NATIONAL RADIO ASTRONOMY OBSERVATORY

CHARLOTTESVILLE, VIRGINIA

ELECTRONICS DIVISION INTERNAL REPORT No. 214

SQUARE-LAW DETECTOR TESTS

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MAY 1981

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SQUARE-LAW DETECTOR TESTS

I. INTRODUCTION

The purpose of this report is to describe an automated test system for measuring the square-law error (i.e., deviation from a linear output voltage vs input power relation) and noise level of an accurate back-diode detector. A few days of operation of the system gave informative results regarding linearity of power meters, error of a back-diode detector circuit vs load resistor and input signal level, and very low-frequency noise of operational amplifiers; these results will be described.

It should be noted that all detectors become perfectly square-law at sufficiently low signal level and it is the noise level which then limits performance. The dynamic range of the detector; i.e., the input power range between noise level and an acceptable square-law error is thus an important parameter.

The noise in a detector circuit is predominately in the low-frequency amplifier following the detector rather than in the detector non-linear element and usually has a 1/f type spectrum. For detection of a noise-like signal, as occurs in radio astronomy, the inherent fluctuation in detector output due to this noise-like signal has a flat video spectrum with power level inversely proportional to IF bandwidth. In order for the radiometer sensitivity to be limited by this inherent noise, it must be greater than the detector noise. This criteria is more difficult to meet at wide IF bandwidth and low video bandwidth (long averaging time). As a numerical example, the detector described in this report has detector noise equal to inherent noise at an IF bandwidth of 1 GHz, averaging time of 1 second, and 0.2% square-law error.

II. TEST SYSTEM DESCRIPTION

A block diagram of the detector test system is shown in Figure 1. A digitally-controlled attenuator, 0 to 31 dB in 1 dB steps, is used to provide a variable-level noise or CW signal which is simultaneously applied to both a power meter and the detector under test. Detector error is determined by comparing power meter and detector output voltages; the attenuator accuracy and repeatability has a negligible effect upon measurement accuracy. The zero offset of both the power meter and detector is determined for each measurement and is used to correct data. A definition of square-law error and its computation is described in Appendix I. In general terms, the error is defined as the percent deviation of the detector output voltage vs input power curve from a straight line passing through a reference power level and .01 times this reference level, see Figure 2. The analog/digital input-output system, ADIOS, for the Apple II Plus Computer is described in NRAO Electronics Division Internal Report No. 212. The digital attenuator and driver are described in Appendix II of this report.

Since a power meter is the measurement standard for determining square-law error, four power meters were first compared using the square-law error measurement program. These were the General Microwave 467A, H-P 436A/8485A, H-P 432A/478A, and H-P 436A/8484A. The first two are thermoelectric sensors, the third is a thermistor sensor, and the fourth is a diode detector. Some results are illustrated in Figure 3. In general, the error between the first 3 power meters and the last meter at 1 μW or lower scale is < 0.3%. The H-P 436A/8484A on the 10 μW scale has ∿ 1% error in the 3 to 10 μW range and should not be used as a standard at this high level.
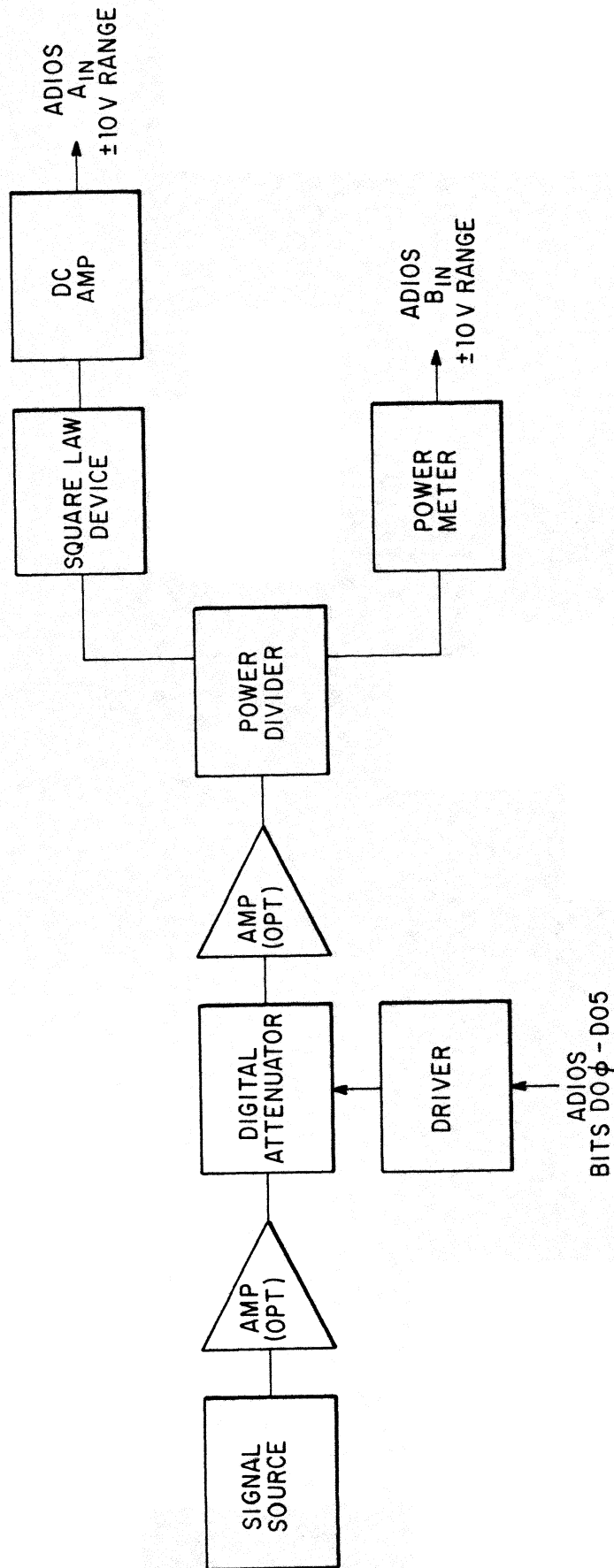
Fig. 1. Block diagram of test measurement system. ADIOS is an analog-digital input-output system for the Apple Computer and is described in NRAO EDIR No. 212.
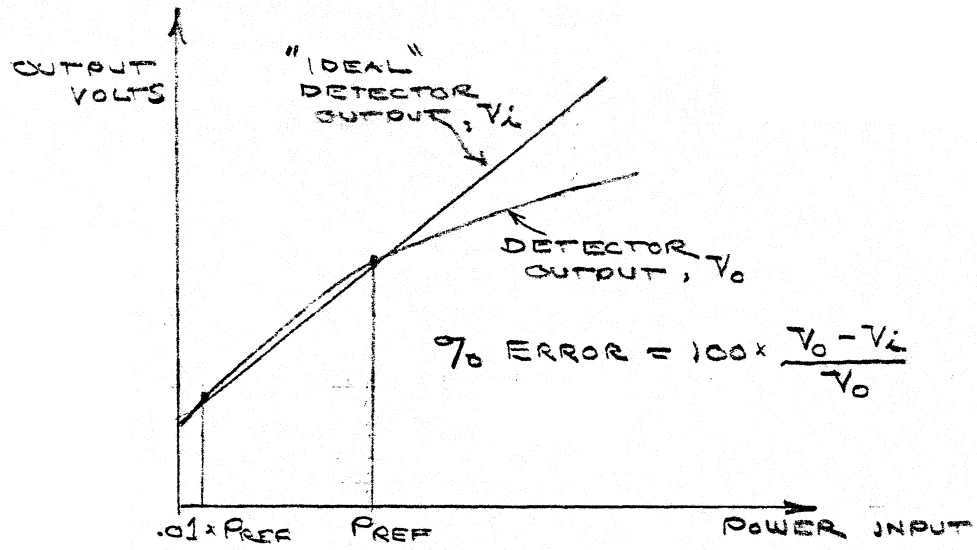
Fig. 2. Definition of detector error; also see Appendix I.

HP 432A,1MW SCALE,INTO AIN;GM 467A,1MW SCALE, INTO BIN. 2-300MHZ NOISE
  SIGNAL
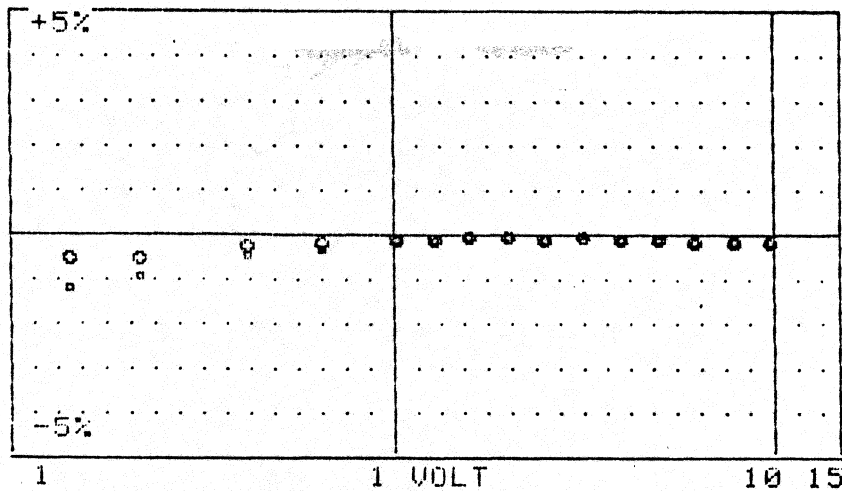
HP 436A/8484A INTO AIN,10UW SCALE; HP 432A INTO BIN,1MW SCALE. NOISE
  SIGNAL
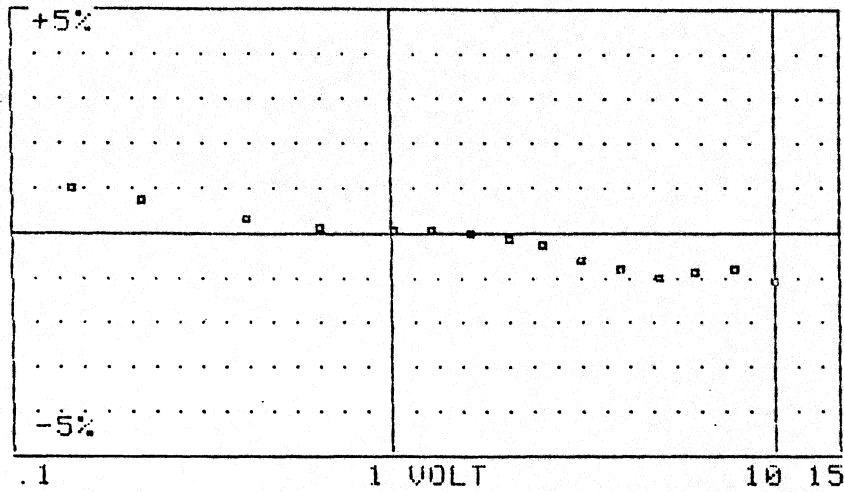
HP 436/8484A,100NW SCALE,INTO AIN;HP432, 1MW SCALE,INTO BIN. NOISE
  SIGNAL.

Fig. 3.   Examples of power meter comparisons. The horizontal axis is
          10 times the meter DC output voltage; for values < 1 volt
          the error is determined by noise and should be ignored. The
          middle curve shows an ∿ 1% error of the HP436A/8484A meter
          at its maximum input level of 10 µW. A broadband, 2-300 MHz,
          noise signal was used for these tests.

III. DETECTOR DESCRIPTION

The detector used for these tests was one similar to a design used at NRAO for many years.[1] A General Electric BD-4 back-diode is utilized into an adjustable, 0-5k ohm, load resistance connected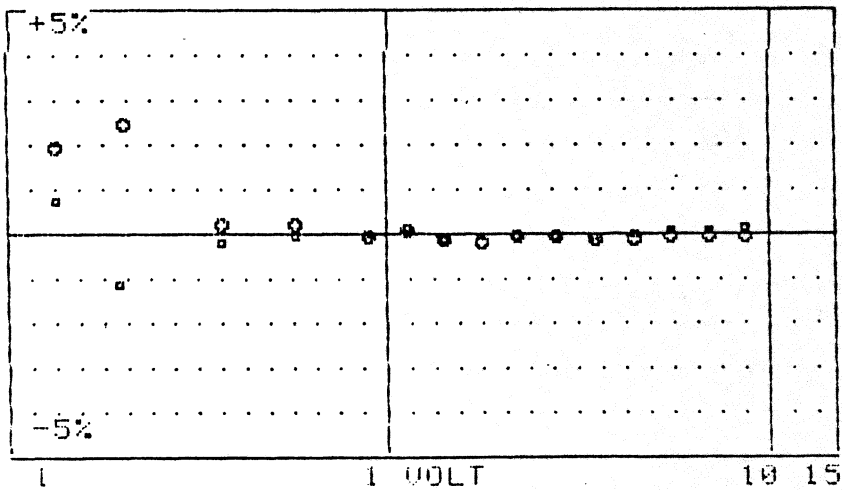 to the summing input of an operational amplifier; a schematic of the detector and a photograph are shown in Figure 4. The load resistance is adjusted for minimum square-law error.

The input op amp is a low-drift, low-noise variety; three types were tried and noise test results are reported in the next section. The input op amp is operated at typical voltage gain of 100 and output voltage of < 1 volt to eliminate thermal transients which may occur if an op amp is operated at high-level output. The entire circuit is enclosed in a 3/4" x 3¼" x 1½" box which includes a mu-metal shield to reduce 60 Hz AC pickup from nearby power supply transformers. The RF input match is a function of input layout and perhaps diode capacity. For the constructed unit the input return loss is > 20 dB from 5 to 500 MHz and > 10 db from 2 to 800 MHz.

It should be noted that the performance of a detector can be calculated in terms of the derivatives of the current-voltage characteristic; i.e., a non-linear device with all derivatives zero except first and second will give perfect square-law response. An excellent reference on this subject is given by Cowley and Sorensen.[2] These calculations have not been performed for the back-diode detector. However, a calculation of the square-law range of a biased-Schottky diode has shown that it will have a much smaller dynamic range than measured for the back-diode detector.

The BD-4 diodes which were tested for this report gave quite variable results from one diode to another. Four out of eight diodes gave acceptable

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[1] Peter Camana, "The GE BD-7 Back Diode as a Square-Law Detector," NRAO Electronics Division Internal Report No. 106, September 1971.

[2] A. M. Cowley and H. O. Sorensen, "Quantitative Comparison of Solid-State Microwave Detectors," IEEE Trans. Microwave Theory Tech., vol. MTT-14, no. 12, pp. 588-602, December 1966.

square-law performance of less than 0.5% error at < -16 dBm RF input level. The remaining diodes could not achieve this; increasing the load resistance decreased error but not to an acceptable value at 5,000 ohms. Larger load resistances were not tried as the error was not decreasing appreciably as 5k was approached. The I-V characteristics of two BD-4 diodes are shown in Figure 5 and are quite different. However, no correlation has been made between the I-V characteristic and square-law performance.

IV.   RESULTS

The results of tests upon a particular detector, #3, are shown in Figures 6, 7, and 8 with discussion in the captions of each figure.
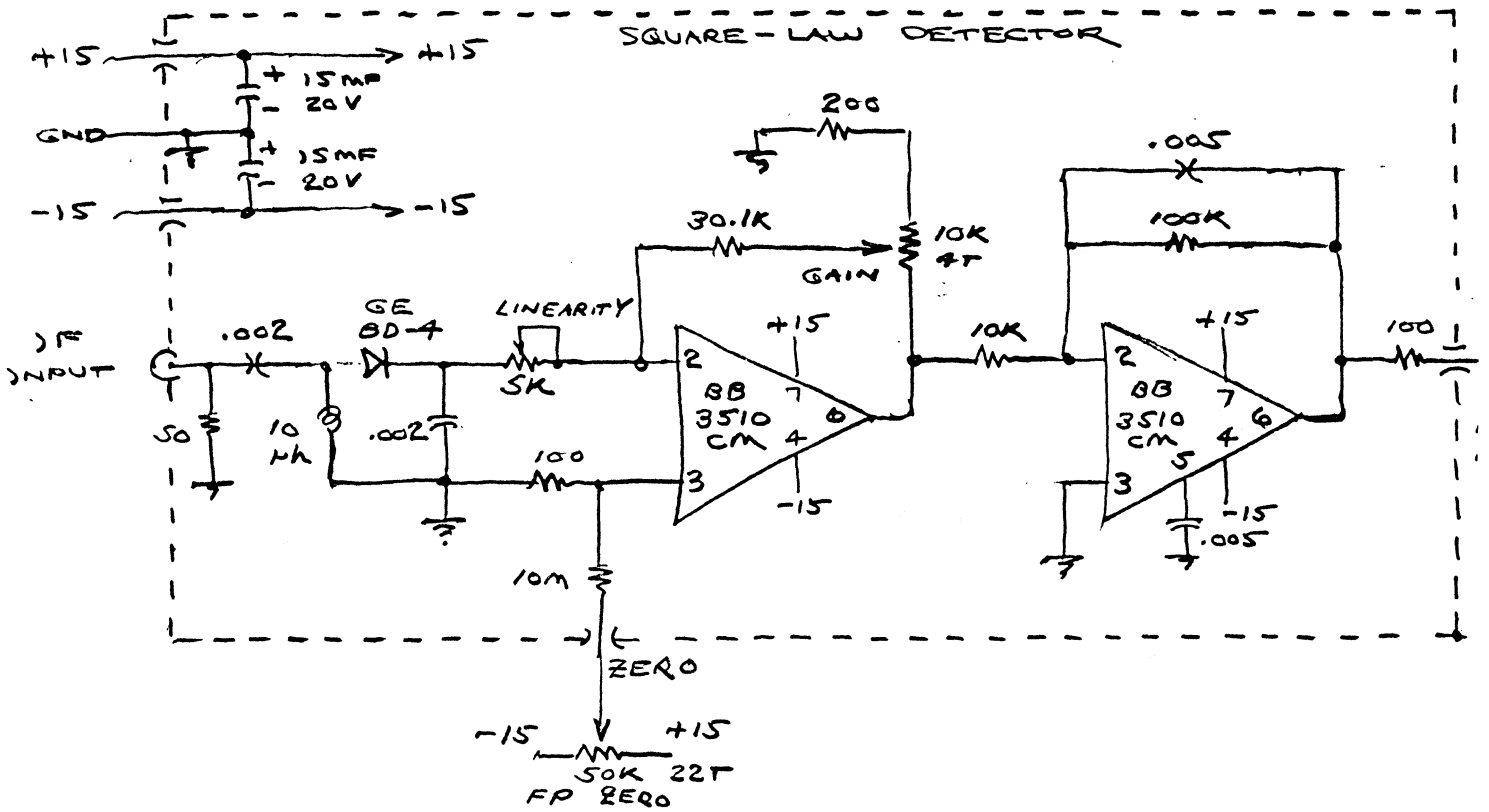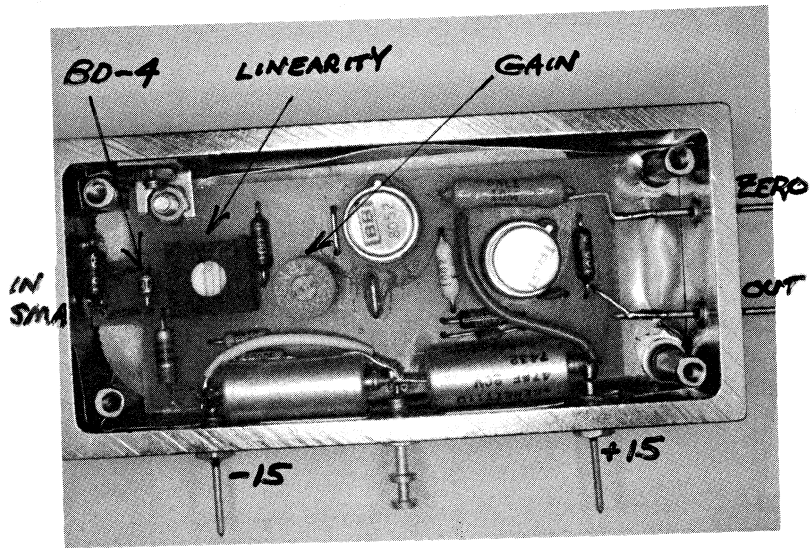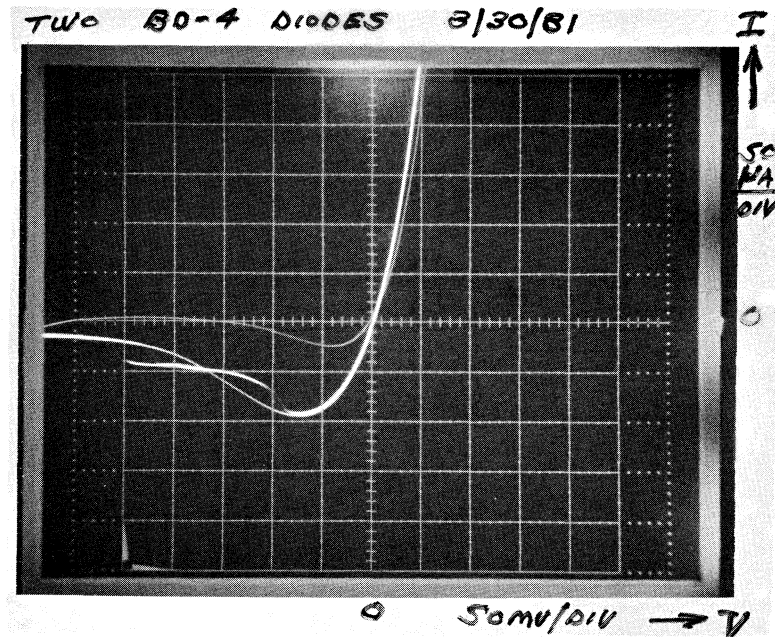
Fig. 5. Current-voltage characteristic of two
        BD-4 diodes (dim curve and bright curve).
        An instability, due to negative resistance
        oscillations occurred on the bright curve
        but could be surpressed by small capacitance
        (fingers!) across the diode. The slope of
        the I-V characteristic at the origin is the
        video output conductance of the detector;
        for the bright curve above, this is 1/(330 ohms).

DETECTOR #3, -15DBM AT 10VOLTS,RL=5K,3.7K,AND 2.5K

#3 AT -16DBM
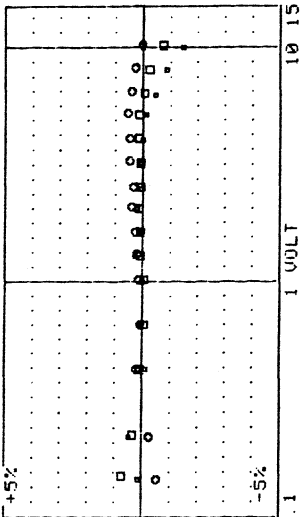
DETECTOR #3 FINAL MARCH 25,1981

UZ=26.17	PZ=-3.65	S=5.14	
ATTEN	DET MV	MTR MV	ERROR
31	36.3	-1.67	0%
11	1039.63	193.4	0%
1	10260.25	1990.38	-.21%
2	8180.8	1583.03	-.07%
3	6441.58	1243.65	0%
4	5188.58	999.15	.09%
5	4090.5	786.2	.05%
6	3256.48	624.42	0%
7	2568.83	490.92	-.04%
8	2083.48	396.2	-.04%
9	1646.13	311.67	-.11%
10	1313.63	246.85	-.07%
11	1039.63	193.53	-.06%
13	667.7	121.63	-.41%
15	428.05	74.33	.2%
18	230.33	36.38	-.73%
20	155.42	21.38	.37%

Fig 6. Example of use of square-law error program. The data in the top-left graph was obtained with detector maximum input power level at -15 dBm and 3 different values of detector load resistance; the detector amplifier gain was adjusted at each load resistance setting to give 10 volts amplifier output at -15 dBm input power. A desired maximum error of 0.3% could not be obtained at this power level. The maximum power level was reduced to -16 dBm (lower left graph) and finally to -17 dBm (upper right) where satisfactory performance was obtained at a load resistance of ∿ 3k and amplifier gain of 780. A table of attenuator dB, detector and power meter output mV corrected for zero, and % error was then printed.

SAMP=50 TIME=1000MS RMS=.107MV DRIFT=5E-03MV/S AV=1016.89MV

DETECTOR #3 -27DBM INPUT

11DB

1000MS

225MHZ

50 SAMPLES

THEORETICAL
RMS=7E-03%
OR .07MV

VZ=21.89 MV

VN=1016.7 MV

RMS=.107MV DRIFT=5E-03 MV/S AV=1016.89 MV

SAMP=50 TIME=1000MS RMS=.061MV DRIFT=5E-03MV/S AV=3.15MV

NO SIGNAL

11DB

1000MS

225MHZ

50 SAMPLES

THEORETICAL
RMS=7E-03%
OR 0MV

VZ=25.69 MV

VN=2.9 MV

RMS=.061MV DRIFT=5E-03 MV/S AV=3.15 MV

RMS = 78 NV REFERRED TO INPUT OR 86 3510CM OF AMP
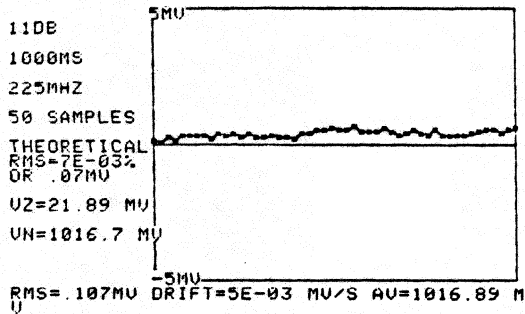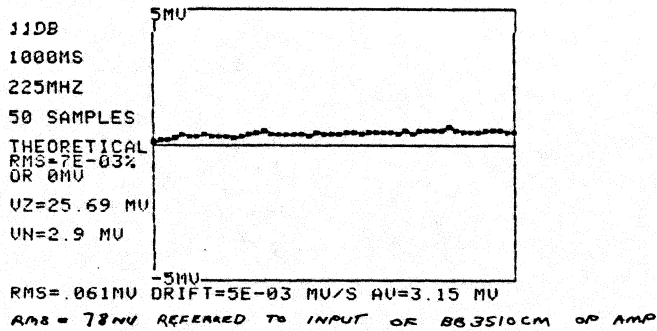
SAMP=50 TIME=1000MS RMS=.272MV DRIFT=-.016MV/S AV=4065.31MV

DETECTOR #3 ,-21 DBM INPUT

5DB

1000MS

225MHZ

50 SAMPLES

THEORETICAL
RMS=7E-03%
OR .27MV

VZ=26.6 MV

VN=4065.1 MV

RMS=.272MV DRIFT=-.016 MV/S AV=4065.31 MV
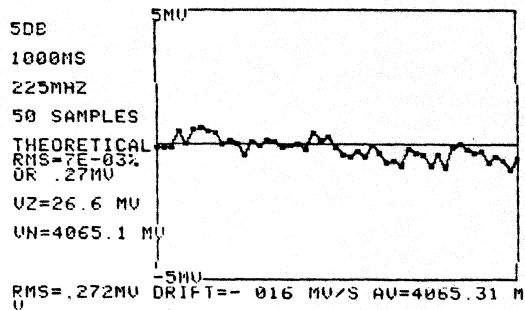
Fig. 7. Example of noise tests of a detector and amplifier. The
variation in amplifier output is plotted as a function of
time; more specifically, fifty one-second averages of the
output minus the first average are plotted. Statistics
such as the rms deviation, drift rate, and average output
are then computed and printed. The theoretical rms noise
due to the noisy IF input signal of stated bandwidth is
also given at the left of each plot. The three plots are
for different input signal levels. The middle plot, at
zero input signal, shows a rms output noise of 61 µV
which is equal to the theoretical noise at ∿ 0.9 volts
detector output (27.5 dBm input); at this level the op
amp noise is equal to the inherent fluctuation of the
detected noise for 1 second.

SAMP=50 TIME=1000MS RMS=.397MV DRIFT=-1E-03MV/S AV=1.45MV

OP27CJ OP AMP. ADIOS GAIN X10 AND OP AMP GAIN=780 GIVING 51NV RMS OP AMP NOISE.

210B
1000NS
225MHZ
50 SAMPLES
THEORETICAL RMS=7E-03%
OR 0MV
VZ=52MV
VN=1.6MV

RMS=.397MV DRIFT=-1E-03 MV/S AV=1.45 MV
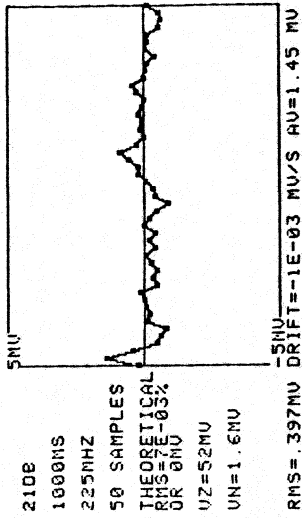
SAMP=50 TIME=1000MS RMS=.59MV DRIFT=.057MV/S AV=1.78MV

SAMP=50 TIME=1000MS RMS=.464MV DRIFT=-.012MV/S AV=2.7MV

SAMP=50 TIME=1000MS RMS=.623MV DRIFT=.03MV/S AV=2.05MV

BURR-BROWN 3510CM. AVERAGE OF 3 IS 70NVRMS REFERRED TO INPUT

210B
1000NS
225MHZ
50 SAMPLES
THEORETICAL RMS=7E-03%
OR 0MV
VZ=546.73MV
VN=2.5MV

RMS=.623MV DRIFT=.03 MV/S AV=2.05 MV
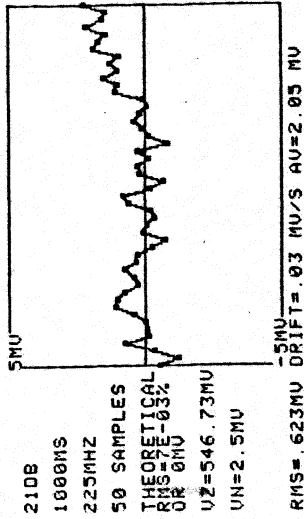
SAMP=50 TIME=1000MS RMS=.52MV DRIFT=.084MV/S AV=1.79MV

SAMP=50 TIME=1000MS RMS=.397MV DRIFT=.014MV/S AV=1.55MV

SAMP=50 TIME=1000MS RMS=.477MV DRIFT=.014MV/S AV=2.21MV

SECOND OP27. AVERAGE RMS 59NV

210B
1000NS
225MHZ
50 SAMPLES
THEORETICAL RMS=7E-03%
OR 0MV
VZ=336.44MV
VN=2.5MV

RMS=.477MV DRIFT=.014 MV/S AV=2.21 MV
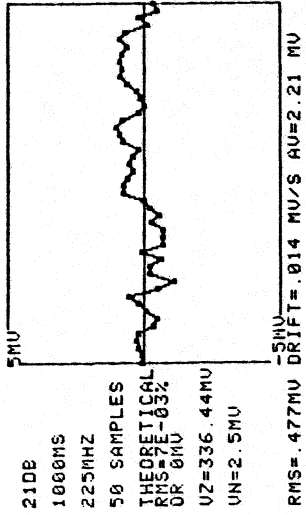
SAMP=50 TIME=1000MS RMS=1.947MV DRIFT=.105MV/S AV=-.91MV

SAMP=50 TIME=1000MS RMS=1.89MV DRIFT=-7E-03MV/S AV=5.29MV

MP-5507EJ. RMS 242NV RTI

210B
1000NS
225MHZ
50 SAMPLES
THEORETICAL RMS=7E-03%
OR 0MV
VZ=329.63MV
VN=6.5MV

RMS=1.89MV DRIFT=-7E-03 MV/S AV=5.29 MV
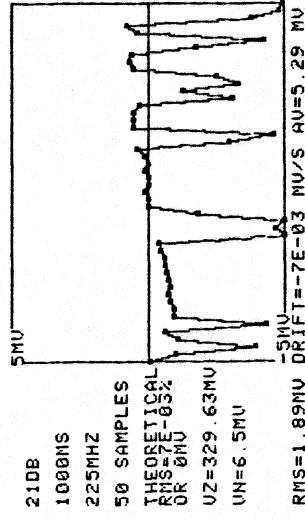
SAMP=50 TIME=1000MS RMS=.514MV DRIFT=.011MV/S AV=1.82MV

SAMP=50 TIME=1000MS RMS=.585MV DRIFT=.052MV/S AV=.82MV

Fig. 8. Examples of noise tests of operational amplifiers. Detector diode was connected, no RF signal was applied, op amp voltage gain was 780, ADIOS gain was 10, and integration time was 1 second. The rms noise is thus measured in the .01 Hz to 0.5 Hz band where it is not specified by manufacturers. The OP27CJ rms input noise is ~ 58 nV which should be compared to a specification of 250 nV peak-to-peak in the .01 to 10 Hz band.

Appendix I. Square-Law Error Definition

Let V(K) and P(K) be the voltages measured by ADIOS at its AIN and BIN inputs connected to the detector output and power meter outputs, respectively; zero error within ADIOS is included in V(K) and P(K). The digitally controlled attenuator setting, in dB, corresponding to these values is A(K). The index. K, runs from 0 to N which is normally 16.

The first set of numbers, for K = 0, is taken at maximum attenuation, A(0) = 31, and is used, primarily to determine the total zero errors, VZ and PZ. The second set of numbers, K = 1, is taken at a reference attenuation level, A(1) = 11, which should be in the middle of the dynamic range of the detector. The gain factor, G, is defined as,

$$G \equiv 10^{-[A(0) - A(1)]/10} = .01,$$

and the zero offsets and scale factor, S, are computed as,

$$VZ = \frac{V(0) - G * V(1)}{1 - G} \qquad (I.1)$$

$$PZ = \frac{P(0) - G * P(1)}{1 - G} \qquad (I.2)$$

$$S = \frac{V(1) - VZ}{P(1) - PZ} \qquad (I.3)$$

The equations for VZ and PZ reduce to V(0) and P(0) as $G \rightarrow 0$.

The attenuator is then stepped thru 15 values listed in the program statement 540. For each value the % error is computed as,
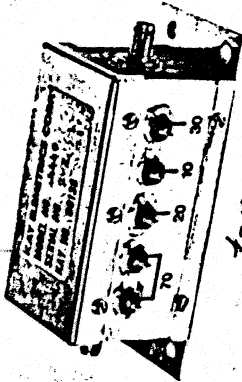
$$E(K) = 100 * \frac{V(K) - VZ - S * (P(K) - PZ)}{V(K)} \qquad (I.4)$$

Digital Attenuator Driver schematic — 7406 HEX INVERTER, 2N3906, 1N914, toggle switches OFF-ON-EXT, cable to radios. Labeled "DIGITAL ATTENUATOR 3/5/81, J WEINREB". Channels F, H, J, A, B, C, E with attenuation values 1 DB, 2 DB, 4 DB, 8 DB, 16 DB, SPARE.

Kay Electric Co., Pine Brook, NJ
PROGRAMMABLE ATTENUATORS
- RAPID RELAY SWITCHING
- EASY FIELD SERVICE

THESE ATTENUATORS MAY BE TAILORED FOR CUSTOM REQUIREMENTS, INCLUDING FRACTIONAL STEPS — CONSULT FACTORY.

MODEL		4440	4450	4460	4447	4457	4467
FREQUENCY RANGE (MHz)		DC-1500	DC-1500	DC-1500	DC-1000	DC-1000	DC-1000
ATTENUATION RANGE (dB)		0-130	0-127	0-31	0-130	0-127	0-31
STEPS (dB)		10,20,30,70	1,2,4,8,16,32,64	1,2,4,8,16	10,20,30,70	1,2,4,8,32,64	1,2,4,8,16
ACCURACY: ±dB or %dB	DC-500MHz	1.0	1.0	.5	1.0	1.0	.5
	500-1000MHz	1.5	1.5	.75	1.5	1.5	.8
	1000-1500MHz	2.5	3.0	1.0			
VSWR 1:	DC-500MHz	1.3:1	1.3:1	1.3:1	1.3:1	1.3:1	1.2:1
	500-1000MHz	1.4:1	1.4:1	1.4:1	1.4:1	1.5:1	1.3:1
	1000-1500MHz	1.4:1	1.5:1	1.4:1			
INSERTION LOSS(dB)	DC-500MHz	1.5	1.5	1.5	1.5	2.0	1.5
	500-1000MHz	2.0	3.0	2.0	2.0	3.0	2.0
	1000-1500MHz	2.0	4.0	2.5			
POWER (WATTS)		.5	.5	.5	.5	.5	.5
SWITCH SPEED		6 MILLISECONDS PER STEP					
SWITCH LIFE		10,000,000 OPERATIONS					
CONTROL VOLTAGE		ATTENUATION INSERTED ±12V, 370 MILLIWATTS PER STEP (OPTIONAL VOLT 5,6,9,18,26.5) ATTENUATION OUT 0 TO +5 VOLT					
CONNECTORS		BNC STANDARD (OPTIONS SMA,TNC,N)					
WEIGHT		12 ounces					.34 Kgs.

50 OHMS — 75 OHMS

MODEL	A	B	C
4440 4460 4447 4467	4" 10.16 cm	31/8" 7.9 cm	31/2" 8.9 cm
4450 4457	51/8" 13.0 cm	41/8" 10.4 cm	45/8" 11.7 cm

Appendix II. Digital Attenuator and Driver

Appendix III. DETECTOR1 Program

Hardware Connection

A system such as that shown in Figure 1 must be connected thru the ADIOS interface to the Apple Computer. The ADIOS analog-input scaling toggle switches should be set for +/- (bipolar) mode with AIN full scale at 10 volts and BIN full scale at 1 volt.

Program Entry

The DETECTOR1 program must be on a disk along with auxiliary programs SHAPES (plotting symbols), HGR CHR GEN (to label plot), ADIOS-INITB (to initialize the A/D interface), and LOMEM: (to move program in memory). Type "RUN DETECTOR1" to load and run the program; the program will subsequently load in the auxiliary programs.

The program chooses integration time, COUNT = 800 MS, and settling time between attenuator steps, BLANK = 800 MS, for the square-law error measurement. These may be changed by typing the CTRL and E keys and then 192 when EDIT appears on the screen. The desired values are substituted in program line 192, the RETURN key is pressed, and "RUN" is typed to start the program with the new values. A similar procedure can be used on line 540 to change attenuator step values.

Program Operation

The program has several tasks; each is initiated by first typing the ESC key and then a number as described below. Any task may be terminated by typing "CTRL C."

ESC 1 - This starts a square-law error measurement. If the program
        has previously plotted square-law errors or noise measurements
        on the CRT, the screen may be first erased by typing "ESC 8."

ESC 2 - Pressing this after a square-law error measurement temporarily removes the plot and gives a table of results on the CRT.

ESC 3 - Brings back the square-law error plot after using ESC-2.

ESC 4 - This starts a detector noise measurement. The program first allows changing the number of samples, the attenuator DB setting, the integration time per sample in milliseconds, the IF bandwidth in MHz, or the plot scale in mV. Pressing RETURN will start the measurement.

ESC 6 - This prints the graph which is (or has been) on the CRT screen in a 5" wide format.

ESC 7 - This prints the graph double-size and rotated 90°.

ESC 8 - Erases graph memory.

ESC 9 - Prints a table of square-law error values.

Program Listing

A listing of the program as on March 26, 1981 follows:

```
01/23/81  0823.9


PROGRAM LENGTH= 11813 BYTES          VARIABLES= 2459 BYTES
FREE MEMORY= 6207 BYTES
START=16385 LOMEM=28198 FREE=30577 STRING=36784 HIMEM=36864


100  REM     DETECTOR1 PROGRAM OF MARCH 26,1981 MEASURES SQUARE LAW
 ERROR OF A DETECTOR
110  REM     REQUIRED HARDWARE: 48K APPLE II+WITH DISK,CRT,PRINTER,CLOCK,AN
D ADIOS A/D INTERFACE

120  REM     REQUIRED ON DISK: SHAPES (PLOTTING SYMBOLS),HGR CHR GEN
 (TO LABEL PLOT), ADIOS-INITB (TO INITIALIZE A/D INTERFACE), AND LOMEM:
 (TO MOVE PROGRAM LOCATION)
130  REM  NEXT MOVES PROGRAM START TO 16384
140  PRINT  CHR$ (4);"BRUN LOMEM:": &  LOMEM: 16384
145  REM  LOMEM IN A816,L160
150  HIMEM: 36864
160  REM    NEXT  POKES RESTORE MEMORY AFTER 1013 SINCE LOMEM: CHANGED
 VALUES
170  POKE 1013,76: POKE 1014,12
180  POKE 1015,151: POKE 1016,76
190  POKE 1017,0: POKE 1018,151
```

```
192 CN = 800:BN = 0800: REM      DEFAULT COUNT AND BLANK TIMES IN MS
195  REM    NEXT ANNOUNCES PROGRAM
197  HGR : TEXT : HOME : SPEED= 255
200  PRINT "DETECTOR1 OF  3/26/81": PRINT
202  PRINT "MEASURES SQUARE-LAW ERROR AND DETECTOR NOISE AND DRIFT.
 CONNECT DETECTOR TO AIN AND POWER METER TO BIN. ADIOS INTERNAL SWITCHES
 MUST BE SET FOR +/- 10 VOLT MODE"
204  PRINT : PRINT "INTEGRATION PARAMETERS ARE COUNT=";CN;" AND BLANK=";BN
;". CHANGE THESE BY CONTROL-E 192. CHANGE ATTENUATOR STEPS BY CONTROL-E
 540."
206  PRINT : PRINT "START SQUARE-LAW TEST BY ESC-1 OR NOISE/DRIFT TEST
 BY ESC-4"
208  REM        NEXT LOADS CHARACTER GENERATOR  IN A2048,L3328
210  PRINT  CHR$ (4);"BLOAD HGR CHR GEN"
220  REM    DEFINES CONTROL D FOR DOS PRINT
230 D$ =  CHR$ (4):DC$ = D$ + "CLOSE"
270  REM   NEXT LOADS PLOTTING SYMBOLS
275  PRINT D$;"BLOAD SHAPES"
280  POKE 232,191: POKE 233,31: REM  BLOADED  SHAPES, A8127,L24
290  DIM A(050),V(200),P(050),E(050)
310  REM   NEXT INITILIZES A/D INTERFACE  AND SETS UP INTEGRATION CYCLE
320  PRINT D$;"BLOAD ADIOS-INITB"
330  REM    BLOADED 85 = $55 BYTES IN 7986 = $1F32
350 COUNT = CN:BLANK = BN
360  GOSUB 4100: REM  LOADS COUNT AND BLANK INTO ADIOS
420  REM   GOSUB 5300 TO TURN ON PRINTER
430  REM   CALL 1013 TURNS OFF PRINTER
450  POKE 33,40: REM  NORMAL TEXT WINDOW
480  REM  : CONSTANTS FOR SCALING
490 CA = 32:CB = 0.5:CC = 100:CE = 10:CD = 4.3429:CF = .23025851
492 CG = 1000
495 C1 = 100:C2 = 55.677:C3 = 4.605:C4 = 75:C5 =  - 15
496 C8 = 278:C9 = 150
500  REM   CONSTANTS FOR DATA TRANSFER
510 MC = 3.2768:MJ = 128:MK = 256:MM = 65536
520  REM   DEFAULT PARAMETER VALUES
530  FOR K = 0 TO 16: READ A(K): NEXT K
540  DATA    31,11,1,2,3,04,05,6,7,8,9,10,11,13,15,18,20
550  RESTORE
555 G =  EXP (CF * (A(1) - A(0)))
600  REM   ROUND-OFF FUNCTIONS NEXT
610  DEF  FN F0(X) =  INT (X + CB)
615  DEF  FN F1(X) =  INT (CE * X + CB) / CE
620  DEF  FN F2(X) =  INT (CC * X + CB) / CC
625  DEF  FN F3(X) =  INT (CG * X + CB) / CG
630  REM   PLOTTING FUNCTIONS NEXT
640  DEF  FN Y(E) = C4 + C5 * E
650  DEF  FN X(V) = C2 * ( LOG (V) - C3)
700 DB = 11: GOSUB 4200: REM  SET ATTENUATOR TO REFERENCE LEVEL
800  REM   DEFAULT RMS NOISE PARAMETERS NEX
810 SAMPLES = 25:D1 = 11:TI = 1000:BW = 2:PS = 5
990 L = 1
998 N = 16
999  END
```

```
1100   GOSUB 3300: END
1200   TEXT : END
1300   POKE  - 16304,0: POKE  - 16301,0: VTAB (21): END
1400   REM  NOISE TEST
1410   GOSUB 2000: END
1600   REM  PRINT GRAPH
1605   INPUT "TYPE QUOTE MARK,COMMENT, AND (RETURN)    ";CM$
1610   GOSUB 5300: REM  TURN ON PRINTER
1620   PRINT CM$
1625   POKE 1145,105: REM  REGULAR SIZE
1630   CALL  - 16038: REM   FOR TRENDCOM 200
1640   CALL 1013: REM  PRINTER OFF
1650   END
1700   REM  BIG PLOT ON TRENDCOM 200 PRINTER
1705   INPUT "TYPE QUOTE MARK,COMMENT, AND (RETURN)    ";CM$
1710   GOSUB 5300
1720   POKE 2041,0: REM  DEFEAT PAGE
1730   PRINT CM$
1740   POKE 1145,107: REM  DOUBLE SIZE
1750   CALL  - 16038: REM  PLOT
1755   POKE 2041,68: REM  RESET11" PAGE
1760   CALL 1013: END : REM

1800   HGR : TEXT : HOME :L = 1: END : REM   ERASE GRAPHICS SCREEN
1900   GOSUB 5800: REM   PRINT TABLE
1910   POKE  - 16304,0: POKE  - 16301,0: VTAB (21): END
2000   REM  RMS NOISE MEASUREMENT
2010   SCALE= 1: ROT= 0
2015   TEXT : HOME
2018   PRINT
2019   HOME
2020   PRINT "PRESENT PARAMETERS ARE:"
2025   PRINT "(1) SAMPLES= ";SA
2030   PRINT "(2) DB= ";D1
2035   PRINT "(3) INTEGRATION= ";TI;" MS"
2040   PRINT "(4) BANDWIDTH= ";BW;" MHZ"
2042   PRINT "(5) PLOT SCALE,MV=";PS
2045   PRINT
2050   PRINT "CHANGE (1),(2),(3),(4),(5) OR (RETURN) TO START MEASUREMENT"
2055   GET J$
2060   ON  VAL (J$) GOTO 2080,2100,2120,2130,2137
2070   GOTO 2140
2080   INPUT "(1) SAMPLES= ";SA
2085   GOTO 2018
2100   INPUT "(2) DB= ";D1
2105   GOTO 2018
2120   INPUT "INTEGRATION= ";TI
2125   GOTO 2018
2130   INPUT "BANDWIDTH= ";BW
2135   GOTO 2018
2137   INPUT "PLOT SCALE,MV= ";PS
2138   GOTO 2018
2140   REM  CHANGE COUNT AND BLANK IN ADIOS
2150   COUNT = TI:BLANK = 80
```

```
2160  GOSUB 4100: REM   INITIALIZE ADIOS
2165 DB = A(0): GOSUB 4200: REM   ZERO
2170 SG = .031 / SQR (BW * TI): REM   THEORETICAL RMS
2175  REM   DEF PLOT AXIS NEXT
2180  DEF  FN Y1(W) = 75 - 74 * W / PS
2190  DEF  FN X1(K) = 79 + 200 * (K - 1) / SA
2195 WL =  - PS:WH = PS
2200  HGR
2207  FOR W = WL TO 1.1 * WH STEP WH
2210  HPLOT  FN X1(1), FN Y1(W) TO  FN X1(SA), FN Y1(W): NEXT W
2220  HPLOT  FN X1(1), FN Y1(WL) TO  FN X1(1), FN Y1(WH)
2230  HPLOT  FN X1(SA), FN Y1(WL) TO  FN X1(SA), FN Y1(WH)
2240  REM   LABEL
2250  HCOLOR= 0: CALL 3072: PRINT  CHR$ (1): PRINT  CHR$ (17): HCOLOR=
 3
2260  VTAB (2): PRINT D1;"DB"
2270  VTAB (4): PRINT TI;"MS"
2280  VTAB (6): PRINT BW;"MHZ"
2285  VTAB (8): PRINT SA;" SAMPLES"
2290  VTAB (10): PRINT "THEORETICAL"
2292  VTAB (11): PRINT "RMS="; FN F3(100 * SG);"%"
2300  VTAB (21): CALL 1013: POKE  - 16301,0
2310 DB = A(0): GOSUB 4200
2315 K = 0
2320 DB = A(1): GOSUB 4200:V0 = AIN
2330 DB = D1: GOSUB 4200:VR = AIN
2340 VZ = (V0 - G * VR) / (1 - G)
2350  GOSUB 4200:VN = AIN - VZ
2355  REM   USE HGR CHR GEN FOR VZ AND VN
2360  HCOLOR= 0: CALL 3072: PRINT  CHR$ (1): PRINT  CHR$ (17): HCOLOR=
 3
2365  VTAB (12): PRINT "OR "; FN F2(VN * SG);"MV"
2370  VTAB (14): PRINT "VZ="; FN F2(VZ);"MV"
2380  VTAB (16): PRINT "VN="; FN F1(VN);"MV"
2385  VTAB (1): HTAB (12): PRINT  FN F1(WH);"MV"
2390  VTAB (19): HTAB (12): PRINT  FN F1(WL);"MV"
2400  VTAB (21): CALL 1013: POKE  - 16301,0
2410 V1 = 0:V2 = 0:V3 = 0
2430  FOR K = 1 TO SA
2440  GOSUB 4200:V(K) = AIN - VZ
2445 DV = V(K) - VN
2450 V1 = V1 + DV:V2 = V2 + DV ^ 2
2460 V3 = V3 + K * DV
2470 P0 = (V(K - 1) - VN)
2472 P1 = (V(K) - VN)
2475  IF P0 > WH THEN P0 = WH
2476  IF P0 < WL THEN P0 = WL
2477  IF P1 > WH THEN P1 = WH
2478  IF P1 < WL THEN P1 = WL
```

```
2480  IF K < > 1 THEN  HPLOT  FN X1(K - 1), FN Y1(P0) TO  FN X1(K),
      FN Y1(P1)
2490  DRAW 2 AT  FN X1(K), FN Y1(P1)
2500  NEXT
2510 K0 = SA:K1 = SA * (SA + 1) / 2:K2 = K1 * (2 * SA + 1) / 3
2520 BB = (V3 - V1 * K1 / K0) / (K2 - K1 ^ 2 / K0): REM  DRIFT SLOPE
2530 AV = V1 / K0 - BB * K1 / K0: REM    AVERAGE  ABOVE VN
2540 DR = 1000 * BB / (TI + 80): REM     DRIFT IN MV/SEC
2550 MZ = V2 - 2 * AV * V1 - 2 * BB * V3 + AV ^ 2 * K0 + 2 * AV * BB
      * K1 + BB ^ 2 * K2
2555 AV = AV + VN
2560 RMS = ( SQR (MZ / K0))
2565  HCOLOR= 0: CALL 3072: PRINT  CHR$ (1): PRINT  CHR$ (17): HCOLOR=
      3
2568  VTAB (20)
2570  PRINT "RMS="; FN F3(RMS);"MV";" DRIFT="; FN F3(DR);" MV/S";"
      AV="; FN F2(AV);" MV"
2575  CALL 1013: POKE  - 16301,0
2600  GOSUB 5300: REM  TURN ON PRINTER
2605  PRINT
2610  PRINT "SAMP=";SA;" TIME=";TI;"MS  RMS="; FN F3(RMS);"MV  DRIFT=";
      FN F3(DR);"MV/S    AV="; FN F2(AV);"MV"
2620  HOME : VTAB (21): CALL 1013: END
2800  REM    INITIALIZE PLOT *************
2805  REM  HANDLE LINE TYPE PARAMETER,L
2807  HCOLOR= 3
2810  ON L GOSUB 2820,2825,2830,2835,2840,2845
2815  GOTO 2850: REM      LINE TYPE SET
2820 SH = 2: ROT= 0: SCALE= 1: RETURN
2825 SH = 2: ROT= 08: SCALE= 2: RETURN
2830 SH = 2: ROT= 0: SCALE= 2: RETURN
2835 SH = 1: ROT= 0: SCALE= 1: RETURN
2840 SH = 3: ROT= 00: SCALE= 1: RETURN
2845 SH = 3: ROT= 32: SCALE= 1: RETURN
2850  POKE  - 16304,0: POKE  - 16301,0: POKE  - 16297,0
2890 L = L + 1
2895  IF L < > 2 THEN  RETURN
2900  REM  DRAW GRID AND LABEL
2905  POKE  - 16301,0: REM    TEXT/GRAPHICS
2918  HCOLOR= 3
2920  FOR J =  - 5 TO 6 STEP 5
2930  HPLOT  FN X(100), FN Y(J) TO  FN X(15000), FN Y(J)
2940  NEXT J
2945 Q(1) = 100:Q(2) = 1000:Q(3) = 10000:Q(4) = 15000
2950  FOR J = 1 TO 4
2970  HPLOT  FN X(Q(J)), FN Y( - 4.90) TO  FN X(Q(J)), FN Y(5)
2980  NEXT J
3000  REM  LABEL
3010  HCOLOR= 0
3020  CALL 3072: REM  INIT HGR CHR GEN
3030  PRINT  CHR$ (1); CHR$ (17)
3035  HCOLOR= 3
3040  VTAB (1): HTAB (2): PRINT "+5%"
3045  VTAB (18): HTAB (2): PRINT "-5%"
3050  VTAB (20): HTAB (1): PRINT ".1"
3060  VTAB (20): HTAB (18): PRINT "1 VOLT"
3070  VTAB (20): HTAB (36): PRINT "10"
3080  VTAB (20): HTAB (39): PRINT "15"
3150  VTAB (21)
3160  CALL 1013
3170  POKE  - 16301,0
```

```
3180 J1 =  FN Y(4):J3 =  FN Y( - 4)
3185 J2 = J1 -  FN Y(3)
3190  FOR J = J3 TO J1 STEP J2
3195  FOR K = 0 TO 279 STEP 8
3200  HPLOT K,J
3210  NEXT K: NEXT J
3220  RETURN
3299  REM

3300  REM  MEASUREMENT TASK
3302 COUNT = CN:BLANK = BN
3304  GOSUB 4100: REM  LOADS COUNT AND BLANK INTO ADIOS
3310 DB = A(0): GOSUB 4200
3320  GOSUB 2800
3330 DB = A(0): GOSUB 4200
3350 DB = A(1): GOSUB 4200
3360 V(0) = AIN:P(0) = BIN
3370  PRINT  FN F1(AIN), FN F1(BIN)
3400 DB = A(2): GOSUB 4200
3410 V(1) = AIN:P(1) = BIN
3420  PRINT  FN F1(AIN), FN F1(BIN)
3430 VZ = (V(0) - G * V(1)) / (1 - G)
3440 PZ = (P(0) - G * P(1)) / (1 - G)
3450 S = (V(1) - VZ) / (P(1) - PZ)
3460  PRINT "VZ= "; FN F2(VZ);"   PZ= "; FN F2(PZ);"  S= "; FN F2(S)
3500  FOR K = 2 TO N
3510 DB = A(K + 1): GOSUB 4200
3520 V(K) = AIN:P(K) = BIN
3530 E(K) = C1 * (V(K) - VZ - S * (P(K) - PZ)) / V(K)
3540  PRINT A(K); TAB( 10); FN F2(V(K)); TAB( 20); FN F2(P(K)); TAB(
  30); FN F2(E(K));"%"
3548 XX =  FN X(V(K)):YY =  FN Y(E(K))
3550  IF XX < 0 THEN XX = 0
3552  IF XX > C8 THEN XX = C8
3554  IF YY < 0 THEN YY = 0
3556  IF YY > C9 THEN YY = C9
3560  DRAW SH AT XX,YY
3570  REM  DRAW
3580  NEXT K
3610 DB = 11: GOSUB 4200
3620  RETURN : REM

4100  REM  LOAD COUNT,BLANK IN ADIOS
4110 CS = 10 / COUNT
4115 CT = 2 * CS:CZ = 10000
4120 CX = COUNT / 10:BX = BLANK / 10
4130 CH% = CX / 256:BL% = BX / 256
4140  REM  NEXT LOADS COUNT AND BLANK TIMES INTO ADIOS
4150  POKE 7988,CX - 256 * CH%: POKE 7989,CH%
4160  POKE 7990,BX - 256 * BL%: POKE 7991,BL%
4170  CALL 8018: REM  STARTS ADIOS
4180  RETURN
4200  REM  DATA TRANSFER ROUTINE WITH PARAMETERS DB (ATTENUATION),AIN,
  AND BIN
4201  REM  GOTO 4700  :REM THIS IS TO  GENERATE A TEST INPUT TO PROGRAM
4205  REM  NEXT 4 LINES TO SET UP 9513
4210  POKE 49342,20: REM  ADDRESSES 9513 HD4
4220 ZZ =  PEEK (49334): REM  ZZ IS DUMMY
4230  POKE 49334,172: REM  CALL BIT SET HIGH
4240  IF  PEEK (49335) < 128 THEN 4500
4250  WAIT 49335,128,128: REM  WAIT UNTIL  DATA READY BIT =0 AT BLANK
```

```
TIME START
4260  POKE 49335,128: REM   RESET DATA    READY BIT
4280 DB% = DB
4290  POKE 49332,DB%
4300  POKE 49342,20: REM      ADDRESS 9513   TO OUTPUT LSWORD OF BIN
4310 BIN =  PEEK (49334) + MK *  PEEK (49334)
4320  POKE 49342,21: REM      ADDRESS 9513   TO OUTPUT MSWORD OF BIN
4330 BIN = BIN + MM *  PEEK (49334)
4335 BIN = CT * BIN - CZ
4340  POKE 49342,18: REM      ADDRESS 9513   TO OUTPUT LSWORD OF AIN
4350 AIN =  PEEK (49334) + MK *  PEEK (49334)
4360  POKE 49342,19: REM      ADDRESS 9513   TO OUTPUT MSWORD OF AIN
4365 AIN = AIN + MM *  PEEK (49334)
4367 AIN = CT * AIN - CZ
4370  POKE 49342,20: REM      ADDRESS 9513    HD4
4380 ZZ =  PEEK (49334): REM   DUMMY PEEK
4390  POKE 49334,168: REM  CLEAR CALL BIT
4400  RETURN
4500  REM   TURN ON MISSED DATA LIGHT
4510  POKE 49342,18: REM    ADDRESS HOLD1
4520 ZZ =  PEEK (49334): REM   DUMMY
4530  POKE 49334,172: REM  CLOCKS MISSED DATA ONE-SHOT
4540  POKE 49342,18
4550 ZZ =  PEEK (49334)
4560  POKE 49334,168: REM  CLEARS MISSED DATA CLOCK
4570  POKE 49335,0: REM  CLEAR FLAG
4580  GOTO 4250: REM

4590  REM

4700 AIN = 20 +  EXP (CF * (41 - DC)) + .05 * K + 2.4 * ( RND (K) -
      .5)
4705 DC = DB
4707 BIN = .1 * AIN
4710  RETURN
4800  REM    SETS T$ TO TIME
4805 YR$ = "81"
4810 D$ =  CHR$ (4)
4820  PRINT D$;"IN#4"
4830  PRINT D$;"PR#4"
4840  INPUT " ";T$
4850  CALL 1013
4870 DT$ =  LEFT$ (T$,5) + "/" + YR$ + " "
4872 SC$ =  MID$ (T$,13,2)
4874 EM = .1 *  INT ( VAL (SC$) / 6)
4876 EM$ =  STR$ (EM)
4880 TM$ =  MID$ (T$,7,2) +  MID$ (T$,10,2) + EM$ + " "
4890  RETURN
5300  REM        TURNS ON TRENDCOM 200 PRINTER
5310  REM   :GOTO 5400: REM  FOR APPLE PRINTER
5315  PR# 1: PRINT  CHR$ (0): REM    FIRST CHARACTER NOT PRINTED
5320  POKE 1913,6: POKE 1785,72: REM    MARGINS
5330  POKE 1657,80: REM   LINE LENGTH
5340  RETURN
5400  REM    TURN ON APPLE PRINTER
5410  PRINT  CHR$ (4);"PR#1"
5420 Q$ =  CHR$ (17): REM   PRINT Q$ TO DUMP GRAPHICS
5430  POKE  - 12524,0: REM    BLACK ON WHITE PLOT
5440  POKE  - 12528,7: REM    DARK PRINT
5450  POKE  - 12527,8: REM    LEFT MARGIN
5460  RETURN
```

```
5800    REM    PRINTS TABLE
5810    GOSUB 5300: REM    TURN ON PRINTER
5820    HOME : PRINT  CHR$ (9);"N": REM    DISABLE CRT
5830    POKE 33,80: REM    SET MARGIN
5835    PRINT "VZ=";  FN F2(VZ); TAB( 15);"  PZ=";  FN F2(PZ); TAB( 30);"S=";
 FN F2(S)
5840    PRINT "ATTEN"; TAB( 15);"DET MV"; TAB( 30);"MTR MV"; TAB( 45);"ERROR
"
5850    FOR K = 0 TO N
5860    PRINT A(K); TAB( 15);  FN F2(V(K)); TAB( 30);  FN F2(P(K)); TAB(
 45);  FN F2(E(K));"%"
5870    NEXT : POKE 33,40
5880    PRINT  CHR$ (9);"I": REM    ENABLE CRT
5890    CALL 1013
5900    POKE  - 16301,0
5910    RETURN : REM

6000    REM    FORMATTED LIST
6002    GOSUB 4800: REM     GET TIME
6005    POKE 33,33
6010    GOSUB 5300: REM    TURN ON PRINTER
6025    DEF  FN CT(AD) =  PEEK (AD) + 256 *  PEEK (AD + 1)
6028 SR =  FN CT(103)
6030 LM =  FN CT(105):FR =  FN CT(109)
6035 HM =  FN CT(115):ST =  FN CT(111)
6043    PRINT : PRINT DT$,TM$: PRINT
6045    PRINT "PROGRAM LENGTH= ";LM - SR;" BYTES         VARIABLES= ";HM
 - ST + FR - LM;" BYTES"
6050    PRINT "FREE MEMORY= ";ST - FR;" BYTES"
6051    PRINT "START=";SR;" LOMEM=";LM;" FREE=";FR;" STRING=";ST;" HIMEM=";H
M
6055    PRINT
6060    LIST
6065    CALL 1013
6070    END
```

Appendix IV. Noise Analysis

Given a sequence of samples, V(K), for K = 1 to SA, , we wish to compute

the linear function, A + B * K, which minimizes the total mean square

deviation, M, from V(K)

$$M = \sum_{k=1}^{SA} [V(K) - A - B * K]^2 \qquad \text{(IV.1)}$$

The minimization is performed in the usual manner by setting the derivatives

of M with respect to A and B equal to zero and then solving the two simultaneous

linear equations for A and B. The result is expressed in terms of six quantities

which are defined below, all summations being for K = 1 to SA:

$$V1 = \sum V(K) \qquad \text{(IV.2)}$$

$$V2 = \sum V^2(K) \qquad \text{(IV.3)}$$

$$V3 = \sum K*V(K) \qquad \text{(IV.4)}$$

$$K\emptyset = \sum 1 = SA \qquad \text{(IV.5)}$$

$$K1 = \sum k = SA*(SA + 1)/2 \qquad \text{(IV.6)}$$

$$K2 = \sum k^2 = K1*(2SA + 1)/3 \qquad \text{(IV.7)}$$

$$A = V1/K\emptyset - B*K1/K\emptyset \qquad \text{(IV.8)}$$

$$B = (V3 - V1*K1/K\emptyset)/(K2 - K1^2/K\emptyset) \qquad \text{(IV.9)}$$

$$M = V2 - 2*A*V1 - 2 \times B*V3 + A^2*K\emptyset + 2*A \times B*K1 + B^2*K2 \qquad \text{(IV.10)}$$

The rms deviation, RMS, and drift rate are then given by,

$$RMS = \sqrt{M/K0} \qquad \text{(IV.11)}$$

$$DR = B/(SA*T1) \qquad \text{(IV.12)}$$

where T1 is the time interval of one sample.

To ease computational accuracy requirements, a voltage, VN, equal to the value of an initial sample is subtracted from the measured voltage before computation of the sums IV.2-4. The same quantity is then added to A to give the average value of the sequence with drift removed.

The theoretical rms deviation of the output of a square-law detector driven by noise of bandwidth, BW, is given in % as $100*/\sqrt{BW*T1}$ or as a voltage value, $VN/\sqrt{BW*T1}$. These values are printed by the program for comparison with measured values. It should be noted that the % accuracy of a rms deviation measurement is equal to $100/\sqrt{SA}$; thus, for SA = 50 a rms accuracy of 14% or a peak-to-peak error of $\pm$ 30% is expected.