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QUARTERLY PROGRESS REPORT NO. 3

Contract No. AF 19(122)-7, Item II

June 1, 1952 to August 31, 1952

Reliability Research

Prepared by

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RELIABILITY RESEARCH

ABSTRACT

This report summarizes the research performed under the contract during the period from May 31, 1952 to August 31, 1952 that is specifically directed toward the improvement of the reliability of IFF systems.

Included herein are further descriptions and evaluations of schemes suggested in the previous reports for combatting the detrimental effects of noise and pulse jamming. Some examples are given of the use of redundancy coding to improve the reliability of pulse-train transmissions in the presence of noise. A discussion is given of construction currently in progress on a pulse-train correlator and its associated test equipment.

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a. Personnel and Administration

1. Martin W. Essigmann, Coordinator (half time, engineer)
2. George E. Pihl (one-tenth time, engineer)
3. John S. Rochefort, liaison man (full time, engineer)
4. Harold L. Stubbs (half time, mathematician)
5. Walter H. Lob (full time, physicist)
6. Myron L. Bovarnick (full time, engineer)
7. Louis J. Nardone (full time engineer from June 23, 1952)
8. Walter Goddard (one-tenth time, technician)
9. Mary D. Reynolds (half-time secretary from August 11, 1952)

The staff assigned to this item of work under the contract was increased during this report period by the addition of Louis J. Nardone and Myron L. Bovarnick. Nardone has had considerable training and experience in the field of electronic computers. Bovarnick has had recent experience as a field engineer on radar and IFF equipment. Both men hold the rank of Research Associate.

It is planned to transfer Jacob Wiren, a Research Associate employed on work under Item I since February 1948, to the work on this item on or about September 15, 1952.

The vacations of the staff assigned to this item of the work were arranged to fall within this report period.

b. Communications

1. Correspondence

Listings of all non-expendable property received for use under this contract have been sent to the Research Accountable Property Officer under the dates of May 31, 1952, June 30, 1952, and July 31, 1952.

2. Conferences

June 10, 1952. Conference at AFCRC among E. W. Samson, C. F. Hobbs, W. Bishop, C. Ryan, et al. of AFCRC; and J. S. Rochefort, H. L. Stubbs, W. H. Lob, M. L. Bovarnick, G. E. Pihl, and M. W. Essigmann, all of Northeastern.

The purpose of this conference was to discuss plans for a proposed expansion of the work to include an Item III on coding circuitry and transistors, to discuss the second quarterly progress report, and to discuss future work. It was agreed that future work would include additional work on filtering of the type described in the last report, and experimental investigation of the use of correlation to increase system reliability.

June 11, 1952. Conference at AFCRC among W. Bishop, C. Ryan, R. Wagner, et al. of AFCRC; and G. E. Pihl, J. S. Rochefort, and W. H. Lob of Northeastern.

The purpose of this conference was to discuss circuitry details pertinent to the work under this item, and to the proposed work under Item III.

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June 26, 1952. Conference at AFCRC among A. Bishop, C. Ryan, and R. Wagner of AFCRC; E. F. Ormsby and H. C. O'Connor of Haller, Raymond, and Brown, Inc.; M. W. Essigmann, H. L. Stubbs, and W. H. Lob of Northeastern.

The purpose of this conference was to interchange information concerning the work at Northeastern and AFCRC with the representatives of Haller, Raymond, and Brown, Inc. who are working on a related contract sponsored by WADC. The discussion at this meeting led to the visit made to Haller, Raymond, and Brown, Inc. on August 7 and 8, 1952.

August 7-8, 1952. Visit by J. S. Rochefort and H. L. Stubbs to Haller, Raymond, and Brown, Inc. at State College, Pa. During this visit, Rochefort and Stubbs took part in a series of conferences among representatives of Haller, Raymond, and Brown, Inc., AFCRC, WADC, and Northeastern. Others in attendance were:

AFCRC - W. Bishop, R. Richardson, C. Walter

WADC - N. Braverman (the Project Engineer for HR&B contract)

HR&B - E. Johnson (the Project Supervisor)	H. D. Friedman
W. A. Burnett	K. W. Houpp
W. N. Brown, Jr.	J. R. Kinney
W. P. Cogswell	H. C. O'Connor, Jr.
A. J. Detzer	E. F. Ormsby
L. A. Doggett	E. S. Roscoe

The primary object of the conferences was that of preventing the duplication of work at HR&B, AFCRC, and Northeastern. A detailed trip report on the visit has been prepared by Northeastern for the AFCRC. A final report is being prepared by HR&B for submission to WADC in the near future.

J. S. Rochefort, as liaison man between AFCRC and Northeastern, has made regular visits to AFCRC to fulfill this obligation.

c. Statement of the Problem

This is the third quarterly progress report prepared under this item of the contract. The specific problem under study to this writing involves the investigation of the communication aspects of the ground-to-air FF system, with the final aim that of determining methods by which its reliability can be improved. The approaches taken so far have emphasized the aspect of system reliability and, for the most part, studies of ways of improving equipment reliability have been deferred pending the development of transistor circuitry techniques.

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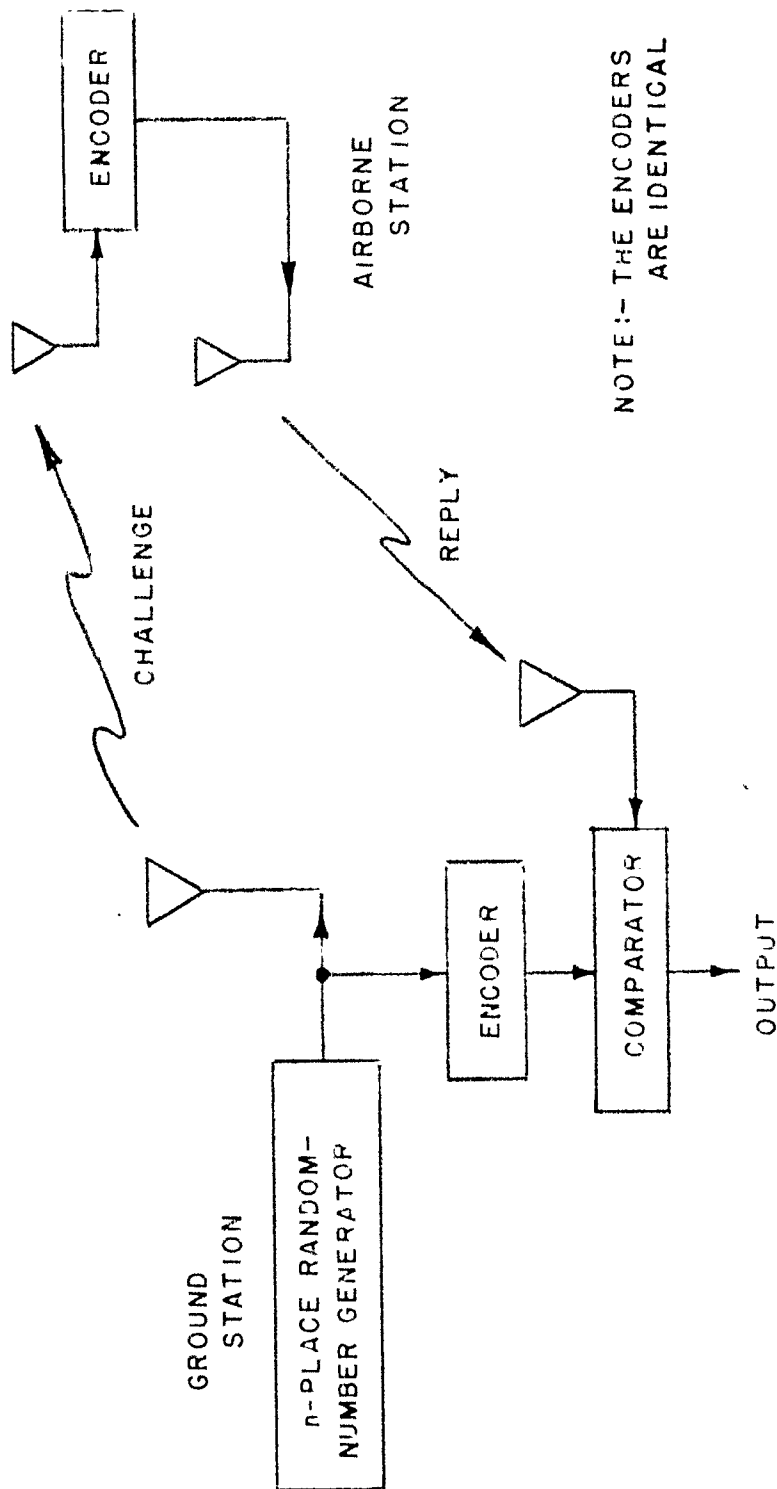


FIG. 1. BLOCK DIAGRAM OF IFF SYSTEM UNDER STUDY.

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The IFF system assumed in this study operates in accordance with the scheme shown in Fig. 1. The aspects of cryptographic security introduced by the two encoders are not a part of the problem considered, the system under consideration being assumed secure against an enemy who can only listen. Of importance, however, is the vulnerability of the system to enemy jamming, enemy interrogation, and atmospheric disturbances. A resumé of the methods for improving system reliability that were studied during the first and second report periods is given in the following section.

d. Methods of Attack

In approaching the problem of theoretical reliability, the first step was to enumerate the factors which might reduce reliability. They include "atmospherics" and receiver noise, inadequate space resolution, fading, and fruit, as well as jamming and deception on the part of the enemy. Since this interference on the part of the enemy seems to constitute the major threat to reliable operation, it has been given the most attention in the work done thus far.

To combat broad-band noise jamming (or noise from any source), many methods have been considered. Cross-correlation of pulse trains by a process discussed in detail below has been shown to improve the signal-to-noise power ratio by a factor of m^2/n where the pulse train consists of m pulses and $n - m$ raps. This method can very well be used at the ground station of a ground-to-air IFF system, since the correct reply is available there. It has been shown that cross-correlation may also be used at the airplane if challenges are transmitted in a pre-arranged sequence which can be duplicated at the airplane with the aid of certain stored information. This system requires two stages of synchronization, the coarser to be achieved by a mechanical clock and the finer by a crystal-controlled or tuning-fork-controlled oscillator.

Optimum filters which sacrifice pulse shape and merely indicate when a pulse occurs have been shown to be equivalent to cross-correlation. The transfer characteristic of such a filter should be the conjugate of the Fourier transform of the signal waveform. The maximum improvement in signal-to-noise ratio is obtained only when a different filter is available at the receiver to match every possible pulse train. However, if each pulse is evaluated individually, only one filter, matching a single pulse, is required. Such a filter has been shown to improve the signal-to-noise power ratio by a factor of about 3 over that of a conventional low-pass filter.

Other methods which have been considered for combatting noise and noise-jamming fall under the heading of redundancy coding. They include the transmission of a number followed by its complement, the use of additional digits for error detection and correction (assuming a limited number of possible errors), restriction to a specified number of pulses in the pulse train, and coding to match the channel capacity as defined by Shannon. The latter method is discussed in more detail below.

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To combat pulse jamming, the method of cross-correlation may be fairly successful, but a more definite statement cannot yet be made. Redundancy coding can certainly be used to detect the presence of jamming, but shows little promise for combatting it. A system which shows most promise for combatting pulse jamming, as well as any other type of jamming, is one which uses a narrow-beam directional antenna on the airplane. This system combats pulse jamming by virtue of the fact that its directional communication feature reduces the probability that an enemy jamming signal and a friendly challenge will be received simultaneously by the airplane. The last report discussed one method by which a system possessing these qualities could be realized. This method required the use of a rotating airborne antenna. This system appeared to have sufficient merit that the development of such an antenna warranted a more detailed consideration. Consequently the rotating antenna problem is in the process of being formulated for evaluation by the Antenna Laboratory of AFRCRC.

At the time the last progress report was in preparation, it was felt that the directional airborne antenna should be capable of rotation through 360 degrees in azimuth in order that, irrespective of its course, the airplane might be challenged by any interrogator which was within its interrogation range. However, for certain applications (ADC for example) where it appears feasible that airplanes would be required to approach interrogators along certain prescribed courses*, a rotating airborne antenna would not be necessary. A narrow-beam antenna mounted in the nose of the airplane would suffice for this purpose and thus considerably simplify the antenna development problem.

Redundancy Coding

Coding to match the channel capacity is one of the methods previously considered** for improving reliability of transmission of a pulse train in the presence of noise. Assuming that a pulse is always received correctly, but that a gap may be received as a pulse with probability a , it was shown that the channel capacity C is given by

$$C = \log \left\{ 1 + \exp \left\{ \frac{a}{1-a} \log a + \log(1-a) \right\} \right\}$$

where the base 2 is understood for the logarithms and exponential. In particular it was shown that

Example I: If $a = \frac{1}{2}$, then $C = .32$, $P_1 = .60$, $P_2 = .40$

Example II: If $a = \frac{1}{4}$, then $C = .56$, $P_1 = .97$, $P_2 = .43$

where P_1 is the probability that a transmitted symbol will be a pulse in an ideal code that matches C , and $P_2 = 1 - P_1$.

* See, for example, Ref. No. 28.

** See quarterly Progress Report No. 2 dated May 31, 1952 for this contract.

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Although a very long coding period is required to approximate errorless transmission at a rate equal to C, the following illustrations for 8-place codes give about 15% probability of error for both of these examples. No original uncoded messages are shown; the coded messages are numbered and can be considered as a catalogue of permissible 8-place pulse trains. A received signal would be identified as that permissible message having the smallest number of gaps including those received.

Example I. Rate of transmission .323 bits per symbol
Probability of error .148 (for 8-place message)

Coded Messages: 1. P P P P P P P P (P₁ = .52)
2. P P P P P G G G
3. G G G P P P P P
4. P P G G G G P P
5. G G P P G P G G
6. G G G G G G G G

(P = pulse, G = gap)

Example II: Rate of transmission .557 bits per symbol
Probability of error .149 (for 8-place message)

Coded Messages: 1. P P P P P P P P 12. P G P P G P G P (P₁ = .53)
2. P P P P P P G G 13. G P P P P G P G
3. P P P P G G P P 14. G G G G G P P P
4. P P G G P P P P 15. P P P G G G G G
5. G G P P P P P P 16. G G G P P P G G
6. P G P G P G P P 17. G P G G P G G P
7. P G G P P P P G 18. P G G P G G P G
8. G P P G P P G P 19. G G P G G P G G
9. G P G P G P P P 20. P G G G G G G P
10. P P P G G P P G 21. G P G G G G P G
11. P P G P P G G P 22. G G G G G G G G

It is possible to reduce the probability of error by reducing the rate of transmission. In Example I, the following simple 8-place code yields a rate of transmission of .25 bits per symbol with .062 probability of error:

P P P P P P P P
P P P P G G G G
G G G G P P P P
G G G G G G G G (P₁ = .50)

These four coded messages can be thought of as encoded versions of the four possible two-place messages, PP, PG, GP, and GG; where the code consists merely of repeating each symbol four times.

No way has been found to determine whether or not the codes shown above are optimum in the sense of smallest probability of error for a given rate of transmission. However, they give some idea of how much improvement in reliability can be obtained by this method, at the cost of redundancy. It should be noted that there is a difficult problem of devising automatic means for identifying the received signal with the permissible message which it most nearly resembles in the sense explained above. Furthermore, the method becomes rapidly more complex as the length of the coding period is increased.

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Pulse-Train Correlator

Enough changes have been projected in the pulse-train correlator since its first mention*, and especially in this report period, to warrant restating its purpose and philosophy at this time.

Basically, the correlator is to produce an output upon reception at one of its two inputs of a probably "correct" pulse train, and to yield no output in the absence of such a pulse train, all in the presence of noise and/or pulse jamming. Here by a "correct" pulse train is meant a pulse train whose pulse- and gap assignment has been supplied to, and stored in, the correlator via the other input at some previous time.

The comparison of the stored pulse train $f_1(i)$ and the received one $f_2(i)$ (i being the place number in the train, running from 1 to n for an n -place pulse train) is to be achieved by correlation, i.e. by evaluating with an analogue computer the value of $\rho = \sum_{i=1}^n f_1(i) f_2(i)$. Roughly speaking, the greater

the value of ρ the greater is the probability that the correct pulse train was received. A threshold device is to be provided to produce an output whenever ρ exceeds a threshold value, the magnitude of which has to be varied automatically to give the best possible results under various conditions of signal strength, jam, etc.

The block diagram for the proposed correlator is shown in Fig. 2. The received video signal is fed into a tapped delay line, the n taps being arranged such that when the last place of a correct n -place pulse train is just entering the line all the other places are at their proper taps. At that instant, therefore, the signal which was received in time sequence, exists in space sequence along the line. Proper staggering of the intervals between places (and of the spacings between taps) will prevent multiple coincidences of places and taps prior to and subsequent to that instant.

In accordance with the theory developed earlier** the stored function $f_1(i)$ is assigned the levels 1 at the " m places" (i.e. where a pulse is expected) and x ($x < 0$) at the " k places" (where no pulse is expected). The multiplication $f_1(i) f_2(i)$ then is performed by using the signal at each " m tap" directly, and passing it through a phase-inverter-amplifier-attenuator of total gain x at each " k tap". The resulting signals are added and fed to the threshold device.

The best choice of x , m and k depends on the type and intensity of jam that is expected. When considering pulse jamming it should be borne in mind that, regardless of how the jammer times the transmission of jam pulses, they

* See Appendix A of Quarterly Progress Report No. 11, (February 8, 1952) Reliability Research, for this contract.

** loc. cit.

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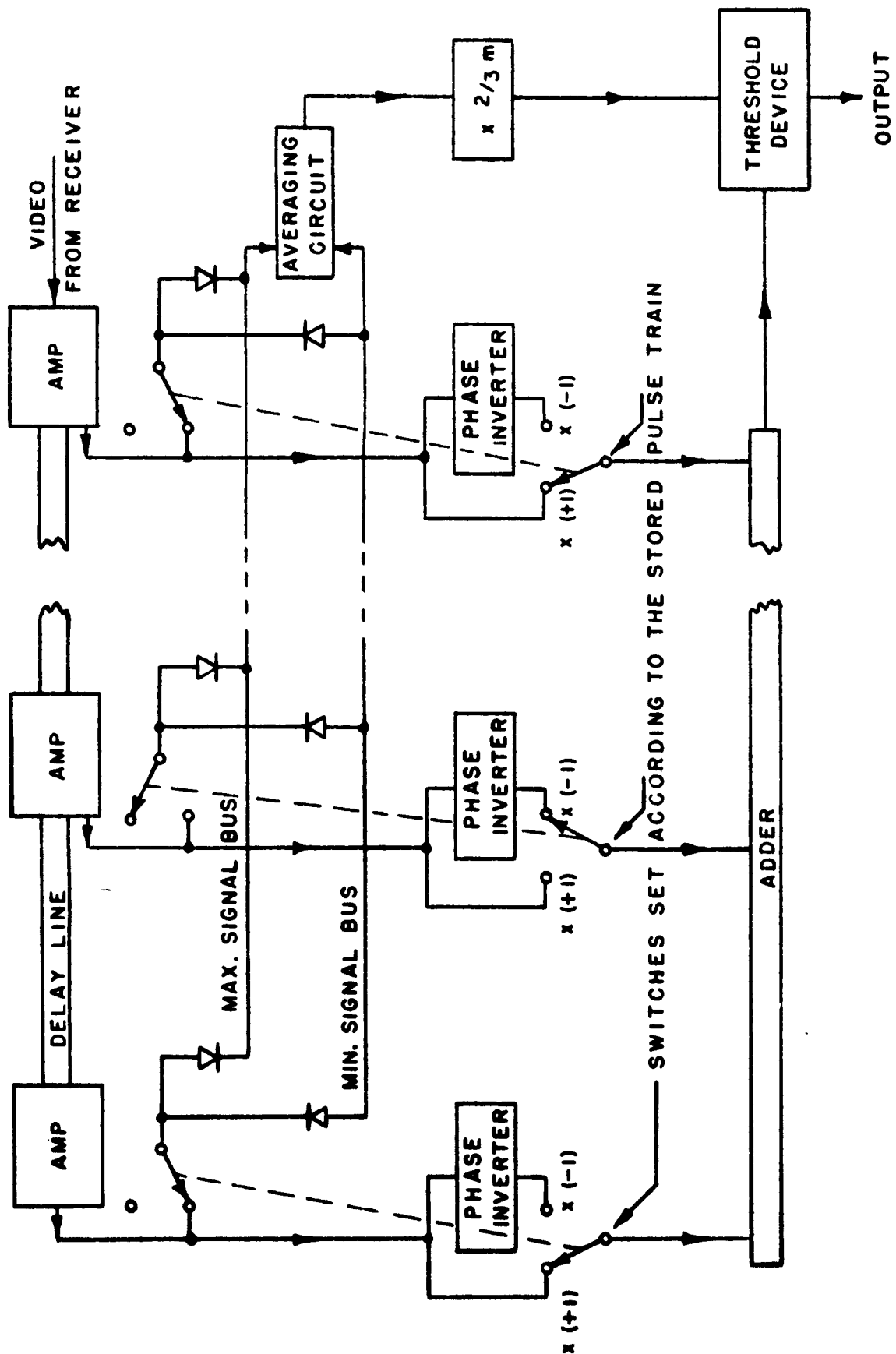


FIG. 2. BLOCK DIAGRAM OF PULSE-TRAIN CORRELATOR.

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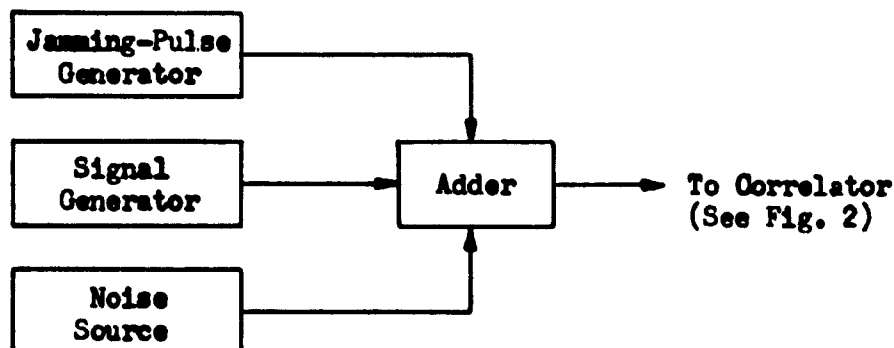
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will arrive in essentially random positions of the friendly signal, due to the varying time of transmission. The expected value of the effect of such random pulse jam in the adder is zero if x is given the value $-\frac{m}{k}$. With that assignment of x , however, the improvement in signal to random noise ratio is greatest if $m \leq k$ and $x = -1$.

The optimum threshold setting for such a system in the presence of a friendly pulse train is a level slightly less than m times its signal strength, while in the absence of a friendly pulse train the threshold should not be allowed to drop so low that practically any (enemy) signal will produce an output. These requirements are contradictory, and a compromise solution has to be sought. One such solution is to set the threshold level at any instant to m times two thirds of the average between the maximum and minimum signals existing at the " m taps" at that instant. This method will make the threshold equal to m times the friendly signal strength if a pulse jam of intensity equal to the friendly signal S is assumed and if at least one of the friendly signal pulses coincides with a jam pulse (giving a maximum " m tap" signal of strength $2S$) and at least one of the friendly pulses has no jam on it (giving a minimum " m tap" signal of strength S), while in the absence of a friendly signal the threshold will not drop unduly low. A signal-to-jam ratio of 1 is chosen in this analysis since it is felt that with much lower values of signal-to-jam ratio the signal is probably irretrievably lost, and that with much higher values the jam will have relatively little effect.

A more detailed theoretical analysis of this problem appears promising. At the same time, a working model of a correlator and associated test equipment are under construction. The correlator is designed for eight-place pulse trains using 0.6 microsecond pulses spaced respectively 3, 7, 6, 2, 12, 5, and 4 pulse widths apart. These spacings prevent any undesired multiple coincidences. The test equipment consists of an eight-place pulse-train generator, a jamming-pulse generator, a broad-band noise source for noise jamming, and an adding circuit for combining signals and jamming. A block diagram of the test equipment under construction is shown below. The correlator together with the associated test equipment could be considered to



represent the air-to-ground link of a possible IFF system. The signal generator is equivalent to the airborne transponder while the correlator represents the essential part of the I-R unit. Jamming is introduced in the transmission link and thus the adder is used to represent this section of the air-to-ground system.

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e. Apparatus and Equipment

Pulse-Train Generator

The pulse-train generator under development will generate an eight-digit number consisting of 0.6- μ s pulses spaced at intervals of 1.8, 4.2, 3.6, 1.2, 7.2, 3.0, and 2.4 microseconds respectively. The repetition rate of the number will be variable from 1 to 2 kc.

A chain of eight delay multivibrators will generate the interval between pulses in the number, and also initiate a common one-shot multivibrator to generate the 0.6- μ s pulses. Internal synchronization will be incorporated in order to ensure time stability.

A breadboard model for the generation of a three-digit number, without internal synchronization, has been constructed and is operating satisfactorily. The internal synchronization circuit is under development at the present time.

Random-Noise Generator

A General Radio Company Type 1390-A Random-Noise Generator is available for broad-band noise jamming. It is planned to rectify the output of the noise source so that a jamming signal will be available which bears some resemblance to that obtained at the output of the detector in a receiver. The rectifier design will be started in the near future.

Pulse-Jamming Generator

The pulse-jamming generator is under development at the present time. The pulse-repetition frequency will be variable from 40 kc to 1 mc, and the pulse width will be variable over the range of 0.5 to 1.5 μ s.

The pulse-repetition frequency will be determined by an oscillator. The output of the oscillator, after being passed through suitable shaping circuits, will be used to trigger a one-shot multivibrator. At the present time the development of the pulse-jamming generator is in the breadboard stage.

Adder

Subsequent to the decision to rectify the output of the random-noise generator, a breadboard adder had been constructed to add either noise jamming or pulse jamming to the output of the pulse-train generator. However, it is felt that this adder will not be adequate for general purpose use and consequently a new adder will be developed so that noise jamming and/or pulse jamming may be combined with the output from the pulse-train generator.

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Pulse-Train Correlator

The required seven pieces of delay line have been cut to the proper lengths, using 1350-ohm distributed-constants delay cable purchased from the Millen Co. The circuit for the in-line amplifiers has been developed, consisting of a grounded-grid voltage amplifier (grounded grid to prevent phase reversal) driving a cathode-follower output stage. Direct coupling is used to preserve the zero level independent of noise and pulse repetition frequency.

f. Assembled Data

This section does not apply to this report.

g. Conclusions and Recommendations

1. The "theory of games" approach, while a powerful one, requires data that are difficult to obtain in practice even when narrow specific problems are postulated for solution. It is evident that there are definite limitations to the usefulness of this approach to the general IFF problem.

2. Since it appears that the studies on equipment and system reliability will inevitably require consideration of the composite signal in a pulse receiver before and after detection, and low-pass filtering, the completion of a survey of contemporary related projects - such as those of Middleton and Johnson at Harvard^{12,16}, Kraft and Weinberg at M.I.T.¹⁴, etc. - is most appropriate. This may include the necessity for certain experimental work since it has been pointed out* that analytical approaches to such problems may not be feasible.

3. The use of Shannon coding has been shown to provide a systematic way for improving reliability. It however appears that any such system would require a complexity of equipment.

4. The rotating-antenna scheme for providing geometric security (as discussed in the previous report) still has high merit as a practical device providing increased system reliability in the presence of enemy jamming. It is recommended that the evaluation of this idea by other groups (as has already been begun at AFCRC) be continued. The attention of these groups is also called to the idea of the use of a fixed directional airborne antenna and corridors.

h. Future Work

In view of the work of this and previous report periods, and the above conclusions and recommendations, it is intended that future work include:

* See, for example, the work of Johnson (Ref. No. 16)

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1. A study of the findings of those groups working on operational analysis with the multiple aims of (1) obtaining up-to-date estimates of the requirements on the IFF systems of the future insofar as expected reliability are concerned, and (2) providing data for a comparative evaluation of various IFF systems which fall within the scope of the contract.

2. Conferences with other groups working on related problems in order that full advantage can be taken of the results of their studies.

3. A continuation of the survey to obtain factual data to be used in a comparison of S and X-band frequencies insofar as IFF applications are concerned.

4. The continuation of the survey covering jamming techniques as applied to radar and other related pulse communication methods.

5. The following-up of the work on the rotating-antenna scheme that has been referred to the Antenna Laboratory of AFCRC.

6. The completion of the working model of the pulse-train correlator designed to provide reliable detection of pulse trains.

7. The completion of the construction of the pulse-train generator providing non-uniform symbol-interval lengths for testing the pulse-train correlator.

8. The completion of the construction of the pulse- and noise-jamming sources for use in testing future equipment devised as part of the work of this contract.

9. An investigation of the feasibility of instrumenting systems for improving overall reliability by the use of redundancy. Examples of schemes using redundancy are Shannon coding of the pulse train and the transmission of a number and its complement.

10. Further analytical work for determining the optimum method for setting the threshold in the pulse-train correlator.

11. Further investigation of the theoretical and practical aspects of optimum filtering.

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