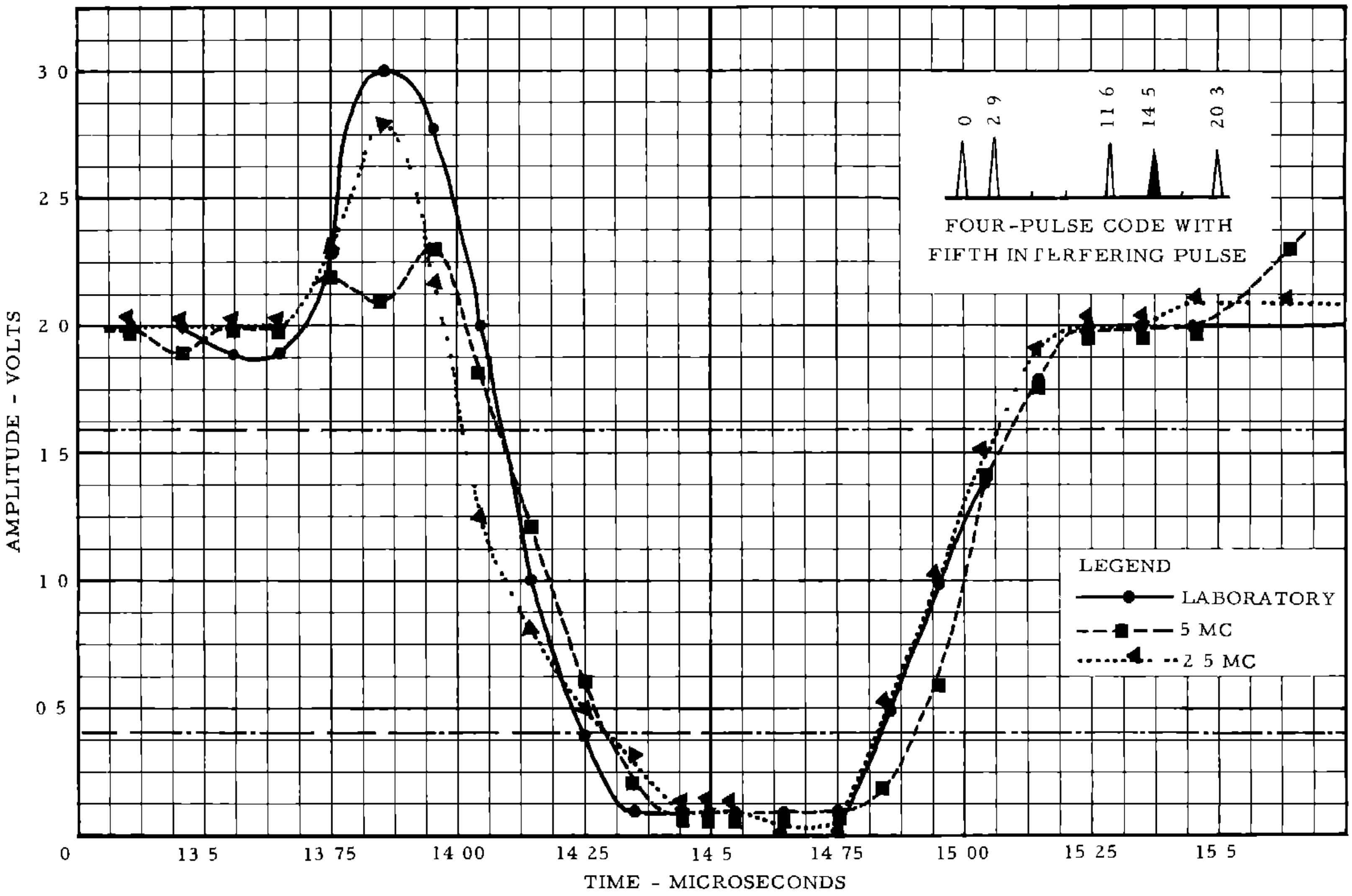


FIG 5 AMPLITUDE OF DECODER OUTPUT VERSUS POSITION OF INTERFERING PULSE