NBS REPORT

5543

REDUCTION OF ADJACENT-CHANNEL INTERFERENCE FROM ON-OFF AND FREQUENCY-SHIFT-KEYED CARRIERS

by

A. D. Watt, R. M. Coon, and V. J. Zurick

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
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NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT		NBS REPORT
8320-11-8321	December 17, 1957	5543

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SUMMARY

A large percentage of radio communication transmissions employ binary amplitude or frequency modulation of the carrier, and the abrupt changes associated with binary modulation generate sideband components which frequently interfere with services in adjacent channels. By employing relatively simple filters in the keying circuits of linear AM or class C operated frequency-shift-keyed transmitters which smooth the transition from mark to space, it is possible to greatly reduce the amplitude of these interfering sidebands. The amount of amplitude reduction obtained is found by calculations and experimental measurements to be related to the attenuation characteristics of the low pass filter for both AM and FSK. Characteristics of desirable keying circuit filters to obtain these reductions are outlined.

The minimum channel spacing required for a given ratio of undesired to desired carriers is shown to be determined by both the interfering frequency spectrum and the receiver selectivity characteristics. Methods of calculating the undesired output under both limiting conditions are described, and several typical examples are included.

1. INTRODUCTION

The abrupt changes in amplitude or frequency which occurs during normal on-off or FSK (frequency-shift-keying) transmitter operation produce sideband components of considerable amplitude at frequencies widely spaced from the carrier frequency. It is well known that some reduction in sideband amplitude can be obtained by shaping the transition between mark and space for both on-off[1] and FSK [2] transmitters.

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1. F. E. Terman, "Radio Engineers Handbook," McGraw-Hill Book Co., New York, 1943, pp. 629-632.

2. J. R. Davey and A. L. Matte, "Frequency-Shift Telegraphy-Radio and Wire Applications," Trans. A.I.E.E., Vol. 66, pp. 479-493, 1947.

The fact that modulating function filtering can be directly translated to the RF spectra of linear AM transmitters is employed in an earlier paper[3], which describes in detail the factors affecting sideband amplitudes and the amounts of reduction which can be obtained in practice. The spectra of FSK transmitters with shaped keying have been obtained for several special shapes by Cawthra and Thompson[4], and Allnatt and Jones[5], while a general method for obtaining the FSK spectra from the square wave spectra and the keying circuit filter admittance is described in detail in a recent paper[6].

It is the purpose of this paper to briefly show the types and amounts of sideband amplitude reduction which are obtainable under a few typical conditions of keying circuit filtering, and to show how they can be employed in obtaining expected reductions in necessary adjacent channel spacing. In addition, we shall compare calculated permissible ratios of desired to undesired carriers with experimental results.

The manner in which the keying filters are applied to prevent excessively rapid changes in carrier amplitude or frequency can readily be seen from Fig. 1, where factors such as: f_r, the keying frequency; $T = f_c/f_r$, the transmitter keying wave shape factor; and $2\,\Delta f$, the total frequency shift can readily be visualized.

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3. A. D. Watt, R. M. Coon, and V. J. Zurick, "Reduction of Adjacent Channel Interference from On-Off Keyed Carriers," I.R.E. Transactions on Communications Systems, Vol. CS-4, No. 3, Oct., 1956.

4. W. A. Cawthra and W. E. Thomson, "Bandwidth of a Sinusoidal Carrier Wave, Frequency-Modulated by a Rectangular Wave with Half-Sine-Wave Build-Up," Proc. I.E.E. (London), Pt. 3 on Radio and Communication Engineering, Vol. 98, pp. 69-74, 1951.

5. J. W. Allnatt and E. D. J. Jones, "An Investigation of the Spectra of Binary Frequency-Modulated Signals with Various Build-Up Waveforms," Proc. I.E.E., Vol. 104, Part B, No. 14, March 1957.

6. A. D. Watt, V. J. Zurick and R. M. Coon, "Reduction of Adjacent Channel Interference Components from Frequency-Shift-Keyed Carriers," NBS Report 5096 (submitted to the I.R.E. Transactions on Communication Systems.)

2. THE EFFECT OF LOW PASS FILTERING ON THE KEYING WAVE SHAPE

Before attempting to determine the specific effect of wave shaping on the radio frequency spectra, we shall first consider the effect of filtering upon the shape of the keying wave. The frequency responses for several idealized filters which cover the range from the abrupt cutoff of the rectangular response to the very gradual cutoff of the RC filter are shown in Fig. 2. The frequency responses have been normalized to f_c which is the average voltage band for all but No. 6, and is the 6 db band for all but No. 5. It is rather well known and can be seen from the step function response, Fig. 3, that the shape of the transition from mark to space in a filtered keying wave is primarily determined by the shape of the filter frequency response out to about the 20 db attenuation point while the length of this transition is primarily determined by the filter (6 db) cutoff frequency f_c. The transmitter keying wave shape factor is defined as $T = f_c/f_r$, i.e., the ratio of filter 6 db cutoff frequency to fundamental keying frequency. Fig. 4a shows the keying waveforms for various values of T, and it is evident that if the transition must be short compared to the keying element length, a large T factor must be employed. When this requirement is not placed on a keying waveform, it can be seen that T factors as low as 2.9 may be entirely adequate.

The optimum transient response shown in Fig. 4a is defined as one which for a given cutoff frequency permits the filter output to reach a new state or level that has been fed into the filter as rapidly as possible with a minimum of oscillations about this new level. The type of frequency response, Fig. 2, which yields this step function response, Fig. 3, is seen to be one intermediate between filter response 3 and 5, and is one which can readily be approximated in practice by filters employing LCR circuits[7, 3] or RC circuits with feedback[2].

3. FREQUENCY SPECTRA OF ON-OFF-KEYED TRANSMITTERS

The original keying wave from a binary type of signal source can be represented by a square wave with a fundamental repetition frequency f_r and an amplitude of 1. The actual keying wave may have

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7. T. E. Shea, "Transmission Networks and Wave Filters," New York, D. VanNostrand Company, 1929.

several consecutive marks or spaces instead of the alternating square wave; however, since the amplitude of the square wave frequency components are not exceeded by the component amplitudes of any other arrangement of marks and spaces, we shall use the square wave case as the representative limiting condition.

A transmitter with a maximum peak RF mark voltage E, which is on-off keyed with a square wave, has a frequency spectrum

$$A_n = \frac{E \sin \frac{n\pi}{2}}{n\pi} \tag{1}$$

where A_n is the peak sine wave voltage of the n^{th} sideband. If we now consider the RF spectrum envelope relative to the carrier frequency, it can be shown that

<u>square wave AM</u>

$$A(f) = \frac{E f_r}{\pi f} \tag{2}$$

where the spectrum envelope amplitude is seen to decrease directly with f, the frequency spacing from the carrier. When linear transmitters are employed, it is well known that the change in frequency spectrum resulting from low pass filtering in the keying circuit is simply obtained by a translation of the frequency response to the carrier frequency. In view of this we can now write

<u>filtered AM</u>

$$A(f) = \frac{E f_r}{\pi f} \cdot Y(f) \tag{3}$$

where, as in the preceding equation, frequencies are measured relative to the carrier frequency, and Y (f) is the low pass filter admittance.

In order to visualize the effect of this type of filtering, three typical keying waveforms are presented in Fig. 4b, with the addition that in the lower figure a dotted waveform is included which shows a typical wave which would result from nonlinear amplification of transmitter response after the keying filter.

When a typical keying rate of 60 c/s is considered, we find, as shown in Fig. 5, the resulting frequency spectra for the four keying waveforms shown in Fig. 4b. It is rather evident from Figs. 4b and 5 that for the same amount of wave shaping the single section RC filter is much less efficient in restricting the adjacent channel radiation than is true of the LC filter configuration. It is also apparent that even a small amount of clipping or nonlinearity following the low pass keying filter will reintroduce an appreciable amount of adjacent channel energy. With nonlinear transmitters, special shaping circuits can be employed in the RF stages, and if the RF output envelope has the same shape as the desired keying waveform, the output frequency spectrum will be the same as that from the linear transmitter.

4. FREQUENCY SPECTRA OF FSK TRANSMITTERS

The frequency spectrum for FSK transmissions with unfiltered, i.e., square wave, keying can be readily determined by conventional mathematical methods as has been shown by van der Pol[8], Corrington[9], and others; however, when the keying function is changed from a square wave to a typical keying wave with rounded corners, an analytical solution becomes very difficult. That some reduction in bandwidth can be obtained by keying circuit filtering has been known for some time, as has been shown for example by Davey and Matte[2]. Recent experimental results by Allnatt and Jones[5] have indicated the spectra obtained for several specific waveforms.

The method of obtaining frequency spectra employed here, and described in greater detail in an earlier paper[6], is first to develop mathematically an asymptotic expression for the frequency spectrum which is accurate in the high order sideband region, and then show how it can be modified empirically to obtain results which can be applied even in the area immediately outside the frequency shift limits.

Before attempting to determine the effect of low pass filtering on the FSK frequency spectrum, we shall first consider the characteristics of the frequency spectrum of square wave keying. The general expression for the square wave FSK spectrum, previously derived[8,9] have given

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8. Balth van der Pol, "Frequency Modulation," Proc. I.R.E., Vol. 18, pp. 1194-1205, July, 1930.

9. M. S. Corrington, "Variation of Bandwidth with Modulation Index in Frequency Modulation," Proc. I.R.E., pp. 1013-1020, October, 1947.

$$A_n = \frac{2mE}{\pi(m^2 - n^2)} \sin\left[\frac{\pi(m - n)}{2}\right] \tag{4}$$

where n is the sideband order and m is the modulation index. This index is defined as the ratio of one half the total frequency shift to the square wave keying rate, i.e., $m = \Delta f/f_r$. The envelope of the discrete frequency component amplitudes A_n of equation (4) is plotted for a wide range of values in Fig. 6. Only the upper sidebands are shown since the square wave spectrum is symmetrical. It should be pointed out that the rectangular pulse spectra is not symmetrical; however, since it can be shown that for a fixed keying element length and frequency shift that the greatest interfering bandwidth is caused by alternate marks and spaces, we need only consider the square wave case when determining interference capabilities of FSK systems.

The envelope of the spectrum generated by an AM square wave is also plotted in Fig. 6 for comparison, and it can be clearly seen that the high order harmonic interference components arising from the AM case are much greater in amplitude than those caused by FSK signals with normal values of m. For large values of $n = f/f_c$, the AM components decrease as $1/n$ while the FSK components decrease as $1/n^2$. The asymptotic expressions for the envelope of the square wave sideband amplitudes as a function of frequency is readily written as

<u>square wave FSK*</u>

$$\underset{(f > 2\Delta f)}{A(f)} \approx \frac{2mEf_r^2}{\pi f^2} \tag{5}$$

When attempting to obtain the frequency spectrum for frequency shift keying with filtered waveforms similar to those of Fig. 4a, it has been shown[6] that an approximation for the frequency spectrum can be written as

$$\underset{(n >> m)}{A_n} \approx \frac{2m}{\pi n^2} Y_n \tag{6}$$

* It should be noted that the sine term of equation (4), which modifies the envelope amplitude over a range of 1 to 0.707 when m varies from integral values to values ending in 0.5, has been omitted. This omission is permissible since the corresponding phase change compensates for this effect as far as the impulse produced in a receiver in an adjacent channel.

where Y_n is the keying filter admittance in terms of n times the keying rate, and $\frac{2m}{\pi n^2}$ is the asymptotic expression for the sidebands of square wave FSK. When this is converted to an envelope function of frequency for a transmitter with a maximum RF voltage of E, we obtain

$$\underset{(f >> \Delta f)}{A(f)} \approx \frac{2mEf_r^2\, Y(f)}{\pi f^2} \tag{7}$$

where $Y(f)$ is the keying filter admittance as a function of frequency.

A large number of measurements have been made of sideband amplitudes under various conditions of modulation index and keying circuit filtering, and when an attempt was made to employ equation (7) near the shift limits, we observed a systematic departure which led us to try the following approximation

$$\underset{(f > 2\Delta f)}{\overset{\text{filtered FSK}}{\overline{A(f)}}} \approx \frac{2mEf_r^2\, Y(f - \Delta f)}{\pi f^2} \tag{8}$$

where Δf is the amount of shift from the center frequency, f is the frequency of observation relative to the center frequency, and $Y(f - \Delta f)$ is the keying filter admittance transferred to the shift limit. It should be noticed from equation (8) that we have in essence placed the low pass filter zero frequency at the shift limit rather than at the carrier frequency as was the case of the earlier less accurate approximate solution.

Some care should be employed in applying this asymptotic formula or method of translating the audio keying circuit filter attenuation to the square wave spectrum outside the shift limits. The initial mathematical approximations along with experience indicate that the results can be safely applied if the keying circuit filter does not affect the center half of the keying wave, a condition which is met when $T \geq 3$. From this consideration, it can be seen that the filter translation indicated in (8) can be applied in most cases, but should not be used under conditions of extreme filtering such as would cause

sinusoidal modulation. This limitation is not serious since the sinusoidal case is readily solved by the well known Bessel functions. It should be noted here that if the modulating function consists of several sinusoids, that the method described by Crosby[10] of combining Bessel functions is applicable; however, this particular method becomes unwieldly if the number of sinusoids becomes large. Spectra calculated with equation (8) have been compared with experimental results for a wide range of modulation index and filtering factor, T, with very good agreement. A typical comparison is shown in Fig. 7 where the solid lines represent the calculated frequency spectrum envelope and the points the experimental values for the various conditions of filtering.

5. CHOICE OF KEYING CIRCUIT FILTER CHARACTERISTICS

Since signal-to-noise ratio and radio spectrum space cannot be expressed in the same economic units, it is impossible to specify an optimum filter for all conditions; however, in most practical applications there are enough factors available which make a good choice of filter characteristics possible.

There are three primary factors which must be determined for a desirable keying circuit filter:

(a) The ratio, T, of filter 6 db bandwidth to keying rate.
(b) The filter transient response or the manner in which the frequency response varies over the pass band of the filter, i.e., out to approximately the 20 db attenuation point.
(c) The out-of-band rejection, i.e., the manner in which the frequency response varies outside of the 20 db attenuation point.

It is shown in Fig. 3 that the rate of rise of the keying function (assuming a square wave or abrupt change of input) is dependent upon the cutoff frequency f_c, and that very close to 0.7 of the change from mark to space occurs in a period of time equal to $0.4/f_c$ regardless of the other filter factors. From this 0.7 amplitude point on, the manner and rate at which the mark or space levels are approached is primarily determined by factor (b).

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10. M. G. Crosby, "Carrier and Side-Frequency Relations with Multi-Tone Frequency or Phase Modulation," RCA Review, Vol. 3, pp. 103-106, July, 1938.

Factor (b) is important in the AM case in that it determines the peak voltage of the signal, and if considerable overshoot is present it reduces the average usable transmitter power. However, in the FSK case, the adherence to minimum overshoot is not as important since the possibility of overshoot in the instantaneous frequency does not affect the peak voltage or maximum average power of the transmitter. If multiple frequency level operation is contemplated with the transmitter, however, an optimum transient filter, i.e., one with minimum rise time and overshoot, is considered essential because of the increased accuracy of determining each level. Another advantage of this response is that the transition has essentially the same shape for a given filter with varying keying rates.

From these considerations, an optimum transient filter is chosen as the most desirable keying filter and will be assumed in the determination of the other factors.

Factor (a), i.e., T, is best determined after considering the effect of T upon the keying wave. From curve 3 of Fig. 3, it can be seen that the keying wave rises from 1% to within 99% of the shift value in $0.8/f_c$ seconds. If twice this transition time is subtracted from the keying interval $1/f_r$, we obtain the percentage of time that the keying wave shape is flat within 1% of the input mark and space shift limits. Typical values which can be compared with actual waveforms are:

0% flat (sine shaped)	$T = 1.6$
50% flat	$T = 3.2$
90% flat	$T = 16$
100% flat (square wave)	$T = \infty$

If the communication system being considered has very good automatic synchronization and frequency stability, it is desirable to choose a small value of T in the order of 2 or 3. On the other hand, if the system employs frequent resynchronization, as in ordinary teletype, and if there is a possibility of appreciable carrier frequency drift, it is desirable to employ a T in the range of 4 to 16. The actual waveform out of the receiver will be still further shaped by the receiver low pass filter which should be at least as narrow as the transmitter filter. If similar filters are used in both the transmitter keying circuit and receiver post-detection circuit, the effective shaping factor is changed to approximately 0.7 that of a single filter.

Factor (c), see Fig. 8, has very little effect upon the apparent shape of the keying wave but it does determine the amount of transient response interference which is produced in the region considerably outside the frequency band required to transmit the desired intelligence. The choice of this factor is influenced by: (1) the economics involved such as the price of filters (determined by the number and type of sections involved), (2) the separation of adjacent channels, and (3) the selectivity characteristics of the receivers employed on adjacent channels.

Typical filter admittance curves normalized to the 6 db cutoff frequency are shown in Fig. 8 where the improvement obtainable with increase of sections is apparent. It can also be seen that each LC stage is in general equivalent to 2 RC stages. The particular abscissa label employed, is to permit direct application in transient response calculations that follow.

6. TYPICAL FREQUENCY SPECTRA AND ADJACENT CHANNEL REDUCTIONS

Fig. 9 shows the envelopes of the frequency spectra which result when filters, such as shown in Fig. 8, are employed with both AM and FM transmitters. The keying rates and frequency shift employed are typical of ordinary communication circuits, and the amount of sideband reduction which can be obtained by employing keying circuit filtering can readily be seen.

The formation of the transient response can be visualized by observing that in the region far removed from the carrier the interfering components all become phase additive each time the transition from mark to space occurs. The resulting input impulse produces an impulse out of the receiver IF with an amplitude equal to the summation of all the effective interfering spectrum components. An approximation to the output amplitude can be obtained by multiplying the maximum component amplitude by the effective number of these components within the average voltage bandwidth of the receiver. It should be noted that for AM, only odd terms are present; for FSK, integer m's yield every other sideband zero and for other m's, although all sidebands are present, their amplitude and phase are such that the effective sideband summation is always $BW/2f_r$ where BW is the effective voltage bandwidth of the receiver.

When the receiver is tuned relatively close to the undesired carrier and the transmitter frequency spectra has a high attenuation vs. frequency rate, as is the case with good filtering, the dominant frequency components near the carrier produce a quasi-steady-state output from the receiver which is essentially the same as that of the undesired signal amplitude for AM modulation. With FSK, the output will have some amplitude modulation which is introduced by the slope of the receiver selectivity curve. The maximum output amplitude under these conditions is equal to the locked key carrier voltage reduced by the amount of receiver attenuation at the frequency spacing considered.

From the preceding analysis, it is apparent that we have the two rather well known types of interference[11]: (1) the transient response with an amplitude directly related to receiver bandwidth which, for a given receiver bandwidth, can only be reduced by filtering at the transmitter. (2) A quasi steady state response from the undesired carrier which, for a given channel spacing, can only be reduced by improved, i.e., steeper, receiver selectivity characteristics.

The ratio of desired to undesired carrier at the receiver antenna terminal which can be tolerated for a given set of conditions can readily be calculated for most conventional receiving systems after we define the following terms:

D/U	= minimum ratio of desired* to undesired carrier or locked key voltage at antenna terminal permissible for satisfactory adjacent channel operation.
r	= receiver IF output voltage ratio of response from desired channel to peak response from undesired channel necessary for satisfactory service.
BW	= receiver IF average voltage bandwidth in c/s.
$Y_R(f)$	= receiver admittance as a function of frequency in c/s.
G	= receiver voltage gain from antenna terminal to IF output.

11. E. A. Guillemin, Communication Networks, Vo. 1 and 2, John Wiley and Sons, New York.

* If the desired system is single sideband, D will be expressed in terms of maximum sideband envelope amplitude. It should be noted that the impulse signal variation out of such a receiver will be twice that of a conventional double sideband receiver; however, since the desired signal out will also be twice D, the effective value required for r will not change for a SSB receiver.

The receiver output for the three possible conditions can be written as:

$$\text{Desired output} = D \cdot G$$

$$\text{Undesired transient output} = \frac{U \cdot A(f) \cdot BW \cdot G \cdot CF}{2 f_r}$$

where CF is a correction factor which is equal to the ratio of the peak receiver output spectrum amplitude relative to that at the center frequency of the receiver. With narrow band receivers and large frequency spacing, this can be neglected since it is equal to 1.

$$\text{Undesired quasi steady state output} = U \cdot Y_R(f) \cdot G$$

Since the total undesired output is equal to the sum of both types of responses and realizing that for the FSK condition our effective spacing for the quasi steady state output is determined from the nearest shift limit we can write

$$D/U = r \left[\frac{A(f) \cdot BW \cdot CF}{2 f_r} + Y_R (f - \Delta f) \right] \tag{9}$$

In practice, it is difficult to obtain analytical expressions for $A(f)$ and $Y_R(f - \Delta f)$ and because of this we have prepared a typical set of normalized receiver selectivity curves in Fig. 10 which cover the majority of conditions anticipated. The keyed carrier spectrum, when FSK is included, has such a wide range of possible combinations that instead of attempting to present a set of typical normalized curves for A(f) we will employ the relations of equations (3) and (8) and write

$$D/U = r \left[\frac{A(f)_{sq.\ w.} \cdot Y(f - \Delta f) \cdot BW \cdot CF}{2 f_r} + Y_R (f - \Delta f) \right] \tag{10}$$

where $A(f)_{sq.\ w.}$ is the square wave spectrum shown in normalized form in Fig. 6, and $Y(f - \Delta f)$ is the keying circuit filter admittance shown in normalized form in Fig. 8.

With equation (10) and Figs. 6, 8, and 10, we are now in a position to calculate D/U for almost any set of conditions likely to be encountered. For example assume that: our receiver (6 db) bandwidth is 1.5 kc and that its complete response is shown by the curve with the square data points of Fig. 10, a protection factor r = 2 is required

(typical for FSK teletype reception), our carrier separation (f) is 15 kc/s, and the transmitter is FSK with $f_r = 23$ c/s, m = 18, $\Delta f = 415$ c/s, and $T \rightarrow \infty$. We now see that from Fig. 6 $A(f) \approx 2.6 \times 10^{-5}$, from Fig. 8 $Y(f - \Delta f) = 1$, from Fig. 10 $Y_R\,(f - \Delta f) \approx 3 \times 10^{-6}$, CF ≈ 1.2 and the resulting D/U is -53 db. If we had chosen a simple 2 stage RC keying circuit with a T = 7, we would have obtained $Y(f - \Delta f) = 1.3 \times 10^{-4}$ from Fig. 8 and a D/U of -103 db. Since the limitation is now primarily caused by receiver selectivity, any increase in transmitter filtering either by increase in filter sections or decrease in T will not reduce D/U any further. The results of these calculations along with those for a number of other conditions are presented in Fig. 11.

Tentative values of r which can be employed in equations (9) or (10) are given in Table I for several types and qualities of service.

TABLE I

Tentative values of receiver IF output ratio $r = D_o/U_o$ *

Desired Transmission Type	Quality: Interference not Objectionable	Quality: Desired Signal Fairly Readable
FSK Teletype	2	1.5
Voice (message circuit)	2 to 10	0.1 to 1
High Quality Voice or Music	100	2 to 10
AM - Facsimile	30	4
FS - Facsimile	6	2

* r is expected to vary to some extent with keying rate, receiver bandwidth, and other system parameters; however, the values given are expected to be representative of the averages required.

In addition to the type of analysis employed based on frequency spectrum, it is also possible to analyze interference effects on a time basis[11] by calculating the response of one or more tuned circuits to source functions such as a suddenly impressed sinusoid. This type of analysis has been described for several cases by J. Marique[12].

12. Jean Marique, "Contribution to the Study of Interference Due to Radio-telegraph Transmissions," Extrait de la Revue H.F. - 1955, Vo. III, No. 1.

7. RECEIVER LINEARITY REQUIREMENTS

A receiver operating in close proximity to a strong transmitter may be adversely affected by overload or capture as well as actual sideband interference. In order to minimize these effects and fully utilize the keying wave filtering and receiver selectivity, it is essential that the receivers employed have a large linear dynamic range prior to the circuits providing the selectivity.

ACKNOWLEDGMENT

We are indebted to K. A. Norton, J. A. Krcek and F. F. Fulton for helpful discussions during the formulation of the work reported here, to E. F. Florman and J. W. Herbstreit for their suggestions relative to the presentation of the results, and to Mrs. W. M. Mau for her assistance during the preparation of the manuscript.

DIAGRAM OF ON-OFF AND FREQUENCY-SHIFT-KEYED TRANSMITTERS

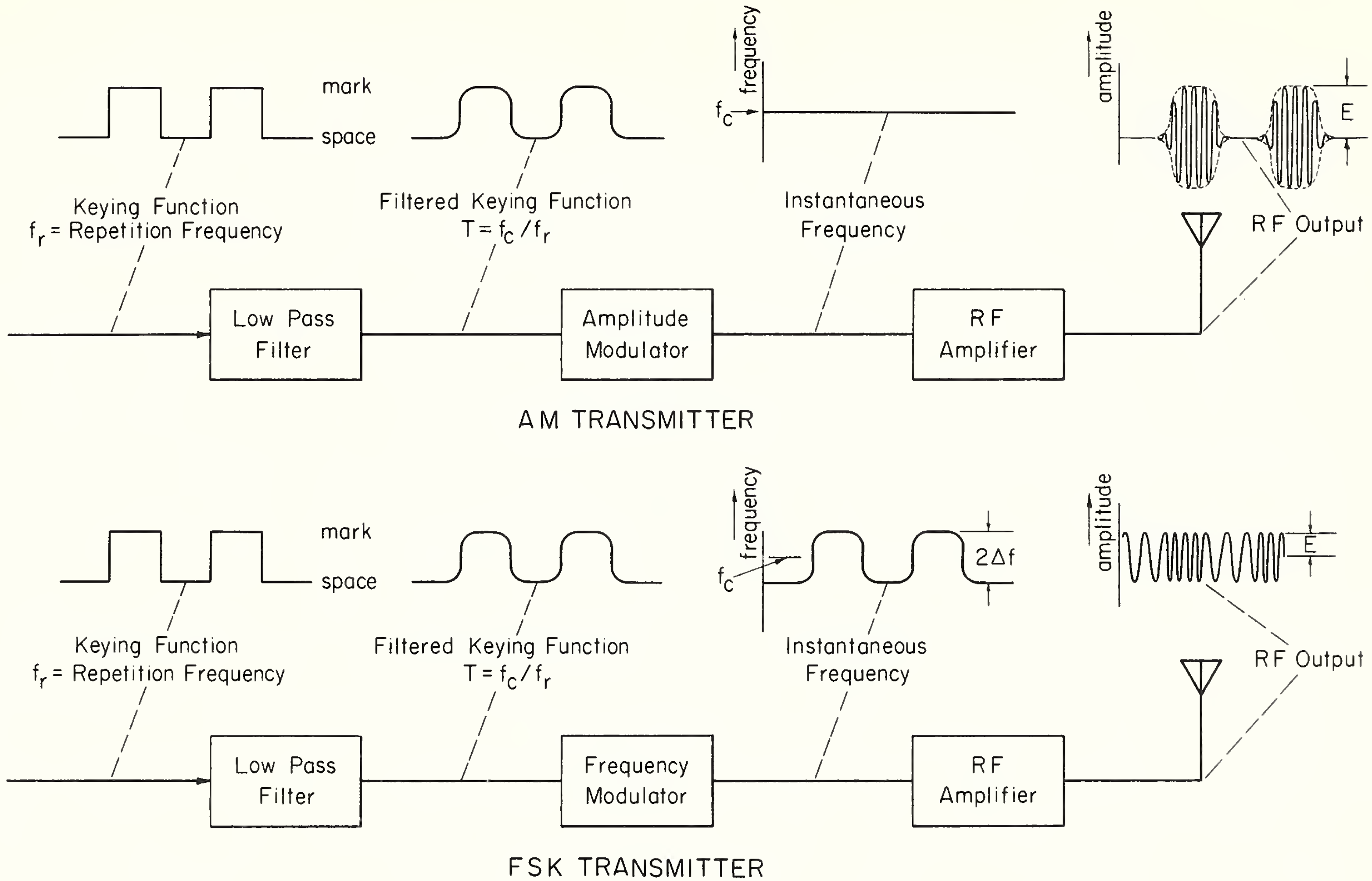


Figure 1

IDEALIZED FILTER FREQUENCY RESPONSE
WHERE f_c IS THE 6 DECIBEL CUT OFF FREQUENCY

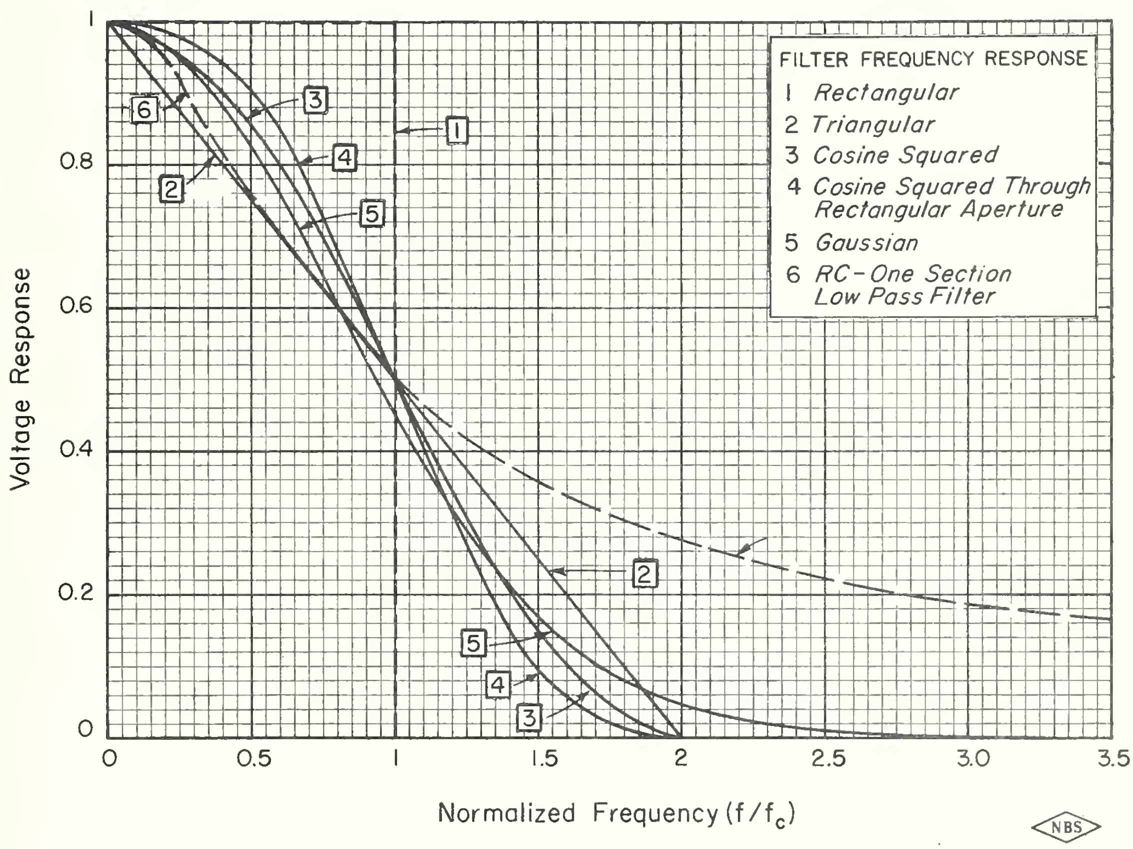


Figure 2

STEP FUNCTION RESPONSE OF IDEALIZED FILTERS

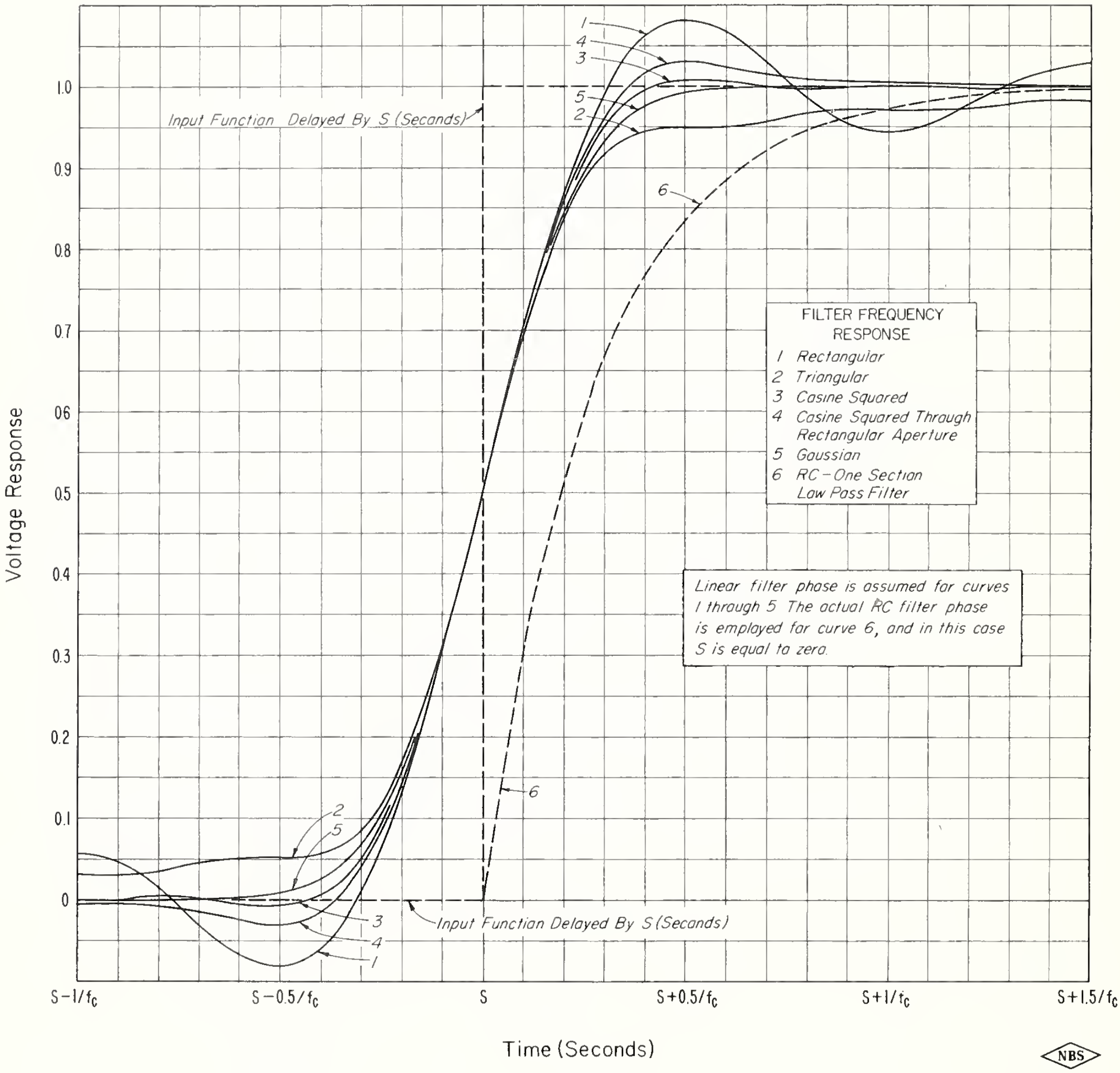
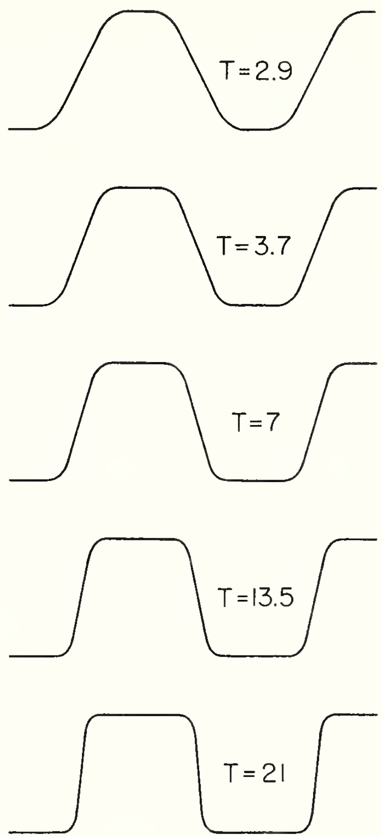


Figure 3

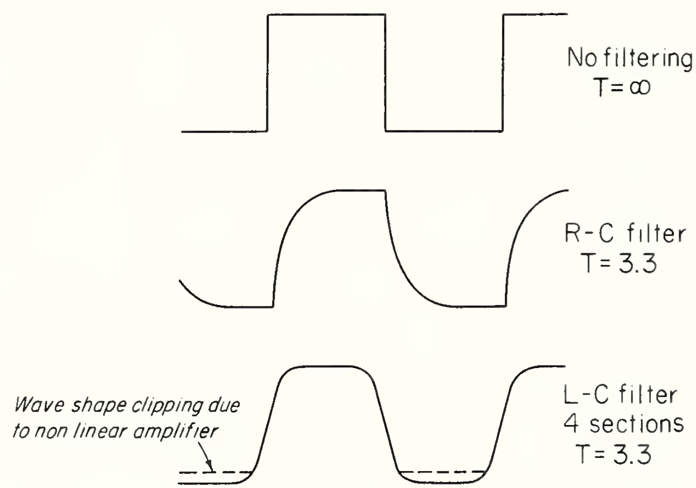
KEYING WAVEFORMS OUT OF FILTERS



OPTIMUM TRANSIENT RESPONSE
(SEE FILTER Nº 3 OF FIG. 2)

Figure 4a

$$T = \frac{f_c}{f_r} = \frac{\text{6 db Filter Bandwidth}}{\text{Repetition Frequency}}$$



KEYING WAVEFORMS FOR
SPECTRA SHOWN IN FIG. 5

Figure 4b

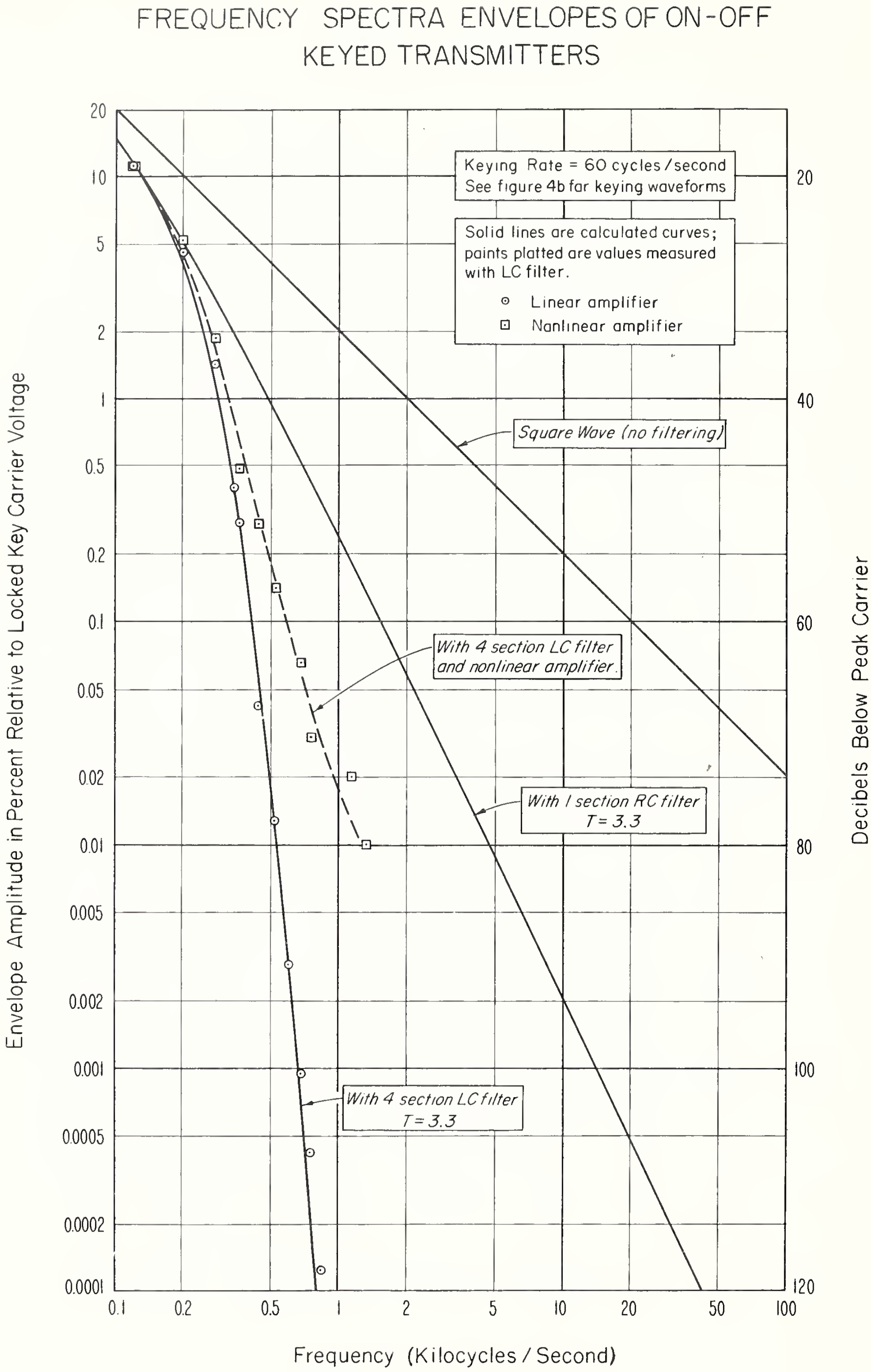

FREQUENCY SPECTRA ENVELOPES OF ON-OFF KEYED TRANSMITTERS
Keying Rate = 60 cycles/second
See figure 4b for keying waveforms
Solid lines are calculated curves; paints platted are values measured with LC filter.
Linear amplifier
Nonlinear amplifier
Square Wave (no filtering)
With 4 section LC filter and nonlinear amplifier
With 1 section RC filter T = 3.3
With 4 section LC filter T = 3.3
Envelope Amplitude in Percent Relative to Locked Key Carrier Voltage
Decibels Below Peak Carrier
Frequency (Kilocycles / Second)
20
10
5
2
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
0.0005
0.0002
0.0001
20
40
60
80
100
120
0.1
0.2
0.5
1
2
5
10
20
50
100

Figure 5

ENVELOPES OF SQUARE WAVE FREQUENCY-SHIFT-KEYING SPECTRA

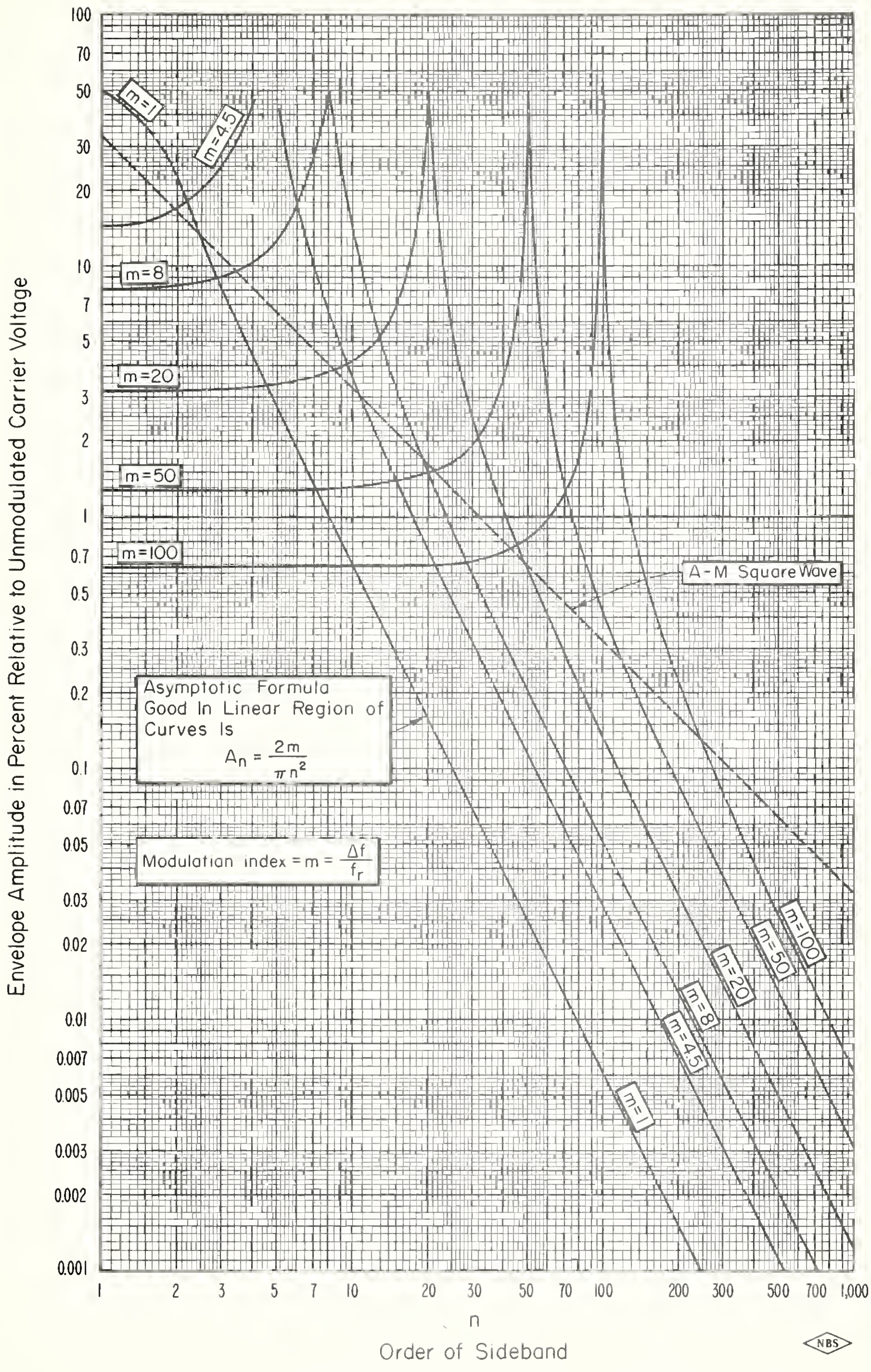


Figure 6

FREQUENCY SPECTRA ENVELOPES OF FREQUENCY-SHIFT-KEYING TRANSMITTER
WITH KEYING CIRCUIT FILTERING

m = 4.5

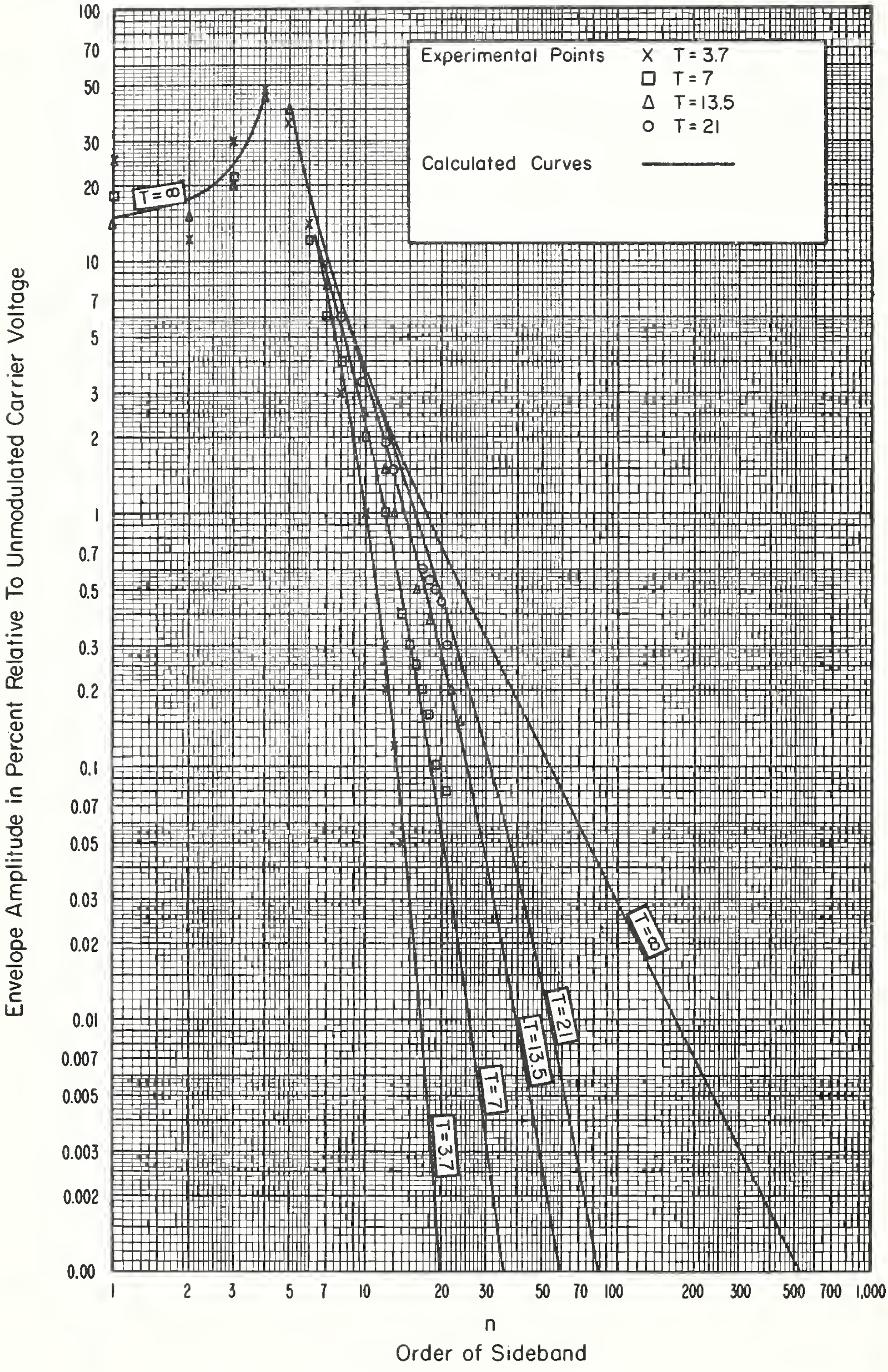


Figure 7

LOW-PASS FILTER ADMITTANCE CURVES
NORMALIZED TO THE 6 DB CUT-OFF FREQUENCY
$f_c = T f_r$

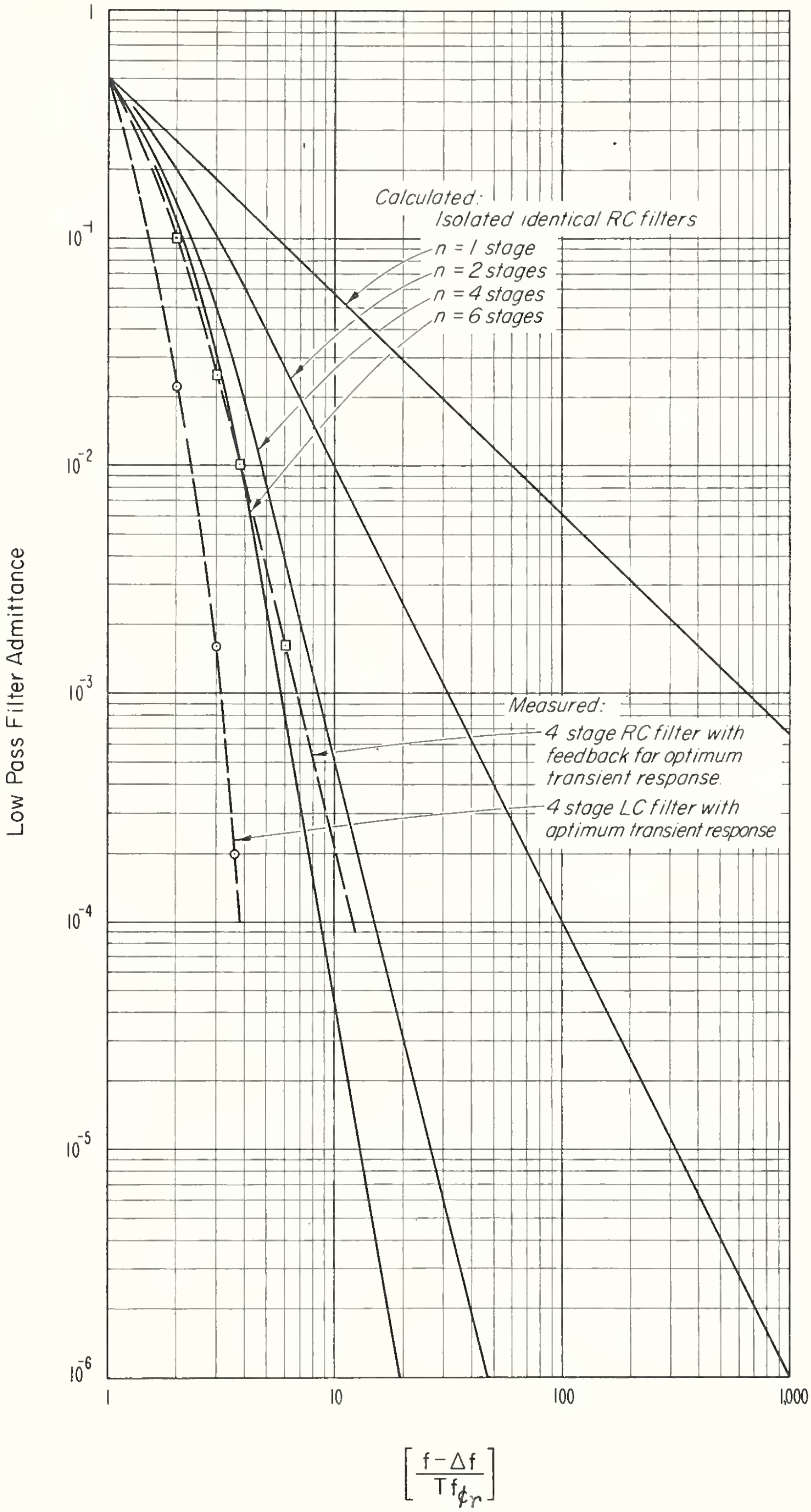


Figure 8

EFFECT OF DIFFERING OUT-OF-BAND KEYING FILTER ATTENUATION ON THE FREQUENCY SPECTRA ENVELOPES OF KEYED AM AND FM TRANSMITTERS

(Modification by Power Amplifier and Antenna Circuits Not Included)

KEYING RATE = 60 CYCLES/SECOND

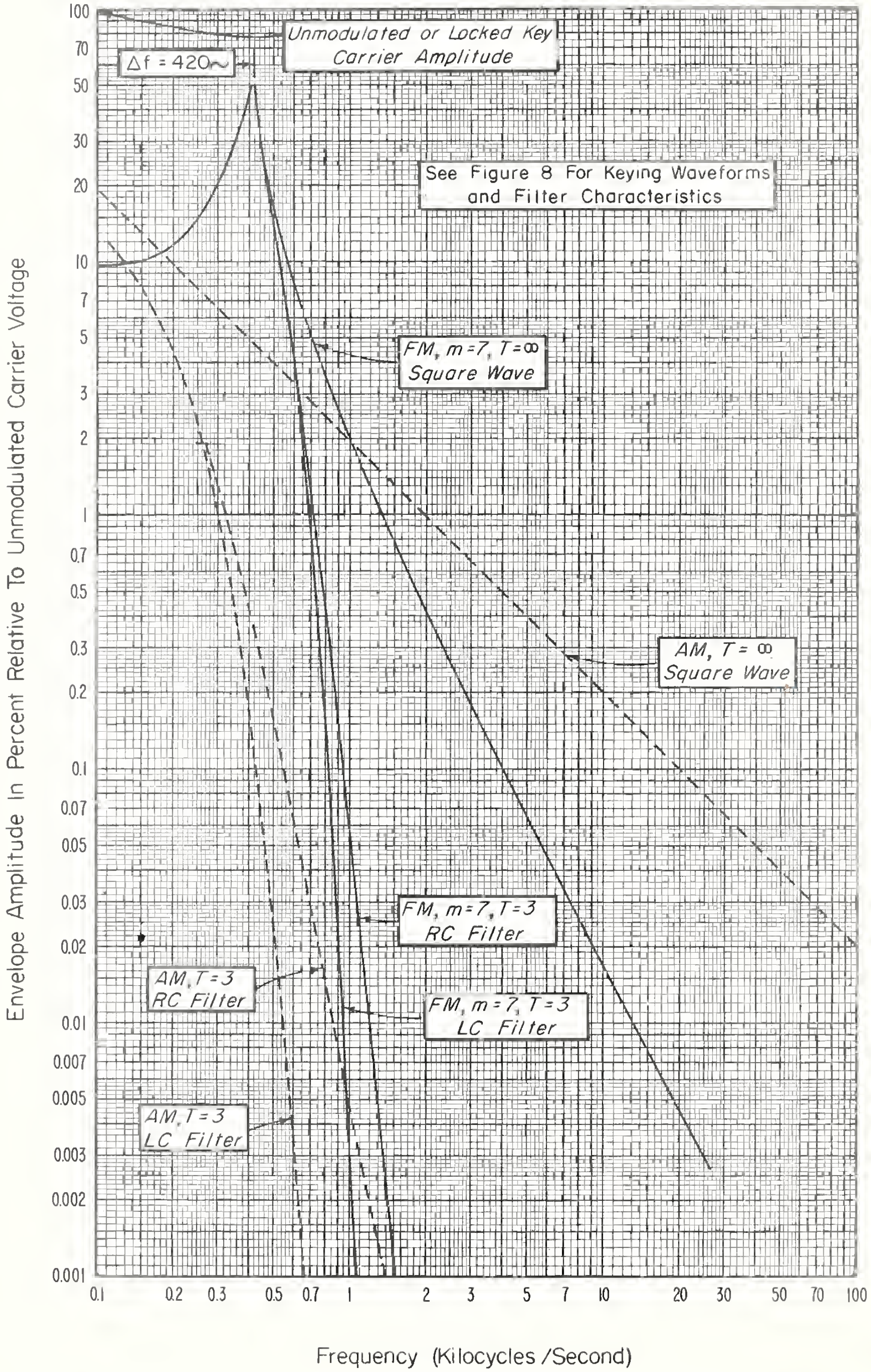


Figure 9

RECEIVER ADMITTANCE CURVES
NORMALIZED TO 6 DB CUT-OFF FREQUENCY
$f_C = BW/2$, for Obtaining Quasi-Steady-State Response

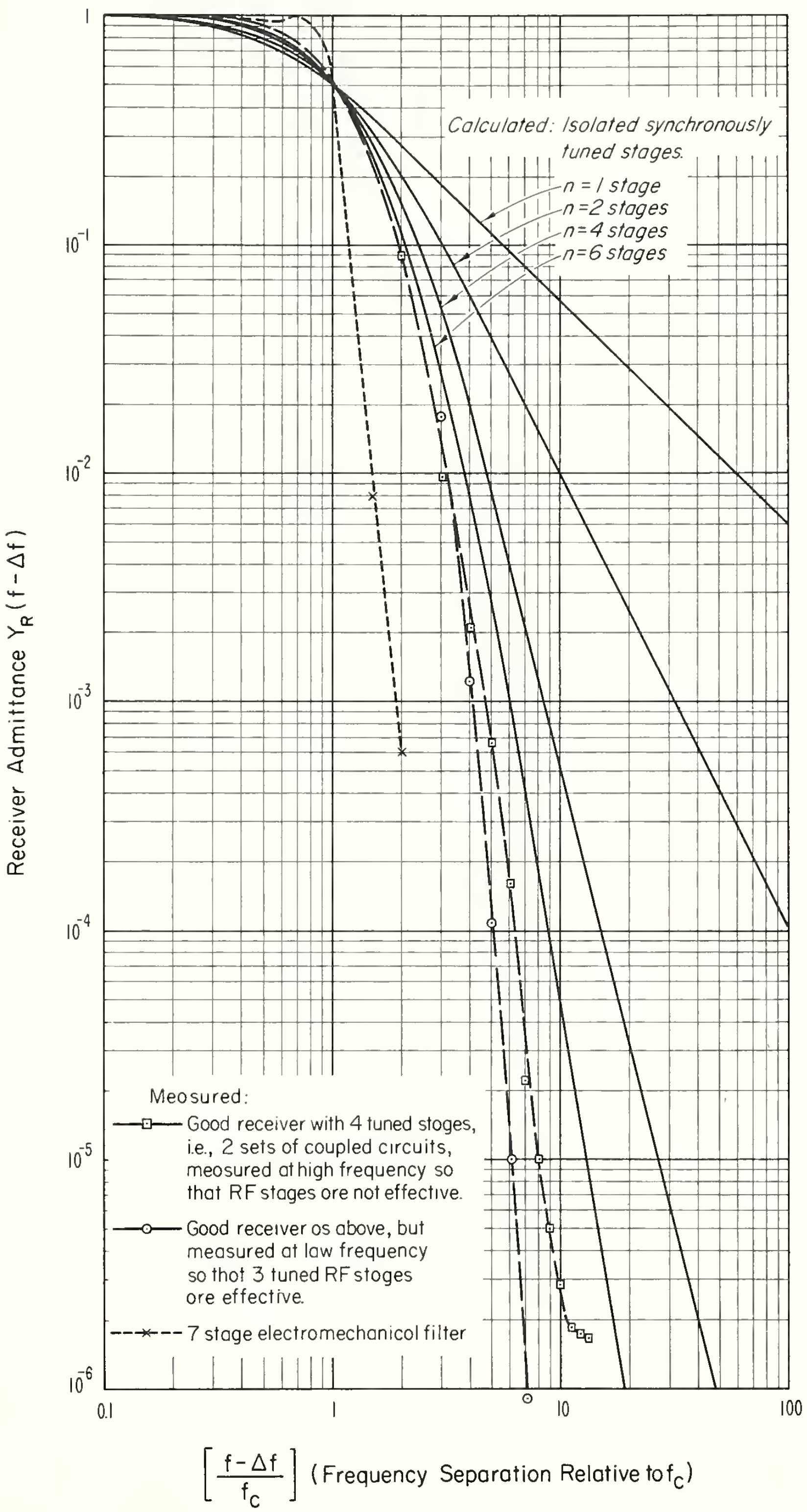


Figure 10

MINIMUM D/U VALUES FOR THE TRANSMITTER AND RECEIVER CHARACTERISTICS INDICATED

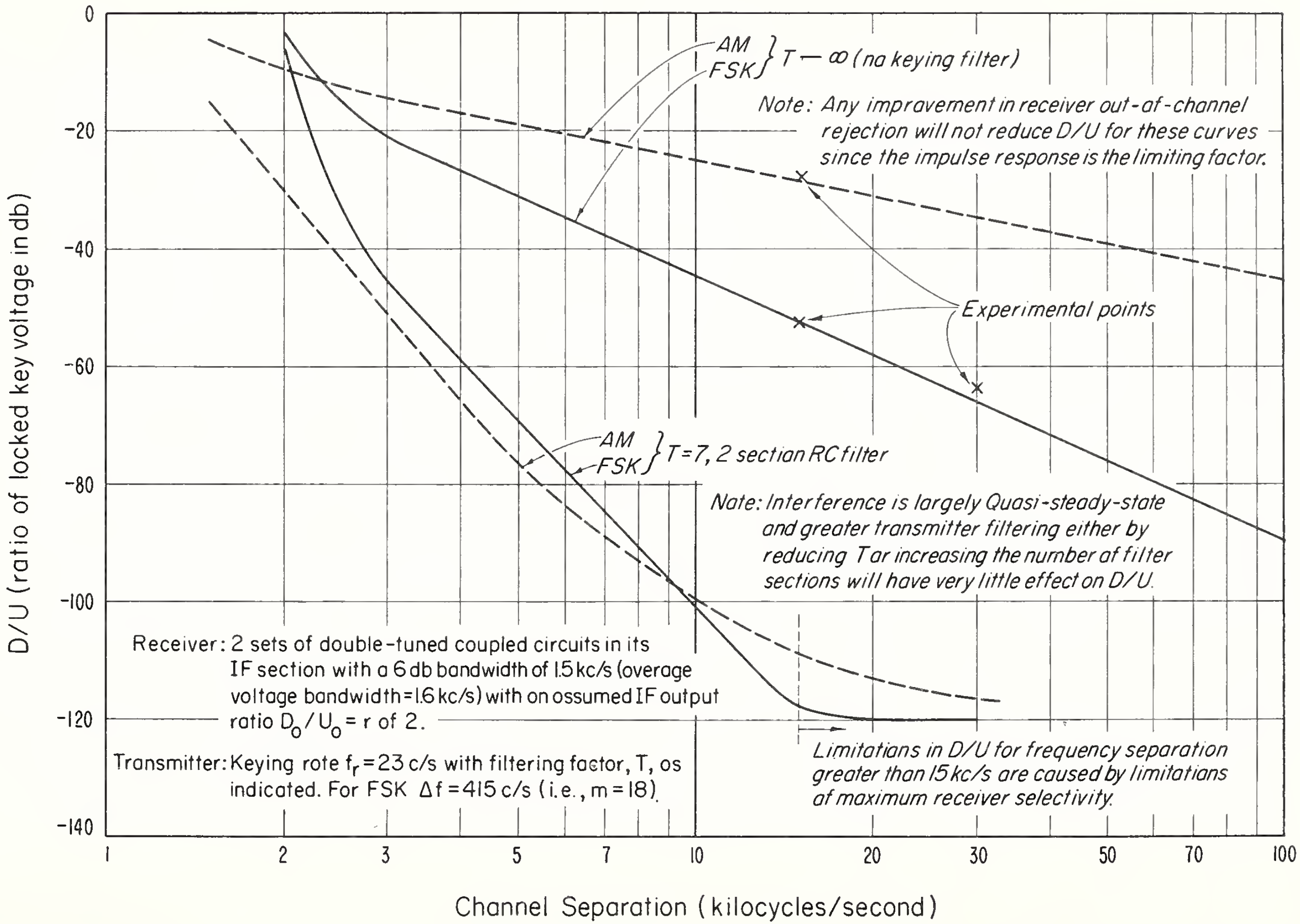


Figure 11

U. S. DEPARTMENT OF COMMERCE
Sinclair Weeks, *Secretary*

NATIONAL BUREAU OF STANDARDS
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- Office of Basic Instrumentation
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Boulder, Colorado
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