

**A CRYSTAL LIMITER FOR USE IN AN  
FM RECEIVER IN THE PRESENCE  
OF IMPULSE INTERFERENCE**

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**RESEARCH LABORATORY OF ELECTRONICS  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY**

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Abstract

An analysis of impulse noise in an ideal (amplitude insensitive) FM receiver has indicated that the effect of impulse noise should be negligible. From the analysis additional transient functions of a limiter are inferred. These functions are shown to be approximated by two germanium crystals paralleled with reversed polarities. Experimental results are shown in the form of oscillograms.

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1. Introduction

It is a generally accepted fact today that frequency modulation (FM) is a realizable means of faithfully transmitting intelligence, and one which offers many advantages and improvements over amplitude modulation (AM). The development of FM, extending back to approximately the beginning of this century, has not been an easy task. One of the more important problems has been the development of a successful FM receiver. This hurdle has been responsible, more than any other single factor, for the failure of many early attempts to use FM, and, in fact, today still presents a reduced, but definite, limitation of the FM system.

The difficulty in realizing a satisfactory FM receiver can in general be narrowed down to the development of its two basic component parts - the limiter and the FM detector, since, with the exception of these two elements, the FM receiver may be considered similar to the conventional AM receiver.

Impulse Noise. It has been shown theoretically that the effect of impulse noise on an ideal FM receiver, should be negligible. Bradley and Smith<sup>1</sup> have pointed out that for a system with 75-kc deviation and a de-emphasizer time constant of 100  $\mu$ sec, the peak amplitude of the generated noise signal resulting from impulse noise of short duration should be not more than 13 per cent of the peak signal amplitude. It has also been shown that the polarity of the detected noise signal is always opposite to the polarity of the detected program signal at the time of the noise impulse. The audio system will tend to integrate these "holes" in the program signal (Fig.1). One has only to listen to most commercial receivers today, however, to discover that actual practice is far removed from these theoretical predictions.

Limiters. A study has been made of the necessary functions of the limiter in order to help resolve this difference.

The theoretical analysis of impulse noise in an FM receiver hinges on two assumptions:

1. The resonant frequency of the tuned circuits of the FM receiver is independent of the amplitude of the input signal.
2. The amplitude variations of the input signal are removed before the signal reaches the discriminator.

The second condition is quite commonly described as the sole function of the limiter. A physical realization of this function can be reasonably approximated.

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1. W. E. Bradley and D. B. Smith, "The Theory of Impulse Noise in Ideal Frequency-Modulation Receivers", Proc. IRE, 34, 743 (1946).

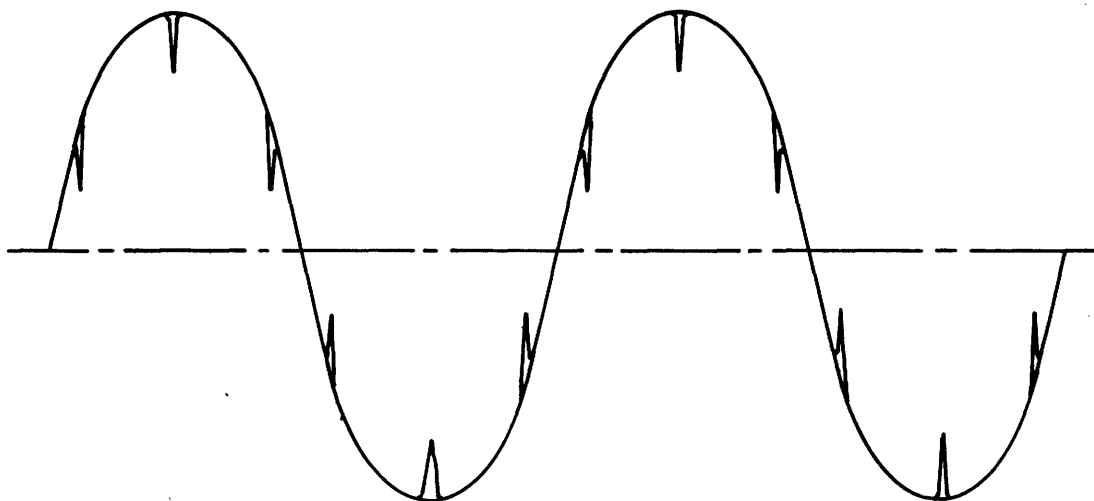


Figure 1. Sinusoidal FM signal plus impulse noise at the output of the de-emphasizer.

The first condition, however, appears to have been neglected. Results obtained to date indicate that this function of the limiter is of principal importance in the reduction of impulse noise in FM reception.

It can be shown<sup>1</sup> that an oscillatory frequency transient results when a unit step function of angular frequency  $p$  is impressed upon a resonant tuned circuit of frequency  $\omega$ . The initial frequency of the resultant is the arithmetic mean of the driving and resonant frequencies:  $(\omega+p)/2$ . The resultant frequency then oscillates with a period  $\approx \omega-p$  and reaches a steady-state condition at the frequency  $p$  in a manner determined by the damping coefficient,  $\alpha = 1/2RC$ , of the resonant circuit. If the driving frequency  $p$  and the resonant frequency  $\omega$  are equal, no transient oscillation in frequency will result. It is for this reason that the tuned circuits of each stage of the FM receiver must be accurately aligned. Initial alignment, however, is not sufficient. The necessary requirement is that the tuned circuits of the FM receiver be maintained in this condition independent of the received signal amplitude.

The input capacitance of an amplifier stage varies as a function of input signal. A large input transient, resulting from the injection of impulse noise into the receiver filter circuit will overload the tube, reduce its conductance, and thus cause a transient change in the input capacitance of the tube and hence the resonant frequency of the tuned circuit. The character and magnitude of the resulting frequency transient will depend on the tube used, the envelope of the impulse transient (number of preceding stages, receiver bandwidth, amplitude of impulse noise, etc), and the parameters of the resonant circuit. In general terms, however, it is sufficient to recognize the existence of such a combination of related factors.

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1. T. P. Cheatham, "Transient Analysis of Impulse Noise in FM Receivers", RLE Technical Report No. 28, January 20, 1947.

Additional functions of an ideal limiter can then be inferred:

1. To minimize the effect of varying grid-bias by acting as a fast d-c restorer.
2. To maintain the signal level at a constant low amplitude.
3. To act as a circuit with a variable damping coefficient to minimize oscillatory frequency transients. (Ideally the damping coefficient should be proportional to the amplitude of the transient.)
4. To minimize changes in input capacitance by preventing any amplifier tube from overloading; i.e., by preventing any tube from going to cut-off or saturation.

In order to fulfill these transient functions, the limiter should be distributed throughout the amplifier rather than placed as a single lumped device preceding the discriminator.

Quite fortunately, it has been found that the four functions listed above overlap in certain respects. As a result, it has been possible to approximate these functions in the laboratory with a single simple device, a pair of germanium crystals.

## 2. Logarithmic Limiter

As presently used in the laboratory, the logarithmic limiter consists of two 1N34 germanium crystals paralleled with reversed polarities and placed at the grid of each amplifier tube in the receiver as indicated in Fig. 2.

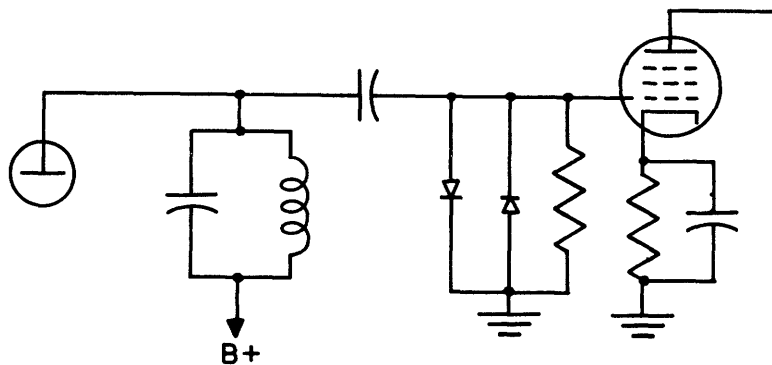


Figure 2. Position of logarithmic limiter.

The name of this type of limiter and its desirable features are derived from the approximately logarithmic characteristic curves of the germanium crystal.

If one plots  $\log I$  versus  $E$  for the forward direction of a germanium crystal, one obtains a characteristic curve as indicated in Fig. 3.

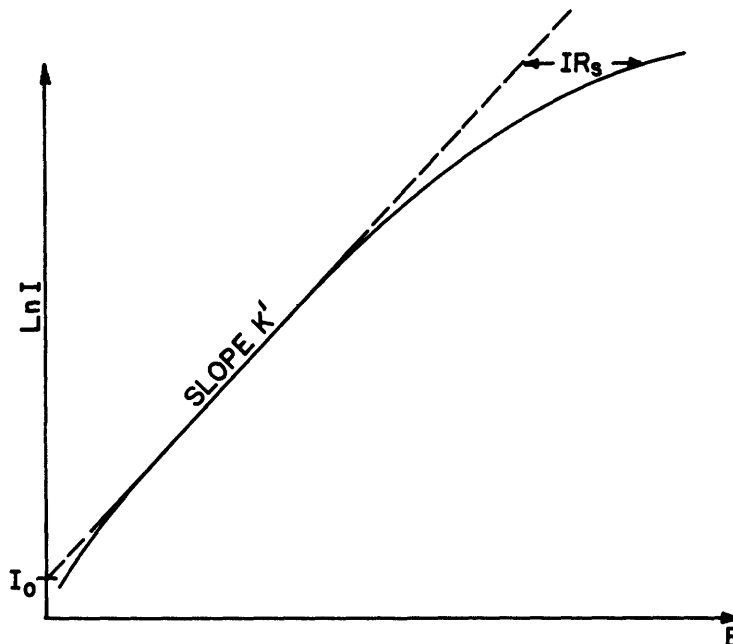


Figure 3. General characteristic curve for germanium crystals.

It has been shown<sup>1</sup> that this curve can be approximated by an equation of the form:

$$\ln (I+I_0) = K' (E-IR_s) \quad (2)$$

where

$I_0$  is the intercept on  $E = 0$

$K'$  is the slope, and

$R_s$  is the spreading resistance.

If we restrict ourselves to the straight line portion of the curve of Fig. 3, Eq. (2) can be simplified to

$$\ln (I+I_0) = K'E$$

$$\text{or } E = K \ln (I+I_0), \text{ where } K = \frac{1}{K'}$$

1. H.J. Yearians, "Determination of Logarithmic Constants of Crystal Rectifiers with the Oscilloscope", NDRC 14, Report No. 143, Purdue University, April 20, 1943.



Limiting Action. A simplified explanation of the limiting action of the germanium crystals (Fig. 2) can be given by the equivalent circuit of Fig. 4.

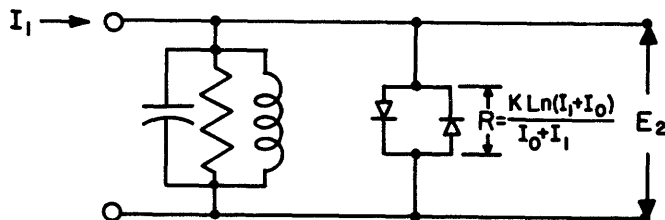


Figure 4. Equivalent circuit for limiting action of logarithmic limiter.

If the frequency of  $I_1$ , the driving current from the preceding pentode amplifier, is close to the resonant frequency of the tuned circuit, the impedance of the tuned circuit can be neglected with respect to  $R$ .

$$\text{Therefore, } E_2 = I_1 \frac{K \ln (I_1 + I_0)}{(I_0 + I_1)} .$$

Since  $I_0$  is small compared to  $I_1$ , the expression for  $E_2$  becomes equal to  $K \ln I_1$ , showing that amplitude variations are reduced logarithmically.

Variable Damping Coefficient Effect. As the amplitude of the driving current increases, the effective shunting resistance of the crystals decreases and hence the damping coefficient ( $\alpha = 1/2RC$ ) of the tuned circuit increases proportionally. The net effect is that the crystals act to damp out frequency transients in a manner proportional to the amplitude of the incoming impulse.

Fast D-C Restorer Action. The d-c restoring qualities result from the front-to-back mounting of the crystals, which provides a path in both directions for any accumulated charge on the coupling condenser to leak off almost instantaneously.

Reduction of Variation in Input Capacitance. The d-c restorer action and limiting action of the crystals reduce the chances of a transient overload. Thus any large change in tube conductance with its resulting variations of input capacitance is reduced.

Experimental Results. Figure 5 shows the wiring diagram of the receiver constructed to test the logarithmic limiter characteristics.

Impulse noise varying up to 300 V peak was obtained by using an A/R range scope, MK-3 test pulser, and an 807 pulse amplifier stage.

The operation of the receiver of Fig. 5 was first compared with a good commercial receiver. The comparison was made in the presence of impulse noise during the reception of a relatively weak signal on 103 Mc from WGTB, Boston. The effect of impulse noise, up

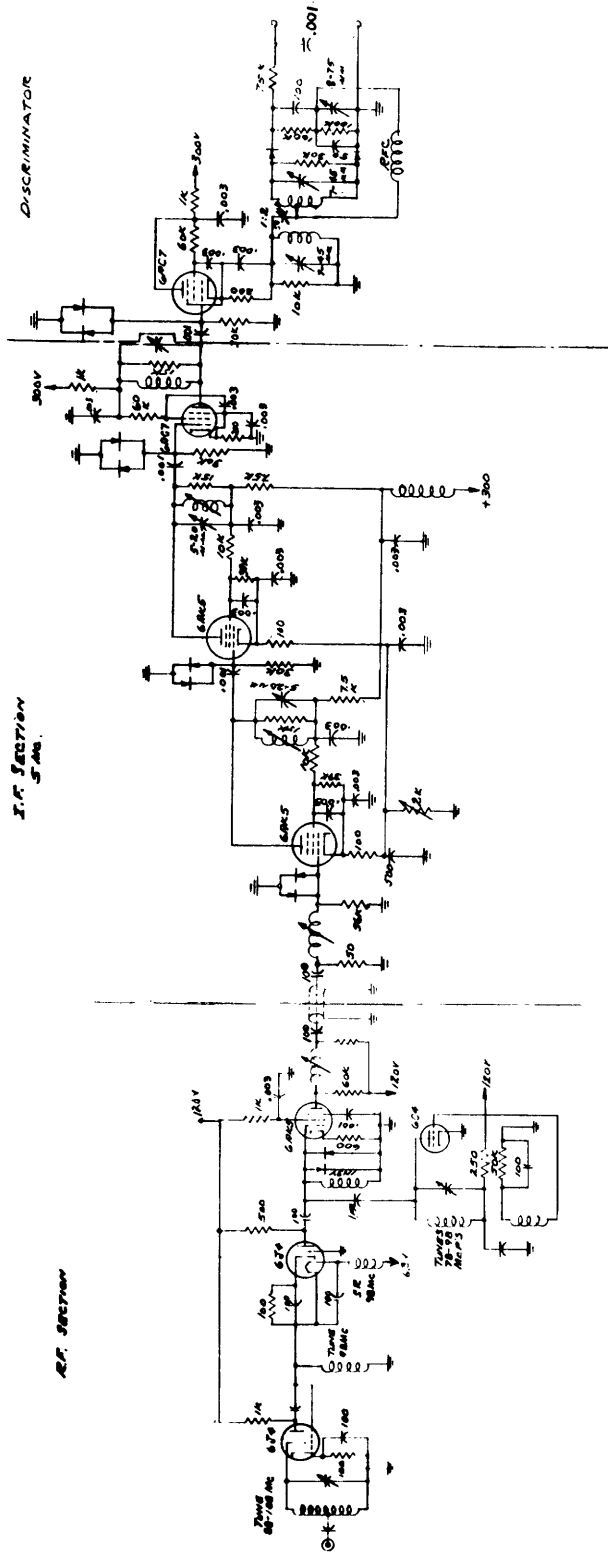


Figure 5. Wiring diagram for experimental receiver used to test logarithmic limiter.

to about 300 V, was negligible on the logarithmic receiver, while the program signal on the standard receiver, under identical conditions, was completely overridden.

It was further observed that local ignition noises and short-time selective fading due to airplanes in the vicinity also had a greatly reduced effect on the operation of the logarithmic receiver, while such interference was observed to be quite noticeable on the commercial test receiver.

Further tests were made, to check the theoretical predictions that have been made concerning impulse noise<sup>1</sup>. These predictions were found to be quite closely substantiated as long as the duration of the disturbance from a single impulse was less than the time constant of the de-emphasizer circuit. Above this point, it was found that a "pop" was no longer essentially independent of the amplitude of the impulse. Instead the amplitude appeared to vary proportionally.

Figure 6 illustrates the variations of the "pop" noise signal as a function of peak noise-to-signal ratio at the input of the receiver i-f filter. The photographs of Fig. 6 were taken at the output of the de-emphasizer. The FM signal and impulse noise were injected directly into the i-f filter. The d-c impulse was kept constant at about 300 V, while the carrier was modulated at 50 kc with a 400-cycle tone. The amplitude of the carrier was varied from 0 to approximately 100,000  $\mu$ W as indicated.

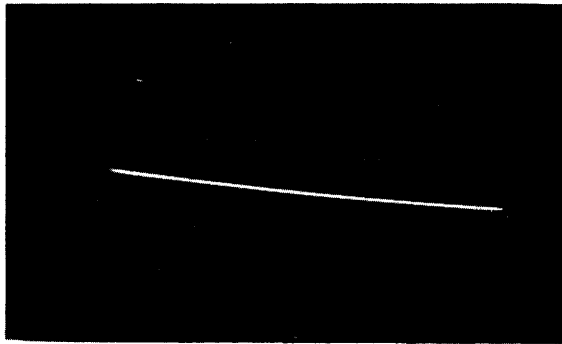
It is to be observed that the amplitude of the noise signal starts from zero, goes through a maximum, and then approaches zero again as the noise-to-signal ratio is made to vary from  $\infty$  to 0. It was observed that the maximum noise signal occurs in the region where the peak amplitudes of the impulse transient and of the program signal are nearly equal.

Figure 7 shows the manner in which the noise signal varies as the impulse amplitude is changed, the input carrier level being kept constant at 40,000  $\mu$ W.

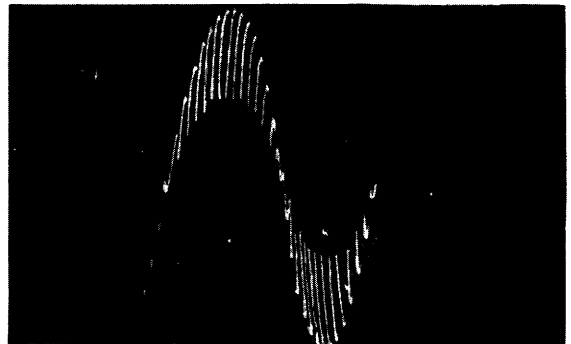
For comparison purposes, the photographs of Fig. 8 were taken with a standard commercial FM receiver having a two-stage grid-leak limiter. The impulse noise and FM carrier were injected into the i-f filter under identical conditions of Fig. 6 for values of  $N$ (= peak impulse/peak signal) of approximately  $30 \times 10^6$ ,  $3 \times 10^6$ ,  $6 \times 10^5$ , and  $3 \times 10^3$  as indicated.

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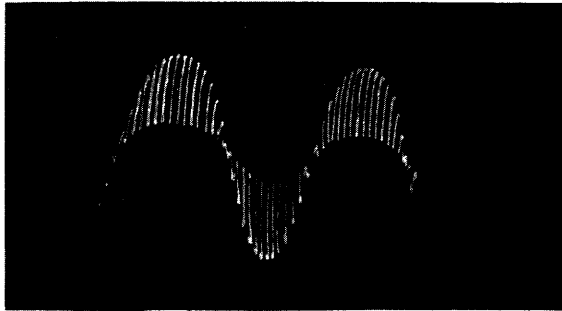
1. Bradley and Smith, loc. cit.



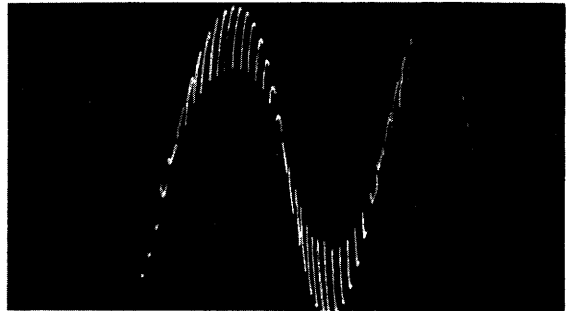
Carrier = 0,  $N = \infty$



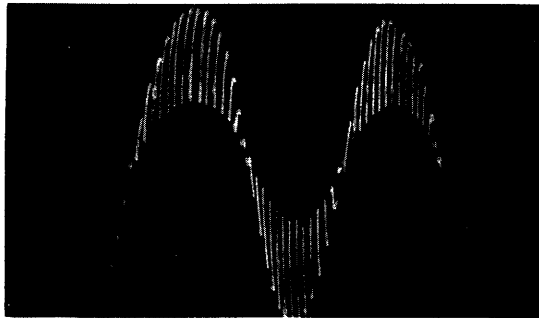
Carrier  $\approx$  500  $\mu$ V,  $N \approx 6 \times 10^5$



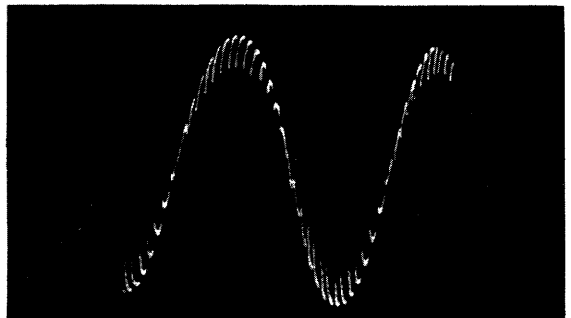
Carrier  $\approx$  10  $\mu$ V,  $N \approx 30 \times 10^6$



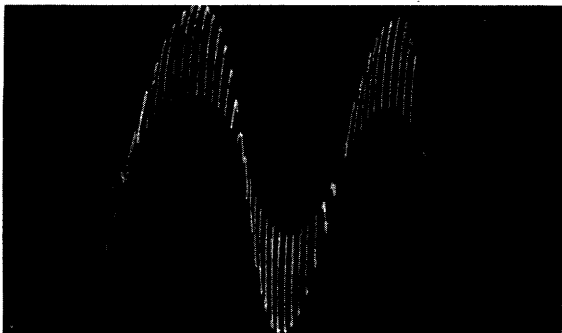
Carrier  $\approx$  5000  $\mu$ V,  $N \approx 6 \times 10^4$



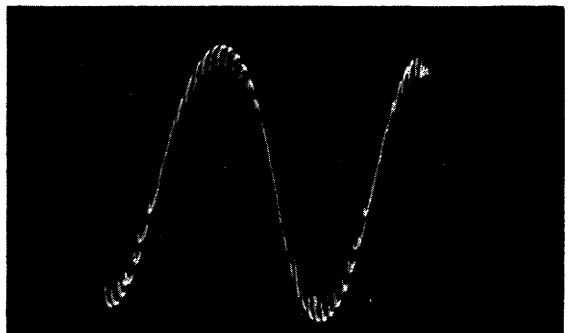
Carrier  $\approx$  50  $\mu$ V,  $N \approx 6 \times 10^6$



Carrier  $\approx$  50,000  $\mu$ V,  $N \approx 6,000$

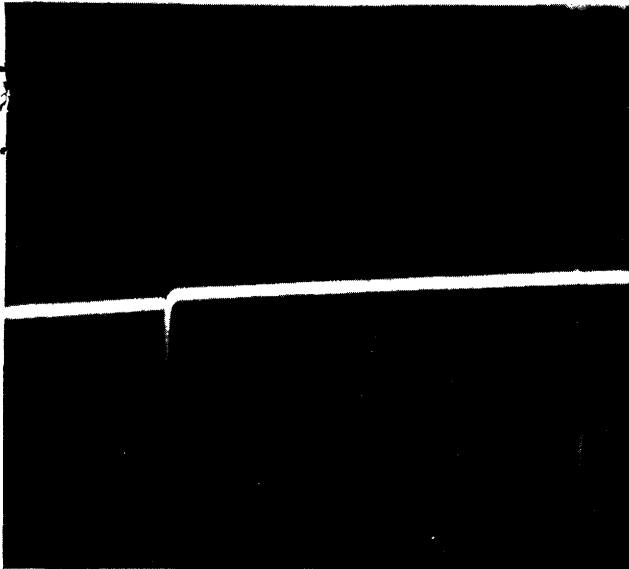


Carrier  $\approx$  100  $\mu$ V,  $N \approx 3 \times 10^6$

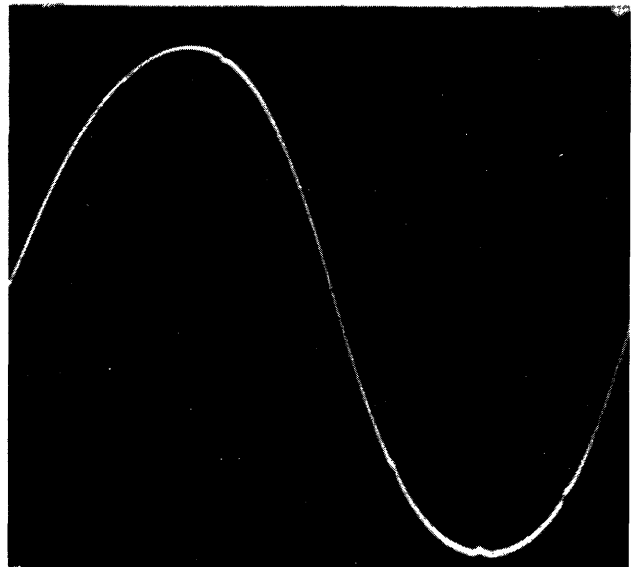


Carrier  $\approx$  100,000  $\mu$ V,  $N \approx 3,000$

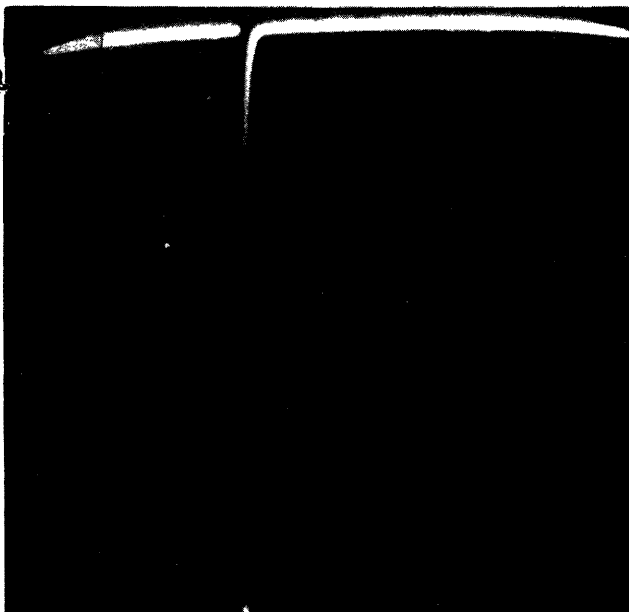
Figure 6. Effect of impulse noise on the laboratory receiver using distributed logarithmic limiters; peak impulse noise kept constant.  
 (Photographs have been retouched to indicate more clearly the resultant noise signals).



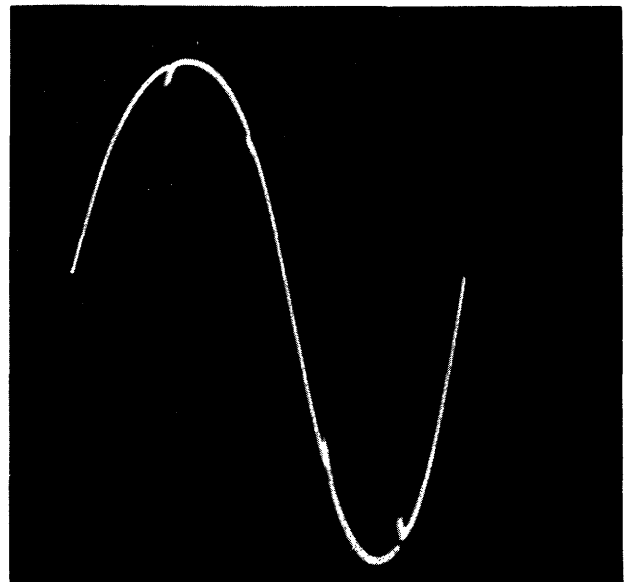
DC impulse amplitude  $\approx 50$  V



Output of discriminator for  
DC impulses of 50 V plus carrier  
modulated 50 kc with a 400 cycle  
tone.  $N \approx \frac{50}{40,000 \times 10^{-6}} = 1,250$

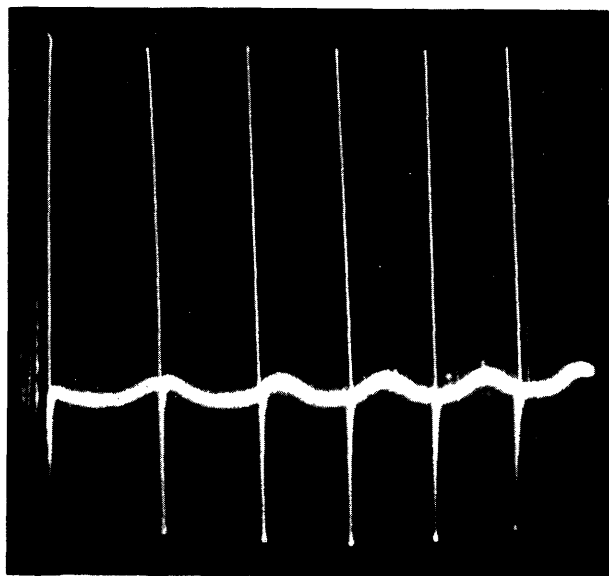


DC impulse amplitude  $\approx 360$  V

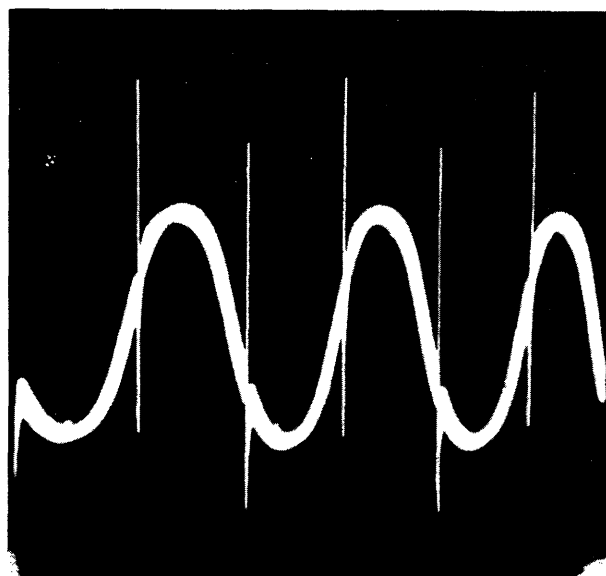


Output of discriminator for  
360 V DC impulses plus carrier  
modulated 50 kc with a 400 cycle  
tone.  $N \approx \frac{360}{40,000 \times 10^{-6}} = 9,000$

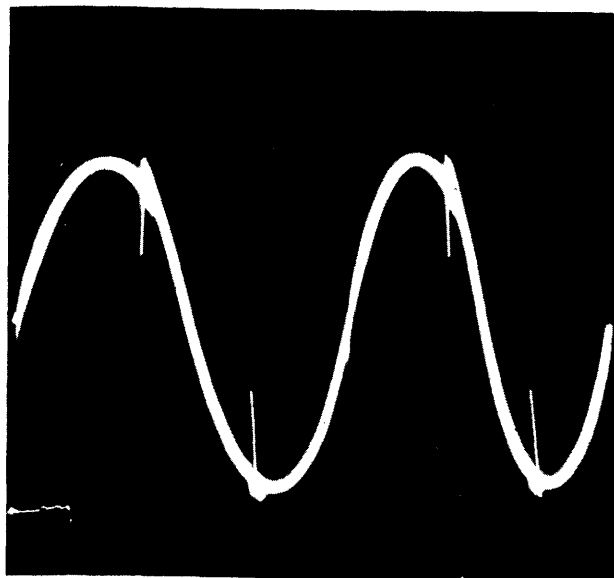
Figure 7. Effect of impulse noise on the laboratory receiver using distributed logarithmic limiters; amplitude of carrier kept constant.



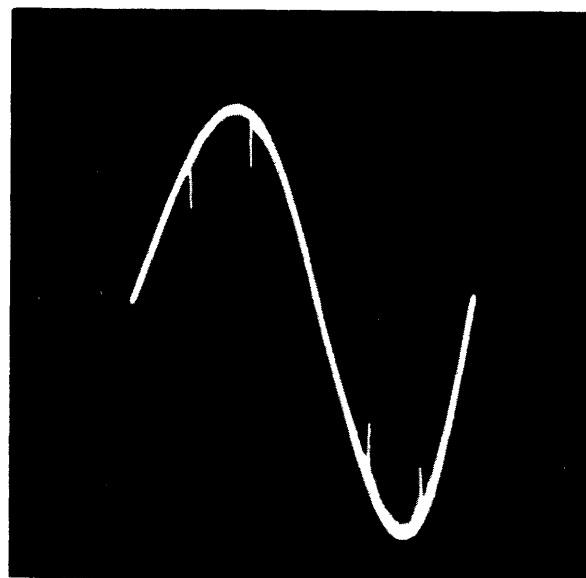
$N \approx 30 \times 10^6$



$N \approx 3 \times 10^6$



$N \approx 6 \times 10^5$



$N \approx 3 \times 10^3$

Figure 8. Effect of impulse noise on a standard commercial FM receiver having two stages of grid-lead limiting.