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NRL REPORT 3915

TIME-DEPENDENT PROBABILITIES

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December 29, 1951

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CONTENTS

ABSTRACT

The problem of intercept probability breaks down into a number of subtle subproblems. An effort is made to establish consistent terminology by using the word "probability" properly in a statistical sense and the word "intercept" properly in its tactical sense. The need then arises for new terms to describe processes of well-known electronic countermeasures. Several probabilities are formulated so that quantitative measurement becomes both meaningful and possible. A procedure is given to measure time-dependent probabilities by an electronic digital analyzer.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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TIME-DEPENDENT PROBABILITIES

INTRODUCTION

Considerable misunderstanding and misinterpretation of time-dependent probabilities exist owing to the absence of solid definitions for the terms used to describe them and because technical applications in the time domain are not as straightforward as the more familiar applications to the theories of elementary games. For these and other reasons, almost everyone who speaks of probability of intercept has some different, vague, intuitive, qualitative notion of what it means.

Before attempting to build up a consistent countermeasures terminology, let us first note that in the bibliography appended hereto is a chronological list of articles sufficient to cover the background material and its historical development. Definitions of the various probabilities are proposed so that a direct experimental approach may be made to the problem using at most a statistical time-series analyzer in which the most complicated mathematical operation is addition. With an adequate source of pertinent data, analysis techniques may be intelligently applied, and quantitative prediction of the probabilities becomes possible in terms of the many systems parameters such as antenna scan rates, receiver tuning rates, and pulse characteristics.

To justify an empirical basis for the present definitions, let us submit the following from various sources:

1. "Before we speak of probabilities, we must agree on an idealized model of a particular conceptual experiment."[1]

2. "All probabilities are in reality determined by an empirical process."[2]

3. "...the probabilities have their counterparts in observable frequency ratios, and any probability number assigned to a specified event must, in principle, be liable to empirical verification."[3]

Let us add one more quotation relative to the importance of considering the several probabilities as functions of time.

"The main interest of physical statistics lies not so much in the description of the distribution of properties in space, as in that of their change in time."[4]

[1] Feller, W., "An Introduction to Probability Theory and its Applications," p. 4, New York: Wiley, 1950

[2] Fisher, A., "The Mathematical Theory of Probabilities," p. 63, New York: MacMillan, 1922

[3] Cramer, H., "Mathematical Methods of Statistics," p. 151, Princeton: University Press, 1946

[4] Mises, R. von, "Probability, Statistics, and Truth," p. 261, New York: MacMillan, 1939

DEFINITIONS OF TERMS

Intercept

To begin, first examine the word intercept. Intercept, as a word, has tactical connotations that are not entirely dependent upon, and sometimes entirely independent of electronics. Webster's unabridged dictionary defines intercept: "1. To take or seize by the way, or before arrival at destination; to interrupt the course of; as to intercept a letter. 2. To prevent; hinder. 3. To cut off communication with, a view of, etc." Now, an unwelcome recipient of transmitted information is not preventing information from reaching its destination, or interrupting the flow, or taking it necessarily before arrival at its destination.

The word intercept, then, should be left to the tacticians where the probability of a missile intercepting an aircraft would have a well-defined, specific meaning. As another example, what is the probability of successfully completing a ground-controlled intercept (GCI)?

To be specific, it will be understood that an intercept is the involuntary physical change in direction of motion of an object from a threatening to a harmless aspect by (a) force or threat of force, or (b) deception, jamming control signals, or other methods.

For an intercept of type (a), we must at least know with sufficient accuracy the equivalent of the azimuth, elevation, and range of the object. For an intercept of type (b), we must know with sufficient accuracy the frequency of the control signal, perhaps the type of modulation (e.g. AM or FM), and possibly the system of coding (e.g. in PAM or PTM).

Synchrocept and Countercept

What, then, is the proper term for the probability of a radar system "contacting" a potential nuisance? And, in addition, what is the probability of a search receiver "picking up" an emission of a given type from a given source and extracting a given bit or set of information such as the frequency, pulse characteristics, azimuth, or combination thereof? These two probabilities are distinct and independent; unambiguous and concise names for them would aid the tactical man who alone is concerned with perhaps all these probabilities.

The word synchrocept[5](or syncrocept) is here submitted as a generic term to describe events inherent in a "closed" (e.g. a radar) system. A typical event is the perception, within a given accuracy, of the range of a spatially fixed object in a given time, t; another event is the perception of an object moving with a relative velocity, $v(t)$, over a given path before the object arrives at a range, R, from some reference range R_0.

Countercept[6] is suggested as a name to describe events corresponding to the gathering of knowledge by an "open" (e.g. an independent receiving) system. Major emphasis here is given to the perception of some combination of features such as the direction, frequency, and pulse characteristics within a given accuracy (a) of a spatially fixed primary or secondary source in a given time, t, or (b) before a source moving with relative velocity, $v(t)$, over a specified path arrives at a range R from some reference range, R_0.

5 The word synchrocept is a dual play on the words synchronous and perception. The receiver involved is synchronously tuned to the transmitter in radar and sonar, and in the case of the AM radar at least, the pulse transmitted is synchronized with the start of the indicator timing trace. If found desirable, specific terms such as radarcept, sonarcept, interrocept (interrogation-reception) might also be used.

6 The word countercept is the equivalent of counter-perception.

An intercept, which prevents an object from completing its mission, may be accomplished by both synchrocept and countercept techniques. It should be especially noted that there can be no intercept which has not been preceded by either a synchrocept and/or a countercept. The word synchrocept would be confined to closed systems such as sonar and radar.

In many systems suggested by the following list, a countercept would be useful, and the study of the corresponding countercept probability would be of considerable importance:

- Primary
  - Point to point communications
  - Broadcast (point to multiple points)
    - Visual
    - Aural
  - Other Services
    - Time signals
    - Standard frequencies
    - Loran
    - Beacon
  - Nuisance
    - Jamming
    - Decoy
  - Control
    - Guided missiles
    - Proximity fuse
  - Radar
  - Sonar
  - Infrared, visible light, or other unintentional radiation
- Secondary
  - Reflected light
  - Other reflected radiation from unrelated sources

STATISTICAL MEASURES OF PROBABILITY

In reviewing the various approaches to the probability problem, it becomes evident that existing expressions for probability as a function of the systems parameters and the time leave little room for direct experimental verification as a test of their suitability. The main object here is to contain the theory so that physical verification becomes possible.

Once proper statistical measures of the various probabilities as functions of time or range are given sound foundations in realizable experiments, it follows that any existing or future expressions giving these probabilities in terms of system parameters must be explanations of these distributions. This means, of course, that when we talk about a particular probability, say the synchrocept probability, we always know that it is defined in a specific way in terms of a particular experiment.

Randomness

In speaking of probabilities, we must keep in mind the concept of equally likely cases. The probability of synchrocept before an aircraft closes to range R cannot be determined easily because there are innumerable ways for the craft to reach R, and even though we could enumerate the paths, they are not all equally likely. In fact, most paths are purposefully and arbitrarily chosen, and this is the antithesis of randomness. We must then consider the synchrocept probability of an aircraft before it closes to a given range over a specified path. For example, consider an aircraft controlled by a null-seeking servomechanism entering the vertical radar pattern (Figure 1) and homing on it. What is the synchrocept probability of this aircraft before reaching a range R? The countercept of an aircraft zeroing on the countercept system is also an important accepted problem.

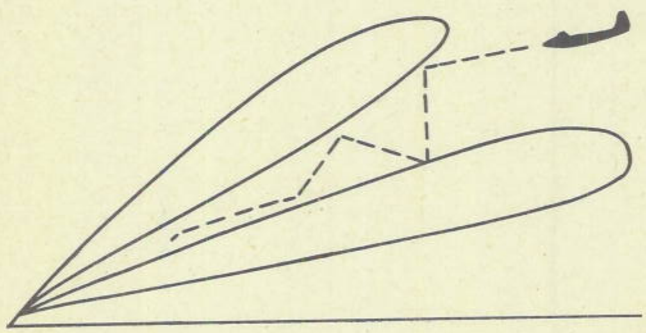

Figure 1 - Aircraft homing on radar

Static or Restricted Dynamic Cases

We first restrict our attack to a solution of what may be called the static or restricted dynamic case of countercept probability. Either there is no relative motion between the transmitting and receiving systems or the relative motion is assumed to take place without appreciable change in parameter values, for example, the effective antenna beamwidths (azimuth and/or elevation resolution) or the apparent receiver bandwidths (receiver resolution) Given the fixed parameters, a similar approach could be set up to measure synchrocept probability.

The effect of the manual or automatic gain control on a synchrocept and/or a countercept receiver should be considered. To read frequency or range to the required accuracy, the operator may compensate the gain control which gives the effect of cancelling the importance of the minor lobes and range in broadening the indication. This effect should, it seems, increase the importance of what is here called the restricted dynamic case, which may accurately describe the probabilities under fully dynamic conditions.

Dynamic Cases

The approach must be modified and defined by another experiment in the dynamic cases for probability reasons connected with nonstationary time series. The impelling reasons for the particular experiment adopted in the restricted case are its usefulness for intercomparison of systems for the design engineer, the determination of quantitative risk probabilities for the tactician, and the much greater simplicity of experiment. The test can be successfully carried out in a laboratory as well as in the field; satisfactory "static" systems simulators are available.

In a laboratory setup, the true dynamic case contains numerous difficulties which have no immediate solution impending, and although an automatic time-series analyzer is used, field collection of sufficient data for high statistical reliability becomes costly. Using rival radars and rival search receiving systems, the complete problem of probability of intercept could be attacked as a single field problem that costs only slightly more than the field setup for the dynamic synchrocept and countercept cases. If handled intelligently, this test could be made a decisive criterion for synchrocept and countercept systems.

COUNTERCEPT PROBABILITY

Nearly all attempts to define what we call countercept probability have assumed a definite form for the distribution function that describes this probability, for example, the binominal or the Poisson distribution.[5,6] This assumption leads, of course, to a well-behaved statistical law. However, the effect of the possible existence of periodic, almost-periodic, nonrandom, or nearly nonrandom parameters on the statistical behavior of a given system such as the pulse repetition frequency of a radar, or receiver- and transmitter-antenna rotation rates, etc., has not been adequately recognized. For example, in a radar or panoramic system, the statistical independence of "scans" has been a source of controversy for some time.[7] Until proof is offered, no a priori reason appears for choosing any definite distribution over another. Other attempts to define countercept probability are made without recognizing the necessity for the existence of a definite distribution.[8]

The problem here is to unambiguously define countercept probability in a general way without assuming any particular probability distribution for the time-dependent events. When a distribution function is found for a family of cases and this function can be defined in terms of the corresponding systems parameters, prediction of countercept probability from known parameters becomes possible. With rare statistical events that can be considered properly random, the Poisson distribution appears satisfactory.[6]

Recognizing the statistical variations of the several parameters about their mean (nominal) rates, an attempt is made to accept the transmission-counterception system as a unit and to let the system generate its own distribution function in a controlled hypothetical experiment. As any hypothetical experiment must have a realizable counterpart in a practical experiment, the proposal is made to duplicate in practice the hypothetical experiment in a finite, reasonable time, and thus give a measure or estimate of countercept probability.

THEORETICAL DEVELOPMENT

Definition 1

A countercept is the perception of specified information within a given accuracy, together with proper information transfer and/or storage, (page 2, "Synchrocept and Countercept").

Hypotheses

(a) A complete transmission-counterception system is assumed.

(b) Any definition of countercept probability must be a monotonically increasing function of time.

(c) Any definition of probability concerning a countercept must satisfy the mathematical rules governing probability:

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5 Hollywood, J. M., "Probability of Intercepting Radar Signals by Search Receivers," NRL Report R-2843 (Confidential), June 18, 1946

6 Lomax, S. E., Great Britain A.S.R.E. Technical Note, Reference CX4/48/10, Nov. 17, 1948

7 Richards, P. I., "Probability Formulas for Simultaneous Periodically, Recurring Events," RRL 411-171, p. 1, May 5, 1945

8 Arnett, H. D., "The Conditions for Certainty of Interception of an Intermittent Signal by a Rotating Directional Antenna," NRL R-2779 (Confidential), July 10, 1946

1. The countercept-probability frequency-function p must be non-negative and normalized to unity, $p \geqslant 0$.

2. The countercept-probability distribution-function p_1 must be a non-negative, nondecreasing function, $0 \leqslant p_1 \leqslant 1$.

The given system (hypothesis a) will generate f(t). According to the definition of a countercept, we are concerned only with impulses exceeding a minimum level, A in Figure 2a.

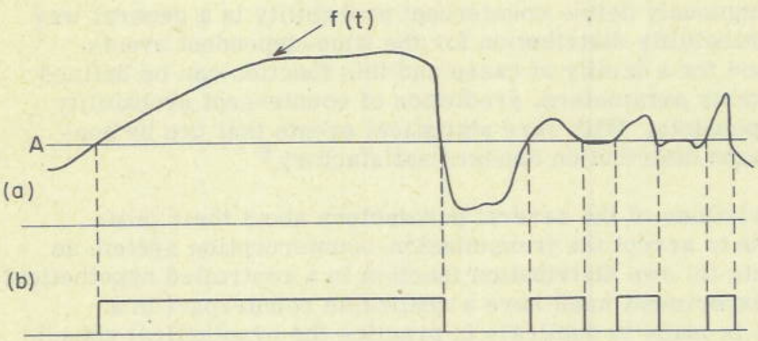

Figure 2 - Original and modified time function. (a) Time-series f(t), (b) Modified time series

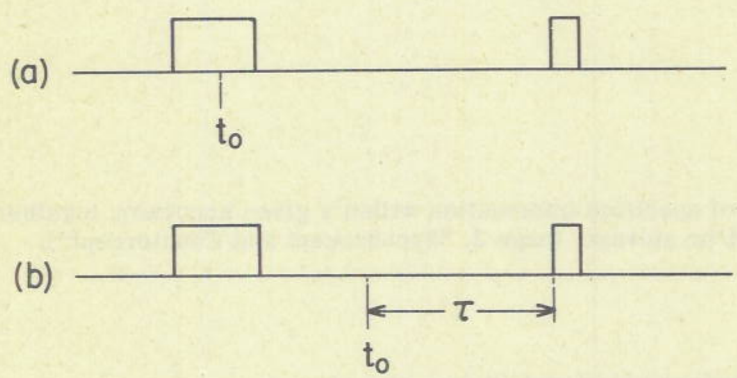

Figure 3 - Various possible time origins. (a) Time origin on impulse, (b) Time origin between impulses

The observer, human or mechanical, will be aware of all discrete pulses shown in Figure 2b. If an observer begins his duties at a time t_0 anywhere within a pulse, he will be on countercept with no waiting period (Figure 3a). If the observer begins anywhere but on signal, he must wait a period τ for a countercept (Figure 3b), τ is the time from t_0 to the first following pulse for a mechanical observer or the time from t_0 to the first impulse on which a human observer commits himself. In this way, the observer factor is automatically incorporated into the over-all probability statement, and there is no longer the necessity for separate consideration of 1, 2, ..., k, ... blips for a countercept.

Hypothetical Experiment

Let the stationary time series f(t) be defined over a finite or infinite period of time T. Assume that an observer may begin anywhere within T with equal probability at any one of n equally spaced points, each separated by intervals T/n (Figure 4). The observer, starting from t_0, must wait a time τ for a countercept. If t_0 lies within a "pulse," $\tau = 0$.

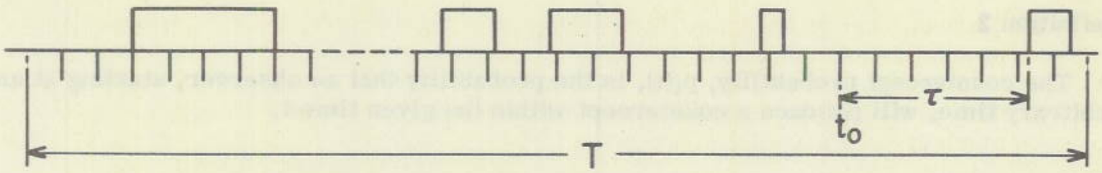

Figure 4 - Modified time series for hypothetical experiment

Let all possible τ in T be ordered and arranged in equal class intervals so that some τ' may exist in $\tau_{i-1} < \tau' \leqslant \tau_i$ where $\tau_i - \tau_{i-1} = \Delta\tau = T/n$; $i = 1, 2, \ldots m$ where $m \leqslant n$. There will be ν_i events in the i^{th} class interval. The ratio ν_i/n is the relative number of τ's in the i^{th} interval (Figure 5a) and represents the relative frequency of waiting times τ' appearing in $\tau_i - \Delta\tau < \tau' \leqslant \tau_i$. In particular, ν_0/n will represent the relative frequency of zero waiting time. In the limit as $n \to \infty$ and $\Delta\tau \to 0$, $\nu/n \to p(\tau)$, which is the probability of waiting a time τ', where $\tau - d\tau < \tau' \leqslant \tau$ for a countercept (Figure 5b); $p(o) = \lim_{n\to\infty} \nu_0/n$. It should be noted that $p(\tau)$ is a frequency- or probability-density function, and yet it is a monotonically decreasing function of τ and will lead to an integral not only non-negative and nondecreasing, but also everywhere convex.

The integral of the function $p(\tau)$ is

$$p_1(t) = \int_0^t p(\tau) d\tau \qquad (1)$$

and is of the form shown in Figure 5c. The function $p_1(t)$ is the probability of waiting t seconds of less for a countercept or the probability of a countercept in t seconds or less. Although negligible in many cases, $p_1(o)$ will always be finite.

The function defined by Equation (1) should be useful from an operational standpoint because it unambiguously gives a measure of the observation time necessary for the countercept probability to reach a predetermined value.

It should be noted that the particular method adopted for the practical measurement of probability is not unique, and several alternative procedures, all leading to the same probability statement, are available. Instead of measuring the on and off times independently, the system was originally set up to measure the on times and the periods, the times between successive leading or trailing edges of the signal.

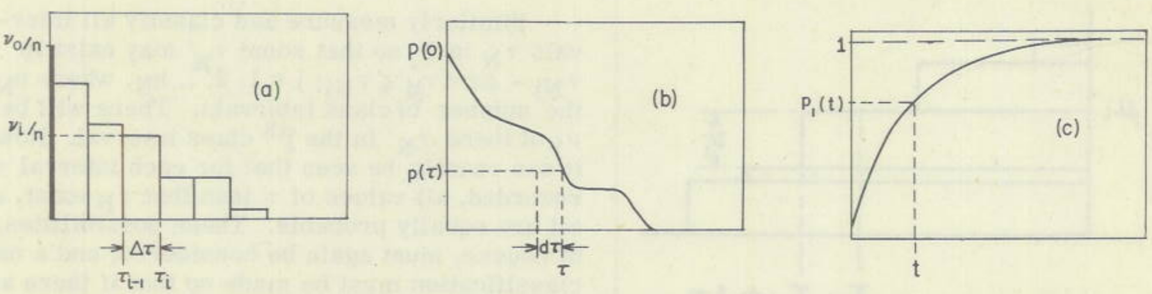

Figure 5 - Method of deriving probability-distribution function. (a) Relative frequency distribution of τ for hypothetical experiment, (b) Probability-density function for hypothetical experiment, (c) Probability-distribution function for hypothetical experiment

Definition 2

The countercept probability, $p_1(t)$, is the probability that an observer, starting at an arbitrary time, will produce a countercept within the given time t.

Practical Measurement of Countercept Probability

The function $p_1(t)$ is a definite statement for a given system which may consist of one of many combinations of transmitters, receivers, antennas, etc. The problem is to design an experiment which, with a minimum effort, will give us an approximation to, or a measurement of $p_1(t)$.

Suppose, following the theory of errors, that either $f_1(t)$ (Figure 6) is a stationary time series or may be so considered over the available observation time, T_1. Assume again that the observer may begin with equal probability anywhere within T_1 at any one of n_1 points, each separated by equal intervals T_1/n_1.

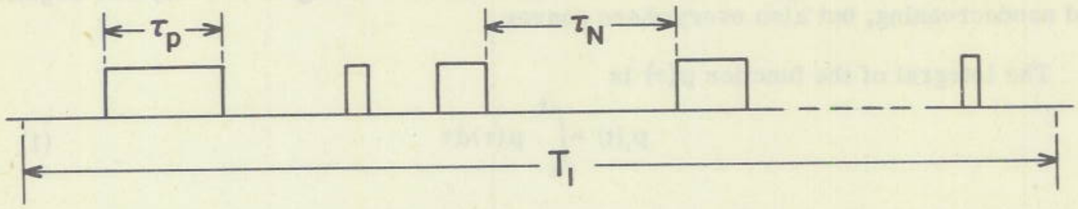

Figure 6 - Modified time series for practical experiment

First, let us measure and classify all intervals τ_p in T_1 so that some τ_p' may exist in $\tau_{pi} < \tau_p' \leqslant \tau_{pi} + \Delta\tau$; i = o, 1, 2, ..., n_p, where n_p is the number of class intervals. There will be ν_i of these τ_p' in the i^{th} class interval. It can be seen that for each τ_p recorded, all values of τ less than τ_p exist and all values are equally probable. These possibilities must, of course, be considered, and a new classification must be made so that if there are ν_i intervals of length τ_p' in $\tau_{pi} < \tau_p' \leqslant \tau_{pi} + \Delta\tau$, there must be added ν_i to each class interval less than the i^{th} (Figure 7). There now will be μ_i possible zero waiting times in the interval $\tau_{pi} < \tau_p' \leqslant \tau_{pi} + \Delta\tau$, and the total number of zero waiting times is $\Sigma_i \mu_i$. The further interpretation of the τ_p distribution (Figure 7) as a probability or otherwise, is not of immediate concern.

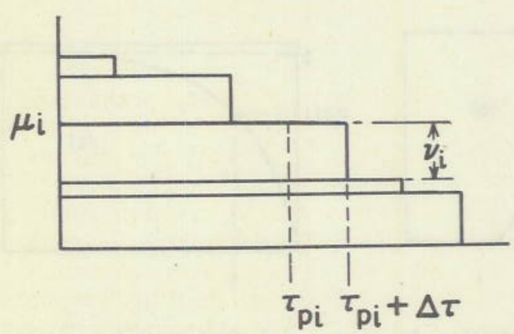

Figure 7 - Absolute frequency distribution of τ_p for practical experiment

Similarly measure and classify all intervals τ_N in T_1 so that some τ_N' may exist in $\tau_{Nj} - \Delta\tau < \tau_N' \leqslant \tau_{Nj}$; j = 1, 2, ...$n_N$, where n_N is the number of class intervals. There will be ν_j of these τ_N' in the j^{th} class interval. Now it can readily be seen that for each interval τ_N recorded, all values of τ less that τ_N exist, and all are equally probable. These possibilities, of course, must again be considered, and a new classification must be made so that if there are ν_j intervals of length τ_N' in $\tau_{Nj} - \Delta\tau < \tau_N' \leqslant \tau_{Nj}$, ν_j must be added to each class interval less than the j^{th} (Figure 8a).

Now, the sum of ordinates in Figure 7 corresponding to $\mu = \Sigma \mu_i$ gives the total number of ways in which we may have zero waiting time; this total will correspond to the origin (Figure 8a). The total number of equally probable times is now $n_1 = \mu + \sum_{j=1}^{n_N} \nu_j$. Using n_1 to normalize Figure 8a, we arrive at Figure 8b which shows relative frequency ν_j/n_1 of waiting τ' in $\tau_j - \Delta\tau < \tau' \leq \tau_j$ for a countercept, $j = 1, 2, \ldots, n_N$; $\Delta\tau = 0$ for $j = 0$, and $\nu_0 = \mu$.

A sum polygon (Figure 8c) of the data of Figure 8b corresponds to the integration of Figure 5c, and a smooth curve, $p_{11}(t)$, fitting these data is a "measurement" or estimate of the countercept probability, $p_1(t)$, for the given system.

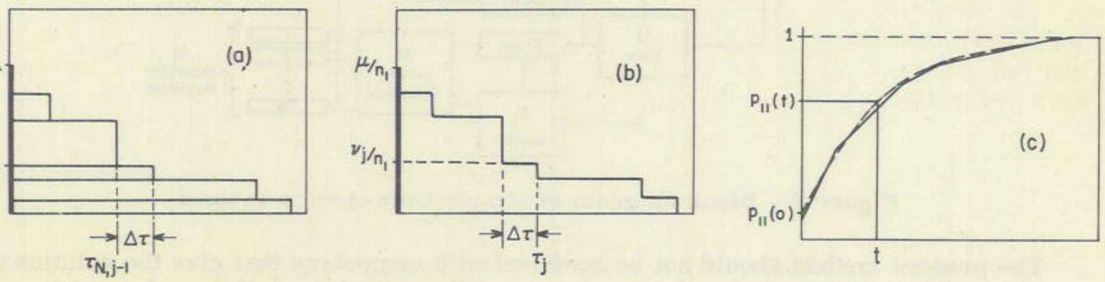

Figure 8 - Procedure for deriving estimate of probability distribution. (a) Absolute frequency distribution of τ_N for practical experiment, (b) Relative frequency distribution of τ for practical experiment, (c) Estimate or measurement of countercept probability

Time-Distribution Analyzer

The time-distribution analyzer (Figure 9) is one means of measuring the various probabilities. The simplicity of the device is not apparent from the block diagram since the main circuits are standard shapers, gates, counters, and indicator decimal-counter registers. The erase and write circuits and the standard (clock) pulse generator present no great difficulties. The system is essentially a stopwatch which automatically measures, sorts, records, and continuously indicates the numbers of pertinent time intervals.

Only the linear quantification is shown, although logarithmic or other time bases are equally useful and practical. An amplitude classifier with equally simple circuitry could gather interpretable amplitude-distribution data. Alternative types of indicators are possible in addition to the one shown.

The system as visualized can be rather compact, and by using the latest techniques in reliable subminiaturization, the size can be further reduced. The resolution or the registration accuracy of the system will depend on the scalers and the gating efficiency.

The system, designed to measure the various probabilities, would run continuously and might include a human observer to press the button of a hand switch each time a signal appeared and to release pressure when the signal disappeared. As the observer cannot ordinarily resolve individual pulses, the analyzer would produce a record of his responses. The "N" distribution would perhaps be of primary importance when the observer provides the video signal (Figure 9). If noise is present in a fully simulated (laboratory) system with a mechanical or human observer, a network of interlocks (gates) could be incorporated so that only true signals would be registered.

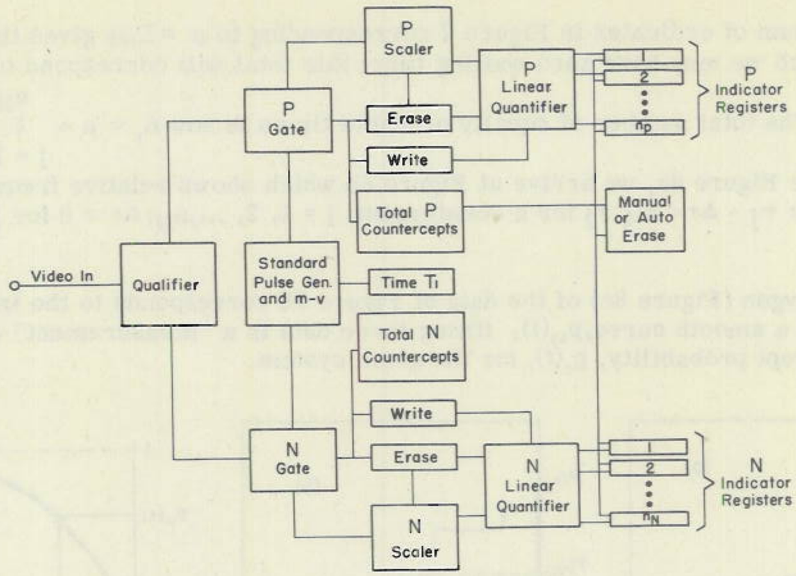

Figure 9 - Block diagram of simple time-series analzer

The present method should not be confused with computers that give the solution of an equation which in itself may be inadequate, or with an autocorrelation analyzer where machine time is often a large multiple of information time. In the present case, the analyzer is applied directly to the real or simulated system under study, and the probability statement arises from a single measurement on a time series in which machine time is essentially the same as the information time T_1; the ensuing economy of data, equipment, and time consumed leads to results directly suitable for use or prediction.

The data (Figure 10a), taken on a system simulator with a preliminary model of the time-distribution analyzer using electromechanical registers, shows the distribution of pulse duration τ_p. Figure 10b should be compared with Figure 7, under "Practical Measurement of Countercept Probability."

CONCLUSIONS

The necessity for consistent terminology is nowhere more evident than in a statistical approach to a physical problem. An attempt is made to stabilize words used in a statistical or probability sense with regard to countermeasures and to uniquely define the important probabilities involved so that quantitative measurements of these probabilities become both possible and meaningful.

For measurement of a specific probability, a practical procedure is outlined and may be extended to the measurement of synchrocept probability or to the time-domain analysis of any sufficiently stationary time series.

ACKNOWLEDGMENTS

Thanks are extended to Mr. G. M. Bullock and Mr. E. N. Munzer, both of the Countermeasures Branch, for constructive criticism at several stages of the work, and to Mr. E. N. Johnson of the Technical Information Division for helpful review of the manuscript.

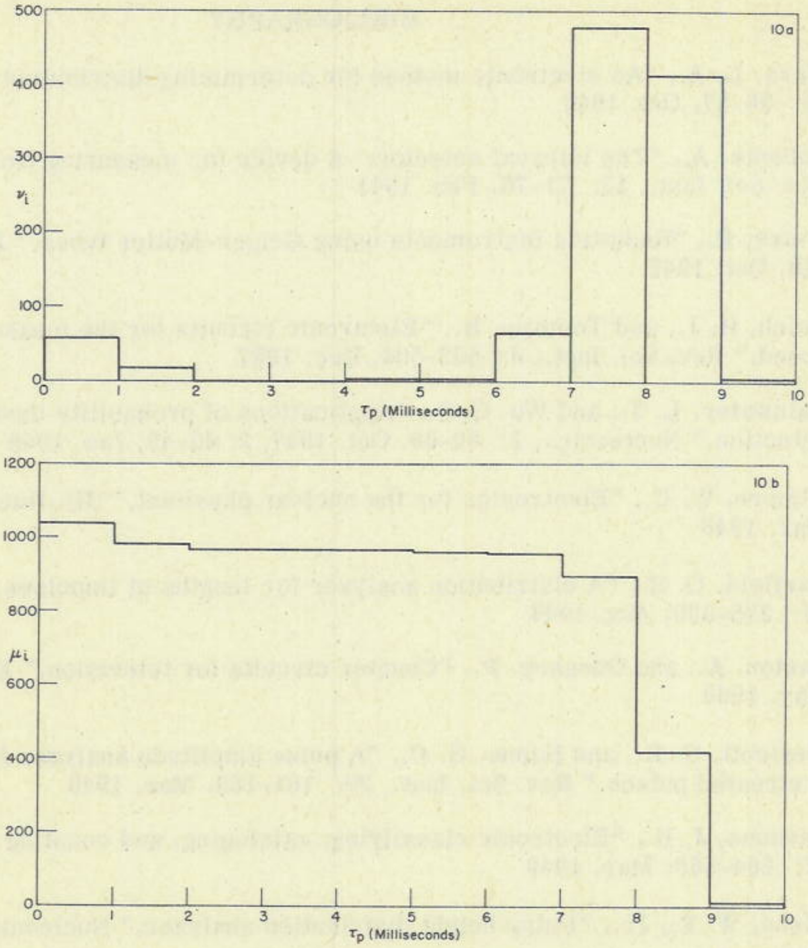

Figure 10 - Experimental data. (a) Data from measurement on simulated system, (b) Frequency distribution corresponding to Figure 7 from this data

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