NATIONAL RADIO ASTRONOMY OBSERVATORY
CHARLOTTESVILLE, VIRGINIA

CTRONICS DIVISION INTERNAL REPORT NO. 214

SQUARE-LAW DETECTOR TESTS

S. WEINREB

MAY 1981

NUMBER OF COPIES: 150

SQUARE-LAW DETECTOR TESTS

Table of Contents

Appendices

Figures

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 describe 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.

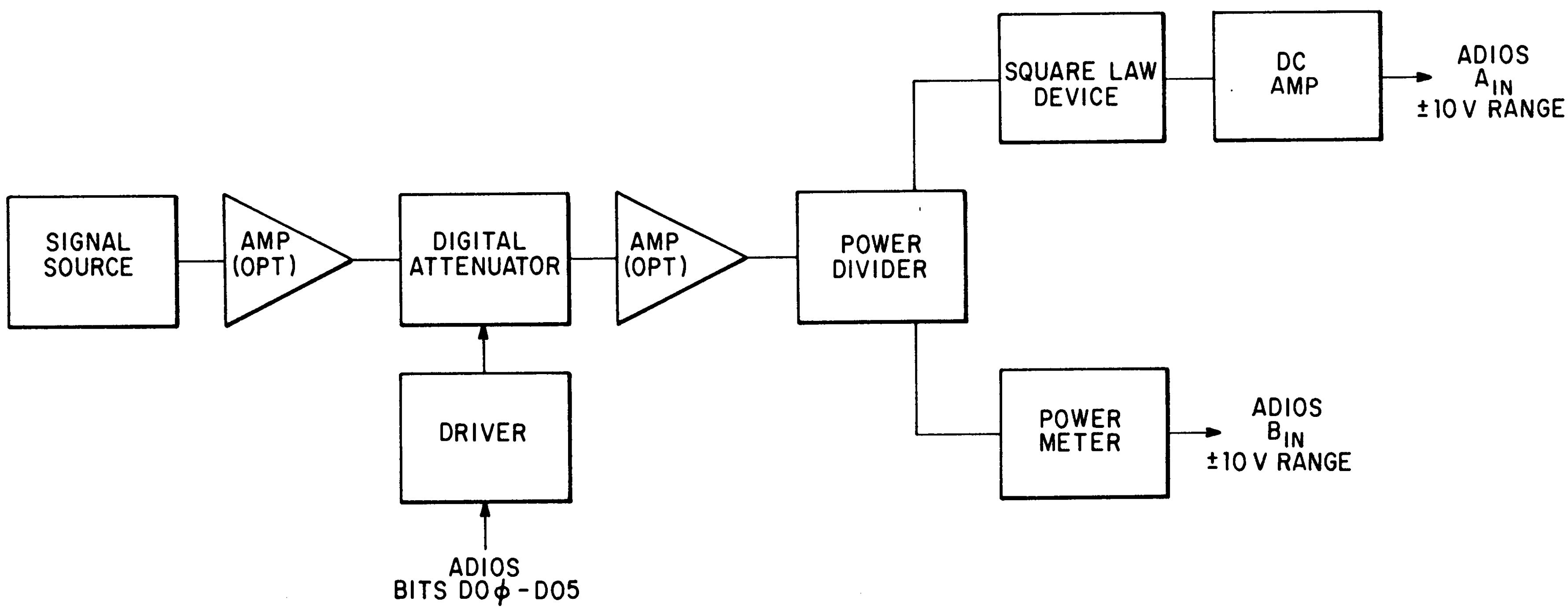


Fig. 1. Block diagram of test measurement system. ADIOS is an analog-digital input-output system for the Apple Computer and is described in NRAO EDIR No. 212.

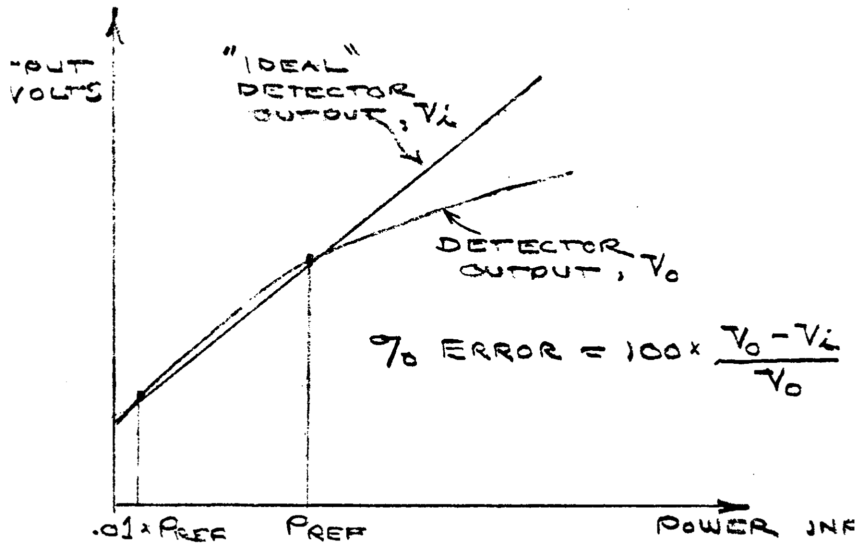
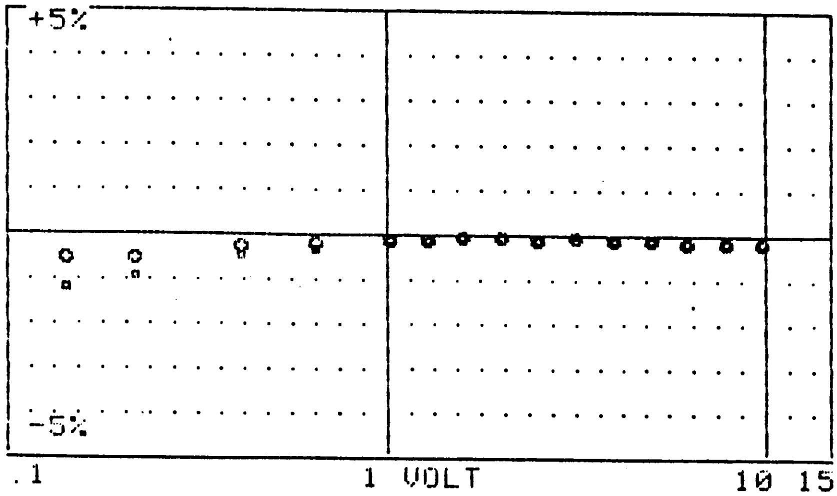
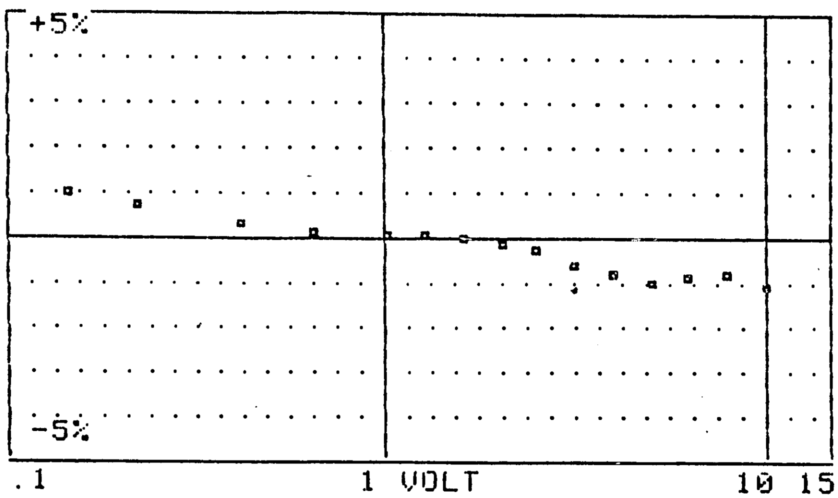


Fig. 2. Definition of detector error; also see Appe

HP 432A,1MW SCALE,INTO AIN;GM 467A,1MW SCALE, INTO BIN. 2-300MHZ N(
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.

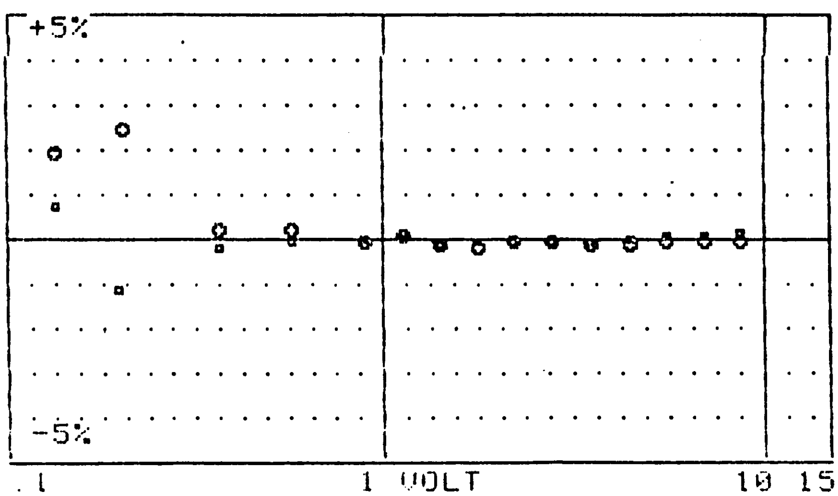


Fig. 3. Examples of power meter comparisons. The horizontal axis is 10 times the meter DC output voltage; for values < 1 volt the error is determined by noise and should be ignored. The middle curve shows an ∿ 1% error of the HP436A/8484A meter at its maximum input level of 10 μW. A broadband, 2-300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

---

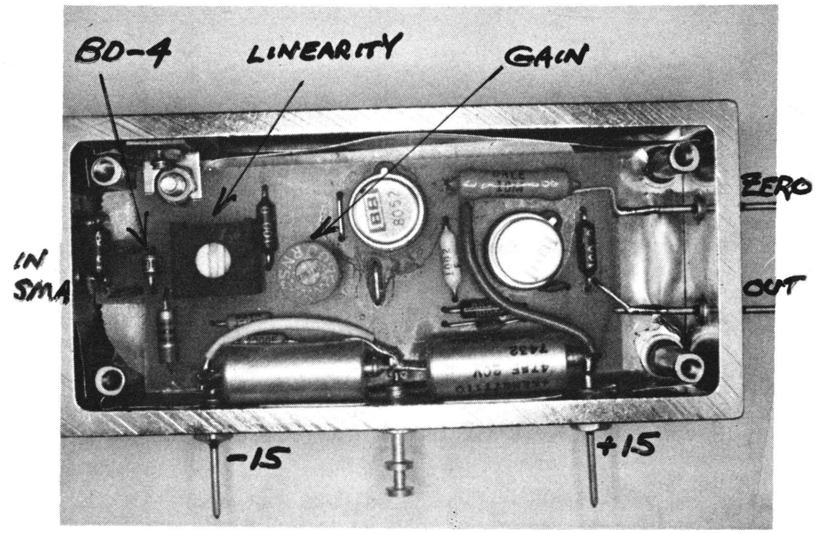
[1] Peter Camana, "The GE BD-7 Back Diode as a Square-Law Detector," NRAO Electronics Division Internal Report No. 106, September 1971.

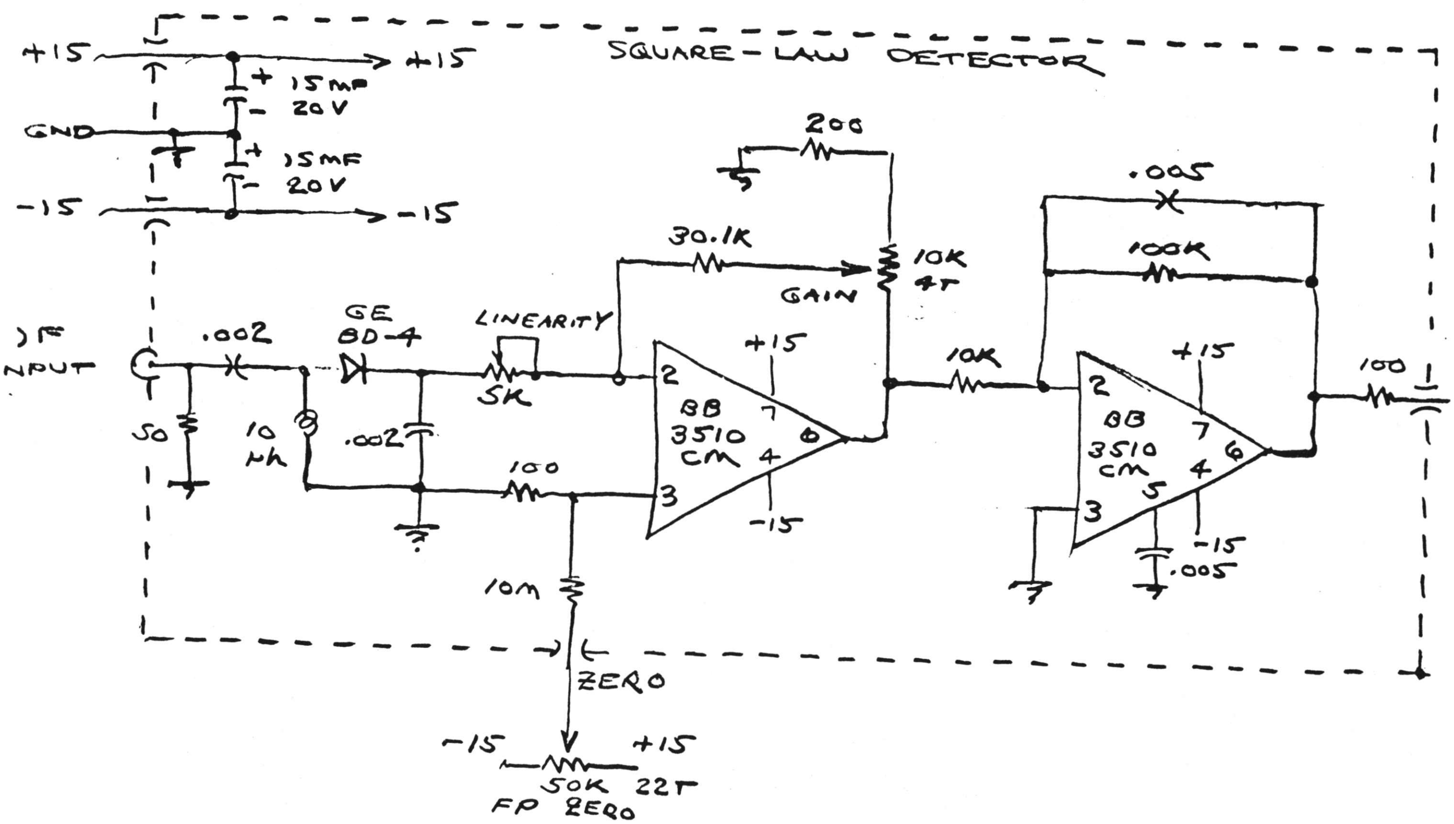
[2] A. M. Cowley and H. O. Sorensen, "Quantitative Comparison of Solid-State Microwave Detectors," IEEE Trans. Microwave Theory Tech., vol. MTT-14, no. 12, pp. 588-602, December 1966.

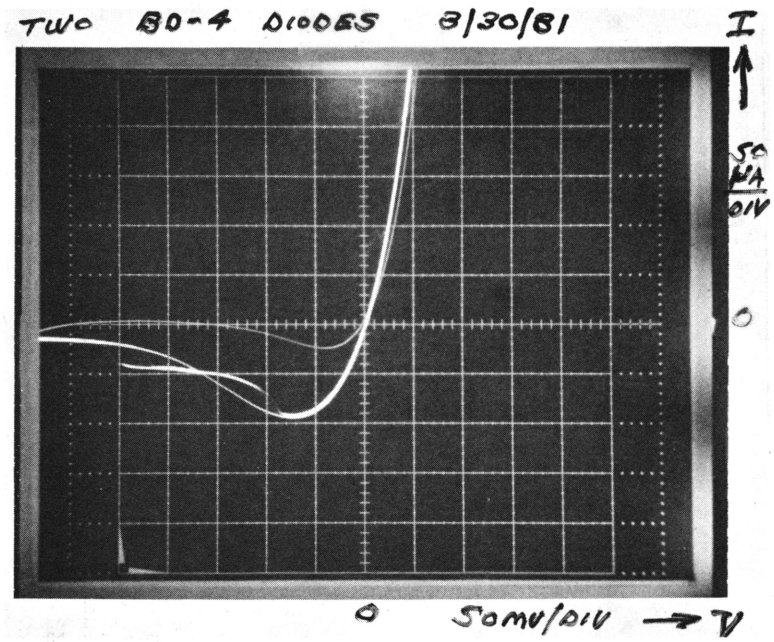
square-law performance of less than 0.5% error at < -16 dBm RF input level. The remaining diodes could not achieve this; increasing the load resistance decreased error but not to an acceptable value at 5,000 ohms. Larger load resistances were not tried as the error was not decreasing appreciably as 5 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.

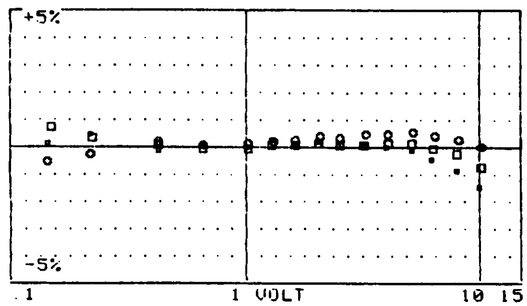

BD-4
LINEARITY
GAIN
ZERO
IN
SMA
OUT
-15
+15


SQUARE-LAW DETECTOR
+15
+15
15MF
20V
GND
15MF
20V
-15
-15
200
.005
30.1K
10K
4T
GAIN
100K
GE
BD-4
LINEARITY
.002
5K
+15
10K
+15
100
BB
3510
CM
BB
3510
CM
50
10
μh
.002
100
-15
-15
.005
10M
ZERO
-15
+15
50K 22T
FP ZERO

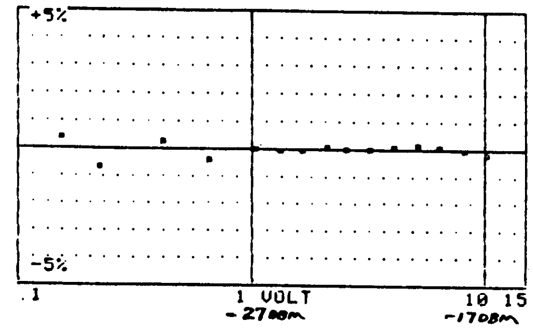


5. Current-voltage characteristic of two BD-4 diodes (dim curve and bright curve). An instability, due to negative resistance oscillations occurred on the bright curve but could be surpressed by small capacitance (fingers!) across the diode. The slope of the I-V characteristic at the origin is the video output conductance of the detector; for the bright curve above, this is 1/(330 ohm

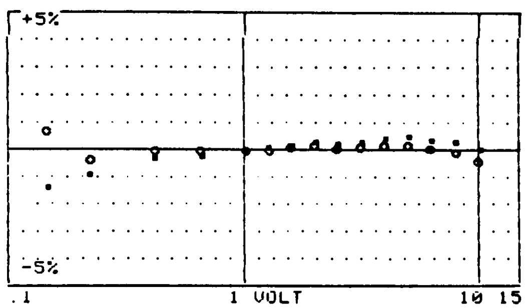
DETECTOR #3, -15DBM AT 10VOLTS,RL=5K,3.7K,AND 2.5K



DETECTOR #3 FINAL MARCH 25,1981



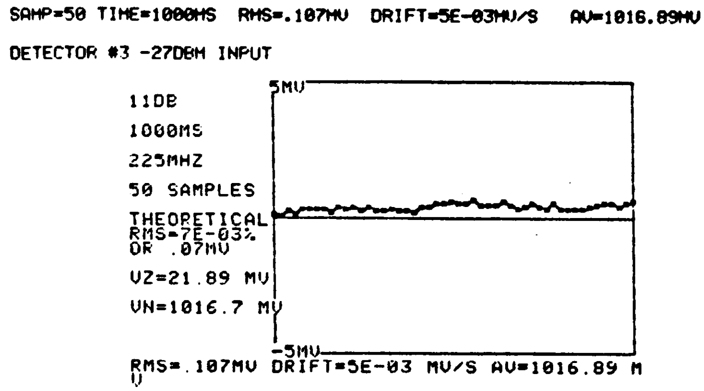
#3 AT -16DBM

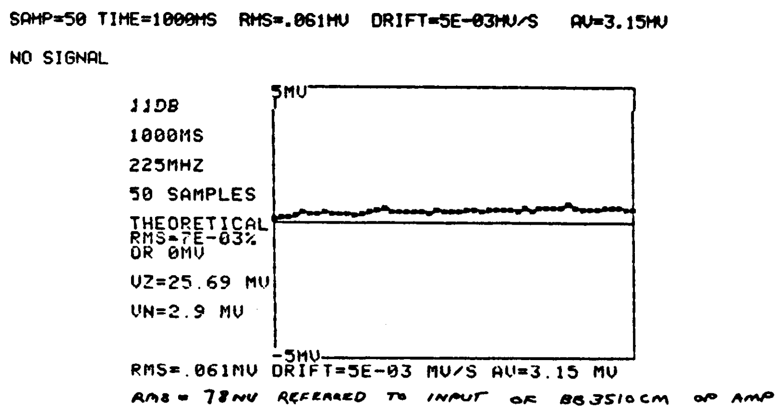


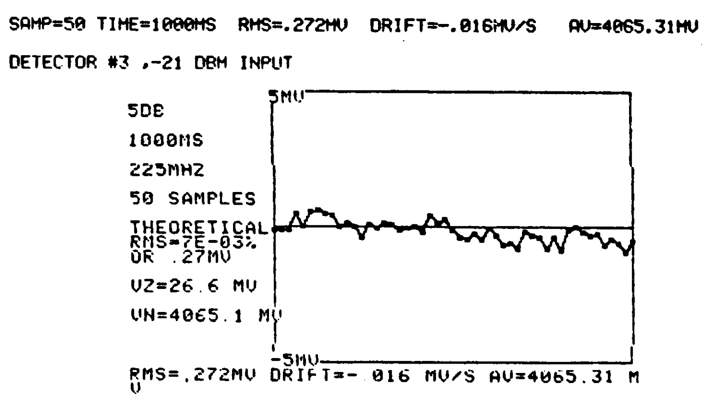
VZ=26.17 PZ=-3.65 S=5.14

ATTEN	DET MV	MTR MV	ERROR	P_{IN}
31	36.3	-1.67	0%	
11	1039.63	193.4	0%	
1	10260.25	1990.38	-.21%	-17dBm
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%	-27dBm
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.







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.

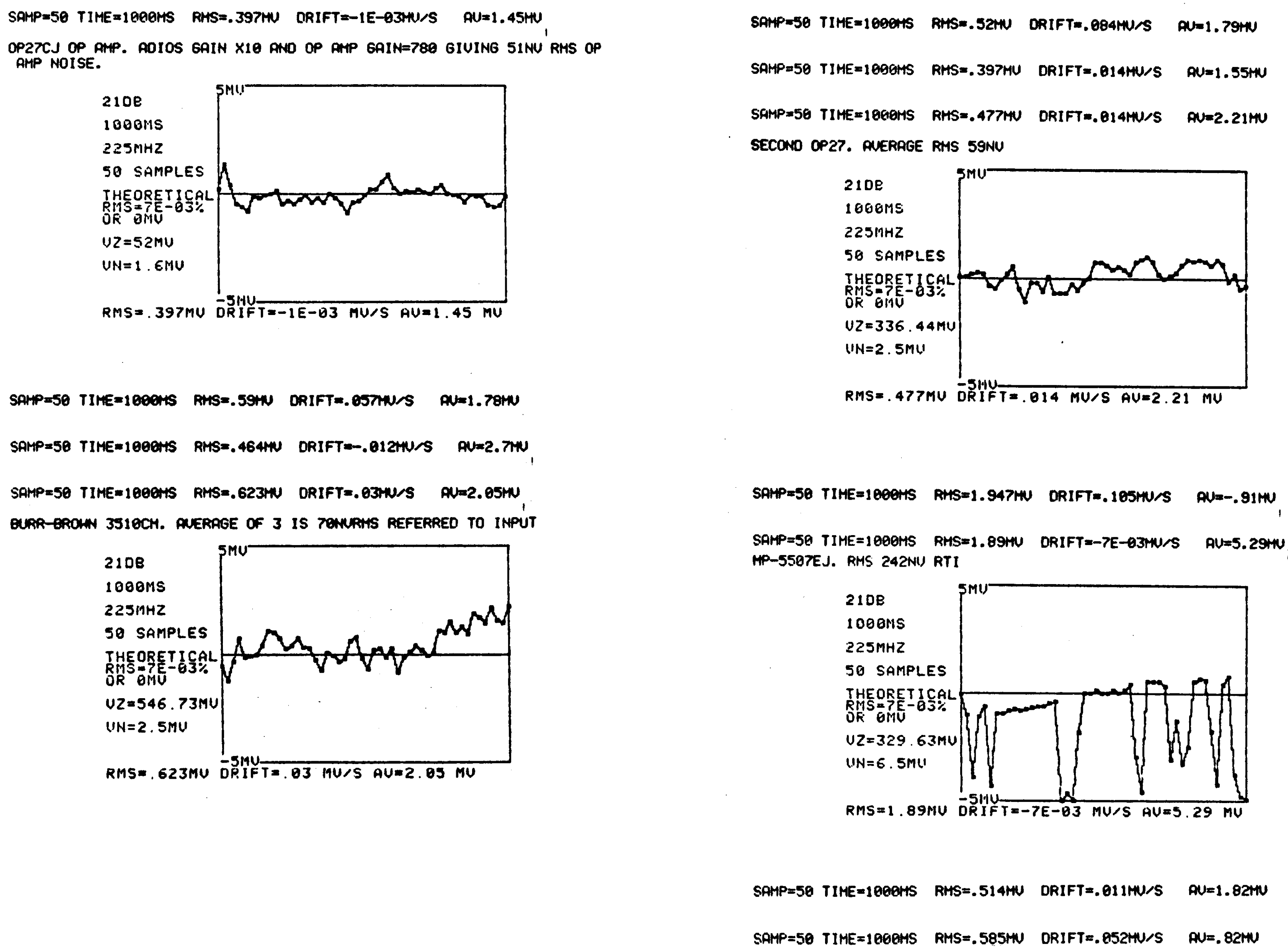


Fig. 8. Examples of noise tests of operational amplifiers. Detector diode was connected, no RF signal was applied, op amp voltage gain was 780, ADIOS gain was 10, and integration time was 1 second. The rms noise is thus measured in the .01 Hz to 0.5 Hz band where it is not specified by manufacturers.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

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,

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

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

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

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,

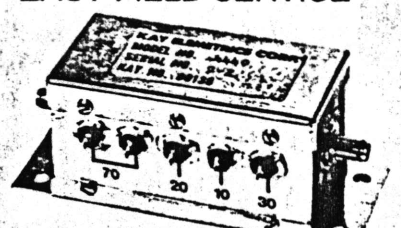
$$E(K) = 100 * \frac{V(K) - VZ - S * (P(K) - PZ)}{V(K)} \tag{I.4}$$

Kay Electric Co., Pine Brook, NJ

PROGRAMMABLE ATTENUATORS

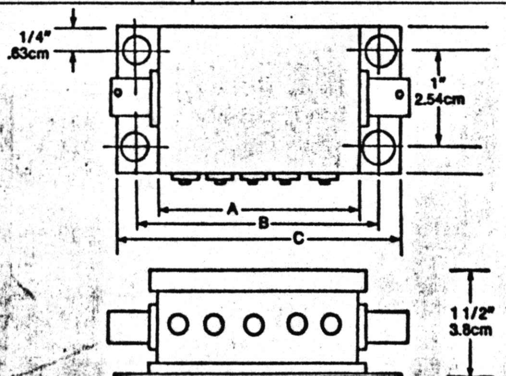
- RAPID RELAY SWITCHING
- EASY FIELD SERVICE

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



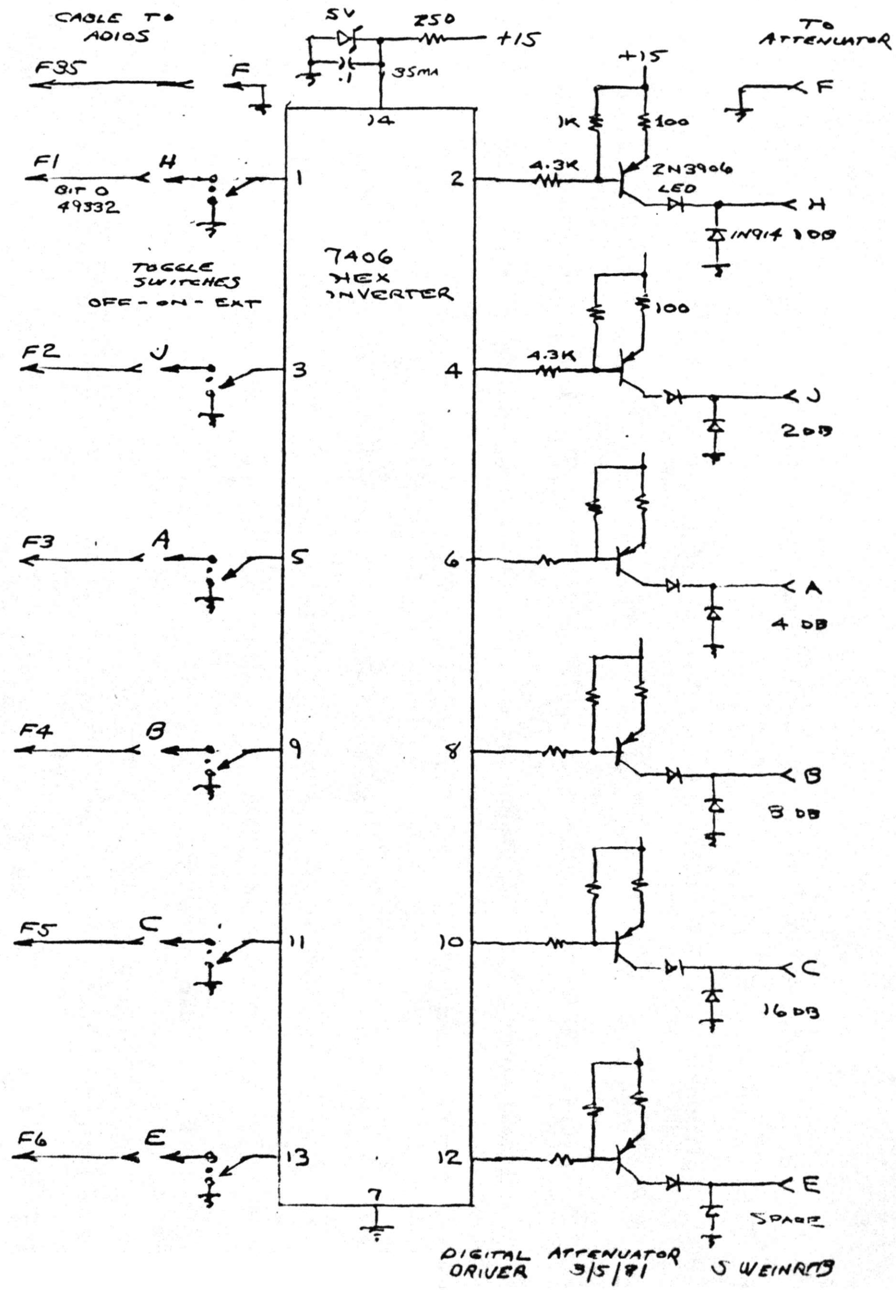
#349 #2-9

		50 OHMS			75 OHMS		
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	2.5	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.					



MODEL	A	B	C
4440 4460 4447 4467	4" 10.16 cm	3 1/8" 7.9 cm	3 1/2" 8.9 cm
4450 4457	5 1/8" 13.0 cm	4 1/8" 10.4 cm	4 5/8" 11.7 cm

14



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 initiali 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
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=";
;". 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-0FF 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 MEASU
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 PROGR
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)

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

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:

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

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

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

$$K\emptyset = \sum 1 = SA \tag{IV.5}$$

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

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

$$A = V1/K\emptyset - B*K1/K\emptyset \tag{IV.8}$$

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

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

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

$$RMS = \sqrt{M/K\emptyset} \tag{IV.11}$$

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

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.