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GENERAL ELECTRIC CORPORATE RESEARCH AND DEVELOPMENT --ETC F/G 9/4
ESTIMATION OF THE DETECTION PERFORMANCE OF A DISPLAY.(U)

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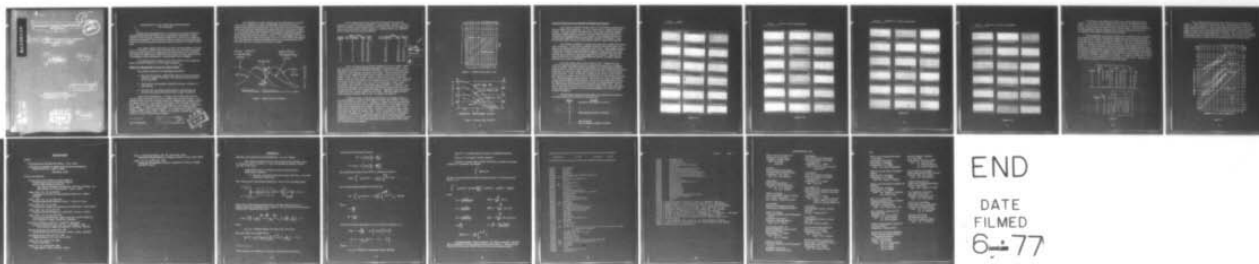
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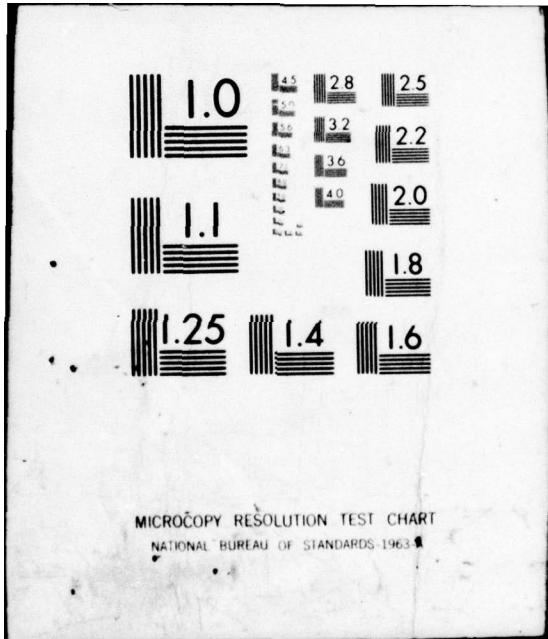
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6 ESTIMATION OF THE DETECTION PERFORMANCE OF A DISPLAY



7 TECHNICAL REPORT TO OFFICE OF NAVAL RESEARCH

Contract No. N00014-71-C-0229

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D. E. Wood
15 Jan 1975

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ESTIMATION OF THE DETECTION PERFORMANCE OF A DISPLAY

Signal detection performance is commonly described by "Receiver Operating Characteristic" (ROC) curves plotting the probability of signal detection (PD) versus the probability of false alarm (PFA) over a range of detection thresholds.* This report describes a method for determining ROC curves for visual displays and presents results obtained from display evaluations.

The visible displays discussed here will represent functions derived from a meaningless random noise waveform that has a particular controlled waveform added whenever a "signal plus noise" message is to be displayed. The addition of signal will be detected by the change in visible patterns from a meaningless noise background to a significantly ordered pattern.

The signal-to-noise ratios are the relative power in the signal and noise waveforms combined to create signal messages.

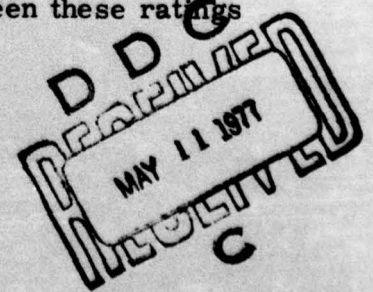
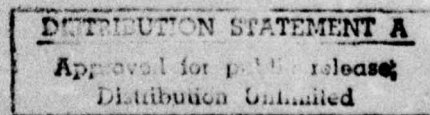
Method for Obtaining ROC Curves for Visual Displays

The method is based on the following assumptions:

1. The observer can set a "threshold" which he can use to decide whether a "signal" is present. This threshold will determine the PD and PFA.
2. The observer can maintain a threshold through a sequence of observations.
3. The observer can change his threshold or equivalently can describe his degree of confidence that a signal is present.

Under these assumptions, a "rating scale" method will provide several points on an ROC curve from a single series of observations. The ratings are the observers' relative degree of confidence that a signal created the pattern observed. For example, an integer scale 0 through 10 may be used. The observer would rate an observation as 0 if he saw no evidence at all of signal. A rating of 5 would indicate the observers' feeling that no signal or signals were equally probable. A 10 rating would signify unqualified confidence that a signal exists. Degrees of confidence between these ratings would be recorded as intervening integers.

*See Bibliography.



The rationale for using a rating scale to obtain points on an ROC curve can be explained in terms of probability density distributions. Assume that a detection function has one probability density distribution for noise and a different distribution for signal plus noise as shown in Figure 1. Now assume that a detection function threshold is established as shown. The area under the portion of the S + N probability density distribution curve to the right of the threshold is the PD. Correspondingly, the PFA is the area under the portion of the noise only curve to the right of the threshold. By selecting a series of threshold points one can determine the PD and PFA curves as a function of threshold settings.

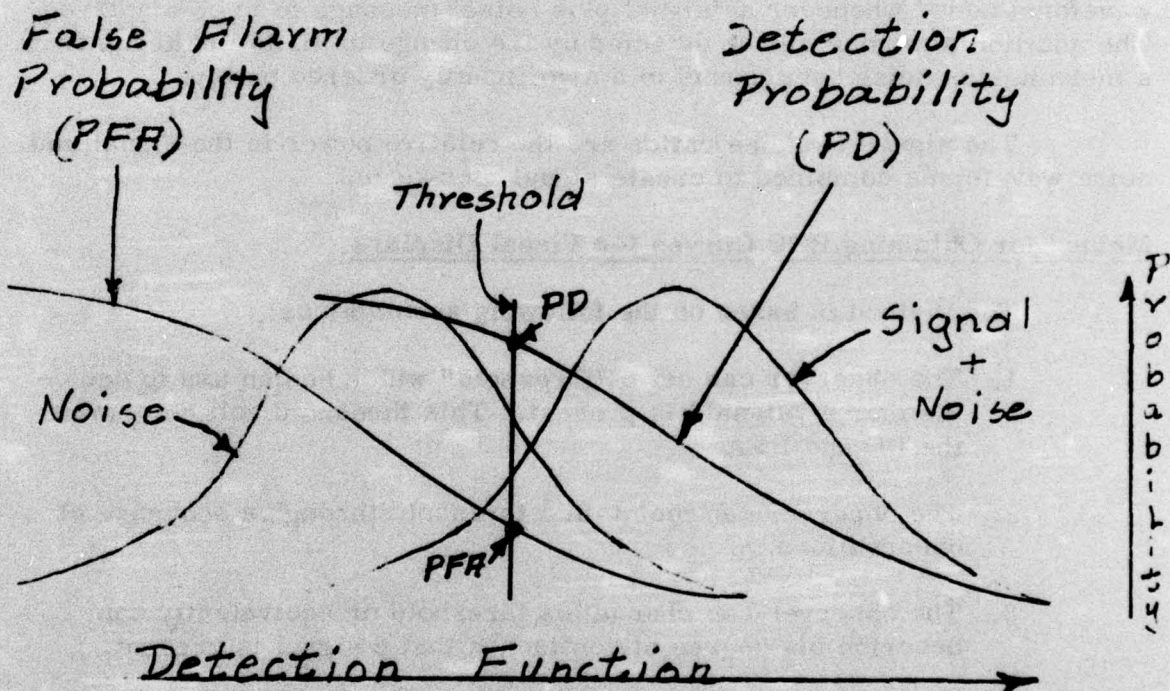


Figure 1 Signal detection relations.

In the rating scale test of detection performance the observer specifies a series of relative thresholds. For example, consider a test in which the observer rates observations of 308 noise cases and 96 signal plus noise cases presented in random sequence. Assume that he has classified the S+N and noise only cases as follows:

Signal + Noise				Noise		
Rating	No. of Obser.	Sum	%PD	No. of Obser.	Sum	%PFA
10	5	5	5.2	1	1	.3
9	13	18	19	2	3	1.0
8	6	24	25	1	4	1.3
7	9	33	34	9	13	4.2
6	15	48	50	20	33	11
5	12	60	62	22	55	18
4	1	61	63	13	68	22
3	5	66	69	18	86	28
2	8	74	77	17	103	33
1	7	81	84	57	160	52
0	15	96	100	148	308	100

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 JUSTIFICATION *See sample*
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At the 10 level he has correctly identified 5 cases of signal + noise and had made one mistake by identifying noise as signal plus noise. Thus, one point on the ROC is 5.2% PD vs 0.3% PFA. At the 9 level the observer identified 13 true signals and made 2 false calls. What the observer means is that 9 is the highest threshold level at which he would call these cases signal + noise. Thus, the total number of cases the observer would call signal + noise (for true signal + noise cases) for a threshold set at 9 would be the number at the threshold level 9 (5) plus the number at level 10 (13) for a sum equal to 18 for signal and a sum of 3 for false calls. Thus, these cumulative sums provide a second ROC point of 19% PD vs 1.0% PFA. Continuing this summing process through successively lower threshold levels, we generate the ROC curve plotted in Figure 2. This ROC curve represents performance for a single signal-to-noise ratio. Different signal-to-noise ratios generate different ROC curves, as outlined in Figure 3.

In typical studies of detection performance a separate series of test observations is made for each signal-to-noise ratio--that is, each test series produces one ROC curve. In theory, a single series of test observations could provide more than one ROC curve if two or more signal-to-noise ratios were represented in the signal + noise test cases observed. In the experiments reported here, we mixed examples of 3 signal-to-noise ratios with noise only cases in random order. Thus, we generated 3 ROC curves from each evaluation test. These ROC curves seemed to bear reasonable relations to each other in light of the signal to noise ratios represented. Evaluating observer display detection performance for mixed signal-to-noise ratios corresponds to real world situations in which signal-to-noise ratios are variable and unpredictable.

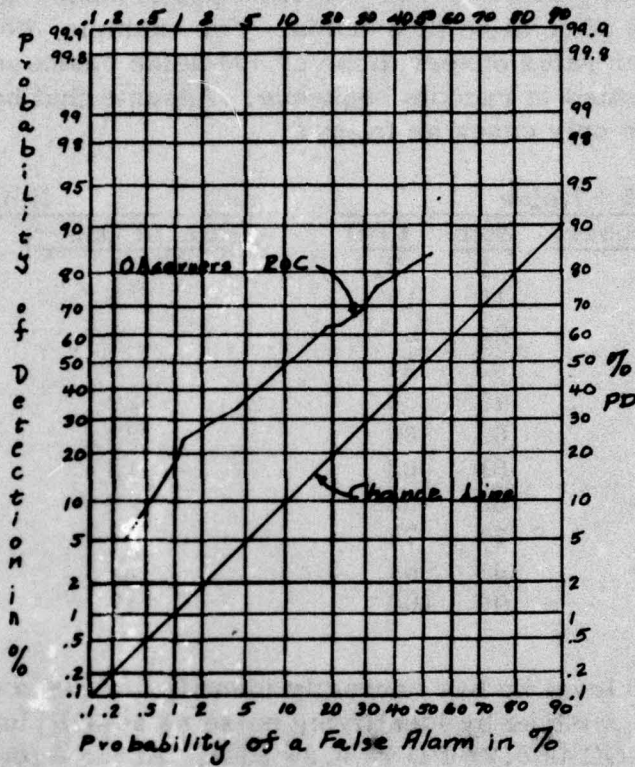


Figure 2 Visual display ROC curve.

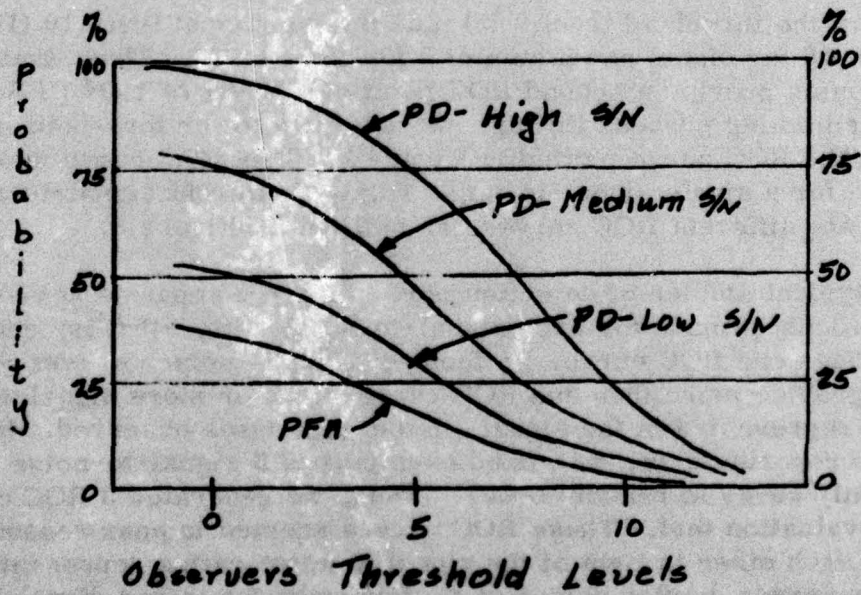


Figure 3 Rating scale relations.

Detection Performance for Intensity Modulated Spectrograms

Time history displays of signal spectra representing amplitude gray scale shadings (Kay Sonagraph, etc.) are widely used in signal processing studies. The spectrograms evaluated here were made by passing signals through an analog spectrum analyzer and recording the spectra on 35 mm strip film by photographing a C. R. T. display. The amplitude function recorded is the magnitude of the spectrum as a function of frequency. Continuous film motion produces a time history record of successive spectra.

For display evaluation, a random noise generator supplied the "noise only" conditions. A sine wave of constant frequency and known power was added to the random noise for signal plus noise cases. Three signal-to-noise ratios were selected to span the general region of 10% to 90% PD for a PFA of about 2%. A total of 600 cases were prepared--approximately 300 noise only and about 100 each at the three signal-to-noise ratios. Observer endurance and the cost of testing limited both the number of sample observations and the number of observers.

Each test sample was a piece of 35 mm film. Figures 4a, 4b, 4c and 4d reproduce samples that were shown to the observer for training prior to testing. Each film section represents a time bandwidth product of about 70 over a frequency span of about 40 spectral lines (resolution elements). If present, the sine wave signal would appear at the center of the frequency range (vertical). Thus, the general background was always random noise. The actual test samples were mounted individually on cards placed in a rotary file. The rotary file presents only one card in view at a time, preventing comparisons of different test samples. Each card was numbered for use by the observer in rating and for use by the scorer in calculating ROC curves. The 600 samples were divided into 5 groups of 120 samples each. The observer does only one group at a time to avoid fatigue. Our experience shows that an experienced observer can estimate probabilities for 120 test cases in about 15 minutes.

The following rating scale instructions were given to each observer on a sheet which he kept with him during the tests.

<u>Rating</u>	<u>Meaning</u>
10	Absolutely sure target is present
9	
8	
7	
6	
5	50% probability target is present
4	
3	
2	
1	Hint of target
0	See no indication target is present

WT ~ 70

NOISE

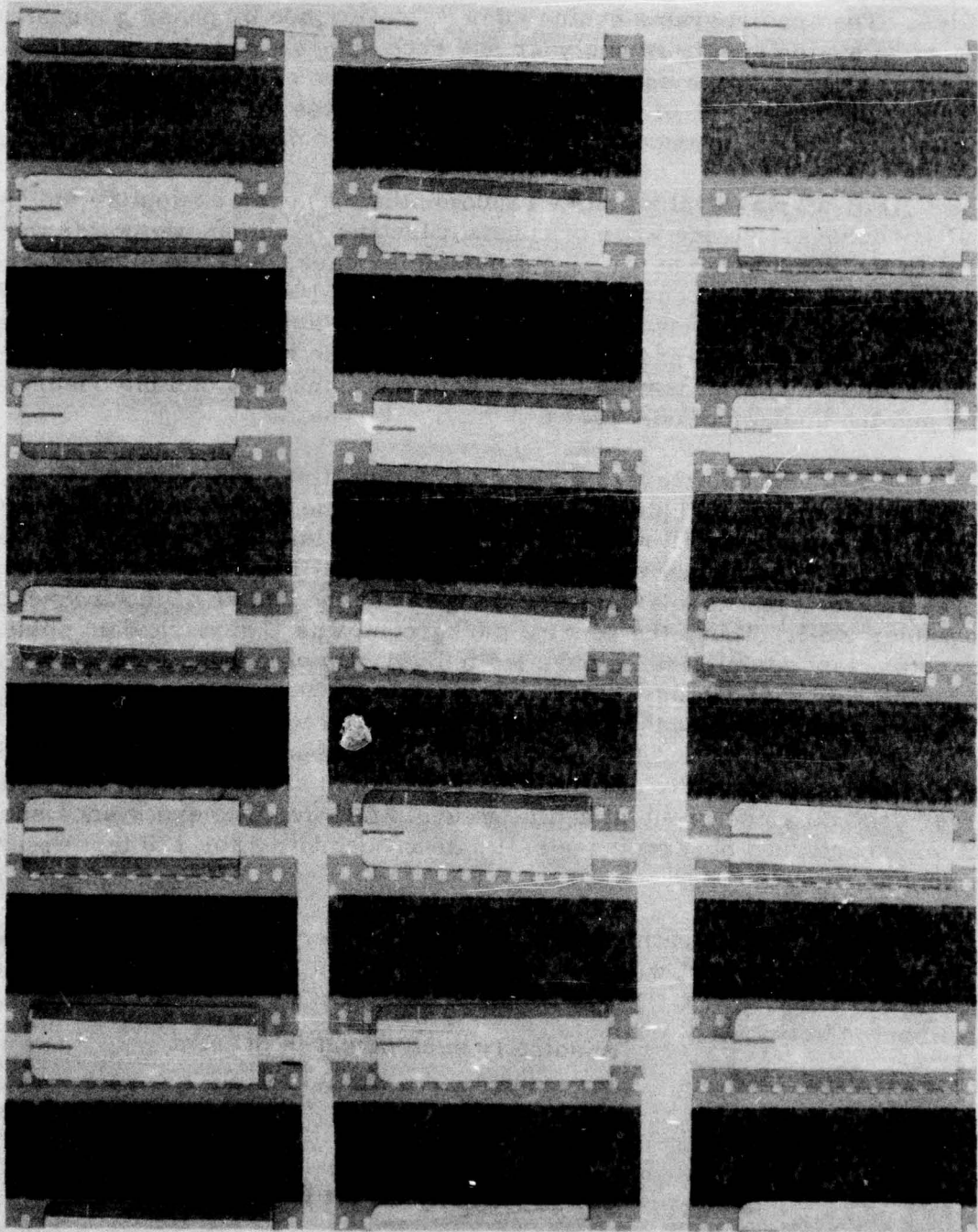


Figure 4-A.

WT ~70 LOW S/N (-5 db IN FILTER BAND)

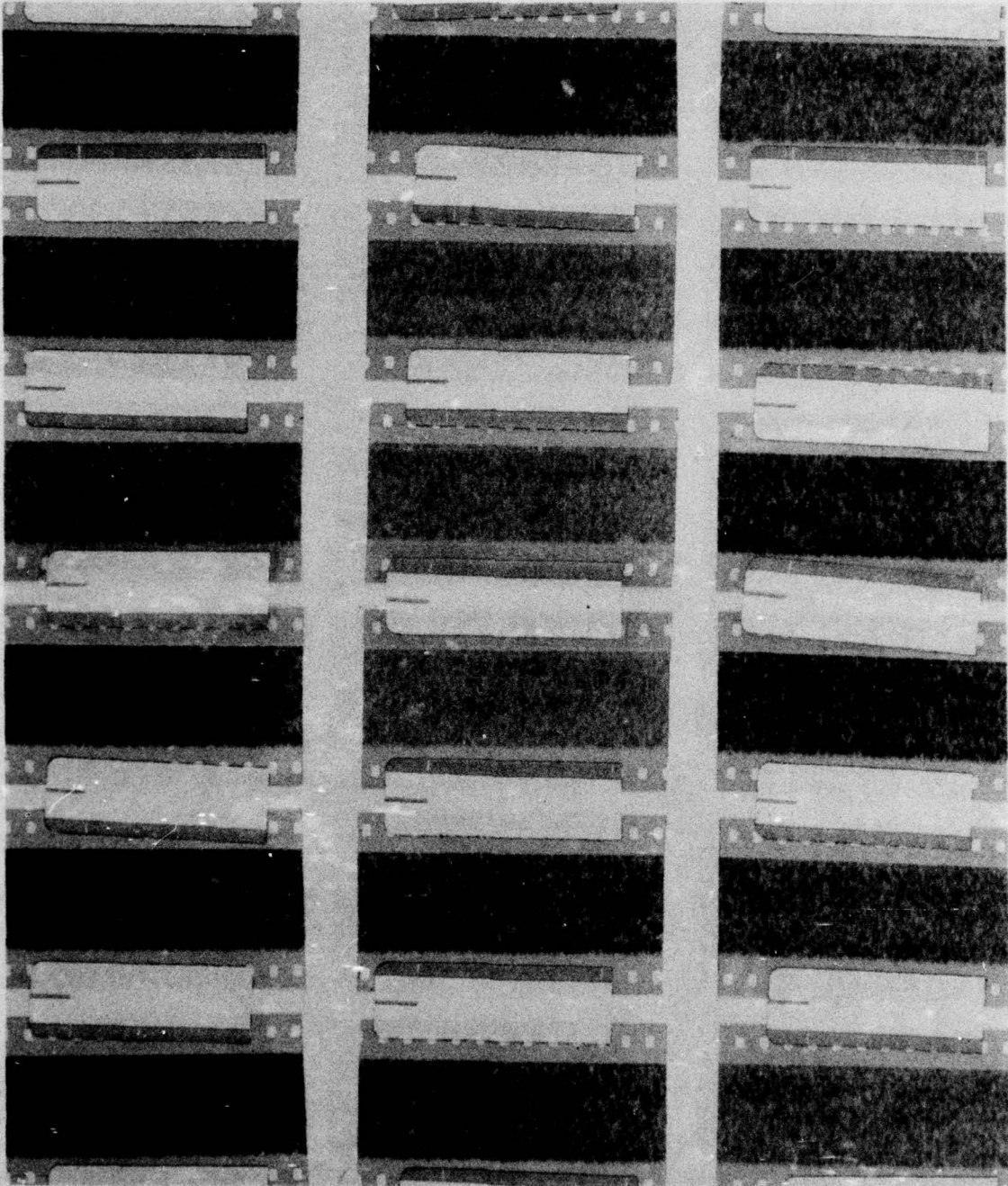


Figure 4-B.

WT ~70

MEDIUM S/N (-2.0 db IN FILTER BAND)

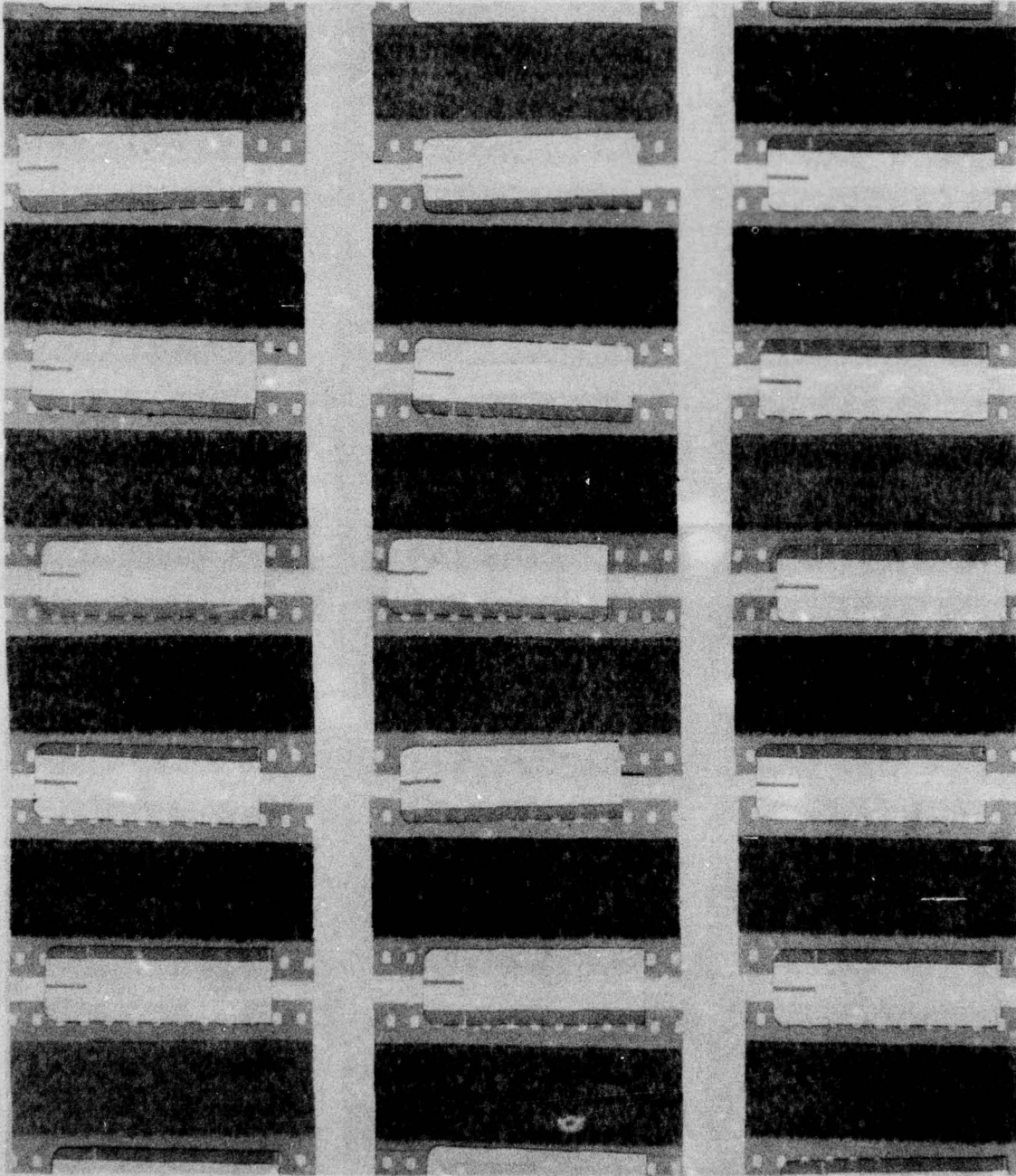


Figure 4-C

WT ~70

HIGH S/N (+ 1.0 db IN FILTER BAND)

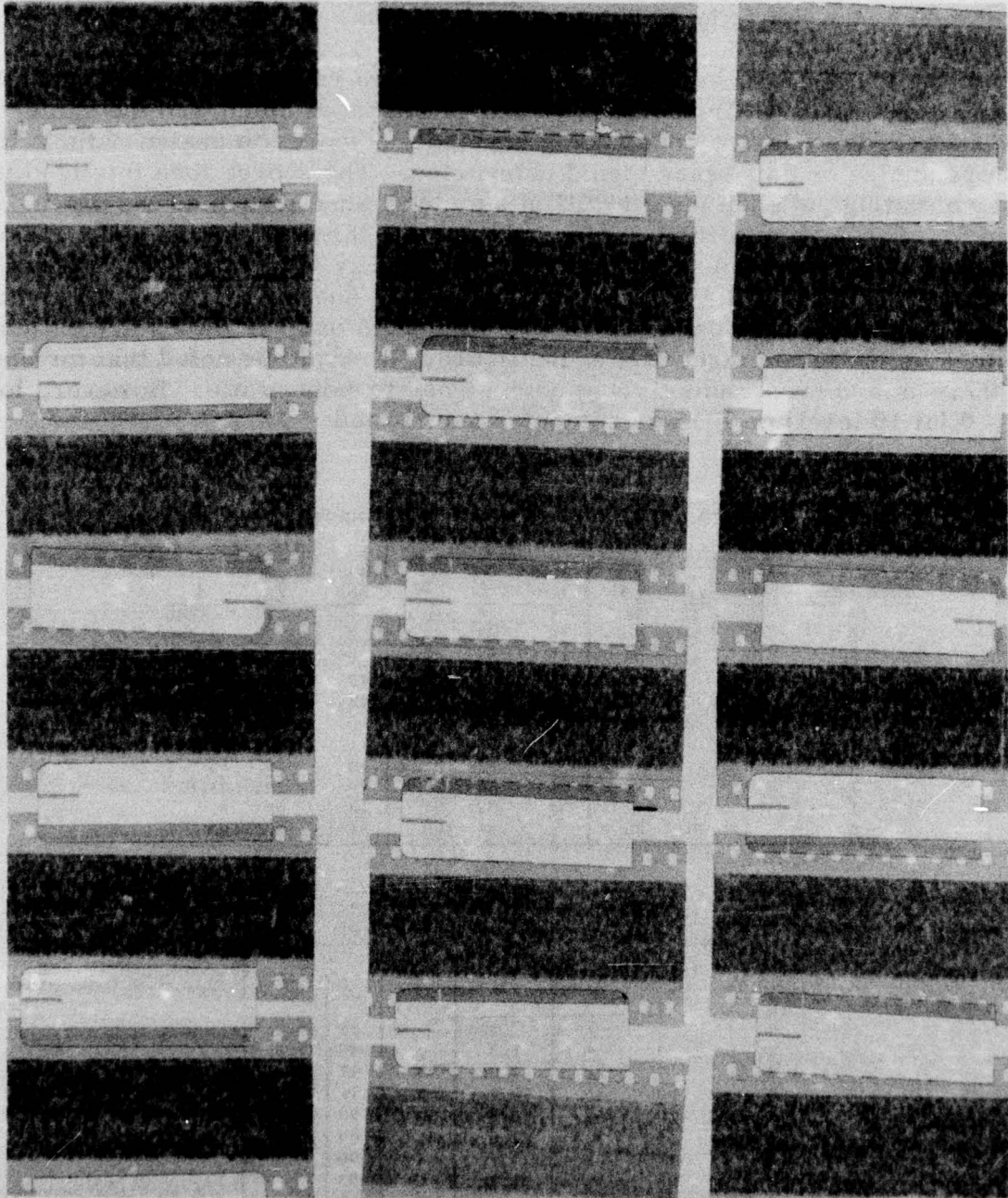


Figure 4-D.

The observer was instructed orally to use all the rating levels as suitable. Test case samples (Figure 4) were shown to the observer before a test. The observer could examine these samples for as long as he chose, but the training sheet was removed before the test began. All of the observers for this particular display evaluation were already acquainted with the interpretation of the intensity modulated spectrogram.

Computing ROC curves from the observers ratings was done manually. The observers wrote their probability ratings in spaces numbered the same as the test cards. Master code sheets enabled the scorer to assign ratings to the proper noise or noise plus signal categories. The scorer then totalized the number of ratings at each level to fill in summary sheets such as the one in Figure 5. For each condition--noise only and the three signal-to-noise ratios--the number of cases rated at each level of probability (0 through 10), the cumulative sums going from the highest level to lowest, and the % of the total number of cases in a category is calculated. The final PFA and PD values are collected in a block on the lower right part of the figure. It should be noted that for each PFA there is a corresponding PD at each signal-to-noise ratio. However, for PFA = 0 (at 10 level) no PD was computed and plotted.

SUMMARY SHEET FOR PLOT OF OBSERVERS ROC

Probability	S/N = 1			S/N = 2			S/N = 3		
	Num-ber	Σ	%	Num-ber	Σ	%	Num-ber	Σ	%
10	52	52	58	4	4	4.17	1	1	.945
9	19	71	79.4	18	22	23	6	7	6.6
8	10	81	90.3	12	34	35.4	5	12	11.3
7	2	83	92.5	11	45	47	16	28	26.6
6	4	87	97	23	68	70.6	12	40	37.7
5	2	89	99	12	80	83.2	9	49	46.3
4	0			5	85	88.7	11	60	56.6
3	0			1	86	90	10	70	66
2	0			3	89	93	9	79	74.6
1	0			4	93	97	13	92	87
0	1	90	100	3	96	100	14	106	100

Probability	N	Num-ber	Σ	PFA				PD		
				N	1	2	3	1	2	3
10		0	0							
9		1	1	.325	79.4	23	6.6			
8		3	4	1.3	90	35	11.3			
7		7	11	3.58	92.5	47	27			
6		20	31	10.2	97	71	38			
5		20	51	16.7	99	83	46			
4		19	70	22.8		89	57			
3		13	83	27		90	66			
2		35	118	38.6		93	75			
1		66	184	60		97	87			
0		124	308							

Figure 5.

The calculated ROC curves for four observers are reproduced in Figure 6. There are three sets of ROC plots representing three different signal-to-noise conditions. There is good agreement among observers' estimates of the ROC curve as shown by the clustering of plots for a particular signal-to-noise and the clear separation between clusters of plots for the signal-to-noise ratios which differed in 3 db steps. One observer (HS) applied a restricted range of thresholds relative to the other three observers, but his "short" ROC curves coincide with corresponding parts of the other plots.

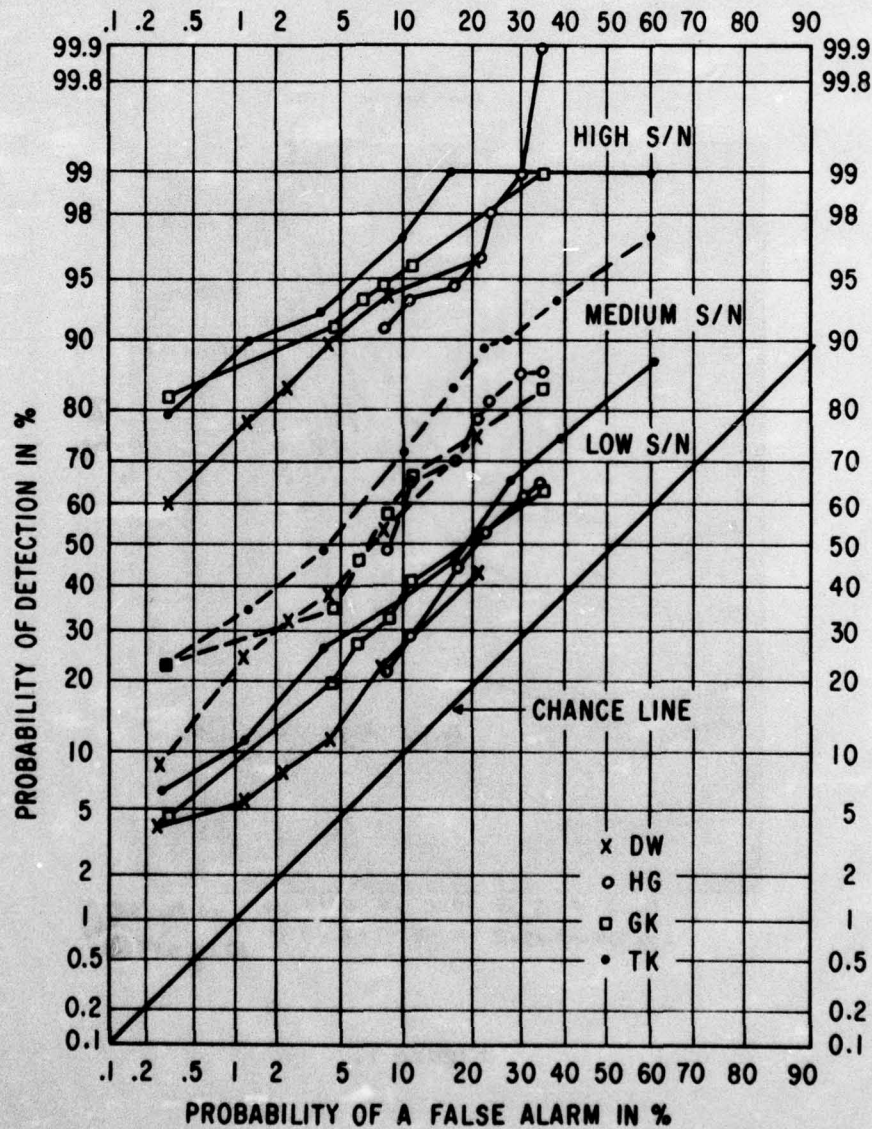


Figure 6.

A comparison of these ROC curves with theoretical detection performance* is shown in Figure 7. Theoretical curves are shown for PFA = 0.01, 0.1, and 0.3. Corresponding "mean" values are shown for the spectrogram ROC curves. The time-bandwidth products ($w_t = 60$ vs 70) are slightly different, but the error is negligible. The detection performance for the visual display seems to lie about 3 db below theoretical--a seemingly reasonable difference in the light of known imperfections in the spectrum analysis process used.

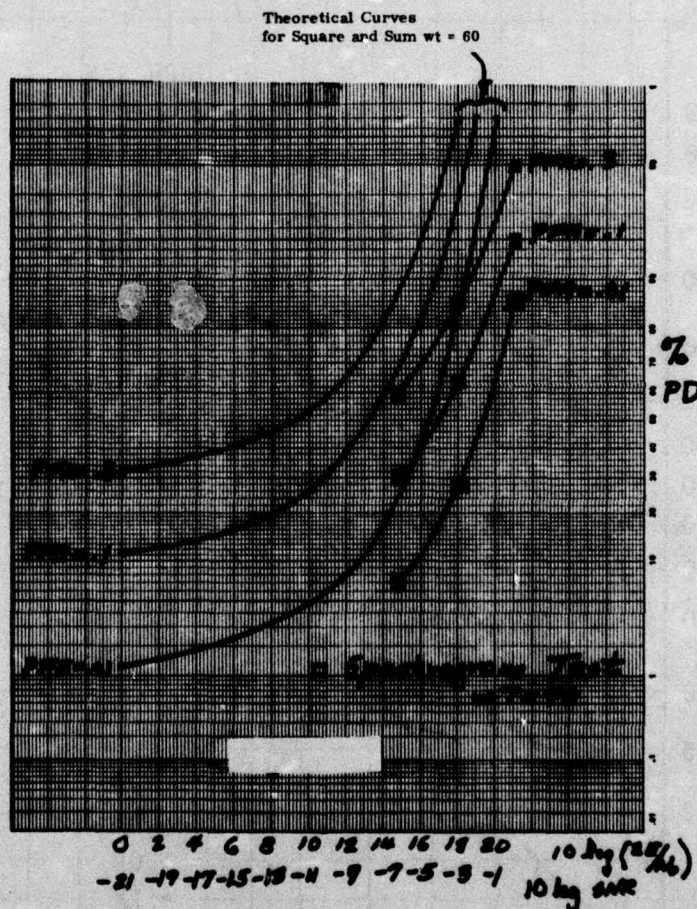


Figure 7.

*See Appendix A of this report for calculation of Square Law Detector Performance

Conclusions

The rating scale method for generating ROC curves of detection performance seems to have worked well here. Mixing cases with different signal-to-noise ratios generated ROC plots with detection performance that varied with expected relations, as shown by comparison to theoretical ROC. Since all of the observers examined the same test cases, the spread between ROC's is caused by differences between observers. Oddly enough, the most experienced observer (DW) had the lowest PD values. Certainly tests with more than four observers would be required to predict performance variation among observers.

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**"Graphical Presentation of Data in Framework of Theory of Signal
Detection" Tanner**

APPENDIX A

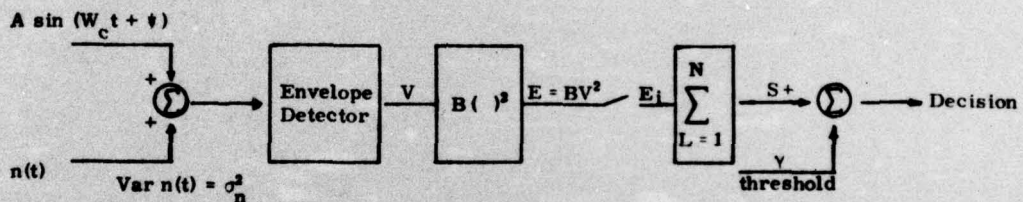
SQUARE LAW DETECTOR PERFORMANCE - by R. R. Rustay

This Appendix briefly describes the computational procedure used to obtain the curves on Figure 7. The computational procedure is based directly on the report

A Statistical Theory of Target Detection by Pulsed Radar:
Mathematical Appendix

J. I. Marcum, The Rand Corporation Report RM-753, 1 July 1948
Reissued 25 April 1952

The "square law" model being considered is shown in the following sketch*



where $n(t)$ is narrow band Gaussian noise centered about W_c and ψ is a random uniformly distributed $(0, 2\pi)$ constant. The probability density function (pdf) $Q_s(S/A)$ associated with sum S

$$Q_s(S/A) = \left(\frac{2\sigma_n^2}{A^2} = \frac{1}{N} \frac{S}{2B\sigma_n^2} \right)^{\frac{N-1}{2}} \frac{e^{-\frac{NA^2}{2\sigma_n^2}} e^{-\frac{S}{2B\sigma_n^2}}}{2B\sigma_n^2} I_{N-1} \left(2 \sqrt{\frac{NA^2}{2\sigma_n^2}} \sqrt{\frac{S}{2B\sigma_n^2}} \right), \quad S \geq 0$$

where

$L_{N-1}(\chi) =$ Modified Bessel Function of the First Kind

The noise alone (zero signal) pdf is

$$Q_s(S/0) = \frac{1}{(N-1)! \cdot 2B\sigma_n^2} \left(\frac{S}{2B\sigma_n^2} \right)^{N-1} \exp \left(-\frac{S}{2B\sigma_n^2} \right), \quad S \geq 0$$

*The constant B was included for purpose of normalizing if desired.

The mean \bar{S} and variance vars are

$$\bar{E} = N \left(2B\sigma_n^2 \right) \left[1 + \frac{A^2}{2\sigma_n^2} \right]$$

$$\sigma^2 = \text{Var } E = N \left(2B\sigma_n^2 \right) \left[1 + \frac{2A^2}{2\sigma_n^2} \right]$$

The probability of false alarm PFM is, given the threshold γ

$$\text{PFM} = \int_{\gamma}^{\infty} Q_s(S/0) ds = 1 - \frac{1}{(N-1)!} \int_0^{Y_B} y^{N-1} e^{-y} dy$$

and corresponding probability of detection PD

$$\text{PD} = \int_{\gamma}^{\infty} Q_s(S/A) ds = 1 - 2 \frac{e^{-q^2}}{q^{N-1}} \int_0^{\sqrt{Y_B}} y^N e^{-y^2} I_{N-1}(2\mu y) dy$$

where

$$q = \frac{NA^2}{2\sigma_n^2}$$

$$Y_B = \frac{\gamma}{2B\sigma_n^2}$$

PFM and PD can be expressed in terms of defined functions, i.e.,

$$\text{PFM} = 1 - I\left(\frac{Y_B}{N^1}, N-1\right) = Q\chi^2\left(2 \frac{Y_B}{2N}\right)$$

$$\text{PD} = 1 - T\sqrt{Y_B} \left(2N-1, N-1, \sqrt{q}\right)$$

where

$I(\mu, p)$ = Pearson's Incomplete Gamma Function

$Q_{\chi^2}(\chi^2 | \nu)$ = Complementary Chi-Square Probability Function

$T_y(m, n, r)$ = Incomplete Toronto Function

However, because tables of these functions are either not readily available or convenient, the integral

$$\int_r^{\infty} Q_S(S|A) ds$$

has been computed digitally using an Edgeworth form of a Gram-Charlier Series, i. e.,

$$\int_r^{\infty} Q_S(S|A) ds = \frac{1}{2} \text{ERFC}\left(\frac{T}{\sqrt{2}}\right) - \sigma C_3 \phi^{(2)}(T) - \sigma C_4 \phi^{(3)}(T) - \sigma C_6 \phi^{(5)}(T)$$

where

$$\sigma C_3 = \frac{1+3\chi}{3N^{1/2}(1+2\chi)^{3/2}}$$

$$\phi^{(2)}(T) = \frac{e^{-\frac{T^2}{2}}}{\sqrt{2\pi}} (T^2 - 1)$$

$$\sigma C_4 = \frac{1+4\chi}{4N(1+2\chi)^2}$$

$$\phi^{(3)}(T) = -\frac{e^{-\frac{T^2}{2}}}{\sqrt{2\pi}} (T^3 - 3T)$$

$$\sigma C_6 = \frac{(1+3\chi)^2}{18N(1+2\chi)^3}$$

$$\phi^{(5)}(T) = -\frac{e^{-\frac{T^2}{2}}}{\sqrt{2\pi}} (T^5 - 10T^3 + 15T)$$

$$\chi = \frac{A^2}{2\sigma_n^2}$$

$$T = \frac{y - \bar{E}}{\sigma} = \frac{Y_B - N(1+\chi)}{N^{1/2}(1+2\chi)}$$

$$\text{ERFC}(y) = 1 - \frac{2}{\sqrt{\pi}} \int_0^y e^{-t^2} dt$$

Computationally a PFM is selected, Y_B found by iteration, and then PD is computed for various signal-to-noise power ratios χ . Notice that the first term in the Gram-Charlier Series is the normal approximation.

R.RUSIAY1

PFMPD

05/16/74

11:48

```
*****
R.RUSIAY1                PFMPD                05/16/74    11:48
*****

00010      ERX=.00001
00020      IMAX=11
00030      SNMIN=0.
00040      SNMAX=20
00050      DDB=(SNMAX-SNMIN)/FLOAT(IMAX-1)
00060  100    PRINT:" "
00070      PRINT:"TYPE NUMBER N"
00080      READ:N
00090      IF(N.LE.0)STOP
00100  200    PRINT:" "
00110      PRINT:"TYPE PFM"
00120      READ:PFM
00130      IF(PFM.LE.0)GOTO100
00140      CONK=4.3429446*ALOG(FLOAT(2*N))
00150      XM2=FLOAT(N)
00160      XM1=XM2-1.0
00170      YM2=PFM-PROB(XM2,U.,N)
00180      YM1=PFM-PROB(XM1,U.,N)
00190      NCOUNT=0
00200  300    CONTINUE
00210      NCOUNT=NCOUNT+1
00220      X=YM1*(XM2-XM1)/(YM2-YM1)
00230      IF(ABS(X).LE.ERX)GOTO400
00240      IF(NCOUNT.GT.100)STOP
00250      XM2=XM1
00260      YM2=YM1
00270      XM1=XM1-X
00280      YM1=PFM-PROB(XM1,U.,N)
00290      GOTO300
00300  400    T=XM1-X
00310      PRINT:"I=",I
00320      PRINT 440
00330  440-   FORMAT(2X,"N",5X,"PFM",5X,"PD",10X,"T",10X,"X",9X,"DB",
00340  &        5X,"DBK",4X,"100*PD")
00350      DO 500 I=1,IMAX
00360      DBK=SNMIN+FLOAT(I-1)*DDB
00370      DB=DBK-CONK
00380      X=10.**(.1*DB)
00390      PD=PROB(I,X,N)
00400      PRINT 450,N,PFM,PD,I,X,DB,DBK,100.*PD
00410  450-   FORMAT(13,1P5F11.3,0P2F8.2)
00420  500    CONTINUE
00430      GOTO200
00440      END
00450      FUNCTION PROB(I,X,N)
00460      XN=FLOAT(N)
```

```

00470      RN=SQRT(XN)
00480      OP2X=1.+2.*X
00490      SQOP=SQRT(OP2X)
00500      CI=(T-XN*(1.+X))/(RN*SQOP)
00510      TI=CI*CI
00520      CALL ERFC(.70/107*CI,EX,CX)
00530      CEXP=.3989423*EXP(-.5*TI)
00540      SC3=-(1.+5.*X)/(3.*RN*OP2X**1.5)
00550      SC4=(1.+4.*X)/(4.*XN*OP2X**2)
00560      SC6=(1.+3.*X)**2/(10.*XN*OP2X**3)
00570      H2=TI-1.0
00580      H3=CI*(TI-3.0)
00590      H5=CI*((TI-10.0)*TI+15.0)
00600      U2=CEXP*H2
00610      U3=-CEXP*H3
00620      U5=-CEXP*H5
00630      SC3U2=SC3*U2
00640      SC4U3=SC4*U3
00650      SC6U5=SC6*U5
00660      PRUB=-SC6U5-SC4U3-SC3U2+.5*CX
00670      IF (PRUB.LI.0.)STOP
00680      RETURN
00690      END

```

```

00700 * THIS PROTOTYPE PROGRAM IS BASED ON MARCOM'S ANALYSIS
00710 * (SUPPLEMENTED BY RCK ANALYSIS) AND INPUTS N INDEPENDANT
00720 * SAMPLES FROM A SQUARE LAW DETECTION OF ADDITIVE NARROWBAND
00730 * GAUSSIAN NOISE AND A CW SIGNAL. ALSO INPUTED IS THE
00740 * SPECIFIED PROBABILITY OF FALSE ALARM PFM. THE PROGRAM
00750 * COMPUTES THE PROBABILITY OF DETECTION FOR VARIOUS
00760 * SIGNAL TO NOISE POWER RATIOS (VARIABLE DB IN PROGRAM). THE RANGE
00770 * OF S/N IS CONTROLLED BY BUILTIN PARAMETERS. DB IS
00780 * RELATED TO DBK USED BY KINCAID AND IS GREATER THAN DB BY
00790 *  $10 \cdot \text{LOG}_{10}(2N)$ .
00800 * THE FUNCTION PRUB CONTAINS THE GRAM CHARLIER SERIES
00810 * APPROXIMATION, THE FIRST TERM OF WHICH WOULD BE THE NORMAL
00820 * DISTRIBUTION APPROXIMATION.

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