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THE USE OF FREQUENCY MODULATION FOR TELEVISION TRANSMISSION

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only

RESEARCH LABORATORY OF ELECTRONICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS

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Abstract

We have investigated the application of frequency modulation to television transmission. We have tested the possibility of improving the picture quality by using a receiver capable of taking full advantage of the capture effect. This procedure does not necessarily provide a distortionless signal. A ghost, characteristic of frequency modulation, is obtained under multipath propagation conditions. It is quite different from the ghost produced by amplitude modulation under similar conditions. By the use of de-emphasis, the effects of the frequency-modulation ghost can be reduced but not removed. A wider bandwidth system can give a better reduction of the interference. The question of whether the ghost obtained with frequency modulation is less objectionable than that obtained with amplitude modulation is a subjective one and is difficult to answer.

THE USE OF FREQUENCY MODULATION FOR TELEVISION TRANSMISSION

1. Introduction

Previous work (1, 2, 3) has shown that the effects of interference caused by multipath propagation may be considerably reduced by the use of frequency modulation. By designing the receiver to take full advantage of the capture effect it is possible to obtain distortionless operation in the presence of high-level, co-channel interference. A theoretical investigation of this effect was carried out some years ago, and experiments on the application to sound transmission were made (1, 2, 3).

2. Theory of the Method

Consider the case of two-path transmission. The time variation of instantaneous frequency of the signals arriving at the receiver over the two different paths will be the same, but one will be delayed relative to the other by an amount depending upon the difference in length of the two paths (see Fig. 1).

Over a short interval of time (such as that between t_1 and t_2) we can consider that the frequency of the one signal has a constant value, p; the other, a constant value, $p + r$. Suppose that the amplitude of the signal of frequency p is unity and that the amplitude of the other signal is a (a is less than unity). The resultant signal is then given by the vector sum of these two components (see Fig. 2). The interfering signal will rotate with a frequency r relative to the wanted signal and will cause the amplitude of the resultant to vary. It will also cause the instantaneous speed of rotation of the resultant to differ from that of the wanted signal, but since a is less than unity it is easily seen that the total number of rotations round the origin made by the resultant is the same as that made by the wanted signal. In practice p is always large compared with r, and so the average frequency of the resultant is the same as that of the wanted signal. This is the "capture effect."

If the amplitude of the resultant vector is A, then we can write (see Fig. 2)

$$Ae^{j\theta} = 1 + ae^{jrt}$$

$$\theta = \operatorname{Im}\left[\log\left(1 + ae^{jrt}\right)\right]$$

The instantaneous frequency of the resultant is obtained by differentiating the phase, θ, with respect to time.

$$\frac{d\theta}{dt} = \operatorname{Im}\left[\frac{d}{dt}\log\left(1 + ae^{jrt}\right)\right]$$

$$= ar\frac{(a + \cos rt)}{1 + 2a\cos rt + a^2}$$

as $a \rightarrow 1$, $d\theta/dt \rightarrow r/2$, $\left[\cos rt \neq -1\right]$.

When $\cos rt = -1$, we have $d\theta/dt = (-ar)/(1-a)$.

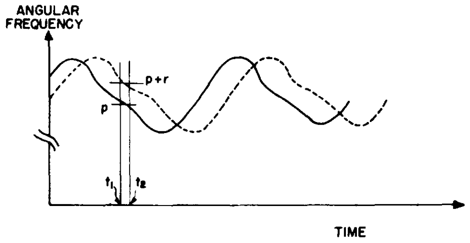

Fig. 1
Variation of angular frequency of direct and delayed signals.

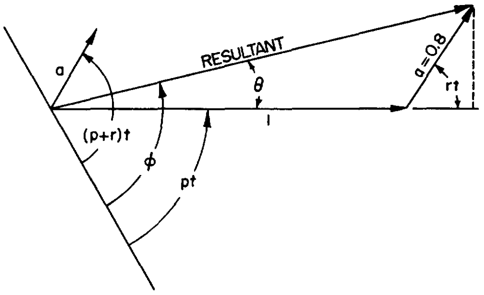

Fig. 2
Vector diagram for two-signal interference.

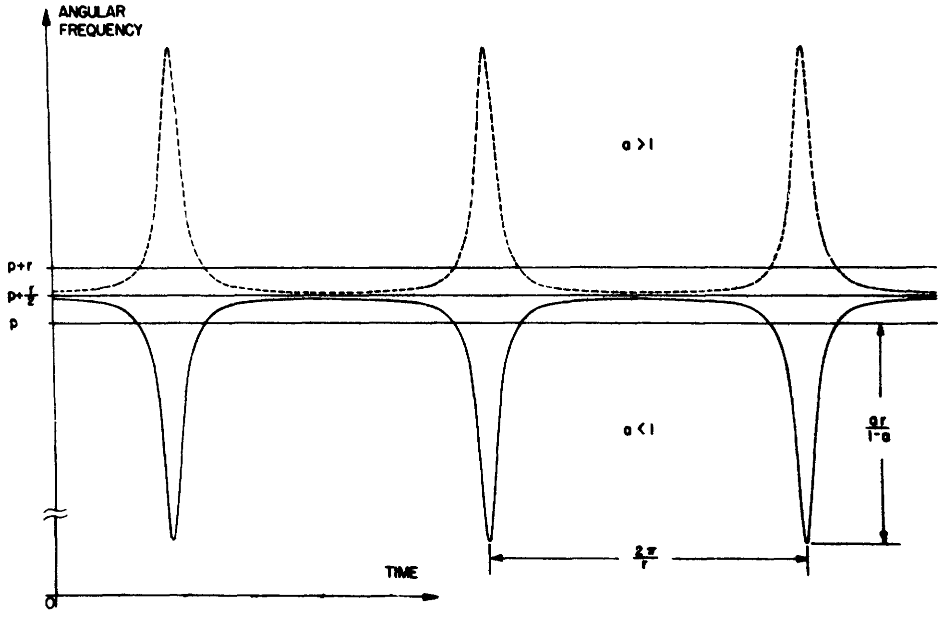

Fig. 3

Variation of instantaneous frequency for two-signal interference.

a = 0.8 (solid line)
a = 1.25 (dotted line)

Thus over the major part of the beat frequency cycle the frequency of the resultant is approximately the mean frequency of the two components. At the instant when these components are in antiphase there is a large shift in frequency in the direction of the stronger signal, which makes the average frequency of the resultant the same as that of the stronger signal. A plot of instantaneous frequency against time is shown in Fig. 3. The maximum difference between the instantaneous frequency and the frequency of the stronger signal is given by $(-ar)/(1-a)$ and is largest when r is largest. The largest possible value of r occurs when the two signals are at opposite extremes of the range of deviation. If the weaker and stronger signals are interchanged, the spikes are in the opposite direction (shown dotted in Fig. 3). The total range covered by the spikes is therefore $\left[(1+a)/(1-a)\right] r_m$ where r_m is the frequency deviation. When $a = 0.7$, this range is nearly 6 times the deviation; when $a = 0.95$, it is 39 times the deviation.

To preserve the average frequency, it is necessary to preserve the spikes; therefore the frequency detector must be linear over this wide range. Further, for large values of a, the frequency changes very rapidly with time during the period of the spike, and the detector must be fast-acting to prevent diagonal clipping. When the two components are in antiphase, not only is there a rapid variation in instantaneous frequency, but there is also a sharp dip in amplitude. Thus the limiters must be able to remove this downward amplitude modulation, which also means that they, too, must be fast-acting. The intermediate-frequency amplifiers must be flat over the deviation range to insure that the stronger signal at the input always remains the stronger signal at the output, irrespective of its own frequency or that of the interfering signal. In practice, there will always be some ripple in the passband. The worst situation will arise when the wanted signal falls at a minimum of the characteristic and the interference falls at a maximum. The ratio of unwanted to wanted signals at the output is then higher than that at the input by a factor given by the ratio of maximum to minimum amplification in the passband. Thus, if the percentage ripple in the passband is 100ϵ, and the limiter and detector are designed for a capture of a^1, then the over-all capture ratio of the receiver is given by $a = (1-\epsilon)a^1$. It should be noted that the intermediate-frequency bandwidth is not determined by the same considerations which determine the total frequency range covered by the spikes. (In fact, it could not be, since then the receiver would have no selectivity.) The signal in the intermediate frequency consists of two spectral components, one at p and one at $p + r$. These are obviously always within the range of deviation, and this range, consequently, determines the required intermediate-frequency bandwidth. This signal, however, contains large spikes in its instantaneous frequency and also large amplitude modulation. It is the removal of the amplitude modulation by the limiters which gives rise to the higher-order spectral components and implies the need for a broad bandwidth in all subsequent stages (i.e., in the limiters and the detector).

Although it is possible by these means to obtain from the receiver an output signal whose average frequency is the same as that of the wanted signal, it does not necessarily follow that this output will be distortionless. This depends upon the amount of filtering it is possible to employ for the removal of the spikes. We shall return to this point later in connection with pre-emphasis.

3. Method of Experimenting

It was found convenient to make the experimental tests with a facsimile system rather than a standard television system. The particular facsimile system that we used operates without synchronizing signals during the transmission of the picture. This means that attention is concentrated on the picture quality attainable. The time taken to scan one line in this system is about 0.6 sec; in television it is approximately 60 μsec. The scale factor in time is therefore about $1 : 10^4$.

A block schematic diagram of the equipment is shown in Fig. 4. The signal from the facsimile transmitter is obtained as an amplitude-modulated carrier at a frequency of 1800 cps. This signal is detected and the video waveform used to frequency-modulate a 14 kc/sec carrier, which can then be passed through a filter to limit the frequency band used. To simulate multipath conditions, an acoustic delay line is used to give a delay of some 25 msec. The two signals, direct and delayed, are passed through separate limiters and then added together in the desired ratio. The resulting signal is then passed through a limiter and a frequency detector and the video output fed, as amplitude modulation of a carrier of 1800 cps, to the facsimile receiver.

Although the experimental work has been done with a facsimile system, the figures quoted in this report will be those that correspond to the television system.

A value of 140 Mc/sec was chosen as suitable for the carrier. The bandwidth assigned for television channels in practice is 3 Mc/sec for single sideband operation. Double sideband operation was employed here and a bandwidth of 5 Mc/sec was used. Interfering signals up to 70 percent of the wanted signal were investigated; hence the bandwidth required in the detector is about 28.5 Mc/sec. In order to assess the advantages of a wider transmission bandwidth, the detector is linear over a range of 60 Mc/sec. This allows for an interference of 70 percent and a maximum bandwidth of about twice the present television standard. A ratio detector was used to insure rapidity of action and to take advantage of the limiting properties of this type of detector. It is preceded by a three-stage crystal limiter. In this equipment no i-f amplifier is used.

The effect of multipath interference in television, when using amplitude modulation, is to produce a ghost picture in addition to the main image. A typical value for the spacing of the two images on a 12-inch screen is approximately 0.5 inch, which corresponds to a delay of 2.5 μsec.

In these experiments we used the whole of the available bandwidth for deviation. Since this will not allow the transmission of the higher-order sidebands, intolerable distortion of the picture might, at first sight, be expected. However, a picture waveform is composed mainly of fairly rapid transitions from one level of grey to another. The most stringent case to be dealt with consists of a transition from black to white with the maximum rise time of which the system is capable. Tests were made with a

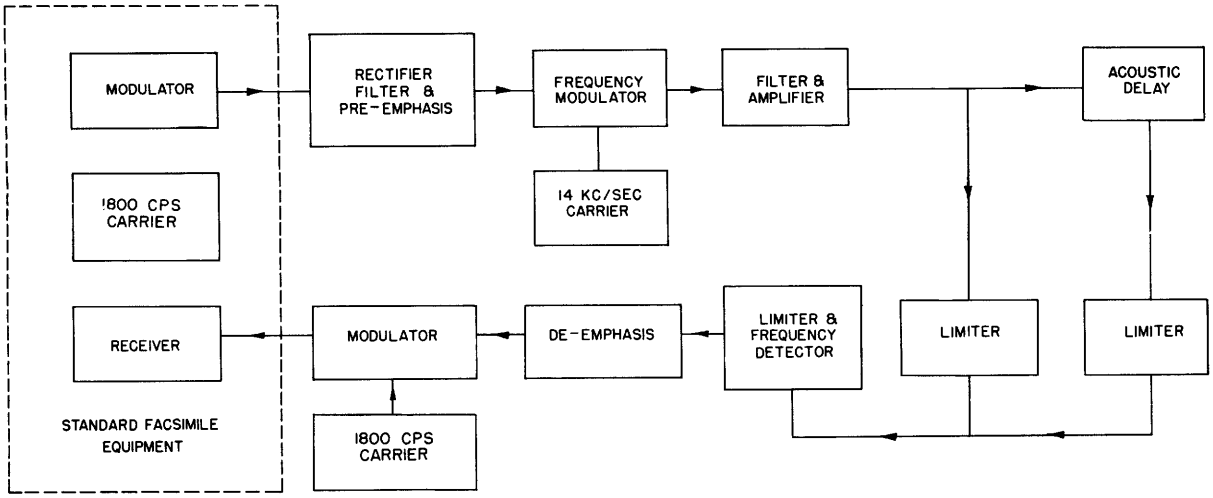

Fig. 4

Block schematic diagram of equipment.

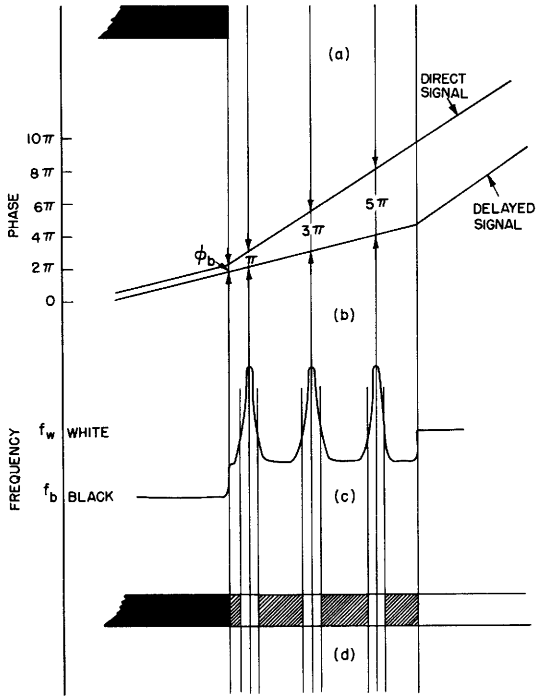

Fig. 5

The formation of frequency-modulation ghosts.

three-element Butterworth filter with 3-db points at 140 ± 2.5 Mc/sec. The test signal was frequency-modulated with a trapezoidal wave of 0.08 μsec rise time. The output of the filter was then detected and the rise time of the output waveform observed. When the frequency swing was 5 Mc/sec the rise time increased to 0.2 μsec. (A slight overshoot was also observed.) Thus in the worst case the rise time is increased by a factor of only 2.5. Pictures were taken with and without this filter in the experimental system and very little over-all difference in picture quality is noticeable.

An important difference between the system shown in Fig. 4 and an actual transmitter-receiver system might be mentioned. In section II we noted that the intermediate-frequency stages of the receiver must have a flat frequency response to obtain effective capture. This, in fact, applies equally to all of the stages which are previous to the intermediate-frequency stage, including the amplitude-frequency characteristics of the transmitted signals. However, in the arrangement shown in Fig. 4, the two signals are received separately and are passed through separate limiters. The outputs of the two limiters are then added in the desired ratio. Thus the frequency characteristic of the transmitting system produced by the filter in the transmitter, or by the characteristic of the delay network, cannot upset the capture properties. But since the higher-order sidebands removed by the filter cannot be recovered by limiting, the frequency characteristic of the transmitting system can give rise to distortion.

4. Results

We shall first discuss the effect of the spike interference on the picture. Consider a simple black-to-white transition, as shown in Fig. 5a, and suppose that we have two-path transmission. Suppose, also, that the direct signal is the larger. Before the transition takes place, the frequency of the signals arriving by both paths is that corresponding to black, f_b; therefore, the frequency of the resultant is f_b (Fig. 5c). For a period equal to the time delay of the weaker signal on the stronger, the frequency of the stronger signal is that corresponding to white, f_w, whereas that of the weaker signal is still f_b. Throughout most of this period, then, the resultant signal has a frequency $1/2\ (f_b + f_w)$ which corresponds to some shade of grey. However, since the average frequency of the resultant must be f_w, there will be frequency spikes in the direction corresponding to white. These spikes will exceed the white level but since a signal corresponding to "whiter than white" will be registered as white by the system, the resulting pattern will consist of white spots on a grey background. (See Fig. 5d.) (Note that in Fig. 5, the abscissa can be thought of as either time or distance across the picture; the two are related by the speed of scanning, which is constant.)

Now suppose that the time delay of the interfering signal is τ. Then during a period of "black" transmission, the phase difference between the two signals is $\phi_b = 2\pi\tau f_b + 2\pi k$ (where k is an integer). When the direct path changes frequency, the phase difference between the two signals increases linearly at a rate given by $2\pi(f_w - f_b)$, as shown in Fig. 5b. Thus, if the instant at which the direct path changes corresponds to $t = 0$, the phase difference at time t later is given by

$$2\pi\tau f_b + 2\pi k + 2\pi(f_w - f_b)t$$

A spike is formed when this expression has a value $(2n - 1)\pi$, where n is an integer

$$(2n - 1)\pi = 2\pi\tau f_b + 2\pi k + 2\pi(f_w - f_b)t$$

or

$$t = \frac{1}{2\pi(f_w - f_b)}\left[\left\{2(n-k) - 1\right\}\pi - 2\pi\tau f_b\right]$$

$$= \frac{1}{2(f_w - f_b)}\left[2(n-k) - 1 - 2\tau f_b\right]$$

The first spike is formed when

$$t = \frac{1 - 2\tau f_b}{2(f_w - f_b)}$$

which is dependant only upon τ, f_w, and f_b. Therefore the distance of the spot from the transition is the same for all transitions between two given frequencies. And on any line scan, the white spots will fall adjacent to the ones formed on the previous line and the resulting pattern will consist of white stripes on a grey background, as shown in Fig. 5d. Furthermore, the pattern formed on any particular frame will superimpose exactly on that formed in the previous frame.

From section II we know that the spike recurrence rate is equal to the frequency difference between the two signals. When we use a 5 Mc/sec deviation, the spacing of the stripes following a black-to-white transition, when viewed on a 12-inch screen, will be approximately 0.04 inch, which will be quite noticeable. A transition of lower contrast will give wider spacing and will lead to a more objectionable effect, although the magnitude of the spike (which is also proportional to the frequency difference) is smaller, until the spike becomes small enough to make the variation in intensity negligible.

The problem of removing this effect by filtering is difficult. The major effect of a low-pass filter would be to reduce the height of the sharp spike. This reduction will not make any difference to the picture, since it will still be registered as white. The filter will also cause only a relatively small shift in the grey level of the background. A more promising method of removing the effect would be to increase the spike recurrence rate above the resolving power of the system. In fact, if this resolving power is just sufficient to resolve the highest frequency that we desire to transmit, this solution automatically demands a bandwidth assignment greater than that determined from the frequency components in the modulation waveform. (This is the situation existing in frequency-modulation sound broadcasting where the highest audiofrequency transmitted is about 15 kc/sec, and the bandwidth assignment is ± 75 kc/sec.) If we retain the original 5 Mc/sec bandwidth, the spike frequency will always be in the same region as the picture information. It would appear, therefore, that the spikes cannot be removed without removing some of the picture information, with consequent deterioration of the quality of the final picture. However, the spikes are formed at the receiver; they are not present in the original modulation waveform at the transmitter. Thus it is possible to design a filter for reducing the effect of the spikes without affecting picture quality, if the inverse filter is used at the transmitter to pre-correct for its effect. We are therefore led to a consideration of pre-emphasis, commonly used in frequency-modulation sound transmission.

Consider, again, the case of a rapid transition from black to white. The resulting waveform will approximate a ramp function. If this is applied to a pre-emphasis circuit, which is essentially a differentiating circuit, an overshoot is produced. If the normal black-to-white transition shifts the transmitter frequency from one end of the band to the other, the pre-emphasized transition would, because of the overshoot, take the frequency outside the assigned bandwidth. To prevent this from happening, the frequency difference corresponding to a black-to-white transition would have to be reduced. This, however, would reduce the repetition frequency of the spikes, making them more difficult to remove. An investigation into the problems of video pre-emphasis has been made previously (4). The solution adopted here was to pass the pre-emphasized wave through a clipping circuit that removes all overshoots that would take the transmitter outside the prescribed range. Since a standard de-emphasis circuit is used, some deterioration of picture quality results. The characteristic of the pre-emphasis circuit is given approximately by $\left[1 + (f/f_p)^2\right]^{1/2}$. By using a ramp function with a rise time of 0.08 μsec this circuit gives an overshoot of about 100 percent, with f_p adjusted to 800 kc/sec. From earlier numerical calculations (using the uniform stretch function (5) to represent the transition), we can estimate that removing the whole of this overshoot and then using standard de-emphasis will increase the rise time by a factor of about 8. Hence, there may be some blurring of high-contrast transitions. But this is the worst case that can occur. The rise time of a transition less than full black-to-white will not suffer so much deterioration, since only part of the overshoot is removed. (If the contrast is less than a certain level, none of the overshoot is removed.) However, the blurring of high-contrast transitions will always be present, even under single-path transmission conditions. The characteristic of the de-emphasis circuit is given by $\left[1 + (f/f_p)^2\right]^{-1/2}$. The lower the frequency f_p, the more effective the de-emphasis circuit becomes in reducing the spikes; but the overshoot produced by the corresponding pre-emphasis circuit will increase. This overshoot must be removed to prevent the given bandwidth being exceeded; and the larger that overshoot is, the greater the deterioration of picture quality caused by its removal. Thus the retention of picture quality and the reduction of the spikes are conflicting requirements.

5. Representative Pictures

An original of the picture used for these tests is shown in Fig. 6. The facsimile system operates with a picture 8.5 inches by 7 inches which is scanned along its longer dimension and uses approximately 600 lines. Thus the resolving power of the facsimile system is somewhat greater than that of the television system. A television screen is normally viewed at a distance that makes the line structure unnoticeable. To get a proper comparison, the pictures reproduced here should be viewed at a distance of approximately 5 feet.

The first group of pictures (Fig. 7) was taken using amplitude modulation for comparison. The group of pictures shown in Fig. 8 illustrates frequency-modulation ghosts produced by interfering signals of different strengths. The whole of the 5 Mc/sec bandwidth was used for deviation; a pre-emphasis frequency of 800 kc/sec was used; and any overshoots that would take the transmitted frequency outside the assigned bandwidth were removed. In a typical practical case the interfering signal will be about half the wanted signal; Fig. 9 shows the results of experiments made with this level of interference to determine whether there is any de-emphasis frequency that will give a satisfactory reduction of the spikes without intolerable deterioration of picture quality. With the lowest de-emphasis frequency used (200 kc/sec) the ghosts are still objectionable and the picture quality is already unacceptable. It would appear that with a 5 Mc/sec bandwidth no satisfactory compromise can be made to reduce the effects of the ghosts caused by an interference level of 50 percent without impairing the quality of the picture too much. It may be noted that with the present system used for television broadcasting no effort is made to reduce the effects of ghosts at all. By the same standards this system would also be regarded as unsatisfactory.

The results of using wider bandwidths are shown in Fig. 10. Here the ghosts occurring at high-contrast transitions are removed almost completely without objectionable deterioration of picture quality, but the ghosts occurring at lower contrast transitions are still in evidence. The de-emphasis circuit cannot effectively remove these because the spike frequency is lower.

6. Conclusions

Under conditions of multipath transmission, it is possible for the stronger signal to capture in a frequency-modulation system even in the presence of a strong interfering signal. This does not necessarily result in an undistorted signal. Spike interference is present and its repetition rate depends upon the frequency swing. In television transmission the spikes produce a characteristic ghost. If the assigned bandwidth is the same as the highest components of the video waveform that is to be transmitted, the spike frequency always falls in a region of the spectrum where there is picture information, and effective filtering is difficult. The use of pre-emphasis simplifies this problem but does not completely solve it. If wider bandwidths are employed, then a more effective reduction of the interference is possible.

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CAUTION

Figures 6-10 are meaningless as a gauge of the system unless they are viewed from a distance of at least 5 feet. It is very important to use this viewing distance. This awkward procedure has been adopted to reduce the effects of the printing process.

Fig. 6

Picture used for transmission.
(Viewing distance, 5 feet)

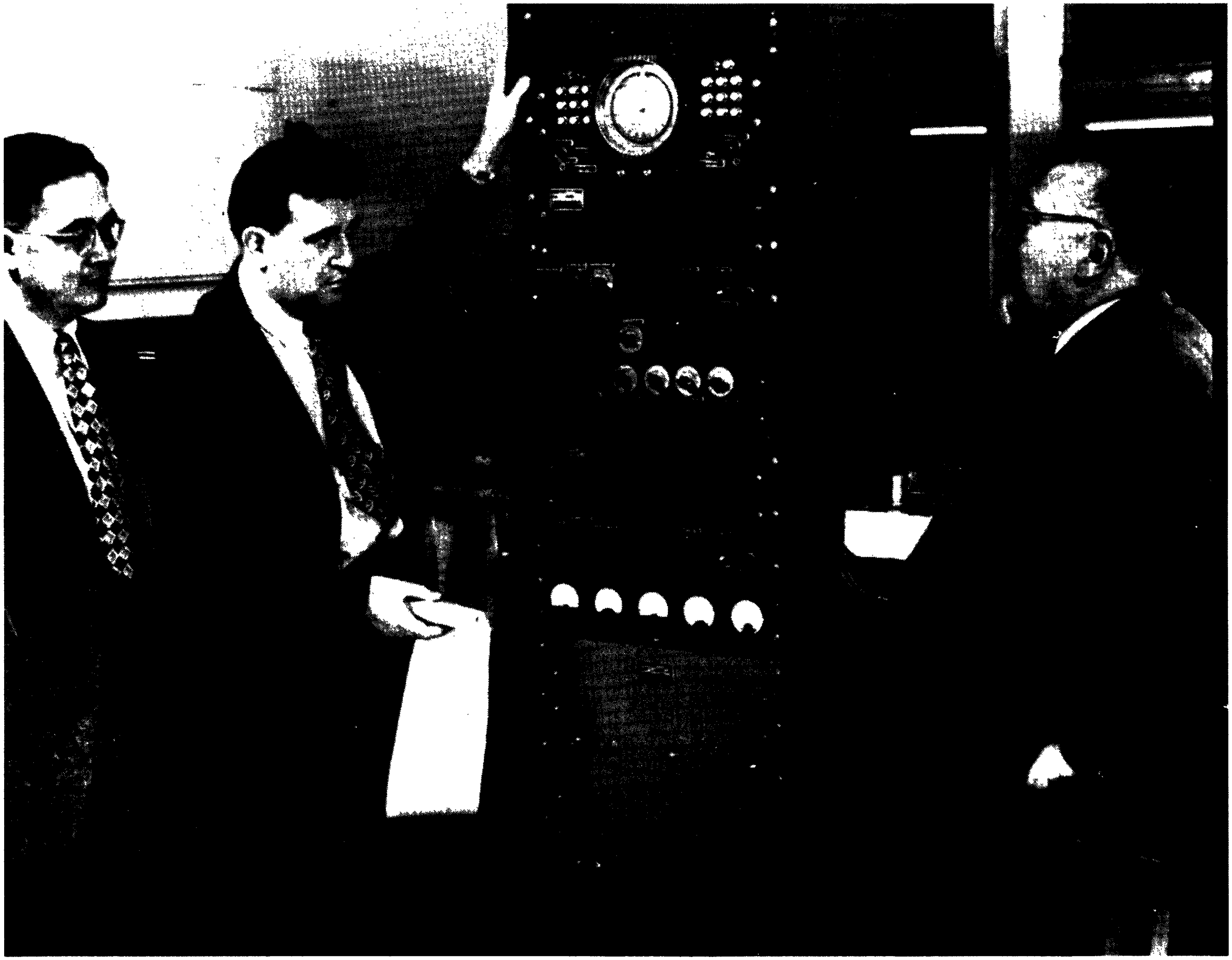


Fig. 7 (i)

To show the effects of multipath interference using amplitude modulation.
a = 0.1
(Viewing distance, 5 feet)

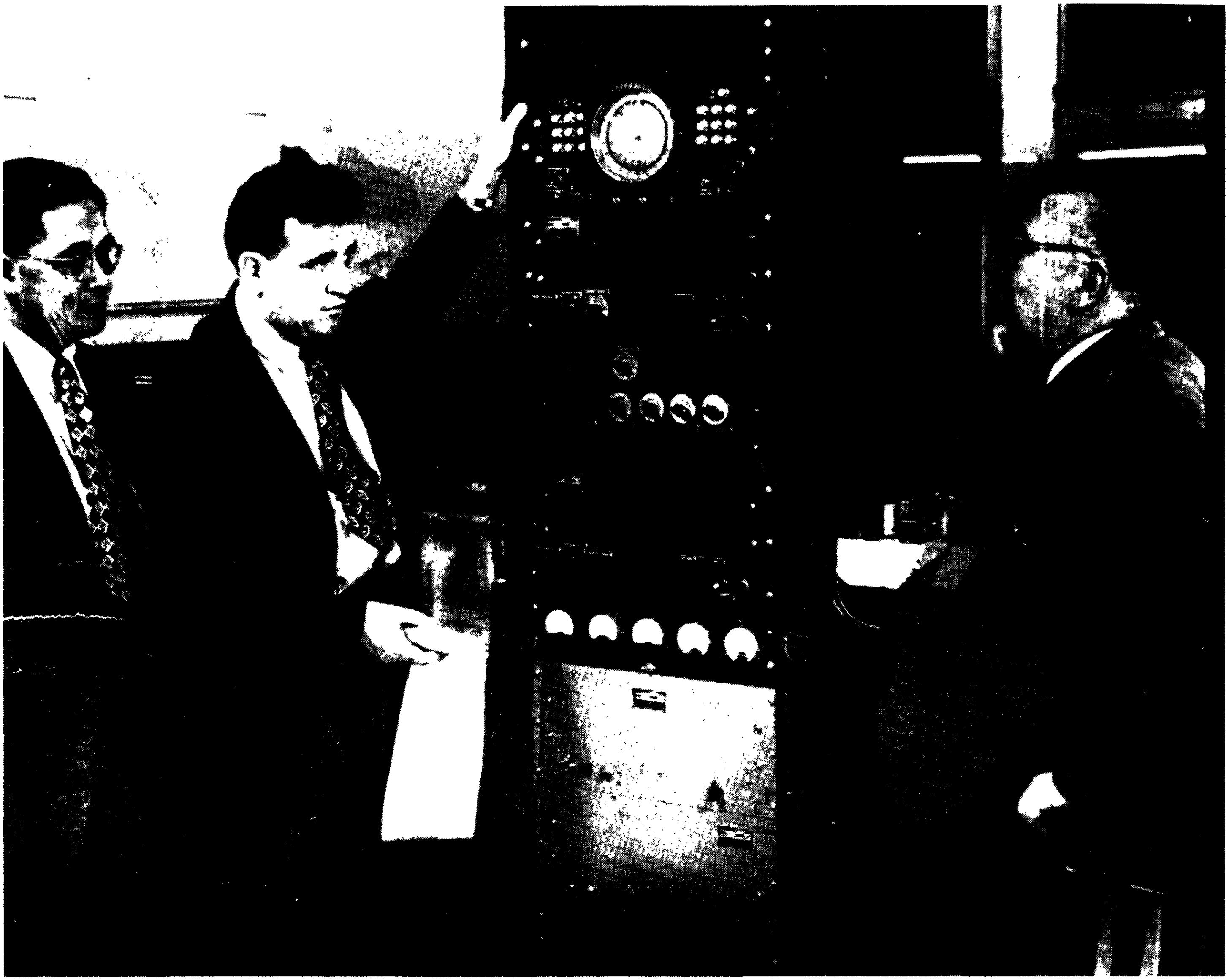


Fig. 7 (ii)

To show the effects of multipath interference using amplitude modulation.
a = 0.3
(Viewing distance, 5 feet)

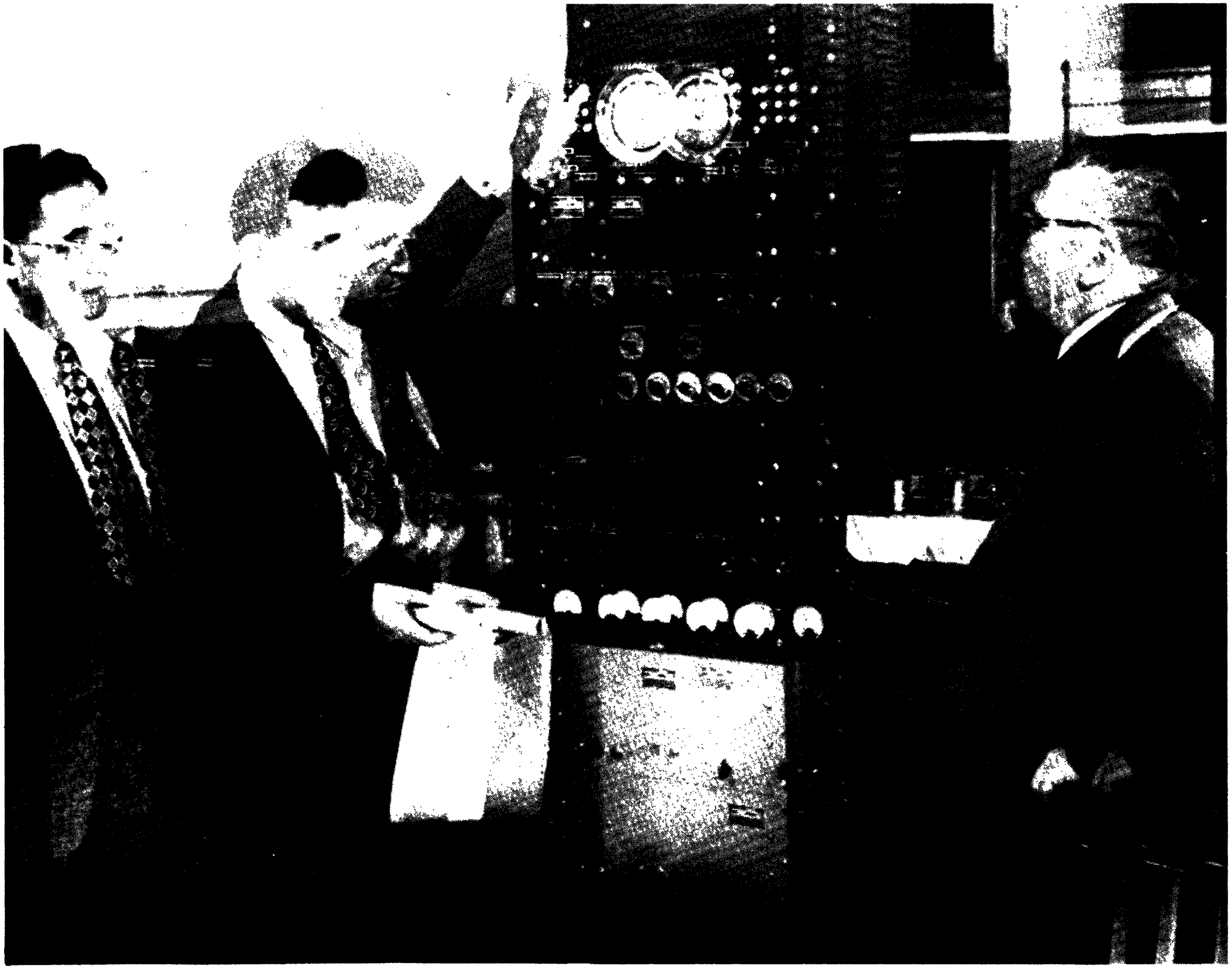


Fig. 7 (iii)

To show the effects of multipath interference using amplitude modulation.
a = 0.7
(Viewing distance, 5 feet)

Fig. 8 (i)

To show how the frequency modulation ghost is affected by interfering signals of different strengths.

a = 0.1
(Viewing distance, 5 feet)

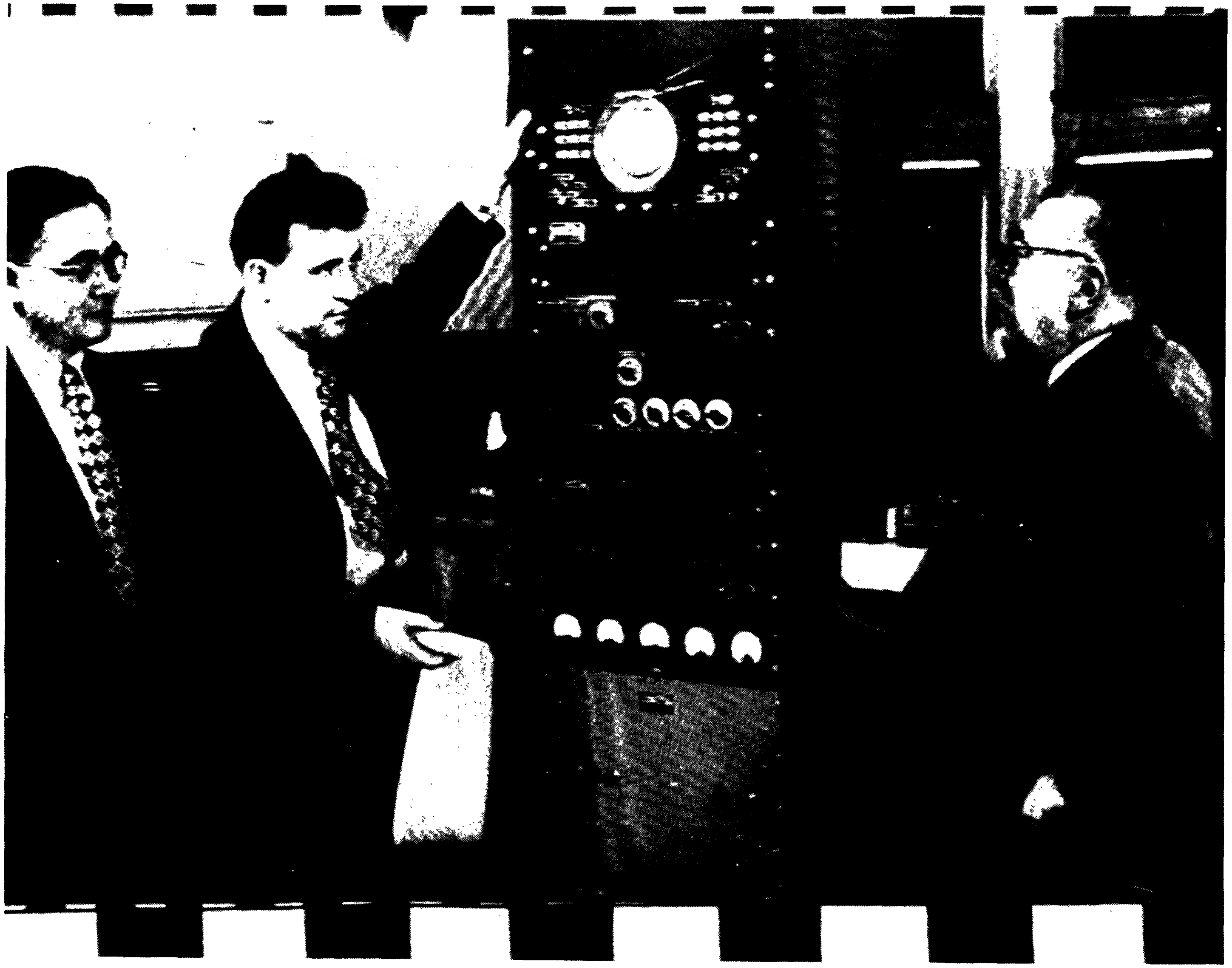


Fig 8 (ii)

To show how the frequency modulation ghost is affected by interfering signals of different strengths.

a = 0.3
(Viewing distance, 5 feet)

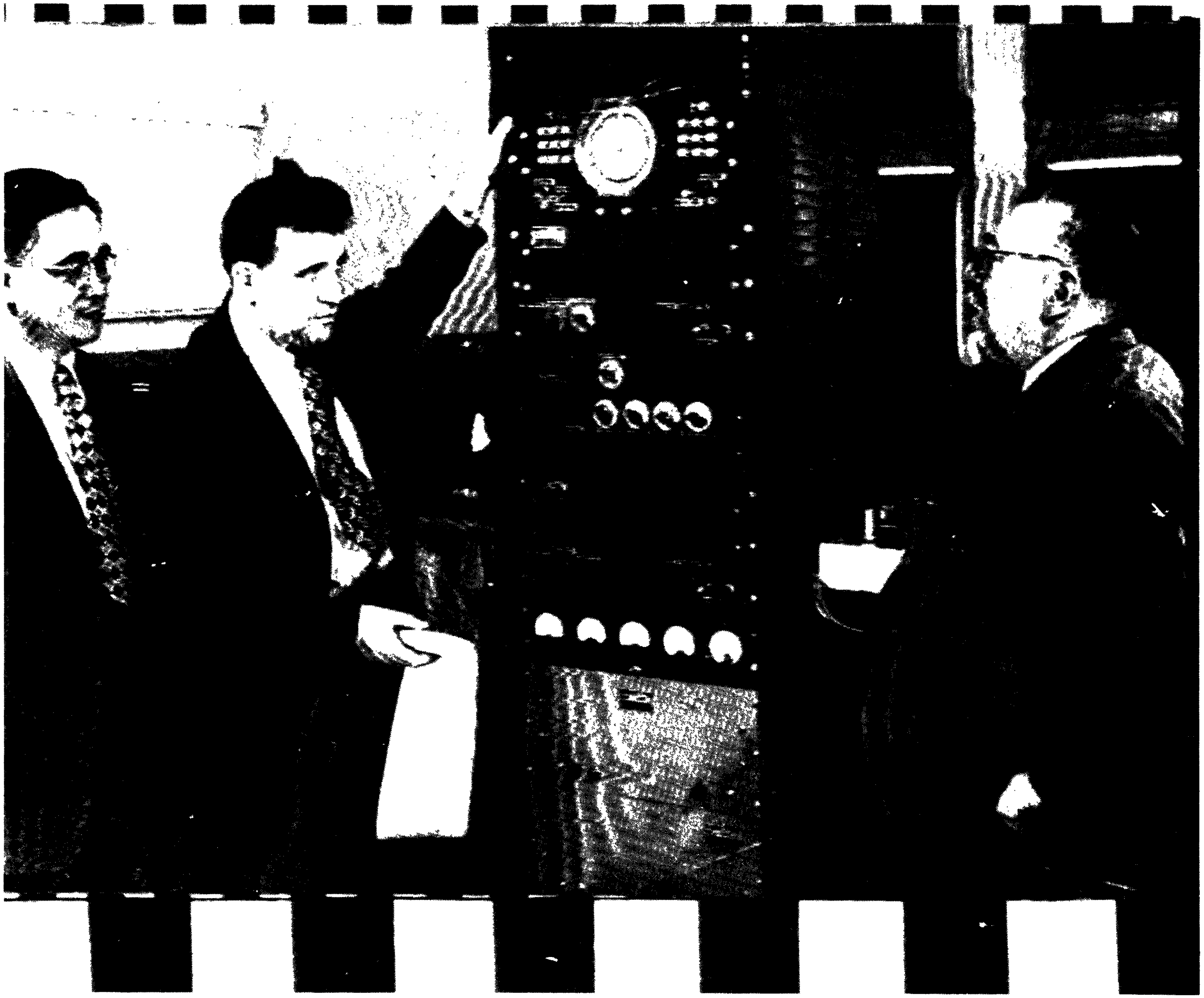


Fig. 8 (iii)

To show how the frequency modulation ghost is affected by interfering signals of different strengths.

a = 0.5
(Viewing distance, 5 feet)

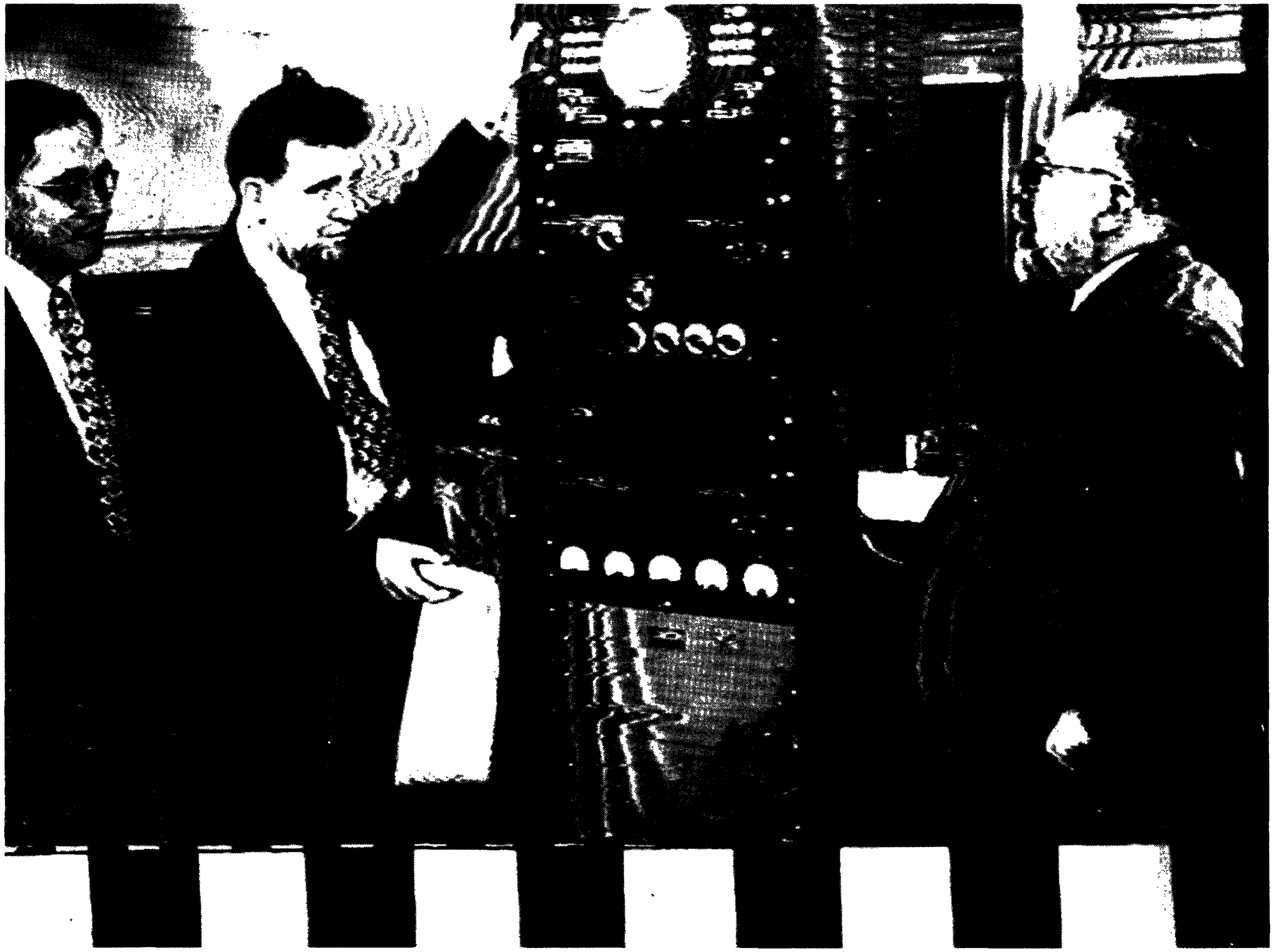


Fig. 8 (iv)

To show how the frequency modulation ghost is affected by interfering signals of different strengths.

a = 0.7

(Viewing distance, 5 feet)

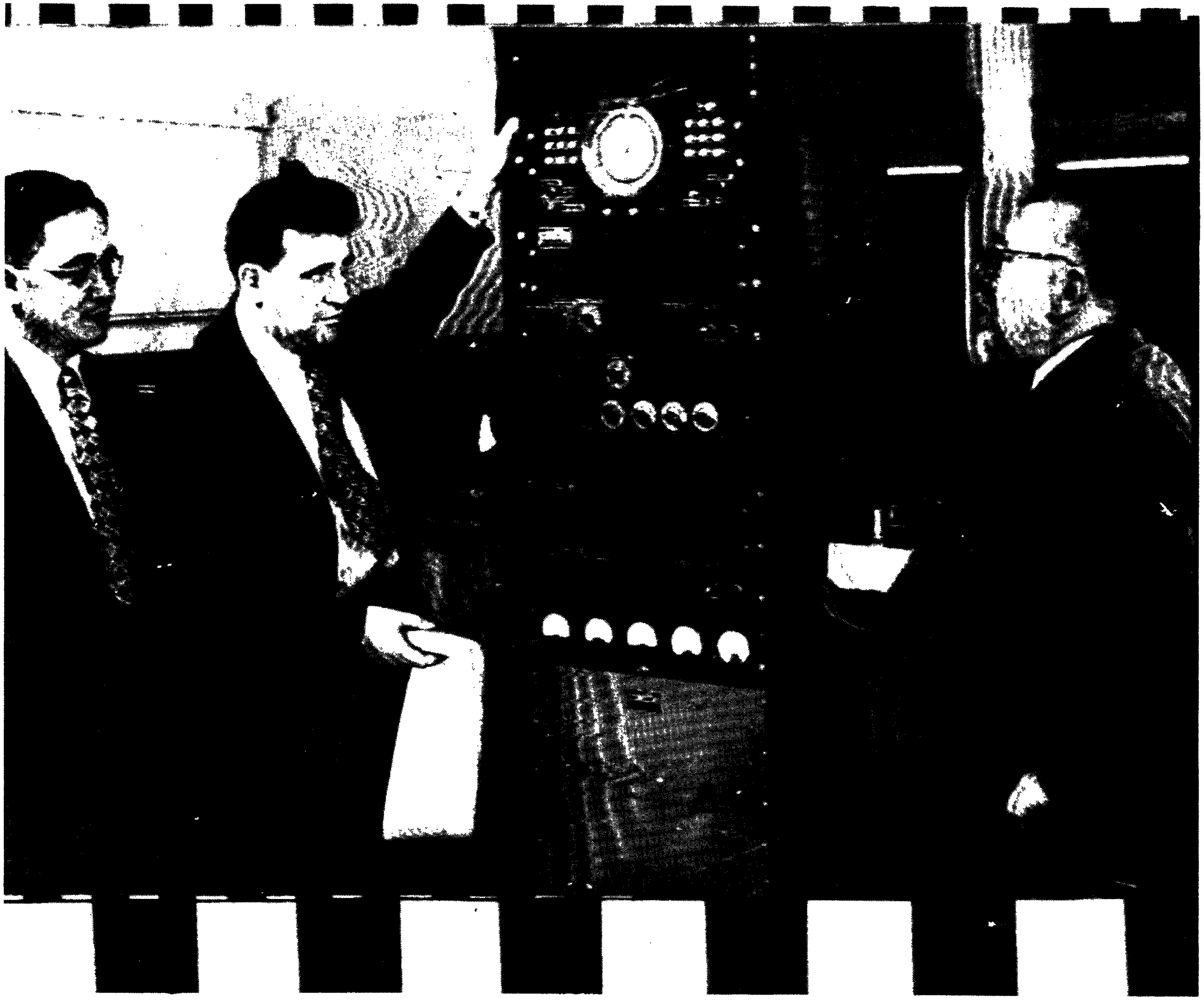


Fig. 9 (i)

To show the effect of varying the de-emphasis frequency.

f = 800 kc/sec
(Viewing distance, 5 feet)

Fig. 9 (ii)

To show the effect of varying the de-emphasis frequency.

f = 400 kc/sec
(Viewing distance, 5 feet)

Fig. 9 (iii)

To show the effect of varying the de-emphasis frequency.

f = 200 kc/sec
(Viewing distance, 5 feet)

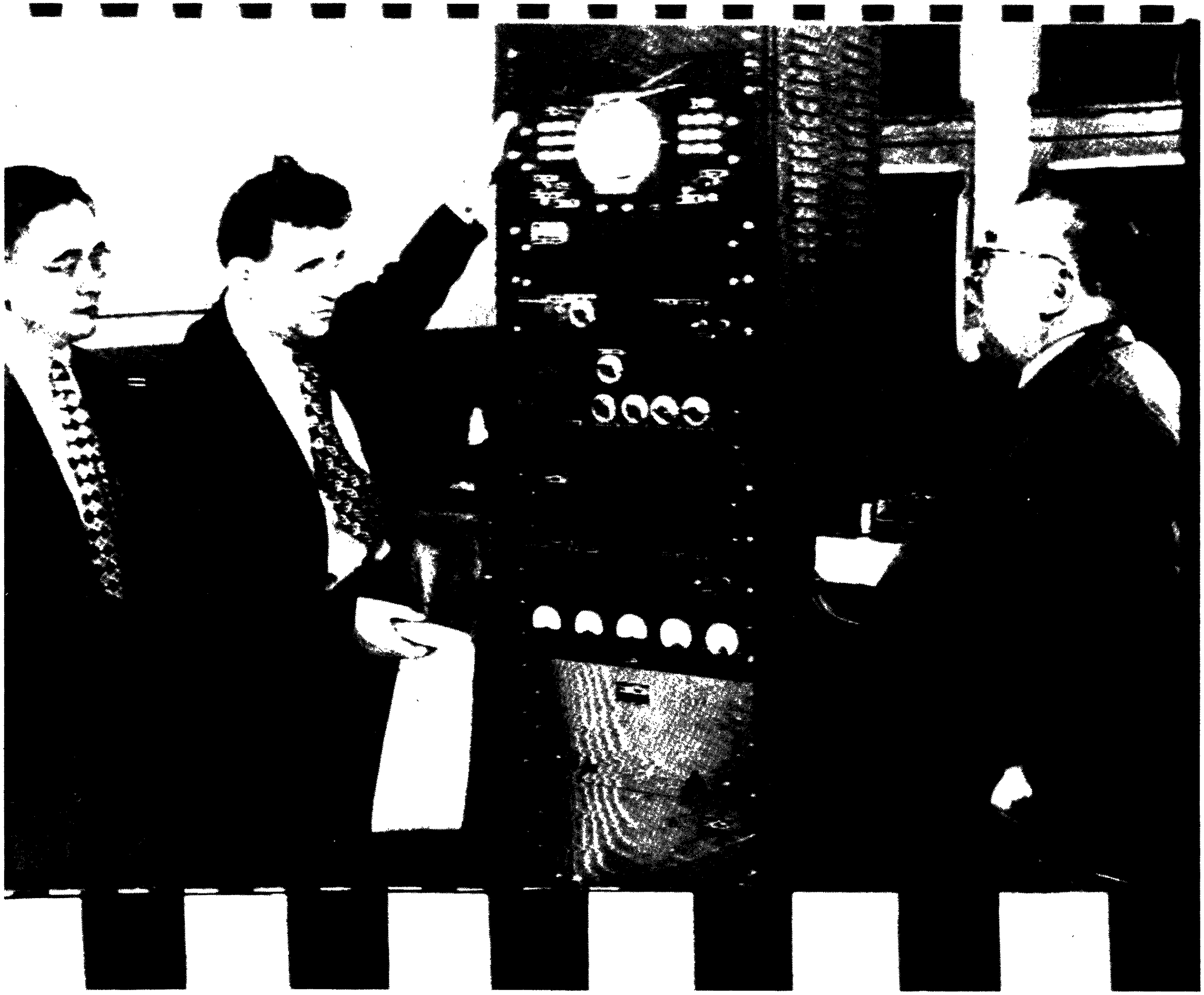


Fig. 10(i)

To show the effect of using wider bandwidths.

a = 0.7 B = 10 Mc/sec
(Viewing distance, 5 feet)

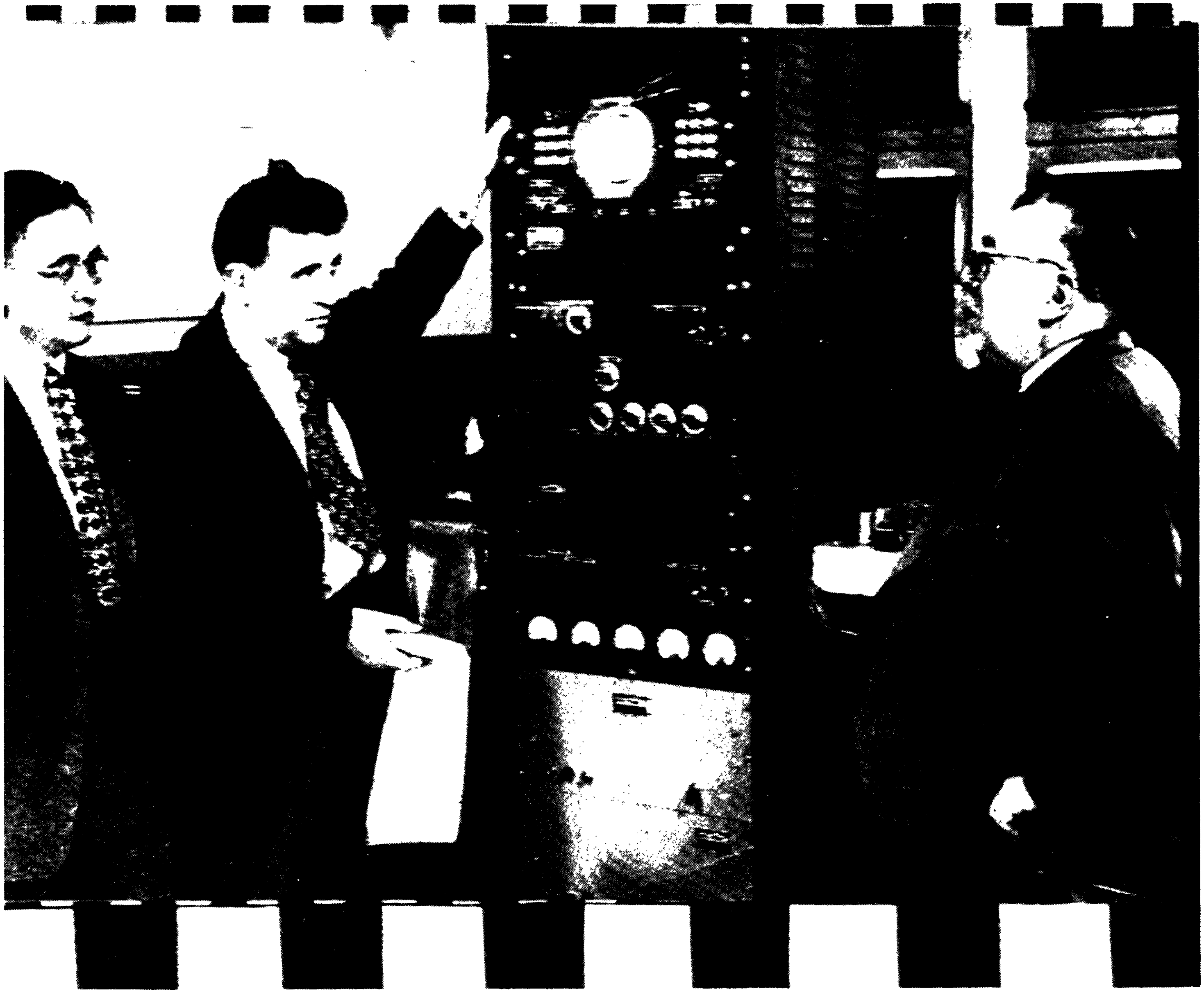


Fig. 10 (ii)

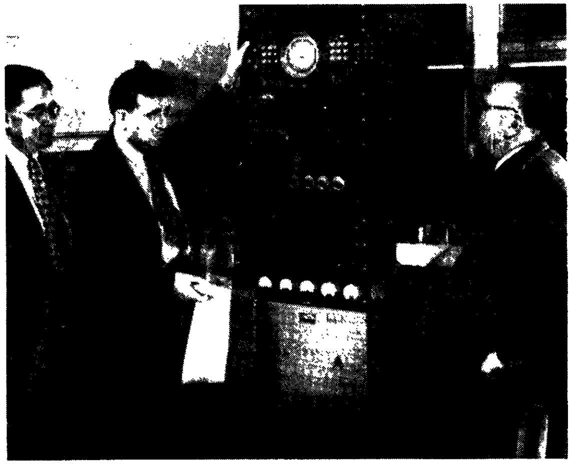
To show the effect of using wider bandwidths.

$a = 0.5$ $B = 12.5$ Mc/sec

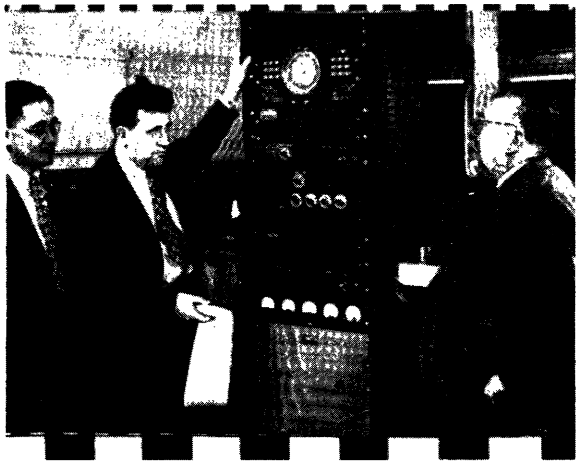
(Viewing distance, 5 feet)

APPENDIX

Amplitude modulation.



Frequency modulation with
5 Mc/sec bandwidth.



Frequency modulation with
10 Mc/sec bandwidth.

For convenience in comparing the different systems, three representative photographs are presented side by side. The viewing distance for these reduced pictures is about 2 feet. All were taken with an interference level of 50 percent.