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NRL REPORT 3861

FR-3861

OPTIMUM PARAMETERS FOR FSK RADIO TELEPRINTER SYSTEMS IN THE PRESENCE OF THERMAL NOISE

DECLASSIFIED: By authority of NRL Classification Change Notice No. 6-62 Dated 5 Mar 62
Drusda Jean Lambert 2028
Entered by NRL Code

DECLASSIFIED by NRL Contract Declassification Team
Date: 3 Feb 2017
Reviewer's name(s) H. Do, P. Hanna
Declassification authority: NAVY DECLASS GUIDE/NAVY DECLASS MANUAL, 11 DEC 2012

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OPTIMUM PARAMETERS FOR FSK RADIO TELEPRINTER SYSTEMS IN THE PRESENCE OF THERMAL NOISE

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September 19, 1951

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ABSTRACT

An experimental investigation has been undertaken to ascertain the optimum frequency shift, receiver i-f selectivity, and post-detection filter characteristics for FSK radio teleprinter operation in the presence of thermal noise. This work has been carried on in connection with "start-stop" teleprinters operating at a speed of 60 words-per-minute. A definite correlation between the total frequency shift and the receiver i-f selectivity characteristic has been found. Continuously decreasing the total frequency shift from a value of 960 cycles to 100 cycles causes a progressive increase in the quantity of thermal noise which can be tolerated before teleprinter errors appear. The advantage gained by decreasing the shift is relatively small, however. A sharp cut-off, "m-derived," 80-cycle, low-pass filter has been found to be the optimum type of post-detection filter.

PROBLEM STATUS

This is the final report on one phase of the problem; work on other phases continues.

AUTHORIZATION

NRL Problem R01-30R
RDB NE 020-445
BuShips Problem S-1507

Manuscript received for publication July 12, 1951

OPTIMUM PARAMETERS FOR FSK RADIO TELEPRINTER SYSTEMS IN THE PRESENCE OF THERMAL NOISE

INTRODUCTION

Frequency shift keyed (FSK) systems have significant advantages over systems employing other forms of modulation for automatic radio teleprinter operation. The parameters of FSK systems which are now in use have been determined from limited factual information. With the increased use and importance of radio teleprinters for long-range communication purposes in the fleet, a need exists for optimizing the parameters to provide, if possible, an improvement in the operation of these systems. One of the difficulties encountered in long-range high-frequency radio communication is caused by atmospheric noise. Because atmospheric and thermal noise have essentially the same characteristics, a detailed study has been undertaken to determine the optimum frequency shift, receiver selectivity, and post-detection filter characteristics for FSK systems in the presence of thermal noise.

Analytical studies heretofore carried out [1,2,3] have indicated that for the comparatively small values of signal-to-noise ratios which produce satisfactory teleprinter operation, relatively narrow frequency shifts (that is, about 100 cycles) and correspondingly small modulation indexes (two or somewhat greater) should be superior to the wide frequency shifts (850 cycles) commonly used. In contrast to the procedures followed in the references cited, the present investigation was conducted on an experimental basis. This method was chosen after a review of the pertinent factors indicated that such a procedure would produce results more rapidly and with the likelihood of greater accuracy than would further analytical treatment, particularly where narrow shifts and comparatively small signal-to-noise ratios are concerned.

DESCRIPTION OF MEASURING EQUIPMENT

Figure 1 is a block diagram which shows the interconnections of the various components used in the experimental work. The description of these components is presented in a sequence related to the diagram.

(a) The TT Sender is a mechanically driven electrical switch which applies an interrupted d-c voltage to the FSK signal generator in accordance with a selected teleprinter character or standard message. A keying rate of 60 words-per-minute was used throughout the investigation.

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[1] Crosby, M. G., "Frequency Modulation Noise Characteristics," IRE, Proc. 25, 472-514 April 1937

[2] Watt, A. D., "Amplitude and Frequency Modulation for Facsimile Transmission and Other Applications," NRL Report R-3154 (Unclassified), September 1947

[3] Middleton, D., "On Theoretical Signal-To-Noise Ratios in F-M Receivers: A Comparison with Amplitude Modulation," J. Appl. Phys. 20, 334-351, April 1949

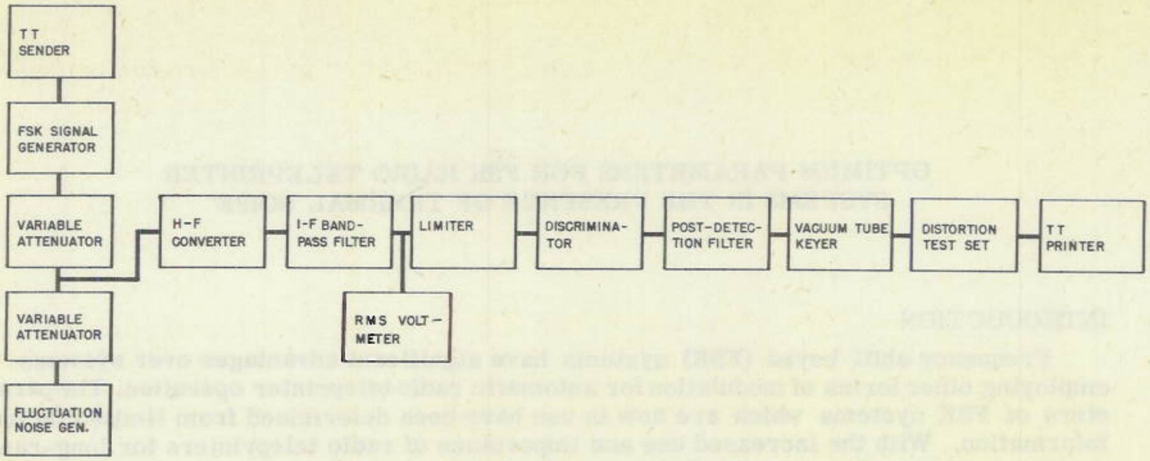

Figure 1 - Block diagram of equipment for measuring performance of FSK teleprinter system

(b) The signal generator delivers a 429-kilocycle signal which is frequency-shift keyed by the TT sender, with a total shift which may be varied over the range from 50 to 3000 cycles.[4]

(c) The frequency of the fluctuation noise generator is centered at 429 kilocycles and has a 15-kilocycle bandwidth between the 6-db attenuation points.

(d) The output levels of the signal and noise generators are controlled by attenuators. Signals from both sources are applied to a converter tube which heterodynes the 429-kilocycle signal to an intermediate frequency of 29.3 kilocycles.

(e) This i-f signal in turn, is applied to any one of a set of four band-pass filters which control the selectivity of the system before demodulation. These filters each have a center frequency of 29.3 kilocycles, but provide passbands of 1600, 920, 450, and 250 cycles, respectively. The attenuation characteristics are quasi-gaussian and have shape factors (bandwidth at 60 db/bandwidth at 6 db) which range from 3 for the 1600-cycle filter to 6 for the 250-cycle filter. Additional information on these filters appears in the Appendix.

(f) The rms voltmeter provided means for measuring the rms value of the signal or noise voltage applied to the limiter.

(g) The limiter circuitry is that employed in the Navy Model FRF Frequency Shift Receiver Converter Equipment and consists of resistance-coupled amplifiers, which accomplish limiting by driving its tubes either to saturation or cut-off. The passband of the limiter circuit is from 5 to 60 kilocycles.

(h) The discriminator is also the one used in the Model FRF Equipment. It has a linear frequency vs. output voltage characteristic, with a frequency separation of 3 kilocycles between the negative and positive output voltage peaks. The center frequency of the discriminator is the same as that of the i-f band-pass filters, that is, 29.3 kilocycles.

(i) A post-detection filter is placed between the discriminator output and keyer to eliminate the components of noise, having frequencies greater than are present in the

---
[4] The term "frequency-shift," as applied to the magnitude of shift, refers to the extreme value of the change in frequency between the "mark" and "space" elements of a teleprinter character.

teleprinter signal. Any one of five specially designed low-pass filters can be inserted. The characteristics of these filters are as follows:

(1) 400-cycle cut-off, "constant-K" type.
(2) 225-cycle cut-off, "m-derived" type.
(3) 125-cycle cut-off, "m-derived" type.
(4) 80-cycle cut-off, "m-derived" type.
(5) 40-cycle cut-off, "m-derived" type.

The "m-derived" filters have frequencies of "infinite" attenuation approximately equal to 1.25 times their respective cut-off frequencies. The minimum attenuation of any filter at the "infinite" attenuation frequency is 55 db; also the minimum attenuation of any filter in the stop band is 32 db. More detailed information regarding the group of filters is contained in the Appendix.

(j) After post-detection filtering, the signal is fed to the vacuum-tube keyer of the Model FRF Equipment. The keyer consists of a series of vacuum tubes which are driven to either cut-off or saturation and which supply the necessary current to actuate the teleprinter mechanism.

(k) Because determination of the accuracy of teleprinter copy by error count is time consuming, a Western Electric Model X75041 Telegraph Transmission Measuring Set is employed as a distortion test set to determine the quality of the circuit. Telegraph bias distortion can thereby be determined.

(l) The final link of the arrangement is the teleprinter, Model AN/FGC-11. This unit was in operation during various measurements and a constant check was kept on the correlation between the accuracy of teleprinter copy and the Distortion Test Set indication.

RESULTS

Optimum Frequency Shift to I-F Bandwidth Ratio

The data presented in Figure 2 were obtained by maintaining fixed values of frequency shift and varying the noise amplitude from a low level which did not appreciably affect the bias distortion up to a value sufficiently high to produce an appreciable number of teleprinter errors. During this series of measurements and in all subsequent ones, the level of the carrier was maintained constant at a value 20 db above the threshold of limiting. The process was carried out at each of the several values of shift indicated in Figure 2. An i-f bandwidth of 920 cycles was used. The carrier-to-noise data have been corrected to values corresponding to those that would prevail in using an input noise bandwidth of 1600 cycles. This correction has also been applied to all subsequent curves presented. Such a procedure – necessary to show properly the relation between measurements made with different i-f bandwidths – resulted because the determination of carrier and noise levels was made at the output terminals of the i-f band-pass filter where the noise voltage outside the passband was not indicated by the rms voltmeter.[5]

Figure 2 shows that when using a 920-cycle i-f bandwidth, more noise is required to produce the same degree of distortion for the 552-cycle shift than for shifts at any of the

[5] This correction, in db, is $20 \log_{10} \sqrt{1600 \text{ cycles}/\text{i-f bandwidth in cycles}}$, and is subtracted from the measured carrier-to-noise ratio when the i-f bandwidth is less than 1600 cycles.

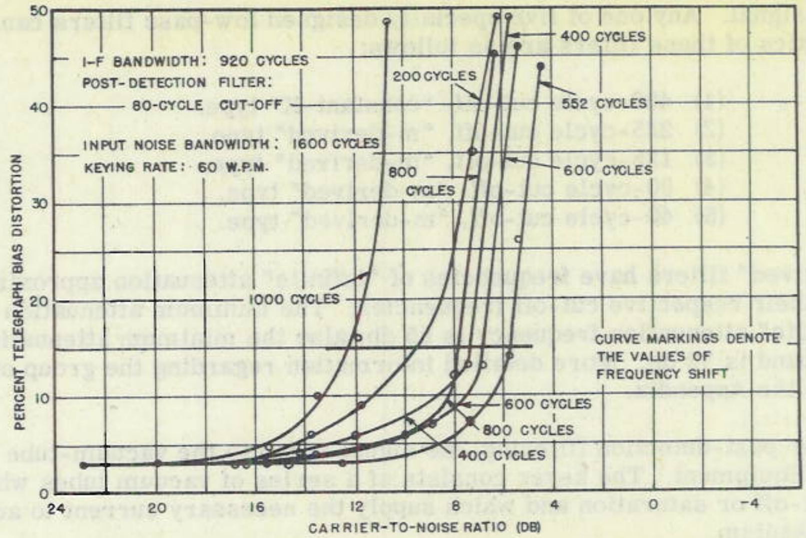

Figure 2 - Effect of carrier-to-noise ratio on bias distortion for various values of frequency shift

other values. The resulting ratio of total frequency shift to i-f bandwidth is 0.6 for this optimum shift. The foregoing procedure was repeated for the i-f filters having passbands of 1600, 450, and 250 cycles. The intersection points of the horizontal line which represents 15 percent bias distortion (Figure 2) with the curves applicable to shifts of various values are plotted in Figure 3 for each of the several i-f filters. Thus it is seen that the 0.6 ratio holds for all bandwidths and shifts considered.

For i-f bandwidths reduced to a value as low as 165 cycles, the 0.6 ratio is still expected to hold as the optimum although no experimental work with such a restricted value of bandwidth was undertaken. Instead, this deduction follows from information obtained by substituting pertinent values for "m" in the equation for the square-wave spectrum of an FSK signal as derived by Watt.[6] This equation is:

$$e\,\frac{2}{\pi}\left\{\frac{\sin(\frac{\pi}{2}m)}{m}\sin\omega_0 t + \frac{m}{m^2-n^2}\cos(\tfrac{\pi}{2}m)\left[\sin(\omega_0-n2\pi f_r)t-\sin(\omega_0+n2\pi f_r)t\right] + \frac{m}{m^2-n^2}\sin(\tfrac{\pi}{2}m)\left[\sin(\omega_0-n2\pi f_r)t+\sin(\omega_0+n2\pi f_r)t\right]\right\} \quad (1)$$

where $m = \dfrac{\text{total frequency shift in cycles}}{2f_r}$

n = harmonic number

ω_0 = angular velocity of carrier wave in radians per second

f_r = square-wave repetition frequency in cycles

6 Watt, op. cit. p. 15

e = instantaneous voltage

t = time in seconds.

For shifts of 150 cycles (250-cycle i-f bandwidth) and 100 cycles (165-cycle i-f bandwidth) the values of "m" values are substituted in the carrier amplitude factor, $\frac{\sin(\frac{\pi}{2}m)}{m}$; in the odd harmonic number amplitude factor, $\frac{m}{m^2-n^2}\cos(\frac{\pi}{2}m)$, and in the even harmonic number amplitude factor, $\frac{m}{m^2-n^2}\sin(\frac{\pi}{2}m)$, it is found that the relative rate of decrease of the amplitudes of the various spectral components is substantially the same for either value of "m." An i-f passband, which is equal to the total frequency shift divided by 0.6, will pass only the significant spectral components in either case. Thus the optimum ratio of frequency shift to i-f bandwidth should be 0.6 for i-f bandwidths as narrow as 165 cycles.

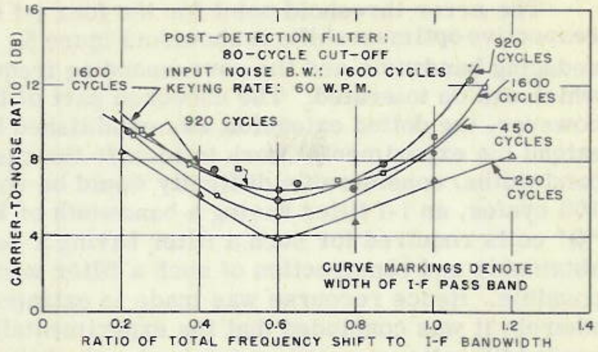

Figure 3 - Carrier-to-noise ratio necessary to produce 15% distortion with various shifts and i-f bandwidths

Effect of Shift on Carrier-to-Noise Ratio

Figure 4 is a series of curves which shows the results obtained by employing the optimum shift for each of the four i-f band-pass filters. As indicated by theory obtained from the previously cited references, reduction of i-f bandwidth and the corresponding frequency shift results in an improvement in the tolerance for noise. The degree of improvement is not large, however, there being only a 2.7-db gain for the 150-cycle shift, as compared with 960-cycle shift, at the error threshold points for teleprinter operation (35 percent bias distortion).

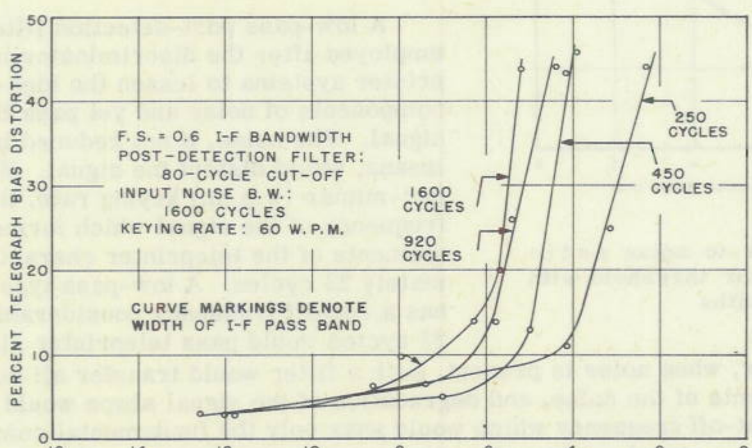

Figure 4 Effect of carrier-to-noise ratio on bias distortion at various i-f bandwidths

The error threshold point for the four i-f band-pass filters when used with their respective optimum shifts is shown in Figure 5. The resulting curve illustrates the effect of reducing bandwidth and the corresponding frequency shift on the carrier-to-noise ratio which can be tolerated. The unbroken part of the curve was determined experimentally; however, the dotted extension was established by extrapolation. Were an effort made to extend the experimental work to include the case of narrower shifts with appropriate i-f bandwidths, considerable difficulty would be encountered. For example, to use a shift of 100 cycles, an i-f filter having a bandwidth of 165 cycles would be needed. The very high "Q" coils required for such a filter having a center frequency of 29.3 kilocycles are hardly obtainable and construction of such a filter would be difficult and time consuming, even if possible. Hence recourse was made to extrapolation. An extension of earlier reasoning, wherein it was concluded that the experimentally determined optimum frequency shift to i-f bandwidth ratio was still maintained with shifts as low as 100 cycles, leads to the conclusion that the experimental portion of the curve in Figure 5 may be extrapolated downward smoothly as far as is shown. The results in the extrapolated region are only approximate, but since the range of extension is not large, the error incurred should be reasonably small. The superiority indicated for the 100-cycle shift over the 960-cycle value is 3.9 db.

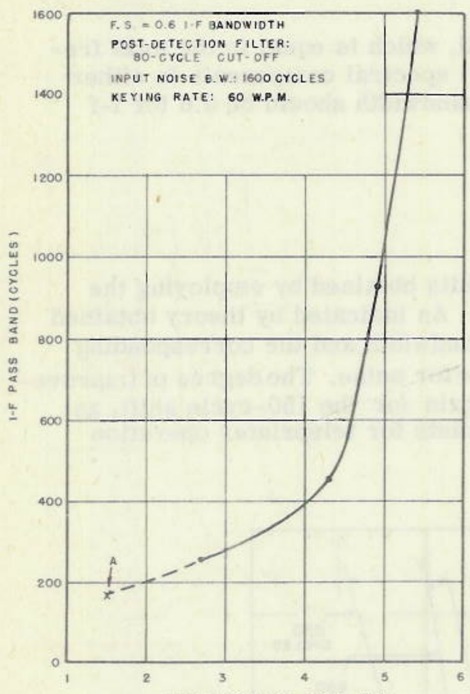

Figure 5 - Carrier-to-noise ratio necessary for error threshold with various i-f bandwidths

Were an effort made to further extend the curve in Figure 5, it would be anticipated that the minimum carrier-to-noise ratio would occur at a point somewhat to the left of the extrapolated point A. The curve would then reverse back to the right and the carrier-to-noise ratio would increase with a further decrease in i-f bandwidth and corresponding frequency shift. This condition is expected because the carrier-to-noise ratio must approach infinity for a finite amount of intelligence to be transmitted as the frequency shift approaches zero.

Optimum Post-Detection Filter Cut-Off Frequency

A low-pass post-detection filter is commonly employed after the discriminator in radio teleprinter systems to lessen the high-frequency components of noise and yet pass the teleprinter signal. The noise, if not reduced in level by such means, would distort the signal. With a 60 word-per-minute (w.p.m.) keying rate, the square-wave frequency of the signal which forms the various elements of the teleprinter characters is approximately 23 cycles. A low-pass type of filter which has a cut-off frequency considerably greater than 23 cycles would pass teleprinter signals satisfactorily. However, when noise is present, such a filter would transfer all but the highest frequency components of the noise, and degradation of the signal shape would occur. A filter of a lower cut-off frequency which would pass only the fundamental component of the 23-cycle square wave signal would reduce the noise, but would also cause rounding of the teleprinter signal shapes which in turn would cause a gradual transition from the stop pulse to the following start pulse of the teleprinter characters. This transition in the boundary between the stop and start pulses would cause an uncertainty to prevail as to the starting time for the teleprinter characters. There would then result considerable bias distortion even without noise, and with the addition of noise, the effect would be aggravated. Between these two extremes of cut-off frequency for a post-detection filter exists a preferred cut-off frequency which would optimize the effects of noise reduction and transmission of the signal. The optimum cut-off frequency is the one that permits error-free teleprinter operation with a minimum receiver input carrier-to-noise ratio. In this investigation, an experimental study was made of the relationship between post-detection filter cut-off frequency and teleprinter performance.

Figure 6 shows the effect of post-detection filters of various cut-off frequencies when used with an i-f bandwidth of 1600 cycles and a frequency shift of 960 cycles. It is noted that decreasing the cut-off frequency from 400 to 80 cycles provides an appreciable improvement. The 80-cycle filter passes the third harmonic of the 23-cycle square wave, but eliminates higher order components. This filter has a 4.7-db factor of superiority over the 400-cycle filter. The 40-cycle filter, however, which passes only the fundamental component of the teleprinter signal, is inferior to the 80-cycle filter, since a greater distortion of the signal is caused.

As the i-f bandwidth is decreased to 920 cycles and the frequency shift to 552 cycles, the performance of the 40-cycle filter more nearly approaches that of the 80-cycle filter. This is illustrated in Figure 7 where it is noted that the 80-cycle filter has only a 0.9-db superiority over the 40-cycle filter at the 35 percent distortion point. The superiority was 1.8 db when the 1600-cycle i-f filter and the 960-cycle shift were employed, as may be noted by reference to Figure 6.

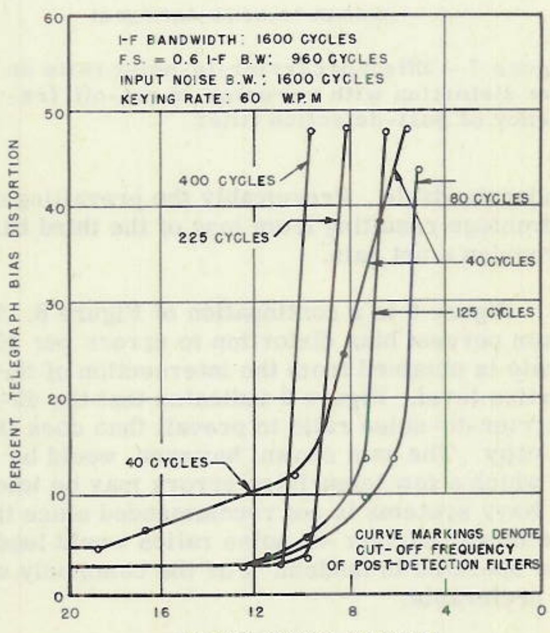

Figure 6 - Effect of carrier-to-noise ratio on bias distortion with variation in cut-off frequency of post-detection filter

Figure 8 presents the information obtained from the use of a 250-cycle i-f bandwidth and 150-cycle frequency shift. With these conditions, the error threshold occurs at the same carrier-to-noise ratio with both the 80- and 40-cycle filters, and the performance of the two filters is nearly equal. This further improvement shown by the 40-cycle filter is due to the fact that when narrow i-f bandwidths and small shifts are employed, it is advantageous to reject as high a fraction of noise as possible even though there occurs an appreciable rounding of the square-shaped teleprinter signal elements. For example, with the 1600-cycle i-f bandwidth, the noise rejection bands of 1600-80, or 1520 cycles, and 1600-40, or 1560 cycles, are nearly equal when compared with the total noise band of 1600 cycles. With the 250-cycle i-f passband, however, the noise rejection band with the 80-cycle filter is 250-80, or 170 cycles, and with the 40-cycle filter, 250-40, or 210 cycles. When these two noise rejection bands are compared with the total i-f bandwidth of 250 cycles, the advantage obtained by use of the 40-cycle filter is

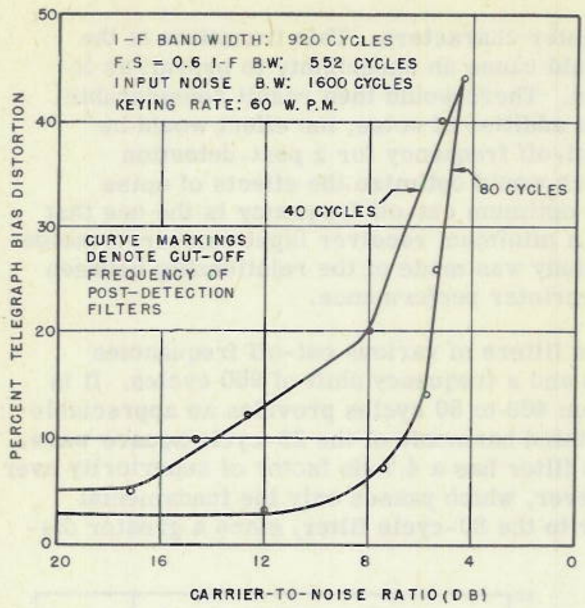

Figure 7 - Effect of carrier-to-noise ratio on bias distortion with variation in cut-off frequency of post-detection filter

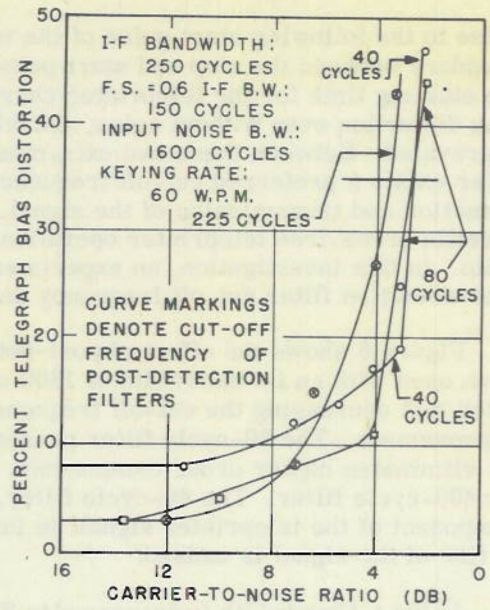

Figure 8 - Effect of carrier-to-noise ratio on bias distortion with variation in cut-off frequency of post-detection filter

understandable. Presumably the prevailing over-all condition tends to outweigh the disadvantage resulting from loss of the third harmonic component of the signal, and thus provides a net gain.

Figure 9 is a continuation of Figure 8. The ordinate scale has been changed, however, from percent bias distortion to errors per 100 lines of teleprinter copy. The origin of this scale is obtained from the intersection of the curves in Figure 8 with the 35 percent distortion level. Figure 9 indicates that the 40-cycle post-detection filter permits a smaller carrier-to-noise ratio to prevail than does the 80-cycle filter for an equal degree of error in copy. The gain shown, however, would be of interest only in connection with systems in which a few teleprinter errors may be tolerated. However, the use of the 40-cycle filter in Navy systems is not recommended since the relatively high distortions resulting at the larger carrier-to-noise ratios would lead to difficulty when several teleprinter stations are operated in tandem. For the commonly used shift of 850 cycles, the 80-cycle filter is preferable.

DISCUSSION

This investigation does not necessarily indicate that an advantage would result from the use of the comparatively narrow i-f bandwidths and correspondingly small frequency shifts found helpful in mitigating thermal noise. Other factors must be considered in determining the optimum parameters for these systems. Among them are the effects of impulse noise and of co-channel and adjacent-channel operation on the system parameters. Also, the frequency stability requirements, which the use of small shifts and i-f bandwidths will impose upon the transmitter and receiver, are difficult to meet in equipments of continuous frequency coverage, except where highly complex apparatus is acceptable.

Reducing the frequency shift is also likely to cause a greater susceptibility of selective fading because comparatively large values of modulation indexes inherently produce some degree of frequency diversity. This can be explained by the fact that the spectral components for a signal with a large modulation index are numerous and have relatively small amplitudes. When selective fading is present, it is probable that the number of components which are affected at any one instant will not be sufficient to cause an interruption of teleprinter operation. Experiments performed between Bolinas, California, and Riverhead, New York have demonstrated that multipath distortion is more troublesome when the frequency shift is reduced.[7]

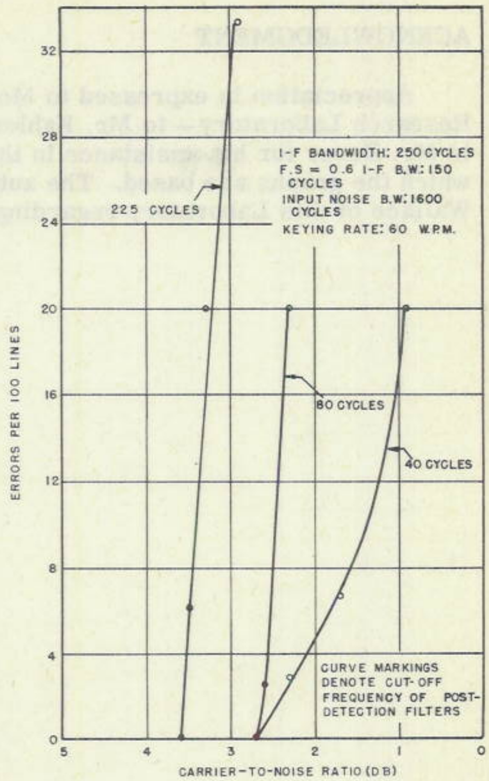

Figure 9 - Effect of carrier-to-noise ratio on teleprinter error with variation in cut-off frequency of post-detection filter

CONCLUSIONS

An optimum ratio prevails between transmitter frequency shift and receiver i-f bandwidth for radio teleprinter systems operating in the presence of thermal noise. This ratio is 0.6 for values of shift from 960 to 100 cycles in the case of "start-stop" teleprinters functioning at a speed of 60 words-per-minute.

An improvement in the quantity of noise an FSK system can tolerate is effected as the frequency shift is reduced. The gain resulting is relatively small, however, as only a 2.7-db advantage is achieved by reducing the shift from 960 to 150 cycles, or a 3.9-db improvement over the wider shift is attained by restricting the shift to 100 cycles. For the commonly used 850-cycle shift, the improvement achieved through employment of either of the narrow shifts is essentially the same as that noted over the 960-cycle shift.

Even though some advantage in the mitigation of thermal noise effects is shown by the employment of shifts appreciably less than the presently used 850-cycle value, it does not necessarily follow that an appreciably smaller value of shift should be adopted. The influence of impulse noise, co-channel and adjacent-channel operation, wave propagation, and requirements for extremely high-order frequency stability, on the degree of shift and the i-f bandwidth have not yet been taken into account.

The optimum cut-off frequency for a post-detection filter is 80 cycles for systems using shifts greater than 150 cycles.

The work herein contained serves as one definite step toward optimizing the parameters of FSK automatic teleprinters. The other factors involved require similarly detailed considerations.

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[7] Peterson, H. O., Atwood, John B., Goldstine, H. E., Harvell, Grant E., and Schock, Robert E., "Observations and Comparisons on Radio Telegraph Signaling by Frequency Shift and On-Off Keying," RCA Rev, VII, 11-31, March 1946

ACKNOWLEDGMENT

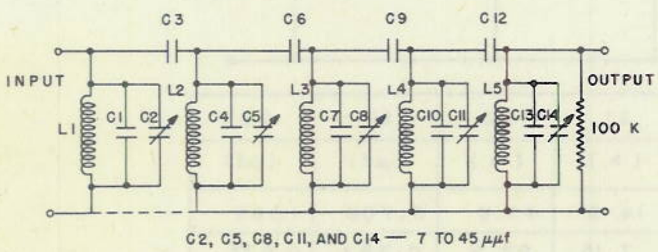
Appreciation is expressed to Messrs. F. C. Kahler and Doyle A. Dever, of the Naval Research Laboratory – to Mr. Kahler for his suggestions in the execution of the work and to Mr. Dever for his assistance in the experimental phase and his many computations on which the graphs are based. The author also appreciates the suggestions of Mr. J. D. Wallace of this Laboratory regarding compilation and preparation of this report.

***

APPENDIX
Filter Characteristics

I-F BAND-PASS FILTERS

Four i-f band-pass filters (Figure 10) were employed in the investigation. The filters are composed of five sections of a three-element shunt type, connected in cascade. The attenuation curves are shown in Figure 11. Because the shapes are quasi-gaussian, a linear phase shift characteristic is obtained. When an attempt is made to obtain general conclusions from a variable frequency shift-bandwidth study, the phase shift of the i-f filters must be considered as one of the important parameters if it is neither constant nor linear. For this reason, the quasi-gaussian type was selected rather that a quasi-rectangular type, which provides a steeper attenuation-frequency slope with consequent irregularities and nonlinear phase shift.



PASS BAND (CYCLES)	L1, L5 (mh)	L2, L3, L4 (mh)	C1, C13 (μμf)	C4, C7, C10 (μμf)	C3, C6, C9, C12 (μμf)
1600	31.86	15.93	845	1717	57
920	18.32	9.16	1529	3084	58
450	9.75	4.87	3020	6070	58
250	3.67	1.84	8000	16000	78

NOTES:

CENTER FREQUENCY: 29.3 kc

A LOW-IMPEDANCE PATH, AT 29.3 kc IS PROVIDED AT THE POINT INDICATED BY DOTTED LINE WHEN THE FILTER IS PLACED IN THE CIRCUIT. THIS PATH IS PROVIDED BY A TUBE ANODE SUPPLY BY-PASS CONDENSER

Figure 10 - I-F band-pass filters

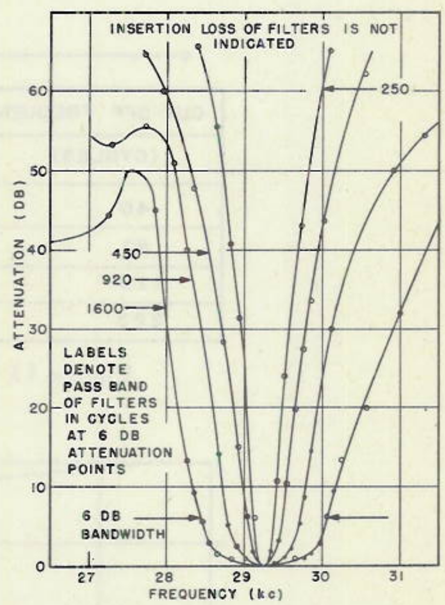


Figure 11 - Attenuation characteristics of i-f band-pass filters

POST-DETECTION FILTERS

Figure 12 is a schematic diagram of the 400-cycle cut-off, low-pass, post-detection filter employed in the Model FRF Equipment and used as one of the filters during this study. Figure 13 is a similar diagram of the "m-derived" types which were specially designed for this work. The attenuation curves of the filters are presented in Figure 14.

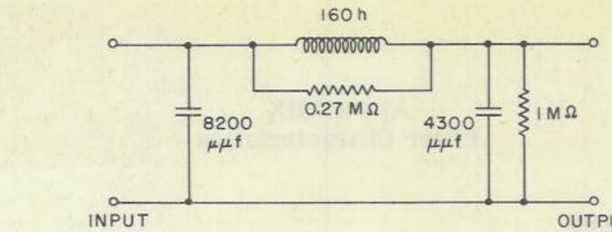
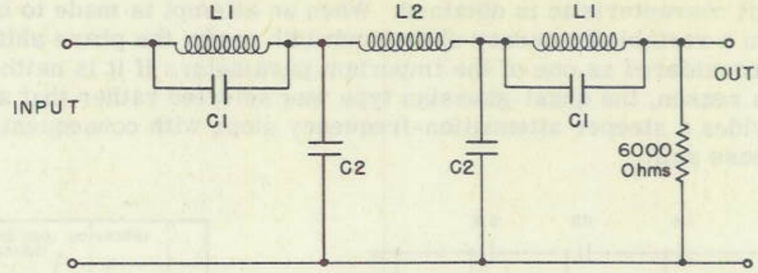


Figure 12 - 400-Cycle post-detection filter



CUT-OFF FREQUENCY (CYCLES)	L1 (h)	L2 (h)	C1 (μf)	C2 (μf)
40	14. 3	47.8	0.708	1.065
80	7. 15	23. 9	0. 354	0.532
125	4.55	15. 2	0. 226	0. 338
225	2.55	8. 5	0. 126	0. 188

Figure 13 - "M-Derived" post-detection filters

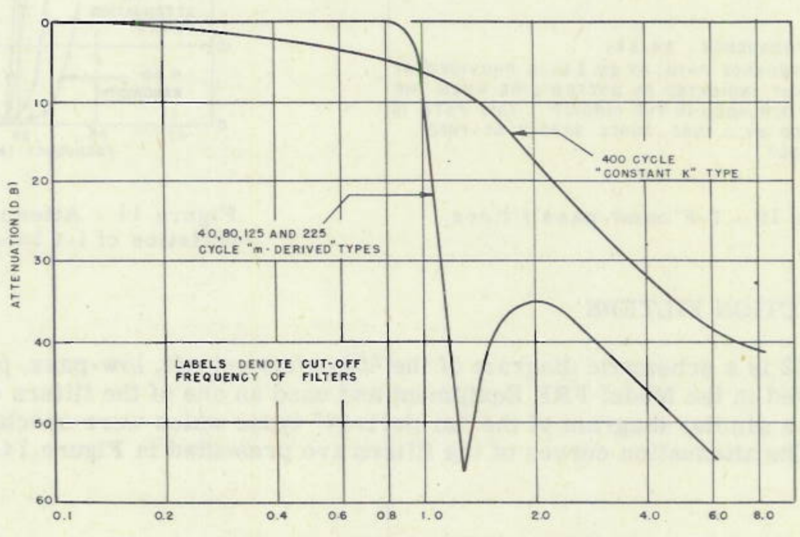


Figure 14 - Normalized characteristics of post-detection filters

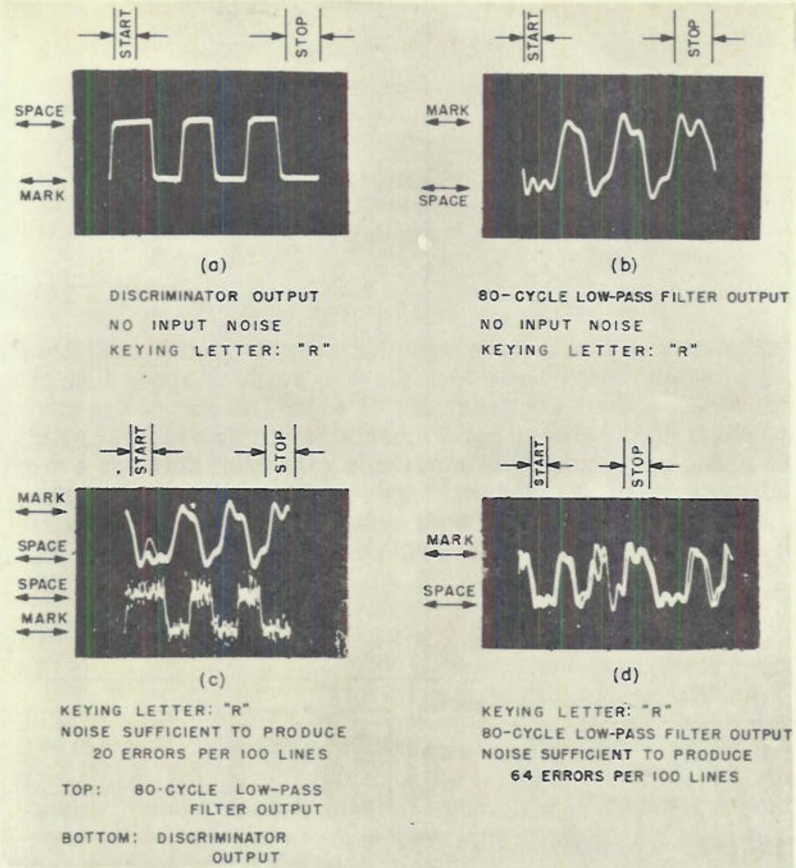


Figure 15 - Discriminator and 80-cycle post-detection filter outputs

Figure 15 shows several photographs of the discriminator and the 80-cycle post-detection filter outputs with various quantities of receiver input noise while teleprinter character "R" was being transmitted. The discriminator and low-pass filter outputs with no purposely introduced input noise are illustrated in Parts (a) and (b), respectively.

Part (c) shows how the high-frequency components of the noise are eliminated; however, the alteration in amplitude of one of the repeated traces of the start pulse of the filtered output is sufficient, even with the filtering, to produce possible error. Part (d) is a repeated trace with more noise applied than in Part (c). The bias distortion or time shift between traces is evident here.

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Figure 18 - Discriminator and 60-cycle post-detection filter outputs

Figure 18 shows several photographs of the discriminator and the 60-cycle post-detection filter outputs with various quantities of receiver input noise while teleprinter character "B" was being transmitted. The discriminator and low-pass filter outputs with no purposely introduced input noise are illustrated in Parts (a) and (b), respectively.

Part (c) shows how the high-frequency components of the noise are eliminated; however, the alteration in amplitude of one of the repeated traces and the start pulse of the filtered output is sufficient, even with the filtering, to produce possible error. Part (d) is a repeated trace with more noise applied than in Part (c). The bias distortion or time shift between traces is evident here.

[redacted]