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ADMINISTRATIVE INFORMATION

This work is a byproduct of a long-term analysis of broadband countermeasure signals. It is not identified with any particular project or program, but addresses a question of general concern in this area.

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13. ABSTRACT (Maximum 200 words) Broadband white Gaussian noise is modelled as a series of sine and cosine functions of discrete frequencies up to a maximum frequency. The series coefficients are Gaussian with uniform variance across the frequency band. For a given sample, the Nyquist-spaced values are generated for a full period of the lowest frequency sinusoid and a peak factor is imposed, clipping the values. The resulting signal is discrete-Fourier transformed via the fast Fourier transform, hard filtered at a prescribed bandwidth, and then inverse transformed to give a set of values for the narrow band signal sample, and these values are used to update a histogram. When a sufficient number of signal samples are generated, the resulting distribution is fitted to a Gaussian distribution by a least-squares technique. It is found that the resulting distributions are noticeably non-Gaussian down to a bandwidth ratio of 1:4, below which the distribution appears to be Gaussian with a reduced variance depending on the peak factor. For a bandwidth ratio of 1:40, it is found that peak factors as low as 1.7 or even 1.5 have little effect on the narrowband distribution.
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CONTENTS

	<u>Page No.</u>
INTRODUCTION	1
THE SIGNAL MODEL	1
NARROWBAND STATISTICS	2
APPENDIX A- LEAST-SQUARES FITTING OF A GAUSSIAN DISTRIBUTION TO A HISTOGRAM	A-1
APPENDIX B- ROCKY MOUNTAIN BASIC 3.0 CODE FOR SIGNAL SAMPLE GENERATION, FILTERING, AND HISTO- GRAM FORMATION	B-1

ILLUSTRATIONS

<u>Figure No.</u>		<u>Page No.</u>
1	Gaussian Fits for a Bandwidth Ratio of 1:40 for Various Peak Factors	4
2	Histograms and Gaussian Fits Compared for a Peak Factor of 1.7 for Various Bandwidth Ratios	5



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INTRODUCTION

In many countermeasure applications, it is necessary to broadcast broadband white noise to influence a device that has a relatively narrowband processor of unknown center frequency. Due to practical limitations, the excursions of the power supply generating the broadband noise are hard limited by a peak factor. An important operational question then is: to what extent does this limit the excursions of a narrowband-filtered output of the power supply?

In this note, the broadband white noise is modelled as a finite sum of discrete-frequency sinusoids, with Gaussian-distributed amplitudes derived from a uniform distribution. The resulting time-domain signal then is hard limited, and the discrete Fourier transform is applied (exact for this type of signal) and executed via the fast Fourier transform. The resulting transform amplitudes then are hard filtered for a particular choice of bandwidth, and the inverse discrete Fourier transform is applied. Time samples of the resulting narrowband time signal then are used to update a histogram of values, the amplitudes of the broadband time signal then are re-seeded, and the process repeated until a sufficient number of signal samples are collected.

The resulting histogram is used to construct a least-squares fit to a Gaussian distribution, and the resulting variance is compared to that for the unclipped case.

THE SIGNAL MODEL

The broadband signal has the form

$$B(n\Delta t) = \sum_{m=1}^{N/2} [a_m \cos(2\pi n m \Delta t \Delta f) + b_m \sin(2\pi n m \Delta t \Delta f)] \quad (1)$$

where $\Delta f = 1/T$ and $\Delta t = 1/2F$ with T the period of the lowest frequency sinusoid, and F the highest frequency present. We will choose N to be a power of 2, and note that $1 \leq n \leq N$, $1 \leq m \leq N/2$, and $\Delta t \Delta f = 1/N$.

The coefficients are chosen using the following algorithm:

$$U_1 \in U[0, 1] \quad , \quad U_2 \in U[0, 1] \quad (2)$$

$$V_1 = 2U_1 - 1 \quad , \quad V_2 = 2U_2 - 1 \quad (3)$$

that is, U_1 and U_2 are chosen from a distribution uniform on the interval $[0, 1]$, and are used to generate a distribution uniform on $[-1, 1]$, of which V_1 and V_2 are samples (most computers generate the distribution uniform on $[0, 1]$ by means of a pseudo-random number generator).

Define $S = V_1^2 + V_2^2$. If $S > 1$ then select new samples U_1 and U_2 from the uniform distribution and repeat the process. The resulting variable S is distributed uniformly on $[0, 1]$. Next, define

$$X_1 = V_1 \sqrt{\frac{-2\sigma^2 \ln S}{S}} \quad (4)$$

and

$$X_2 = V_2 \sqrt{\frac{-2\sigma^2 \ln S}{S}}. \quad (5)$$

The resulting variables X_1 and X_2 have Gaussian distributions with zero mean and variance σ .

For a given broadband signal sample, a pseudo-random sequence is seeded, and the coefficients a_m and b_m are selected using the above procedure for $1 \leq m \leq N/2$. When a new signal sample is constructed, the sequence is re-seeded.

When a peak factor P is specified, the clipped signal has the form

$$C(n\Delta t) = B(n\Delta t), B < \sigma P, C(n\Delta t) = \sigma P \text{ otherwise.} \quad (6)$$

The discrete Fourier transform of the clipped signal is given by

$$D(l\Delta f) = \sum_{n=1}^N C(n\Delta t) e^{-2\pi i l n / N} \quad (7)$$

with the inverse transform given by

$$C(n\Delta t) = \frac{1}{N} \sum_{l=1}^N D(l\Delta f) e^{2\pi i l n / N}. \quad (8)$$

The validity of this transform pair can be established by means of the identity

$$\sum_{m=1}^N e^{2\pi i (n-k)m/N} = \sum_{l=-\infty}^{\infty} \delta_{n,k+lN}. \quad (9)$$

NARROWBAND STATISTICS

The discrete Fourier transform and inverse transform can be executed via the fast Fourier transform algorithm. A subroutine for performing this algorithm is included as part of the code given in Appendix B. The code is written in Hewlett-Packard's Rocky Mountain Basic Version 3.0. The main body of code constructs a histogram for a particular bandwidth and peak factor choice. For a particular broadband signal sample, the time signal is transformed, and then hard filtered by eliminating the transform coefficients outside the chosen band. In doing this, it is important to observe the redundancy and symmetry of the transform coefficients. In particular, because we are using a real time series as input, the transform coefficients satisfy

$$Re\{D(l\Delta f)\} = Re\{D([N-l]\Delta f)\}, \quad l = 1, \dots, N/2 \quad (10)$$

and

$$\text{Im}\{D(l\Delta f)\} = -\text{Im}\{D([N-l]\Delta f)\} \quad , \quad l = 1, \dots, N/2. \quad (11)$$

Consequently, a set of bandpass indices is selected symmetrically about $l = N/2$. Once the filtering is accomplished, the coefficients are inverse transformed to produce the associated time signal. Each time sample is examined and assigned to the appropriate histogram bin. Once this is done, the process is repeated until a sufficient number of samples is accumulated.

For explicit analysis, we have chosen $F = 2048$, and $\Delta f = 4$, so $N = 1024$, $T = 1/4$ and $\Delta t = 1/4096$. The broadband signal is chosen to have $\sigma = 1$, so the amplitudes a_m and b_m are chosen via the above procedure using a σ of $\sqrt{1/512}$. For the filter we consider bandwidth ratios of 1:40, 1:4, 1:2, 3:4, 7:8, 125:128, and 1:1, centered on the frequency 1024. The histogram is constructed as an array of $2M$ elements with element M corresponding to zero amplitude. In some cases, we have used $M = 100$ and in some cases $M = 1000$. It doesn't appear to make much difference in the resulting least-squares Gaussian fit. The matrix index change corresponding to σ for the unclipped case is arbitrarily chosen to be $M/10$ and this number is multiplied by the signal value and divided by the square root of the bandwidth ratio and the result added to M to give the appropriate histogram index. This will give the same distribution for the unclipped case for all bandwidth ratios. Then the effects of the peak factor will appear as departures from a Gaussian distribution, and modifications of the heights and widths of the Gaussian fits.

The distributions and Gaussian fits for a bandwidth ratio of 1:40, for peak factors of 1.7, 1.5, 1.25, 1.0, and 0.5 are shown in Figure 1. Here, and in Figure 2, the abscissa is labelled in units of σ for the unclipped case. The smooth curves are produced by the least-squares fitting procedure described in Appendix A. It is clear from the comparisons given in 1(b)-1(f) that the distributions are Gaussian. The superposition of fits in 1(a) shows that the effect of increasing the peak factor is to reduce the variance and increase the distribution's peak amplitude. It is clear from the curves in 1(a) that imposing a peak factor of 1.7, or even 1.5 has very little practical effect on the resulting narrowband distribution. Note that for peak factors of 1.5, 1.25, and 1.0, we have used $M = 1000$, and have 203 samples, whereas for peak factors of 1.7 and 0.5, we use $M = 100$, and have 146 samples.

To determine when the peak factor does have a significant impact on the shape of the distribution, we start at the other extreme, the distribution for the full bandwidth clipped signal, and reduce the bandwidth in slight increments. In Figure 2, we show the distributions, for peak factor 1.7, for bandwidth ratios 1:1, 125:128, 7:8, 3:4, 1:2, and 1:4. In the 1:1 case shown in 2(a), as expected, the distribution has a delta function behavior at $\pm 1.7\sigma$. In the next case, that for the slight reduction to a 125:128 ratio, shown in 2(b), the distribution is still strongly multimodal. The distribution is still noticeably non-Gaussian for subsequent bandwidth reductions, shown in 2(c)-2(e), but for a ratio of 1:4, shown in 2(f), the distribution is nearly Gaussian with a variance of 92 percent of that of the unclipped case. In these examples, the number of samples varies as follows: 1:1(303), 125:128(177), 7:8(178), 3:4(178), 1:2(223), and 1:4(123).

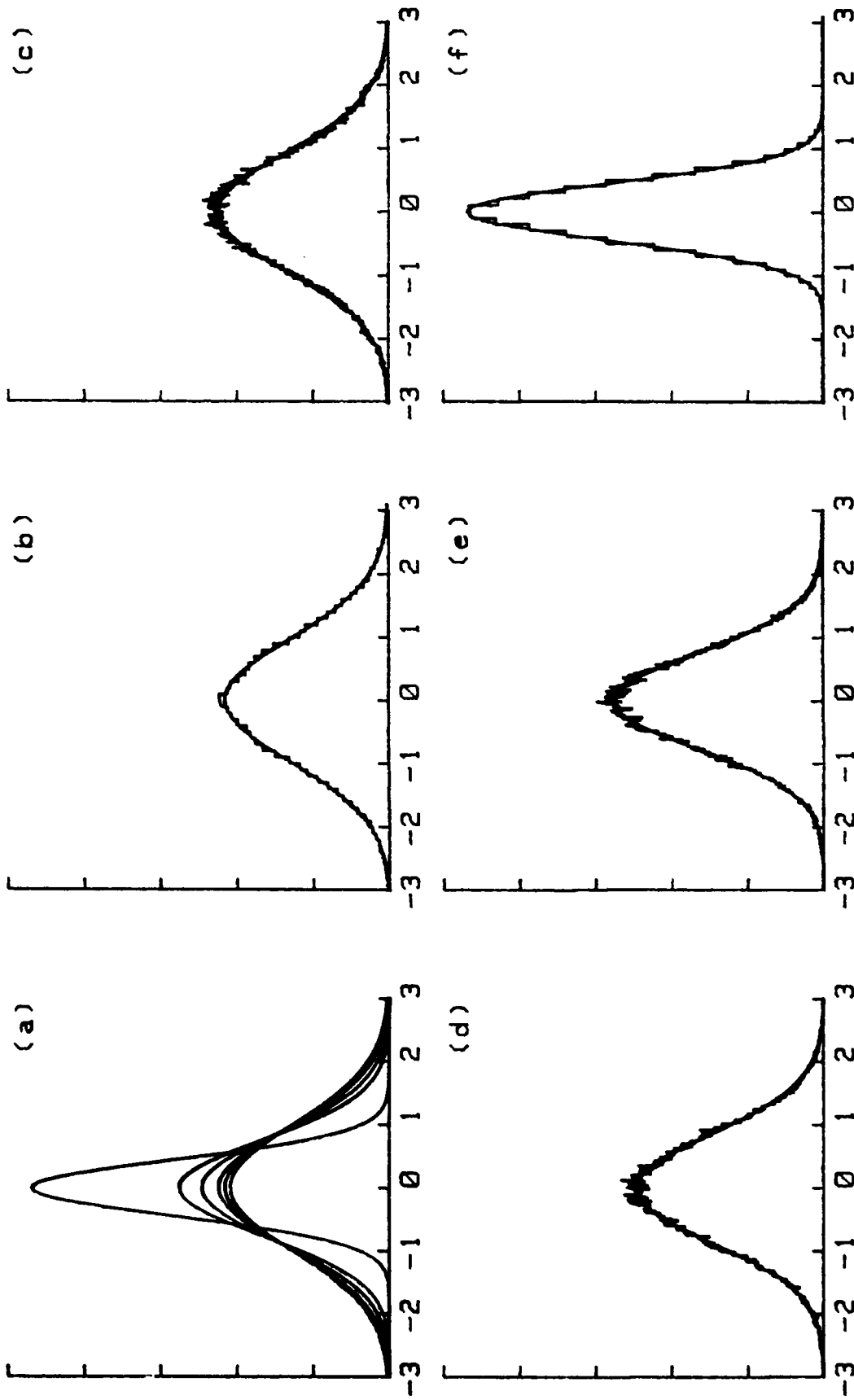


Figure 1. Gaussian Fits for a Bandwidth Ratio of 1:40, for Peak Factors of 1.7, 1.5, 1.25, 1.0 and 0.5. The Percentage Variances Listed after the Peak Factors are Given Relative to an Uncropped Value of 1. (a) Gaussian Fits Compared, Including the Uncropped Case. (b) 1.7, 96.8%. (c) 1.5, 93.1%. (d) 1.25, 84.9%. (e) 1.0, 75.6%. (f) 0.5, 44.5%.

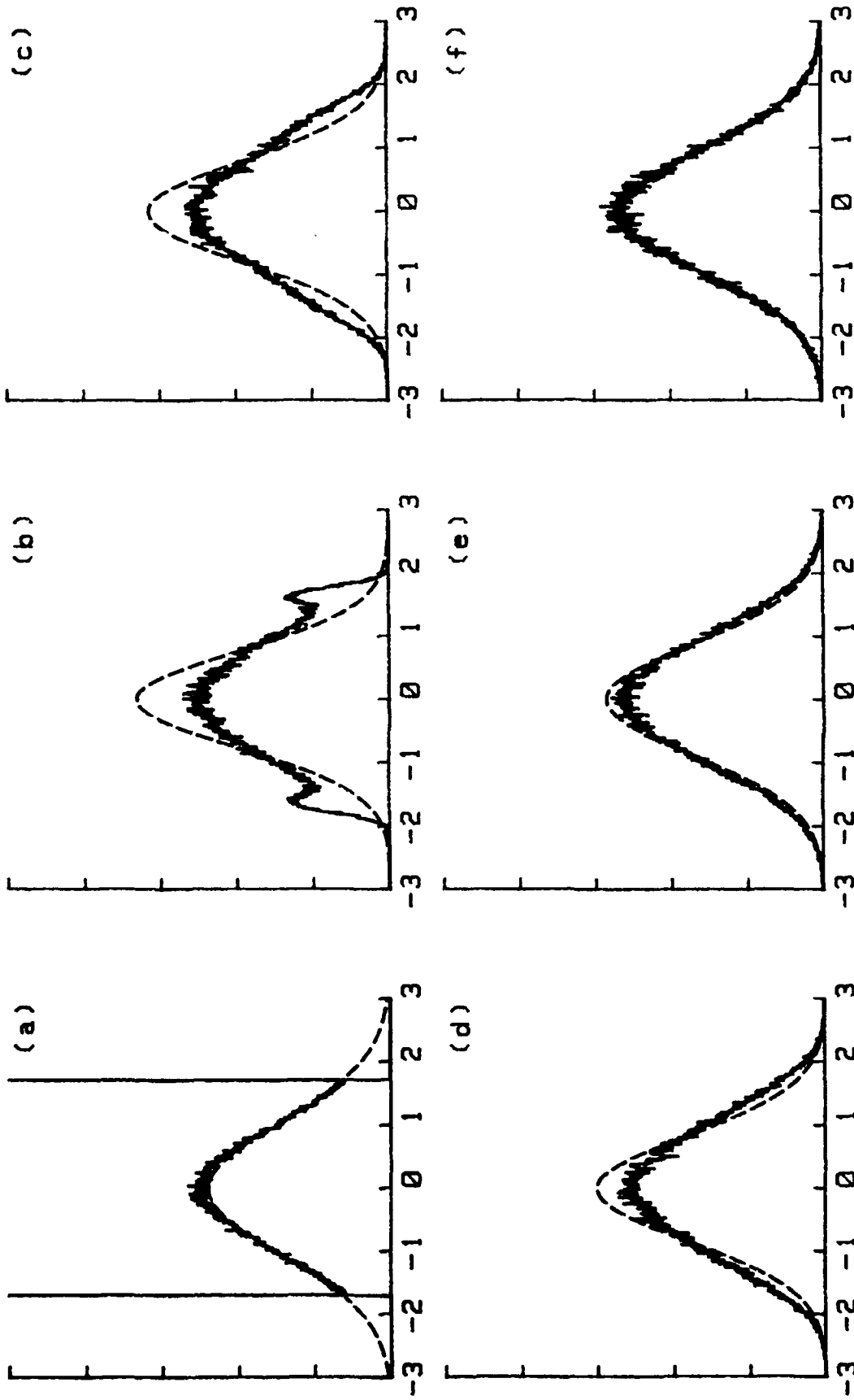


Figure 2. Histograms and Gaussian Fits Compared for a Peak Factor of 1.7, for Various Bandwidth Ratios: (a) 1:1, (b) 125:128, (c) 7:8, (d) 3:4, (e) 1:2, (f) 1:4. The Distribution is Strongly Non-Gaussian Initially, but Approaches a Gaussian Distribution of Reduced Variance as Bandwidth Decreases.

APPENDIX A

**LEAST-SQUARES FITTING OF A GAUSSIAN
DISTRIBUTION TO A HISTOGRAM**

Given a series of variable and probability values $\{x_i, y_i\}$ where $i = 1, \dots, N$, we would like to establish the parameter σ for the representation

$$y_i = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x_i^2}{2\sigma^2}}. \quad (A1)$$

By taking the natural logarithm of both sides of (Eq. A1), we can produce the equivalent equation

$$u_i = v_i w + \ln w \quad (A2)$$

where

$$u_i = 2 \ln(\sqrt{2\pi} y_i) \quad (A3)$$

$$v_i = -x_i^2 \quad (A4)$$

and

$$w = \frac{1}{\sigma^2}. \quad (A5)$$

The least-square fit is accomplished by numerically solving

$$\frac{d}{dw} (u_i - v_i w - \ln w)^2 = 0 \quad (A6)$$

or, expanding, and incorporating all of the data by averaging,

$$\langle v_i^2 \rangle w + \langle v_i \rangle \ln w - \frac{\langle u_i \rangle}{w} + \frac{\ln w}{w} = \langle u_i v_i \rangle - \langle v_i \rangle. \quad (A8)$$

A subroutine for performing this process is given on the following page.

Rocky Mountain Basic 3.0 Code

```

10 SUB Gausisfit(X(*),Y(*),Npts,S1,S2,Nmax,S)
20 !
30 !Gaussian fit to y(x) using Npts points to produce variance S
40 !S1 and S2 bound the search interval for S, Nmax is the number
50 !of partition refinements allowed.
60 !
70 OPTION BASE 1
80 DIM U(2000),V(2000)
90 REDIM U(Npts),V(Npts)
100 Lc=LOG(2*PI)
110 Nav=Npts
120 FOR I=1 TO Npts
130 IF ABS(Y(I))<1.E-10 THEN
140 U(I)=0
150 V(I)=0
160 Nav=Nav-1
170 ELSE
180 U(I)=Lc+2*LOG(Y(I))
190 V(I)=-X(I)*X(I)
200 END IF
210 NEXT I
220 A=DOT(V,V)/Nav
230 B=SUM(V)/Nav
240 C=SUM(U)/Nav
250 D=DOT(U,V)/Nav-B
260 Xl=1/S2/S2
270 Xu=1/S1/S1
280 N=0
290 Y0=A*Xl+B*LOG(Xl)-C/Xl+LOG(Xl)/Xl-D
300 Dx=(Xu-Xl)/10
310 FOR Xx=Xl TO Xu+Dx/2 STEP Dx
320 Yy=A*Xx+B*LOG(Xx)-C/Xx+LOG(Xx)/Xx-D
330 IF Yy*Y0<0 THEN
340 N=N+1
350 IF N<Nmax THEN
360 Xl=Xx-Dx
370 Xu=Xx
380 GOTO 290
390 ELSE
400 S=1/SQR(Xx)
410 GOTO 450
420 END IF
430 END IF
440 NEXT Xx
450 SUBEND

```

APPENDIX B

**ROCKY MOUNTAIN BASIC 3.0 CODE FOR SIGNAL SAMPLE
GENERATION, FILTERING, AND HISTOGRAM FORMATION**

```

10 OPTION BASE 1
21 DIM X1(512),X2(512),C(512),S(512),Br(1024),Bi(1024),H(2000)
30 MAT H= (0)
40 Samp=0
50 INPUT "INPUT PEAK FACTOR",P
51 !Peak value is P times the broadband rms value
60 INPUT "FREQUENCY INDEX FOR NARROW BAND FILTER",If1
61 !Midpoint of the digital filter, In units of 4 hertz
70 INPUT "READ IN A PRIOR HISTOGRAM(Y/N)?",Ph$
80 IF Ph$="Y" THEN
90 INPUT "MSUS OF INPUT FILE?",Mh$
100 INPUT "FILE NAME?",H$
110 ASSIGN @Filein TO H$&Mh$
120 ENTER @Filein;P,Samp,H(*)
130 ASSIGN @Filein TO *
140 INPUT "DOES FILE EXIST ON MSI(Y/N)?",Fe$
150 IF Fe$="Y" THEN
160 GOTO 240
170 ELSE
180 GOTO 230
190 END IF
200 ELSE
210 INPUT "NAME OF OUTPUT FILE FOR HISTOGRAM?",H$
220 END IF
230 CREATE BDAT H$,2002,8
240 ASSIGN @File TO H$
241 INPUT "INPUT THE HALF WIDTH OF THE FILTER IN UNITS OF 4 hertz",Dlf
242 !Number of lines retained on each side of the midpoint, Ifil
243 Sig2=1/512
250 !Sigma squared for 4 hertz interval if 1 for 2048 hertz
251 RANDOMIZE
260 !Re-seed for each broadband signal sample
270 FOR I=1 TO 512
280 U1=RND
290 U2=RND
300 V1=2*U1-1
310 V2=2*U2-1
320 S0=V1*V1+V2*V2
330 IF S0>=1 THEN GOTO 280
340 Rt=SQR(-2*Sig2*LOG(S0)/S0)
350 X1(I)=V1*Rt
360 X2(I)=V2*Rt
370 NEXT I
380 Samp=Samp+1
390 PRINT Samp
400 Timesig: !
410 FOR It=1 TO 1024
411 T=(It-1)/4096
420 !Nyquist spacing for 2048 maximum frequency
430 FOR I=1 TO 512
440 C(I)=COS(2*PI*4*I*T)
450 S(I)=SIN(2*PI*4*I*T)
451 !Line spacing is 4 hertz

```

```

460 NEXT I
470 Bi(It)=0
480 Br(It)=DOT(X1,C)+DOT(X2,S)
490 IF ABS(Br(It))>P THEN
500   Br(It)=SGN(Br(It))*P
510   !Clip the signal sample
510 END IF
520 NEXT It
530 CALL Fft(Br(*),Bi(*),1024,10,-1)
531 !Get discrete transform coefficients
540 MAT Br=(1/1024)*Br
550 MAT Bi=(1/1024)*Bi
560 FOR I=1 TO 513-Ifil-Dlf-1
570   Br(I)=0
580   Bi(I)=0
590 NEXT I
600 FOR I=513-Ifil+Dlf+1 TO 513+Ifil-Dlf-1
610   Br(I)=0
620   Bi(I)=0
630 NEXT I
640 FOR I=513+Ifil+Dlf+1 TO 1024
650   Br(I)=0
660   Bi(I)=0
670 NEXT I
671 !Bandpass filter
680 CALL Fft(Br(*),Bi(*),1024,10,-1)
681 !Create the set of time values for this narrowband signal sample
690 FOR I=1 TO 1024
700   Ix=INT(Br(I)*100*SQR(2048/(2*4*Dlf))+1000)
701   !Normalize such that the histogram is independent of the bandwidth
702   !for the unclipped case
710   IF Ix>0 THEN
720     IF Ix<2001 THEN
730       H(Ix)=H(Ix)+1
731       !Upgrade the histogram
740     END IF
750   END IF
760 NEXT I
770 OUTPUT @File;P,Samp,H(*)
771 !Upgrade the stored histogram
780 GOTO 240
781 !Go back and re-seed and do it all again
790 END
800 SUB Fft(Xreal(*),Ximag(*),INTEGER N,Nu,Isign)
810 INTEGER N2,Nu1,K,K1,L,I,K1n2,P
820 N2=N DIV 2
830 Nu1=Nu-1
840 K=0
850 FOR L=1 TO Nu
860   FOR I=1 TO N2
870     CALL Bitrev(P,K DIV INT((2^Nu1)+.001),Nu)
880     Arg=2*PI*P/N
890     C=COS(Arg)

```

```

900   S=SIN(Arg)
910   K1=K+1
920   K1n2=K1+N2
930   Treal=Xreal(K1n2)*C+Ximag(K1n2)*S
940   Timag=Ximag(K1n2)*C-Xreal(K1n2)*S
950   Xreal(K1n2)=Xreal(K1)-Treal
960   Ximag(K1n2)=Ximag(K1)-Timag
970   Xreal(K1)=Xreal(K1)+Treal
980   Ximag(K1)=Ximag(K1)+Timag
990   K=K+1
1000  NEXT I
1010  K=K+N2
1020  IF K<N THEN GOTO 860
1030  K=0
1040  Nu1=Nu1-1
1050  N2=N2 DIV 2
1060  NEXT L
1070  FOR K=1 TO N
1080  CALL Bitrev(I,K-1,Nu)
1090  I=I+1
1100  IF I<=K THEN
1110    Treal=Xreal(K)
1120    Timag=Ximag(K)
1130    Xreal(K)=Xreal(I)
1140    Ximag(K)=Ximag(I)
1150    Xreal(I)=Treal
1160    Ximag(I)=Timag
1170  END IF
1180  NEXT K
1190  IF Isign=1 THEN
1200  FOR K=1 TO N
1210    Ximag(K)=-Ximag(K)
1220  NEXT K
1230  END IF
1240  SUBEND
1250  SUB Bitrev(INTEGER Ibitr,J,Nu)
1260  INTEGER I,J1,J2
1270  J1=J
1280  Ibitr=0
1290  FOR I=1 TO Nu
1300    J2=J1 DIV 2
1310    Ibitr=Ibitr*2+(J1-2*J2)
1320    J1=J2
1330  NEXT I
1340  SUBEND

```

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