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PERFORMANCE OF THE LINCOLN F9C RADIOTELETYPE SYSTEM

(Title: UNCLASSIFIED)

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ABSTRACT

The Lincoln F9C system is a NOMAC radioteletype system. It transmits a 10-kcps noise-like carrier through jamming for high-frequency fixed-point circuits. In this report, a brief description of the equipment and its operation leads to a discussion of the tests on an experimental transcontinental circuit. After time-diversity was incorporated, F9C performance gave an average anti-jamming advantage of some 17 db over standard FSK at an error rate of two wrong characters or less per line.

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PERFORMANCE OF THE LINCOLN F9C RADIOTELETYPE SYSTEM

I. INTRODUCTION

For several years, communication systems using noise-like carriers (NOMAC systems) have been under study at Lincoln Laboratory as having possible application against enemy jamming.[1,2,3] In July 1953, design and construction was begun on the F9C system, which embodies the basic NOMAC idea in an experimental system for anti-jamming use on high-frequency, point-to-point radioteletype circuits. Through the cooperation of the Signal Corps, facilities were provided for field testing the completed system on a transcontinental link between Davis, California and Deal, New Jersey. The equipment was completed and installed during July 1954, and tests were run from 12 August to 1 October 1954. At the end of this series of tests, several modifications were made. A second series of tests was then run from 1 February to 31 May 1955. As a result of these two series of tests on the experimental system, an operational prototype, the F9C-A, is currently being built for the Signal Corps by the Sylvania Electronic Defense Laboratory at Mountain View, California.

This report includes an explanation of the principles of operation of the F9C system, followed by a discussion of the test results and their significance. The description of system operation given in Sec. II begins with the equipment as it existed at the beginning of the first series of tests, and then takes up subsequent changes. Similarly, each of the test results (Sec. III) is treated chronologically.

II. FUNCTIONAL DESCRIPTION OF THE F9C SYSTEM[4]

A. The Over-all System

The Lincoln F9C system* is a stored-reference NOMAC** communication system. In the F9C system, a teletype signal is modulated onto a noise-like carrier at the transmitter and recovered at the receiver by crosscorrelating the arriving signal with a stored copy of the noise. The system is called a "stored reference" (as distinguished from a "transmitted reference") system, since the reference noise-like signal is stored independently at transmitter and receiver instead of being transmitted.†

For purposes of explanation, it is convenient to compare the F9C NOMAC system with a conventional Frequency-Shift Keying (FSK) radioteletype system. The difference is portrayed in Fig.1, where it is seen that the binary MARK-SPACE teletype data are transmitted for FSK as a sine wave whose frequency is one of two slightly different values, whereas, for the F9C system, the sine wave is replaced by a noise.

The upper expressions at the bottom of Fig.1 give the signal-to-jamming power ratio at the receiver output to the teletype printer for these two systems. It is this $(S/J)_o$ that specifies the frequency of errors in the resulting teletype copy. $(S/J)_i$ is the signal-to-jamming

*UNCLASSIFIED name.
**CONFIDENTIAL name. The word NOMAC stands for NOise Modulation And Correlation.
†A transmitted-reference NOMAC equipment called the Lincoln P9D system was built and field-tested in 1952. This type of system was abandoned in favor of the stored-reference type because of the greater resistance of the latter to jamming. (See footnote on p.3.)

ratio at the receiver input, W is the effective bandwidth of the signal, and T is the symbol (or baud) duration. These expressions assume that the enemy is using his jamming power in a sensible way. In the case of FSK, this means that he will concentrate his power at the MARK or SPACE frequencies. For a stored-reference NOMAC system, it turns out to be substantially immaterial how he distributes his power in the signal passband; the output signal-to-jamming ratio will still be TW times the input signal-to-jamming, whether he sends in the receiver bandwidth W a sine wave, two sine waves, a noise, etc.[5] The only way in which the jamming can be more effective than this for a given power is for the jamming signal to have a waveform like that of the noise-like signal. That is, the jamming signal must correlate positively with one or the other of the possible genuine signals. If the legitimate and jamming signals have precisely the same waveform, then the output signal-to-jamming ratio is no better than that of FSK. This is made as difficult as possible by the complexity of the noise-like carrier. Then, if the enemy wants to interrupt the communication by jamming (or insert a bogus message), he must somehow duplicate the noise-like carrier waveform. If, in addition, the noise-like signals for MARK and SPACE cannot be distinguished as such by the enemy, one has the additional advantage of cryptographic security of the message.

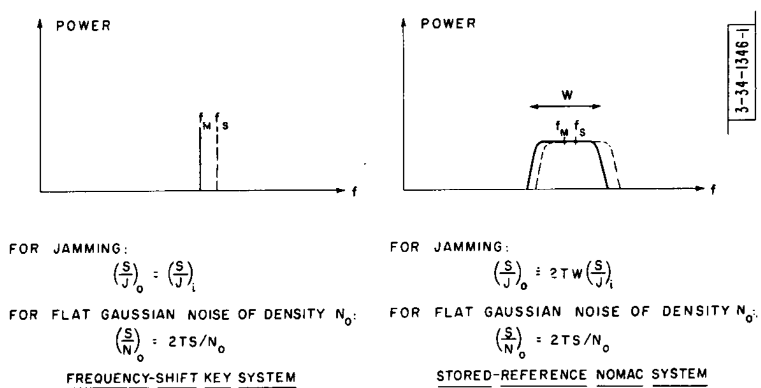

Fig. 1. Signal spectra of stored-reference NOMAC system and FSK system.

In the F9C system, a bandwidth W of 10 kcps is used, and the symbol duration T is 22 msec (60 words per minute) so that TW = 220, or 23 db. Thus we might anticipate from the expression in Fig. 1 that a 23-db advantage of F9C over FSK in the presence of jamming would be observed. Actually, multipath in the propagating medium deteriorates the performance of both systems. (The equations given in the figure do not take multipath into account.) As will appear later in the discussion, this deterioration is greater for F9C than for FSK.

Figure 2 depicts the essential circuit features of the F9C system (the version used in the first series of tests). At the transmitter, a bandpass noise is translated up in frequency by either f_M or f_S through the action of the balanced mixer which is supplied with frequency f_M when a MARK is to be transmitted, and with the slightly different frequency f_S for a SPACE. The filter serves two purposes: first, to eliminate the unwanted sideband resulting from the conversion, and second, to pass only the center of the frequency-shifted noise band, so that there remains almost no tell-tale shift of the band edges due to the frequency-shift keying. This shift, which is shown in Fig. 1, might otherwise allow the message to be discovered.

At the receiver, the incoming signal is converted back down from the operating frequency, and heterodyned in a mixer tube with a locally stored copy of the original noise. Since the difference between the stored signal and that arriving from the transmitter is that the latter has been frequency-shifted by either f_M or f_S, then conversely the mixer output must contain a tone of the same frequency, either f_M or f_S. From here on, the operation of the receiver is similar to that of an FSK system. A pair of narrow-band averaging filters, one tuned to f_M and the other to f_S, is used to detect which is present; that is, whether a MARK or SPACE was sent at the transmitter. The combined operation of heterodyning the received and reference signals and filtering the difference-frequency tone is equivalent to crosscorrelating them. The comparison device compares the envelopes of the two filter outputs and actuates the teletype printer accordingly.

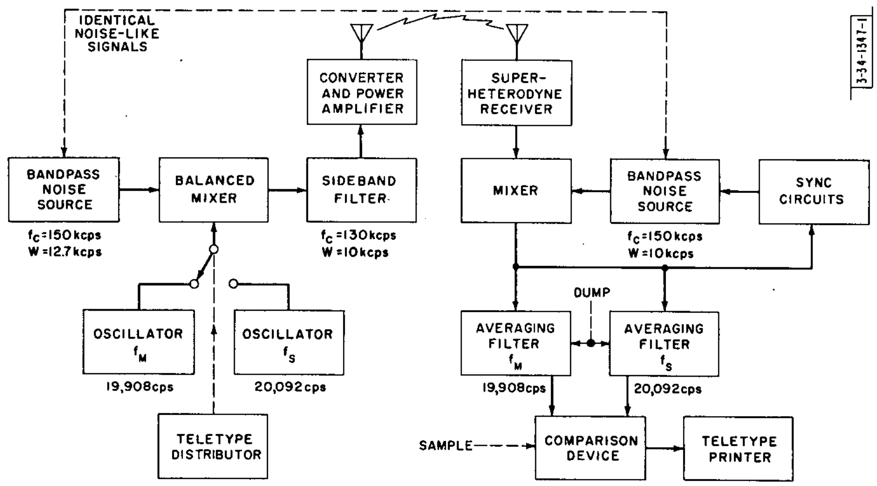

Fig.2. Simplified block diagram of the Lincoln F9C system.

It is clear that the operation of a NOMAC communication system depends on having the noise-like carrier available at both transmitter and receiver. For a stored-reference system, reproducible "noise-like" signals must be generated at transmitter and receiver and then synchronized.* This synchronization is necessary because the output signal-to-noise ratio drops off seriously if the incoming and stored signals are mistimed by more than about the reciprocal of the bandwidth (some 50 μsec for the F9C system). This quantity is the width of the central peak in the "correlation curve", the plot of output vs desynchronism between incoming and reference signals.

One obtains the anti-jamming capability described previously only at the expense of other factors: the system requires simultaneously a large bandwidth allocation and a low data rate, its efficiency against jamming depending on the ratio of just these two quantities. Furthermore, such a system needs considerable equipment complexity to deal with the two problems of signal storage and synchronization, as will appear shortly.

*It is clear why transmitting the reference signal largely eliminates the anti-jamming property. The enemy need only transmit two coherent signals (e.g., two sine waves) — one in the signal band, and the other in the reference band. If the frequency difference is properly adjusted, the beat note generated is indistinguishable from the legitimate one.

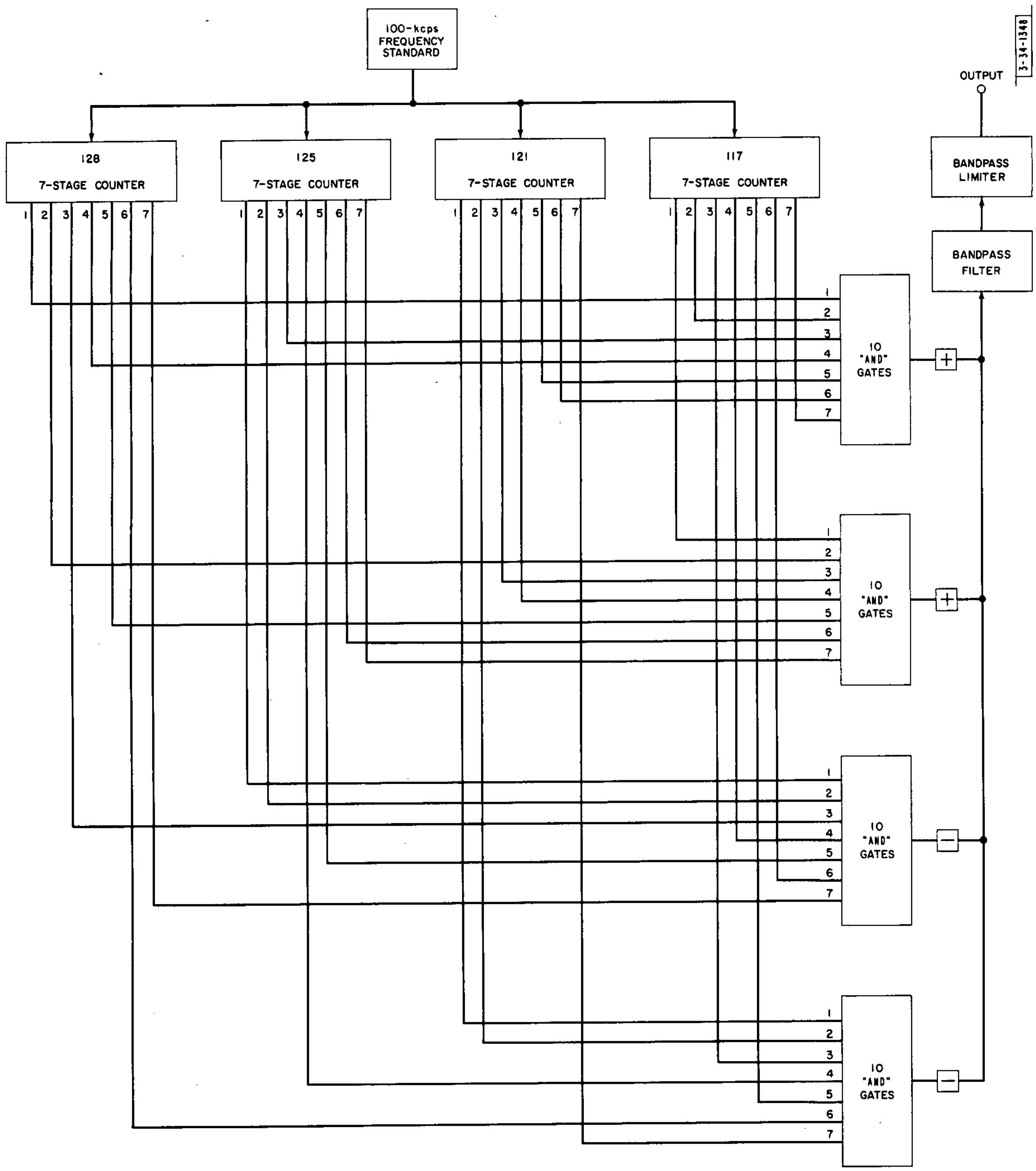

Fig.3(a). Generation of the noise-like signal as used in the first series of tests.

Because of these factors, the F9C system is envisioned to be held in reserve for occasions when jamming is severe. If one is not being jammed, there are several conventional systems that should perform as well, without such an expenditure of bandwidth, equipment, and specially trained operators. For example, the bottom set of equations of Fig. 1 shows that FSK and stored-reference NOMAC systems behave identically when the only interference is Gaussian noise with a flat spectrum. Much non-man-made interference tends to fall in this category.

B. The Noise Source

The synchronization problem requires (1) that the source have an extremely stable time scale, and (2) that this time scale be quickly readjustable. Therefore, a digital type of signal generator driven by a primary frequency standard seemed to be most suitable. The standard provides the stability, and the digital circuitry provides ease of retiming, both being not quite so convenient with most of the alternative storage schemes (magnetic tape, drums, cathode-ray tube and storage-tube devices, etc.)

Block diagrams of the generators of the noise-like signals are given in Fig. 3; Fig. 3(a) shows that used in the first series of field tests, and Fig. 3(b), that used in the second. In both cases, a pseudo-random train of positive and negative pulses is derived from the 100-kcps output of the frequency standard. The desired noise-like waveform is the bandpass signal resulting from shock-exciting the bandpass filter with this pulse train, and then limiting.

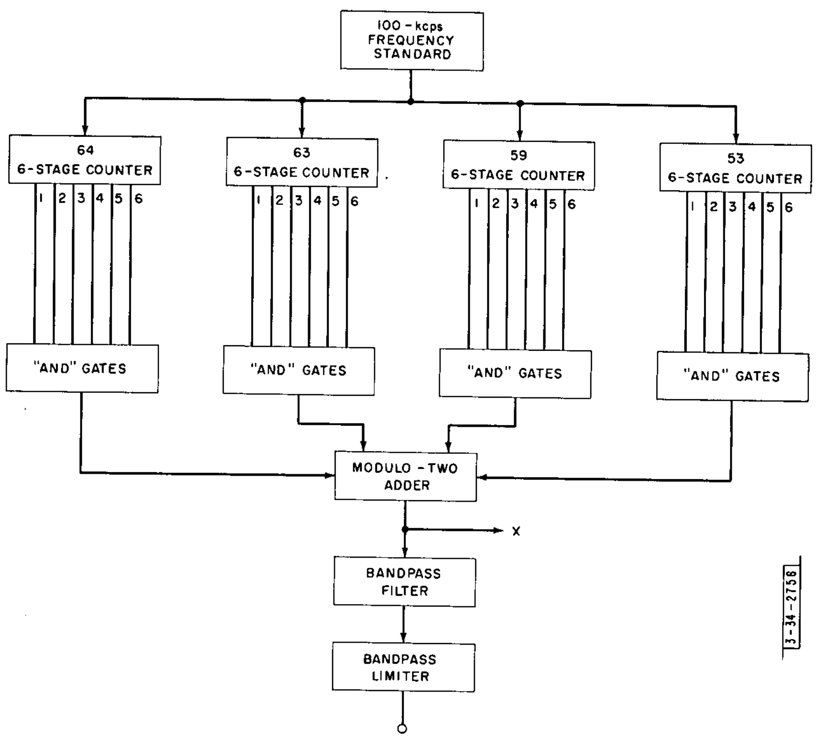

Fig. 3(b). Generation of the noise-like signal as used in the second series of tests.

In Fig.3(a), the exciting pulse train is derived as follows: Four seven-stage binary counters are driven simultaneously at the 100-kcps rate. The repetition periods of these counters are 128, 125, 121 and 117, respectively. The four counts being relatively prime to each other, the over-all repetition period of a given condition of all four counters simultaneously is the product of the counts times 10 μsec, or some 40 minutes. The $4 \times 7 = 28$ counter outputs are connected to 40 seven-digit AND gates in an arbitrary configuration as shown. At least one of the seven inputs is derived from each of the four counters. Half the AND gates supply positive pulses to the filter, and the other half supply negative pulses. For illustration, suppose that the first AND gate of the upper set of ten is set up so that an output will occur if each input voltage is up. Then an output pulse is fed to the bandpass filter every time there is an up output from the first and fourth stages of the 128 counter, the third stage of the 125 counter, the fifth and sixth stages of the 121 counter, and the second and seventh stages of the 117 counter. All the four AND gates are set to respond to independently chosen seven-digit binary numbers. These numbers, which constitute the "key" from which the noise-like carrier is generated, are set up on punched cards which are easily replaced when the key is to be changed.

The newer noise source design of Fig. 3(b) is the result of extensive theoretical work[6,7] initiated in the summer of 1954 while the equipment of Fig.3(a) was nearing completion. The newer system provides an improved correlation curve and greater security. It differs from the older one in four respects:

(1) Each of the four sets of AND gates is fed individually from a corresponding set of counters without the crossconnection used previously. (It was convenient to change the counts to 64, 63, 59 and 53, respectively), thus making the period about 2 minutes.*

(2) The number of AND gates in each set is increased to the point where, at the output of each set, the voltage is in the up state roughly half the time.

(3) The four outputs of the four sets of AND gates are added modulo-two; that is, the output voltage of the modulo-two adder is up when none, just two or all four of the inputs are up, and down for just one or just three inputs up.

(4) Positive or negative pulses excite the filter every 10 μsec, depending on whether the modulo-two adder output is up or down, respectively.

C. Synchronization

Synchronizing the reference noise source with the incoming signal is a considerable problem. Because the system must operate through jamming, it is impractical to transmit synchronization pulses continually, since they would be vulnerable to imitation techniques. The system therefore uses no special synchronization information added to the signal transmitted; the only indication at the receiver of proper synchronism is a sizable output signal from the averaging filters.

The synchronization procedure has three phases, which are, in order of occurrence: initial synchronization, searching and tracking. We will consider them in reverse order.

(1) In tracking, the variable delay τ of the reference noise is continually and automatically readjusted for coincidence with the incoming signal. This is done by developing a

*In operational F9C systems, e.g., the F9C-A, the period will be made at least one day, and the digital key will be changed daily.

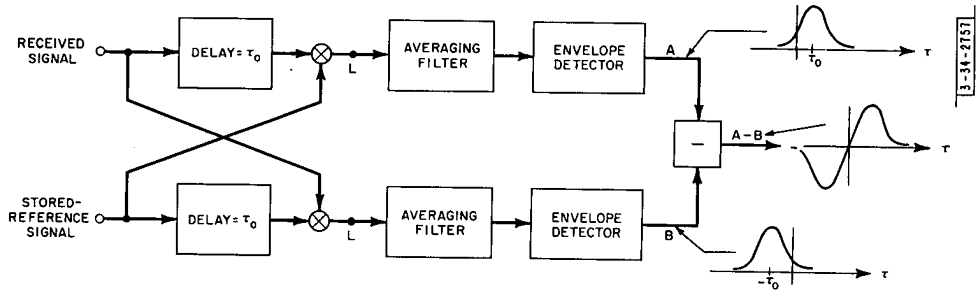

Fig.4. Means of deriving error signal A-B with polarity the same sign as τ, the desynchronism between stored and received signals. Curves of output vs τ are shown at the right.

DC error signal whose polarity corresponds to the direction of any desynchronism (Fig.4). This error signal causes a small positive or negative shift in the effective clocking frequency.

(2) In searching, the narrow region in τ representing synchronism is sought in some wider range of τ by speeding up the reference noise slightly so as to advance it in τ, or by retarding it so as to lag. The long response time of the narrow-band averaging filters limits the search rate to less than one part in 1,000. With a repeat period for the signal of 24 hours, it would take nearly three years to make a complete search. On the other hand, once the proper synchronism has been attained, even if the tracking function is disabled for a day or two (as it would be during a standby condition), the accumulated desynchronism will not amount to more than 2 or 3 milliseconds because of dissimilar drifts of the two standards, plus 5 or 6 msec because of changes in the time of propagation. Therefore in the F9C system, search consisting of an automatic sweep back and forth in τ, 10 msec on either side of the initial value, is considered sufficient. Smaller sweep ranges are also available. During search, an oscilloscope is used to display the integrating filter outputs as a function of τ. Figure 5 shows two typical patterns from this "search scope". Because the signal is propagated to the receiver by several modes having different strengths and times of flight, several correlation peaks are visible in Fig.5(a), instead of just one. By comparison, Fig.5(b), taken using a complete test transmitter locally at the receiver, shows only one peak, since multipath effects are absent.

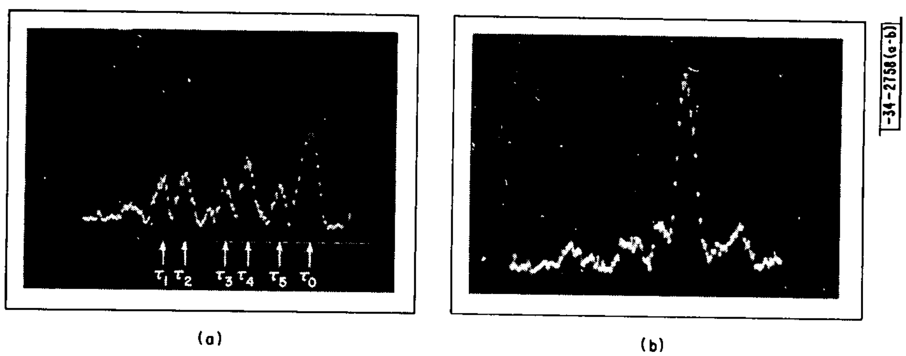

Fig.5. Typical search-scope patterns: (a) transmitted signal received over ionospheric path (note multipath effect); (b) transmitted signal generated locally.

(3) Clearly initial synchronization is required when the system is first set up, and whenever there is a loss of synchronism, because of a power failure, for example. To perform the initial synchronization, a surprise tone burst can be transmitted at a prearranged time and frequency known only to transmitter and receiver. So far as the enemy knows a priori, the burst might appear anywhere in a frequency range so wide that he cannot jam all of it effectively. Upon transmission of the burst, all four transmitter noise-source counters are reset to zero, and upon reception all four receiver counters are likewise reset. Then a brief search for a few milliseconds of τ will reveal the region of synchronism. The method is impervious to repeater jamming since, by the time the jamming is initiated, it is too late to be effective. In the experimental tests, the tone burst was sent at the operating band center, but any prearranged frequency would have served as well.

D. Modulation and Demodulation

At this point it is necessary to discuss in more detail that portion of the receiver circuitry in Fig. 2 between the mixer tube and the output to the teletype printer. As shown in the figure, the f_M or f_S tones from the mixer may be converted into a two-valued DC output to the printer by filtering them separately and then forming the difference of the envelopes of the filter outputs. There are several disadvantages of this scheme as it stands, the principal one being that the time constant of the averaging filters must be a fraction of the baud length for a clean rise and fall in the signal to the printer, whereupon the factor T in the expression of Fig. 1 is reduced accordingly.[8]

The F9C system employs a variation of this method, the so-called baud-synchronous, or integrate-and-dump method of demodulation, developed by Coles Signal Laboratory and Collins Radio Company.[9] In this method (1) the filter time constant is made several times the baud length, (2) the difference in filter envelopes is sampled at a time coinciding with the expiration of each received baud, (3) according to the polarity of the observed sample the printer is supplied a constant DC signal at one of the two levels lasting one baud length, and (4) both filters are dumped, or deenergized, immediately after sampling and are then free to respond to the next received baud. Operations (1) and (2) insure that the factor T in the expressions of Fig. 1 is preserved at the full value of the baud duration. Operation (3) eliminates printer errors due purely to a noisy printer waveform. (The printed characters can still be in error because noise in the filter outputs causes the sample to have the wrong polarity, but at least the signal to the printer is a clean square wave.) Operation (4) eliminates any inter-baud overlap effects by removing before each new baud all traces of signal from the previous one.

To use baud-synchronous demodulation, one must sample and dump within about one millisecond of the expiration of each received baud. In the F9C system the sampling and dumping pulses are derived from the digital circuits of the noise source, which must be already synchronized to the received signal within 50 μsec. It then remains only to modulate the teletype information onto the carrier (the switch in Fig. 2), using identical timing derived from the transmitter's noise source.

Each teletype character consists of a start interval followed by the five information-bearing bauds, followed by a stop pulse. The start and stop pulses are generated internally at the F9C receiver, and those arriving from the transmitter are disregarded, since they are occasionally in error.

It has already been mentioned that the form of noise source was changed radically for the second series of field tests. The study leading to the new noise source design also indicated (as did observations reported in Sec. III-A) that greater security could be had by using the type of modulation and demodulation depicted in Fig.6. Whereas the two binary teletype states are distinguished by a frequency shift in the previous scheme, the newer method in effect uses two different noise sources – one for each teletype state. Actually, the MARK and SPACE digital waveforms need be different only to the extent that they possess a small enough correlation with each other. This was effected by taking the MARK digital signal from point X of Fig. 3(b) and complementing every other output pulse in the "complement" circuit of Fig. 6. To prevent a tell-tale keying transient upon transition from MARK to SPACE or vice versa, actuation of the switch in Fig. 6 is in effect interleaved between two successive pulses exciting the filter.

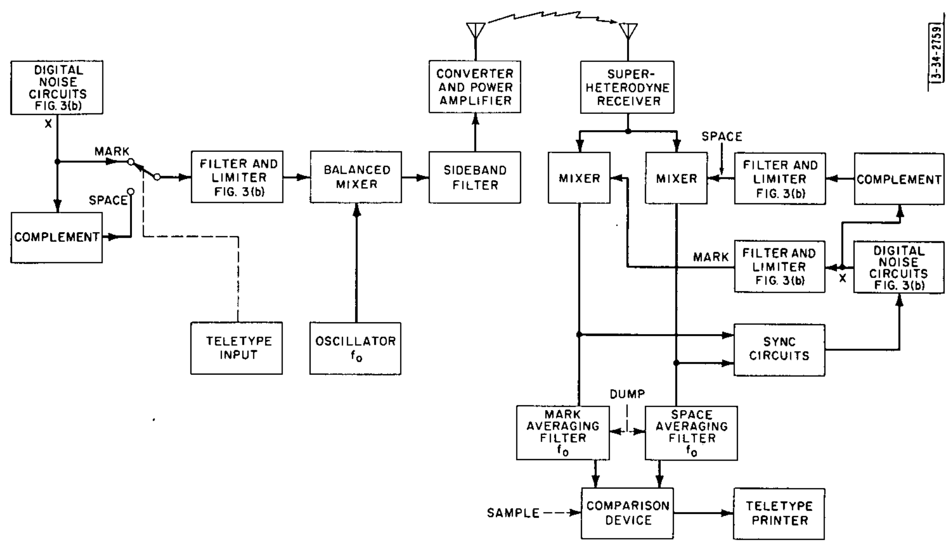

Fig.6. Block diagram of Fig.2, redrawn to show the modulation system used in the second series of tests.

E. RF Circuitry

One of the unique problems in the F9C system is the RF frequency stability required. It is seen from Figs.2 or 6 that the conversion of the noise-like signal up to the carrier frequency at the transmitter, and back down again at the receiver, must involve an accumulated frequency error smaller than the integrating filter bandwidth, since otherwise the difference frequency tone will be shifted out of the filter passband. For this reason, the converters made the desired translations of the signal in several steps in which the injection frequencies for the larger steps were multiples of the 100-kcps standard frequency (having an observed stability of better than one part in 10^8 per day), and those for smaller interpolating steps were taken from separate crystal oscillators. An over-all frequency stability of one cycle per second resulted.

At the transmitting end, an AN/FRT-22 transmitter served as a power amplifier. One reason for using a limited noise-like signal (Fig.3) was to allow this transmitter to be driven Class C. During the first series of tests, adjacent channel interference due to spectrum spreading was reported. Accordingly, the FRT-22 was operated linearly (Class B) thereafter, with an attendant reduction in transmitter power from 40 to 18 kw. During wartime anti-jam operation, the adjacent channel interference (which is 55 db down one bandwidth from the band edge)[10] may not matter.

F. Diversity

During the first series of tests it became apparent that multipath effects were seriously deteriorating F9C performance and would have to be countered with some sort of diversity. The cause of the trouble can be seen by referring back to Fig.5(a).[11] If we imagine the receiver reference noise source to be synchronized at some particular value of τ such as τ_0, the energy delivered to the receiver at τ_1, τ_2, etc., arrives too late or too early to give a correlated output. [This is clear from the narrowness of the correlation curve in Fig.5(b).] These other signals therefore add their power to any noise or jamming present, with the result that the quantity $(S/J)_i$ in Fig.1 is greatly reduced. Specifically, it becomes the ratio of the power in the signal arriving at τ_0 to the sum of the jamming power and the powers in signals at τ_1, τ_2, etc. Because of the random fading of the amplitudes at the various values of τ, occasionally the signal at τ_0 becomes so small compared to the sum of jamming and unsynchronized signal powers that the 23-db gain given by the product TW is not enough, and errors are printed.*

Two diversity schemes were proposed and tested: τ-diversity, and space-diversity. In τ-diversity, the receiving equipment of Figs.2 and 6 connected between the superheterodyne receiver and the decision circuit is duplicated, with the noise sources synchronized to different values of τ. The correlated outputs are added in some fashion in the comparison device so that a large output signal-to-noise ratio is preserved, on the supposition that both paths are unlikely to fade simultaneously. The two noise sources are made to track their respective paths independently. (In many of the tests of Sec.III this tracking was omitted, since their duration was so short that tracking was found to offer negligible improvement.)

Whereas τ-diversity uses one receiver and two noise sources, space-diversity employs, conversely, two receivers whose outputs are correlated simultaneously with the signal from one noise source. (Referring to Figs. 2 and 6, this means a duplication of all the blocks preceding the comparison device, except the noise source and associated synchronization circuits.) By feeding the receivers from antennas spaced far enough apart, one should observe independent fading of the signal component arriving at a given value of τ.

In these tests the two antennas were Signal Corps Type C rhombics spaced 300 feet in the direction of arrival and 550 feet laterally. The method used for combining the two voltages in both forms of diversity was to add linearly immediately prior to the sampling operation. (Each voltage represents a difference in envelopes of MARK and SPACE averaging filters.) A slight improvement in performance would probably have been obtained by a suitable nonlinear form of addition.

*The effect of multipath on FSK is of a different sort. So long as the difference in time delays for the various paths is a small fraction of the band length (which was usually the case in these tests), the only effect is "selective fading" of the received FSK tone due to phase addition or cancellation of signals arriving via the various paths. The received signal has no self-jamming introduced as in a NOMAC system.

III. TEST RESULTS

A. Noise-Source Performance

Several tests were made of the behavior of the noise sources schematized in Fig.3. The bandpass noise spectra and correlation curves were measured, and tests were made to learn whether the MARK-SPACE teletype modulation was audibly perceptible in the transmitted signal. In all respects, the second noise source with its method of modulation (Sec. II-D) proved better.

Figure 7 compares the spectra resulting from the old and new noise sources, respectively. These plots were taken by substituting a variable-frequency signal generator for the receiver in Figs.2 and 6, and observing the averaging filter output with the dump input disconnected. Since the natural bandwidth of the averaging filters without dumping is about 6 cps, it was possible to resolve spectral components as little as 6 cps apart. It is seen from the figures that the many narrow spikes that were present with the old noise source are greatly reduced with the new one. The spikes are caused by hidden periodicities in the digital exciting waveform. A concentration of the signal energy into several strong spectral lines is undesirable, since it makes the system more vulnerable to jamming by multiple sine waves.*

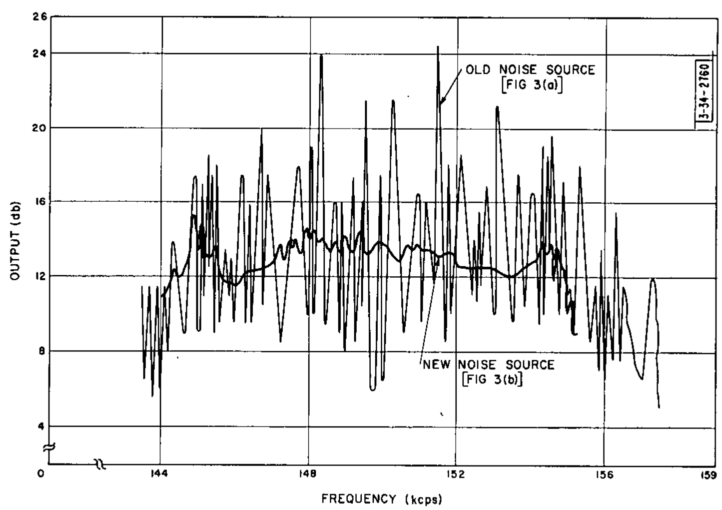

Fig.7. Measured noise-source spectra.

Figure 8 shows the correlation curve for the older noise source. For the newer one, the curve is substantially the same, except that slight humps (such as shown in the figure 1250 μsec from the main peak) are much smaller. These spurious peaks are caused by noise-source periodicities at approximately the average period of the three counters whose periods are most nearly equal, namely, the 128, 125 and 121 counters. A spurious correlation peak produces a vulnerability to repeater jamming having a delay adjusted to arrive in synchronism with the spurious peak. This weakness is portrayed more vividly in Fig. 9(a), which shows the A-B curve used for tracking the old noise source. The spurious peak is accentuated here by limiters[12] used

*The data in Fig.7 (light curve) were taken with the limiter in Fig.3(a) bypassed, but inadvertently the limiter in Fig.3(b) was included for the data of Fig.7 (heavy curve). However, the conclusion that the spectral spikes are greatly reduced should not be affected by this (see Ref.10).

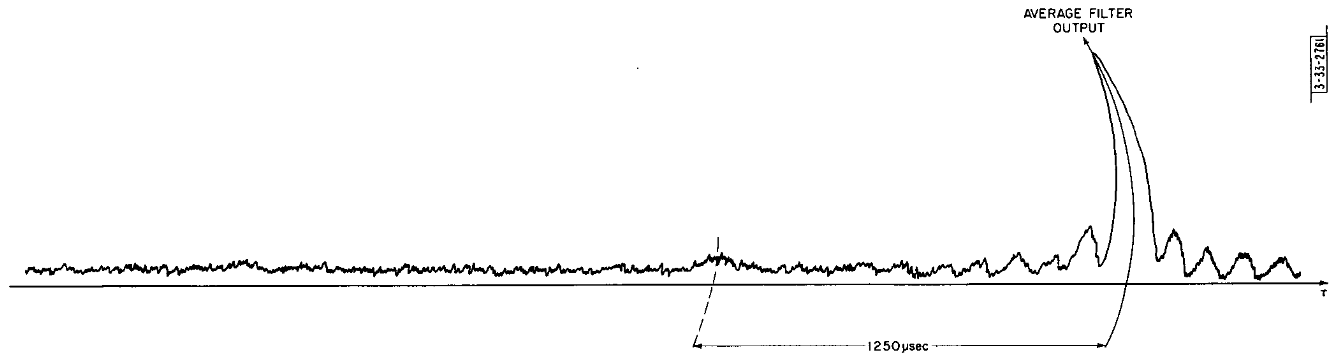

Fig.8. Measured correlation curve for old noise source.

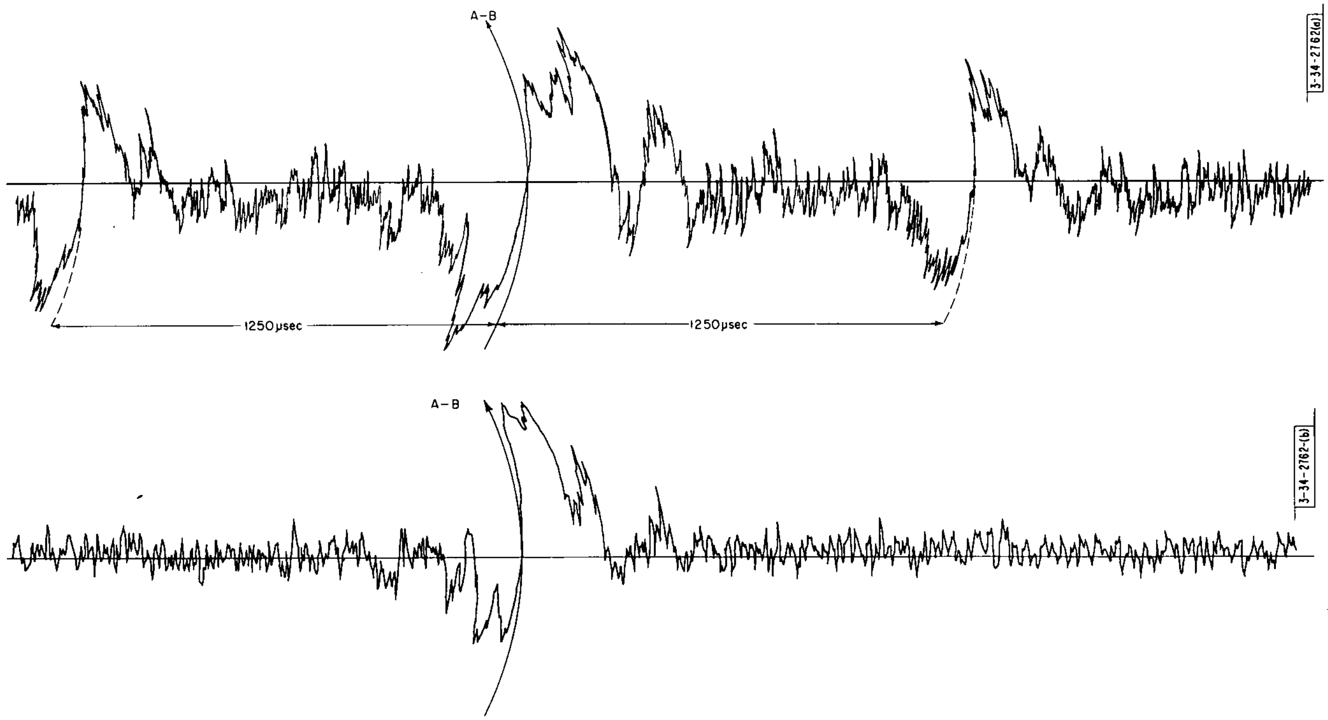

Fig.9. Tracking curves: (a) old noise source [Fig.3(a)]; (b) new noise source [Fig.3(b)].

in the tracking circuit (points L, Fig.4) to stabilize the amplitude of the A-B curve with changes of signal strength. If a strong repeater jamming signal arrives near one of the spurious S-curves, the tracking can be disrupted. (Because of propagation delays, it is probably not possible for the jamming signal to arrive soon enough after the main peak to disrupt tracking there.) Figure 9(b) shows that these spurious peaks have been largely eliminated with the new noise source.

Vulnerability to repeater jamming is also lessened by the new method of modulation. With the older frequency-shift scheme, it was possible for the enemy to receive the transmission, frequency-shift it, and then retransmit it with a suitable delay. Because of the spurious correlation peaks just mentioned, or because of careless synchronization by the operator, this signal could jam the system effectively. With the newer modulation scheme, MARK can be transformed into SPACE, or vice versa, not by a simple frequency translation, but only by recovering the digital waveform at point X of Fig.3(b) and complementing every other digit – a considerably more difficult operation.

During the first series of tests it was observed that, under certain conditions, one could detect keying transients, faintly audible in the noise-like transmission. It was concluded that this perceptibility of the frequency shift was due to the strong lines in the spectrum (Fig.7). The newer noise source was not tried with frequency-shift modulation, but one should find the audibility of such keying much reduced. Using the newer form of modulation, extensive listening tests were made, using keying rates from 6 cps to 100 kcps, and no keying transients were detected.

B. <u>System Operation Without Jamming</u>

Table I summarizes the performance of the F9C system without jamming, using various modes of diversity operation, and compares it with that of a standard FSK system using space-diversity. For each of three frequencies, three conditions of F9C operation were employed: non-diversity, space-diversity and τ-diversity. The test message was the standard "quick brown fox" text, constituting one 70-character printed line. The table gives the number of lines of test copy printed and the number of errors made. It also summarizes the error rate for each frequency, and gives an over-all average error rate for each mode of operation.

It was found that FSK operation was consistently superior to F9C under these no-jamming conditions, and that τ-diversity F9C operation was better than space-diversity, which in turn was better than using no diversity; τ-diversity proved superior to space-diversity even during periods when there was only a single propagation path. At such times the two values of τ were made to straddle the correlation peak.

Figure 10 shows in more detail the way in which the errors listed in Table I occurred. The abscissa is the number of erroneous characters occurring in a run, and the ordinate is the percentage of the runs that were of given length. Data are given for the four modes of transmission at each of the three frequencies. It is seen that FSK tended to make predominantly single errors, whereas F9C errors were often made in longer groups. This is to be expected from the nature of the F9C self-jamming effect in which errors occur when the in-synchronization received signal fades. These fades often persist for several characters. The average length of F9C error runs is seen to be decreased by the use of diversity, and by using higher frequencies.

TABLE I

SUMMARY OF PRINTING DATA COMPARING F9C AND FSK WITHOUT INTENTIONAL JAMMING*

Date	Frequency (kcps)	FSK-S	F9C No diversity	F9C Space-diversity	F9C τ-diversity
25 March	17,460	3/226	110/227	46/328	1/150
25 March	8040	3/69	33/43	46/61	15/33
28 March	12,270	6/165	102/157	23/252	0/10
29 March	12,270	7/275	407/349	157/402	28/260
29 March	17,460	4/210	122/208	22/223	10/200
30 March	12,270	0/80	78/96	7/93	4/55
30 March	17,460	9/214	121/237	38/262	21/218
30 March	8040	2/108	193/98	114/110	85/104
31 March	12,270	1/92	62/119	11/125	5/95
31 March	17,460	5/171	66/167	10/171	6/167
1 April	12,270	0/57	30/52	14/122	8/126
1 April	17,460	1/94	8/96	34/108	2/107
	Summary by Frequency				
	12,270	14/669 = 0.021	679/773 = 0.88	212/994 = 0.21	45/546 = 0.082
	17,460	22/915 = 0.024	427/930 = 0.46	150/1042 = 0.15	40/842 = 0.048
	8040	5/177 = 0.028	226/141 = 1.6	160/171 = 0.94	100/137 = 0.73
	Totals	41/1761 = 0.023	1332/1843 = 0.72	522/2207 = 0.24	185/1525 = 0.12

*Shown as number of erroneous characters per 70-character line.

TABLE II

COMPARISON OF F9C AND FSK PRINTING ERROR RATES IN SEVERE MULTIPATH WITHOUT JAMMING*

FSK Space-Diversity	F9C Space-Diversity	F9C τ-Diversity
4/93 = 0.043	365/165 = 2.21	74/201 = 0.37

*Shown in errors per line.

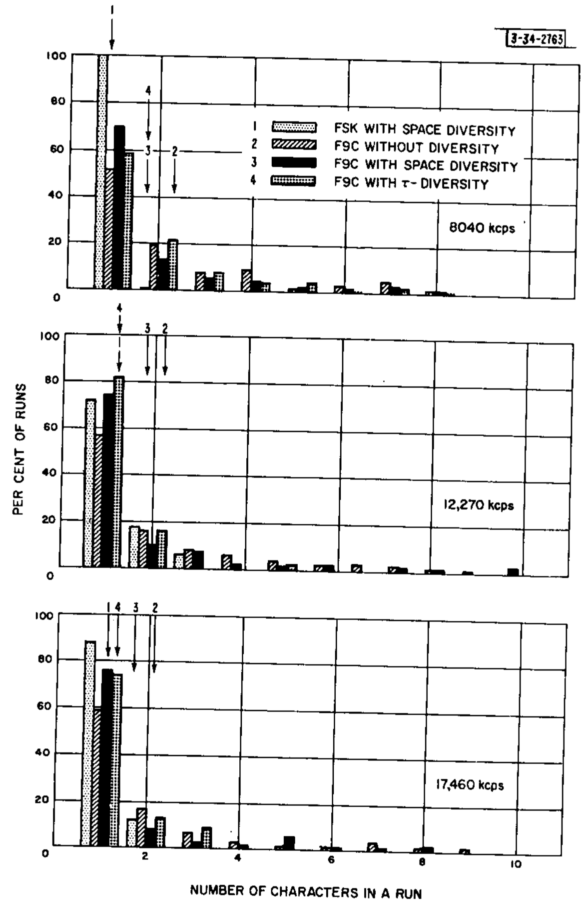

Fig.10. Distribution of errors summarized in Table I (unjammed operation). Arrows indicate average length of error run.

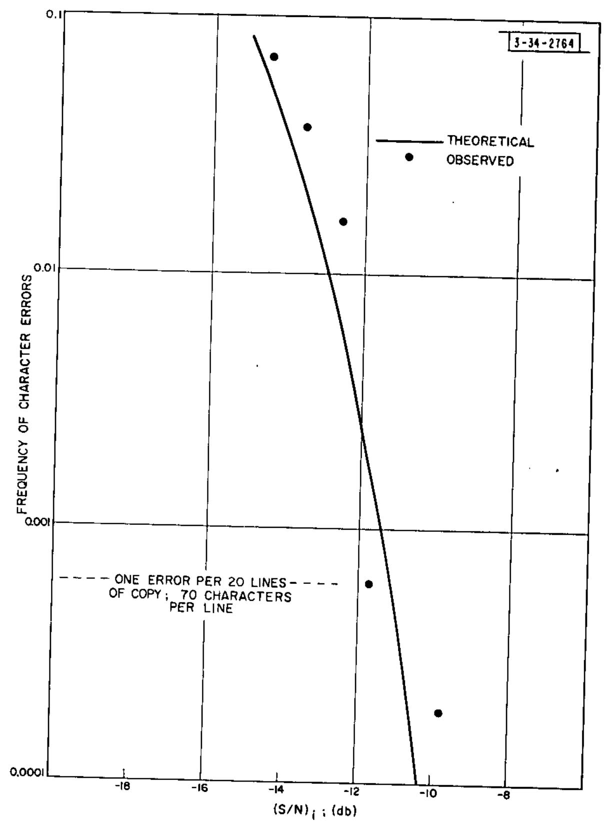

Fig.11. Frequency of character errors vs signal-to-jamming ratio of F9C equipment.

The reason for the disappointing performance of space-diversity is that the receiving antenna spacing used was not enough to make the fading of a given multipath mode at the two antennas independent. The spacing was sufficient for independent fading of a received FSK tone, however. It is not known what spacing is required for good space-diversity F9C performance.

In all the experiments summarized in Table I and Fig.10, the operating frequency chosen was that one of the three giving the best performance, i.e., the highest frequency less than the "maximum usable frequency". At frequencies well below the MUF, where the multipath structure is more complicated, the margin of superiority of FSK over F9C widens, as does that of τ-diversity over space-diversity. This is shown by Table II, which gives data taken at 12,270 kcps when 17,460 kcps would have been a much better choice.

C. Local Jamming of a Locally Transmitted Signal

It will be recalled that when multipath effects are absent, a given signal-to-jamming ratio at the F9C receiver input is improved by a factor TW = 220. A theoretical curve[13] of the frequency of erroneous characters vs $(S/N)_i$ is given as the solid line of Fig.11. Also shown are data from several experimental determinations made using a locally generated NOMAC signal to simulate the transmitter, and a bandpass Gaussian noise (of approximately the same spectral shape) for the jamming. Measurement of the signal-to-noise ratio was accurate to about 0.5 db. The theoretical and experimental results show good agreement.

D. Local Jamming of the Received Signal

Several tests were made in which the received signal was jammed by injecting either a bandpass noise or an FSK signal into the receiving antenna circuits. The noise-spectrum shape was approximately the same as that of the NOMAC signal, and the MARK and SPACE FSK frequencies were adjusted to coincide with those of the FSK transmitter.

The jamming signal had a constant and measurable level, whereas the received signal was subject to the usual time-varying propagation effects. Thus the signal-to-jamming ratio as well as the multipath structure was not constant with time, and the following procedure was used for comparing FSK and F9C performance. During a 2-1/2 minute interval, FSK signals were received (using space-diversity) and the jamming power increased to the point where roughly half the characters were in error. It was possible to make up to five such determinations in the 2-1/2 minute interval. The process was repeated for 2-1/2 minutes of F9C without diversity, then F9C with space-diversity, then F9C with τ-diversity.

Table III presents the data obtained during a number of such 10-minute cycles. The figure given as "average anti-jamming margin" is the difference between the average jamming power used in a 2-1/2 minute F9C interval and that of the preceding FSK interval. It is seen that all three modes of F9C operation show a significant anti-jam advantage over FSK. Conclusions as to the performance of the various F9C modes of operation relative to each other are probably impossible because of (1) the small number of readings of the margin and their large dispersion (about 3 db), and (2) the fact that the readings were made at such a high error rate

TABLE III

MARGIN OF ANTI-JAMMING ADVANTAGE OF F9C vs FSK

	F9C		
	No Diversity	Space-Diversity	τ-Diversity
Noise Jamming (23 March 1955, 8040 kcps)			
Average db margin	9	8	8
Number of comparisons	4	4	4
FSK Jamming (23 March and 1 June 1955, 8040, 12,270 and 17,460 kcps)			
Average db margin	19	20	21
Number of comparisons	6	12	10

that the errors were due more to the intentional jamming than to self-jamming by multipath. This situation, which is not typical of the usual operating condition, tends to obscure the effect of diversity in reducing the self-jamming.

E. Remote Jamming of the Received Signal

To imitate an actual operating environment, remote jamming tests were run using as the jamming signal either a 710-watt transmission at 12,270 kcps from Collins Radio Company at Cedar Rapids, Iowa or an 8- to 10-kw transmission at 17,460 kcps from Army Communication Station ABA in Honolulu. Both jammers used FSK signals with MARK and SPACE frequencies tuned to those of the "friendly" transmitter at Davis, California. A calibrated attenuator was used to adjust the Davis transmitter power to give an error rate at the receiver (Deal, New Jersey) of about two characters per line, and then an average of about twenty lines of copy were printed at this setting. During these tests the F9C system employed that form of diversity which seemed appropriate at the time (i.e., for a single predominant propagation path, space-diversity; otherwise τ-diversity). The data, which are summarized in Fig.12, show that F9C exhibited an average anti-jamming advantage of about 17 db over FSK. Each determination entered in Fig.12 represents an instance where F9C and FSK were compared within 5 minutes or less.

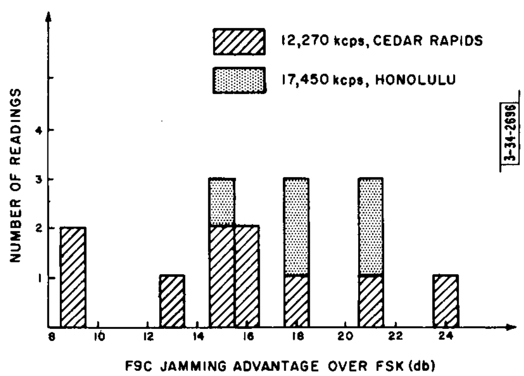

Fig.12. Anti-jam advantage of F9C over FSK when remote jamming is used.

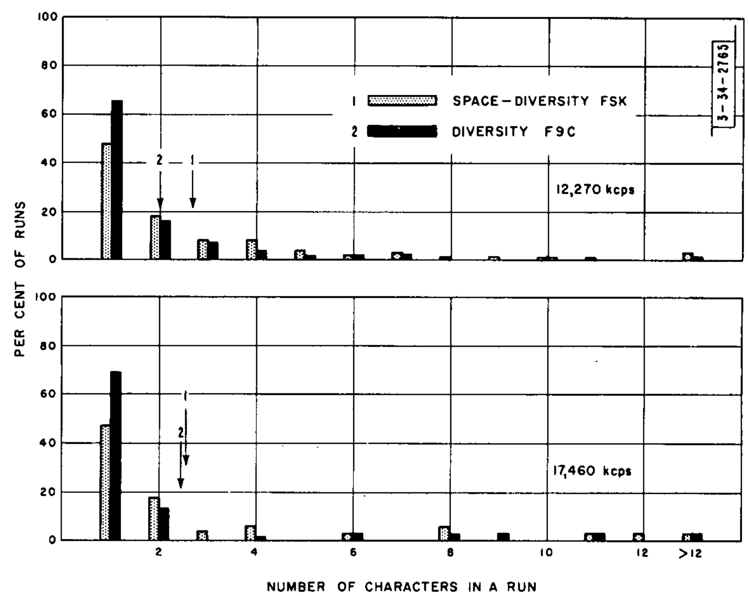

Fig.13. Distribution of errors for remotely jammed operation. Arrows indicate average length of error run.

The printed copy produced in the runs summarized in Fig.12 was analyzed for the length of error runs and tabulated in Fig.13. Comparison with the data of Fig.10 (unjammed operation) reveals several things. Since the over-all error rate was higher for the jammed case (about two errors per line compared with the Table I figures), several longer error runs were observed for both FSK and F9C. With jamming introduced, the FSK error runs tended to last longer than the F9C runs, whereas the reverse was true for the unjammed case. The F9C error runs were usually longer for the highest frequency with jamming present.

IV. CONCLUSIONS

The F9C system was designed to provide an increase in signal-to-jamming ratio for high-frequency radioteletype circuits, not by increasing transmitter power or antenna gain, but by using the NOMAC modulation and demodulation scheme. In such a system a noise-like waveform is the carrier and, with a noise bandwidth of 10 kcps using 60-word-per-minute teletype, a 23-db improvement in anti-jamming capability over conventional FSK is predicted, if multipath is absent. Although superior to FSK with respect to jamming alone, the F9C system without diversity was found to have a very high error rate because of multipath. The inclusion of τ-diversity improved this situation and allowed an average 17 of the 23 db to be attained against jamming in the presence of multipath.

REFERENCES

1. B.L. Basore, "Noise-Like Signals and Their Detection by Correlation," Technical Report No.7, Lincoln Laboratory, M.I.T. (26 May 1952).
2. P.E. Green, Jr., "Correlation Detection Using Stored Signals," Technical Report No.33, Lincoln Laboratory, M.I.T. (4 August 1953).
3. G.L. Turin, "Probability of Error in NOMAC Systems," Technical Report No.57, Lincoln Laboratory, M.I.T. (18 January 1954).
4. A more detailed explanation of the equipment used in the two series of tests is given in: P.E. Green, Jr., "The Lincoln F9C Radioteletype System," Technical Memorandum No.61, Lincoln Laboratory, M.I.T. (14 May 1954), and Addendum (14 July 1954), and P.E. Green, Jr., "Data on the Lincoln F9C-B Radioteletype System," Group Report No.34-36, Lincoln Laboratory, M.I.T. (2 March 1955).
5. B.M. Eisenstadt, P.L. Fleck, Jr., O.G. Selfridge and C.A. Wagner, "Jamming Tests on NOMAC Systems," Technical Report No.41, Lincoln Laboratory, M.I.T. (25 September 1953).
6. N. Zierler, "Several Binary-Sequence Generators," Technical Report No.95, Lincoln Laboratory, M.I.T. (12 September 1955).
7. B. Gold and B.M. Eisenstadt, Technical Reports in progress.
8. B.L. Basore, op. cit., Sec.VIII-A.
9. M. Doelz, "A Predicted-Wave Radio Teleprinter," Electronics 27, 166 (1954).
10. Quarterly Progress Report, Division 3, Lincoln Laboratory, M.I.T. (15 January 1955), p.75.
11. P.E. Green, Jr., op. cit. (Ref.2), Chap.V.
12. Quarterly Progress Report, Division 3, Lincoln Laboratory, M.I.T. (15 January 1954), p.69.
13. G.L. Turin, op.cit.

APPENDIX

Figures A-1 and A-2 show the transmitting and receiving ends of F9C equipment used in the first field tests beginning in July 1954. The transmitting-end equipment consists of a complete transmitter and a test receiver, whereas the receiving end is a receiver plus test transmitter. This duplex arrangement facilitates local testing at both ends of the system. Briefly,[4] the functions of the different units are as follows:

(1) Driver: provides 100 kcps and resetting pulses to drive counters,

(2) Counters: provide cyclic outputs to diode AND gate matrix [see Figs. 3(a) and (b)],

(3) Matrix: forms from counter and driver outputs two pseudorandom trains (MARK and SPACE) of pulses,

(4) Modulator: forms the bandpass noise from the digital output of the noise source, and performs the frequency-shift modulation,

(5) Modulator Timer: retimes incoming teletype signal to synchronism with the transmitting noise source,

(6) Exciter Converters A and B: converts modulator output to proper frequency and power to drive transmitter,

(7) Receiver Converters A and B: a stable superheterodyne receiver,

(8) Multiplier: mixes received and "stored" signals to obtain 20 kcps MARK or SPACE tone,

(9) Demodulator: decides from multiplier output whether MARK or SPACE was transmitted and actuates printer accordingly (see p.8),

(10) Demodulator Timer: provides synchronous dump, sample and start-stop pulses for the demodulator (see p.8),

(11) Discriminator: forms S-curve (Fig.4) for automatic synchronization of received and stored signals,

(12) Synchronizer: advances or delays counters in accordance with discriminator output,

(13) τ-Register Unit: controls cyclic sweep (in τ) of standby noise source to provide a multipath structure presentation on the Search Monitor Oscilloscope.

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The design, construction and testing of the Lincoln F9C system was the cooperative effort of most of Group 34 at Lincoln Laboratory. We would like to record our indebtedness to the many Signal Corps people whose cooperation made possible the field-test portion of the work. We acknowledge particularly the assistance of Mr. H. F. Meyer, Mr. L. Manamon and Capt. H. A. Schulke of Coles Signal Laboratory; and Maj. C. R. Knoeller and Mr. A. Gorricho of the Sixth Army (San Francisco).

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Fig.A-1. Receiving end of F9C equipment.

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Fig. A-2. Transmitting end of F9C equipment.

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