Vulnerability of the Doppler Detection System to countermeasures: Report no. 3 communications jamming

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NATIONAL RESEARCH COUNCIL OF CANADA

RADIO AND ELECTRICAL ENGINEERING DIVISION

VULNERABILITY OF THE DOPPLER DETECTION SYSTEM TO COUNTERMEASURES

Report No. 3 — Communications Jamming

J.K. Pulfer

OTTAWA

June 1959

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ABSTRACT

The vulnerability of the communications system used in the Doppler Detection System was studied. Using a simulated communications link in the laboratory, which carried alarm and signature information, jamming thresholds were determined for CW, AM-by-noise, and pulse jamming. Calculations of propagation losses for airborne and fixed jammers were combined with the experimentally determined jamming thresholds to determine the required jammer power for denial, deceptive, and confusion jamming. Weak points in the susceptibility of the system to jamming are indicated and possible improvements suggested.

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- J.K. Pulfer -

INTRODUCTION

The Doppler Detection System is a bistatic doppler system. When an aircraft crosses a link in the system, the doppler receiver will, with very high probability, indicate the crossing by providing an alarm signal, and a "signature" of the aircraft on a pen recorder [1].

As used in the Mid-Canada Line (MCL), the Doppler Detection System consists of a double chain of links as shown in Fig. 1 (a). The stations marked Tx are transmitting sites, those marked Rx are receiving sites. C_1 and C_2 are section control stations to which the information from the Doppler receiving sites is fed. Each control station receives information from all receiving sites between the control stations adjacent to it on either side.

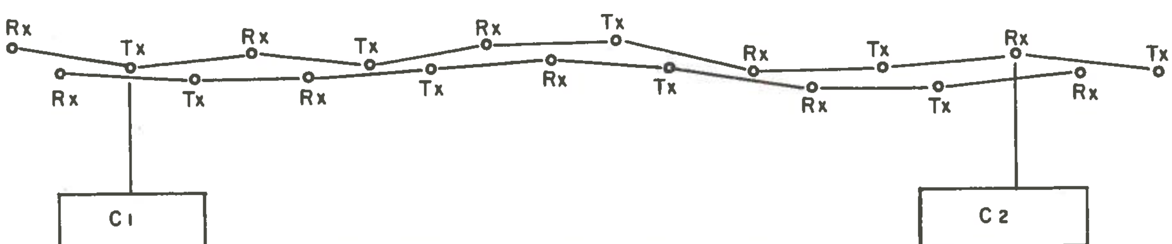

FIG. 1 (a) DIAGRAM ILLUSTRATING THE DOUBLE CHAINS OF DOPPLER DETECTION SYSTEM LINKS AS USED ON THE MID-CANADA LINE

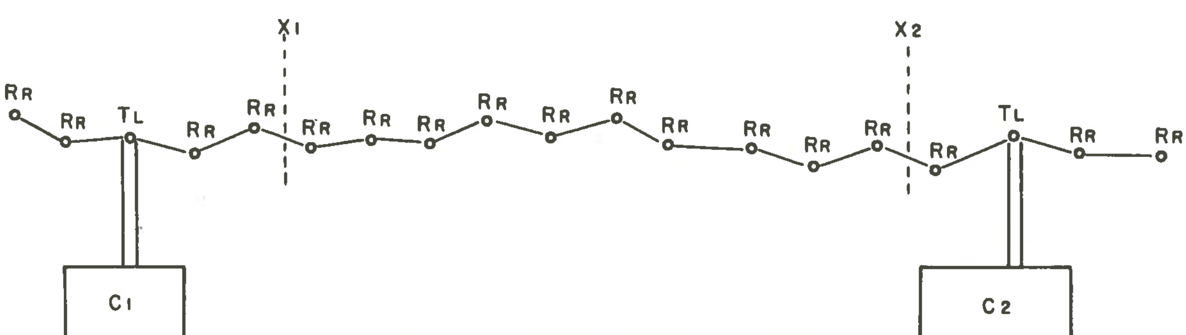

FIG. 1 (b) DIAGRAM ILLUSTRATING THE RADIO RELAY COMMUNICATIONS CHAIN USED ON THE MID-CANADA LINE

Communication of the alarm and signature signals to the section control station is carried out by means of a chain of communication links, as illustrated in Fig. 1 (b). The stations marked T_L are terminal stations, and those marked R_R are repeater stations. Information travels in both directions on the communications system. Flow of information from the receivers on the two links when an aircraft crosses is illustrated in Fig. 2. Fig. 3 (a) is a simplified block diagram of a terminal station, and Fig. 3 (b) is a block diagram of a repeater station.

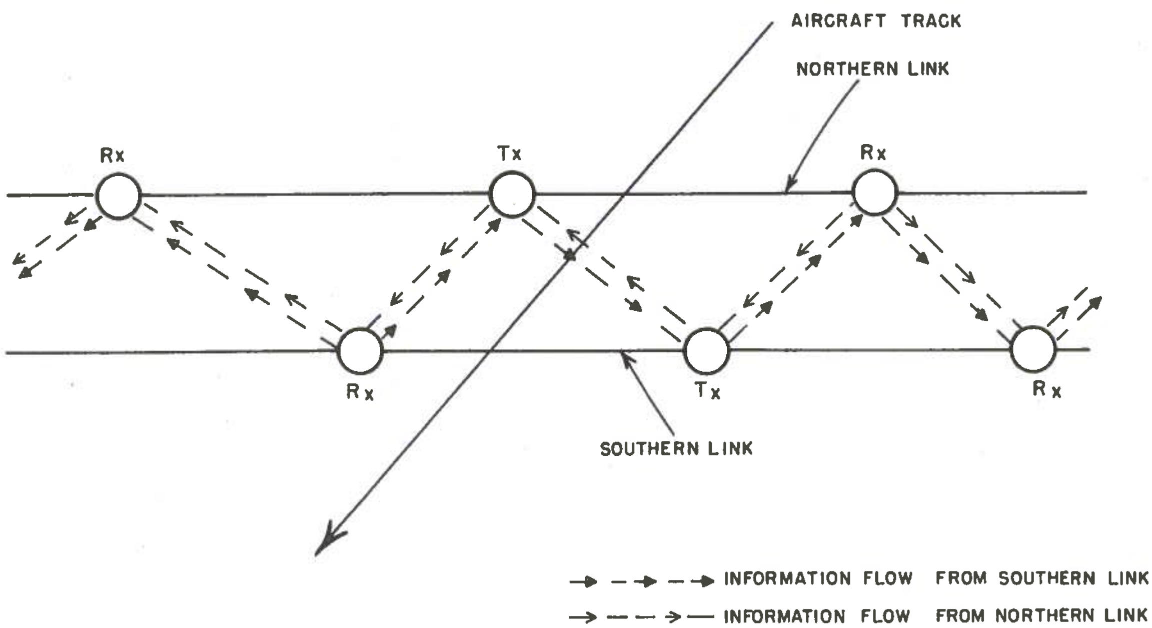

FIG. 2 FLOW OF INFORMATION FROM DOPPLER DETECTION SITES WHEN AN AIRCRAFT CROSSES THE MCL

It is immediately evident that breaking the communications line at two points (X_1 and X_2 of Fig. 1 (b)) will open a gap in the line through which aircraft can pass undetected. Since a gap of up to 300 miles can be produced by only two jammers a study of the susceptibility of the system to jamming is very important.

The communications system is a frequency division FM multiplex system operating in the 410 to 460 mc/s band with a nominal channel deviation of 0.7 radians at 100 kc/s. The receivers have a predectector bandwidth of 3 mc/s. The system uses 25 subcarriers at intervals of 1 kc/s from 8.8 to 34.8 kc/s. Subcarrier channels on 23.8 and 29.8 kc/s are not used. The deviation of the subcarriers is 100 cps and the subcarrier receivers have a bandwidth of 400 cps at -3 db points.

As can be seen from Fig. 3 (a), the terminal station transmitter provides a carrier which is phase modulated by terminal station subcarriers and fed to the antenna to be radiated. At a repeater station, information from subcarrier transmitters at the site is added to the information already on the incoming signal. This is done in the following way. The incoming signal from the adjoining radio relay station is converted to an IF signal in the normal way. It is then amplified at IF frequency and reconverted to a new output frequency by beating with a locally generated carrier. This locally generated carrier has been phase modulated by the subcarriers containing the outgoing information from the station. In case of a failure at some point in the chain of the communications system, each repeater is provided with an IF signal which is automatically injected when triggered by a rise in the receiver output noise, replacing the first mixer output. This automatic repeater changeover therefore results in the loss of all information which was available on the incoming carrier.

The presence of an alarm at a station causes the level of the subcarrier corresponding to that link to increase by 17 db. The signature is then transmitted by frequency modulating the subcarrier with the output voltage from the Doppler Detection System receiver. The power output of the communications transmitter is 25 watts, and the transmitting and receiving antenna gains are 20 db. The average received signal level at a receiver input is of the order of -75 dbw.

Jamming which might be used against the communications system can be divided into three broad groups.

a) Denial Jamming

Denial jamming of an FM multiplex system would accomplish any or all of the following things.

1) Cause the repeater to change over to internal carrier generation, thus denying information supplied by all stations beyond the jammed link by preventing it from reaching the control station.

2) Raise or lower the signal level into the subcarrier receivers, thus denying alarm information.

3) Either raise the noise level or feed useless information into the subcarrier receivers to deny signature information.

b) Deceptive Jamming

For the communications system, deceptive jamming is taken to mean productions of alarms and/or signatures at the output of the communications system when in fact no aircraft is crossing the Doppler Detection System, by providing

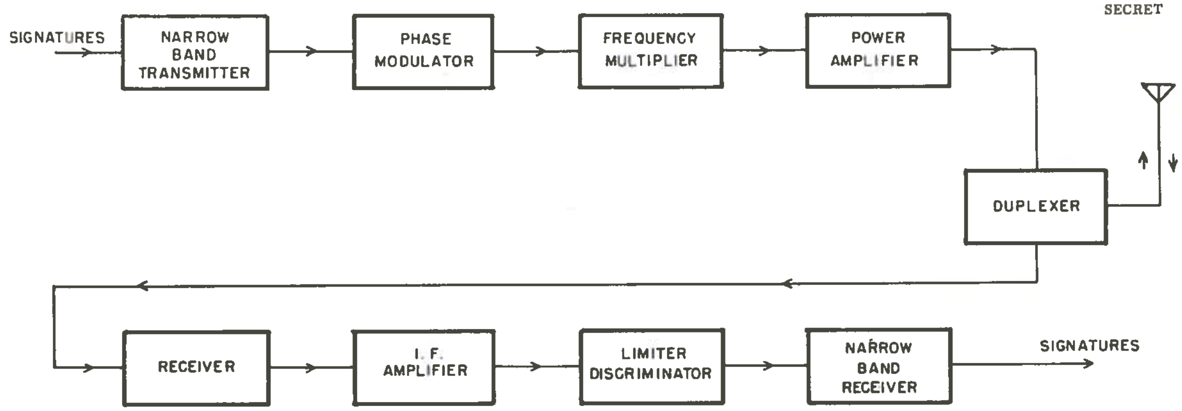

FIG. 3 (a) BLOCK DIAGRAM OF A RADIO RELAY TERMINAL STATION

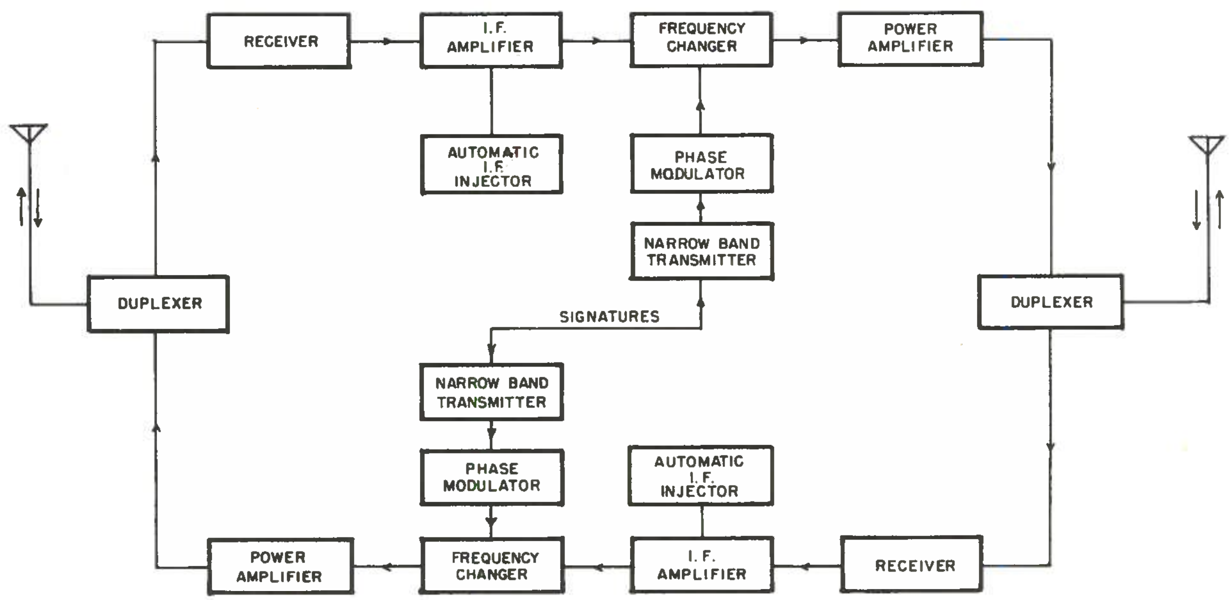

FIG. 3 (b) BLOCK DIAGRAM OF A RADIO RELAY REPEATER STATION the appropriate input to the communications receiver from a jammer. It is also the production of signals during the crossing of an aircraft which may be confused with false alarms.

c) Confusion Jamming

Confusion jamming would result if any or all of the denial or deceptive countermeasures occured in a random or intermittent manner, which would cause delay in recognizing the true signals and perhaps extra work, or an extra load on the facilities.

JAMMING AN FM MULTIPLEX LINK

The behaviour of FM systems, because of their extremely nonlinear amplitude response, is considerably different from that of amplitude-sensitive systems under jamming conditions. The response of a simple FM receiver having no multiplexing will be examined first, and then the results will be used to explain the behaviour of the more complicated system.

Simple FM Receiver

a) CW

Consider jamming by a CW signal within the predetector passband of the receiver. Let J/S be the ratio of CW jamming power to average signal power at the input to the receiver.

When J=S=O, front-end noise will be amplified in the IF stages of the receiver, and so the discriminator will receive wideband clipped noise, and the output of the discriminator will consist of video noise at a high level.

When J=O, but S is at normal operating level, the signal-to-noise ratio at the input to the limiters will be quite high, so that the output of the limiters and filters will be essentially noise free, and, as a result, the discriminator output will be the signal modulation.

When J is increased, the sum of J and S will vary in amplitude at a rate equal to their difference in frequency. The sum will also have some phase variation.

If the receiver has several stages of narrowband limiting, the effect of J will be negligible for J/S less than 0.5. For values of J/S approaching 1.0, the sum of J and S will fall below the limiting level at the minimum of the beat cycle, so that both a beat frequency signal, and noise will be produced by the discriminator. The noise will be maximum at J=S, and will fall almost to zero at J/S = 2.

Fewer limiters or improperly designed filters would increase the range of values of J which would produce a high noise output from the discriminator.

The amount of noise which will be produced by the discriminator at J=S will of course depend on the signal amplitude. If S is just slightly above threshold, (J + S) will be below threshold for a large portion of the beat cycle, whereas, if S is very much above the limiting level, (J + S) will fall below threshold level for only very short intervals, and the output noise will be small.

To summarize, a CW jammer produces negligible effect when its output is less than the signal; it produces maximum noise output when it is equal to the signal; and it effectively suppresses the signal when it is sufficiently greater. This is illustrated qualitatively in Fig. 4. The sharp changeover from signal to jammer output out of the discriminator is usually spoken of as threshold, or "capture" effect.

b) AM-by-noise

Following the reasoning used in the CW jamming case, it can be seen that an AM-by-noise jammer will have negligible effect when its output is much less than the signal, but that noise output from the discriminator will start to appear at values of J/S approaching 1.0. For J/S > 1 the noise will continue to increase although at a decreasing rate, as the jammer signal becomes more and more heavily clipped. Fig. 5 illustrates qualitatively the behaviour of the FM receiver to AM-by-noise jamming. Notice that the anti-jamming threshold is not as sharp for noise as for CW because of the increased ratio of peak to average power with noise. Or, stated in another way, the noise jamming will exceed the receiver capture threshold on peaks at lower values of average power than will CW jamming.

Jamming with a carrier which has been frequency modulated by noise has not been considered in this report, for three reasons:

1) Since jamming an FM receiver by noise is a threshold effect, it is expected that the power required to jam with FM by noise will be very nearly that required to jam with AM by noise.

2) Since the peak power of the FM by noise signal will not be greater than the average, it would be expected that jamming threshold would be reached at a slightly lower average power if AM by noise were used.

3) At a frequency of 450 mc/s, AM-by-noise jamming can be achieved in a much smaller package for a given bandwidth unless special tubes such as backward wave oscillators are used.

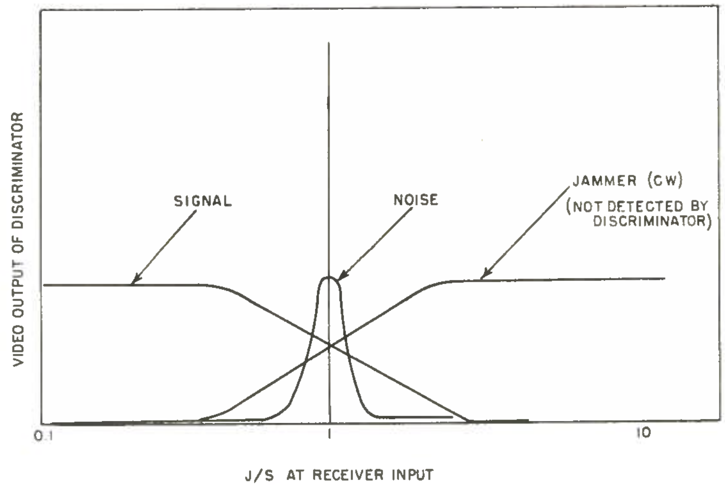

FIG. 4 ILLUSTRATION OF THE THRESHOLD EFFECT WHEN JAMMING A SIMPLE FM RECEIVER WITH A CW SIGNAL

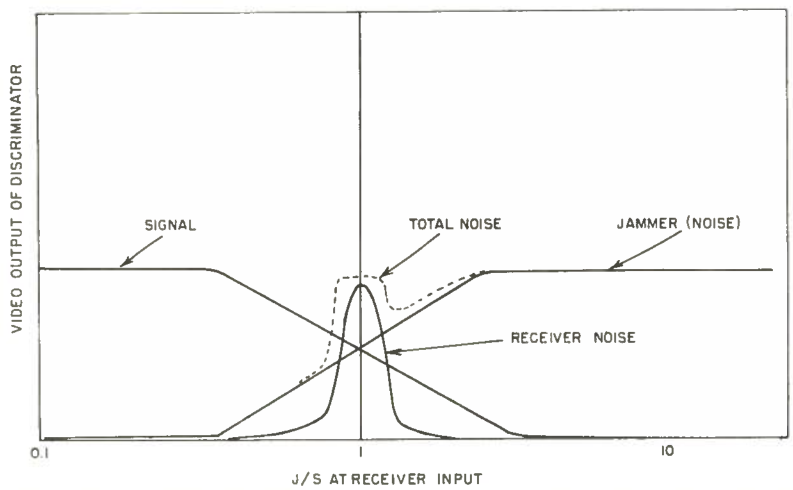

FIG. 5 ILLUSTRATION OF CAPTURE OF A SIMPLE FM RECEIVER BY A JAMMING SIGNAL AMPLITUDE MODULATED BY NOISE

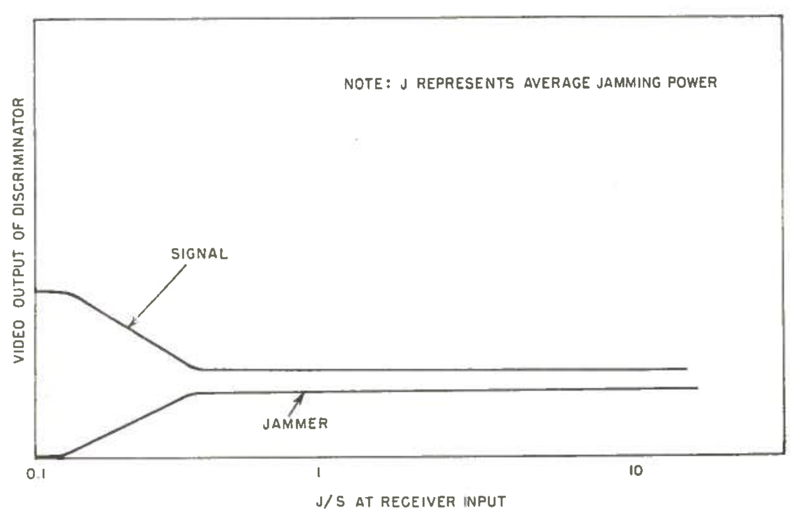

FIG. 6 ILLUSTRATION OF CAPTURE OF A SIMPLE FM RECEIVER BY A LOW DUTY CYCLE PULSED SIGNAL

It should be emphasized that since no study of FM jamming was made, no assessment of the effect of FM jamming is included, although experience with the behaviour of FM systems indicates that the FM by noise should be little different from AM by noise.

c) Pulse Jamming

From the reasoning put forth to explain the broadened capture threshold for noise jamming, it can be seen that low duty cycle pulse modulation can, in effect, shift the threshold down to a lower value. That is to say, even with low average jamming power, the peak power can still be sufficient to capture the receiver. It must be realized, however, that the receiver will be jammed only for a small fraction of the time, and so the output from the discriminator due to the jammer would be correspondingly reduced. This is shown in Fig. 6.

Multiplex FM Receiver

Now consider the multiplex FM receiver. This can be conveniently represented as two FM receivers in cascade for our discussion. The second or subcarrier receiver will also have a capture threshold. With no subcarrier present, the second receiver will produce noise output, which will decrease to a negligible value in the presence of the subcarrier. Output from the first receiver caused by jamming should therefore be concentrated in the band around the subcarrier receiver.

Consider the reaction of a simple multiplex receiver with a single subcarrier receiver to the following types of jamming.

a) CW Jamming

For J/S much less than 1, the first receiver will not be captured by the jamming signal, and so the second will operate in its normal manner.

As J/S approaches 1, the first receiver will be captured, and so the subcarrier level into the second receiver will fall while the noise will rise, resulting in the capture of the second receiver. If the gain between the two receivers is high, then the second receiver will be captured by noise from the first receiver rather than by the reduction of subcarrier level below its own noise threshold. It is therefore advisable to provide as high a level of the subcarrier signal as possible into the second receiver in order to produce the best overall resistance to jamming.

As J/S increases to values > 1, the noise decreases, the jamming signal provides only a d-c output from the first receiver, and the subcarrier level decreases rapidly. Since the noise will drop much more rapidly than the subcarrier level, output signal-to-noise will at first increase, and then decrease again, as the noise level of the subcarrier receiver provides the final limitation. The qualitative graph plotted in Fig. 7, illustrates the CW jamming case.

b) Noise Jamming (AM-by-noise)

Since jamming with AM-by-noise is similar to jamming with CW, with the exception that noise out of the discriminator increases when J/S is increased beyond 1, the behaviour of the multiplex receiver is easily understood. As J/S increases beyond 1, the subcarrier level out of the first discriminator will continue to drop, while the noise will rise slowly. As a result, the second receiver will be captured by the noise, and stay captured for all higher jamming inputs. This is shown in Fig. 8.

c) Pulse Jamming

In the pulse jamming case, if the peak pulse power is sufficient to capture the receiver, the output of the first discriminator will consist of the subcarriers plus the pulse repetition frequency and its harmonics. Complete jamming of the system will therefore occur when the level of the video due to jamming at the output of the first discriminator results in more power in the bandwidth of a subcarrier receiver than does a subcarrier itself, and thus results in the capture of the subcarrier receiver. This will usually occur at an average power less than the signal power — see Fig. 9. One of the most effective pulse jamming signals would be one with a PRF varying randomly over the passband occupied by the subcarrier receivers. It follows also, that the effectiveness of this type of jamming compared with CW and AM-by-noise, would depend on the level of the subcarriers relative to the overall power of the FM transmitter, and thus on the deviation used.

EXPERIMENTAL MEASUREMENTS AND RESULTS

To verify the reasoning used in the preceding Section, and to obtain some idea of the susceptibility to jamming of the Mid-Canada Line communications system, trials were made with a simulated link in the laboratory.

Fig. 10 is a simplified block diagram illustrating the equipment used for the tests. A complete terminal station transmitter and receiver operating on 450 mc/s were used. The transmitter, receiver, and jammer sites were located in separate rooms and isolation between the sites was found to be greater than 120 db. They were then interconnected by cables of which the attenuation had been

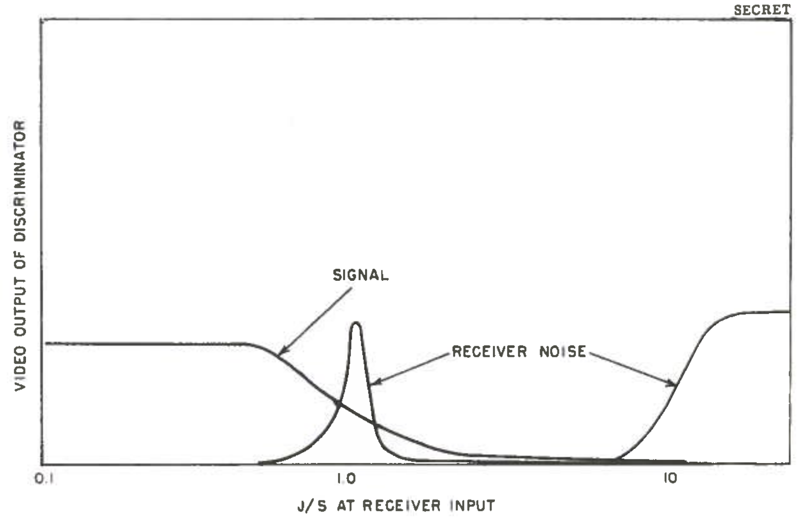

FIG. 7 ILLUSTRATION OF THE USE OF A CW SIGNAL TO JAM A MULTIPLEX FM RECEIVER

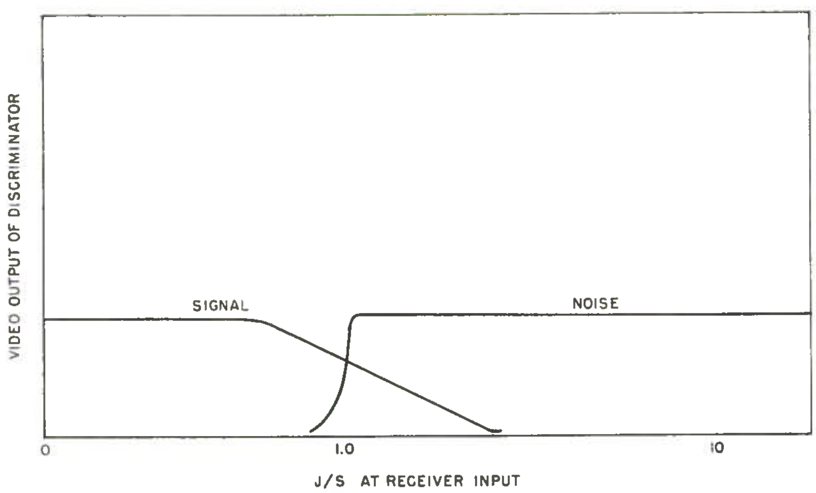

FIG. 8 ILLUSTRATION OF THE USE OF A JAMMER, AMPLITUDE-MODULATED BY NOISE TO CAPTURE A MULTIPLEX FM RECEIVER

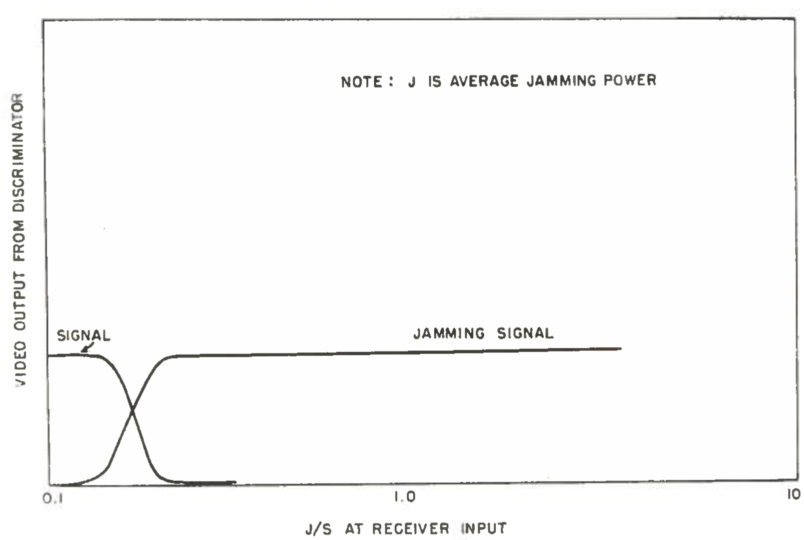

FIG. 9 ILLUSTRATION OF THE USE OF A LOW DUTY CYCLE PULSED SIGNAL TO JAM A MULTIPLEX FM RECEIVER

measured. Piston attenuators were used at the transmitter output and receiver input while the jammer output was controlled by a variable stripline attenuator. By this means, jamming and signal power were fully variable. The block diagram, Fig. 11, illustrates in detail the equipment used for the measurements.

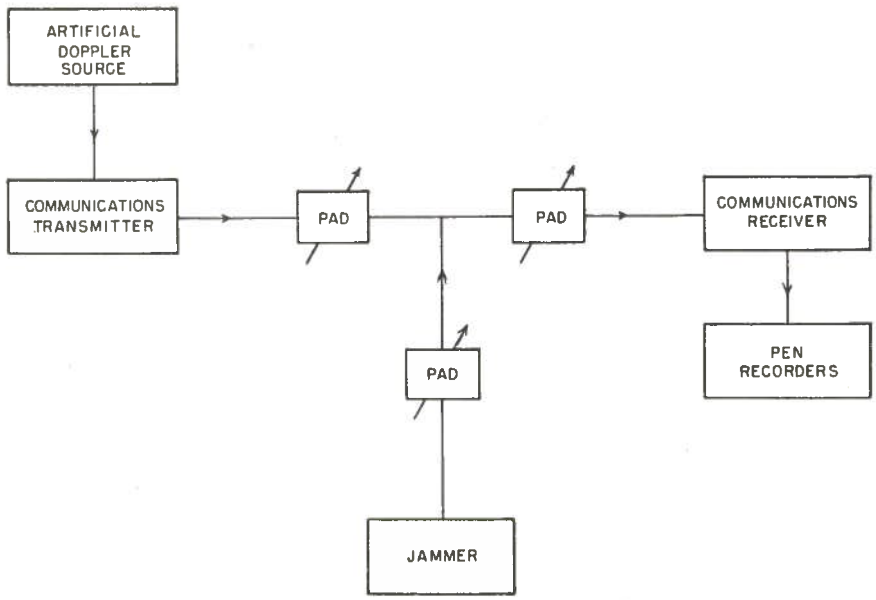

FIG. 10 SIMPLIFIED BLOCK DIAGRAM OF THE EQUIPMENT USED IN THE JAMMING TESTS

Fig. 12 illustrates schematically the attenuation in each line, and the approximate levels at different points, for a typical jamming setup. Attenuation in the cables was measured by several methods using calibrated signal generators and various receivers and power meters. The results were averaged to give the values shown. Error in the measured attenuation is estimated as ± 0.5 db.

The transmitter was a standard DQ-38 terminal station transmitter. Two subcarrier transmitters and their associated receivers operating on 28.8 and 34.8 kc/s were used. To simulate actual operating conditions, these subcarrier transmitters were fed with artificially generated doppler signals. The output of the noise generators was also added to make the artificial doppler signals as realistic as possible. Alarm information was provided to the subcarrier transmitters in conjunction with the artificial doppler signatures. Radio frequency output from the transmitter was taken at the output of the frequency multiplier in the transmitter, to avoid the need for additional attenuation which would be necessary if the final amplifier were used.

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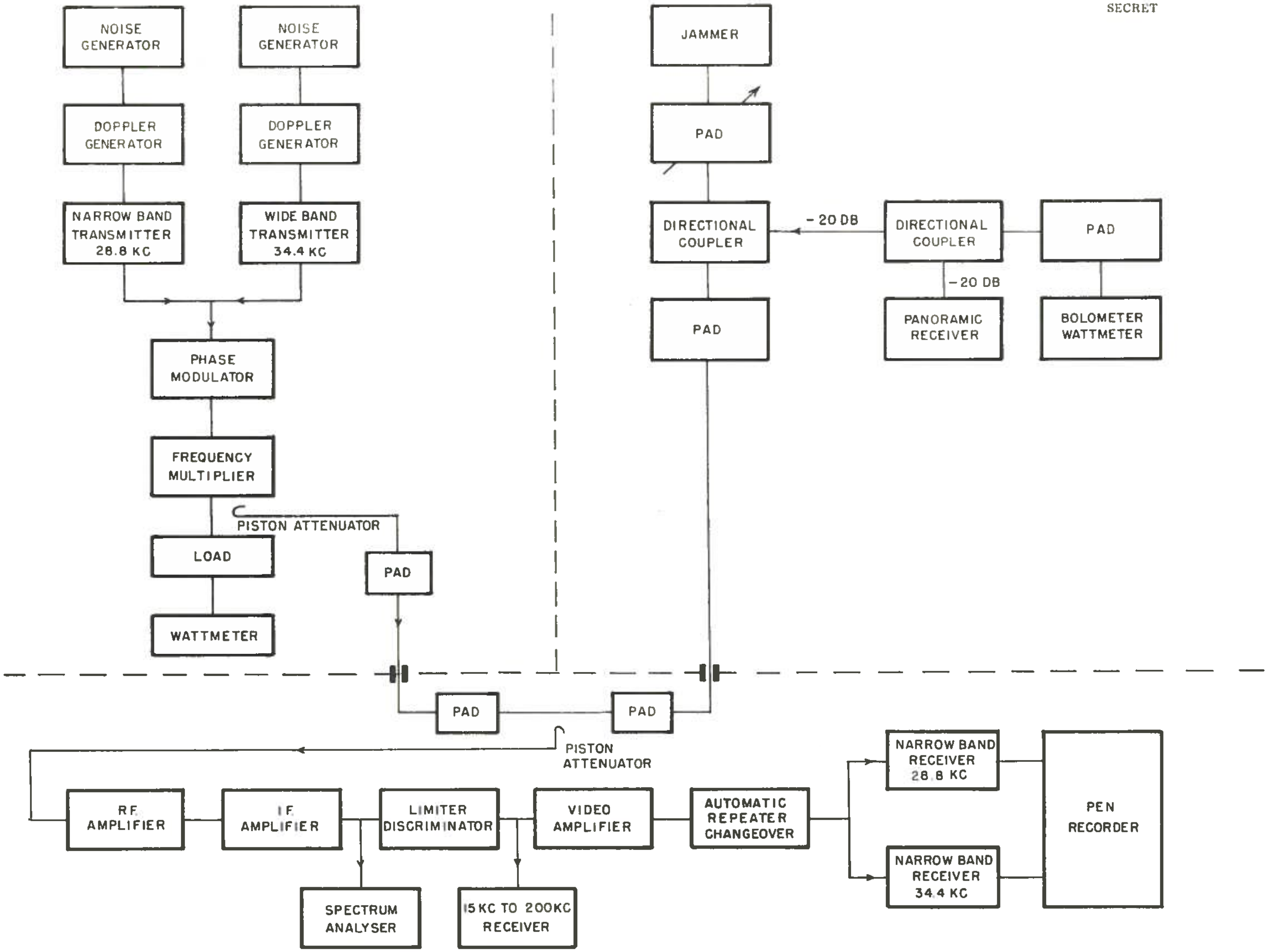

FIG. 11 DETAILED DIAGRAM OF THE EQUIPMENT USED IN THE JAMMING TESTS

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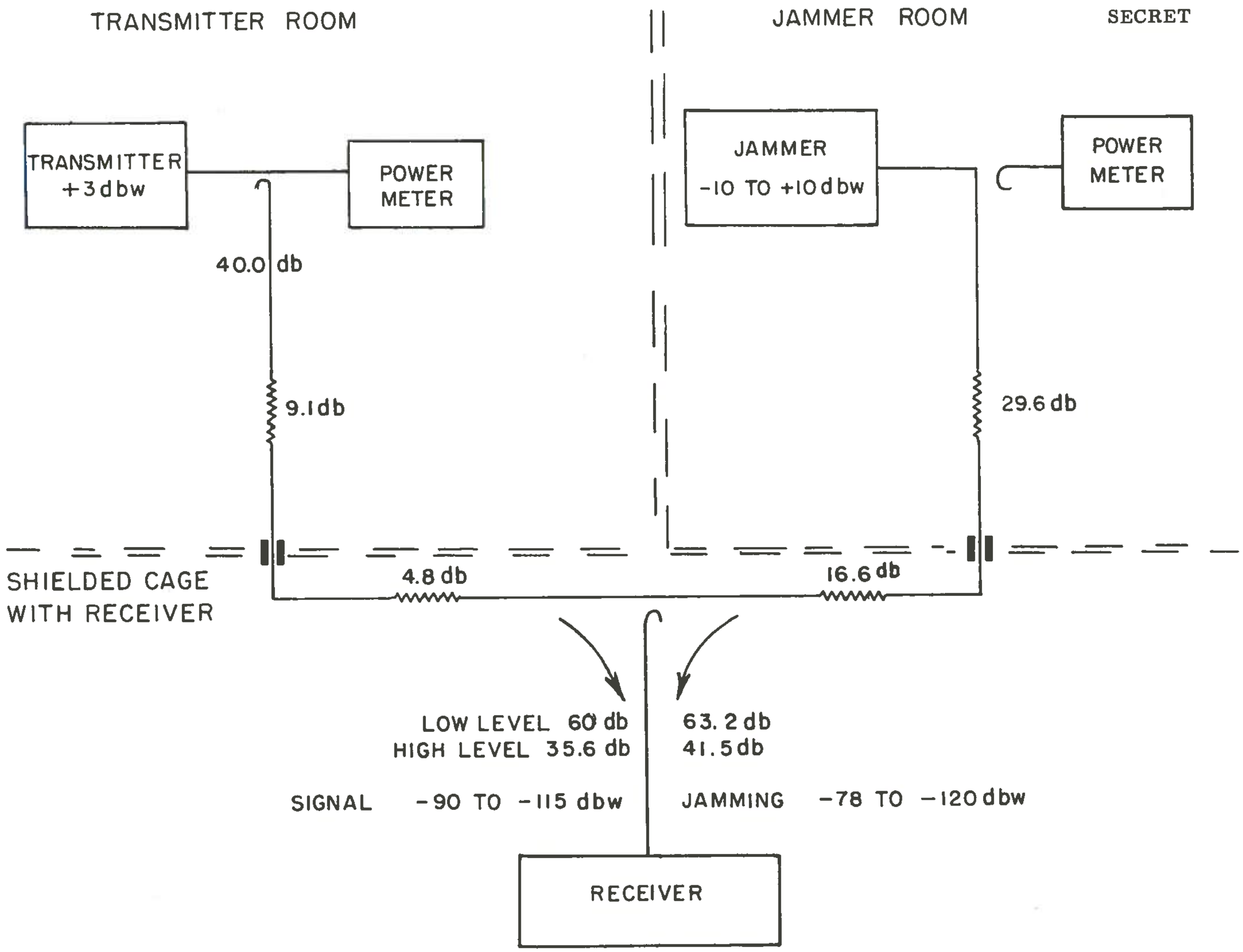

FIG. 12 SCHEMATIC DIAGRAM ILLUSTRATING THE ATTENUATION IN EACH LINE JOINING THE EQUIPMENT IN THE JAMMING SET UP

The DQ-38 transmitter was operated with a phase deviation of ± 1 radian per channel during all tests. This figure is from 3.5 to 5.5 db higher than that which is found on the MCL at a DDS site and 9.5 to 11.5 db higher than that used at a section control centre transmitter [2]. The effect of the lower deviation used on the MCL will be pointed out in the discussion. Power was read on an RF wattmeter calibrated by a bolometer bridge.

The receiver was monitored at several stages to obtain a more thorough understanding of the effects of the jamming. The IF output was observed on a spectrum analyzer at 60 mc/s, which showed the signal and jamming, band limited by the IF, but other-wise unchanged.

The output of the first discriminator was fed to a narrow-band low frequency receiver tunable from 15 to 150 kc/s, which allowed analysis of the discriminator output spectrum. The output from the subcarrier receiver was displayed on pen recorders, and the alarm output operated lights. An additional light on the receiver indicated the state of the noise rise relay which would operate automatically under high noise conditions at a repeater site.

Two modified AN/APT-5 transmitters were used for jamming sources. One was operated with no modulation as a CW transmitter and with internal AM noise modulation as a noise jammer. Pulses were fed to the modulator from an external pulse generator for pulse modulation.

A second AN/APT-5 transmitter, previously modified to operate as a super-regenerative repeater [3], was operated as a pulse jammer in an attempt to determine if there is any advantage in operating in a coherent or repeater fashion.

The bandwidth before the discriminator of the FM receiver was nominally 3 mc/s, so that pulses shorter than $\frac{1}{3}$ microsecond would produce a jammer spectrum too wide to be completely accepted by the receiver. As a result pulses narrower than 1 microsecond were not used.

Two ranges of pulse repetition frequency were of interest, first — in the 8 to 35 kc/s region, i.e., in the subcarrier band, and secondly, at about 400 kc/s, in the noise-rise repeater-changeover band.

At a 400 kc/s pulse repetition rate, the minimum duty cycle used was about 0.3, since the time between leading edges of pulses was only 2.5 μsec. At 30 kc/s however, pulses were spaced by 33 μsec so that a duty cycle of 0.03 was possible.

Some experiments on deception jamming of the communications link were carried out. For these experiments very short pulses from a line-type modulator operating at 14.4 kc/s were applied to the plate of a type-3C22 tube in an

APT-5 cavity. The resultant pulses of 450 mc/s energy were used for jamming.

The pulse width was adjusted so that the energy in the pulse spectrum at the output of the first discriminator was above the subcarrier level. (The optimum pulse width for a nominal channel deviation of 100 kc/s was 1.9 μsec.) The subcarrier receivers at multiples of 14.4 kc/s were therefore captured by the jammer. A small amount of frequency modulation applied to the PRF generator from an artificial doppler source then produced realistic doppler waveforms at the output of the jammed subcarrier receiver.

The tests which were made on the simulated radio relay link have been divided roughly into two classes.

The first type was a run in which the jammer was placed on the receiver frequency, and the jammer output power increased in steps while the transmitter power was maintained at a steady value. At each jamming level, a sample of the receiver output was taken on the pen recorder. The levels at which the receiver changeover and alarm relays were affected by the jamming were also recorded. Error in J/S calculated from the measured power levels was approximately ±1 db which was due almost entirely to the error in the measured attenuation of the cables.

The second type of run was designed to determine the effects of detuning the jammer from the signal frequency. The jammer was slowly tuned across the receiver passband, and the frequencies at which receiver changeover, faulty operation of the alarms, and denial of the received signal took place were observed on the spectrum analyzer and recorded. It was possible to determine jamming bandwidth to within ±100 kc/s by this method.

RESULTS

When an FM multiplex receiver is subjected to AM-by-noise jamming, the level of the subcarrier at the output of the first discriminator is reduced. At the same time, the power level of the noise out of the discriminator increases. To demonstrate this effect, and to determine the frequency spectrum of the jamming power at the discriminator output, measurements of the video output were made with a narrow-band receiver. These results are plotted in Fig. 13. Five levels of jamming power corresponding to values of J/S equal to $-\infty$, -5, -2 and 0 db were used and the results are plotted in Figs. 13(a), (b), (c), and (d), respectively.

The rise in noise level and decrease in subcarrier levels with increased jamming is clearly shown. It is also evident that the video noise power per unit

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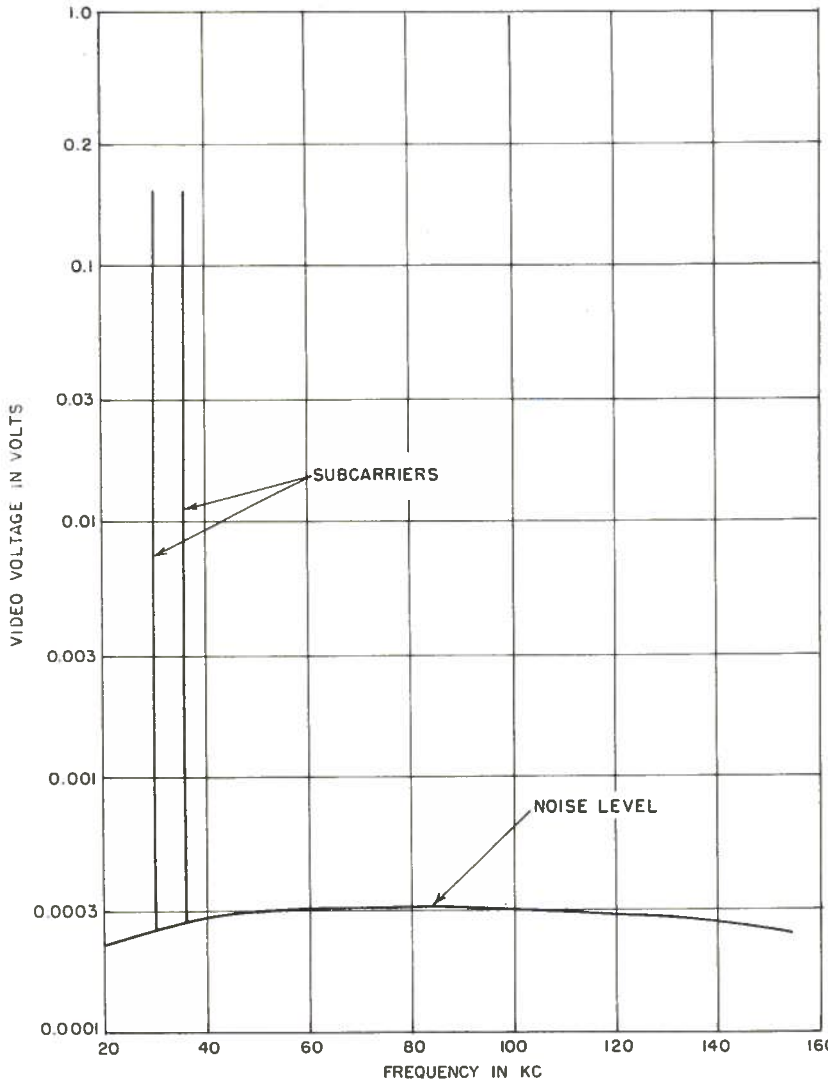

FIG. 13 SPECTRUM OF THE VOLTAGE AT THE OUTPUT OF THE FIRST DISCRIMINATOR: a) J/S = -∞ db

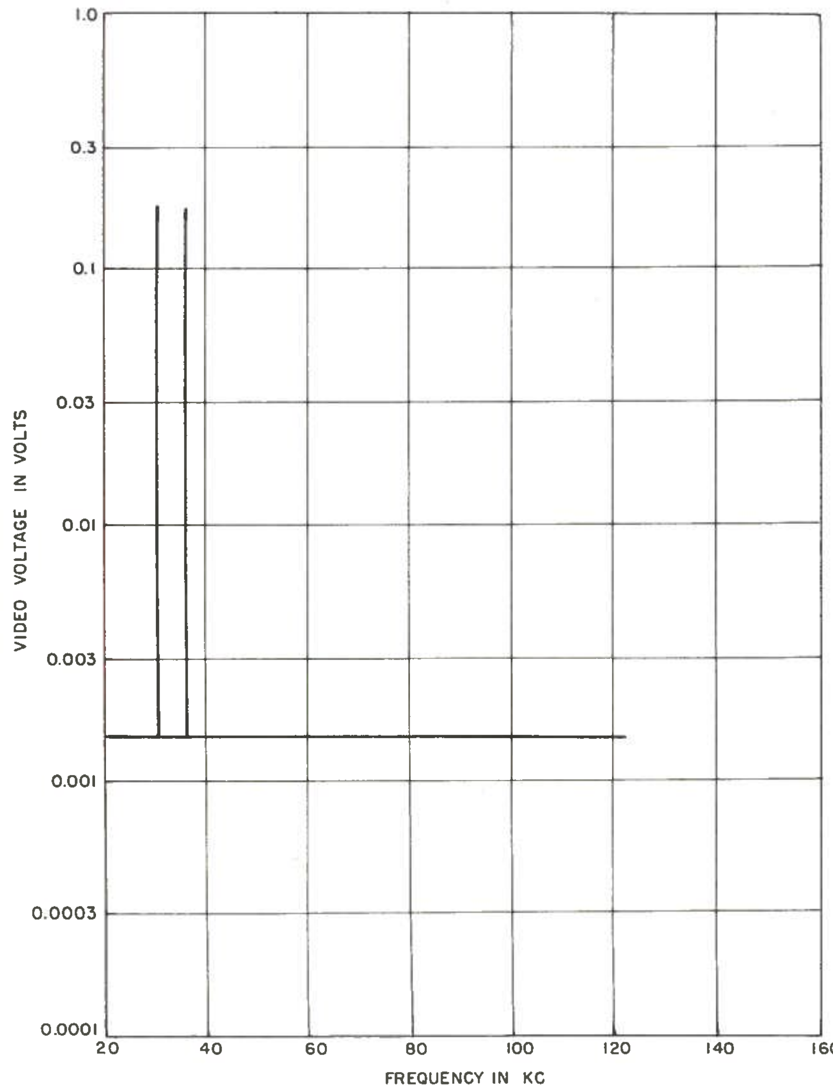

FIG. 13 SPECTRUM OF THE VOLTAGE AT THE OUTPUT OF THE FIRST DISCRIMINATOR: b) J/S = -5 db

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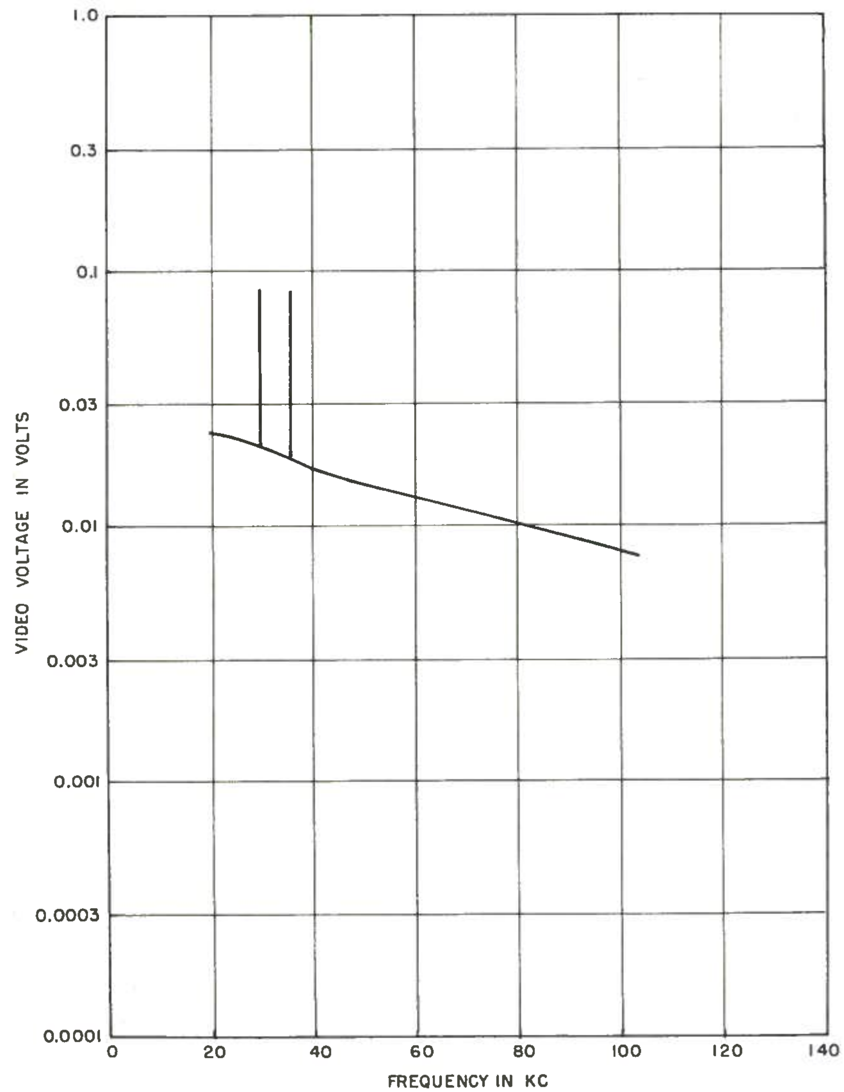


FIG. 13 SPECTRUM OF THE VOLTAGE AT THE OUTPUT OF THE FIRST DISCRIMINATOR: c) J/S = -2 db

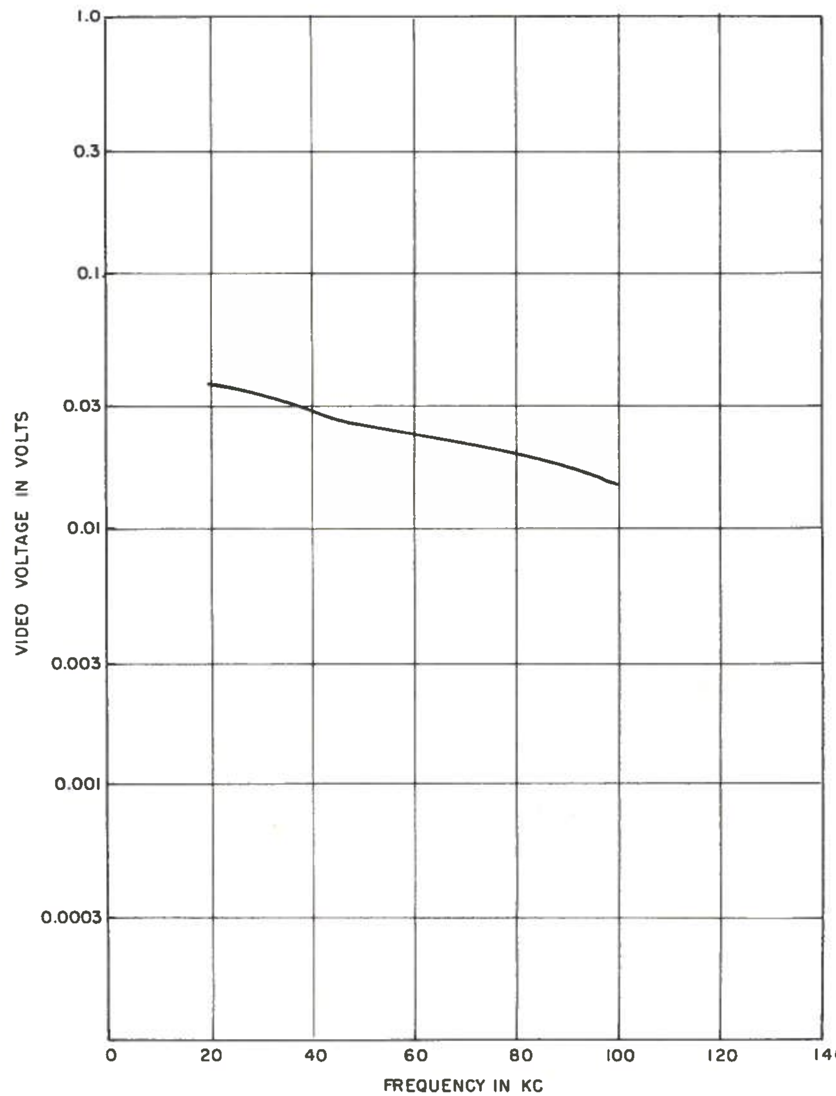


FIG. 13 SPECTRUM OF THE VOLTAGE AT THE OUTPUT OF THE FIRST DISCRIMINATOR: d) J/S = -0 db

bandwidth decreases with increasing frequency so that low frequency subcarriers will be jammed at smaller levels of jamming power than the high frequency subcarriers.

A further indication of this fact is given in Plate I which is a photograph of the output from a dual channel pen recorder fed by the two subcarrier receivers.

At the left side of the figure, the jamming power is quite low, and so artificially generated doppler signals are visible in both channels. The jamming power is increased in steps towards the right side of the figure, and it can be seen that the upper channel which is the output of the 28.8 kc/s subcarrier receiver is jammed at a lower power level than the lower channel (34.4 kc/s).

Throughout the tests, both of the subcarrier channels were operated simultaneously. At no time was there any evidence of inter-modulation due to the jamming. Therefore, the pen recordings from one channel only will be used in most of the following presentation, resulting in considerable simplification.

Two signal levels were used during the jamming tests. Low level tests were done with the communications signal at a level of -114.5 dbw. At this level, the signal was just sufficiently above receiver noise to capture the receiver. At this low level, the jamming threshold was rather broad as would be expected.

High level tests were done with the communications signal at -87 dbw. This level was somewhat lower than the -75 dbw actually used on the Mid-Canada Line, but was sufficiently above receiver noise to result in a sharp threshold, and behaviour was to all intents and purposes the same as at -75 dbw. The figure of -87 dbw was chosen for experimental convenience.

The broad threshold level at -114.5 dbw for CW jamming is illustrated in the pen recording of Plate II. On the right side of the figure, the jamming level is below threshold; then as the CW level is increased, the noise out of the first detector overrides the signal in the subcarrier receiver resulting in jamming as illustrated on the left side of the figure.

When the signal level is raised to -87 dbw, much heavier limiting of the communications signal and jamming CW signal takes place. As a result of this, the threshold is very sharp, and first discriminator noise output is much lower at the threshold. The range of jammer powers at which receiver noise is high enough to capture the subcarrier receivers is very small. In Plate III, the output of a subcarrier receiver is plotted by a pen recorder as the CW jamming level is increased. The only apparent effect of the jamming is to lower the sensitivity of the receiver until at a high level of CW power, the subcarrier output is completely suppressed.

Plates IV and V are similar pen recordings illustrating jamming at signal levels of -114.5 and -87 dbw, respectively. In this case, however, jamming was done using a power oscillator amplitude-modulated by noise having a 30 kc to 3 mc wide spectrum. The figures are photographs of the pen recordings of the output of the 28.8 kc subcarrier receiver with the jamming power increasing slowly in steps from left to right. By comparison with the CW jamming, it is seen that noise jamming is effective at all levels above the threshold, and this is not dependent on signal level.

Plates VI, VII, and VIII are included to show the effects of a simple, pulsed power oscillator on the multiplex receiver. The pulse repetition rate was 28.8 kc. In Plate VI the duty cycle was 0.85, in Plate VII it was 0.5, and in Plate VIII, 0.17.

The figures are photographs of pen recordings of the output of the 28.8 kc subcarrier receiver. Jamming power increases from left to right in steps. At each level of jamming power the repetition rate of the pulses was slowly varied by hand over a 10% bandwidth centered on 28.8 kc. This resulted in a violent fluctuation of the subcarrier receiver output, caused by the pulses, each time it was captured by the video output of the first discriminator.

Fig. 14 is a graph which was based on capture levels of the various aspects of the receiver and for different types of jammers. Expressed in another way, this graph illustrates the range of jammer power levels which will

a) cause denial of signature information,
b) cause denial of alarm information,
c) result in automatic changeover of a repeater to its internally generated IF signal.

All of the measurements on which this graph was based were done at a signal level of -87 dbw. That is to say, these results would correspond closely to threshold levels on the Mid-Canada Line Radio Relay system.

It has been mentioned previously that the deviation and resultant subcarrier level were from 3.5 to 5.5 db higher in the simulated link than on the actual line at a doppler site.

It is obvious from Fig. 14 that jamming by AM-by-noise and jamming by CW are in general threshold effects, and the power level necessary is not influenced by the subcarrier level or deviation of the signal.

The receiver changeover, and denial which can be produced by pulsed jamming are, on the other hand, proportional to video signal from the first discriminator

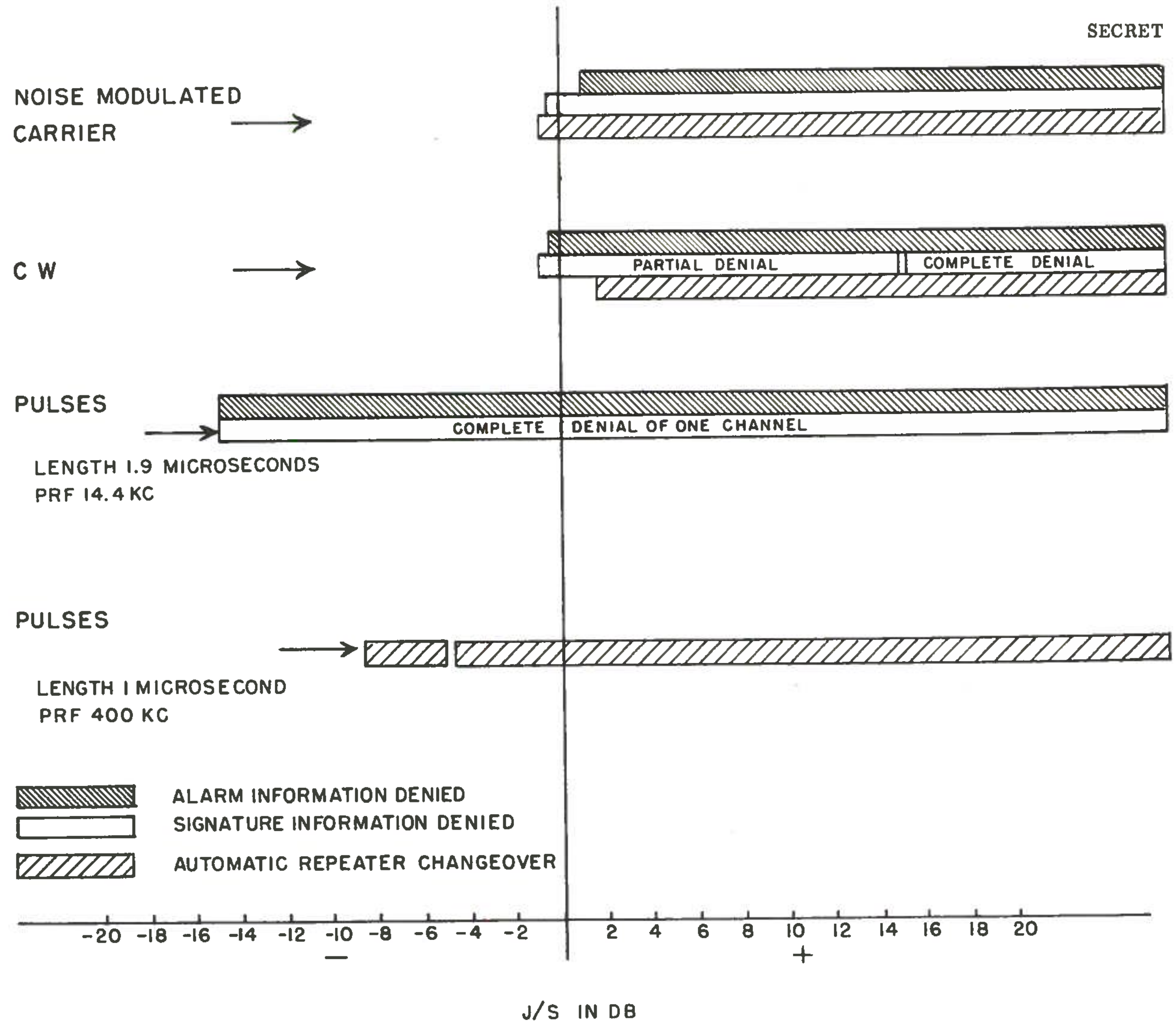


FIG. 14 GRAPH ILLUSTRATING THE CAPTURE LEVELS OF THE VARIOUS ASPECTS OF THE RECEIVER FOR DIFFERENT TYPES OF JAMMERS

which is, in turn, roughly proportional to jammer average power. As a result, the jamming levels illustrated for pulsed transmission are high by 3.5 to 5.5 db. That is 3.5 to 5.5 db less jamming power would be needed on the Radio Relay Link on the Mid-Canada Line.

Plates IX and X are pen recorder outputs of a single subcarrier receiver. The jammer consisted of a CW signal well above threshold level. This signal was tuned through the bandpass of the FM multiplex receiver as the paper moved on the pen recorder. Plate IX shows the case for a signal of -114.5 dbw while Plate X is for a signal level of -87 dbw.

At the low signal level (Plate IX) the subcarrier receiver produced noise at the band edges, and noise in the centre of the band. The noise at the band edges occurs when the jammer signal is attenuated sufficiently by the receiver IF bandpass characteristic to be equal to the signal level, and so is at the threshold. The noise at the centre is caused by beats between the carrier of the signal and the CW jammer falling within the subcarrier band.

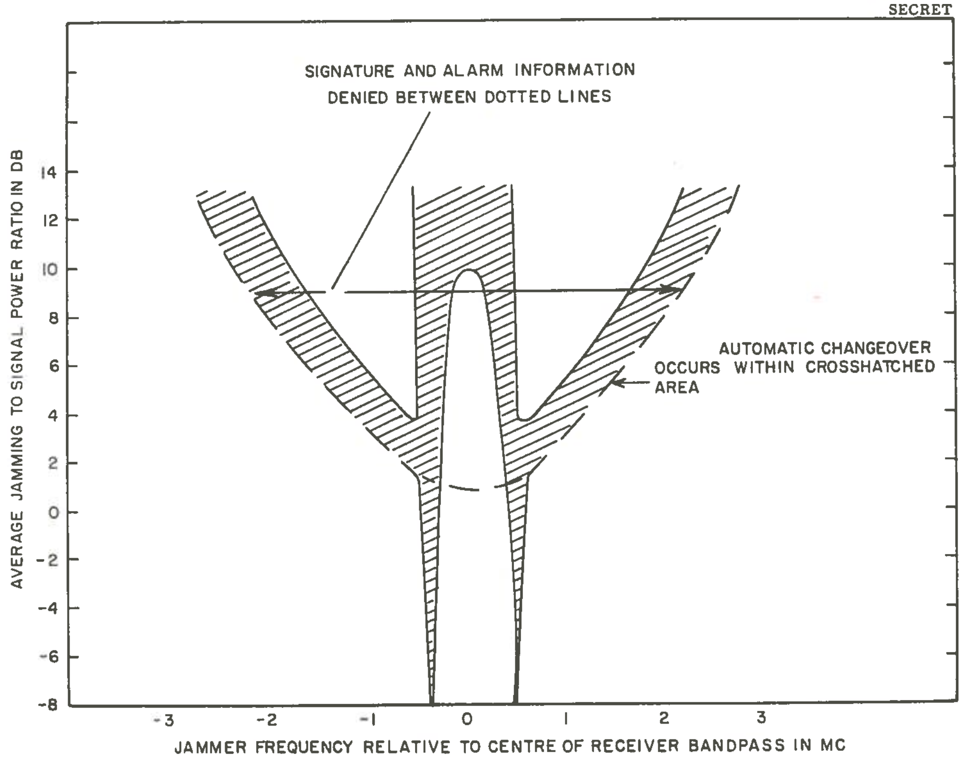
At higher signal level (Plate X) the threshold is much sharper, eliminating the noise at the edges of the bandpass.

It follows that a similar noise rise will occur at 400 kc/s in the output spectrum of the first discriminator. Thus the noise-rise automatic changeover will take place at the centre and at the band edges for CW jamming.

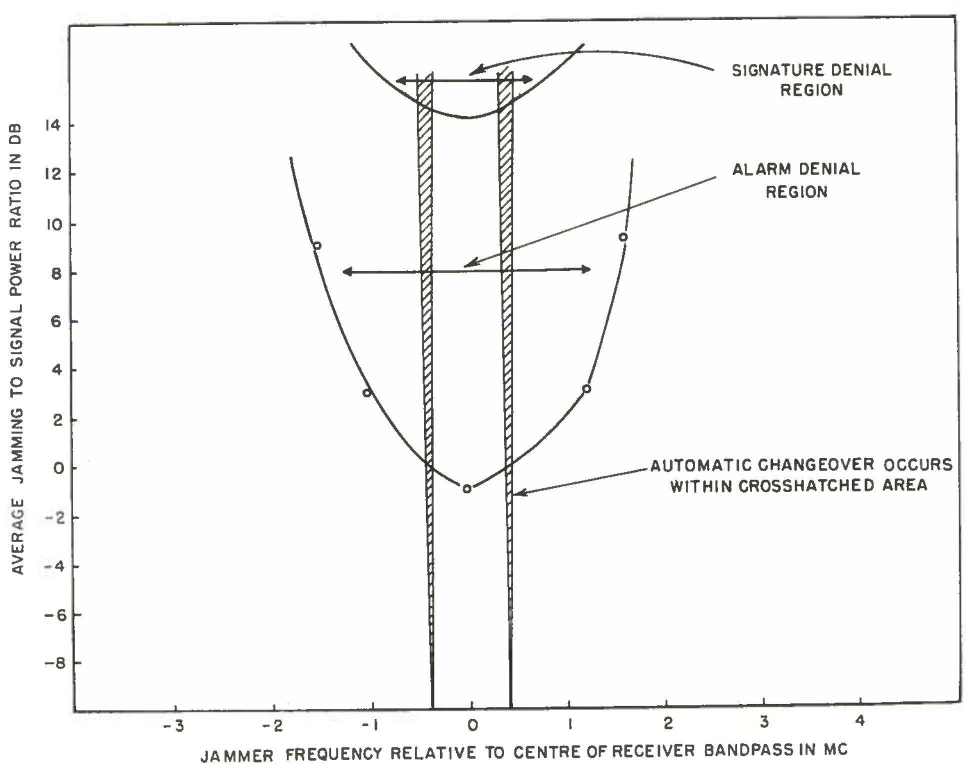
Rather than present a large number of pen recordings, a graph of jammer power vs. frequency has been plotted which illustrates this noise-rise effect. Figs. 15 (a) and (b) are sketches indicating the relative areas on a power-frequency graph where the noise level out of the first discriminator rises sufficiently to trigger the changeover relay. The frequency bands at a given jamming level at which changeover will occur are indicated by the shaded areas. Fig. 15 (a) is for a signal of -114.5 dbw, and 15 (b) is for a signal of -87 dbw.

The effects of tuning a noise modulated jammer across the receiver bandpass are much simpler. The noise increase is above threshold over the entire bandpass of the receiver. Figs. 16 (a) and (b) are power vs. frequency graphs plotted from experimental measurements made with AM-by-noise jamming. The relative bandwidths at any given power level over which the various functions of the receiver are affected is clearly shown. Fig. 16 (a) is for signal strength of -114.5 dbw while 16 (b) is for a signal level of -87 dbw.

In order to study jamming by short pulses more thoroughly to determine its usefulness as a deceptive measure, a plot was made of the video output spectrum of the first discriminator of the multiplex receiver. This spectrum is given in

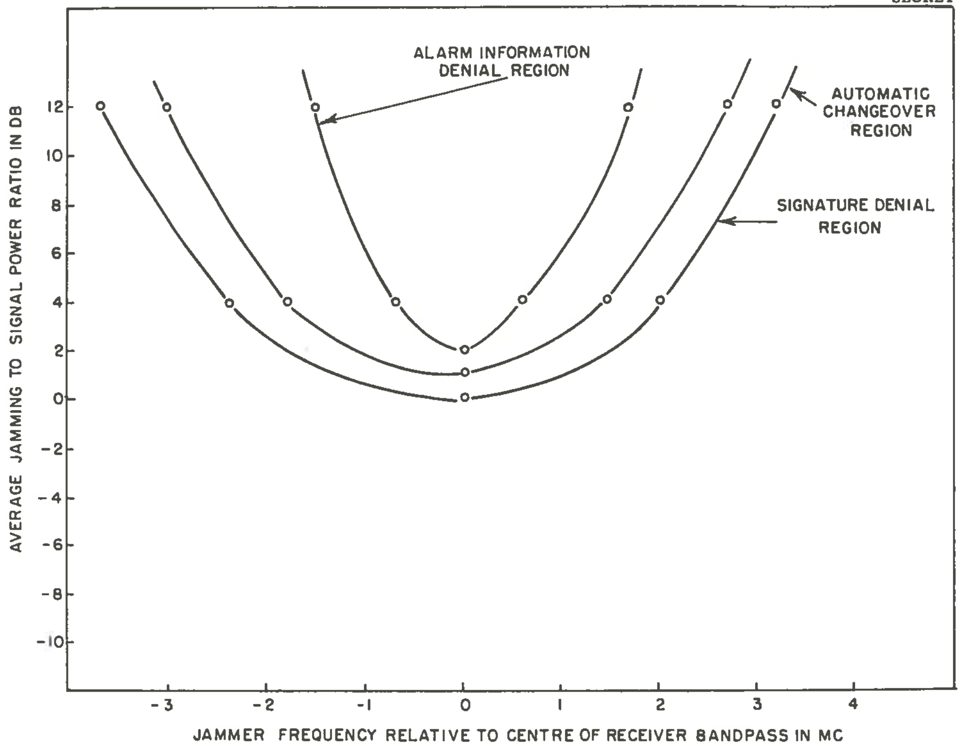


a) SIGNAL LEVEL IS - 114.5 DBW

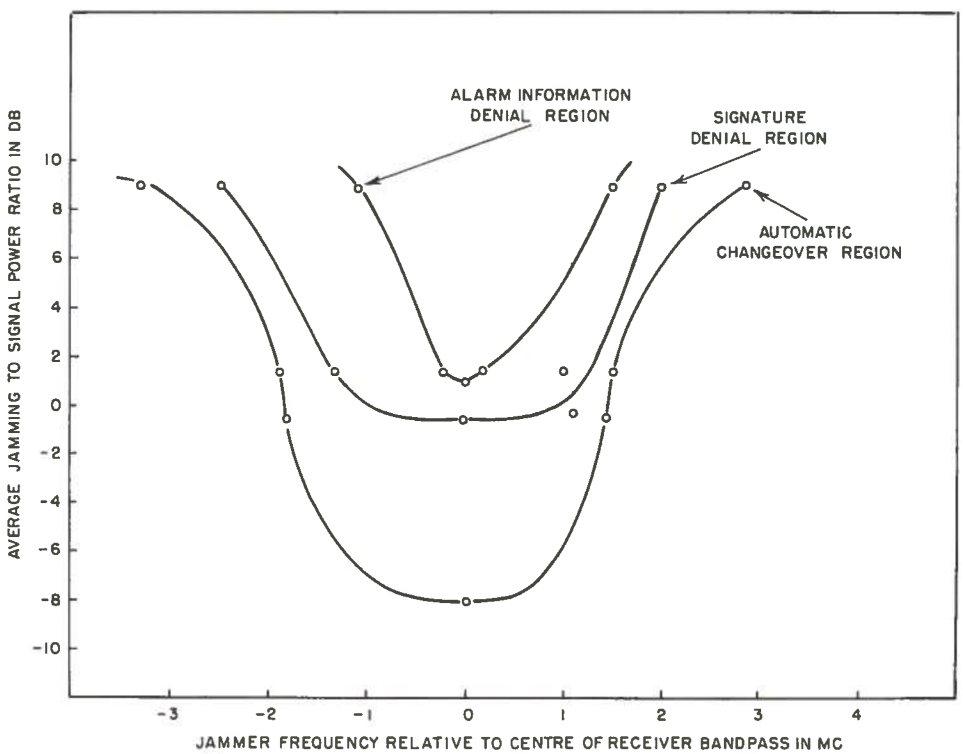


b) SIGNAL LEVEL IS -87 DBW

FIG. 15 CURVES SHOWING THE AREAS ON A POWER VS FREQUENCY GRAPH WHERE THE NOISE LEVEL OUT OF THE FIRST DISCRIMINATOR DUE TO CW JAMMING AFFECTS THE VARIOUS ASPECTS OF RECEIVER PERFORMANCE



a) SIGNAL LEVEL IS - 114.5 DBW



b) SIGNAL LEVEL IS -87 DBW

FIG. 16 CURVES SHOWING THE AREAS ON A POWER VS FREQUENCY GRAPH WHERE THE NOISE LEVEL OUT OF THE FIRST DISCRIMINATOR DUE TO NOISE JAMMING AFFECTS THE VARIOUS ASPECTS OF RECEIVER PERFORMANCE

Fig. 17. As can be seen, the spectrum is typical of a video pulse, indicating that no significant change was introduced by the non-linear system used as a detector — namely a discriminator with a strong signal present. The subcarriers were removed from the communications signal to avoid confusion.

As the centre of the jammer pulse spectrum is tuned across the bandpass of the FM receiver, the amplitude of a given line in the video output spectrum will vary. The amplitude of the video signalwill be proportional to the frequency difference between the jammer and the signal, and will also be attenuated by the skirts of the receiver IF bandpass. Fig. 18 is a curve illustrating the variation of amplitude of a given line in the video output spectrum of Fig. 17 as the centre frequency of the jammer output is tuned across the receiver bandpass. This curve has the standard discriminator response shape as would be expected.

Plate XI is a pen recording of the output of the 28.8 kc and 34.4 kc subcarrier receivers. For this experiment both subcarrier transmitters were fed the same doppler signal. The jammer was modulated with pulses 1.7 μsec long at a repetition rate of 14.4 kc. The second harmonic of the pulse repetition frequency therefore fell in the 28.8 kc subcarrier receiver bandpass, and as the jammer strength was slowly increased, denial occurred as the figure shows.

Plate XII shows deceptive jamming of the FM multiplex receiver on the 28.8 kc subcarrier. Using the same setup as in Plate XI but with the addition of a second artificial doppler generator applying frequency modulation to the pulse rate of the jammer, false doppler waveforms were made to appear on the pen recording as shown.

DISCUSSION

In operation on the Mid-Canada Line, the received signal level at the input of the FM multiplex radio relay receiver is nominally -75 dbw. Using this figure in conjunction with the experimental results in Plate I, and the deviation used on the Mid-Canada Line, the following data has been calculated. The data was obtained by controlled measurements in the laboratory, and has not been verified by actual measurements on the Mid-Canada Line.

a) Denial

i) Complete denial of signature and alarm information for one channel in one direction can be obtained with short pulsed transmissions at an average power level of -91 dbw at a DDS or -97 dbw at a Sector Control Station.

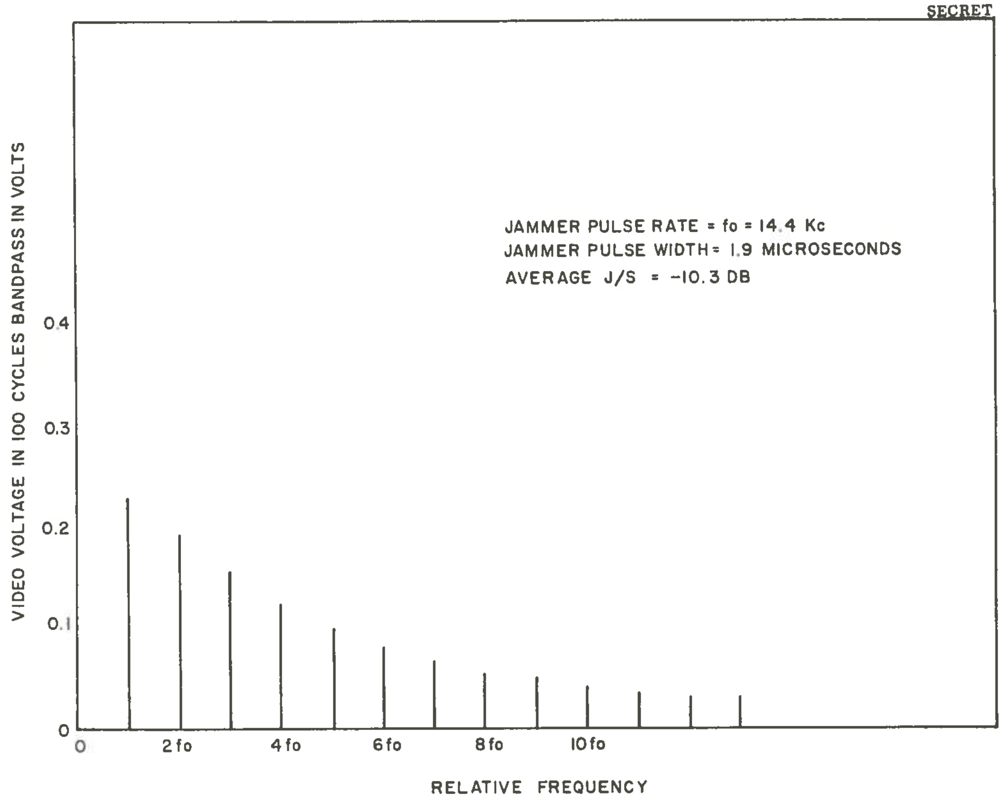


FIG. 17 VIDEO OUTPUT SPECTRUM OF THE FIRST DISCRIMINATOR OF THE MULTIPLEX RECEIVER WHEN SUBJECTED TO 14.4 KC PULSE JAMMING

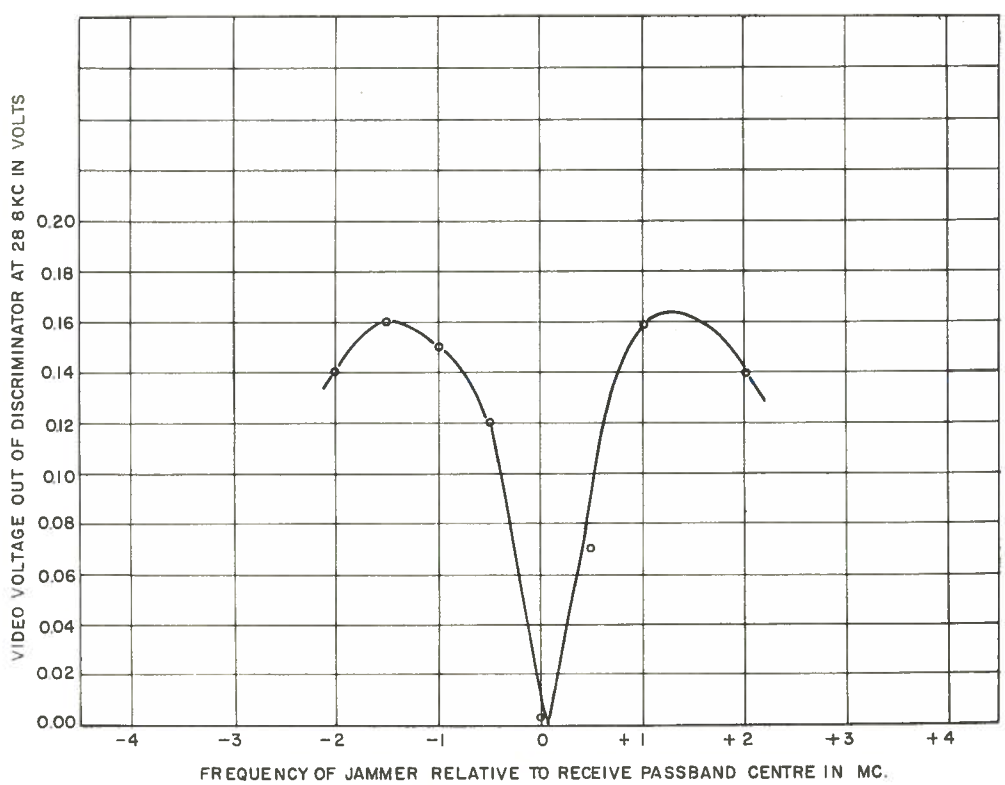


FIG. 18 CURVE ILLUSTRATING THE VARIATION IN AMPLITUDE OF A GIVEN LINE IN THE SPECTRUM OF FIG. 14 AS THE JAMMER IS TUNED ACROSS THE MULTIPLEX RECEIVER BANDPASS

ii) Complete denial for signature and alarm information from all channels in one direction can be obtained with amplitude modulation by noise at an average power level of -74 dbw.

iii) Complete denial of system operation in one direction from all stations previous to the jammed station (repeater changeover) can be obtained with short jamming pulses with a PRF of 400 kc and an average power level of -81 dbw at a DDS site or -87 dbw at an SCS.

iv) Denial similar to that of (iii) i.e., by repeater changeover, can be obtained with a noise modulated signal of -76 to -81 dbw or a CW signal of -73 to -78 dbw.

v) Complete denial of all signature information by means of a CW signal requires -75 + 15 = -60 dbw.

b) Deception

i) Deceptive jamming as a result of production of false dopplers in one channel can be accomplished at an average power level of -91 or -97 dbw depending on the site, using short pulses, with a repetition rate in the subcarrier band.

No other method attempted produces satisfactory deceptive jamming.

c) Confusion Jamming

All of the above types of jamming operating intermittently will produce confusion jamming. Some of the measures used to produce denial jamming require knowledge of system frequencies which would not be necessary for a confusion jammer.

Figs. 19(a), (b), and (c) are plots of power required by a jammer operating in the main beam of the communications system and at various distances from the jammed receiver. These curves are based on calculations done in a separate report [4] and assume a jammer antenna gain of unity relative to an isotropic antenna.

For the curves of Fig. 19(a) the jammer is assumed to be located in an aircraft, which is flying well above the horizon, and in the main lobe of the communications receiver antenna pattern, so that only free space propagation loss is taken into account.

For Fig. 19(b) a noise modulated jammer is assumed to be on the ground but

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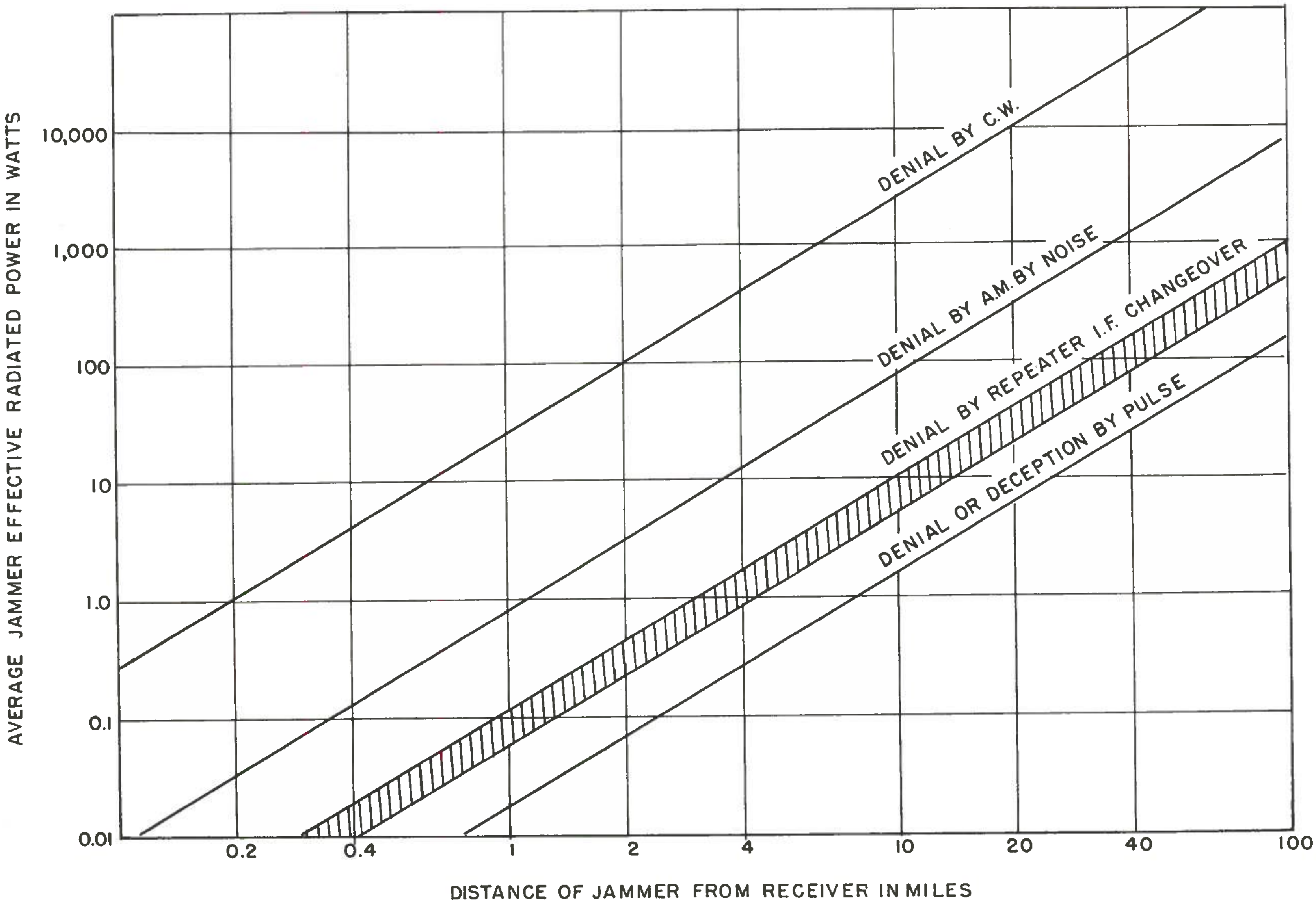

FIG. 19 a) CALCULATED POWER REQUIRED FOR AN AIRBORNE JAMMER FLYING AGAINST THE RADIO RELAY SYSTEM OF THE MID-CANADA LINE

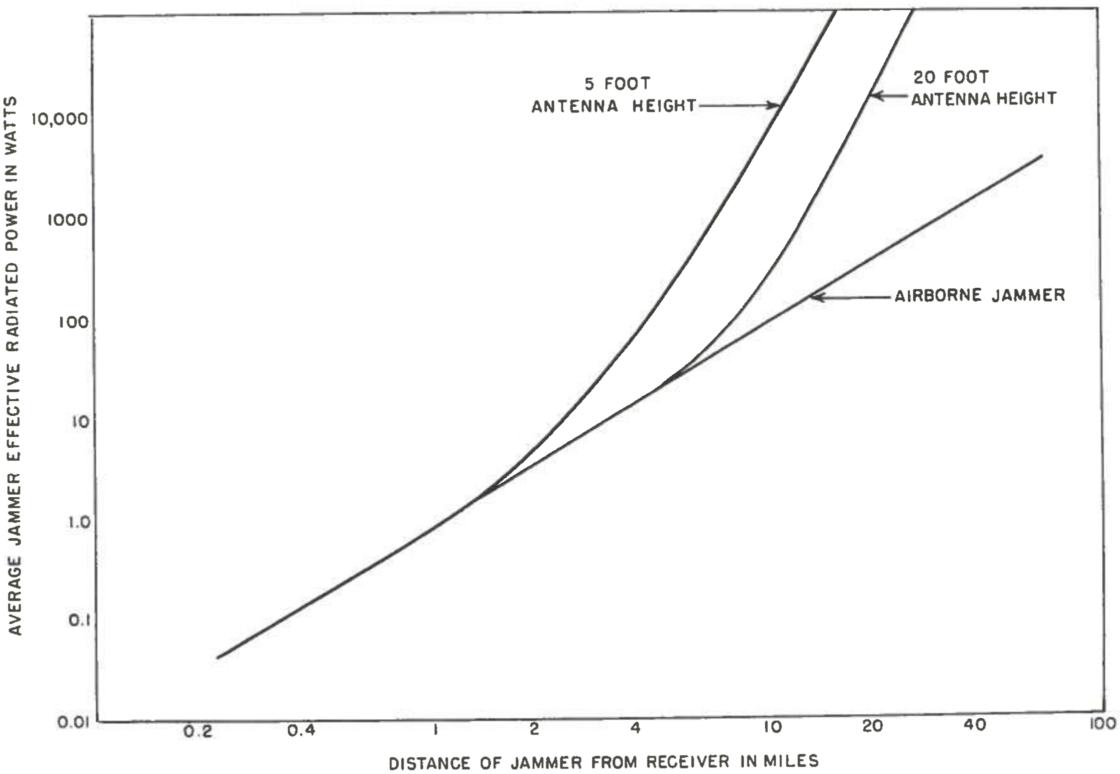

FIG. 19 b) CALCULATED POWER REQUIRED FOR AN AM BY NOISE GROUND-BASED JAMMER USED AGAINST THE RADIO RELAY SYSTEM OF THE MID-CANADA LINE

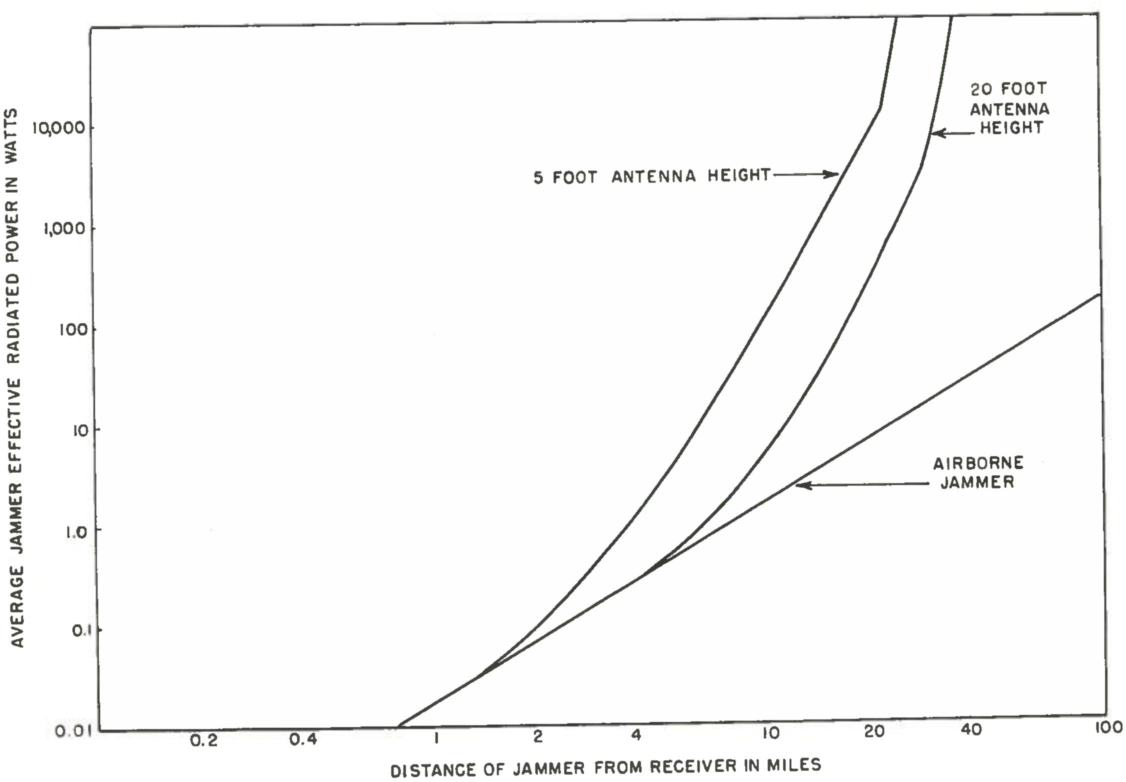

FIG. 19 c) CALCULATED POWER REQUIRED FOR A SINGLE CHANNEL, DENIAL, PULSED, GROUND-BASED JAMMER USED AGAINST THE RADIO RELAY SYSTEM OF THE MID-CANADA LINE still in the main lobe of the antenna pattern. The increased loss as the jammer drops below the horizon is clearly illustrated. It must be kept in mind that the latter propagation losses are based on an idealized model of the earth's surface between the jammer and the communications receiver, and that variations due to local topography will be very large for jammers located near the horizon.

Fig. 19 (c) is for a pulsed ground based jammer.

CONCLUSIONS

From the information presented in this report the following conclusions can be drawn.

1) While a single jammer will cause no loss in the ability of the Mid-Canada Line to detect aircraft, two jammers which cause complete denial to two separate links of the Radio Relay Communications System can cut off the flow of information from a section of the line between the jammers which can be up to 300 miles long.

2) Calculations based on the results of experimental measurements and propagation theory at the present time suggest that complete denial of the information flow on the radio relay link in one direction could be brought about by the use of any of the following jammers. It is emphasized again that these figures have not been verified on the Mid-Canada Line.

i) An airborne pulsed jammer on the beam of the receiver antenna, above the horizon, and at a distance of 50 miles from the receiver (well north of the MCL for approximately 50% of the links) with an average output power of 400 watts and with a frequency stability of 0.5%.

ii) An airborne noise-modulated jammer on the beam of the receiving antenna, above the horizon, and at a distance of 50 miles from the receiver with a frequency stability of 0.5% and power output of 2000 watts.

iii) A ground-based pulsed jammer 15 miles from the jammed receiver, and on the main beam of its antenna with a jammer antenna height of 15 feet or more, frequency stability of 0.5%, and average power output of 800 watts. Such a jammer together with batteries operating for 10 hours could be made to weigh less than 800 pounds [4].

iv) A ground-based noise-modulated jammer 15 miles from the jammed receiver, on the main beam of the antenna, with a jammer antenna height of 15 feet or more, frequency stability of 0.5%, and average power output of 6000 watts. Such a jammer together with batteries operating for 24 hours could be made to weigh less than 4000 pounds using a gasoline or deisel generator, and

10,000 pounds using magnesium silver chloride batteries.

3) Complete denial of any chosen subcarrier channel of the radio relay system corresponding to any DDS link, could be accomplished by a pulsed jammer in any one of the situations given in (2) but with an average power requirement approximately 3% of that of the noise-modulated jammer; i.e., 45 watts in the airborne case and 135 watts for the ground case.

4) Deception of any chosen subcarrier channel of the radio relay system corresponding to a chosen DDS link could be accomplished with the same jammer as in (3).

It can be seen from the above results, that while jamming of the communications system of the Mid-Canada Line is difficult, it does not appear completely impractical, especially when one considers the large gaps which can be made in the line with only a few jammers.

The system has two main weaknesses with respect to jamming susceptibility. These are:

i) the automatic repeater changeover system, and
ii) the susceptibility to single channel denial or deception of the signature and alarm subcarriers.

The first weakness is removed by the use of a simple remotely controlled manual override on the automatic repeater changeover.

The second can be improved only by increasing the DQ-38 deviation for signature subcarriers at the expense of reducing the overall system information carrying capacity.

ACKNOWLEDGEMENTS

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Mr. H. Poapst constructed the apparatus, and assisted with the experimental measurements.

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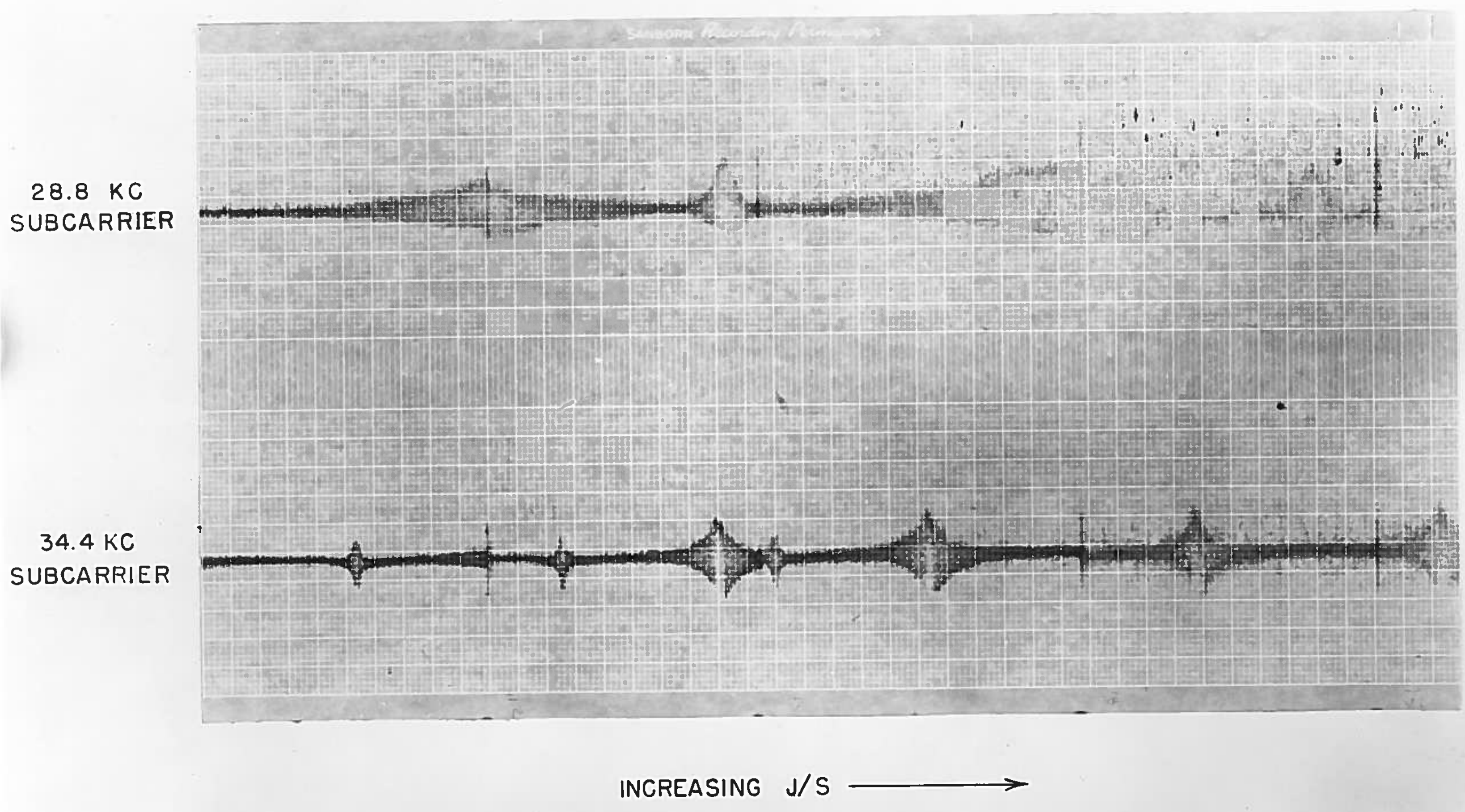

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PLATE I OUTPUT OF DUAL-CHANNEL PEN RECORDER FED BY TWO SUBCARRIER RECEIVERS WHEN SYSTEM IS SUBJECTED TO A JAMMER AMPLITUDE-MODULATED BY NOISE

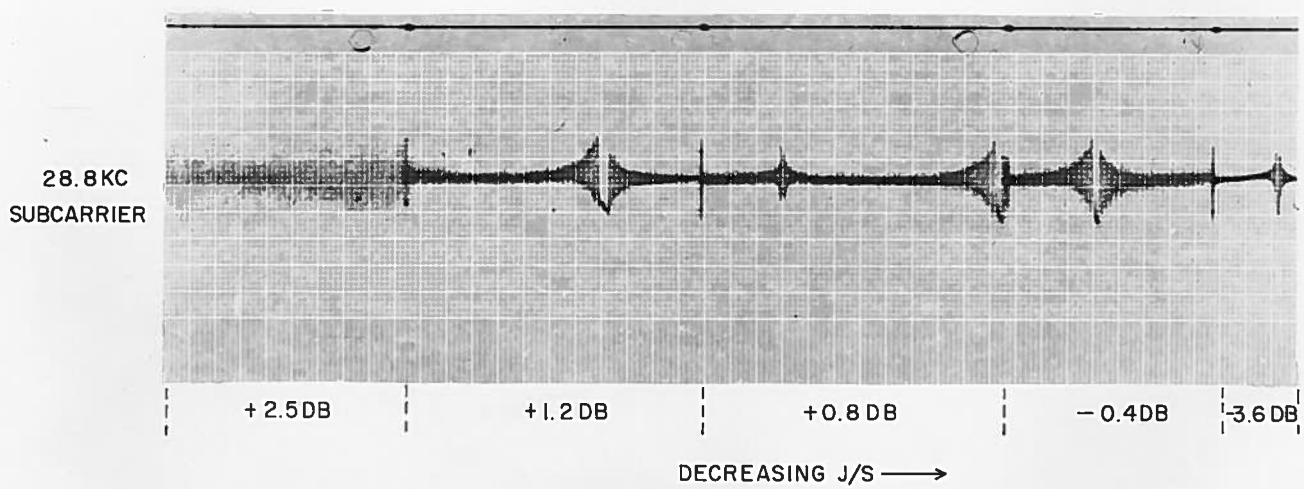

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PLATE II OUTPUT OF PEN RECORDER FED BY A SINGLE SUBCARRIER RECEIVER WHEN SYSTEM IS SUBJECTED TO CW JAMMING. (Signal level: -114.5 dbw)

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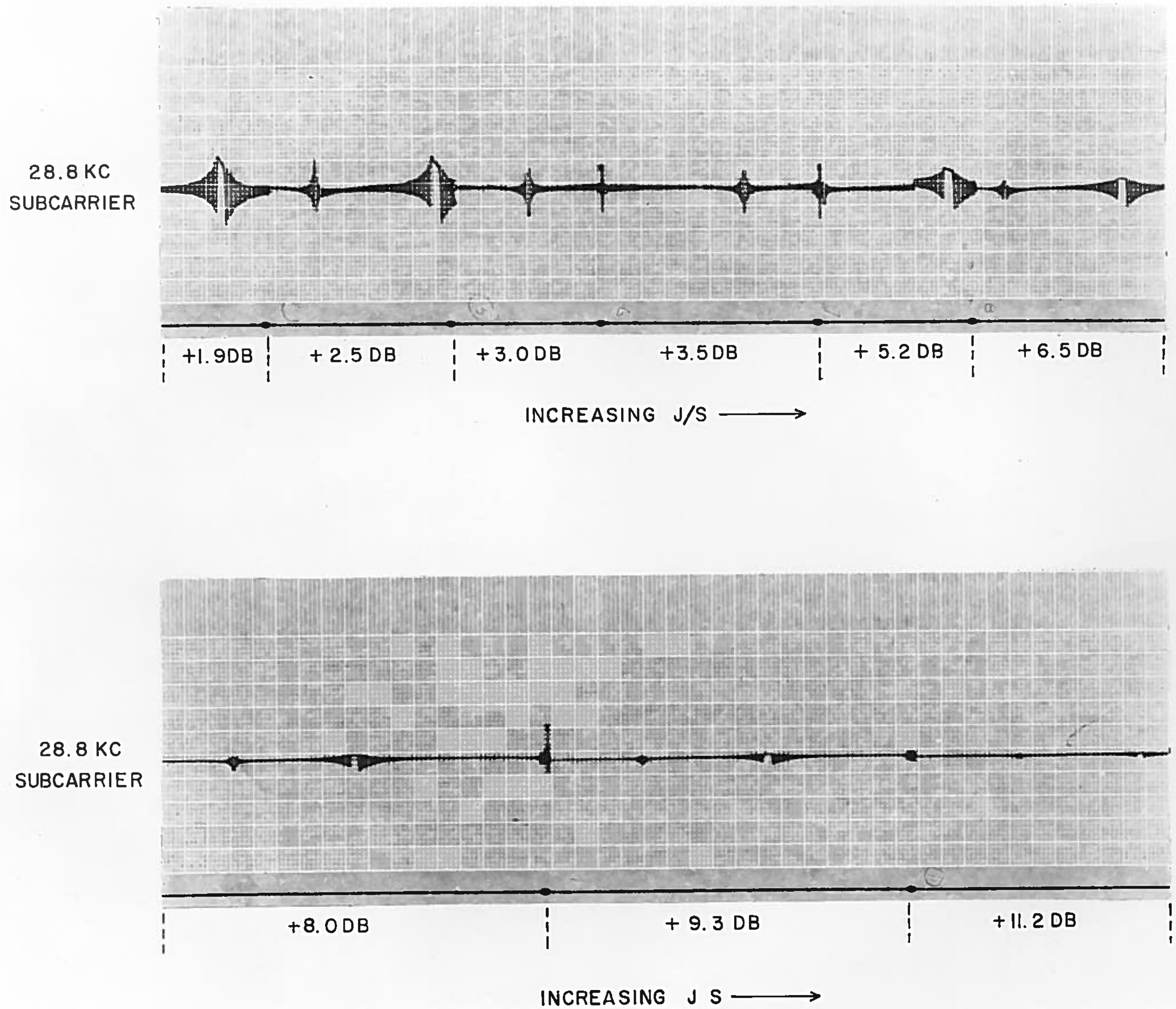

PLATE III PEN RECORDING SIMILAR TO PLATE II
EXCEPT THAT SIGNAL LEVEL IS INCREASED TO-87 DBW

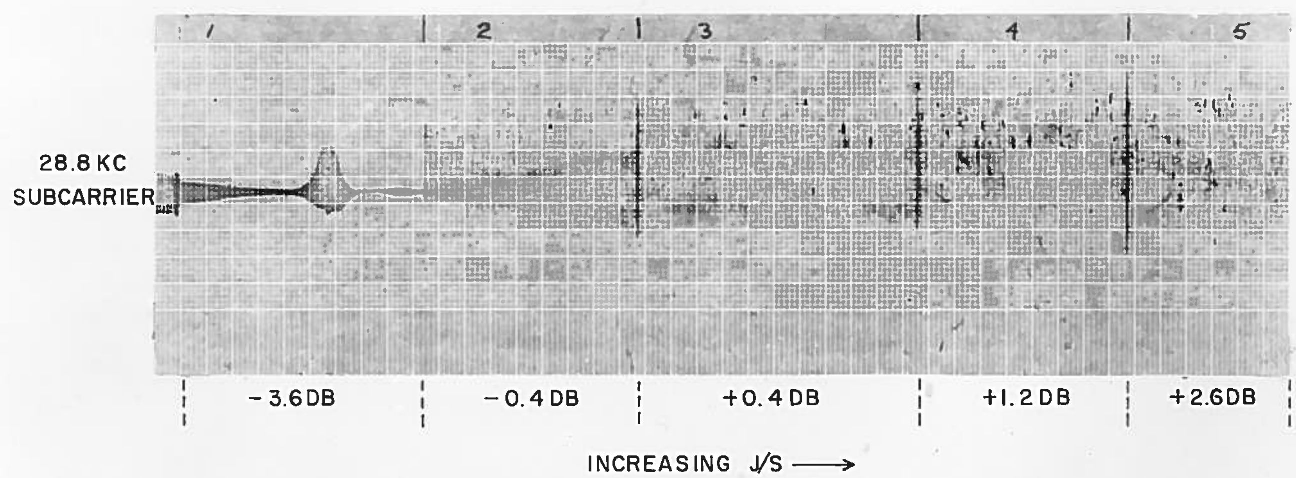

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PLATE IV OUTPUT OF PEN RECORDER FED BY A SINGLE SUBCARRIER RECEIVER WHEN SYSTEM IS SUBJECTED TO A JAMMER AMPLITUDE-MODULATED BY NOISE. (Signal level: -114.5 dbw)

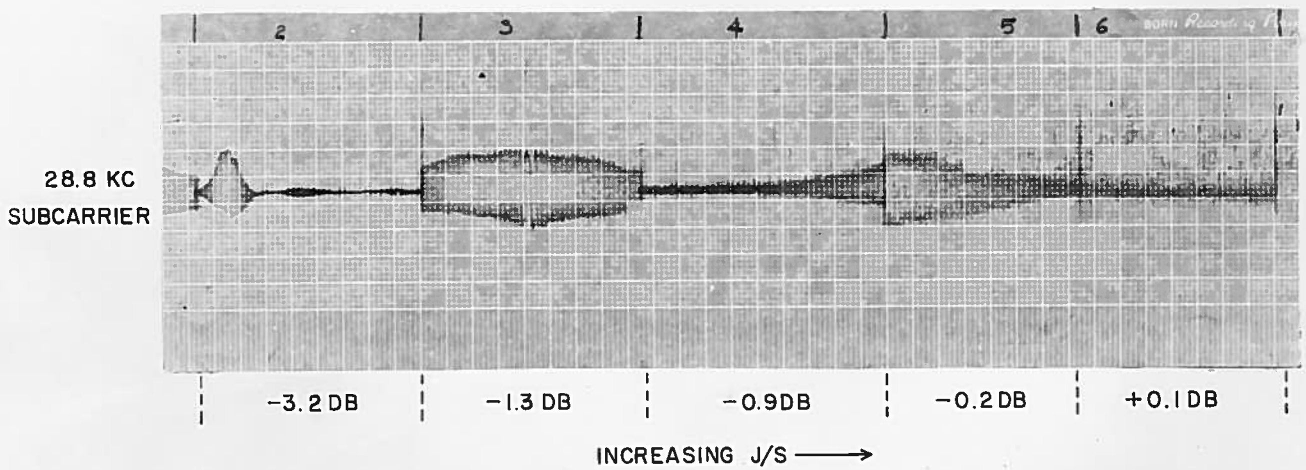

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PLATE V PEN RECORDING SIMILAR TO PLATE IV
EXCEPT THAT SIGNAL LEVEL IS INCREASED TO -87 DBW

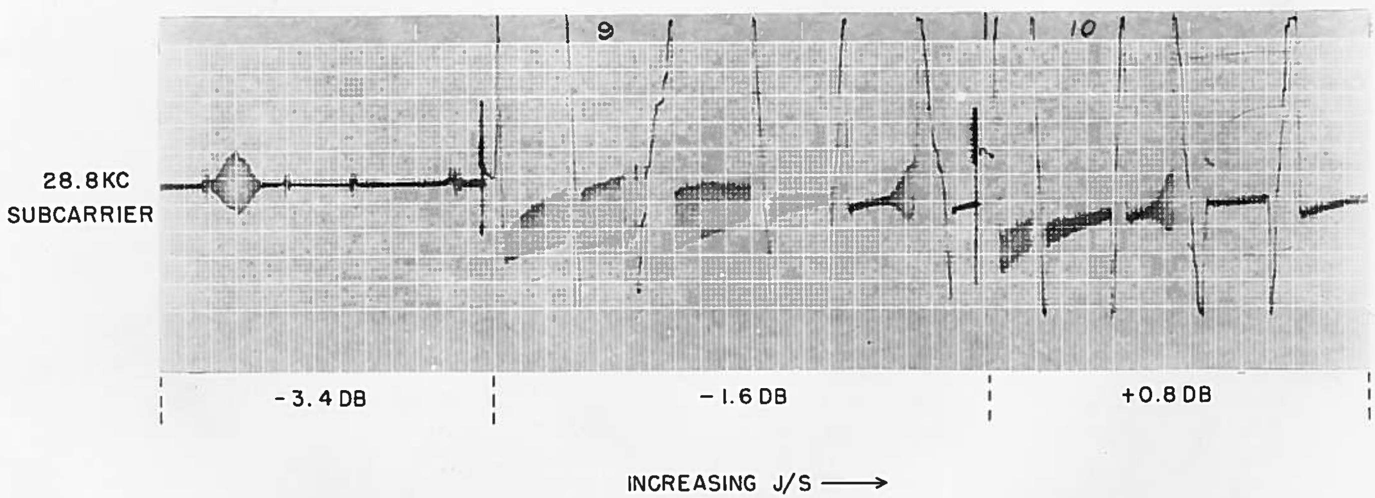

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PLATE VI PEN RECORDING OF OUTPUT OF A SINGLE SUBCARRIER RECEIVER WHEN SYSTEM IS SUBJECTED TO JAMMING BY PULSES WITH A REPETITION RATE AT THE SUBCARRIER FREQUENCY. (Duty cycle of pulses: 0.85)

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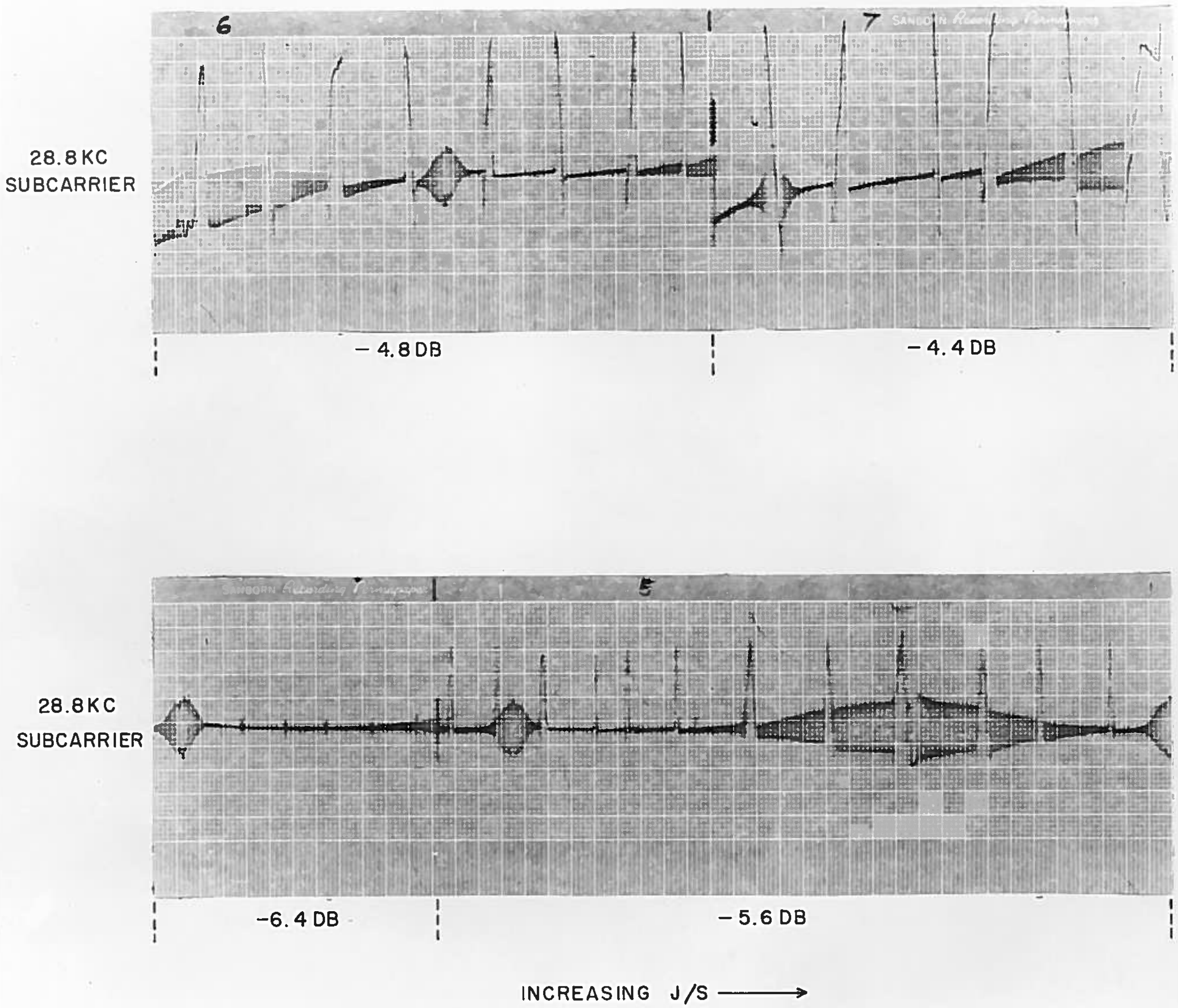

PLATE VII PEN RECORDING SIMILAR TO PLATE VI EXCEPT THAT DUTY CYCLE OF PULSES IS 0.50

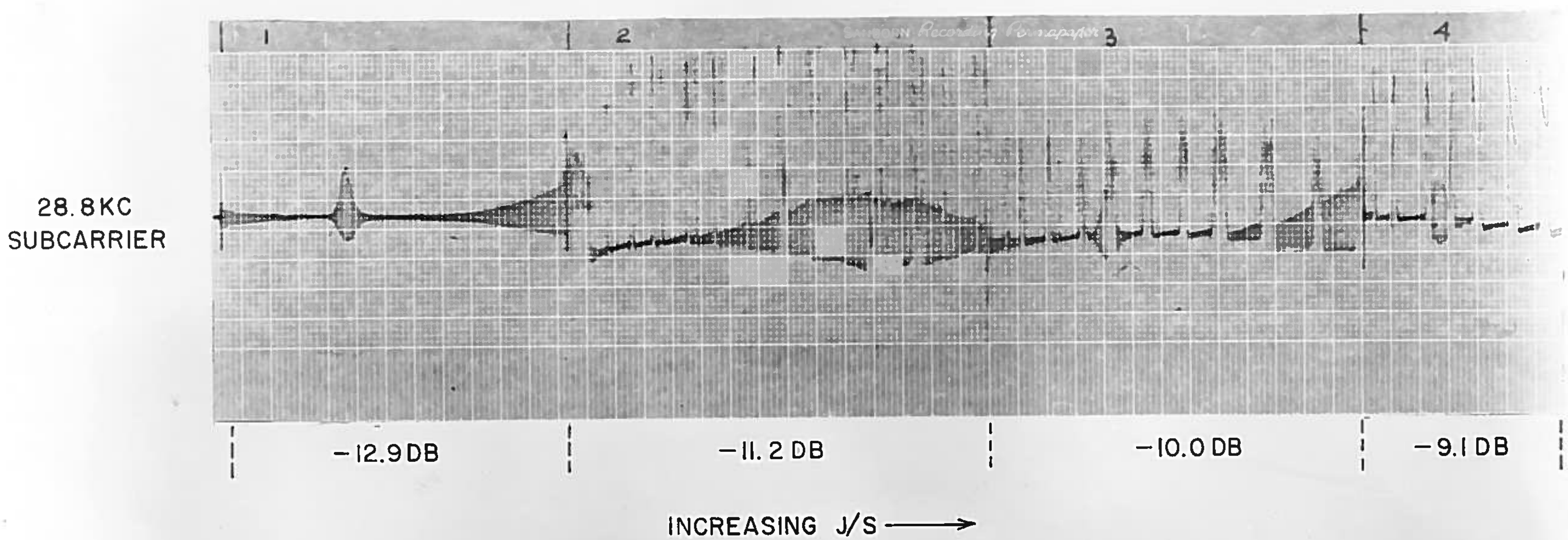

PLATE VIII PEN RECORDING SIMILAR TO PLATE VI
EXCEPT THAT DUTY CYCLE OF PULSES IS 0.17

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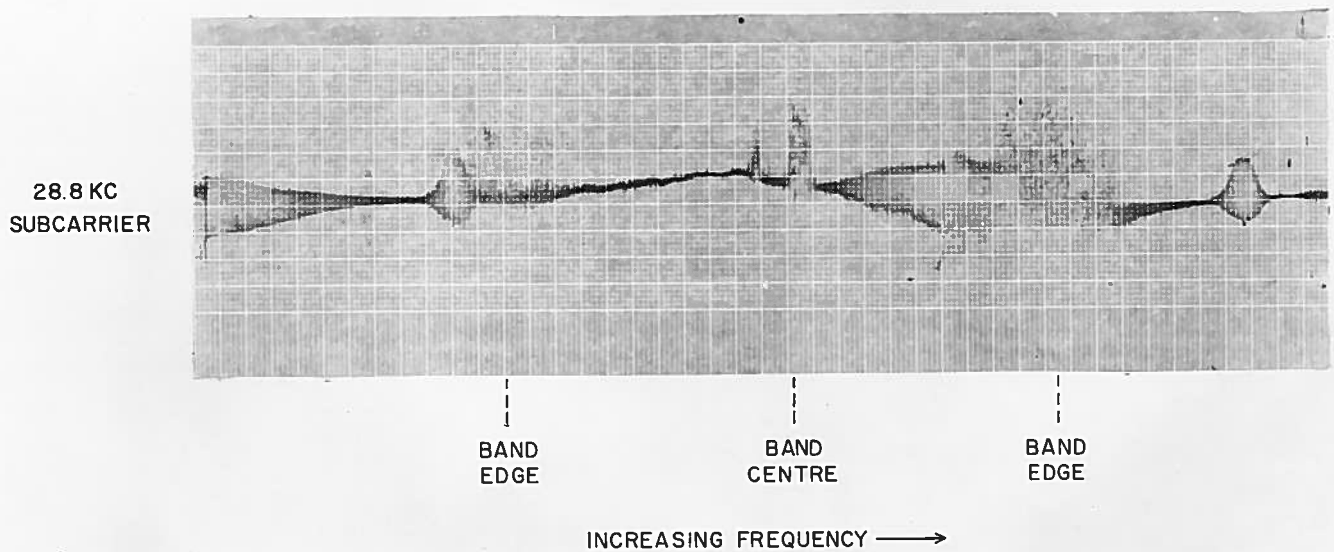

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PLATE IX PEN RECORDING OF OUTPUT OF SUBCARRIER RECEIVER AS A CW JAMMING SIGNAL IS SWEPT ACROSS MULTIPLEX RECEIVER BANDPASS.
(Signal level: -114.5 dbw)

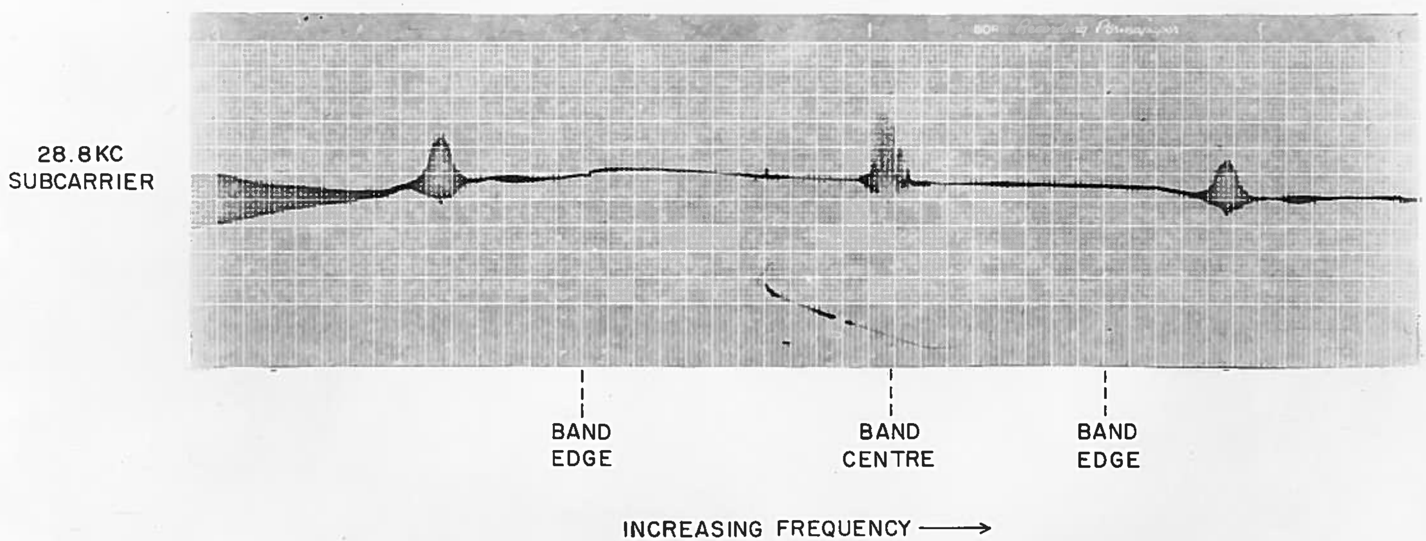

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PLATE X PEN RECORDING SIMILAR TO PLATE IX EXCEPT THAT SIGNAL LEVEL IS INCREASED TO -87 DBW

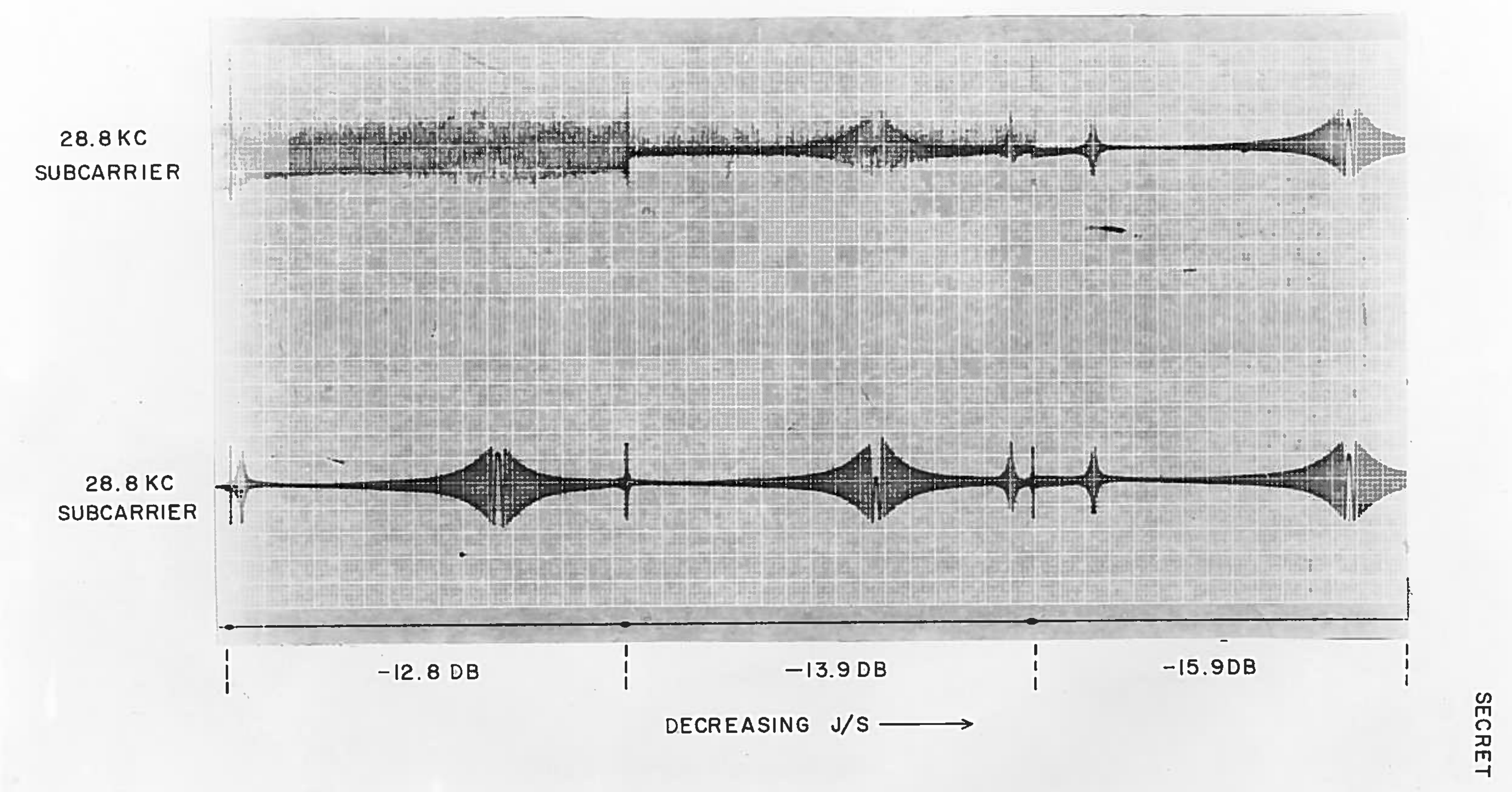

PLATE XI PEN RECORDING ILLUSTRATING DENIAL OF A SINGLE SUBCARRIER RECEIVER BY PULSE-JAMMING OF MULTIPLEX RECEIVER

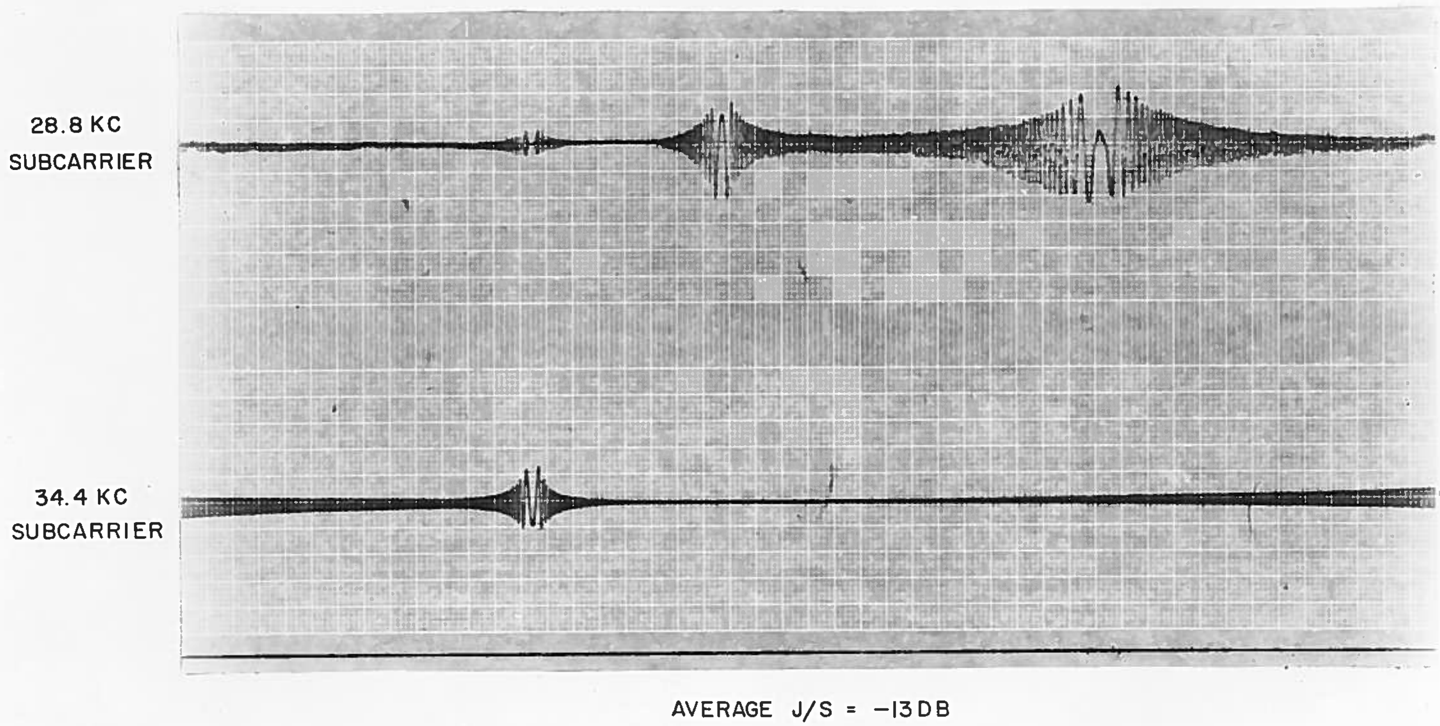

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PLATE XII PEN RECORDING ILLUSTRATING DECEPTIVE JAMMING OF A SINGLE SUBCARRIER RECEIVER BY PULSE-JAMMING OF MULTIPLEX RECEIVER