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NOISE PARAMETERS OF NRAO 1.5 GHz GASFET AMPLIFIERS

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I. Introduction

It is common practice in the low-noise microwave amplifier field to only partially specify the amplifier noise performance. The noise parameter which is usually reported is T_A, the noise temperature of the amplifier when driven from a particular source impedance, which is usually 50 ohms for coaxial input lines. In order to analyze the performance of a system in which the amplifier is driven from some other source impedance, a set of four noise parameters of the amplifier must be known. There are many sets of noise parameters; six sets and the transformations between them are described in [1]. The most common set of parameters are the minimum (vs. source impedance) noise temperature, T_{min}, the impedance, Z_{opt}, which gives this minimum, and a sensitivity parameter, G_n. The particular set of parameters most convenient for the work described here is the noise wave model described by Penfield [2] and Meys [3] and shown in Figure 1c.

The noise parameters, with the exception of a phase angle,* for the 1.5 GHz low-noise amplifier reported in [4] will be described in this report. Approximately

*The missing phase angle is the phase of the wave correlation coefficient which is used to determine the phase of the optimum source reflection coefficient, Γ_{opt}. Data sufficient to determine this angle was collected but the accuracy of the data is not adequate to determine the angle accurately, especially when $|\Gamma_{opt}|$ is small. The angle may be the subject of some future work but was not considered as a necessity for our present study.

ninety of these amplifiers are under construction by NRAO for use as cooled receiver front-ends and as I.F. amplifiers for cooled Schottky-diode and super-conducting tunnel junction millimeter-wave mixer receivers. Questions regarding the effect of mixer-I.F. mismatch have arisen and this is the prime motivation for the measurements. It is also very useful to know the difference between T_A and T_{min} - i.e., how much improvement in noise temperature can be obtained by redesign of the input network.

II. Measurement Method

The measurement configuration and analysis models are shown in Figure 1. When Γ_s is a 50-ohm resistor at known temperature, the Apple computer program NOISE1 tabulates and plots T_A, the amplifier noise temperature at $\Gamma_s = 0$, using values of noise diode excess temperature and source noise temperature with diode off, T_{OFF}, all referred to the amplifier input connector at 15K. These calibration values have been determined by applying hot and cold noise temperature standards [5] at reference plane A and measuring the A to B loss.

After the measurement of T_A, the 50-ohm resistor is replaced by a sliding short, T_{OFF} is changed in the program, and noise measurements are made for several positions of the sliding short. An appropriate value of T_{OFF} is the noise temperature delivered to a noiseless 50 ohm load replacing the amplifier input; i.e., $T_p(1 - |\Gamma_s|^2)$ where T_p is the physical temperature of the lossy part of Γ_s. If this is done, NOISE1 tabulates and plots a quantity which we will call the amplifier noise wave temperature, $T_n' = T_n(1 - |\Gamma_s|^2)$, where T_n is the amplifier noise temperature. Both T_n' and T_n are functions of Γ_s but as $|\Gamma_s| \rightarrow 1$, T_n' is well behaved and $T_n \rightarrow \infty$. Typical plots of T_n' versus frequency for three different amplifiers and two different short positions as produced by NOISE1 are shown in Figure 2.

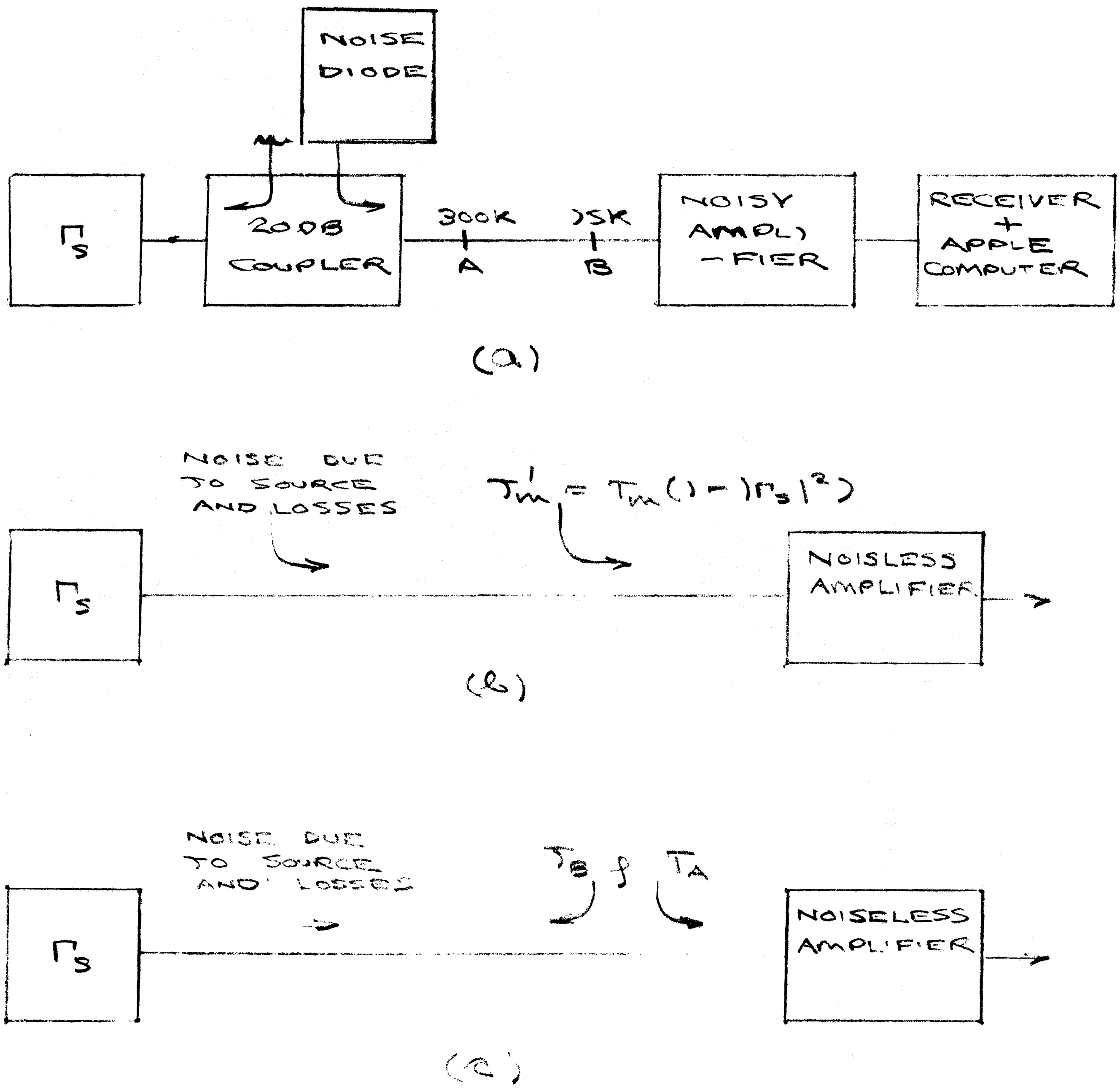

Fig. 1: The measurement physical configuration is shown in (a) where Γ_s is either a 50-ohm resistor at 15K or a sliding short at 300K. The Apple-computer output is then the noise-wave temperature, T_n', shown in (b). This is then used to find parameters of the noise-wave model shown in (c).

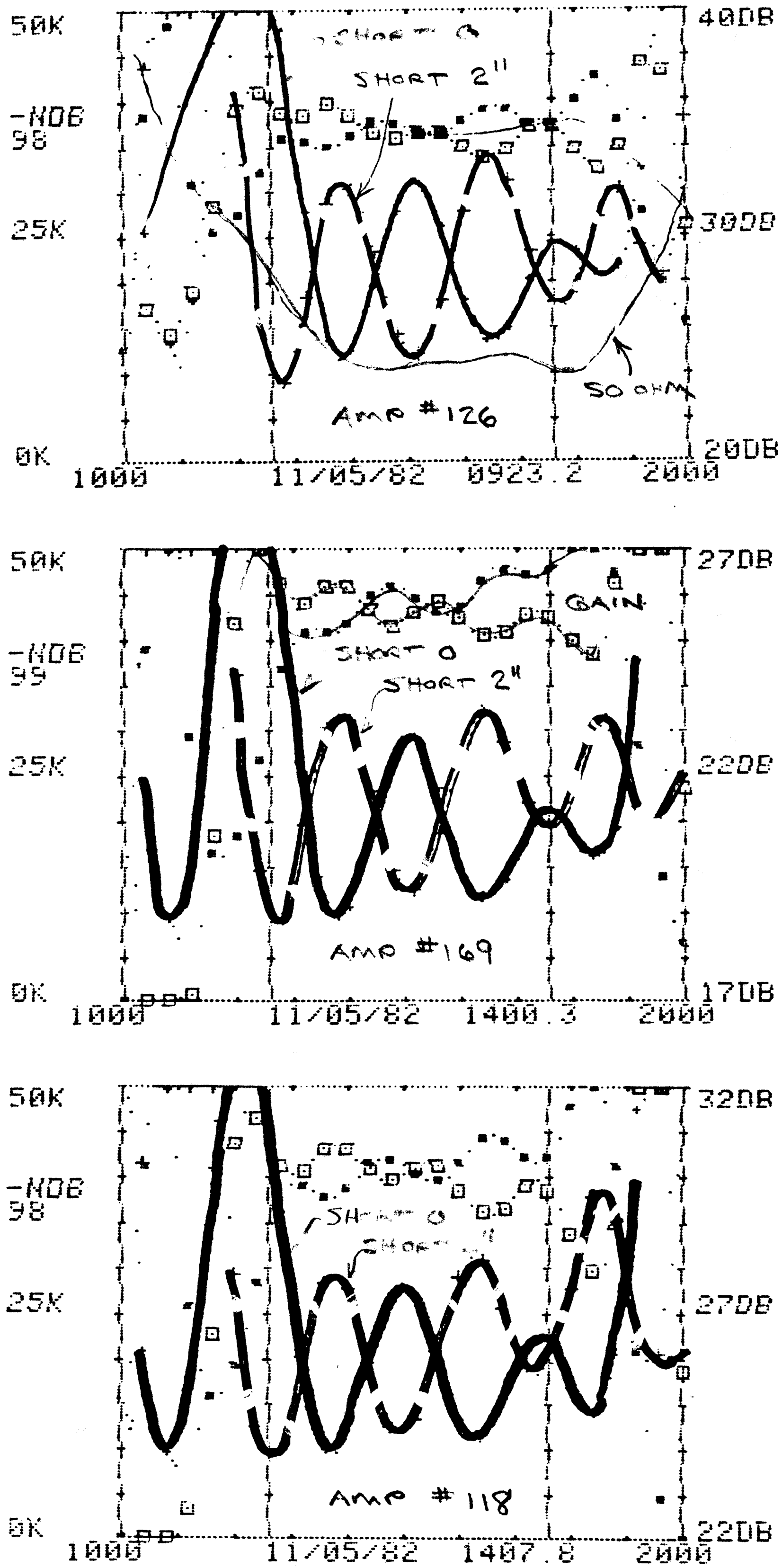

Fig. 2: Noise wave temperature, T_n', at sliding short positions separated by 5.08 cm for 3 different amplifiers at 15K. The main point is that the amplifiers are very similar; detailed analysis was performed only on one amplifier #169 (middle plot).

The noise wave temperature, T_n', is only of intermediate interest. It is easily measured and is related to the noise wave model of the amplifier shown in Figure 1c by,

$$T_n' = T_A + T_B|\Gamma_s|^2 + 2\sqrt{T_A T_B}\ \text{Re}(\rho\Gamma_s) \tag{1}$$

where T_A and T_B are the ingoing and outgoing noise wave temperatures and ρ is the complex correlation coefficient between T_A and T_B. These noise parameters are properties of the amplifier (i.e., independent of Γ_s) and can be transformed to other parameters.

The value of $T_{OFF} = T_p(1 - |\Gamma_s|^2)$ is difficult to determine accurately. An initial estimate was first used in the NOISE1 program and the resulting T_n' was then corrected to give a value of T_B which agreed with a separate direct measurement of T_B. This direct measurement was performed by connecting the amplifier <u>input</u> port to a receiver which has been calibrated with hot and cold termination. The outgoing noise from the amplifier input, T_{OUT} is approximately T_B for a low value of amplifier input reflection coefficient, $|\Gamma_n|$ (which is < .1 at band center) and incident outgoing receiver noise, T_{ISO}, comparable to T_B. The results of this measurement for an amplifier at 300K and 15K are shown in Figure 3. The resulting value of T_{OFF} is 26K. Assuming T_p = 300K, this gives $|\Gamma_s|$ = .955 or .393 dB return loss (.196 dB one-way loss) for a Maury 1929-2 sliding short, a 20 dB coupler, and a dewar transition.

It should be remarked that some difficulty was experienced with three different Maury 1929 sliding shorts which were utilized. Two of the shorts gave erratic results due to dirty contacts and loose bits of metal in the short; much improvement was noted after disassembly and cleaning. The interior surfaces of the coaxial lines appear to be brass and better results may be obtained if they were gold-plated. A 4K difference in noise temperature was measured between short positions spaced $\lambda/2$ apart at 1.5 GHz; this gives a one-way loss of .003 dB/cm. The final data taken on the cooled amplifier was repeated with two different sliding shorts with fairly good agreement; i.e., for $|\Gamma_{opt}|$ results were within .05 from 1.3 to 1.6 GHz and within .20 at all frequencies.

III. Results

An Apple sub-program, SS2 PLOT, used as part of a LADDER main program (which provides plotting and utility functions), was written to analyze $T_n'(f)$ data versus sliding short position; the program is listed in Appendix II. Equation (1), written for four values of Γ_s is inverted to give T_A, T_B, and ρ magnitude and phase. The measurement at $\Gamma_s = 0$ gives directly T_A and measurements at $|\Gamma_s| = .955$ and three values of phase can be fitted to a sinusoidal function as shown in Figure 4. The resulting three noise parameters for amplifier #169 at 15K and 300K and frequencies of 1.2 to 1.9 GHz are given in the first three columns of Table I. The last three columns give the quantities, T_{min}, T_D, and Γ_{opt}, which are convenient for describing the amplifier noise temperature, T_n, vs. source reflection coefficient, Γ_s, as:

$$T_n = T_{min} + \frac{T_D|\Gamma_s - \Gamma_{opt}|^2}{1 - |\Gamma_s|^2} \qquad (2)$$

where

$$T_{min} = \frac{T_A - T_B}{2} + \sqrt{\left(\frac{T_A + T_B}{2}\right)^2 - T_A T_B |\rho|^2} \qquad (3)$$

$$T_D = T_{min} + T_B \qquad (4)$$

$$|\Gamma_{opt}| = |\rho| \cdot \frac{\sqrt{T_A T_B}}{T_D} \qquad (5)$$

Note that when $|\rho| = 0$ then $|\Gamma_{opt}| = 0$ and $T_{min} = T_A$.

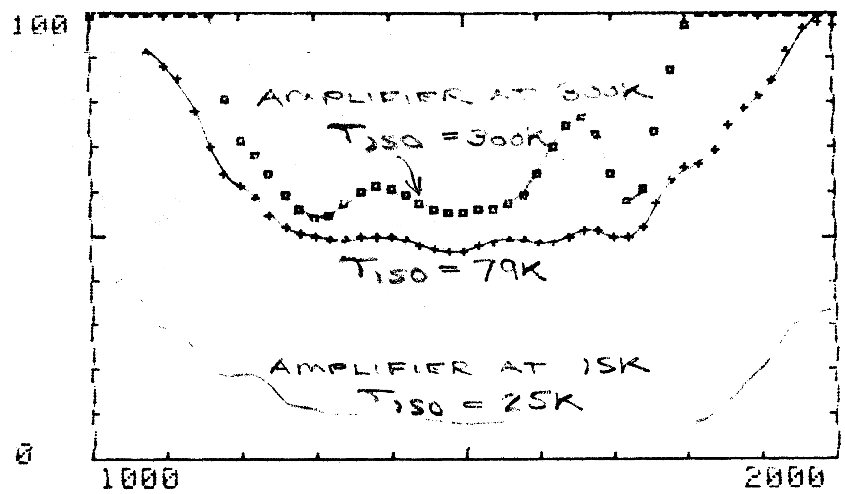

Fig. 3: Noise out of amplifier input terminals with amplifier at 300K (top two curves) and 15K. T_{ISO} is the noise temperature out of the measuring receiver, incident and partially reflected by the amplifier. At 1.5 GHz the amplifier outgoing noise wave, T_B, is found to be 43K with the amplifier at 300K and 8K with the amplifier at 15K.

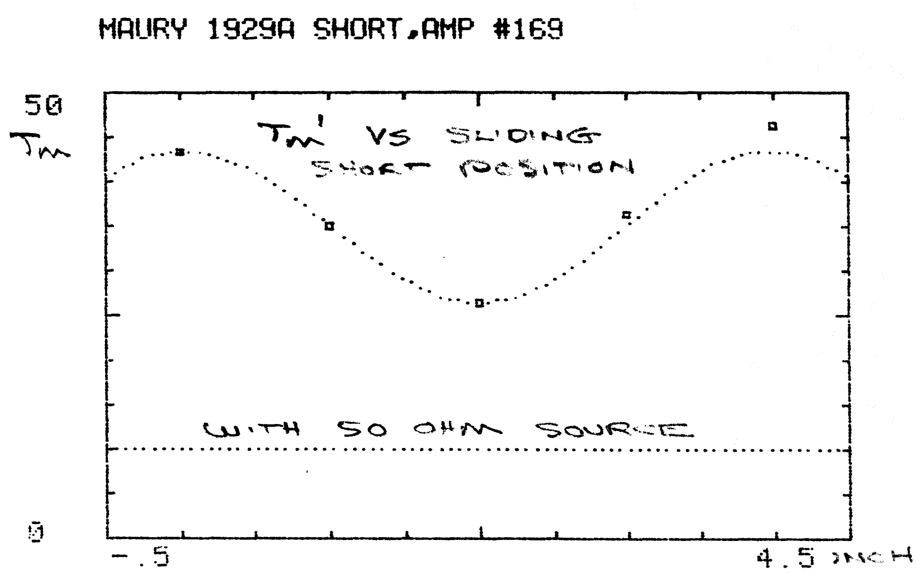

Fig. 4: Noise wave temperature, T_n', of amplifier #169 at 15K and 1.5 GHz as a function of sliding short position (inches). The dotted line is an exact fit to the left 3 points. The right 2 points show effect of additional loss as the short was extended.

Examination of (2) shows that, for a given value of $|\Gamma_s|$, the minimum of T_n with respect to phase of Γ_s, occurs at $|\Gamma_s - \Gamma_{opt}| = \big||\Gamma_s| - |\Gamma_{opt}|\big|$ and maximum at $|\Gamma_s| + |\Gamma_{opt}|$. Thus the range of T_n can be plotted vs. $|\Gamma_s|$ for typical midband values of noise parameters. This is shown in Figure 5 along with the T_n vs. $|\Gamma_s|$ curve assuming an ideal isolator between source and amplifier. Note that at 300K the isolator always increases T_n but at 15K this is not true.

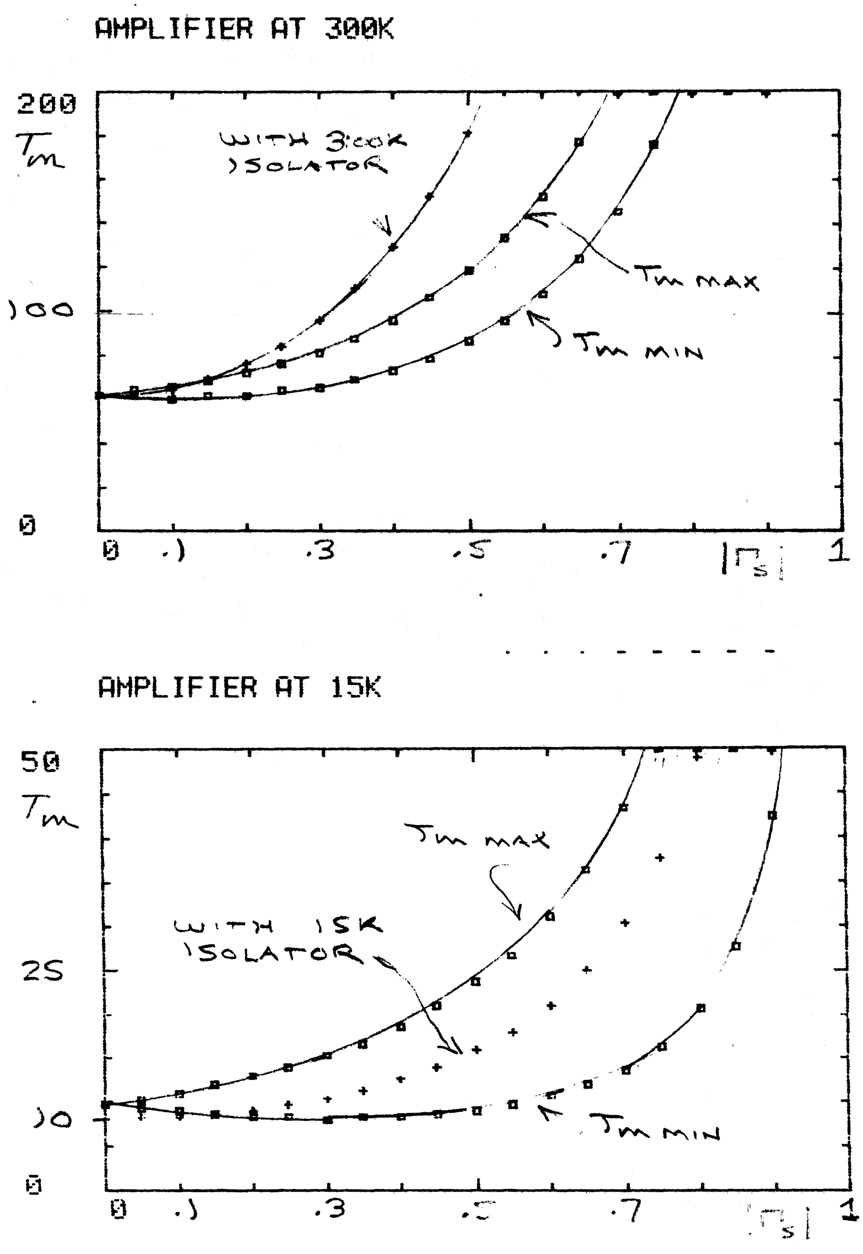

Fig. 5: Ranges of noise temperature vs. source reflection coefficient magnitude with and without isolators for amplifiers at 300K (top) and 15K. Typical values of $|\Gamma_{opt}|$ = .1, T_{min} = 60, T_D = 120 at 300K and $|\Gamma_{opt}|$ = .3, T_{min} = 8, T_D = 18 at 15K are assumed.

TABLE I - Noise Parameters of Amplifier #169 at 15K (top) and 300K (bottom)

	Noise Waves			See Eqs. (2)-(5)		
F GHZ	T_A °K	T_B °K	$\lvert\rho\rvert$	T_{min} °K	T_D °K	$\lvert\Gamma_{opt}\rvert$
1.2	22.1	20.8	.75	15.0	35.7	.45
1.3	14.1	12.9	.70	10.3	23.2	.40
1.4	9.8	6.8	.64	7.9	14.7	.36
1.5	9.8	8.9	.46	8.8	17.7	.24
1.6	9.1	8.7	.59	7.4	16.0	.33
1.7	10.0	7.1	.47	9.0	16.1	.25
1.8	8.7	7.6	.10	8.7	16.2	.05
1.9	15.7	8.8	.76	11.9	20.7	.43
1.2	109	72	.68	85	157	.38
1.3	81	61	.43	74	135	.23
1.4	61	51	.21	60	110	.11
1.5	66	47	.11	66	113	.05
1.6	63	52	.18	62	114	.09
1.7	65	56	.08	65	121	.04
1.8	68	63	.19	67	130	.10
1.9	106	63	.59	91	153	.31

References

[1] D. L. Fenstermacher, "A Computer-Aided Analysis Routine Including Optimization for Microwave Circuits and Their Noise," NRAO Electronics Division Internal Report No. 217, July 1981.

[2] P. L. Perifield, "Wave Representation of Amplifier Noise," IRE Trans. Circuit Theory, vol. CT-9, pp. 84-86, March 1962. Also reprinted in Low-Noise Microwave Transistors and Amplifiers, edited by H. Fukui, Wiley, 1981.

[3] R. P. Meys, "A Wave Approach to the Noise Properties of Linear Microwave Devices," IEEE Trans. Mic. Th. and Tech., vol. MTT-26, pp. 34-37, Jan. 1978. Also reprinted in book described in [2].

[4] S. Weinreb, D. Fenstermacher, and R. Harris, "Ultra Low-Noise, 1.2-1.7 GHz Cooled GASFET Amplifiers," IEEE Trans. Mic. Th. and Tech., vol. MTT-30, no. 6, June 1982. Also published as NRAO Electronics Division Internal Report. No. 220, revised May 1982.

[5] S. Weinreb, "Comparison of Three Liquid Nitrogen Noise Standards at 1.5 and 4.75 GHz," NRAO Electronics Division Technical Note No. 101, September 11, 1981.

APPENDIX I - Quick Use of Sliding Short to Determine Noise Parameters

A setup such as Figure 1a, with either a computer or noise figure meter to indicate noise temperature, can be used to quickly give noise parameters less the phase angle. With Γ_s a matched load the noise temperature measured in the usual way is T_A. The matched load is then replaced by a sliding short and T_{OFF} within the computer is replaced by $300(1 - |\Gamma_{ss}|^2)$ where $|\Gamma_{ss}|$ applies to the sliding short; alternatively $300 \times |\Gamma_{ss}|^2$ can be substracted from the indicated T_n. The sliding short is then moved to find the high, T_H, and low, T_L, extremes. T_B and $|\rho|$ are then computed as:

$$T_B = [(T_H + T_L)/2 - T_A]/|\Gamma_{ss}|^2 \qquad (6)$$

$$|\rho| = \frac{T_H - T_L}{4 \times |\Gamma_{ss}| \sqrt{T_A T_B}} \qquad (7)$$

Other parameters are then computed by equations (3)-(5).

APPENDIX II - SS2 Plot Subprogram

```
100  REM    SLIDING SHORT ANALYSIS,DECEMBER 21,1980
101  VTAB (21)
105  INPUT "L1,L2,L3,L4,AND L5 (INCHES) ?  ";L1,L2,L3,L4,L5
106 GD = .40
110 GS =  EXP ( - .11513 * GD): REM    COUPLER+SLIDING SHORT LOSS
112  GOTO 115
113 F = 1.5:T0 = 10.4:T1 = 46.6:T2 = 40.7:T3 = 28.6:T4 = 38.2:T5
 = 48.3: GOTO 117
115  INPUT "F(GHZ),T0,T1,T2,T3,T4,T5?  ";F,T0,T1,T2,T3,T4,T5
117 XL =  - .50:XH = 4.5:YL = 000:YH = 200: GOSUB 10200
118 XP = L1:YP = T1: GOSUB 10400
119 XP = L2:YP = T2: GOSUB 10400
120 XP = L3:YP = T3: GOSUB 10400
121 XP = L4:YP = T4: GOSUB 10400
122 XP = L5:YP = T5: GOSUB 10400
124  REM      SET UP INTERMEDIATE PARAMETERS
125 BB = 53.19776E - 2 * F:PI = 3.14159
130 A1 = BB * (L2 - L1):A2 = BB * (L3 - L1)
135 A3 = BB * (L2 + L1):A4 = BB * (L3 + L1)
140 GZ = (T2 - T1) *  SIN (A2) / ((T3 - T1) *  SIN (A1))
145 NZ = 4:JM = 10
150 EM = 1E10:P1 = 0:P2 = PI:P3 = P2 / NZ
155  REM    SOLVE FOR P BY ITERATION
160  FOR J = 1 TO JM
165  FOR P = P1 TO P2 STEP P3
170 EZ = GZ *  SIN (A4 + P) -  SIN (A3 + P)
175  IF  ABS (EZ) < EM THEN EM =  ABS (EZ):PM = P:EY = EZ
180  NEXT P
185 P1 = PM - P3:P2 = PM + P3:P3 = P3 / NZ
190  NEXT J
195  REM    P=PM IS NOW KNOWN. FIND TP AND TV NEXT
200 TP = (T1 - T2) / (2 *  SIN (A1) *  SIN (A3 + PM))
205  IF TP < 0 THEN TP =  - TP:PM = PM - PI
210 TV = T1 - TP *  COS (2 * BB * F * L(1) + PM)
215  REM    FIND NOISE WAVE PARAMETERS,TA,TB,AND RHO.
220 TA = T0
225 TB = (TV - TA - 0 * (1 - GS ^ 2)) / GS ^ 2
230  IF TB < 0 THEN TB = .001
235 RH = TP / (2 *  SQR (TA * TB) * GS)
240  REM    FIND NOISE PARAMETERS TMIN,GOPT,GARG, AND TD
245 TC = RH *  SQR (TA * TB)
250 TD = 0.5 * (TA + TB +  SQR ((TA + TB) ^ 2 - 4 * TC ^ 2))
255 TMIN = TD - TB:GOPT = TC / TD:GARG = 3.14159 - PM
260 RH =  INT (1000 * RH + .5) / 1000
265  DEF  FN R1(X) =  INT (10 * X + .5) / 10
270  DEF  FN R3(X) =  INT (1000 * X + .5) / 1000
275  PRINT
280  PRINT F;"MHZ  TMIN="; FN R1(TMIN);" TA="; FN R1(TA);" TB=";
 FN R1(TB);" TD="; FN R1(TD);" GAMMA OPT="; FN R3(GOPT);","; FN R3(GARG);"
 RHO="; FN R3(RH);","; FN R3(PM);" TV="; FN R1(TV);
300 DL = 16 / 250
310  FOR XP =  - .5 TO 4.5 STEP DL
320 YP = TV + TP *  COS (2 * BB * XP + PM)
330 XT = D8 * XP + D9:YT = D6 * YP + D7
332  IF XT < X8 THEN XT = X8
333  IF XT > X9 THEN XT = X9
334  IF YT < Y9 THEN YT = Y9
335  IF YT > Y8 THEN YT = Y8
```

PLOT SUBROUTINE

```
336  HPLOT XT,YT
340 YT = D6 * T0 + D7: HPLOT XT,YT
345  NEXT XP
350  GET ZZ$: GOTO 115
800  REM   TN LIMITS VS REFLECTION COEF.
805 TM = 8:TD = 23:P = .0
810 XL = 0:XH = 1:YL = 0:YH = 50: GOSUB 10200
820  FOR S = 0 TO .95 STEP .05
825 TX = TM + TD * (S + P) * (S + P) / (1 - S * S)
830 TN = TM + TD * (S - P) * (S - P) / (1 - S * S)
835 RL = 8.68 *  LOG (S + .0001)
840 WI = 8:DI = 2
842 X = S: GOSUB 11000
844 X = RL: GOSUB 11000
846 X = TX: GOSUB 11000
848 X = TN: GOSUB 11000
850  PRINT
855 XP = S:YP = TN: GOSUB 10400
860 XP = S:YP = TX: GOSUB 10400
865  NEXT S: END
```

FORMAT SUBROUTINE