ADVANCED TECHNICAL MATERIALS INC.

Fundamentals of Electrical Noise

by

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Jan 2004

White Noise

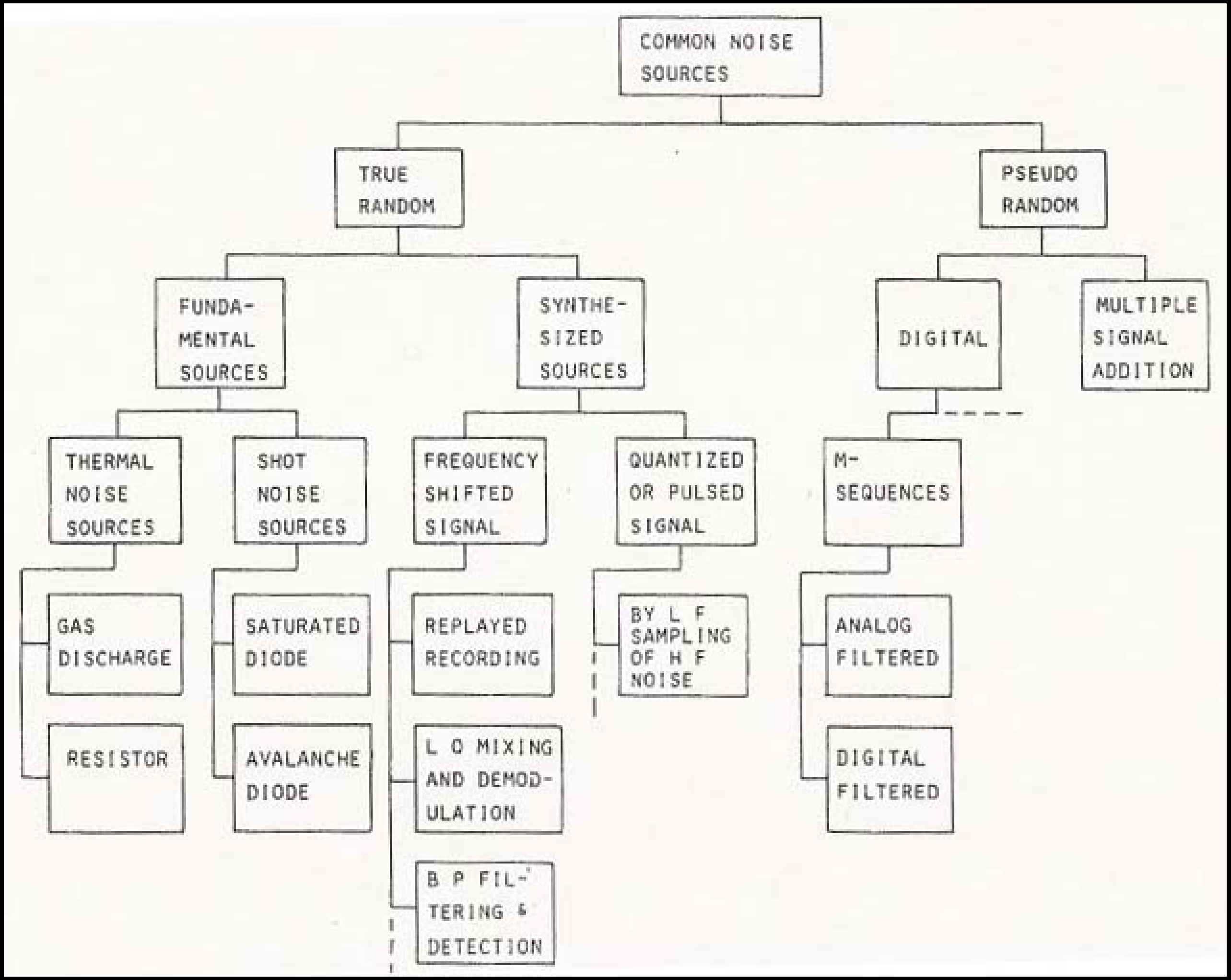
- In 1928 Johnson and Nyquist ID the Problem
- Nyquists Theorem
  P = KTB
  P = Noise Band power in Watts
  T = Temp Degree Kelvin (T)
  K = Boltzmans Constant $1.38X10^{-23}$
  B = Bandwidth (Hertz)

Excess Noise Ratio in dB

$$ENR=10Log((T/290)-1)$$

T in Kelvin is the temperature of a resistor

Noise Generating Devices



Noise Equivalency Reference Chart

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NOISE EQUIVALENCY REFERENCE CHART

EXCESS NOISE RATIO ENR (DB)	EQUIVALENT NOISE TEMPERATURE (°K)	NOISE BANDWIDTH 1MHZ			
		POWER DBM	POWER MW	MICROVOLTS 50 OHMS	MICROVOLTS 600 OHMS
−10	319.0	−113.57	4.40×10^{-12}	.469	1.6
−5	381.7	−112.78	5.27×10^{-12}	.513	1.8
0	580.0	−110.97	8.00×10^{-12}	.633	2.2
5	1207.1	−107.78	1.67×10^{-11}	.913	3.2
10	3190.0	−103.57	4.40×10^{-11}	1.48	5.1
15	9460.6	−98.83	1.31×10^{-10}	2.56	8.9
20	29290	−93.97	4.04×10^{-10}	4.49	15.6
30	290290	−83.97	4.00×10^{-9}	14.14	49
40	2,900,290	−73.97	4.00×10^{-8}	44.73	155
50	29,000,290	−63.97	4.00×10^{-7}	141.42	490

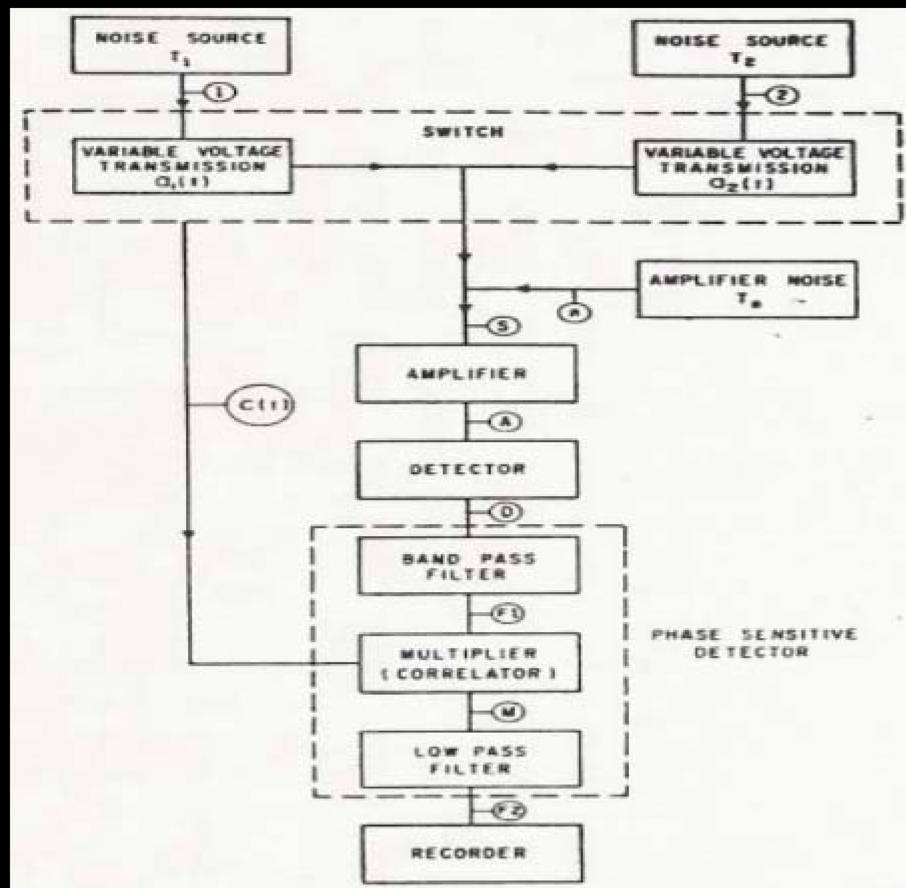
Applications of Noise Technology

- Measure Noise Figure
- Gain and Bandwidth Parameters
- Susceptibility to External Interference
- Jamming
- System Self Test

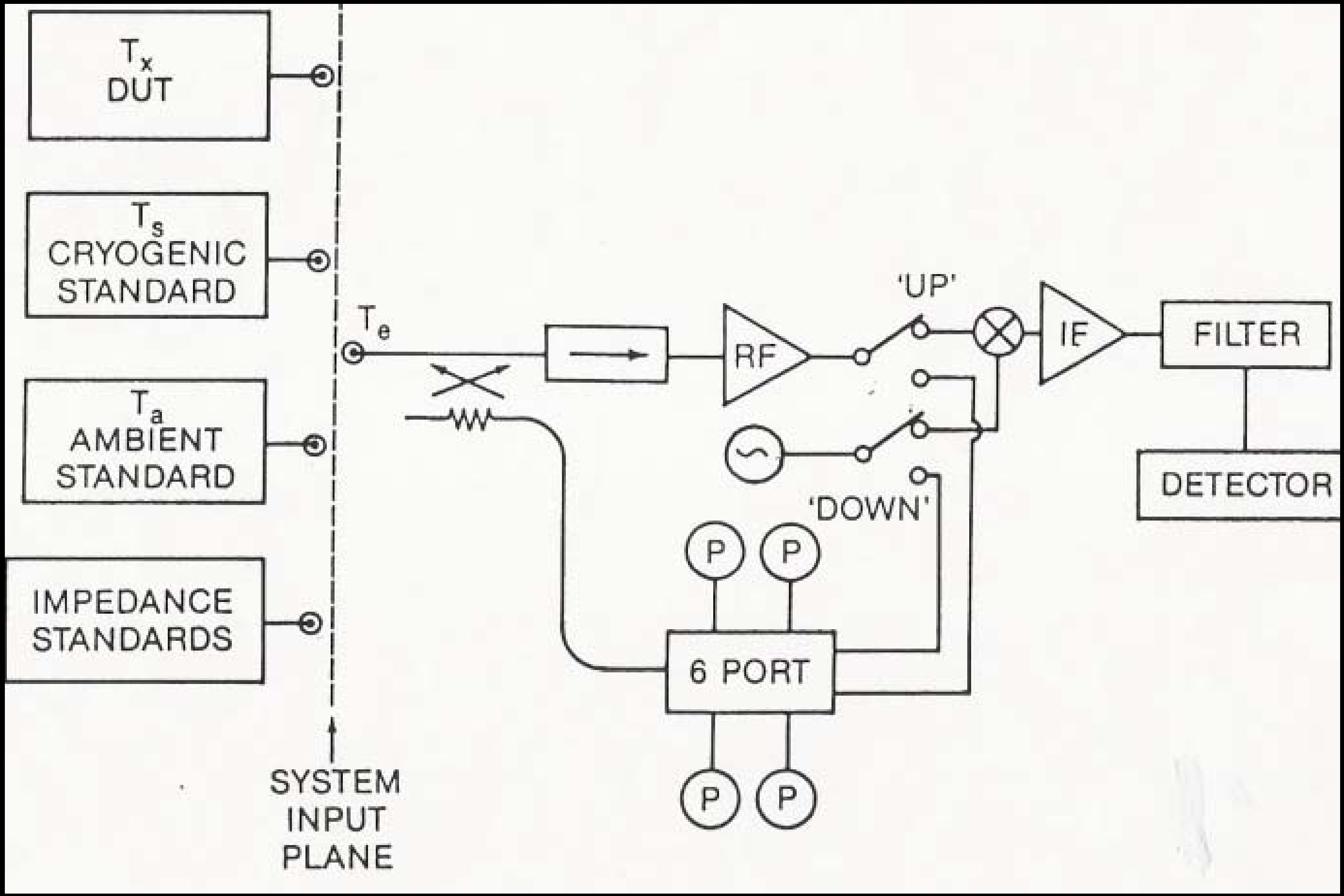
Noise Measurements

- The Radiometer
- Noise Standards
- Calibration of Noise Standards
- Errors in Noise Measurements

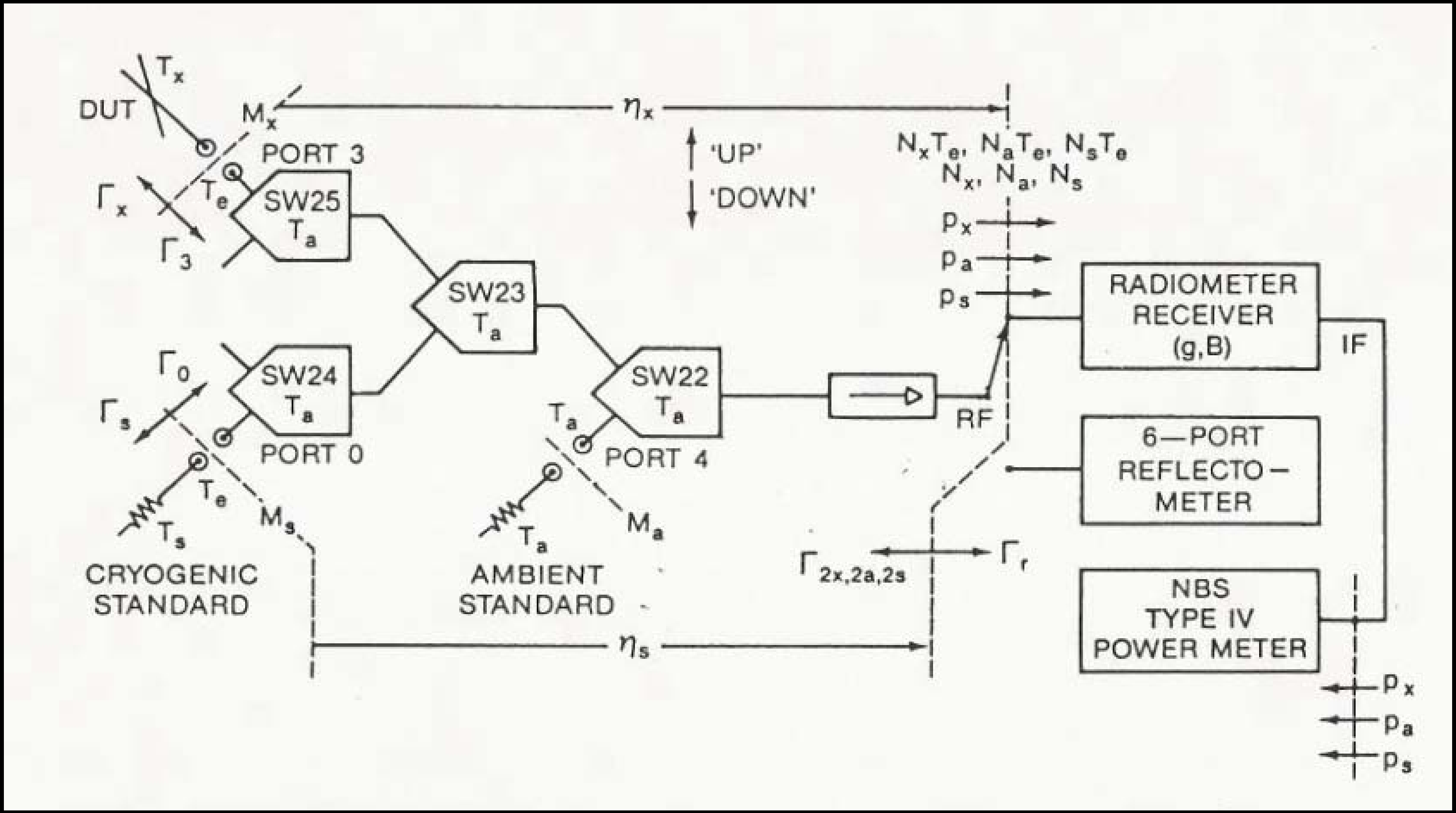
Basic Switching Radiometer



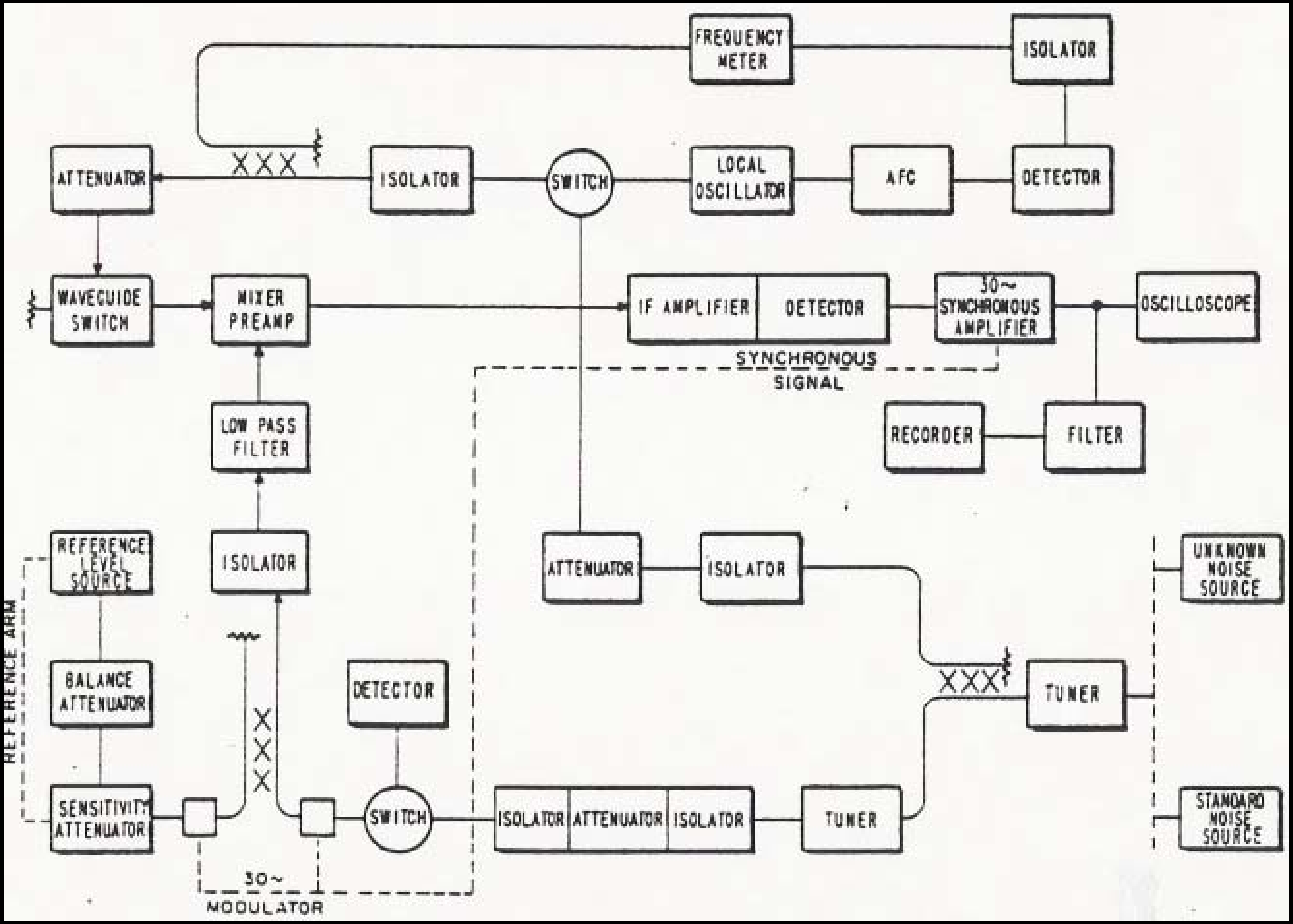
Simplified Automate Radiometer



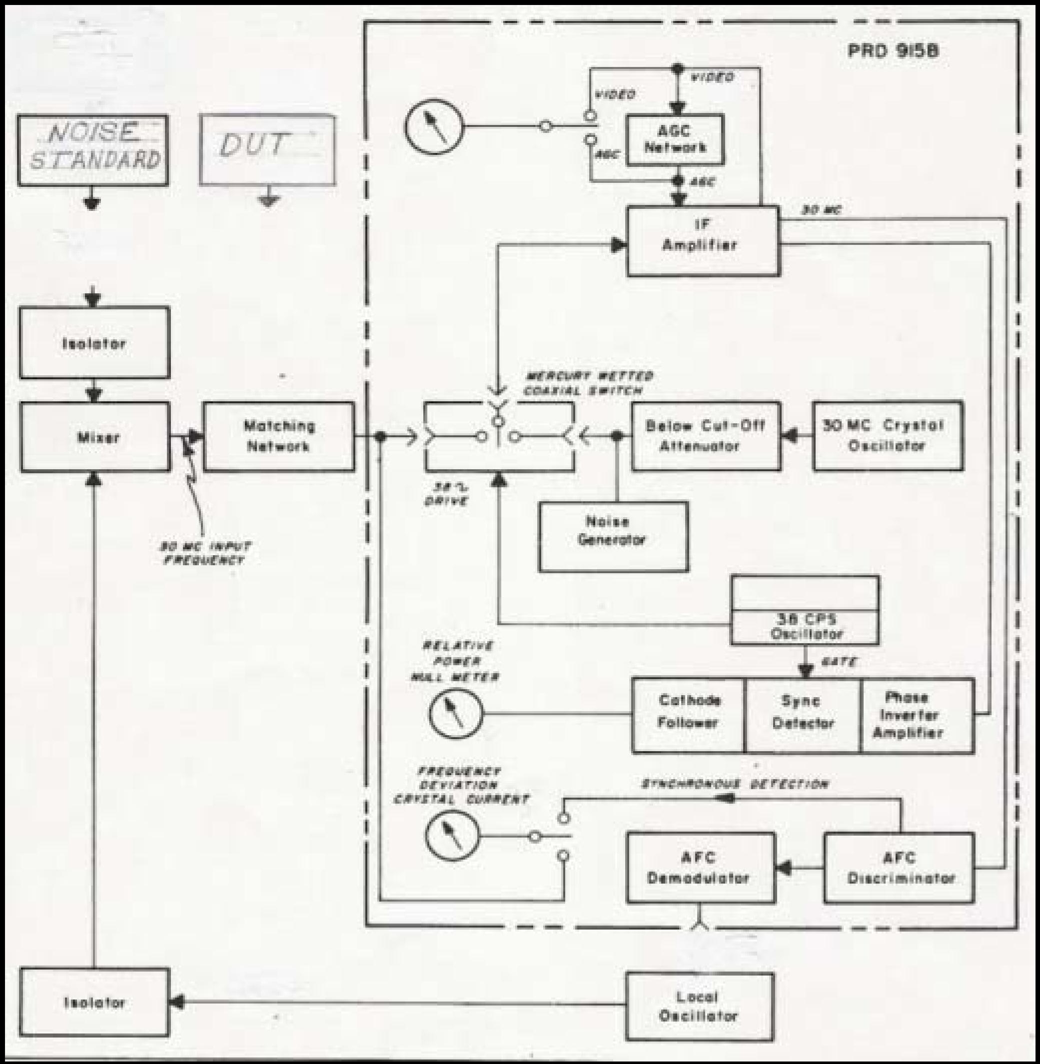
NIST Automated Radiometer



NBS Switching Radiometer



Commercial Switching Radiometer



Commercial Switching Radiometer

ATM ADVANCED TECHNICAL MATERIALS INC.

(Specifications for the PRD 915-B Attenuation Calibrator)

Input Frequency: 30 MHz CW.

Input Impedance: 50 ohms normal; 200 ohm matching network supplied.*

Reference Oscillator: Crystal Controlled: 30 MHz ±0.02%.

30 MHz Measurement:

1. 0-110 db indication with a 4 digit inline readout (least division indication 0.02 db).
2. "0" insertion loss approximately 16 db.
3. Accuracy ±.03 db per 10 db to 70 db. Maximum cumulative error ±0.25 db to 100 db; ±0.35 db to 110 db.

Gain Variation: In excess of 100 db.

I-F AMPLIFIER:

1. Center Frequency: 30 MHz.
2. Input Impedance: 50 ohms nominal.
3. Bandwidth: 30 db, approx. 2 MHz.
4. Noise Figure: 2.5 db maximum.
5. Video output jack, TNC female.

AFC UNIT:

1. Insulated 5000 volts from chassis.
2. Output of AFC powered from floating regulated supply.
3. AFC provides necessary correction voltage to hold L.O. to calibrator I-F.

METERING:

1. Positive and negative crystal current for mixer.
2. Positive and Negative Automatic Frequency Control Indicator.
3. Null Indicator—center zero, two scales (a) high, (b) low. Signal differences can be resolved to better than .01 db at signal levels as low as −100 dbm.
4. Video Signal (volts).
5. Mixer Crystal Current Switch.
   (a) EXT: for balanced mixers with crystal current monitoring port.
   (b) INT.: for unbalanced mixers.

Signal Level at Input:	Accuracy per 10 db increment:
−10 to −80 dbm	±.03 db
−80 to −105 dbm	±.12 db
−105 to −120 dbm	±.20 db

Power Input: 115/230 V ± 10%, 50 or 60 Hz

Dimensions: Cabinet: 19-13/16" W x 11¼" H x 18-1/16" D; Rack Mounted: 19" W x 10½" H x 17" D.

Weight: Approximately 35 lbs.

Frequency Coverage: 10 MHz to above 40 GHz depending upon mixer and L.O. used (PRD 600 Series Mixers recommended to 18 GHz)

*PRD 915-2 Matching Network (400 ohm) avail.

Data Subject to Change Without Notice
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Noise Figure Measurements

- Y Factor
- Twice Power Measurements
- Automatic Measurements
- Noise Figure to Temperature

Y Factor

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B. "Y-Factor" Method of Noise Figure Measurement

A method closely resembling the "Twice-Power" method involves the determination of the numerical ratio N_2/N_1 (which is called Y-Factor) and the calculation of noise figure by substitution in equation (5).

$$F_{db} = 10 \log \frac{(T_2 - T_o)}{T_o} - 10 \log\left(\frac{N_2}{N_1} - 1\right) \quad (5)$$

In practice, the Y-Factor method generally makes use of an IF attenuator with a power indicator set to a convenient reference. The IF attenuator change in going from source OFF to source ON then yields the Y-Factor, which is then entered in the equation. Graphs are also available for specific values of relative excess noise, with co-ordinates calibrated in "Y-Factor" and noise figure. (See figure 5.)

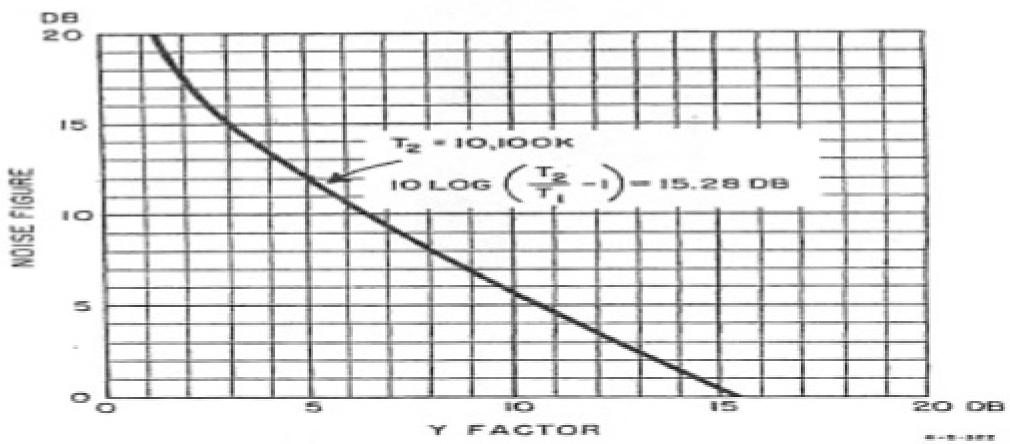

Figure 5. A "Y-Factor" chart for determining noise figure with a 15.28 db excess noise source.

Twice Power NF Measurement

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A. Twice-Power Method of Manual Noise Figure Measurement

In actually measuring the "N_1" and "N_2" of equation (5), if N_2 was set to be twice N_1 then equation (5) reduces to:

$$F_{db} = 10 \log \frac{(T_2 - T_o)}{T_o} - 10 \log (1)$$

$$= 10 \log (T_2 - T_o)/T_o$$

With the proper equipment, the condition of $N_2 = 2 N_1$ can be established by varying the relative excess noise power of the noise source. With the equipment of figure 3, the procedure would be:

1) Set a convenient reference on the power detector with the excess noise source "cold" and the 3 db pad out. This is N_1.

2) Insert the 3 db pad and fire the excess noise source.

3) Vary the rotary vane attenuator until the original power detector reference point is reached. This creates a condition of $N_2 = 2 N_1$.

Figure 4 illustrates this condition, in which the output noise power contributed by the excess noise source exactly equals the sum of the amplified input termination noise plus the receiver noise contribution. Since this excess noise ratio was adjusted with the attenuator to be equal to input termination noise plus receiver noise (thereby causing $N_2 = 2 N_1$), from equation (5) it can be seen that the attenuated excess noise ratio is equal to the noise figure of the receiver. In the case of an argon source, it can be read as 15.2 db minus the attenuator setting (in db).

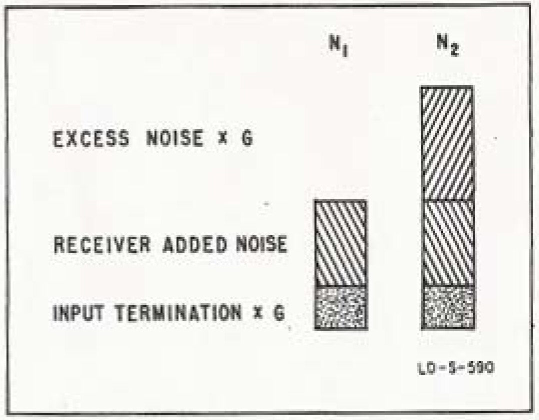


Figure 4. Representation of total noise power output for the "twice-power" method of manual noise figure measurement.

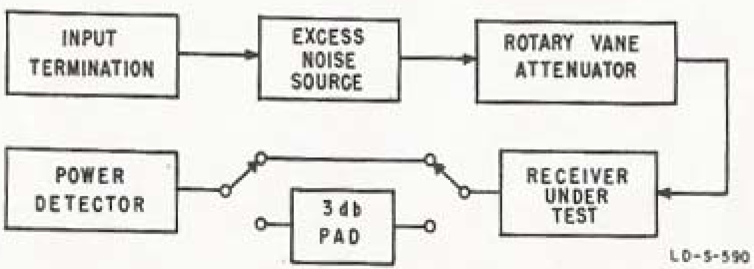
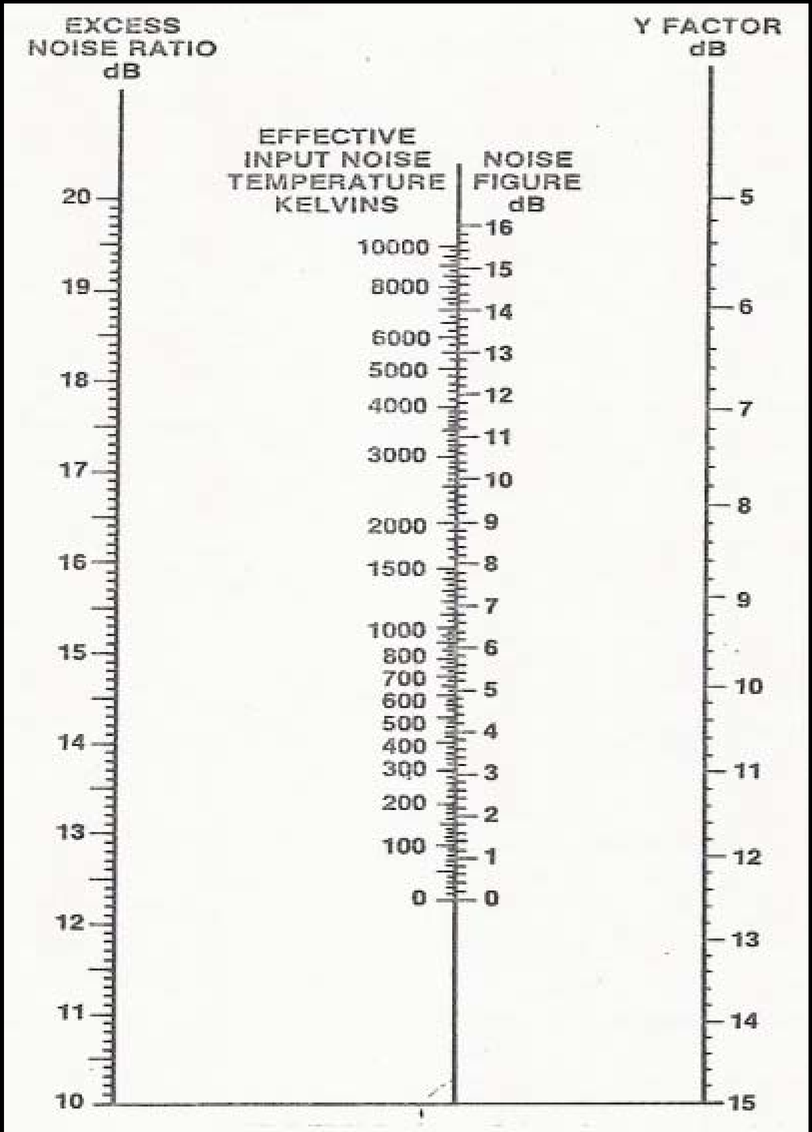
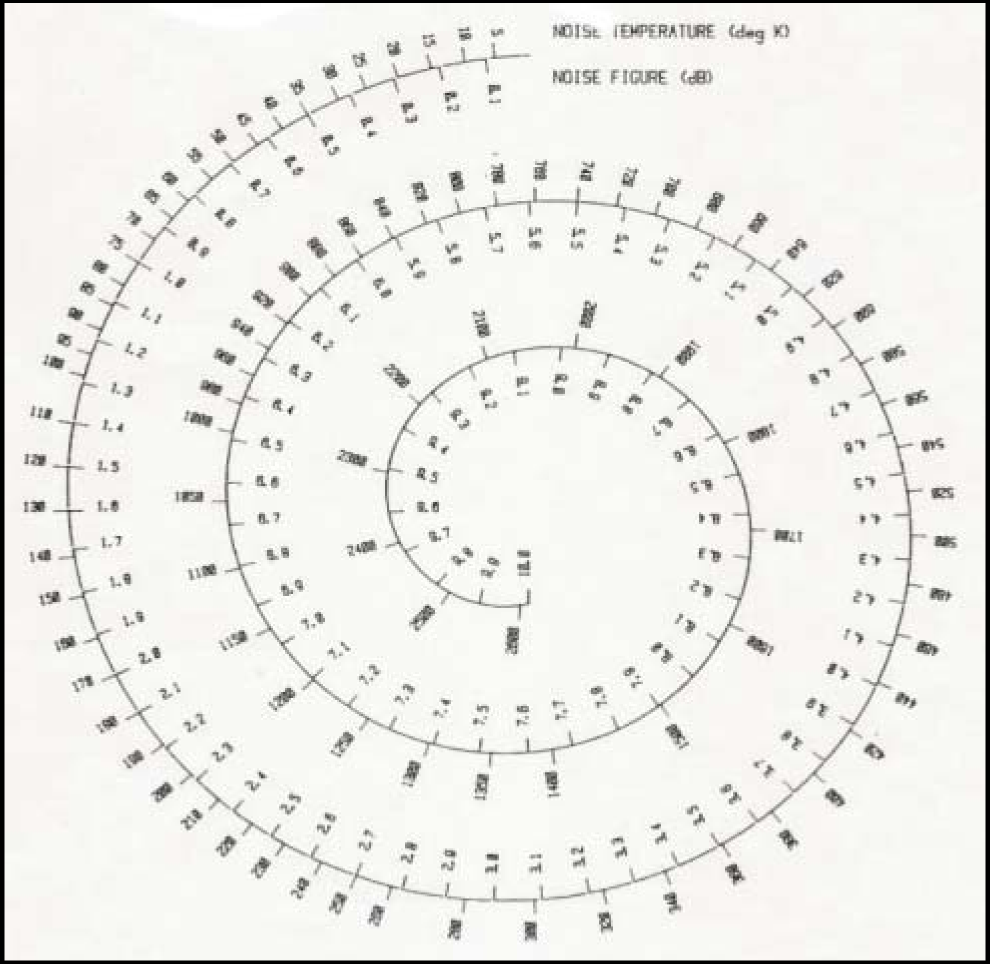


Figure 3. The "twice-power" method of manual noise figure measurement.


EXCESS NOISE RATIO dB
EFFECTIVE INPUT NOISE TEMPERATURE KELVINS
NOISE FIGURE dB
Y FACTOR dB
20
19
18
17
16
15
14
13
12
11
10
10000
8000
6000
5000
4000
3000
2000
1500
1000
800
700
600
500
400
300
200
100
0
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
5
6
7
8
9
10
11
12
13
14
15

Noise Figure vs. Noise Temperature Conversion Chart



ENR Measurement VSWR Error

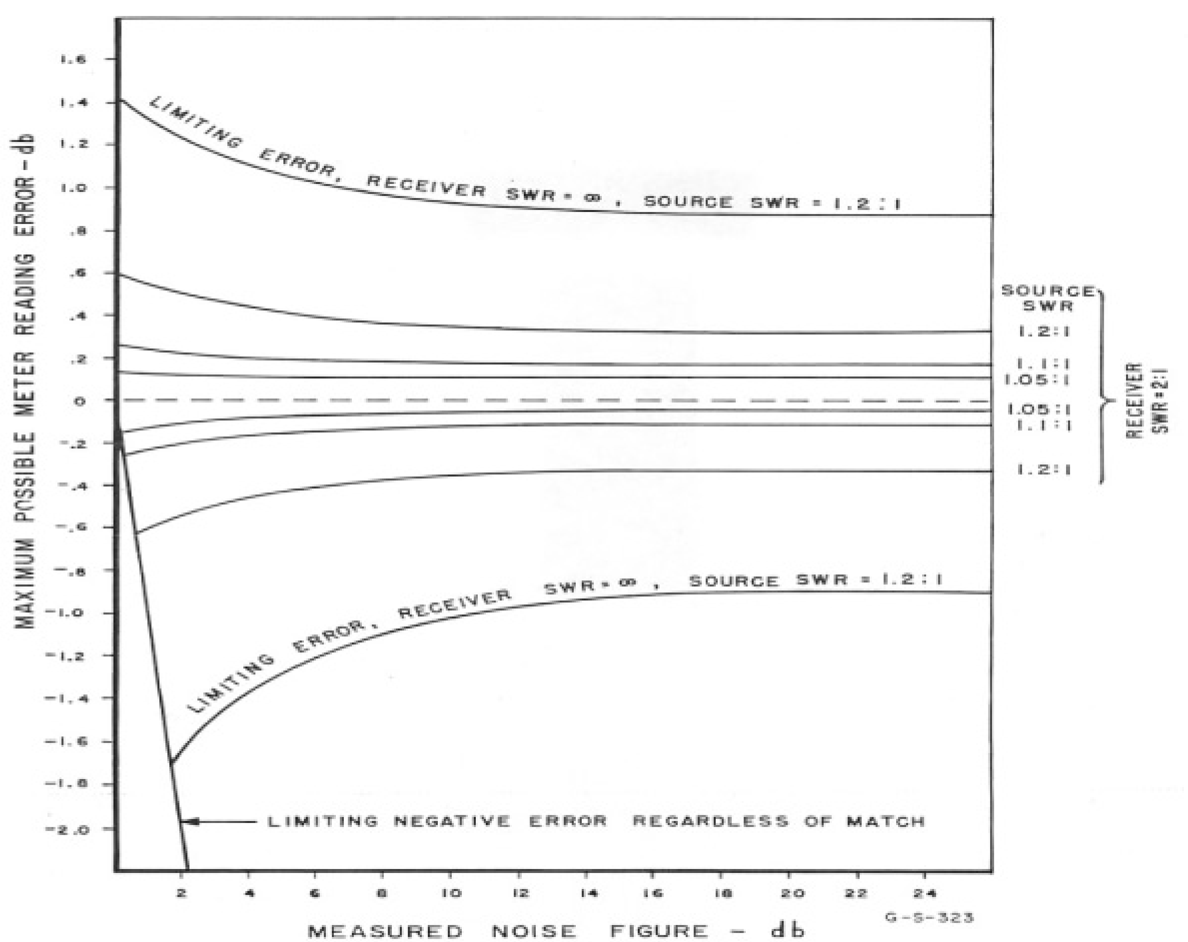


Figure 9. Typical error effects for several possible conditions of mismatch between noise source and receiver.

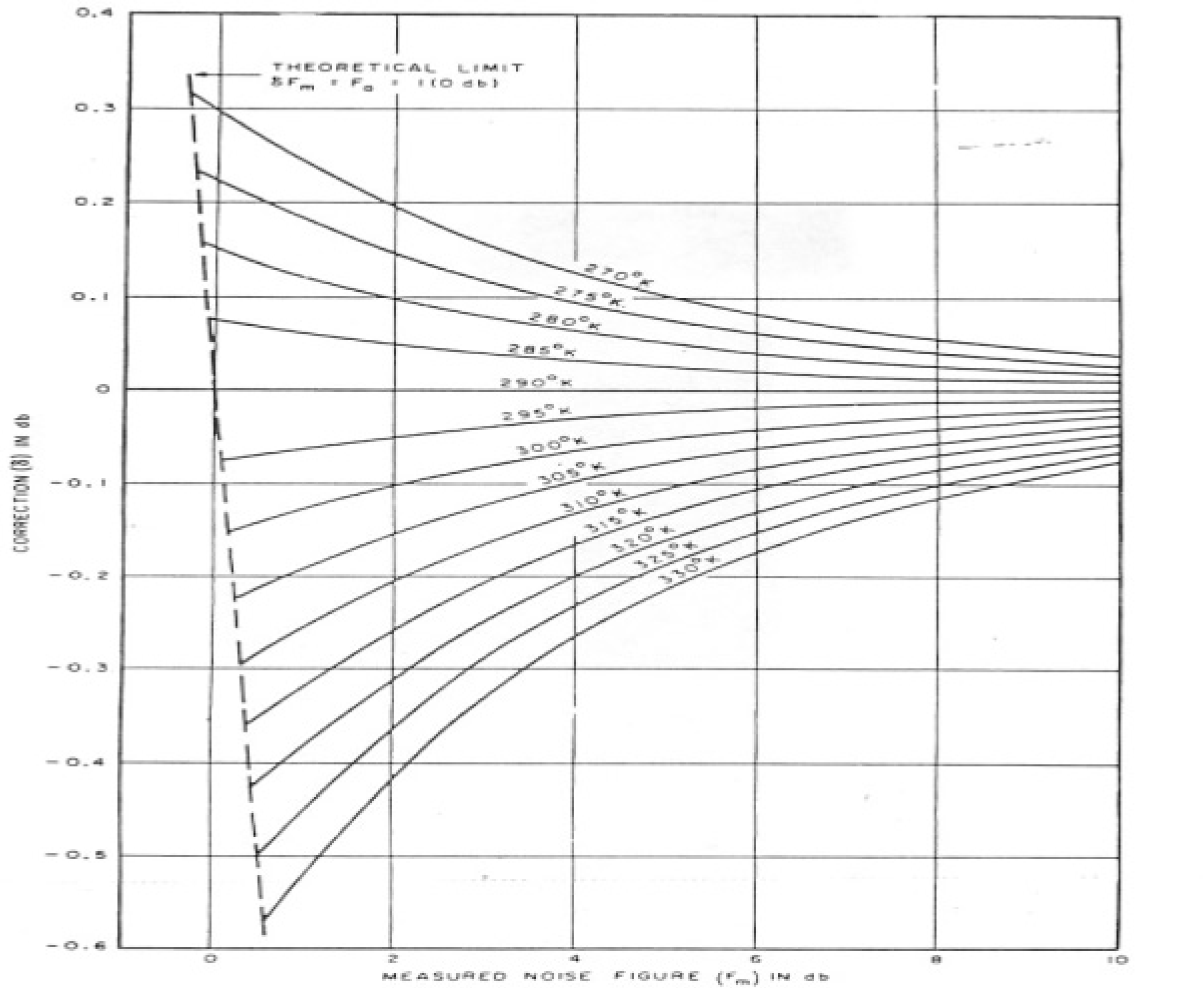


FIGURE 11. ERROR DUE TO TERMINATION TEMPERATURE NOT EQUAL TO 290°K, T_2 = 10,000°K

Noise Source UUT VSWR Error

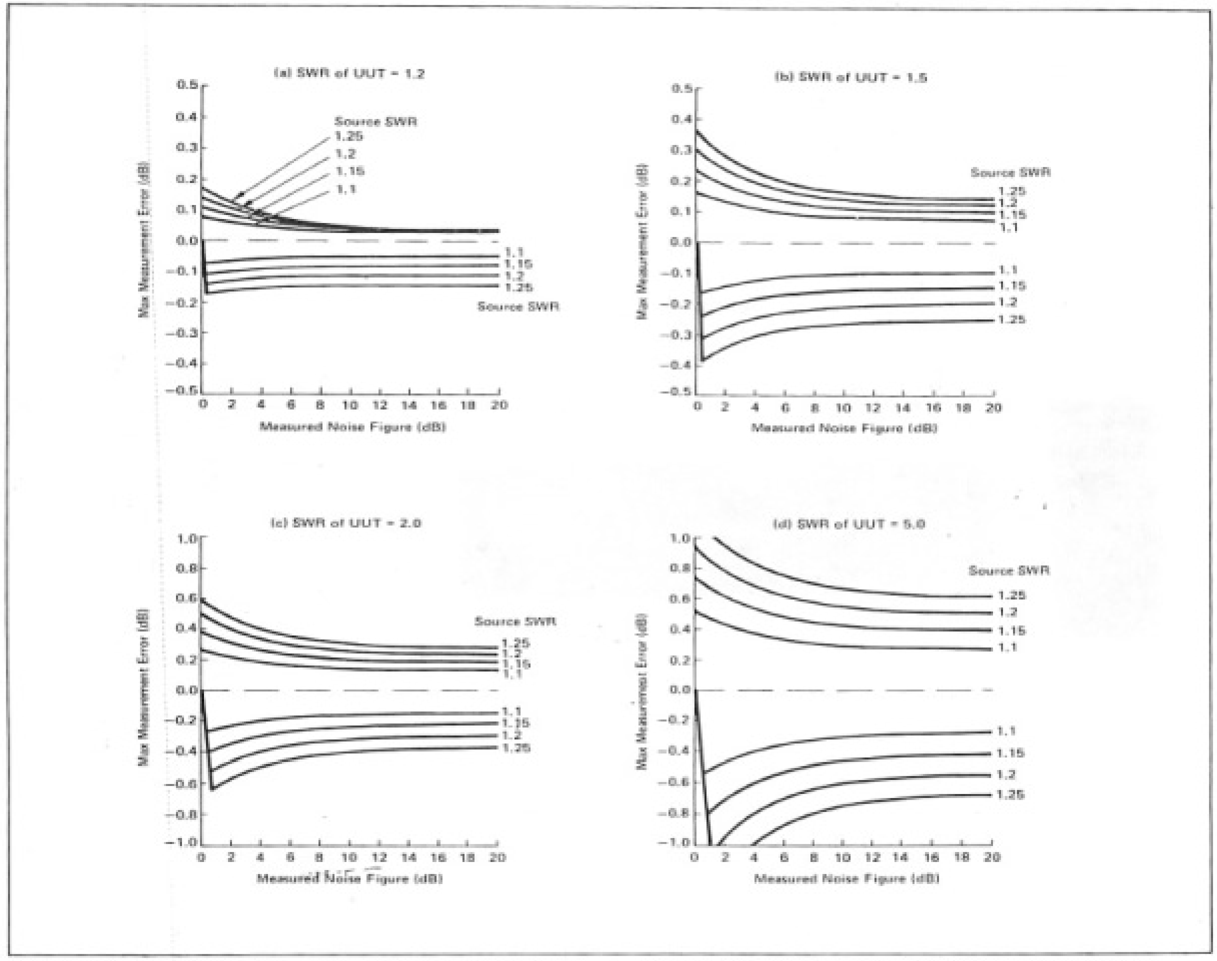
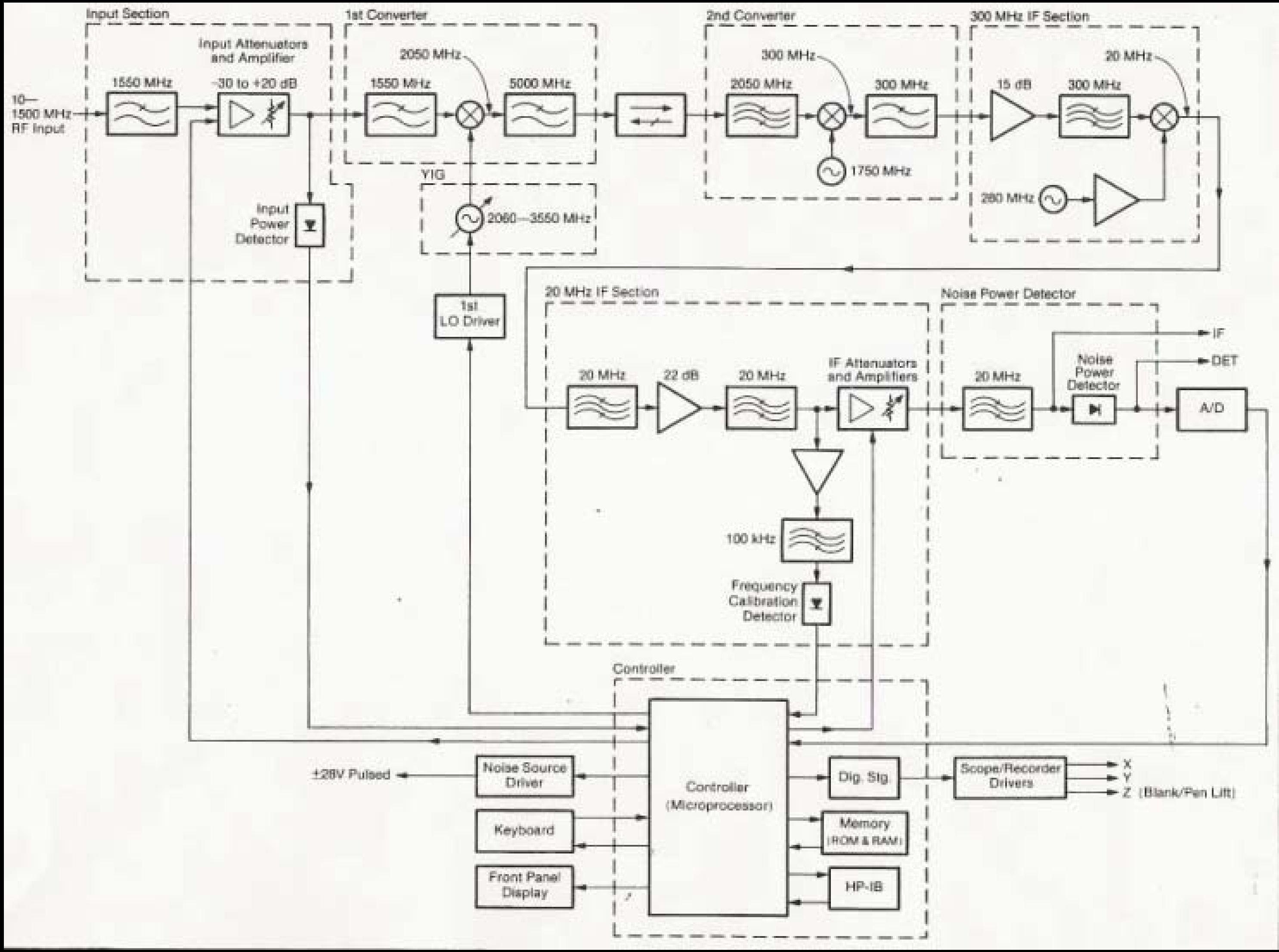


Figure 1-4. The worst case errors in the measured noise figure caused by rereflections between the noise source and UUT. Each graph is for a different UUT input SWR.

Automatic Noise Figure Meter



Noise Figure Equivalence Chart

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emp. K	dBM/Hz	NF (dB)	ENR (dB)
5	−191.6	.074	
10	−188.6	.147	
15	−186.8	.219	
20	−185.6	.290	
25	−184.6	.359	
50	−181.6	.691	
75	−179.9	.999	
100	−178.6	1.287	
150	−176.8	1.811	
200	−175.6	2.278	
250	−174.6	2.700	
300	−173.8	3.085	
400	−172.6	3.765	
500	−171.6	4.352	
600	−170.8	4.870	.29
700	−170.2	5.332	1.50
800	−169.6	5.750	2.45
900	−169.1	6.131	3.23
1000	−168.6	6.482	3.89
1500	−166.8	7.905	6.20
2000	−165.6	8.974	7.71
2500	−164.6	9.832	8.82
3000	−163.8	10.548	9.71
3500	−163.2	11.162	10.44
4000	−162.6	11.701	11.07
4500	−162.1	12.179	11.62
5000	−161.6	12.611	12.11
5500	−161.2	13.003	12.54
6000	−160.8	13.363	12.94
6500	−160.5	13.695	13.31
7000	−160.2	14.003	13.64
7500	−159.9	14.291	13.96
8000	−159.6	14.562	14.25
8500	−159.3	14.816	14.52
9000	−159.1	15.056	14.78
9500	−158.8	15.284	15.02
10000	−158.6	15.500	15.25
10500	−158.4	15.706	15.47
11000	−158.2	15.903	15.67
11500	−158.0	16.091	15.87
12000	−157.8	16.272	16.06
12500	−157.6	16.445	16.24
13000	−157.5	16.611	16.42
13500	−157.3	16.772	16.59
14000	−157.1	16.926	16.75
14500	−157.0	17.076	16.90
15000	−156.8	17.220	17.05
15500	−156.7	17.360	17.20
16000	−156.6	17.495	17.34
16500	−156.4	17.627	17.47
17000	−156.3	17.754	17.61

Temp. K	dBM/Hz	NF (dB)	ENR (dB)
17500	−156.2	17.878	17.73
18000	−156.0	17.998	17.86
18500	−155.9	18.115	17.98
19000	−155.8	18.229	18.10
19500	−155.7	18.340	18.21
20000	−155.6	18.449	18.32
30000	−153.8	20.189	20.11
40000	−152.6	21.428	21.37
50000	−151.6	22.391	22.34
60000	−150.8	23.178	23.14
70000	−150.2	23.845	23.81
80000	−149.6	24.423	24.39
90000	−149.1	24.932	24.90
100000	−148.6	25.359	25.36

Applications by Industry

- Military
- Electronics Manufacturing
- Communications

Noise Standards

- Characteristics
  - Flat Power Spectrum
  - High Degree of Stability
- 3 Classes
  - Noise Diodes
  - Gas-Discharge Tubes
  - Thermal Noise Sources

Generation of Noise

Source	Mechanism	Frequency Range of Use
1) Resistor	Thermal Noise	Subaudio to Milli-meter Waves
2) Gas Discharge Tube	Radiation from Plasma	VHF to Millimeter Waves
3) Saturated Vacuum Diode	Shot Noise	Audio to VHF
4) Avalanche Diode	Avalanche Noise	Audio to Microwave
5) Shift Registers	Pseudorandom Noise	Subaudio to RF

Thermal Noise Calculation

Calculate the thermal noise voltage for a 1 k resistor when *B* (f)= 1 Hz and the temperature is 25 °C, 77 K (liquid nitrogen) or 4.2 K (liquid helium).

At 25 °C, *T* = (273.16 + 25) K ~ 298 K.

$$E_t^2 \quad 4 \; 1.38 \times 10^{-23} \text{ J/K} \;\; 298 \text{ K} \;\; 1\text{Hz} \;\; 1000$$

$$1.65 \times 10^{-17} \text{ W} \qquad 1.65 \times 10^{-17} \text{ V}^2$$

$$E_t \text{ (rms)} \quad 4\text{nV}$$

At 77 K, $E_t^2 = 4.25 \times 10^{-18} \text{ V}^2$ and E_t (rms) = 2nV

At 4.2 K, $E_t^2 = 2.32 \times 10^{-19} \text{ V}^2$ and E_t (RMS) = 0.5nV

Avalanche Noise Region

This is a form of noise produced by Zener or avalanche breakdown in a *pn* junction.

In avalanche breakdown, holes and electrons in the depletion region of a reverse-biased *pn* junction acquire sufficient energy to create hole-electron pairs by colliding with silicon atoms.

This process is cumulative, resulting in the production of a random series of large noise spikes.

The noise is always associated with a direct-current flow, and the noise produced is <u>much</u> greater than shot noise in the same current, as given by $i^2 = 2qI_D \cdot B$

Vacuum Diode Noise Source

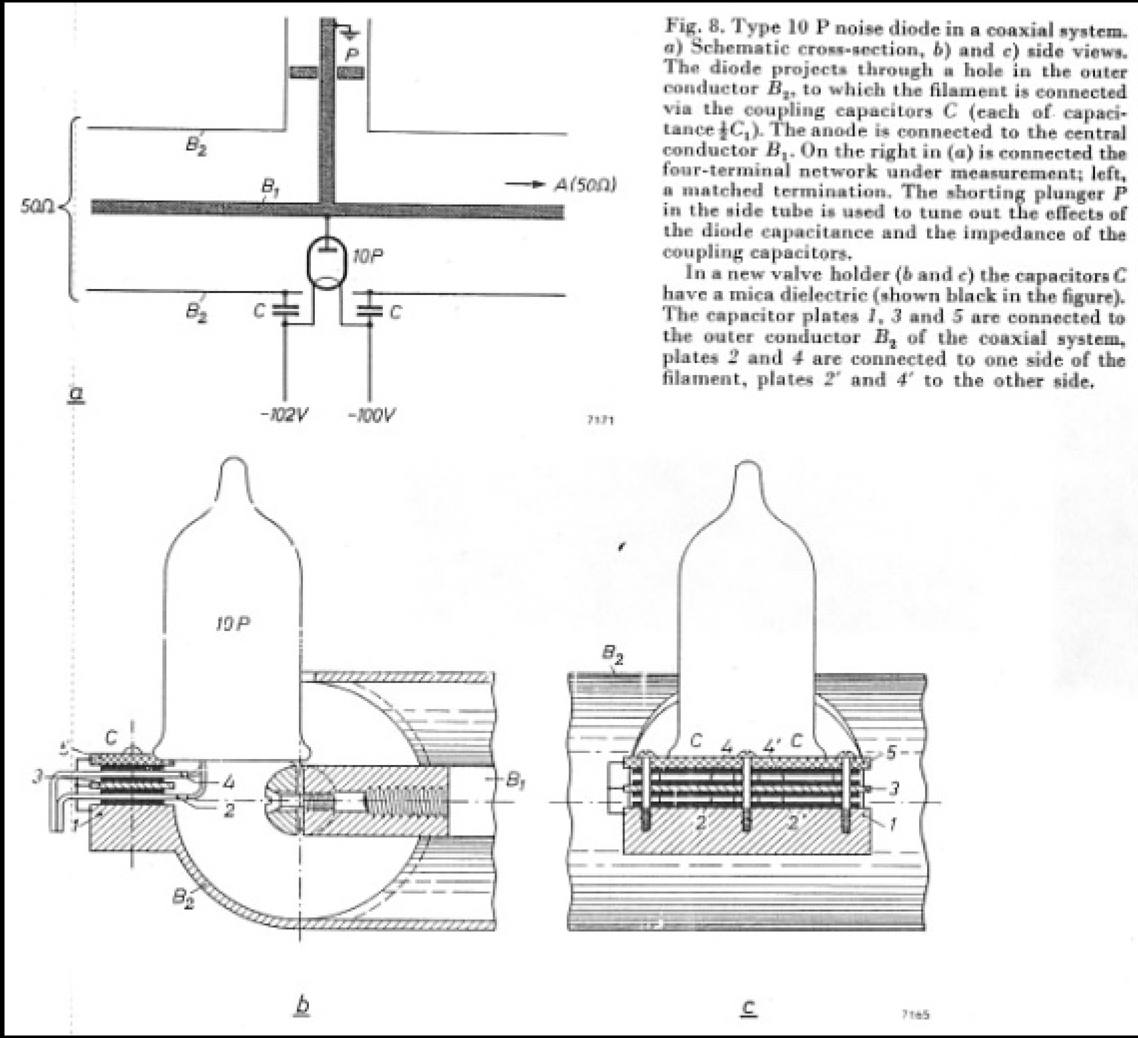
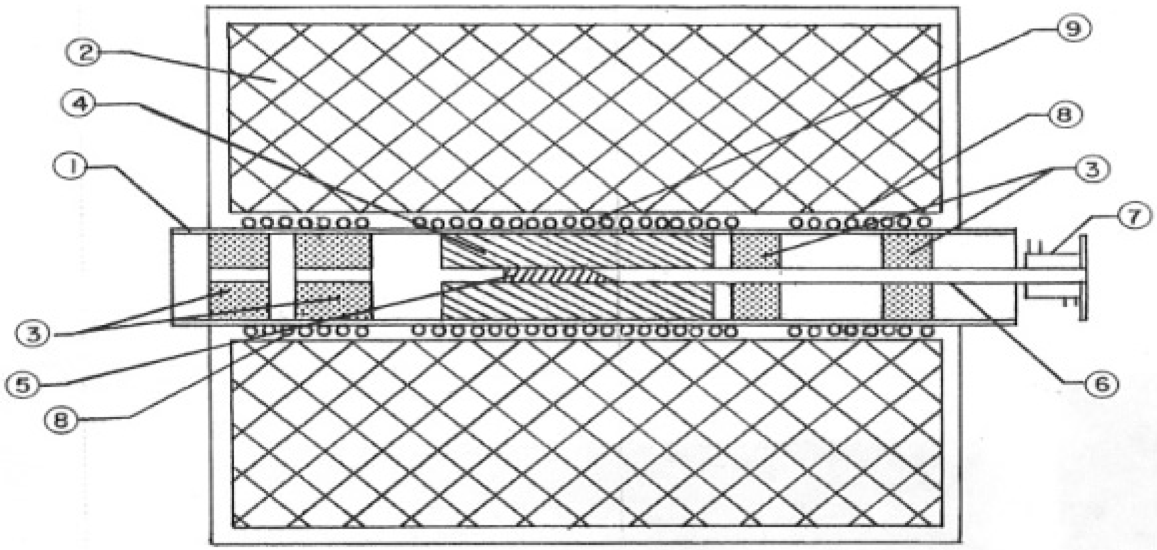


Fig. 8. Type 10 P noise diode in a coaxial system. *a*) Schematic cross-section, *b*) and *c*) side views. The diode projects through a hole in the outer conductor B_2, to which the filament is connected via the coupling capacitors *C* (each of capacitance $\frac{1}{2}C_1$). The anode is connected to the central conductor B_1. On the right in (*a*) is connected the four-terminal network under measurement; left, a matched termination. The shorting plunger *P* in the side tube is used to tune out the effects of the diode capacitance and the impedance of the coupling capacitors.

In a new valve holder (*b* and *c*) the capacitors *C* have a mica dielectric (shown black in the figure). The capacitor plates *1*, *3* and *5* are connected to the outer conductor B_2 of the coaxial system, plates *2* and *4* are connected to one side of the filament, plates *2'* and *4'* to the other side.

High Temperature Noise Standard



1. ALUMINA TUBE (NON-POROUS)
2. REFRACTORY MATERIAL
3. INSULATORS OF HIGH PURITY
4. HEAT DISTRIBUTOR
5. RESISTIVE MATERIAL WEDGE (NOISE GENERATOR)
6. WAVEGUIDE
7. WATER JACKET ATTACHED TO FLANGE
8. MANUALLY CONTROLLED HEATING COILS
9. SERVO-CONTROLLED HEATING COIL

Low Temperature Noise Standard

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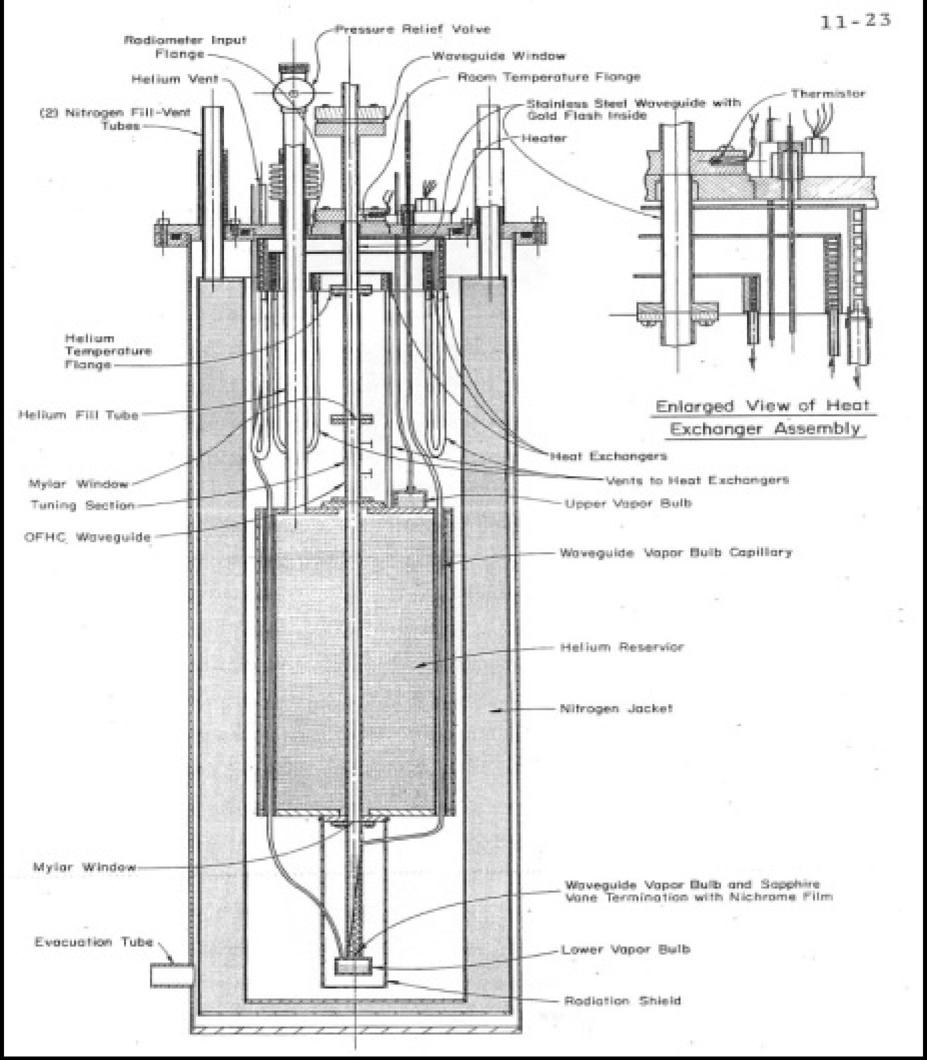
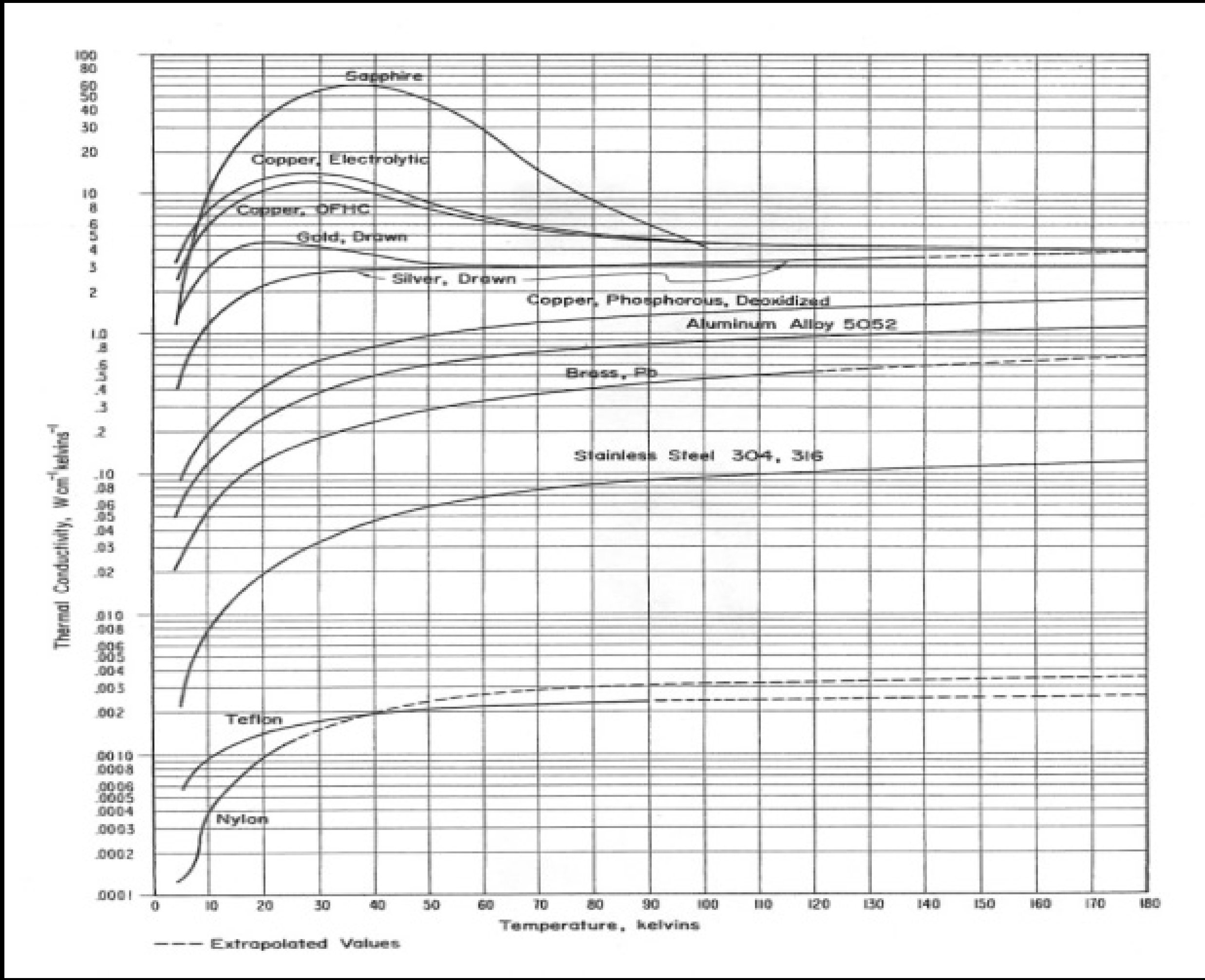
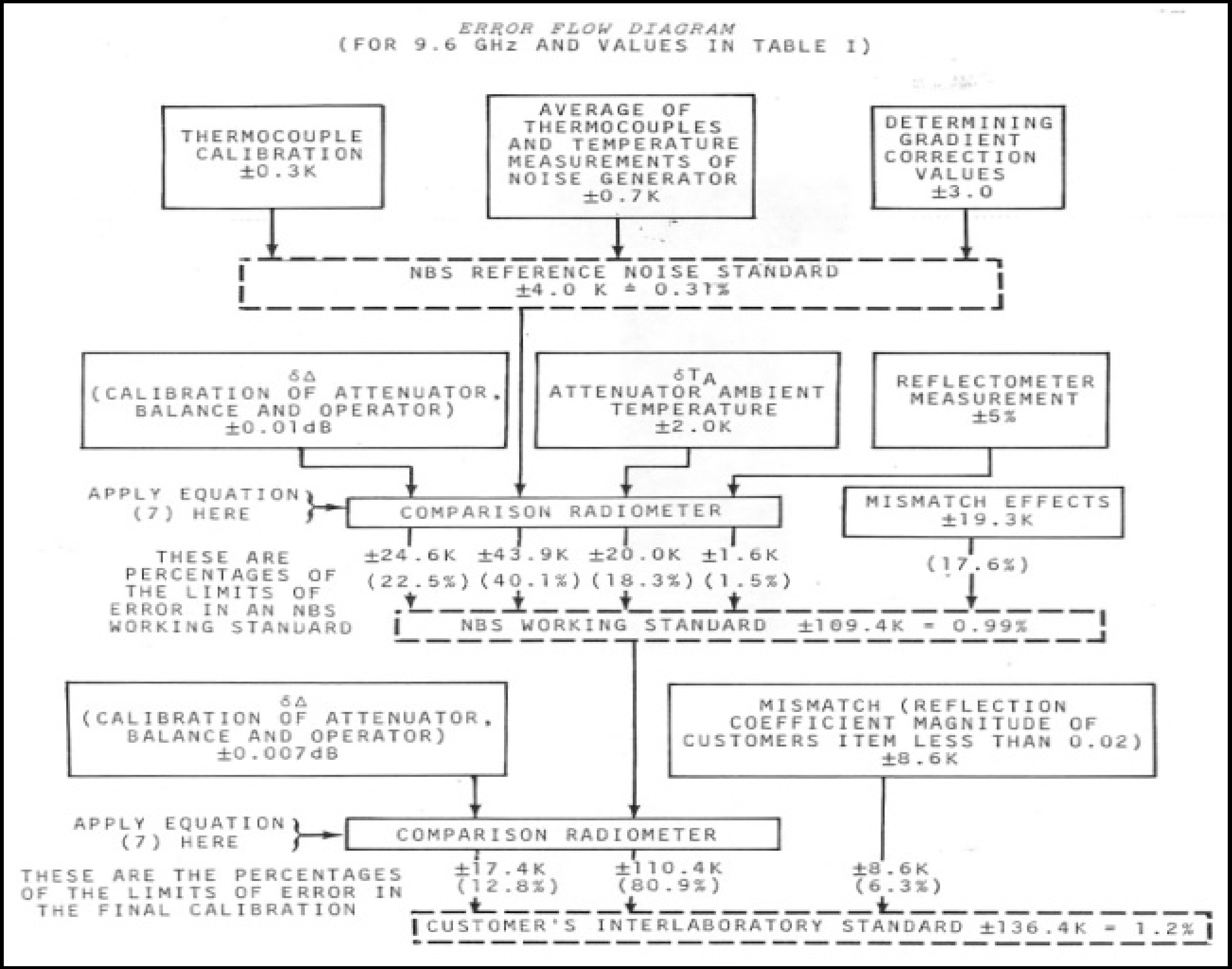


Low Temperature Thermal Conductivity



Error Flow Diagram



DUT Noise Temperature Errors

Table 1. A typical set of systematic errors at 3 GHz for a DUT noise temperature of 11000 K. The source errors in column two are explained in the text. Column three shows the resulting % errors in the DUT noise temperature.

DUT NOISE TEMPERATURE ERROR		
Frequency = 3 GHz		Noise Temp = 11000 kelvin
Source	*Source Error*	*± % Error in T_x*
T_m	eq (3.2)	0.64
T_a	0.25 K	0.17
Mismatch	0.005	0.14
Asymmetry	0.01 dB	0.22
Isolation	50 dB	0.09
Connector	$0.05 f^{1/2}$	0.15
Offset	eq (10.1)	0.07
Nonlinearity	$1.42 * 10^{-8}$	0.02
Total Error (linear sum)		1.72
RSS Error		0.90

USA-England Intercomparison

INTERCOMPARISON WITH ENGLAND

	9.0 GHz		9.8 GHz		11.2 GHz	
	T_{ne}* in Kelvin	ENR in Decibels	T_{ne}* in Kelvin	ENR in Decibels	T_{ne}* in Kelvin	ENR in Decibels
Tube No. 261						
SVTL	11178	15.745	11192	15.751	11234	15.763
NBS	11160	15.738	11216	15.761	11196	15.753
SVTL	11178	15.745	11199	15.754	11228	15.765
NBS	11150	15.734	11201	15.755	11191	15.751
SVTL	11183	15.747	11197	15.753	11230	15.766
Tube No. 277						
SVTL	11213	15.759	11229	15.766	11271	15.782
NBS	11188	15.750	11245	15.772	11236	15.768
SVTL	11210	15.758	11232	15.767	11266	15.780
NBS	11178	15.745	11240	15.770	11223	15.762
SVTL	11211	15.758	11229	15.766	11264	15.779
Tube No. 302						
SVTL	11336	15.808	11349	15.814	11384	15.826
NBS	11315	15.800	11370	15.821	11354	15.815
SVTL	11334	15.808	11352	15.815	11386	15.827
NBS	11303	15.795	11368	15.821	11342	15.811
SVTL	11335	15.808	11351	15.815	11388	15.828

*All effective noise temperature measurements are related to the IPTS-48 temperature scale.

USA-Sweden Intercomparison

INTERCOMPARISON WITH SWEDEN

Comparison of January-June 1965 [9]

		9.0 GHz ENR	9.8 GHz ENR	11.2 GHz ENR
NBS Test No. 40020				
	NBS	15.77 dB (11,240 K*)	15.73 dB (11,150 K*)	15.75 dB (11,190 K*)
	FOA	15.80 dB	15.86 dB	15.83 dB
NBS Test No. 40021				
	NBS	15.77 dB (11,230 K*)	15.74 dB (11,160 K*)	15.75 dB (11,190 K*)
	FOA	15.80 dB	15.86 dB	15.83 dB
NBS Test No. 40022				
	NBS	15.78 dB (11,260 K*)	15.75 dB (11,180 K*)	15.76 dB (11,210 K*)
	FOA	15.80 dB	15.88 dB	15.86 dB

Comparison on May-June 1966 [9]

NBS Test No. 40021				
	NBS	15.70 dB (11,060 K)	15.73 dB (11,140 K)	15.74 dB (11,170 K)
	FOA	15.79 dB	15.82 dB	15.83 dB
NBS Test No. 40022				
	NBS	15.71 dB (11,090 K)	15.74 dB (11,170 K)	15.76 dB (11,200 K)
	FOA	15.81 dB	15.84 dB	15.86 dB

*All effective noise temperature measurements are related to the IPTS-48 temperature scale.

Noise Amplification

- Bandwidth Power
- Crest Factor

Crest Factor (CF)

The peak value of a signal divided by its root-mean-square (rms) value is termed *crest*

Statistical tables for the normal distribution provide the CF values shown in Table.

Probability (%)	Crest Factor
4.6	2
1	2.6
0.37	3
0.1	3.3
0.01	3.9
0.006	4
0.001	4.4
0.0001	4.9

For example, CF = 3.3 for a 0.1% probability means that the peak value will exceed 3.3 times the rms value only 0.1% of the time.

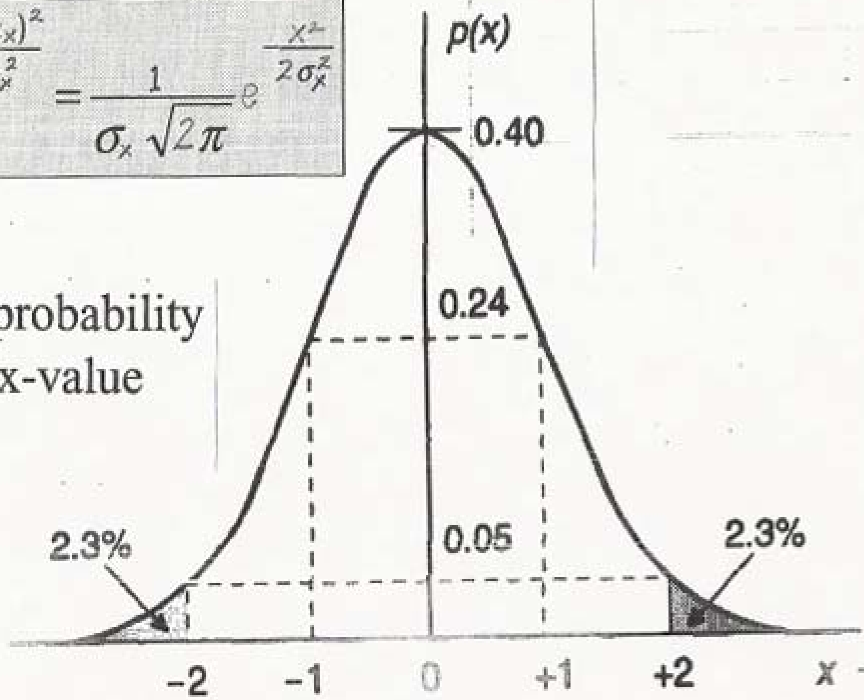
Gaussian Noise Distribution

Electronic noise has a Gaussian PDF because it results from a large number of random, independent events.

This means that its PDF is bell-shaped and follows the equation:

$$p(x) = \frac{1}{\sigma_x\sqrt{2\pi}}\, e^{-\frac{(x-\mu_x)^2}{2\sigma_x^2}} = \frac{1}{\sigma_x\sqrt{2\pi}}\, e^{-\frac{x^2}{2\sigma_x^2}}$$

Ordinates are the probability density of a specific x-value (in s–units).



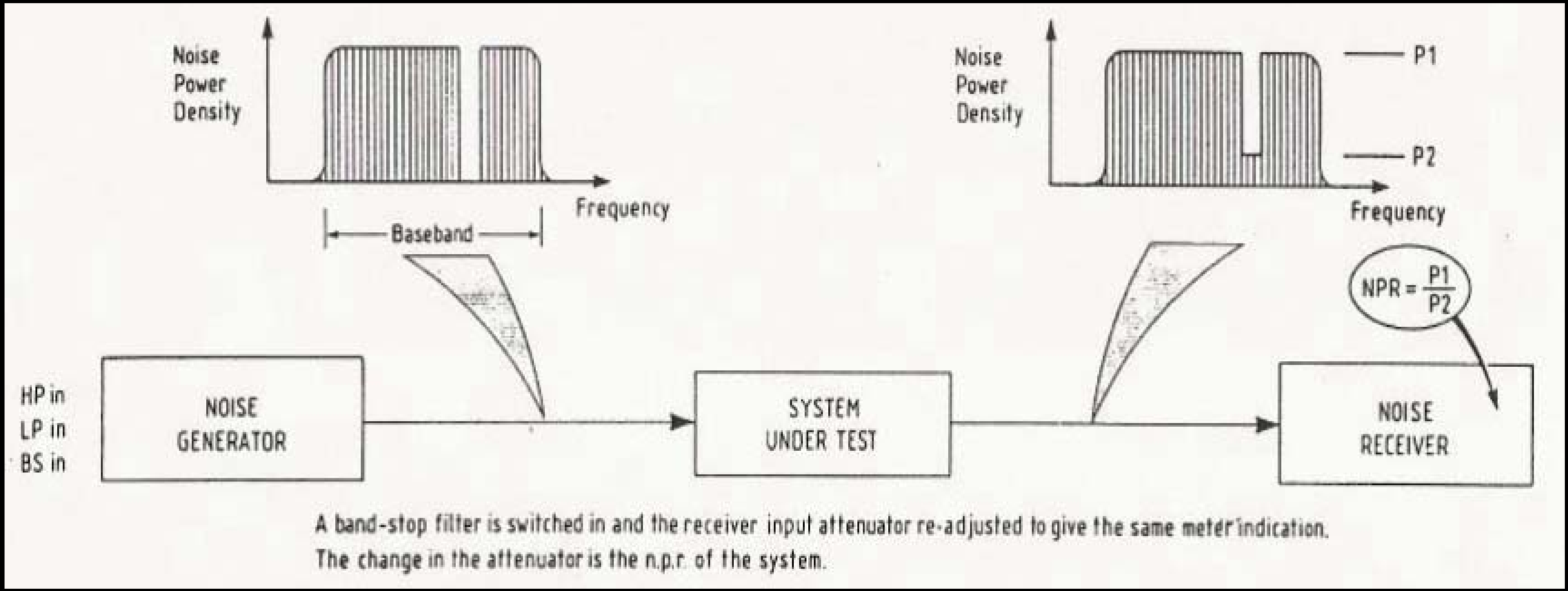
Amplifier Bandwidth & Power

- Noise Power =
  Unit noise power X bandwidth
- Consequently for some designs wider bandwidths may require a higher compression point amplifier

Communications Systems Testing

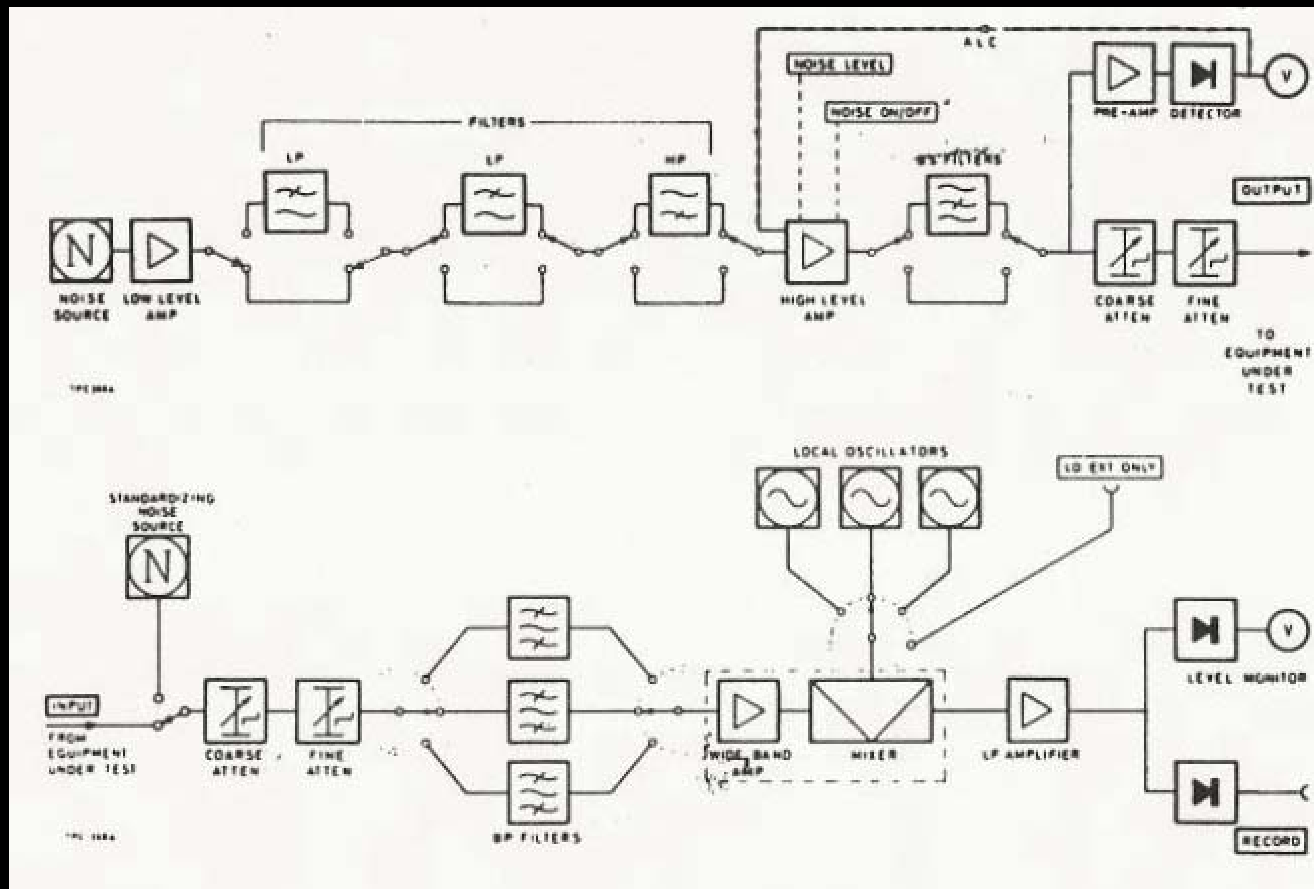
- White Noise Testing
- Bit Error Rate vs. Noise

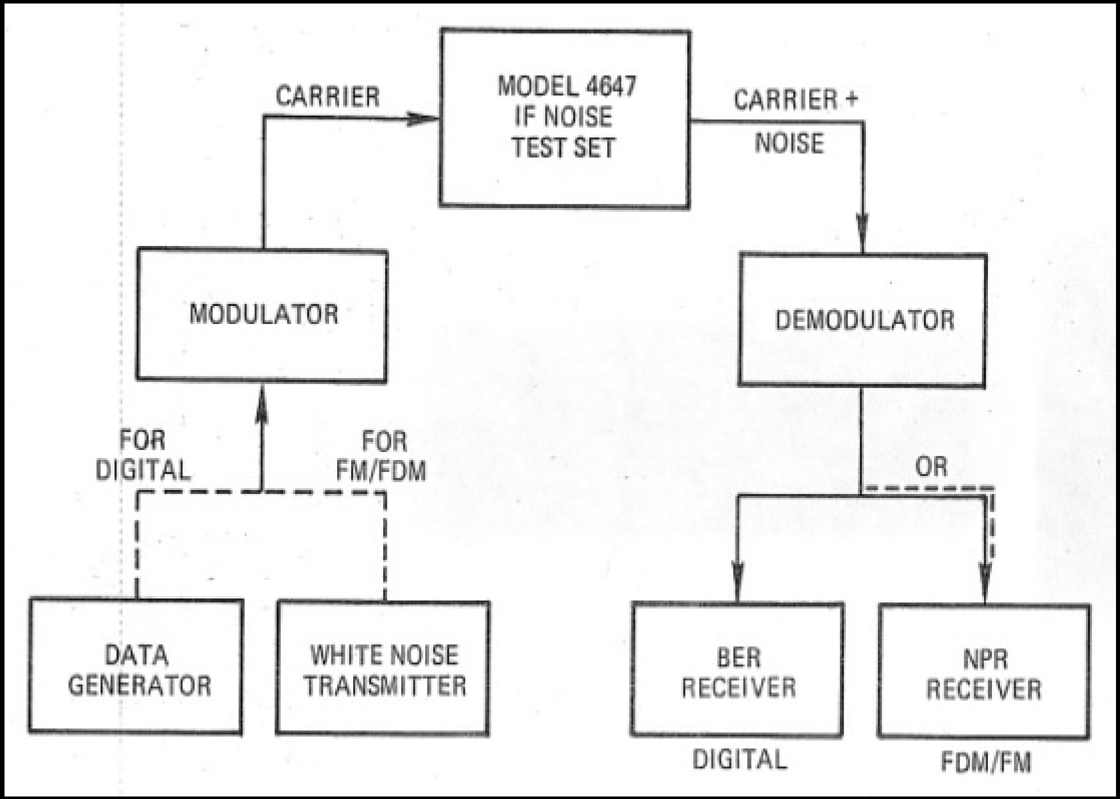
White Noise Testing



White Noise Test Equipment

- Noise Generator
- Noise Receiver





CARRIER
MODEL 4647
IF NOISE
TEST SET
CARRIER +
NOISE
MODULATOR
DEMODULATOR
FOR
DIGITAL
FOR
FM/FDM
OR
DATA
GENERATOR
WHITE NOISE
TRANSMITTER
BER
RECEIVER
NPR
RECEIVER
DIGITAL
FDM/FM

ATM Noise Sources (Z Model)

ATM Noise Source (Y Model)

Z Package Microwave Noise Generators

15.5 dB Noise Figure Meter Compatible Noise Sources Z- Package

HOUSING:	.94" X .81" X 4.2" (Max.)
DC INPUT:	BNC (F) CONN.
RF OUTPUT:	TYPE-N (M) CONN.

Freq Range GHz	Noise Output ENR (dB)	VSWR max ON/OFF	Calibration Frequencies	Model No.	Package Code*
1.0 - 4.0	15.5+/-0.5	1.25:1	1.0 GHz increments	NX153EZ	Z
2.0 - 8.0	15.5+/-0.5	1.25:1	1.0 GHz increments	NX154FZ	Z
1.0 - 12.4	15.5+/-0.5	1.25:1	1.0 GHz increments	NX153GZ	Z
4.0 - 12.4	15.5+/-0.5	1.25:1	1.0 GHz increments	NX155GZ	Z
1.0 - 18.0	15.5+/-1.2	1.35:1	1.0 GHz increments	NX153HZ	Z

*Models offered in package Z are only available in this package, no X or Y substitution can be made.

X Package Microwave Noise Generators

15.5 dB Noise Figure Meter Compatible Noise Sources - X Package

HOUSING:	.75" X .75" X 3.4" (Max.)
DC INPUT:	BNC (F) CONN.
RF OUTPUT:	SMA (M) CONN.

Freq GHz	Noise Output ENR (dB)	VSWR Max. ON/OFF	Calibration Frequencies	Model No.	Package* Code
1.0 - 2.0	15.5 +/- 0.5	1.20:1	0.5 GHz increments	NX1512X	X
2.0 - 4.0	15.5 +/- 0.5	1.20:1	1.0 GHz increments	NX1524X	X
4.0 - 8.0	15.5 +/- 0.5	1.20:1	1.0 GHz increments	NX1548X	X
8.0 - 12.0	15.5 +/- 0.5	1.35:1	1.0 GHz increments	NX15812X	X
12.0 - 18.0	15.5 +/- 0.5	1.35:1	1.0 GHz increments	NX151218X	X

*X or Y package may be selected for either series by changing the suffix of the model number
Example: NX1512X = NX1512Y

Y Package Microwave Noise Generators

High Noise Output Noise Sources
Y - Package

HOUSING:	.5" X .5" X 2.84" (Max.)
DC INPUT:	SMA (F) CONN.
RF OUTPUT:	SMA (M) CONN.

Freq Range GHz	Noise Output ENR (dB)	Noise Flatness (dB)	Calibration Frequencies	Model No.	Package* Code
0.01 - 0.15	30 - 36	+/-2	10, 70, 140 MHz	NX3201Y	Y
1.0 - 2.0	30 - 35	+/-1	0.5 GHz increments	NX3212Y	Y
2.0 - 4.0	30 - 35	+/-1	1.0 GHz increments	NX3224Y	Y
4.0 - 8.0	30 - 35	+/-1	1.0 GHz increments	NX3248Y	Y
8.0 - 12.0	28 - 33	+/-1	1.0 GHz increments	NX32812Y	Y
12.0 - 18.0	26 - 32	+/-1	1.0 GHz increments	NX321218Y	Y

*X or Y package may be selected for either series by changing the suffix of the model number
Example: NX3201Y = NX3201X

Thank You

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