# Performance Characteristics of Various Carrier Telegraph Methods

By T. A. JONES and K. W. PFLEGER

This paper describes laboratory tests of certain carrier telegraph methods, to determine their relative advantages from the standpoints of signal speed, and sensitivity to level change, carrier frequency drift, interchannel interference, and line noise.

## Introduction

MOST of the carrier telegraph methods mentioned below are well known,[1,2,3,4,5] but the selection of the best method for a particular application is difficult without comparative tests on specific designs. It is the purpose of this paper to record data taken during such tests and to explain the results so that they may be helpful to those concerned with the selection of the optimum method for a given set of requirements.

The conclusions here reached regarding methods of telegraph transmission do not necessarily apply to transmission of sound, pictures, or television, because their requirements differ. In telegraph transmission it is important that signal transitions be received at approximately the correct times, and wave rounding is permissible.

Computations for a square cut-off band-pass filter with zero phase distortion[6] show that the shape and duration of the transient in the received wave are about the same for a sudden transition in both on-off and frequency-shift arrangements (explained in the next section), when the total frequency shift is not more than half the channel width. As telegraph distortion depends largely upon the transient, one might therefore infer that, if the transients are about alike, there is no particular advantage in frequency-shift over the on-off method as far as signal speed is concerned. However, the computation for the idealized filter gives no assurance that a physical filter will per-

[1] H. Nyquist: "Certain Topics in Telegraph Transmission Theory", *A. I. E. E. Trans.*, Vol. 47, pp. 617–644, April 1928.

[2] H. Nyquist and K. W. Pfleger: "Effect of Quadrature Component in Single Sideband Transmission", *Bell System Technical Journal*, Vol. XIX, pp. 63–73, Jan. 1940.

[3] E. H. Armstrong: "Methods of Reducing the Effect of Atmospheric Disturbances", *Proc. I. R. E.*, Jan. 1928, pp. 15–26.

[4] J. R. Carson: "Reduction of Atmospheric Disturbances", *Proc. I. R. E.*, July 1928, pp. 966–975.

[5] F. B. Bramhall & J. E. Boughtwood: "Frequency Modulated Carrier Telegraph System", *Electrical Engineering*, Vol. 61, No. 1, Jan. 1942, *Transactions Section*, pp. 36–39.

[6] Fig. 3 of H. Salinger: "Transients in Frequency Modulation", *Proc. I. R. E.*, August 1942, pp. 378–383.

form thus. In order to investigate this experimentally, as well as other factors that concern the choice of method, the effects on telegraph transmission of interchannel interference and of varying the signaling speed, transmission level, mean carrier frequency, and line noise, were determined for several different methods, using the same channel filters. In order to test the two-band methods* using the same frequency range occupied by the one-band arrangements, narrow-band filters would be required to divide the frequency range into two parts. Since such filters were not available, it was necessary to use two adjacent frequency bands each similar to that used with the on-off method. However, some tests were made of a two-band arrangement using somewhat narrower filter pass bands.

A special wide-band frequency-shift arrangement using filters of about twice the band width of the other frequency-shift arrangement, was tested mainly in order to observe the effect of band width on sensitivity to noise and interference.

In all of the noise tests, thermal or resistance noise was used. With noise of the impulse type it is possible that somewhat different results would have been obtained, but it is believed that the difference would not have been great.

## Conclusions

A study of the test results leads to the following conclusions which apply for the conditions assumed, and which are thought to be of general application, except for modifications which may be made necessary by future technical advances:

1. There is no important advantage in frequency-shift carrier telegraph over the on-off method as used in the Bell System for stable, quiet circuits, either wire or radio. However, the frequency-shift method shows some improvement in operating through noise. The frequency-shift method has disadvantages as regards complication and cost. Furthermore, it may be seriously affected by carrier frequency drift and interchannel interference, although the effects of these can be mitigated to some extent by special devices.
2. For high-frequency radio transmission over long distances, which is subject to comparatively severe non-selective fading, a great advantage is realized from the use of frequency-shift telegraphy with a fast receiving limiter instead of the conventional "continuous wave" or on-off method. For satisfactory operation it is still necessary that the signal level be kept sufficiently higher than the noise level in the transmission band.

* See the section entitled "Explanation of Terms".

3. Single-sideband telegraphy has an advantage of providing somewhat higher speeds without increasing the band width. Whether it holds much promise for any general application in multi-channel systems utilizing narrow bands and moderate signal speeds is questionable in view of certain difficulties. For a single-channel high-speed circuit, single-sideband telegraphy might be found worth while from the standpoint of economical use of the frequency spectrum.
4. Certain other arrangements tested possessed some characteristics which have advantage under particular conditions. For example, two-band arrangements may sometimes be conveniently obtained by combining existing on-off arrangements. These two-band arrangements are capable of furnishing high-grade service over radio circuits subject to severe fading. The use of a single source of carrier instead of two sources on a two-band arrangement results in a substantial transmission improvement. The performance then is comparable to that of a single-band frequency-shift channel occupying the same frequency space.

A more complete discussion of the results is given under the heading "Summary of Results", at the end of this paper.

## Explanation of Terms

The following is intended to explain what is meant by certain terms used in this paper. They apply specifically to carrier telegraph operation in the voice range but, in general, they could also apply to radio telegraphy. (It will be appreciated that various other combinations of the instrumentalities involved in the present discussion could be used.)

### *Channel*

A telegraph channel is a path which is suitable for the transmission of telegraph signals between two telegraph stations. In the present discussion the term "channel" is restricted to mean one of a number of paths for simultaneous transmission in different frequency ranges as in carrier telegraphy, each channel consisting of an arrangement of carrier telegraph equipment designed for the transmission of one message at a time, in only one direction.

### *On-Off Method*

This, the most common form of amplitude modulation, is the same as "continuous wave" in radio telegraphy. It is a method of signaling over a channel utilizing a single carrier frequency, normally located at the center of the transmission band of the channel filters. The presence of carrier current on the line corresponds to the marking condition of the channel, and its absence, to the spacing condition. A Fourier analysis of the line current during signaling would show a steady carrier frequency component and substantially symmetrical upper and lower sideband frequency components.

*Single-Sideband Method*

This is similar to the method just described except that: (1) the carrier frequency is located near one boundary of the channel filters, so that during signal transmission one of the sidebands is attenuated much more than the other before the signals reach the line, and (2) during the spacing condition, carrier current may be either absent from the line, or present with amplitude less than that of marking current. (The latter condition tends to reduce that part of the distortion which is due to the quadrature component.[2])

*Frequency-Shift Method*

This is a method of signaling over a channel utilizing a carrier current of substantially constant amplitude from a frequency-modulated oscillator. The carrier current has no phase discontinuity and its instantaneous frequency varies between two limits within the transmission band. In the present discussion the two limits, symmetrically located in the transmission band, correspond respectively to the marking and spacing conditions of the channel. Variation of the instantaneous frequency may be abrupt or gradual, for example, sinusoidal. Throughout this paper the reader should assume that the variation is substantially abrupt except where otherwise indicated. At the receiving terminal the variable frequency signals are converted to amplitude-modulated signals by means of a frequency detector.

*Two-Source Method*

This is also a frequency-shift method, but it differs from that described above in that it is made up by combining two on-off channels, each supplied with carrier current of a different but substantially constant frequency from a separate source. In the present discussion each of the two on-off channels has a separate oscillator and occupies a different frequency band on the same line, and the sending relays of the channels have their operating windings differentially inter-connected so that one oscillator delivers current to the line during marks, and the other during spaces. Thus the marking and spacing signals are confined to separate frequency bands on the line. This is sometimes referred to as two-band operation. The switching takes place abruptly. No attempt is made to control the phases of the two sources. Therefore phase discontinuities are likely to occur at the instants of switching, causing brief transients of varying shapes in the line current. The output circuits of the two receiving detectors are differentially interconnected to obtain polar signals for the operation of a common receiving relay.

*One-Source Two-Band Method*

This is also a frequency-shift method, and is substantially the same as the two-source method except that a single frequency-modulated oscillator is used at the sending end instead of two oscillators, and thus there is no phase discontinuity in the sent signals.

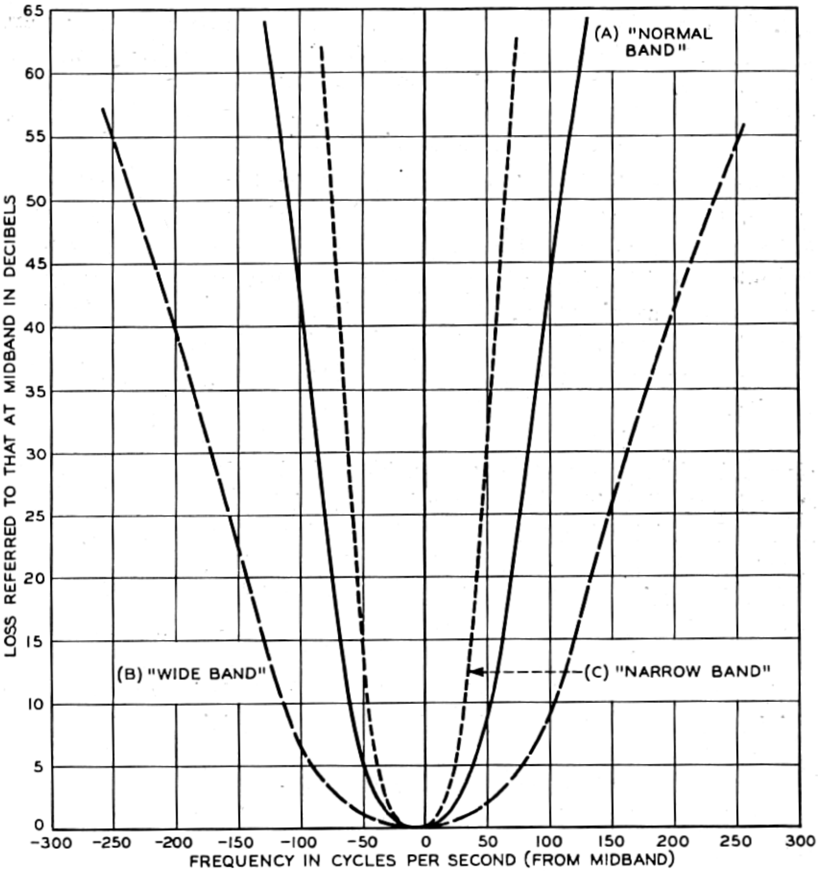


Fig. 1—Loss characteristics of channels tested, including sending and receiving filters and two repeating coils.

These methods will be more clearly understood from the following description of apparatus.

## Apparatus

### *Channel Filter Characteristics*

In Fig. 1, curve A represents the loss vs. frequency characteristic of the majority of channels used in the tests, including both sending and receiving filters and associated repeating coils. The two-source arrangements each occupied two such bands with midband frequencies spaced 170 cycles apart, except in the case of the narrow-band two-source arrangement which occupied two bands having characteristics similar to curve C with midband frequencies spaced 120 cycles apart. Curve B represents the loss vs. frequency characteristic of the wide-band frequency-shift arrangement, having approximately twice the band width of curve A. These characteristics were all measured between 600-ohm terminations, without adjacent channel filters present.

### *On-Off Terminal Apparatus*

Figure 2 shows in block form the different circuit arrangements tested, together with the location of the carrier frequencies in the transmitted bands. In the on-off arrangement, the oscillator transmitted 1955-cycle current to a modulator which contained a polar telegraph relay controlled by signals from the local sending loop. During spacing signals this relay short-circuited the carrier supply, and during marking signals it allowed the carrier current to flow through the sending band-pass filter to the adjustable resistance line.

When it was desired to measure the effect of interference from other channels working in adjacent pass bands, their terminal equipment was added by connecting the line sides of their sending or receiving filters to the common sending or receiving bus (See dashed lines designated "bus" in Fig. 2), so that all the channels would transmit over the same line.

After the carrier signals passed through the receiving filter connected to the output of the line, they were converted by a detector-amplifier into direct current for operating a polar receiving relay, which, in the absence of incoming signals, was held on its spacing contact by local biasing current. The receiving relay contacts transmitted into the local receiving loop.

### *Single-Sideband Terminal Apparatus*

In testing the single-sideband arrangement shown in Fig. 2, the terminal equipment of the on-off arrangement was used and the carrier frequency was placed 43 cycles above midband, at 1998 cycles. In some of the tests the modulator was modified to transmit during spacing intervals a carrier current 6 db below its marking value. Since the loss in the receiving filter was greater at the edge of the band than at the center, it was necessary to increase the gain of the linear detector-amplifier in order to have the same change of current in the line winding of the receiving relay of the single sideband arrangement as in the on-off arrangement. A further increase in the detector-amplifier gain was necessary when the single-sideband arrangement was operated with spacing carrier 6 db below the marking carrier.

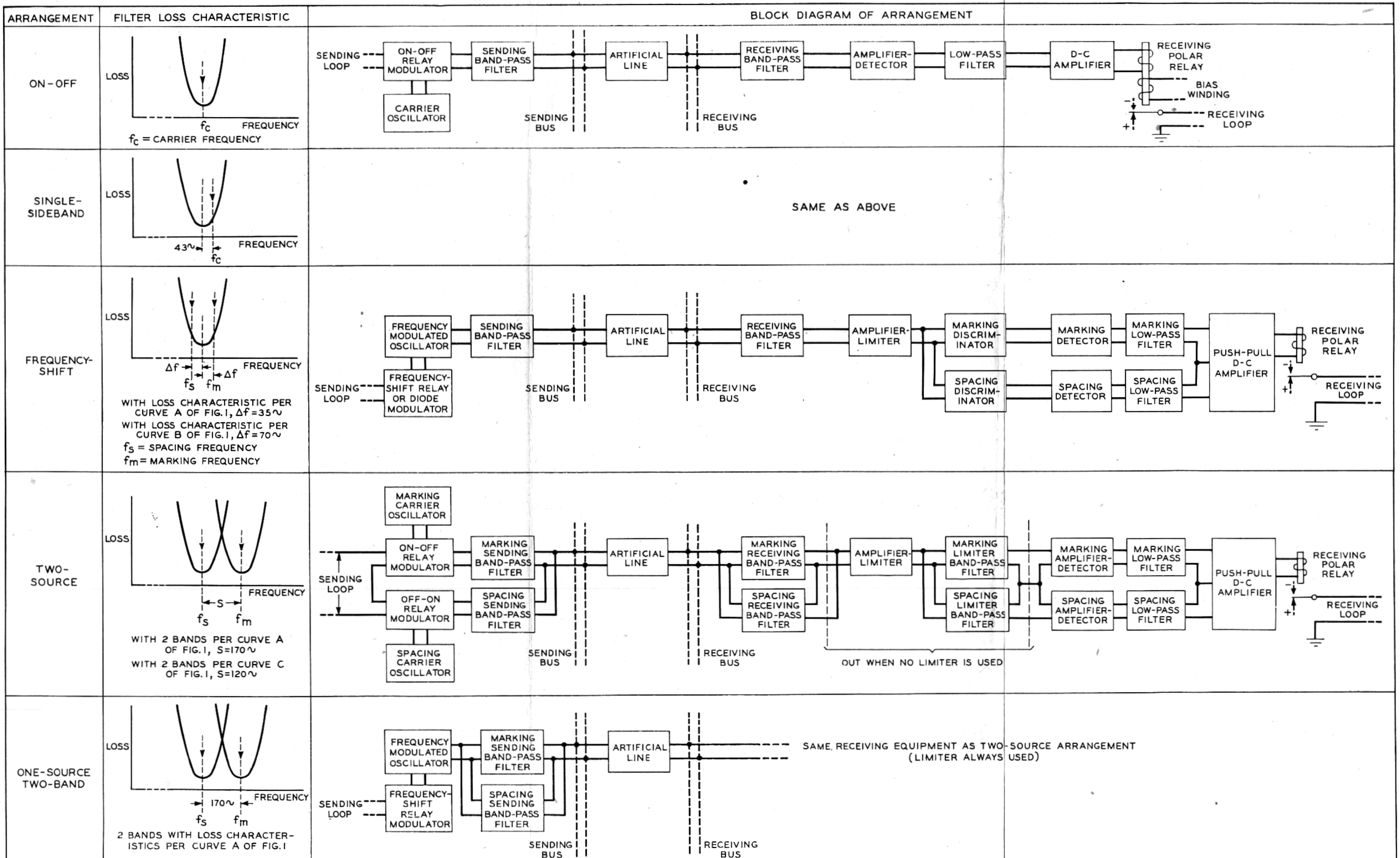

Fig. 2—Telegraph arrangements tested.

*Frequency-Shift Terminal Apparatus*

In most of the tests on the frequency-shift arrangement shown in Fig. 2, the oscillator frequency was caused to vary abruptly by a relay modulator. The sending relay was of the same type as used in the on-off arrangement and varied the tuning capacity of the oscillator. For some other tests the frequency variation was made more gradual by converting the sent signals into polar signals and passing these through a low-pass filter in order to round the wave so that the pulses had an approximately sinusoidal shape during reversals and attained steady-state value only at the center of each pulse. These polar signals were used to control the plate resistance of either of two diodes, thereby connecting a positive or negative reactance across the tuned circuit of the oscillator.[5] This caused the oscillator frequency to be either increased or decreased in proportion to the amplitude change of the control current. During most of the tests the spacing frequency was 1920 cycles and the marking frequency was 1990 cycles, both equally spaced from the midband frequency, 1955 cycles. The oscillator, when on marking frequency, was set to produce one milliwatt into the 600-ohm resistance artificial line. After passing through the receiving filter connected to the output of the artificial line, the signals entered a limiter (unless otherwise stated) delivering an output current which was practically constant for input levels between $-55$ and $+25$ dbm. From the limiter the signal passed into a frequency discriminator circuit having two output branches, each of which was connected to a diode detector tube followed by a low-pass filter. The two discriminator branch circuits in combination with their detectors and low-pass filters had output amplitude vs. input frequency characteristics of opposite slopes. After differential recombination of the two low-pass filter outputs, the resultant characteristic was linear over the range of fundamental frequencies transmitted by the limiter. The differentially recombined wave in the final d-c amplifier had an amplitude substantially proportional to the instantaneous deviation from the average value of the received carrier frequency over a range of $\pm$ 70 cycles. (Some calculations by one of the writers indicate that the use of discriminators of this type is helpful in reducing characteristic telegraph distortion.) In most of the tests the low-pass filters associated with the detector output had a cut-off frequency (about 503 cycles) low enough to suppress the carrier but high enough not to affect the telegraph transmission. The final d-c amplifier was substantially linear and increased the d-c wave to a suitable value for operating the polar receiving relay.

The wide-band frequency-shift arrangement was similar to that just described, except for the change in filters and tuning of the sending oscillator and the discriminator. The spacing frequency was 2055 cycles and the marking frequency was 2195 cycles which were equally spaced from the midband frequency, 2125 cycles. In this arrangement a limiter was always used at the receiving terminal. The discriminator was adjusted to be linear over twice the frequency range of the previously described discriminator, and the slope of the new discriminator characteristic was adjusted to give the same marking or spacing output as before. The wide-band frequency-shift arrangement was also tested with low-pass filters associated with the detector outputs which had a cut-off frequency (about 58 cycles) low enough to give a distortion vs. speed characteristic close to that obtained on the normal-band frequency-shift arrangement. The loss of each of these low-pass filters was about 10 db at 58 cycles. Since each filter consisted of only one section the cut-off was gradual.

### *Two-Source Terminal Apparatus*

The sending circuits of the two-source arrangement shown in Fig. 2 included separate oscillators of different frequency for marking and spacing signals. Two sending relays were operated in synchronism by the signals in the sending loop. The relay contacts were so connected that marking carrier was transmitted to a marking band-pass filter and spacing carrier was cut off from a spacing band-pass filter, or vice versa. Thus either the marking or the spacing carrier frequency was transmitted to the line at any instant. At the receiving end of the line the incoming signals flowed through two receiving filters, one passing the marking current and the other passing the spacing current. When a limiter was not used, the outputs of these filters were connected directly to separate amplifiers, detectors and low-pass filters. The rectified marking and spacing signals were combined differentially, passed through a push-pull d-c amplifier, and operated the receiving relay just as in the frequency-shift arrangement. When a limiter was used the outputs of the receiving filters were recombined and passed through the limiter, after which they were again separated by means of additional band-pass filters whose losses were about half those of the receiving band-pass filters. The two-source arrangement was tested both with and without limiter when the loss characteristics of the spacing and marking paths were each similar to curve A of Fig. 1 and had midband frequencies of 1785 and 1955 cycles, respectively.

The two-source arrangement with limiter also was tested with filters having loss characteristics for the spacing and marking paths each similar to curve C of Fig. 1, and having midband frequencies of 1980 and 2100 cycles, respectively. This arrangement occupied a frequency band approximately 12/17 that used for the two-source arrangement with filters having characteristics similar to curve A.

### *One-Source Two-Band Terminal Apparatus*

The one-source two-band sending circuit was similar to that of the frequency-shift arrangement with relay modulator, except that the frequency shift was 170 cycles, and the marking and spacing frequencies were adjusted to be at the centers of the pass bands of the marking and spacing sending filters, as shown in Fig. 2. The receiving circuit was the same as that used for the two-source arrangement. A limiter was always used.

### *Telegraph Transmission Measuring Apparatus*

In all of the tests, the d-c open-and-close signals in the local sending loop were substantially rectangular and consisted either of reversals (a succession of alternate marks and spaces of equal duration) or of the test sentence: THE QUICK BROWN FOX JUMPED OVER A LAZY DOG'S BACK 1234567890 BTL SENDING. The customary 7.42 unit teletypewriter code was used, consisting of a stop pulse, a start pulse, and five code pulses per character[7]. The distributors supplying these signals were driven by synchronous motors controlled by an adjustable frequency oscillator. The speeds utilized experimentally ranged from 60 to 180 words per minute (about 23 to 68 dots per second).

In order to measure the telegraph distortion of the signals obtained in the receiving loop, a cathode-ray tube distortion measuring set was used which measured maximum total distortion in per cent of a unit pulse in much the same manner as a start-stop distortion measuring set previously described[8], except that electronic circuits were used to replace the distributor and all but one relay, which made possible precise measurements over a wide range of speeds. The bias of received signals was measured on reversals by means of a highly damped zero-center d-c milliammeter inserted in the receiving loop.

### *Source of Resistance Noise*

In order to measure the effect of line noise, resistance noise was reproduced from a phonograph record, amplified, and combined with the carrier signals by means of a symmetrical three-way pad (part of the artificial line). A variable attenuator was used to regulate the amount of noise entering the line. The r.m.s. noise power or marking carrier power was measured with a thermocouple.

## MEASURING PRECISION

The signals generated by the dot and test sentence distributors were distorted less than 3 per cent of a dot length. As these distributors were of a

[7] E. F. Watson: "Fundamentals of Teletypewriters Used in the Bell System", *Bell Sys. Tech. Jour.*, Vol. XVII, Oct. 1938, pp. 620–639.

[8] R. B. Shanck, F. A. Cowan, S. I. Cory: "Recent Developments in the Measurement of Telegraph Transmission", *Bell Sys. Tech. Jour.*, Vol. XVIII, Jan. 1939, p. 149.

commercial type, they are believed to be representative. This distortion was erratic, depending upon the speed and wear of brushes and commutators. The distortion measured at the receiving relay could not be corrected by subtracting the distortion of the sent signals because during miscellaneous signals maximum distortion in the received signals might occur on a different transition from that in the sent signals. The small errors which existed in the sent signals are therefore believed to have been neither serious in their effect on the measured distortion, nor the sole cause of irregularity in the data.

The accuracy of the distortion measuring set itself was in the order of 1 per cent, as determined by measuring known amounts of bias in signals sent from a special distributor. Usually two observers took independent readings which were required to check closely or the observations were repeated. The average of the two observations was taken as the final measurement.

Although the line loss was constant in these tests, amplifiers, oscillators, power packs, and telegraph batteries were subject to slight voltage variations. Precautions were taken to reduce all variables as far as was practicable, yet it seems likely that the telegraph transmission measurements may be slightly in error due to such variations.

The individual sources of error mentioned in the last three paragraphs seem reasonable and sufficient to account for most of the irregularities in the following curves of telegraph transmission vs. speed. Yet it did not seem fair to draw smooth curves and neglect the irregularities, because these can also be due to the telegraph system itself, as was found by careful and repeated measurements. For example, it is known that relay performance is erratic and depends upon the speed. Chattering of relay contacts and periodic vibration of the armature have appreciable effect upon the distortion and can cause irregularities in distortion vs. speed characteristics, particularly at the higher speeds. Furthermore, such irregularities may not be wholly reproducible in repeated measurements due to changes in the relay temperature or contact surfaces and due to the occasional readjustments of relays. Another cause of irregularities in a distortion vs. speed characteristic may be the loss and phase characteristics of the channel filters. For example, consider an ideal transducer[1] which is distortionless at a speed s near the cut-off. It is also distortionless at speeds such as s/2, s/3, s/4, s/5, etc. At intermediate speeds distortion may exist, so that a curve of distortion vs. speed would show irregularities with minima at these optimum speeds. (Some computations by one of the writers for a frequency-shift arrangement using idealized filters show irregularities in the distortion vs. duration curve for a single dot.) No attempt was made to shape the channel filter characteristics to be perfectly distortionless at a particular speed; and it seems reasonable that there could likewise be a number of speeds where maxima and minima occur in the distortion.

It is practically impossible to sift out and measure all causes of irregularities in a reasonable time. Therefore the irregularities have been shown exactly as measured in all the following curves wherein noise and interchannel interference were absent.

Transmission fluctuations due to the causes just mentioned were small compared to those encountered when strong interference or noise was present, because the latter varied greatly with time. In resistance noise, for example, peaks of great amplitude occur occasionally, although most of the time the fluctuations are relatively minor. It was necessary to observe for several minutes the distortion measured in the presence of resistance noise before one could be sure of finding anything approaching the maximum distortion; and the longer the period of observation, the greater was the peak distortion. In order to complete the testing in a reasonable time, watching periods were restricted to five minutes per observer and his maximum distortion reading was recorded. The results of two such observation periods for the same noise condition were averaged to determine a point for an experimental curve of distortion vs. noise-to-carrier ratio. Such points when plotted failed to lie in a perfectly smooth curve, but a smooth curve disregarding irregularities was drawn through the available points in what was estimated to be the correct location. The curves are described under the heading "Noise Tests" and may be used for comparison purposes, but are not an exact measure of the worst distortion to be expected over a long period of time. A similar procedure was followed for distortion measurements with interchannel interference.

## Distortion vs. Speed Tests

The distortion mentioned throughout this paper is the absolute value of the maximum total distortion measured with the test sentence, and for brevity is merely called distortion. Except where otherwise specified, the arrangements were previously adjusted to have zero bias on reversals at the same speed. In these tests line noise and interchannel interference were absent.

### *Frequency-Shift Arrangements*

*Limiter*

Some preliminary measurements on a frequency-shift arrangement having the loss characteristic of curve A of Fig. 1, with carrier varied abruptly from 1920 to 1990 cycles, showed that the limiter has little effect on the speed of the channel whether or not channel filters are used. The fact that low distortion was measured without channel filters indicated that the channel and measuring devices were in good condition as far as could be reasonably expected over the range of speeds. The distortion measured without channel filters ranged from 2.5 per cent at 60 w.p.m. (23 d.p.s.) up to 10 per cent at 170 w.p.m. (65 d.p.s.).

*Swing*

Some measurements were made on the complete frequency-shift arrangement over the same range of speeds, using several values of abrupt frequency swing from $\pm$ 15 cycles to $\pm$ 55 cycles, keeping the marking and spacing frequencies equidistant from 1955 cycles. With a swing of $\pm$ 55 cycles the distortion was slightly worse than when the swing was $\pm$ 35 cycles. The measurements showed least distortion for a swing of $\pm$ 15 cycles. It has been previously shown[6] that the less the swing the smaller the amplitude of the oscillations in the transient for a given channel frequency band width. Accordingly one might expect distortion to be least when the swing is least. If only a small swing is used the signal bias change with carrier frequency drift is worse, unless automatic bias compensation is provided. Greater amplification is also required in the detector-amplifier in order to maintain the same relay operating current. A swing of $\pm$ 35 cycles was used in most of the frequency-shift tests as a good compromise between the distortion caused by the greater swings and the severe apparatus requirements and greater susceptibility to noise when using the lesser swings.

*Types of Modulator*

Figure 3 shows distortion characteristics of a frequency-shift arrangement using different types of modulator. Curve A was measured with sinusoidal frequency variation obtained by the use of a diode modulator and low-pass filter at the modulator input[5]. When the low-pass filter was omitted, the frequency variation was substantially abrupt, and curve B was obtained. When the diode modulator was replaced by a relay modulator, which also produced a substantially abrupt frequency change, curve C resulted. There is not much difference between these characteristics at low speeds. At high speeds the abrupt frequency variation appears to give somewhat lower distortion than sinuosidal variation. The distortion shown by curve A depends not only upon the speed and channel filter characteristic but also upon the characteristic of the low-pass filter used in rounding the sent wave in order to produce sinusoidal frequency variation. A considerable amount of care was necessary to prevent this low-pass filter from introducing too much distortion and at the same time to produce sufficient rounding. The cut-off frequency of this low-pass filter was adjusted at each signaling speed to be about three times the dot frequency. It was apparently low enough to

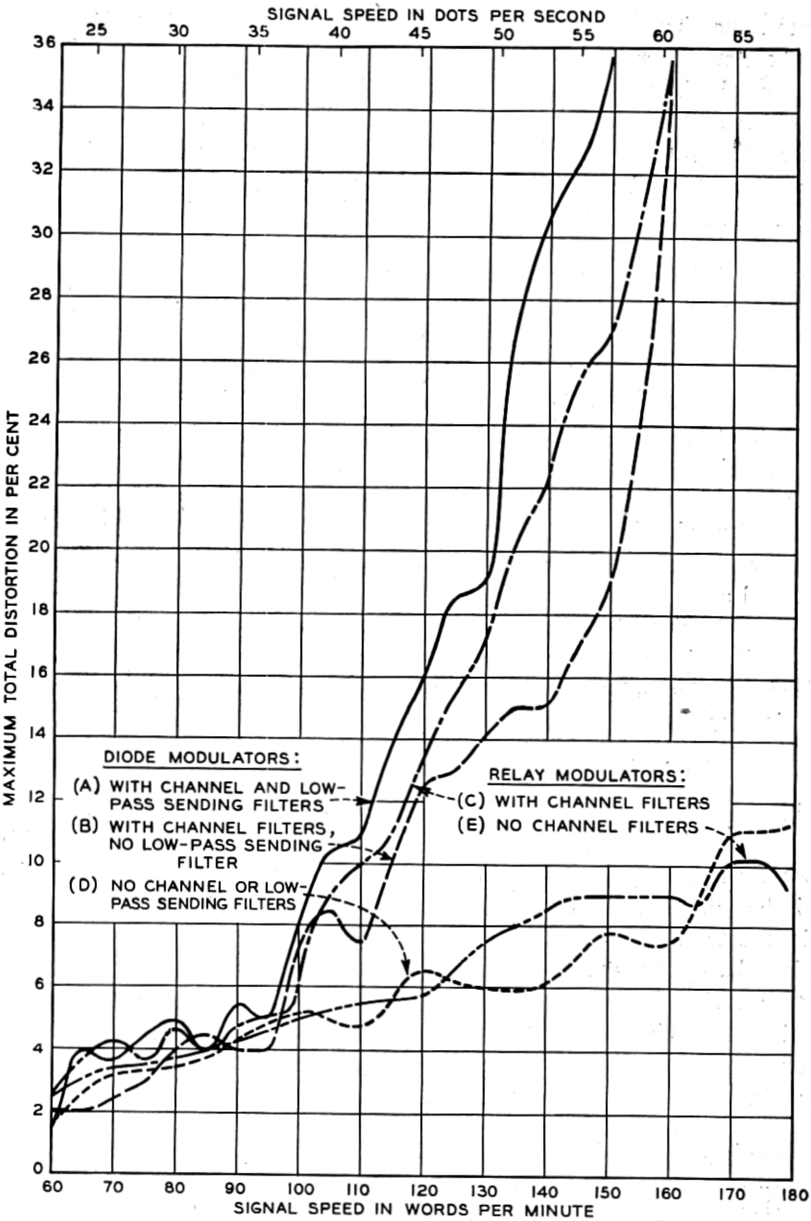


Fig. 3—Distortion vs. speed characteristics of normal-band frequency-shift arrangements, using two different types of modulator.

cause some characteristic distortion. No attempt was made to obtain an ideal distortionless filter characteristic because it would have been necessary also to take into account the characteristics of other parts of the circuit, which would have required considerably more time than was then available. Curves D and E of Fig. 3 show that the modulators caused very little distortion when channel and low-pass sending filters were absent.

*Band Width*

Figure 4 shows a comparison of the distortion vs. speed characteristics of the normal-band and wide-band frequency-shift arrangements when a relay modulator was used. Curve A of Fig. 4 is the same as curve C of Fig. 3 and shows the characteristic of the normal band arrangement. Curve C of Fig. 4 shows the characteristic of the wide-band arrangement when the low-pass filters at the detector output were the same as for the normal-band arrangement, their cut-off frequency being about 503 cycles. The distortion shown in curve C is much lower than that of curve A since the width of the side-bands transmitted was doubled. Curve B of Fig. 4 shows the characteristic of the wide-band arrangement when the low-pass filters at the detector output had a cut-off at about 58 cycles. As previously indicated, the latter cut-off was selected in order to give the wide-band arrangement about the same distortion vs. speed characteristic as the normal-band arrangement. The reason for the use of the lower cut-off is explained under the heading "Noise Tests".

## *Comparison of Frequency-Shift and On-Off Arrangements*

Figure 5 is a comparison of the distortion vs. speed characteristic of the frequency-shift arrangement having a relay modulator (curve B), with characteristics of two on-off arrangements having commercial receiving circuits[9, 10, 11]. The 40B1 detector had no level compensator and included a triode detector having an output vs. input characteristic which roughly followed a square law. The other detector had a slow acting level compensator[11] designed to eliminate receiving bias due to slow changes in line equivalent. The output vs. input characteristic of this detector was much steeper than that of the 40B1 arrangement at the transition points of the signals. The level compensated arrangement was adjusted at each speed to

[9] B. P. Hamilton, H. Nyquist, M. B. Long and W. A. Phelps: "Voice Frequency Carrier Telegraph System for Cables", *Jour. A. I. E. E.*, Vol. XLIV, No. 3, Mar. 1925.

[10] A. L. Matte: "Advances in Carrier Telegraph Transmission", *B. S. T. J.*, Vol. XIX, pp. 161–208, Apr. 1940.

[11] A separate paper describing a commercial system using an improved level compensator is now in preparation by other Bell System authors. The function of the level compensator is to vary the gain of the receiving amplifier-detector so as to automatically compensate for relatively slow level changes. See also: V. P. Thorp: "A Level Compensator for Carrier Telegraph Systems", *Bell Laboratories Record*, Vol. XVIII, No. 2, October 1939, pp. 46–48.

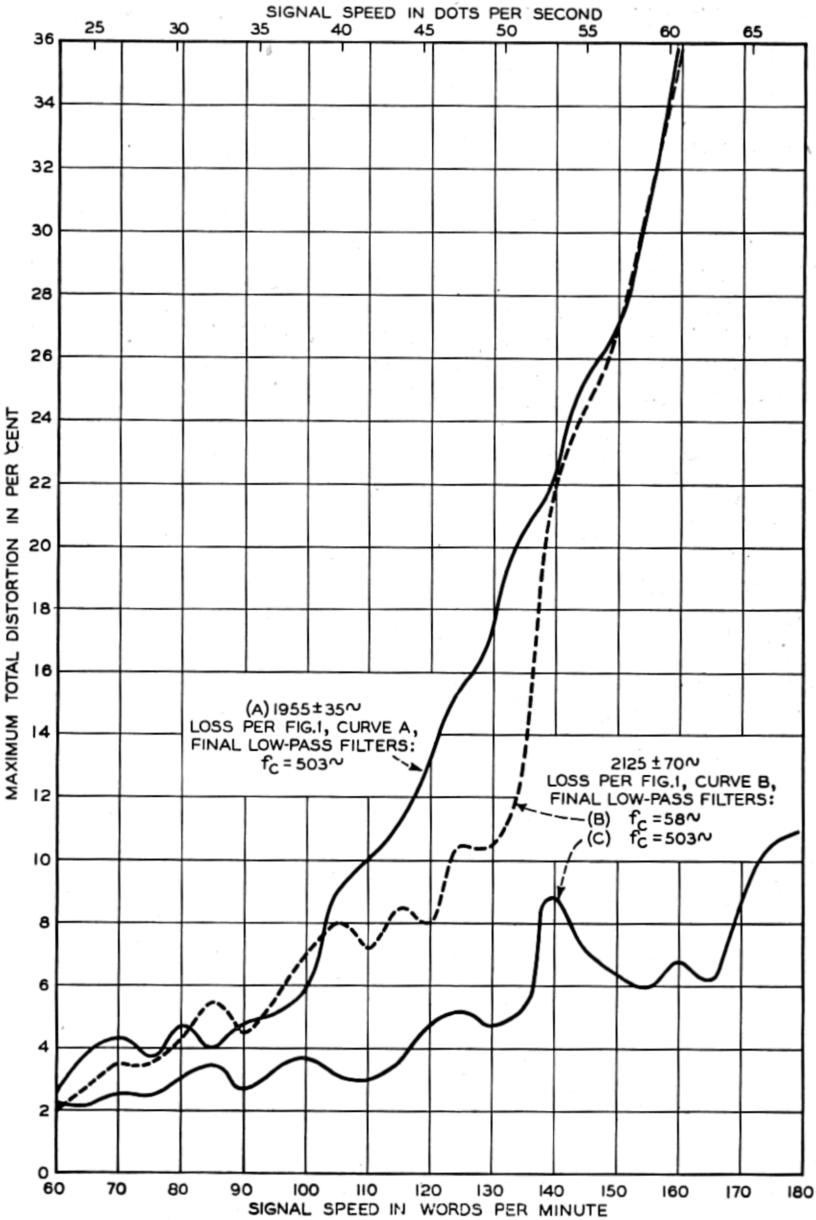


Fig. 4—Distortion vs. speed characteristics of normal- and wide-band frequency-shift arrangements.

have zero bias while transmitting the test sentence because the characteristic of the level compensator was such that reversals could not be used to adjust for zero bias of the received signals. The distortion vs. speed characteristics of the level compensated on-off and 40B1 arrangements are given by curves A and C, respectively, in Fig. 5. This figure indicates that at high speeds the frequency-shift arrangement is subject to somewhat greater distortion than the on-off method.

It may be argued that Fig. 5 is not a fair comparison between frequency-shift and on-off methods because of the difference in detector characteristics. In order to overcome this objection an experimental on-off arrangement was set up utilizing a linear detector and the same receiving relay as in the frequency-shift arrangement. The effective operating ampere-turns in the 255A receiving relay were kept the same for both frequency-shift and linear on-off methods of transmission. The line winding current varied from about 10 mils during spacing signals to 50 mils during marking signals, and the biasing winding current tending to move the armature toward spacing was about 30 mils for the on-off arrangement. The effective relay operating current in the frequency-shift arrangement was +20 mils in the marking condition and −20 mils in the spacing condition.

The distortion measurements are shown in Fig. 6. In order to compare frequency-shift with the linear on-off arrangement, consider curves A and B of Fig. 6. There is not much difference between them, but the frequency-shift characteristic shows slightly higher distortion over part of the speed range, as in Fig. 5.

In these tests the channel loss characteristic used was that of Fig. 1, curve A.

### *Two-Source and One-Source Two-Band Arrangements*

The same linear detector, receiving relay, and effective relay operating current were used for these two-band arrangements as for the frequency-shift arrangement. Curves C, D, and E of Fig. 6 show the speed characteristics of various two-source and one-source two-band arrangements in which the marking and spacing paths had loss characteristics similar to curve A of Fig. 1. Curve C of Fig. 6 applies to the arrangement using two oscillators and no limiter and does not differ greatly from the characteristic for the on-off method, curve B. Curve D applies to the arrangement using two oscillators and limiter, and shows greater distortion than curve C because of modulation products arising in the limiter between the sidebands of the marking and spacing carriers. This type of interference was due to discontinuities in phase of the carrier wave at the signal transitions, and was eliminated by the use of a frequency modulated oscillator in place of the two independent oscillators, as indicated by curve E. The latter is somewhat similar to curve C on Fig. 4 measured on the frequency-shift arrangement with the wide

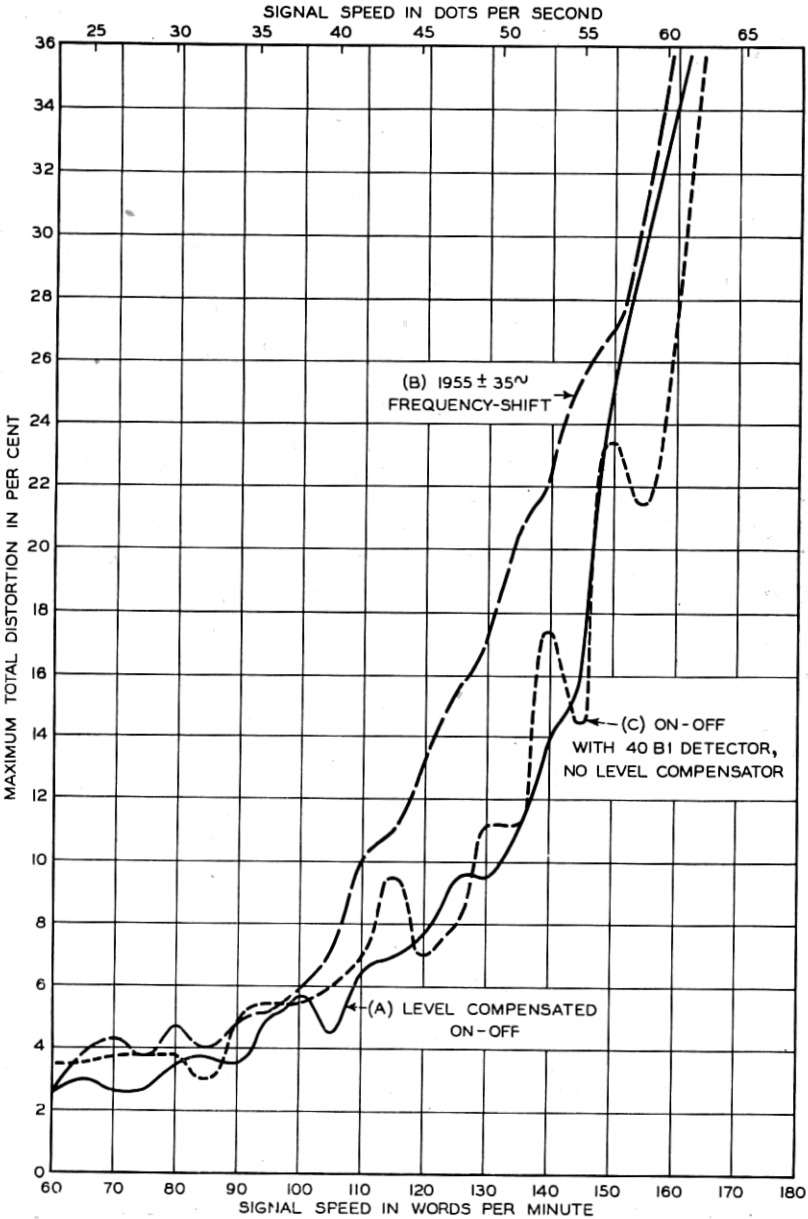


Fig. 5—Distortion vs. speed characteristics of frequency-shift and non-linear on-off arrangements.

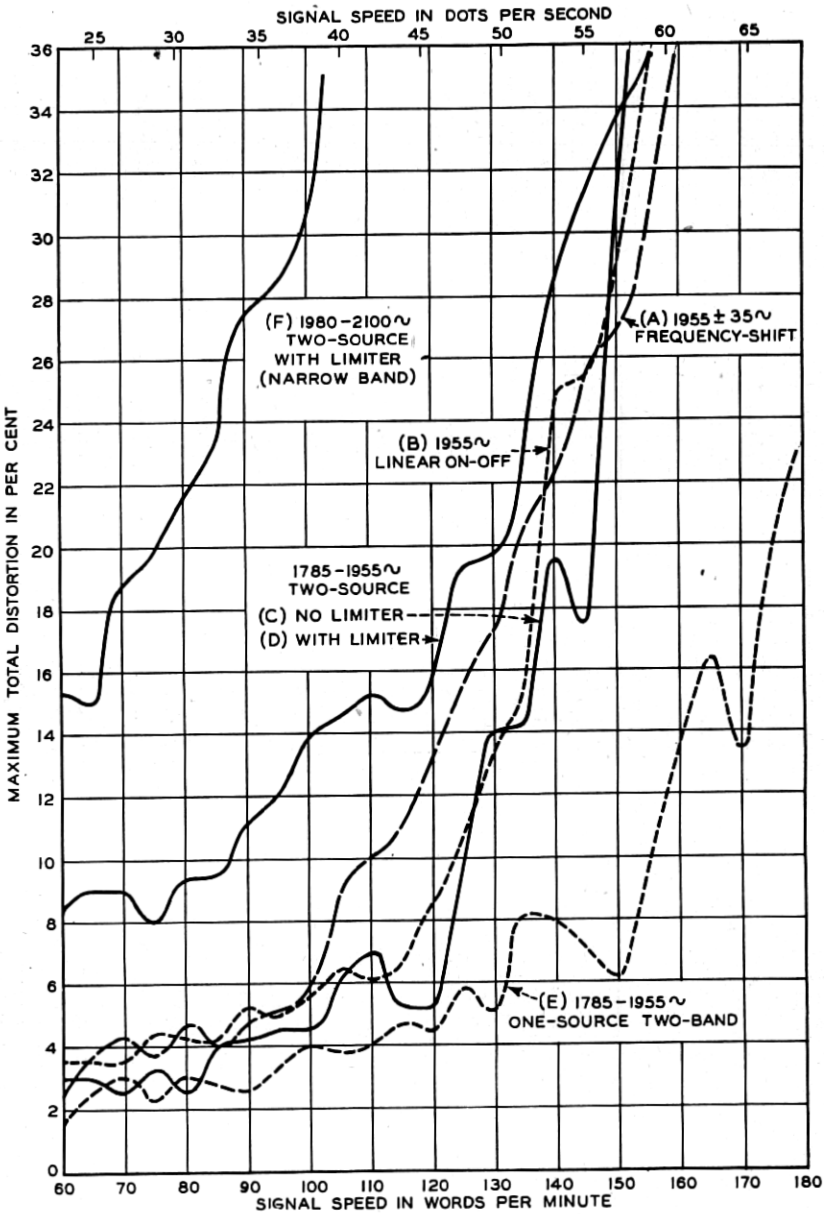


Fig. 6—Distortion vs. speed characteristics of frequency-shift, linear on-off, two-source and one-source two-band arrangements.

band, except that the distortion at the higher speeds is greater with curve E of Fig. 6 because sideband components in the middle portion of the total frequency band were considerably attenuated by the channel filters of the one-source two-band arrangement, but not by those of the wide-band frequency-shift arrangement. The distortion vs. speed characteristic of the two-source arrangement having paths with loss characteristic similar to curve C of Fig. 1, is shown by curve F of Fig. 6. The large distortion is due to the narrower sidebands transmitted and to the combined use of two independent oscillators and a limiter, the effect of which is discussed above.

### *Single-Sideband Arrangement*

The same linear detector, receiving relay, and effective relay operating current were used for the single-sideband tests as for the linear on-off tests.

An ideal single-sideband arrangement should operate at twice the speed of the on-off arrangement for the same pass band, if the quadrature component[2] is eliminated. The cost of a phase discrimination method of reception[1] for this purpose would probably be prohibitive in practice. If the quadrature component is allowed to remain, it is a principal cause of distortion, so that the single-sideband method gives only a slight increase in speed. The effect of the quadrature component on telegraph distortion can be reduced[2] by the transmission of a certain amount of spacing carrier current. Curve B of Fig. 7, measured with a spacing current 6 db below the marking current, shows less distortion than curve A of Fig. 7, measured with no spacing current; and, in the range of speeds investigated, does not differ greatly from curve C, taken on the linear on-off arrangement without channel filters. Thus, it is apparent that the single-sideband arrangement is capable of higher speeds, for a given distortion and band width, than the other arrangements here considered.

## Tests of Carrier Frequency Variations

When a carrier telegraph circuit contains a radio or carrier telephone link, some instability may occur in the average received carrier frequency. In order to investigate the effect of varying the mean carrier frequency, the carrier supply frequency was varied as a matter of convenience. Since the signals were transmitted through both sending and receiving channel filters the effects observed were doubtless about twice as bad as if only the received carrier frequency had been varied, except perhaps in the frequency-shift arrangements where the discriminator produced a large effect.

### *Distortion at 60 Words per Minute*

In Figs. 8 and 9, the distortion obtained over the various arrangements is shown as a function of carrier frequency variation from the nominal value, when the speed was 60 w.p.m. The marking and spacing frequencies of the two-source, one-source two-band, and frequency-shift arrangements were

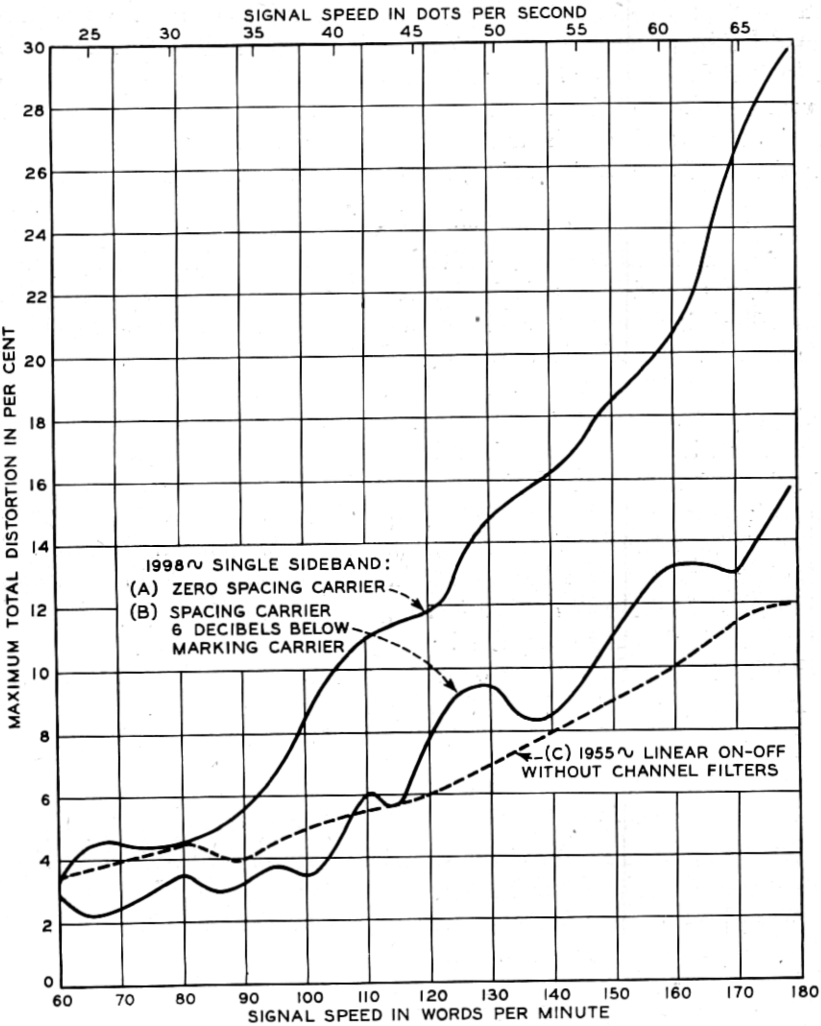


Fig. 7—Distortion vs. speed characteristics of single-sideband arrangements and on-off arrangement without channel filters.

both varied by the same amount from their normal values without changing their relative separation. It is evident from Fig. 8 that the arrangements ranked in the following order as regards the permissible carrier frequency

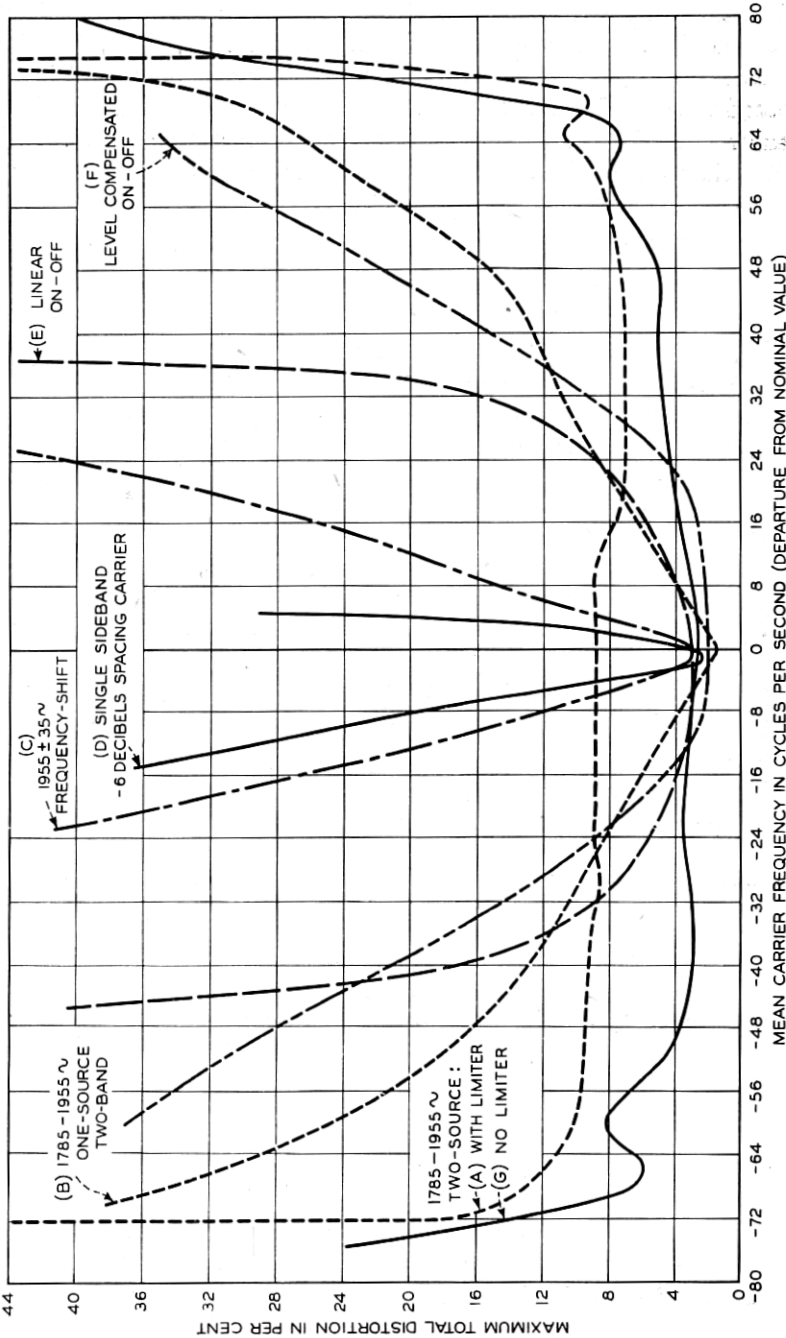


Fig. 8—Distortion vs. mean carrier frequency characteristics of normal-band arrangements at 60 w.p.m. (23 d.p.s.).

variations when the distortion was about 20 per cent: two-source without limiter on a par with two-source with limiter, one-source two-band with limiter, level compensated on-off, linear on-off, frequency-shift, and single-sideband with −6 db spacing carrier. This comparison includes only those arrangements using the same type of filter (with loss per curve A, Fig. 1). Figure 9 shows the results obtained by making similar tests on the wide-band frequency-shift (with loss per curve B, Fig. 1) and on the narrow-band two-

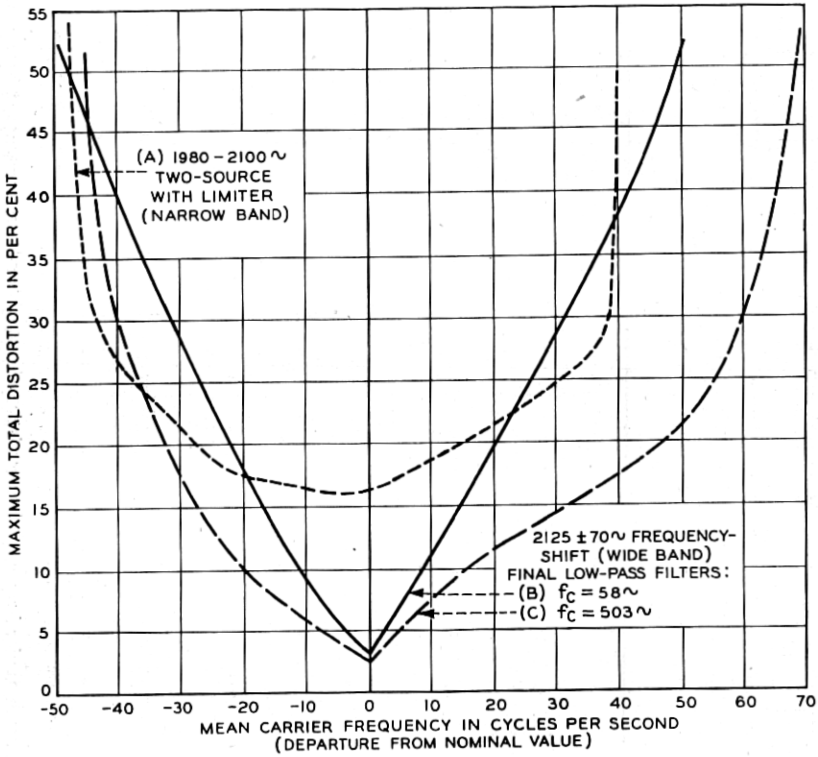


Fig. 9—Distortion vs. mean carrier frequency characteristics of narrow- and wide-band arrangements at 60 w.p.m. (23 d.p.s.).

source arrangements (with loss per curve C, Fig. 1). The distortion curves for the wide-band frequency-shift arrangement in the latter figure are more favorable than the curve for the normal-band frequency-shift arrangement shown in Fig. 8 because the wide-band arrangement had a discriminator with only half the slope of that used in the normal-band arrangement. The wide-band arrangement with the higher cut-off low-pass filter could tolerate a greater change in carrier frequency than the arrangement with the lower cut-off low-pass filter because of the steeper wave front of the signals delivered by the former low-pass filter, resulting in a lower signal bias when the detected amplitudes of the marking and spacing signals differed.

When the average carrier frequency of a two-source arrangement was varied, the marking and spacing frequencies moved toward one side of their respective pass bands. As they approached the cut-off frequencies of the band-pass filters, telegraph distortion occurred due to suppression of the carrier and adjacent components. The narrow-band two-source arrangement was more sensitive to variation in the average carrier frequency than the normal-band two-source arrangement, and the reason is obvious.

### *Bias at 60 Words per Minute*

When tested with reversals at 23 d.p.s. (corresponding to 60 w.p.m.), the arrangements also ranked in the same order from the bias standpoint as from the distortion standpoint, as the mean carrier frequency was varied. In Figs. 8 and 9 the distortion due to carrier frequency variation consisted mainly of bias, except in the two-source arrangements, where the received marking and spacing pulses were substantially equal on reversals so that there was little bias. (Bias measurements referred to here and below have not been shown graphically in order to save space.)

The on-off, two-source, and one-source two-band arrangements were fairly insensitive to carrier frequency variations since the loss vs. frequency characteristics of the channel filters changed but slowly near the middle of the transmission band. Since the frequency-shift arrangement had a discriminator which was sensitive to frequency changes, drifting of the average carrier frequency resulted in a rise in detected current in one half of the push-pull detector and a reduction thereof in the other half, thus causing serious bias in the differentially combined rectified waves, since no frequency compensator was provided. It is outside the scope of this paper to describe such a compensator, but it is no more complicated than the level compensator used with an on-off arrangement. In the single-sideband arrangement the carrier was located at a point on the filter loss vs. frequency characteristic where the slope was steep. Consequently small frequency changes produced large amplitude variations in the operating current of the receiving relay. Since there was no compensating change in the biasing current of the relay, large bias variations resulted from small changes in carrier frequency.

### *Distortion at 120 Words per Minute*

Figures 10 and 11 give distortion for the arrangements at 46 d.p.s. or 120 w.p.m. when the mean carrier frequency was varied. The arrangements ranked in the following order when the distortion was 20 per cent: two-source without limiter, two-source with limiter, linear on-off, one-source two-band,

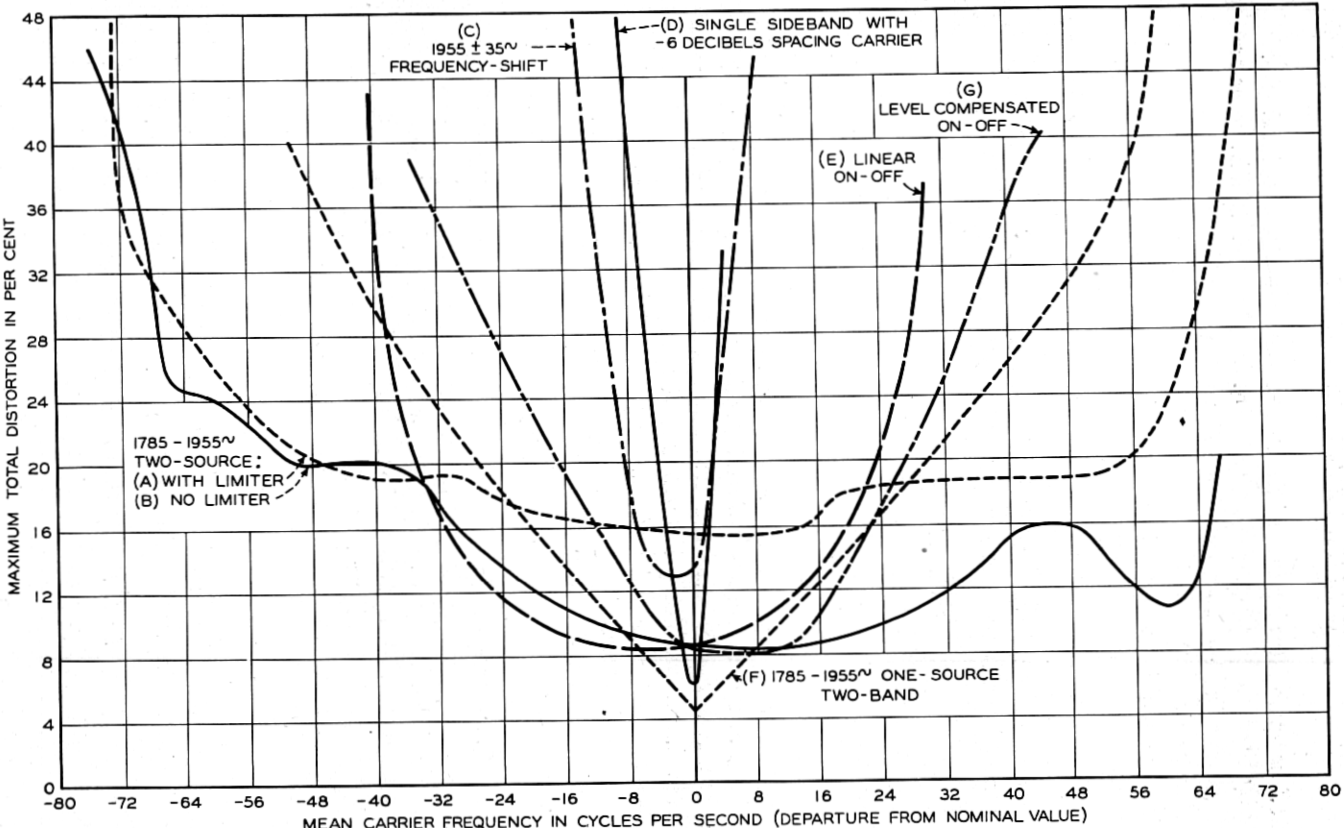


Fig. 10—Distortion vs. mean carrier frequency characteristics of normal-band arrangements at 120 w.p.m. (46 d.p.s.).

level compensated on-off, frequency-shift, single-sideband with −6 db spacing carrier.

In both Figs. 8 and 10 there appears to be considerable difference between the distortion vs. carrier frequency characteristics of the two-source and one-source two-band arrangements with limiter. The two-source arrangement was better for large carrier frequency variations, and the one-source two-band arrangement was better for small carrier frequency variations.

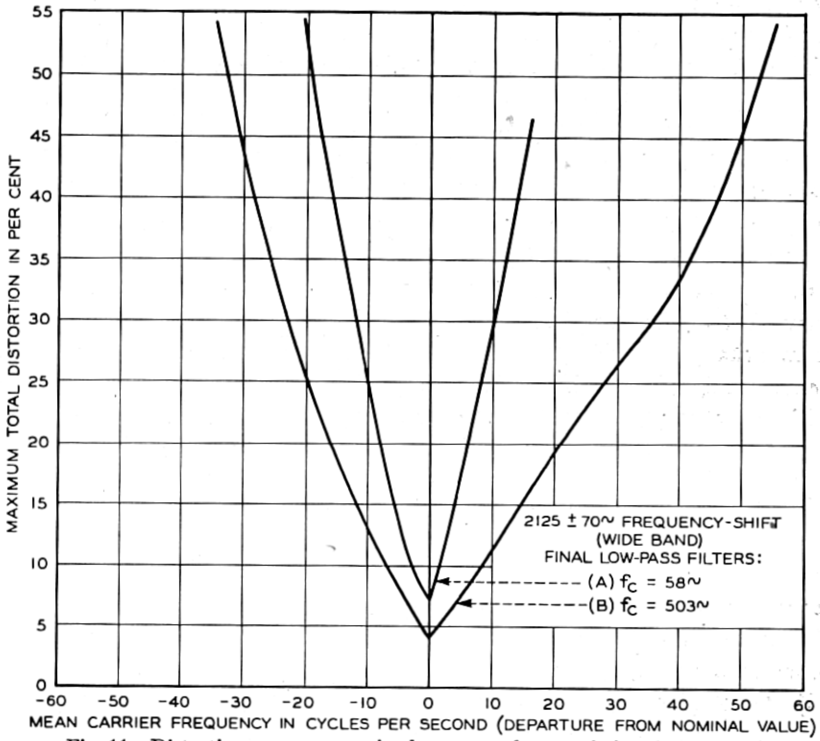


Fig. 11—Distortion vs. mean carrier frequency characteristics of wide-band frequency-shift arrangements.

The difference between the performance of these two arrangements was partly due to interference between sidebands in the two-source arrangement as previously mentioned, and partly due to the difference in the sending arrangements used. In the case of the two-source sending arrangement shown in Fig. 2, the sidebands of the marking and spacing paths were separated by the sending filters, and a small shift in carrier frequency affected each branch similarly, and relatively little bias or distortion resulted. In the case of the one-source two-band method also shown in Fig. 2, the sidebands of the marking and spacing frequencies were not completely separated by the sending filters and a shift in carrier frequency affected the two sets of sideband components dissymmetrically, thus causing bias and distortion.

### *Bias at 120 Words per Minute*

The bias resulting from carrier frequency change in the various arrangements at 46 d.p.s. or 120 w.p.m. was in general worse than at half this speed because the received wave shape was more rounded. The distortion due to carrier frequency variation, as shown in Figs. 10 and 11, consisted mainly of bias, except in the two-source arrangements, as explained above.

### *Other Considerations Relating to Single-Sideband Arrangement*

The single-sideband arrangement with −6 db spacing carrier was found to have the lowest distortion at high signal speeds. Consequently it was thought desirable to study this arrangement further in order to see what might be done to improve its stability during carrier frequency variations, and to select an optimum location for the average carrier frequency. First, curve A of Fig. 12 was plotted showing the distortion at 160 w.p.m. resulting from a change in carrier frequency. Then it was assumed that a level compensator might be provided. In order to simulate the effect of such a device without actually constructing one, the line loss was adjusted manually to keep the r.m.s. marking carrier power constant at the receiving filter output. Curve B of Fig. 12 shows an improvement in the change in distortion vs. carrier frequency under this condition. Large variations in bias still persisted in spite of level compensation, due to variations in shape of the envelope of the received carrier signals caused by various amounts of quadrature component and sluggish in-phase component[1] depending on the location of the carrier frequency. In order to simulate the effect of a level compensator providing automatic bias adjustment, the relay bias current was adjusted to give zero receiving bias at each setting of the carrier frequency, and also the receiving filter output was maintained at a constant value as before. The results are given by curve C in Fig. 12 which shows a considerably increased tolerance to carrier frequency changes when the arrangement was stabilized in this manner. This curve indicates that the carrier frequency could be increased about 17 cycles before the distortion started to increase rapidly, and could be reduced about 5 cycles before a gradual increase in distortion began to appear.

It has been shown that for a certain ideal filter[1], a suitable location of the carrier frequency for the single-sideband method is at a point either at the upper or lower side of the band where the loss is 6 db with respect to that in the middle of the band. It can be demonstrated that the envelope of the received wave is the same when the carrier frequency is set at either of these locations, if the filter characteristic is symmetrical about the midband frequency, if the pass band is narrow, and if the carrier frequency is high compared to the dot speed, as in the arrangement tested. Consequently there was no point in duplicating measurements for carrier locations at the lower edge of the band except perhaps to discover the second order effect of slight asymmetry in the channel filters. 1998 cycles is at the right-hand 6 db point of the filter characteristic given by curve A of Fig. 1; and as there is not much choice in the region from 5 cycles below to 17 cycles above this

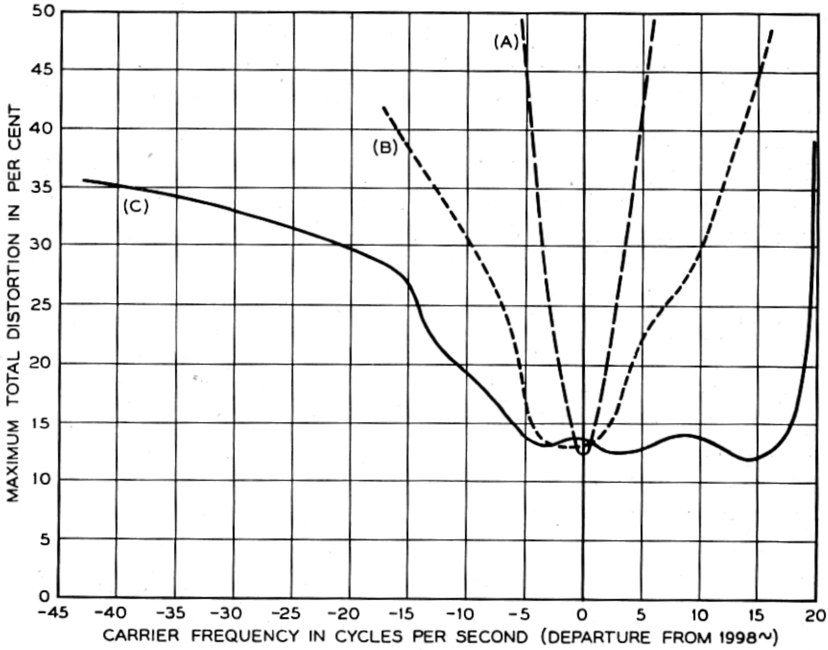


Fig. 12—Distortion vs. carrier frequency characteristics of 1998-cycle single-sideband arrangement using spacing carrier current 6 db below marking current at 160 w.p.m. (61 d.p.s.).

A: Fixed adjustments. B: Constant marking output level from receiving filter, and fixed relay bias current. C: Same as B, except receiving signal bias adjusted to zero by varying receiving relay bias current while transmitting reversals.

frequency, according to curve C of Fig. 12, it was considered satisfactory to locate the carrier at 1998 cycles for certain other single-sideband tests covered in this paper, although a slightly higher or lower value would probably have done about as well. As previously indicated, the reason for assuming a spacing carrier current 6 db below the marking value for single-sideband tests was to reduce the distortion due to the quadrature component[2]. Still less effect from the latter would have existed if the spacing carrier current had been further increased, but this would have reduced the difference between the marking and spacing current amplitudes on the line, causing a corresponding reduction in sideband power. If the quadrature component had been completely eliminated it is possible that 1998 cycles would have been found to be a more favorable carrier location than some of the other closely adjacent frequencies. However, no attempt was made to design the filters for the theoretical single-sideband requirement that the transfer admittance of the vestigial sideband should be complementary[1] to that of the other sideband near the carrier frequency.

## Tests of Received Level Variations

Any transmission path is likely to have level variations caused by temperature and weather changes in case of wire lines and by fading in case of radio links. Each arrangement was therefore tested for susceptibility to level changes by varying the artificial line over a wide range. As the artificial line was made of resistances, the effect of equal fading over the entire frequency range was thereby simulated.

### *Distortion at 60 Words per Minute*

In Fig. 13 is shown the total distortion at 60 w.p.m. vs. level change for different arrangements using the same type of filter. As may be seen from Fig. 13, the arrangements which had the same loss characteristic ranked in the following order at 20 per cent distortion and 60 w.p.m. as regards stability when the line level was varied: two-source with limiter on a par with one-source two-band, frequency-shift, level compensated on-off, two-source without limiter, linear on-off, and single sideband with −6 db spacing carrier. The range of levels over which the first three arrangements mentioned above were stable, in the absence of interference, was largely a function of the range of the limiter, which was over 80 db. The on-off arrangement including a level compensator had a range of approximately 40 db, but it should be remembered that a level compensator is effective only for level changes slow compared to the signal speed. The range of the two-source arrangement without limiter depended on the accuracy with which the marking and spacing halves of the receiving circuit were balanced. In the arrangement tested this range was about 30 db. The linear on-off arrangement without level compensator was very sensitive to level changes because the operating current in the receiving relay varied without a compensating variation in the bias current. The single-sideband arrangement had greater sensitivity than the linear on-off arrangement because a variation of 6 db in the line current of the single-sideband arrangement was accompanied by a 15 db variation in relay operating current due to the use of increased gain and a large grid bias in the receiving d-c amplifier.

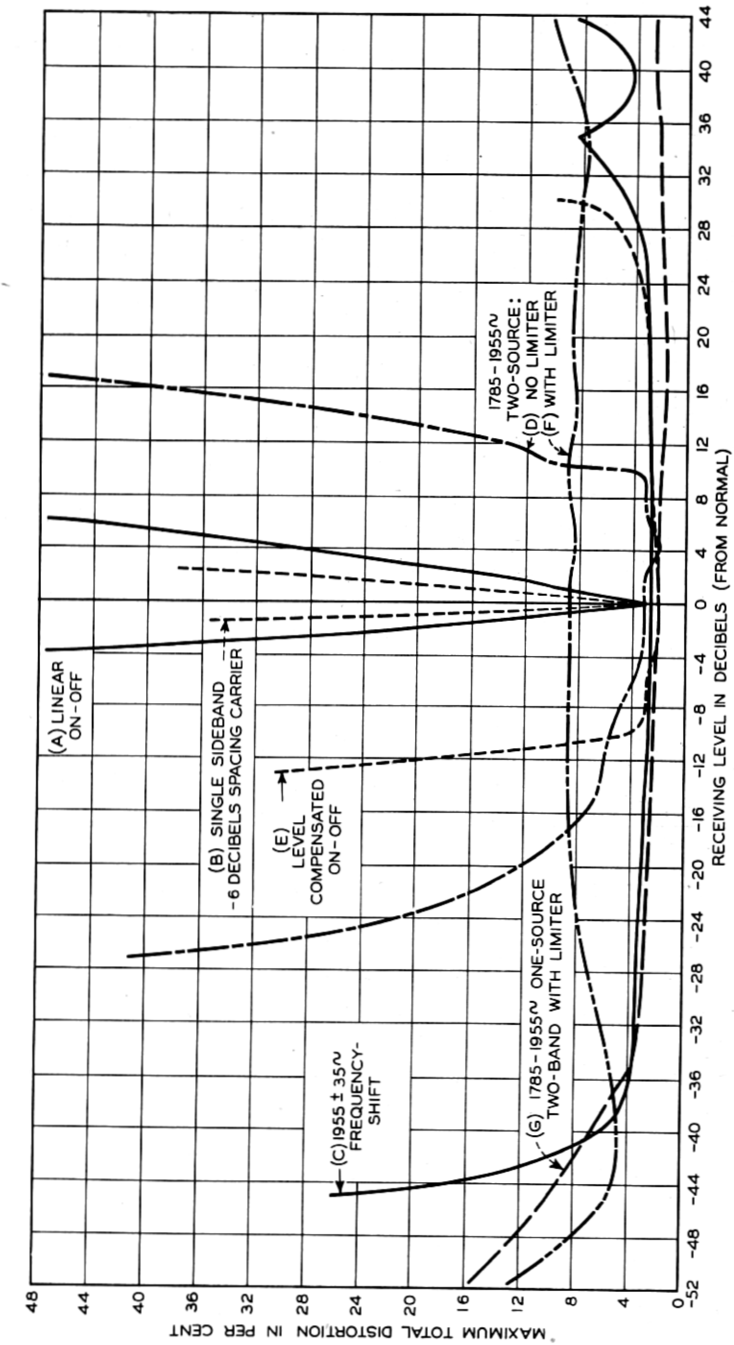


Fig. 13—Distortion vs. receiving level characteristics of normal-band arrangements at 60 w.p.m. (23 d.p.s.).

Just as the line level range of an on-off arrangement may be extended by the use of a level compensator, so it seems reasonable to expect that a similar improvement could be obtained by using level compensators on the linear on-off and single-sideband arrangements. However, when a level compensator is applied to such arrangements, it must be a slow acting device in order not to cause characteristic distortion. When large and rapid level changes are frequent, as may occur on a radio circuit due to fading, an arrangement including a fast acting device like a limiter is preferred, such as a two-source, one-source two-band, or frequency-shift arrangement.

The effect of level variations on the distortion of the narrow-band two-source arrangement and of the wide-band frequency-shift arrangement with and without low cut-off low-pass filter is shown in Fig. 14. At 60 w.p.m. the wide-band frequency-shift arrangement with low cut-off low-pass filter could

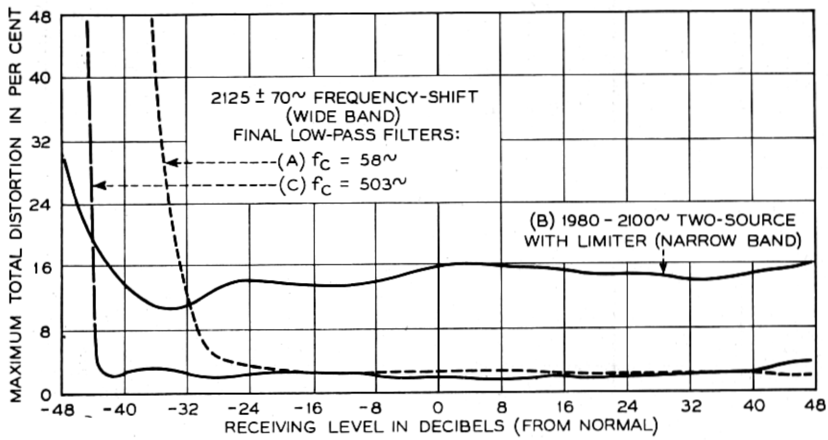


Fig. 14—Distortion vs. receiving level characteristics of narrow- and wide-band arrangements at 60 w.p.m. (23 d.p.s.).

tolerate the nearly same level change as the normal-band frequency-shift arrangement if 20 per cent distortion is the limit. When the low-pass filter of the wide-band frequency-shift arrangement had a high cut-off, the tolerance was somewhat greater due to the steeper wave front of the detected signals which rendered them less suceptible to bias caused by slight unbalance in the detector and d-c amplifier at levels below the cut-off of the limiter. The narrow-band two-source arrangement tolerated slightly less level change than the normal-band two-source arrangement with limiter, for the same reason.

## *Distortion at 120 Words per Minute*

When the speed was doubled the effects of level change on distortion were found to be as shown by Figs. 15 and 16, except that tests on the narrow-band two-source arrangement were omitted because of high distortion at

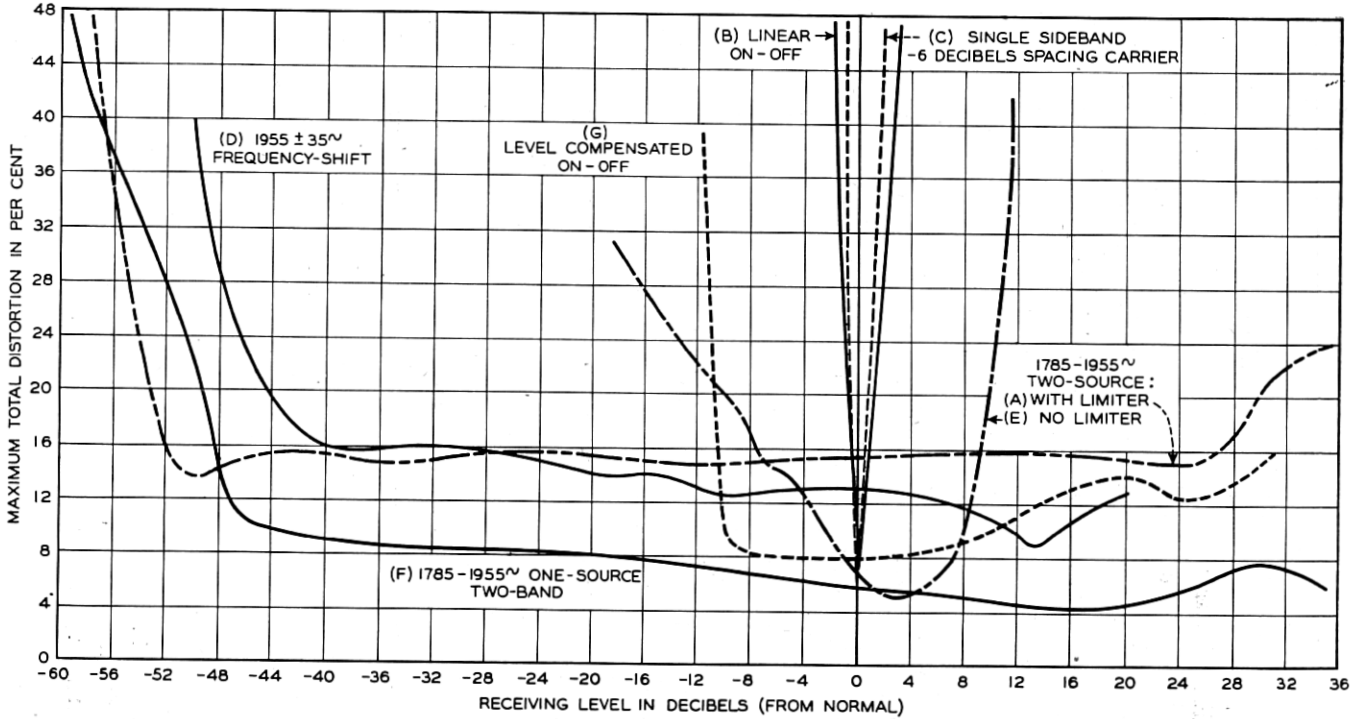


Fig. 15—Distortion vs. receiving level characteristics of normal-band arrangements at 120 w.p.m. (46 d.p.s.).

120 w.p.m. The arrangements tested were found to have about the same relative susceptibility to level changes at this speed as at 60 w.p.m.

The distortion shown in Figs. 13 and 15 consisted largely of bias for the arrangements having no limiter. The distortion shown in Figs. 13, 14, 15, and 16 for arrangements which had limiters rose faster than the absolute value of the bias as the level dropped below the cut-off of the limiter. This was partly due to extraneous noise in the laboratory apparatus.

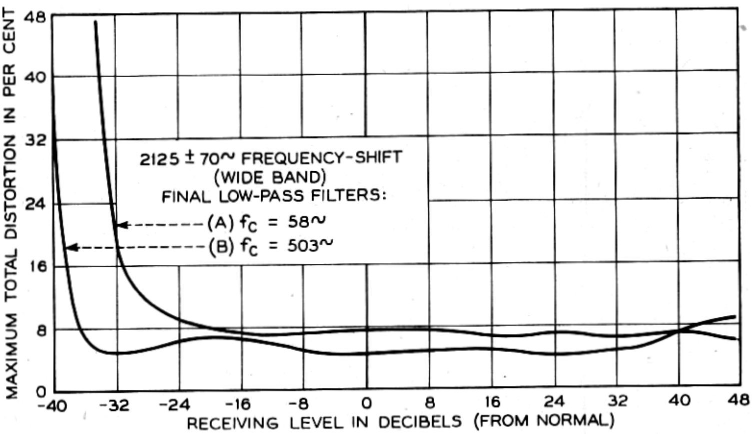


Fig. 16—Distortion vs. receiving level characteristics of wide-band frequency-shift arrangements at 120 w.p.m. (46 d.p.s.).

## *Selective Level Changes*

When frequency-shift, two-source, or one-source two-band arrangements are operated over a radio link, selective fading may occur which affects the marking and spacing frequencies by different amounts. Tests were made only on the two-source arrangements to measure the effect on distortion and bias of differences between received marking and spacing levels. This effect was simulated by setting the level of one of the two carrier oscillators at different values with respect to the other, and measuring the distortion and bias for each level setting. The distortion measurements are shown in Fig. 17 and are summarized below in Table I.

It may be seen from Fig. 17 that the distortion rose rather rapidly as the marking level was changed with respect to the spacing level and thus the distortion due to selective fading was not greatly reduced by the use of a limiter. The increase in distortion was mainly bias.

## Tests of Adjacent Channel Crossfire

In order to investigate the effects on distortion due to interference from adjacent channels, certain arrangements having the same loss characteristic were tested while upper and lower adjacent flanking channels were transmitting reversals produced by separate vibrating relays at roughly 23 d.p.s.

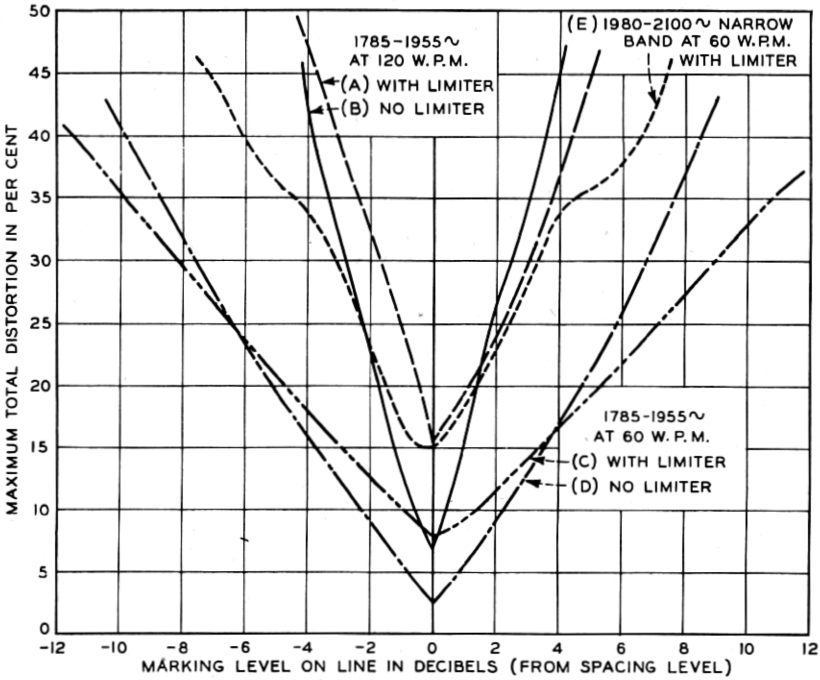


Fig. 17—Distortion vs. difference between marking and spacing level. Comparison of two-source arrangements.

TABLE I
COMPARISON OF TWO-SOURCE ARRANGEMENTS, EFFECT OF DIFFERENCE BETWEEN MARKING AND SPACING LEVELS

| Mid-band Frequencies | Limiter | Marking Level on Line—DB from Spacing Level | | | |
|---|---|---|---|---|---|
| | | For 10% Distortion | | For 20% Distortion | |
| | | At 60 W.P.M. | At 120 W.P.M. | At 60 W.P.M. | At 120 W.P.M. |
| 1785–1955~ | Out | −2.2 to +2.2 | −0.6 to +0.4 | −5.1 to +4.7 | −1.7 to +1.4 |
| 1785–1955~ | In | −1.0 to +1.4 | * | −4.7 to +5.3 | −0.4 to +1.0 |
| 1980–2100~ (narrow band) | In | * | failed | −1.5 to +1.3 | failed |

* Distortion exceeded 10%.

The distortion with and without the flanking channels operating and the difference in distortion are shown in the following tables, from which it is seen that the various arrangements tested ranked approximately in the following order as regards their insensitivity to flanking channel crossfire: linear on-off and two-source without limiter about the same, single sideband with no spacing carrier about the same as with −6 db spacing carrier, frequency-shift.

It may be observed from Tables II and III that the interchannel crossfire obtained for the linear on-off and two-source arrangements was small, due to the location of the carrier frequencies at the centers of the channel filter bands. The crossfire obtained for the single-sideband and frequency-shift methods given in Tables IV to VI was greater, due to the location of the marking or spacing frequencies near the edges of the channel filter bands.

TABLE II

1955-CYCLE LINEAR ON-OFF ARRANGEMENT, EFFECT OF OPERATING ADJACENT 1785-CYCLE AND 2125-CYCLE ON-OFF CHANNELS OVER LINE

| Signal Speed, W.P.M. | Maximum Total Distortion, Per Cent | | Increase in Distortion, Per Cent |
|---|---|---|---|
| | Flanking Channels Off | Flanking Channels On | |
| 100 | 6.2 | 6.2 | 0 |
| 120 | 7.8 | 8.6 | 0.8 |
| 140 | 18.0 | 20.0 | 2.0 |

TABLE III

1785 AND 1955-CYCLE TWO-SOURCE ARRANGEMENT WITHOUT LIMITER, EFFECT OF OPERATING ADJACENT 1615-CYCLE AND 2125-CYCLE CHANNELS OVER LINE

| Signal Speed, W.P.M. | Maximum Total Distortion, Per Cent | | Increase in Distortion, Per Cent |
|---|---|---|---|
| | Flanking Channels Off | Flanking Channels On | |
| 80 | 3.2 | 4.2 | 1.0 |
| 100 | 3.5 | 4.5 | 1.0 |
| 120 | 7.7 | 8.5 | 0.8 |
| 140 | 18.5 | 19.7 | 1.2 |

The other arrangements previously mentioned were not tested for flanking channel crossfire. The two-source arrangement with limiter and normal band width is thought to be no worse from this standpoint than that without limiter, since a limiter usually helps in discriminating against small spurious currents. From theoretical considerations the one-source two-band arrangement with limiter is thought to be better than the two-source arrangement without limiter, using the same channel filters and carrier frequencies. The narrow-band two-source arrangement had considerably sharper cut-off filters than the normal-band arrangement, thus causing greater attenuation of frequencies outside the desired band. Consequently the narrow-band two-source arrangement is thought to be no worse than the normal-band arrangement as far as interchannel interference is concerned. The wide-band frequency-shift arrangements are thought to be no worse than the normal-band frequency-shift arrangement from this standpoint, because of the greater separation between the sidebands of the adjacent channels. According to a study of the frequency spectra produced by abrupt or sinusoi-

TABLE IV

1998–CYCLE SINGLE-SIDEBAND ARRANGEMENT (NO SPACING CARRIER), EFFECT OF OPERATING ADJACENT 1828-CYCLE AND 2168-CYCLE SINGLE-SIDEBAND CHANNELS OVER LINE

| Signal Speed, W.P.M. | Maximum Total Distortion, Per Cent | | Increase in Distortion, Per Cent |
|---|---|---|---|
| | Flanking Channels Off | Flanking Channels On | |
| 100 | 7.1 | 7.9 | 0.8 |
| 120 | 12.0 | 14.9 | 2.9 |
| 140 | 18.5 | 22.7 | 4.2 |
| 160 | 21.0 | 25.5 | 4.5 |

TABLE V

1998-CYCLE SINGLE-SIDEBAND ARRANGEMENT (WITH SPACING CARRIER 6 DB BELOW MARKING CARRIER), EFFECT OF OPERATING ADJACENT 1828-CYCLE AND 2168-CYCLE SINGLE-SIDEBAND CHANNELS OVER LINE

| Signal Speed, W.P.M. | Maximum Total Distortion, Per Cent | | Increase in Distortion, Per Cent |
|---|---|---|---|
| | Flanking Channels Off | Flanking Channels On | |
| 100 | 5.7 | 9.2 | 3.5 |
| 120 | 8.5 | 12.0 | 3.5 |
| 140 | 14.0 | 17.7 | 3.7 |
| 160 | 14.0 | 18.2 | 4.2 |

TABLE VI

1955±35-CYCLE FREQUENCY-SHIFT ARRANGEMENT (WITH RELAY MODULATOR), EFFECT OF OPERATING ADJACENT 1785 ± 35-CYCLE AND 2125 ± 35-CYCLE FREQUENCY-SHIFT CHANNELS OVER LINE

| Signal Speed, W.P.M. | Maximum Total Distortion, Per Cent | | Increase in Distortion, Per Cent |
|---|---|---|---|
| | Flanking Channels Off | Flanking Channels On | |
| 60 | 2.5 | 6.0 | 3.5 |
| 100 | 5.5 | 11.0 | 5.5 |
| 120 | 11.0 | 19.0 | 8.0 |
| 140 | 20.0 | 28.0 | 8.0 |

dal frequency-shift arrangements during transmission of reversals[12], it appears that the sinusoidal shift is better than abrupt shift from the standpoint of interference between adjacent channels, when the sending channel filter does not sufficiently attenuate undesired sideband components. But

[12] Balth. van der Pol: "Frequency Modulation", *Proc. I. R. E.*, Vol. 18, No. 7, July 1930, pp. 1194–1205.

there is probably little use in complicating the modulating arrangement to produce sinusoidal shift, merely for the purpose of simplifying the sending filter.

In the multi-channel (on-off type) voice frequency carrier telegraph used in the Bell System plant, the carrier currents of the different channels have frequencies which are odd multiples of an 85-cycle base frequency, and the channel filters have corresponding midband frequencies. Even order modulation of these carrier currents, which occurs to a certain extent in the line repeaters of the system, results in the production of interfering frequencies which are even multiples of 85 cycles. These products fall midway between the pass bands of the receiving channel filters and the loss which they encounter in these filters greatly reduces their effect. In a telegraph system having this channel frequency arrangement, but designed to operate on a frequency-shift basis, with the carrier frequencies shifted over a large portion of the channel frequency bands, even order modulation products originating in the line repeaters would, to a much greater extent, lie in frequency ranges freely passed by the receiving filters; and the effect of such interference would be correspondingly greater than in the on-off system.

## Noise Tests

One way to judge the relative noise sensitivity of carrier telegraph arrangements is to subject each to measured amounts of noise on the line and then to compare the resulting signal distortions. Resistance or thermal noise was used in these tests because it is the most general kind of noise. It consists of a superposition of rapidly recurring random impulses, some of which may overlap. No tests were made using impulse noise such as caused by lightning, ignition, or sharp static, because it was thought that resistance noise tests would suffice. Impulse noise, when considered in a strict mathematical sense, consists of isolated pulses of very short duration and the component frequencies are so phased with respect to each other that their amplitudes add arithmetically at the instants of occurrence of the pulses. Atmospheric disturbances range all the way from isolated pulses to grinding static caused by dust storms which has characteristics approaching those of resistance noise. It is difficult to choose a representative type of impulse noise for testing. Another reason for not testing with impulse noise was that theoretical considerations[13] indicate there is not much difference in the advantage of frequency-shift over on-off methods whether the disturbance is of the impulse or resistance type.

In order to compare the sensitivities of the different arrangements to re-

[13] M. G. Crosby: "Frequency Modulation Noise Characteristics", Proc. I. R. E., Vol. XXV, No. 4, April 1937, pp. 472–514.

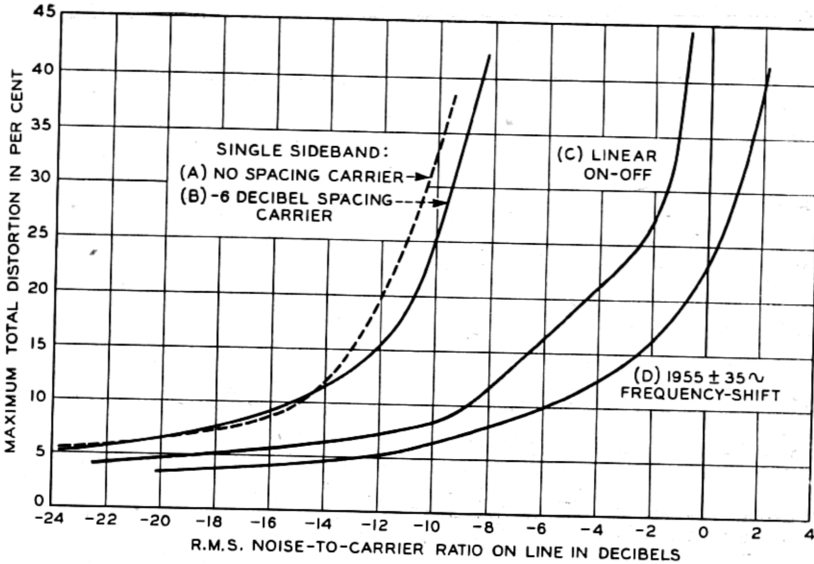


Fig. 18—Distortion vs. noise characteristics of single-sideband, linear on-off and frequency-shift arrangements at 60 w.p.m. (23 d.p.s.).

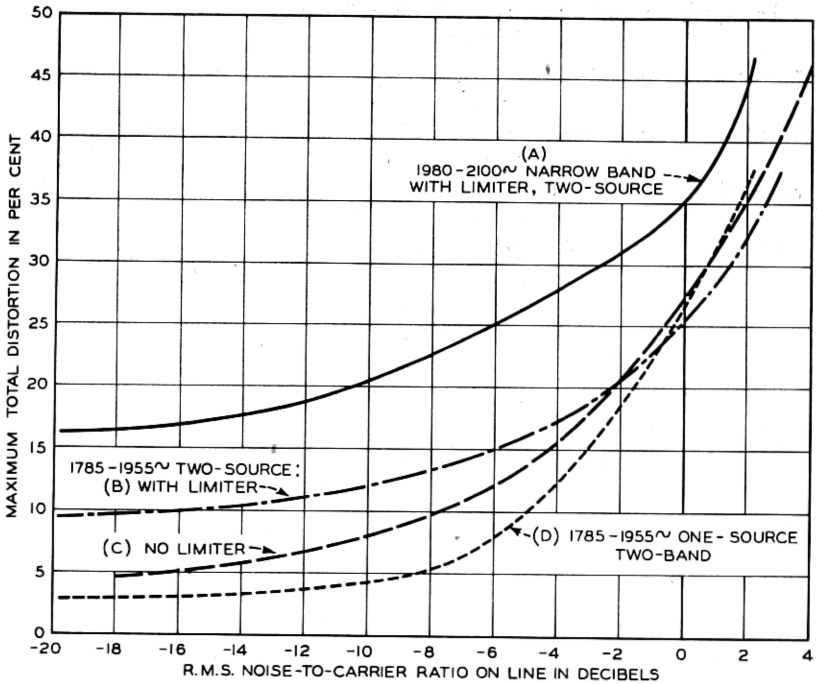


Fig. 19—Distortion vs. noise characteristics of two-band arrangements at 60 w.p.m. (23 d.p.s.).

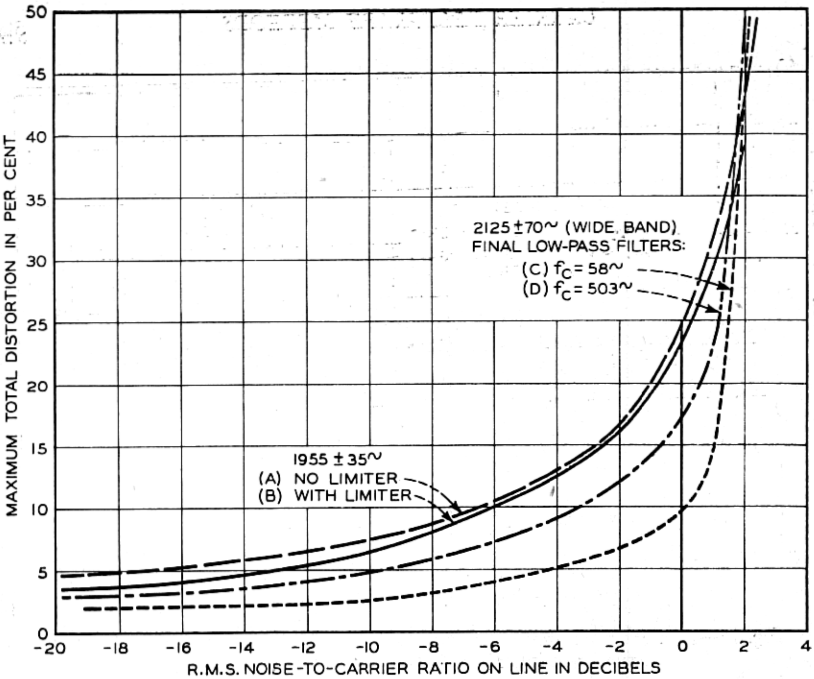


Fig. 20—Distortion vs. noise characteristics of frequency-shift arrangements at 60 w.p.m. (23 d.p.s.).

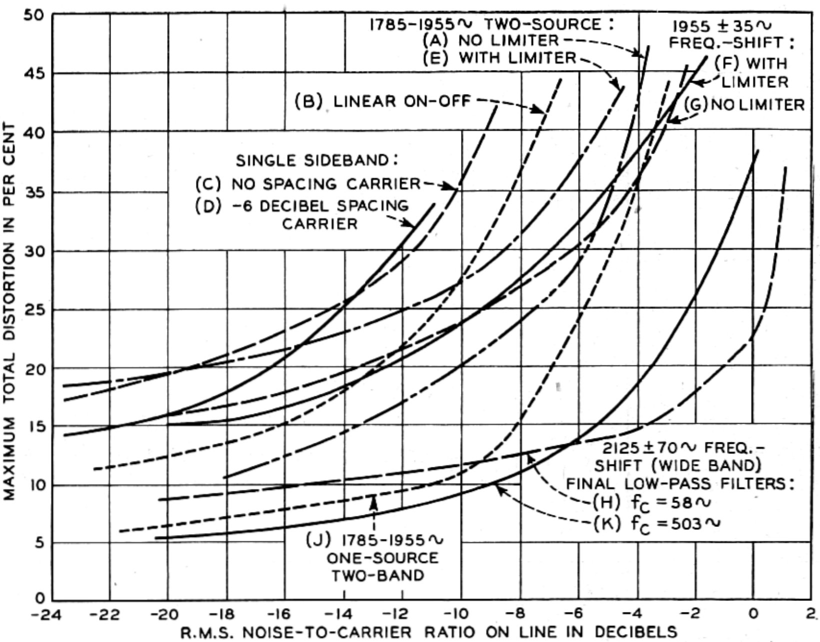


Fig. 21—Distortion vs. noise characteristics of various arrangements at 120 w.p.m. (46 d.p.s.).

sistance noise, the noise was introduced into the line through a symmetrical three-way pad, as previously mentioned. The marking carrier level at one input of the noise pad was kept at a constant value. The level of the noise current entering the other input of the noise pad was adjustable, and its r.m.s. value was measured with a thermocouple, permitting the computation of the r.m.s. noise-to-carrier ratio at the output of the three-way pad, since the loss through the pad was the same for both signal and noise. This ratio was used for abscissae in Figs. 18 to 21, inclusive, and the ordinates represent distortion for various arrangements. These curves are useful in comparing the relative noise sensitivities of the different arrangements, because the same noise source was used in all tests. The absolute noise sensitivities of the various arrangements were not known accurately because the band width of the noise source was not known exactly. The band width must have been about 3 kc. because the measured signal-to-noise power ratio of the on-off arrangement was 15 db better at the receiving filter output than on the line. Fifteen db corresponds to a power ratio of 31.6, which also should be the ratio of the band width of the noise source to the 95-cycle band width of the receiving filter. In comparing the various distortion vs. noise curves, one should note that certain arrangements have different amounts of distortion when noise is absent, which affects the comparison when noise is present.

### *Distortion at 60 Words per Minute*

According to Figs. 18, 19, and 20 the arrangements having the same loss characteristic rank in the following order as regards their insensitivity to resistance noise at 60 w.p.m. and 20 per cent distortion: frequency-shift with limiter, closely followed by frequency-shift without limiter, one-source two-band with limiter, two-source without limiter on a par with two-source with limiter, linear on-off, single-sideband with −6 db spacing carrier, and single-sideband with no spacing carrier. All the tests recorded in Figs. 18, 19, and 20 were made on arrangements having linear receiving detectors. No noise data were taken by the writers on the level compensated on-off arrangement. Measurements made by other Bell System engineers on a similar level compensated arrangement follow the general shape of curve C of Fig. 18 for the linear on-off arrangement, except for an average displacement of about one db to the left. It is not known whether the difference in performance of the level compensated on-off arrangement was due to the difference in detector characteristics or to a difference in measuring technique.

The frequency-shift arrangements tested were all less sensitive to noise than the on-off arrangement. When a limiter was not used, this difference was due mainly to differential recombination of the rectified output currents of the two branches of the discriminator[14]. When a limiter was used and the noise was small compared to the carrier current, the limiter theoretically should have reduced the noise-to-carrier ratio at least 3 db. Therefore, one might expect curves A and B of Fig. 20 to be separated horizontally at least 3 db in the region of low noise and to come together as the noise approaches zero. However, since curves A and B are fairly flat in the region of low noise, small errors in distortion measurement may have caused appreciable errors in the horizontal separation between the curves. When noise is not small compared to signal current, it is expected from theory that a limiter would give only a small reduction in distortion caused by noise on a frequency-shift arrangement. This appears to be verified experimentally by curves A and B of Fig. 20.

The main purpose of testing the wide-band frequency-shift arrangements was to compare their sensitivity to noise with that of the normal-band frequency-shift arrangement with limiter. According to Fig. 20, curves B and D, at 60 w.p.m. the tolerance to noise interference in the wide-band arrangement with low-pass filters having a cut-off frequency of about 503 cycles was 2.7 db greater than that in the normal-band arrangement at 10 per cent distortion and 1.3 db greater at 20 per cent distortion. This improvement was unexpected because the wider band admitted more noise. The improvement must have been due to the smaller distortion in the wide-band arrangement when no noise was present. The theoretical difference in noise tolerance between these two frequency-shift arrangements, which had a two-to-one ratio of frequency band width and of frequency swing, would have been 6 db at low noise levels if low-pass filters had been used at the detector outputs of the wide-band channel to cut off components in the detected current which are higher in frequency than those transmitted by the normal-band arrangement[13]. However, the low-pass filters used in the tests had a cut-off well above this value in order to permit signaling at very high speeds. Consequently, there was some unnecessary noise passed by these filters which accounts for an increase in noise tolerance of less than 6 db at 60 w.p.m.

In order to verify the fact that low cut-off low-pass filters improve the noise tolerance[13] of the wide-band frequency-shift arrangement, the 503-cycle cut-off filters were replaced by filters having a cut-off at about 58 cycles. According to Fig. 20, curves B and C, at 60 w.p.m. the tolerance to noise interference in the wide-band arrangements was then 6.1 db greater than in the normal-band arrangement at 10 per cent distortion, and 2 db greater at 20 per cent distortion.

[14] J. R. Carson and T. C. Fry: "Variable Frequency Electric Circuit Theory with Application to the Theory of Frequency Modulation", *Bell Sys. Tech. Jour.*, Vol. XVI, No. 4, October 1937, pp. 513–540.

The superiority of the two-source arrangements over the on-off arrangement may be accounted for by differential recombination of the detected waves, and by the greater amount of sideband power transmitted with two separate carriers.

As shown in Fig. 19, the tolerance to noise of the narrow-band two-source arrangement at 60 w.p.m. was less than that of the normal-band two-source arrangement with limiter because of the greater distortion obtained when operating at this speed without noise. Also, the two-source arrangement illustrated by curves B and C in Fig. 19 appears to have been made worse at low noise values by use of a limiter. Actually the limiter probably did reduce the noise power, but the improvement in distortion obtained thereby was greatly outweighed by the distortion increase which occurred without noise when the limiter was added, as explained above under the heading "Distortion vs. Speed Tests", and illustrated in curves C and D of Fig. 6.

The single-sideband arrangements were both more sensitive to noise than the on-off arrangement. In the case of the single-sideband arrangement with no spacing carrier the presence of quadrature[2] component increased the marking bias; and in order to have zero bias on reversals it was necessary to increase the d-c bias current in the receiving relay, which reduced the effective marking current and therefore made the arrangement more susceptible to interference occurring during the marking intervals. In the case of the single-sideband arrangement with −6 db spacing carrier the amount of sideband power transmitted was less than in the on-off arrangement and consequently noise was more troublesome.

### *Distortion at 120 Words per Minute*

Further tests were conducted at 120 w.p.m. on the arrangements having linear receiving detectors, and results are shown in Fig. 21. The increase in speed caused an increase in distortion on all arrangements at a given noise level, but the increase in speed has less effect on the single-sideband arrangements than on the others having the same loss characteristics, at medium and high noise levels. On account of the narrower sidebands transmitted on the two-source, normal-band frequency-shift, and on-off arrangements, an increase in speed was accompanied by a greater decrease in amplitude of received signal and therefore by a greater increase in noise-to-signal ratio than in the case of the single-sideband arrangements, each of which used a wider sideband. Consequently, at a given noise-to-signal ratio, the speed increase was accompanied by a greater distortion increase on the former group of arrangements than on the latter.

As was previously found at 60 w.p.m. the frequency-shift arrangement with limiter was less sensitive to noise than the arrangement without, when the noise was small. But the reduction in distortion was negligible, because the distortion was small in either case.

In Fig. 21, a comparison of curve F, applying to the normal-band frequency-shift arrangement with limiter, and curve K, applying to the wide-band frequency-shift arrangement with 503-cycle low-pass filter, shows that at 20 per cent distortion the increase in band width and frequency swing resulted in a 9 db improvement in noise-to-carrier ratio. This improvement may be explained on the same basis as the 1.3 db improvement obtained at 60 w.p.m. and was larger due to the higher distortion of the normal-band arrangement when operating at 120 w.p.m. When the cut-off frequency of the low-pass filter of the wide-band frequency-shift arrangement was changed from 503 cycles to 58 cycles, this improvement in noise-to-signal ratio was increased to 11.6 db. It is apparent that tolerance to noise was appreciably increased by this change of filters but, of course, this was accompanied by a reduction in maximum operating speed.

### *Noise-to-Signal Ratio at Receiving Relay*

Another method that was used to measure noise-to-signal ratio on the on-off and single-sideband arrangements was as follows: With the carrier turned off, the receiving gain was increased until the receiving relay just operated on occasional noise peaks. Then with the carrier on the line, and with the noise absent, the receiving gain was readjusted until the receiving relay again just operated. The difference in receiving gain in these two tests was called the noise-to-signal ratio at the receiving relay. When this method of measuring the noise-to-signal ratio was used it was found that the on-off and single-sideband arrangements had distortion vs. noise-to-carrier ratio characteristics similar to those given in Figs. 18 and 21. However, in order to express these characteristics correctly when substituting the words "at receiving relay" for "on line" in the scale of abscissae, it was found experimentally that it was necessary to shift the curves for the on-off arrangement 7 db to the left and to shift those for the single-sideband arrangement 4 db to the left, relative to their present positions in these figures. Such a change of scale was necessary because the noise-to-signal ratio was smaller at the output of the receiving filter than it was on the line.

## Summary Of Results

### *Explanation of Tables VII and VIII*

Tables VII and VIII have been prepared from the test data in order to compare the various arrangements for a given amount of distortion on each. Table VII describes certain of their properties for 10 per cent maximum total distortion. In column A (see bottom line of the table) are listed the different arrangements. In columns B and C are given the speeds in dots per second and words per minute respectively at which these arrangements operated with 10 per cent distortion. In taking these data all other variables such as noise and level or frequency changes were absent. (Similarly in the other columns only the variable mentioned was allowed to change.) Column D gives the order of preference for arrangements having the same channel filter loss characteristic (but not necessarily the same total frequency band) on the basis that the highest speed is the most desirable. These data apply when no flanking channels were present. The one-source two-band arrangement and the single-sideband arrangement with −6 db spacing carrier were the fastest of those having the same channel filter loss characteristic, as might be expected from the widths of the transmitted sidebands. However, for a given band width, the single-sideband arrangement with −6 db spacing carrier was the fastest. If frequency band width is of paramount importance, consideration should be limited to arrangements with the same band width, which would change the order of preference.

Columns E, F, and G apply, respectively, in place of columns B, C, and D, when flanking channels were in operation. According to column G, the single-sideband arrangement lost its place in preferential rating due to interference from the adjacent channels; and the on-off and two-source arrangements were the best, as might be expected, because their carriers were located at midband.

In column H are listed the ranges of levels over which the received signal power could vary without causing more than 10 per cent distortion. The order of preference listed in column I indicates that arrangements with limiters were the most stable.

In column L are listed the ranges of carrier frequency variations which could be tolerated without causing the distortion to exceed 10 per cent. In column M it is seen that the two-source arrangements performed better than the others when the mean frequency changed.

In column P the arrangements are rated on the basis of the resistance noise which could be tolerated on the line compared to the linear on-off arrangement. For example, the frequency-shift arrangement in item 1.11 could tolerate 2.7 db more noise than the on-off arrangement for 10 per cent distortion at 60 w.p.m. According to column Q the one-source two-band arrangement performed the best in this respect.

Table VIII is arranged similarly to Table VII except that the maximum total distortion is 20 per cent throughout, and additional data are given in columns J, K, N, O, R, and S to cover speed at 120 w.p.m.

## Discussion

It is believed that the circuit arrangements tested were reasonably representative of those commonly used in carrier telegraph practice, so that

### Table VII

Comparison of Different Arrangements when Maximum Distortion is 10% on Each. Unless Otherwise Stated: Channel Spacing 170 Cycles & Loss per Fig. 1, Curve A

Note: d.p.s. = dots per sec.; w.p.m. = words per min.; o.p. = order of preference based on performance. (In practise, consideration should also be given to economic advantages, and in this respect the on-off arrangements rank high.)

| Arrangement | Basis of Comparison | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed | | | | | | Flat Level Change | | Mean Carrier Freq. Change | | Signal-to-Noise Advantage on Line Compared with On-Off at 60 w.p.m. | |
| | No Flanking Channel | | | With Flanking Channels | | | Range at 60 w.p.m. | | Range at 60 w.p.m. | | | |
| | *d.p.s.* | *w.p.m.* | *o.p.* | *d.p.s.* | *w.p.m.* | *o.p.* | *db* | *o.p.* | *c.p.s.* | *o.p.* | *db* | *o.p.* |
| 1. *Arrangements with Same Band Width* | | | | | | | | | | | | |
| 1.1. Frequency-Shift, 1955 ± 35 Cycles, with Relay Modulator: | | | | | | | | | | | | |
| 1.11. With Current Limiter | 42 | 110 | 8 | 36 | 94 | 5 | >82 | 3 | 11.6 | 5 | +2.7 | 2 |
| 1.12. Without Current Limiter | 41 | 107 | 9 | | | | | | | | +2.2 | 3 |
| 1.2. Frequency-Shift, 1955 ± 35 Cycles, with Limiter, Diode Modulator: | | | | | | | | | | | | |
| 1.21. Abrupt Frequency Change | 44 | 115 | 7 | | | | | | | | | |
| 1.22. Sinusoidal Frequency Change | 39 | 103 | 11 | | | | | | | | | |
| 1.3. Linear On-Off, 1955 Cycles | 47 | 123 | 6 | 48 | 126 | 1 | 2.1 | 6 | 60 | 3 | 0 | 5 |
| 1.4. On-Off with 40B1 Detector, 1955 Cycles (No Level Compensator) | 48 | 127 | 4 | | | | | | | | | |
| 1.5. Level Compensated On-Off, 1955 Cycles | 50 | 132 | 3 | | | | >41 | 4 | 59 | 4 | | |
| 1.6. Single-Sideband, 1998 Cycles: | | | | | | | | | | | | |
| 1.61. No Spacing Carrier | 40 | 105 | 10 | 41 | 108 | 3 | | | | | −6.3 | 6 |
| 1.62. Spacing Carrier −6 db | 56 | 147 | 2 | 41 | 107 | 4 | 1.0 | 7 | 7 | 6 | −6.7 | 7 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2. *Arrangements with Different Band Widths* | | | | | | | | | | | | |
| 2.1. Two-Source, 1785 and 1955 Cycles: | | | | | | | | | | | | |
| 2.11. Without Current Limiter | 47 | 125 | 5 | 47 | 124 | 2 | 29 | 5 | 138 | 1 | +1.0 | 4 |
| 2.12. With Current Limiter | 33 | 87 | 12 | | | | 93 | 1 | 126 | 2 | −7.3 | 8 |
| 2.2. One-Source Two-Band, 1785 and 1955 Cycles, with Current Limiter | 59 | 155 | 1 | | | | >90 | 2 | 59 | 4 | +3.7 | 1 |
| 2.3. Two-Source, 1980 and 2100 Cycles, 120-Cycle Spacing (Narrow-Band), 2 Bands per Fig. 1, Curve C, with Current Limiter | (Distortion always greater than 10% at speeds greater than 60 W.P.M.) | | | | | | | | | | | |
| 2.4. Frequency-Shift, 2125 ± 70 Cycles, 340-Cycle Spacing (Wide-Band), with Limiter, Loss per Fig. 1, Curve B: | | | | | | | | | | | | |
| 2.41. With Final L.P. Filters, $f_c$ = 503 cycles | 66 | 173 | * | | | | >90 | * | 36 | * | +5.4 | * |
| 2.42. With Final L.P. Filters, $f_c$ = 58 cycles | 47 | 123 | * | | | | >81 | * | 20 | * | +8.8 | * |
| Column No.: A | B | C | D | E | F | G | H | I | L | M | P | Q |

* No order of preference given because the loss characteristics of these channels differ from those of the other channels.

## Table VIII

Comparison of Different Arrangements when Maximum Total Distortion Is 20% on Each. Unless Otherwise Stated: Channel Spacing 170 Cycles & Loss per Fig. 1, Curve A

Note: d.p.s. = dots per sec.; w.p.m. = words per min.; o.p. = order of preference based on performance. (In practise, consideration should also be given to economic advantages, and in this respect the on-off arrangements rank high.)

| Arrangement (same as Table VII) | Basis of Comparison | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Speed | | | | | | Flat Level Change | | | | Mean Carrier Frequency Change | | | | Signal-to-Noise Advantage on Line Compared with On-Off | | | |
| | No Flanking Channels | | | With Flanking Channels | | | At 60 w.p.m. | | At 120 w.p.m. | | At 60 w.p.m. | | At 120 w.p.m. | | At 60 w.p.m. | | At 120 w.p.m. | |
| | | | | | | | Range | | Range | | Range | | Range | | | | | |
| | *d.p.s.* | *w.p.m.* | *o.p.* | *d.p.s.* | *w.p.m.* | *o.p.* | *db* | *o.p.* | *db* | *o.p.* | *c.p.s.* | *o.p.* | *c.p.s.* | *o.p.* | *db* | *o.p.* | *db* | *o.p.* |
| 1. *Arrangements with Same Band Width* | | | | | | | | | | | | | | | | | | |
| 1.1. Freq.-Shift, 1955 ± 35 Cycles, Relay Modulator: | | | | | | | | | | | | | | | | | | |
| 1.11. With Current Limiter | 51 | 134 | 9 | 46 | 121 | 5 | >84 | 2 | >64 | 3 | 25 | 5 | 10.6 | 6 | +3.5 | 1 | +0.3 | 3 |
| 1.12. Without Current Limiter | 55 | 144 | 7 | | | | | | | | | | | | +3.3 | 2 | −0.5 | 5 |
| 1.2. Freq.-Shift, 1955 ± 35 Cycles, Diode Modulator: | | | | | | | | | | | | | | | | | | |
| 1.21. Abrupt Frequency Change | 57 | 151 | 4 | | | | | | | | | | | | | | | |
| 1.22. Sinusoidal Frequency Change | 50 | 131 | 10 | | | | | | | | | | | | | | | |
| 1.3. Linear On-Off, 1955 Cycles | 52 | 137 | 8 | 53 | 140 | 3 | 4.8 | 5 | 1.9 | 6 | 75 | 4 | 59 | 3 | 0 | 5 | 0 | 4 |
| 1.4. On-Off40B1 Detector, 1955 Cycles (No Level Compensator) | 56 | 148 | 5 | | | | | | | | | | | | | | | |
| 1.5. Level Compensated On-Off, 1955 Cycles | 56 | 147 | 5 | | | | >42 | 3 | >41 | 4 | 85 | 3 | 44 | 5 | | | | |
| 1.6. Single-Sideband, 1998 Cycles: | | | | | | | | | | | | | | | | | | |
| 1.61. No Spacing Carrier | 60 | 157 | 3 | 50 | 131 | 4 | | | | | | | | | −7.7 | 7 | −6.4 | 7 |
| 1.62. Spacing Carrier − 6 db | 72* | 190* | 1 | >68 | >180 | 1 | 2.5 | 6 | 1.3 | 7 | 12.3 | 6 | 6.7 | 7 | −6.4 | 6 | −3.7 | 6 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2. *Arrangements with Different Band Widths* | | | | | | | | | | | | | | | | | | |
| 2.1. Two-Source, 1785 & 1955 Cycles: | | | | | | | | | | | | | | | | | | |
| 2.11. Without Current Limiter...... | 55 | 146 | 6 | 54 | 141 | 2 | 37 | 4 | 19.7 | 5 | 145 | 1 | 117 | 1 | +2.0 | 4 | +2.8 | 2 |
| 2.12. With Current Limiter......... | 50 | 132 | 10 | | | | >100 | 1 | 83 | 2 | 145 | 1 | 102 | 2 | +2.0 | 4 | −6.2 | 8 |
| 2.2. One-Source, Two-Band, 1785 & 1955 Cycles, with Current Limiter..... | 66 | 175 | 2 | | | | >100 | 1 | >84 | 1 | 110 | 2 | 57 | 4 | +2.6 | 3 | +6.0 | 1 |
| 2.3. Two-Source, 1980 & 2100 Cycles, 120-Cycle Spacing (Narrow-Band), 2 Bands per Fig. 1, Curve C, with Current Limiter.................. | 29 | 76 | ** | | | | >94 | ** | fails | | 44 | | fails | | −6.2 | | fails | |
| 2.4. Frequency Shift, 2125 ± 70 Cycles, 340-Cycle Spacing (Wide-Band), with Current Limiter, Loss per Fig. 1, Curve B: | | | | | | | | | | | | | | | | | | |
| 2.41. Final L.P. Filt., $f_c = 503\sim$.... | >68 | >180 | ** | | | | >90 | ** | >89 | ** | 80 | ** | 37 | ** | +4.9 | ** | +9.3 | ** |
| 2.42. Final L.P. Filt., $f_c = 58\sim$.... | 52 | 138 | ** | | | | >84 | ** | >82 | ** | 42 | ** | 14 | ** | +5.6 | ** | +11.9 | ** |
| Column No.: A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S |

* Extrapolated.
** No order of preference given because the loss characteristics of these channels differ from those of the other channels.

fairly general conclusions are warranted. With the use of other types of filters, relays, etc., somewhat different results would doubtless be obtained.

Relative advantages and disadvantages of frequency-shift, on-off, and single-sideband methods of carrier telegraphy were deduced from measurements utilizing the same channel filters and covering a range of signalling speeds, noise, interference, and other variables.

A frequency-shift arrangement with amplitude limiter is substantially unaffected by non-selective level changes and relatively insensitive to noise currents. However, interfering currents from similar flanking channels are greater than when using the other methods. It has bias instability when the mean carrier frequency drifts. None of the arrangements tested had any compensation for drifting of the mean carrier frequency. However, it is known that automatic compensation for this may be obtained by various special methods not here described.

A channel using the on-off method is less sensitive to frequency drift, slightly faster for a given band width, and cheaper in terminal equipment than that using the frequency-shift method. The interfering currents from similar flanking channels using the on-off method are quite small. Weaknesses of the on-off method are greater sensitivity to noise and level changes. However, on good wire lines, when a level compensator[11] is used, these weaknesses are unimportant, and the on-off method is satisfactory. Of course, these weaknesses become important on radio circuits when noise is strong and when fades are too rapid or too severe to be overcome by the level compensator.

The greatest speed for a given band width is attainable by the single-sideband method. Unfortunately this method is poor from the standpoint of interchannel interference, is the most susceptible to noise, and, unless special compensating devices are used, is the most sensitive to carrier frequency drift and level changes.

Several arrangements were also investigated which utilized approximately double the band width of those mentioned in the preceding paragraph. Among these, the two-source method is the best of all the methods herein mentioned from the standpoint of insensitivity to changes in carrier frequency, whether or not a limiter is used. If a limiter is used this arrangement ranks well in its ability to withstand non-selective level changes. Two-source arrangements are sensitive to differences between the marking and spacing levels, but some advantage is obtained by the use of a limiter. The distortion vs. speed characteristic of the two-source method without limiter is about the same as that of the linear on-off method utilizing half the band width of the two-source method. As previously explained, the use of a limiter with this method causes distortion and materially reduces the maximum operating speed. From a noise standpoint the two-source arrangement without limiter has a slight advantage over the linear on-off method. When a limiter is used, the two-source arrangement is inferior to the linear on-off method due to the distortion inherent in this arrangement.

In the one-source two-band arrangement the limiter does not cause distortion, and a wider range of frequency components is transmitted than by the two-source method. For these reasons, the one-source two-band arrangement has a maximum working speed considerably higher than the two-source arrangement. The one-source two-band arrangement ranks close to the two-source method with limiter in its ability to withstand non-selective level changes, but its susceptibility to carrier frequency changes is greater.

A frequency-shift arrangement utilizing approximately the same band width as the two-source arrangement is found to have appreciably higher speed and less sensitivity to noise, but unless compensation is provided this frequency-shift arrangement is considerably more susceptible to carrier frequency changes. A further reduction in noise sensitivity may be obtained by the use of a low-pass filter at the detector output with a cut-off frequency low enough to limit the speed to that attainable with the normal-band frequency-shift arrangement.

Economic considerations should also be given due weight in selecting an optimum arrangement for a specific application. For example, the on-off method has been widely used on certain wire lines of the Bell System, because appreciable level changes are gradual and the lines are relatively quiet. For this application, the level compensated on-off method therefore gives satisfactory service with a minimum amount of apparatus, and the terminal arrangements are fairly simple and easy to maintain. On radio links subject to noise and fading, the more expensive frequency-shift and two-source methods have frequently been selected because of their greater reliability under such adverse conditions. The on-off and two-source arrangements have the advantage that common carrier generators (or oscillators) may be used for a number of channels.