NATIONAL RADIO ASTRONOMY OBSERVATORY
CHARLOTTESVILLE, VIRGINIA

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ULTRA LOW-NOISE, 1.2-1.7 GHz COOLED GASFET AMPLIFIERS

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ULTRA LOW-NOISE, 1.2 - 1.7 GHz

COOLED GASFET AMPLIFIER

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ULTRA LOW-NOISE, 1.2 - 1.7 GHz COOLED GASFET AMPLIFIERS

S. Weinreb, D. Fenstermacher, and R. Harris

I. Introduction

In the microwave frequency range between 1 and 3 GHz, the antenna noise temperature due to cosmic and atmospheric sources is quite low, $\sim$ 5K, and it is a challenge to receiver engineers to design low-noise amplifiers and low ground-radiation pickup antennas to take advantage of this low source temperature. The noise figure, in dB, of a receiver is equal to the signal-to-noise degradation caused by the receiver when the source temperature is 290K. When the source temperature including antenna noise is 10K, a reduction of receiver noise figure from 1.0 dB (or a noise temperature of 75K) to 0.1 dB (6.8K) causes a signal-to-noise improvement of (75 + 10)/(6.8 + 10) = 5.1 or 7.0 dB.

The amplifier described in this article has a noise figure of approximately 0.1 dB at 1.3 GHz. This is achieved with wide bandwidth, impedance match, excellent stability and relatively small cost and complexity compared with masers which have been required in the past for this noise performance. Cryogenic cooling to a temperature of $\sim$ 15K is required but this can now be obtained with closed cycle helium refrigerators [1] at a cost of under $5,000 and a weight less than 42 kg. Some specific applications for the amplifier are: 1) as a radio astronomy front-end for observations of the 1.42 GHz hydrogen line and OH lines at 1.61, 1.66 and 1.72 GHz; 2) as an I.F. amplifier for millimeter wave or infrared receivers utilizing cooled mixers; 3) as a front-end for detection of extraterrestrial civilizations communicating in the "optimum" frequency range of 1.42 to 1.67 GHz [2].

In a previous article [3] a cryogenically-cooled L-band amplifier utilizing source inductance feedback to achieve input match was described. This paper reports on the further development of this amplifier utilizing computer-aided design techniques to incorporate the following improvements:

1) The input circuit bandwidth has been increased by the addition of a shunt quarter-wave line. A noise temperature variation of less than 2K over a 500 MHz bandwidth is achieved.

2) The load impedance for the first stage has been optimized to give > 15 dB input return loss over the same 500 MHz bandwidth optimized for noise.

3) Series R-C bypass networks for the first-stage source and drain and second-stage drain have been added to reduce the tendency to oscillate at frequencies above 2 GHz. The amplifier is stable for a sliding short of any phase placed at input or output.

4) A third stage has been added and the gain equalized to be flat within $\pm$ 1.0 dB over a 500 MHz bandwidth.

5) A chip 10 dB attenuator has been incorporated into the output circuit to insure stability independent of out-of-band termination impedance.

A photograph and schematic of the amplifier are shown in Figures 1 and 2. A small size was desired so that as many as 8 front-ends, for different frequencies and polarizations, could be cooled with one cryogenic refrigerator.

II. Design

A first step in the amplifier design concerned the question of how to handle the mismatch which results when a FET device is driven by its optimum-noise generator impedance, Z_{opt}. For a FET in the lower microwave

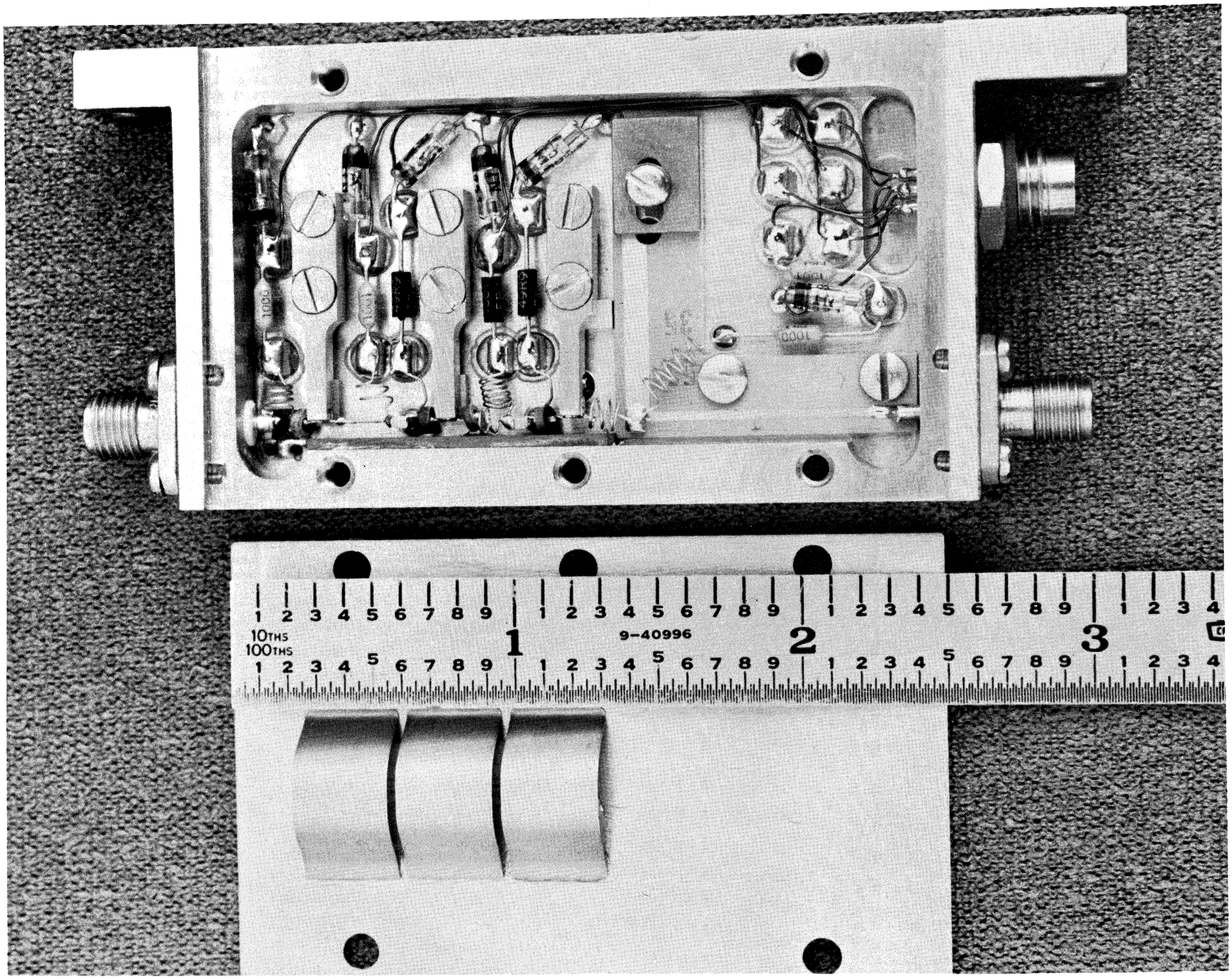


Fig. 1. Photograph of 3-stage amplifier with cover removed. Input is at right. Overall size less connectors is 9.14 cm x 4.06 cm x 1.27 cm.

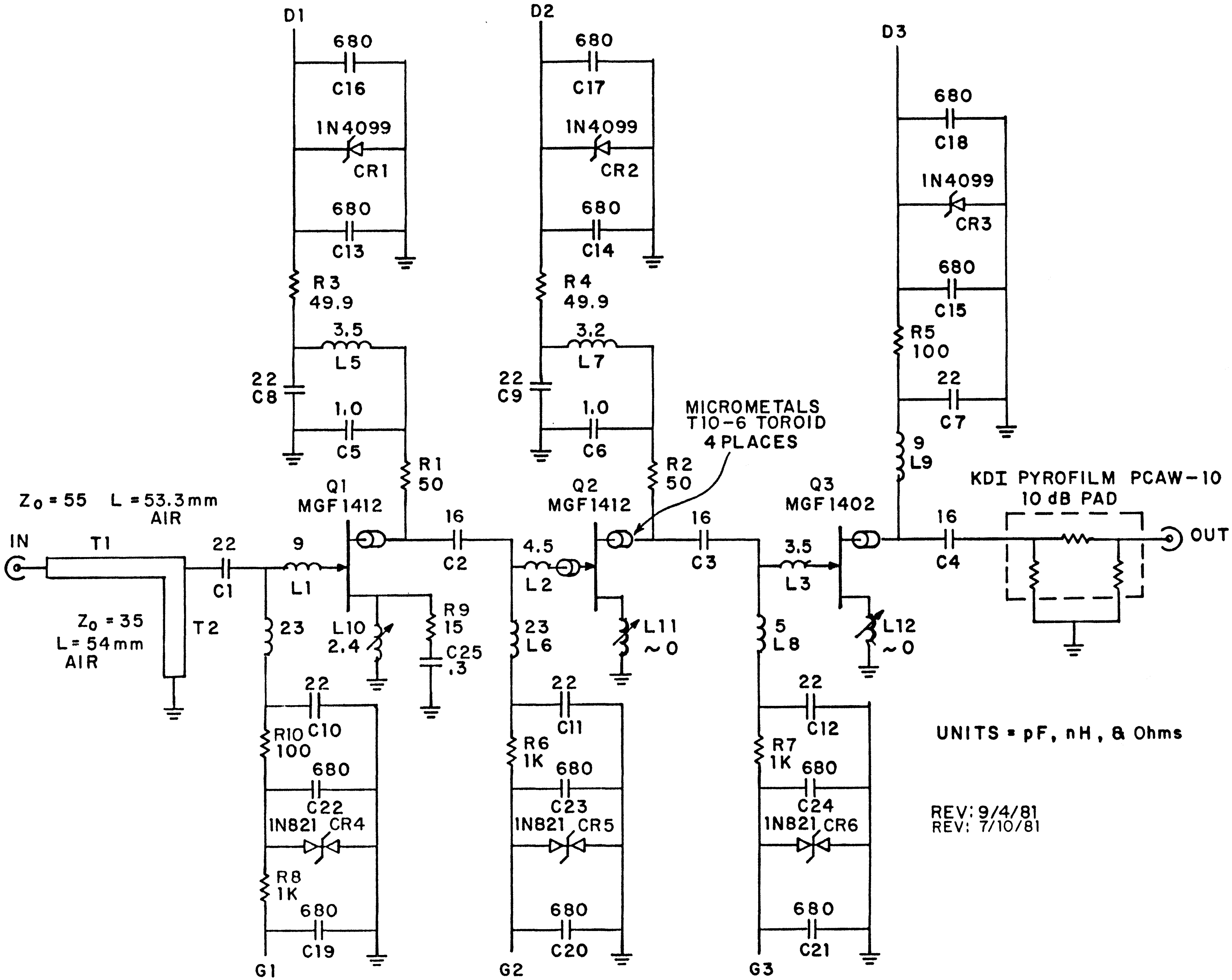


Fig. 2. Amplifier schematic. Bias voltages are supplied from a separate regulator which adjusts gate voltage for constant drain current.

range, this difference is quite large; typical values are $Z_{opt} = 42 + j175$ and $Z_{in} = 10 - j145$, giving an input voltage reflection coefficient magnitude of 0.73. It is, of course, possible to operate the amplifier with a large input mismatch, but small variations of the antenna feed impedance will then cause large ripples in the gain vs frequency response. Possible remedies to this problem are: 1) an isolator, 2) a balanced amplifier, or 3) use of feedback. The latter choice was taken because it results in the most compact, fewest component amplifier and because of previous experience with this technique [3,4]. It should be mentioned that a cooled isolator in this frequency range has recently been developed [5].

A second major decision was whether to use lumped or transmission-line matching elements. At 1.5 GHz this is a close decision as it is difficult to determine the parasitic reactances of lumped elements with sufficient accuracy, yet transmission lines are somewhat large. A compromise was made; the input network was constructed on high-dielectric constant (10.5) transmission-line circuit board [6] while the remainder of the amplifier was constructed with lumped elements. The input circuit board could be easily changed to vary the source resistance in a known manner.

A somewhat unconventional construction of the amplifier was based upon the following considerations:

1) The lowest-noise GASFET's for use at 1.5 GHz have considerable gain and a tendency to oscillate at 10 to 20 GHz, especially when source inductance feedback is utilized. The 1.5 GHz inductors have widely varying reactance in the 10 to 20 GHz frequency range and series R-C bypass networks are necessary to stabilize the amplifier. For these bypass networks to be effective, their total length must be less

than $\lambda/4$ at 20 GHz ($\sim$ 0.4 cm); they must be located extremely close to the FET and ideally would be built into the FET package.

2) The first-stage source inductance and $\lambda/4$ shunt stub length are critical and should be easily adjustable.

3) The thermal resistance from the FET source leads to the amplifier case must be low at cryogenic temperatures to avoid self-heating. For this reason the FET source leads are soldered to a copper FET holder with pure indium solder. The thermal resistance within the FET package is discussed in [7].

4) A "springy" mechanical design is needed to prevent fractures due to thermal stresses caused by the wide temperature range and materials with different thermal expansion coefficients. For this reason a dielectric-loaded Teflon substrate material [6] was used even though the temperature coefficient of its dielectric constant is much greater than that of alumina. (A 12% increase in dielectric constant was measured for cooling from 300K to 15K).

The Mitsubishi MGF-1412 transistors used in the design were selected on the basis of previous evaluations at 5 GHz [7] and also upon the results reported in [3]. Noise parameters of a MGF-1412 at approximately 1.6 GHz were measured at 300K and 15K by performing noise measurements with 3 different input circuit boards; these had no shunt $\lambda/4$ stub and had Z_o values of 41, 51 and 69 ohms for the series $\lambda/4$ line. The results for a drain bias of 5 volts and 10.8 mA are shown in Table I where they are compared with the theoretical values of Pucel, et al. [8]. The agreement with theory is poor, in contrast to results reported at 5 GHz in [7], due to low frequency noise mechanisms not accounted for in the theory.

A MGF-1402 is used in the final stage because of its lower cost. The amplifier output is isolated from the load by an internal 10 dB chip attenuator [9]. Unlike an isolator, the attenuator terminates the amplifier over the entire microwave frequency range and thus insures that the amplifier will not oscillate for some particular out-of-band termination impedance.

Optimization of the amplifier was performed using the FARANT program developed at NRAO [10]. The optimization trade-offs are illustrated by the impedance plot of Figure 3 and consideration of the noise temperature dependence upon generator impedance, $R_s + jX_s$, for any linear two-port,

$$T_n = T_{min} + 290 \times \frac{g_n}{R_s} [(R_s - R_{opt})^2 + (X_s - X_{opt})^2]$$

where $R_{opt} + jX_{opt}$ is the optimum-noise generator impedance and g_n is the amplifier noise conductance as given in Table I. The first-stage source inductance, L10, and load reactances, C5, L5 and L2, have been adjusted to make the FET input resistance, R_{in}, approximately equal to R_{opt}. The series and shunt $\lambda/4$ line lengths and characteristic impedances and the input inductor, L1, are then adjusted to make R_s as close as possible to R_{in} and R_{opt} and to bring the source reactance, X_s, to a value between X_{in}^* and X_{opt}. If the shunt stub is not present, X_s is a linear increasing function of frequency and R_s has little frequency variation. This results in narrower bandwidth in both noise temperature and match due to the difference between X_s and X_{opt} or X_{in}. A more complex input circuit could give still wider bandwidth but has not been attempted.

At the time the input impedance optimization was performed, R_{opt} was thought to be 75 ohms; later measurements, described in Table I, showed R_{opt} = 42 ohms. However, a higher value of generator resistance gives less

TABLE I - NOISE PARAMETERS OF MITSUBISHI MGF-1412 AT 1.6 GHz, TEMPERATURES OF 300K AND 15K, AND DRAIN BIAS OF 5 VOLTS, 10 mA.

AMBIENT TEMP °K	T_{min}	$1/g_n$ ohms	R_{opt}	X_{opt}	COMMENT
300	63 ± 3	250 ± 50	42 ± 4	-	Measured
300	20.3	1785	60.7	221	Theory [7,8]
15	8 ± 2	1200 ± 500	29 ± 2	-	Measured
15	4.2	5882	39.3	196	Theory [7,8]

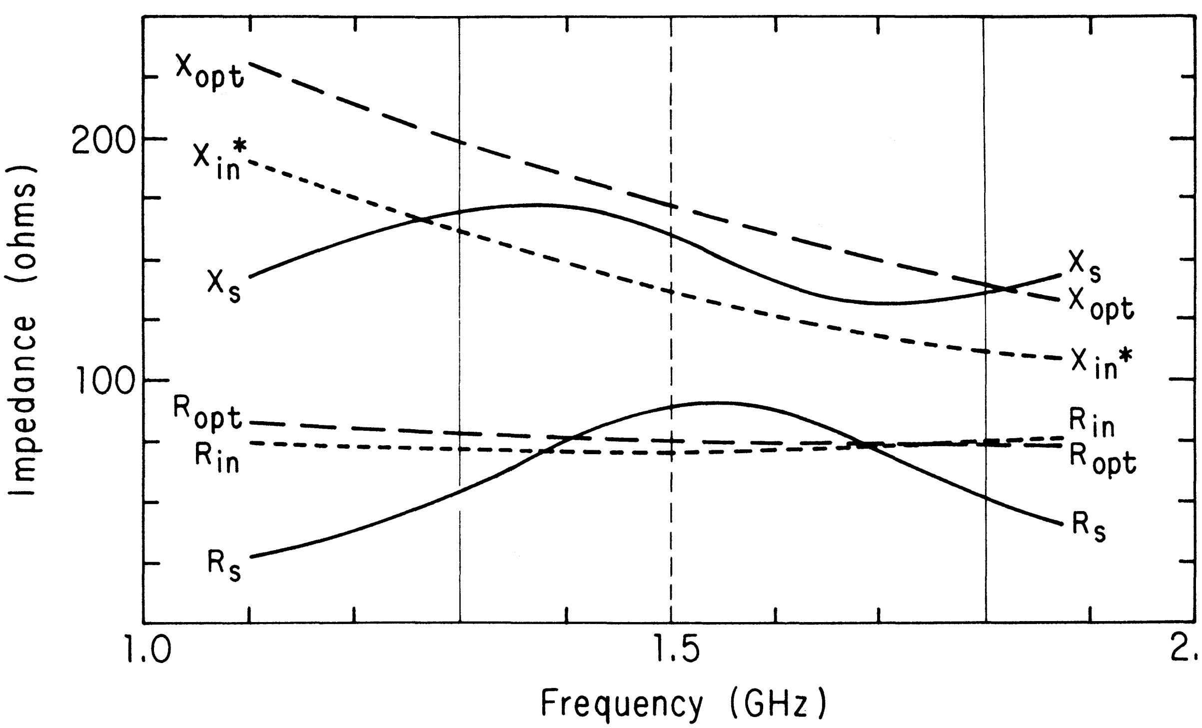


Fig. 3. Source impedance optimization example. The minimum noise impedance is $R_{opt} + jX_{opt}$, the FET input impedance is $R_{in} + jX_{in}$, and the generator impedance is $R_s + jX_s$. The negative slope in X_s is due to the shunt $\lambda/4$ transmission line.

noise temperature variation with frequency and a center-frequency value of 60.5 ohms is used in the amplifier.

III. Construction

The amplifier chassis, shown in Figure 4, is milled from a 1.27 cm x 4.07 cm x 9.15 cm block of copper which is then gold plated for corrosion protection and to reduce absorption of thermal radiation. FET holders, shown in Figure 5, are also machined from copper. Inductors are fabricated as described in Table II using either gold-plated phosphor-bronze wire or copper wire which is not as mechanically stable but is easier to deform for tuning purposes.

The following procedures are used for soldering of components; a small hot plate is the heat source for steps 1) thru 3):

1) The chassis is heated to 200°C and chip capacitors used as stand-offs are soldered in 0.5 mm deep holes using solder of 62% tin, 36% lead, and 2% silver [11].

2) The chip attenuator is soldered into the chassis using a low temperature solder [12] and flux [13] at 110°C. This same low temperature solder can be used if a chip capacitor must be replaced after assembly is complete.

3) The bellows contact [14] is soldered to the first-stage FET holder using 60% tin, 40% lead solder at 200°C. The FET source leads are then soldered into the holder using pure indium solder [15] and flux [13] at 175°C. Drain leads are cut to 3 mm length and gate leads are cut to 0.75 mm for stages 1 and 3 and 2 mm for stage 2.

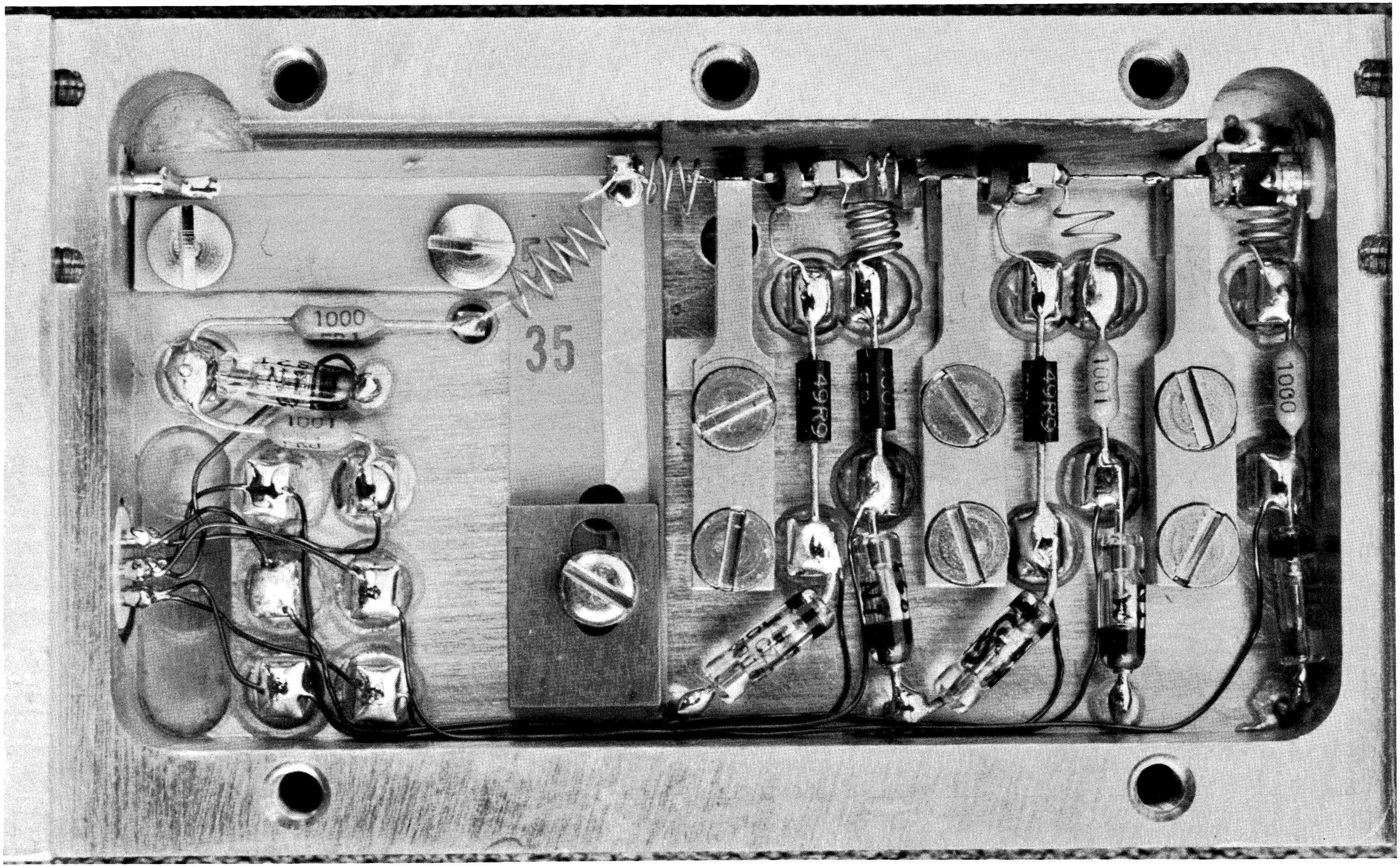


Fig. 4. Amplifier chassis. The length of the shunt $\lambda/4$ line, T2, is adjusted by moving the small plate under its ground screw. Source-lead inductance is adjusted by moving the shim under the FET holder.

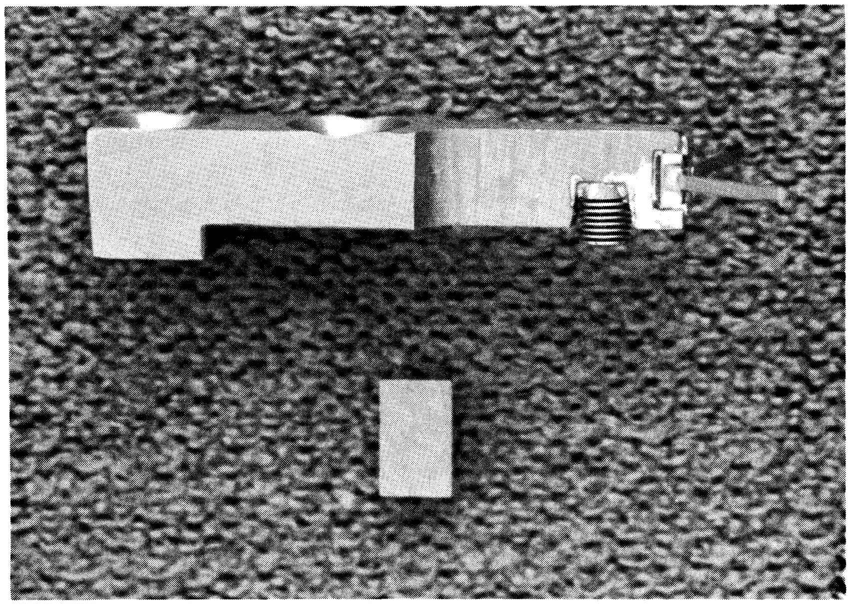


Fig. 5. Close-up side view of FET holder and grounding shim. The bellows contacting a 15 ohm chip resistor in series with a 0.3 pF chip capacitor to ground is used only on the first stage and is needed to prevent oscillation at $\sim$ 10 GHz. The size of the holder is 2.03 cm x .41 cm x. 46 cm high with a .127 cm gap for the shim.

TABLE II - INDUCTOR DESCRIPTION

INDUCTOR	INNER DIAMETER mm	LENGTH mm	TURNS	INDUCTANCE, nH	
				COIL	TOTAL
L1	2.1	2.0	3	8.2	9
L2*	1.8	2.5	2	2.6	4.5
L3	1.8	0.8	1	1.4	3.5
L4	2.1	3.8	5	20.5	23
L5	-	5.8	wire	0	3.2
L6*	2.1	3.8	5	20.5	23
L7	-	4.6	wire	0	3.2
L8	2.1	3.8	2	3.2	5
L9	2.1	3.8	3	7.3	9

All wound with 0.25 mm diameter wire.

*Wind in reverse direction from other coils.

4) Starting at the output, coils and FET holders are installed using a soldering iron and the 2% silver solder.

A rectangular bar, 1 mm x 7 mm x 27 mm, of iron-epoxy absorber material [16] is glued into the chassis as shown in Figure 4. This material has been tested to retain its loss at cryogenic temperatures. Berylium-copper finger stock material [17] is soldered to the top cover with 60% tin, 40% lead solder. Both of these items, as well as ferrite beads [18] on some of the leads, are for the purpose of suppressing high-frequency oscillations, particularly when the amplifier is cooled.

IV. Tuning

Tuning of the amplifier is necessary due to variability in the construction and installation of the inductors and to meet slightly different specifications for each application. Drain-bias voltage and current for stages 1, 2 and 3 are initially set at 5.5 V, 15 mA, 5.5 V, 12 mA, and 4V, 10 mA, respectively. Inductor L1 and transformer T2 lengths are trimmed to minimize the noise at a desired frequency. The inductance of a coil may be raised or lowered by moving the turns closer or further apart; larger changes require more or less wire but this is usually not necessary. Inductors L2 and L10 are adjusted to achieve input match; it may be necessary to also change L1 and T2 for this requirement. Inductors L5, L6, L8 and L9 are adjusted to achieve the desired gain response.

The amplifier input match vs frequency changes appreciably as it is cooled as is shown in Figure 6. This is due to the dielectric constant change in the input circuit board and to changes in gate-to-source capacitance caused by gate

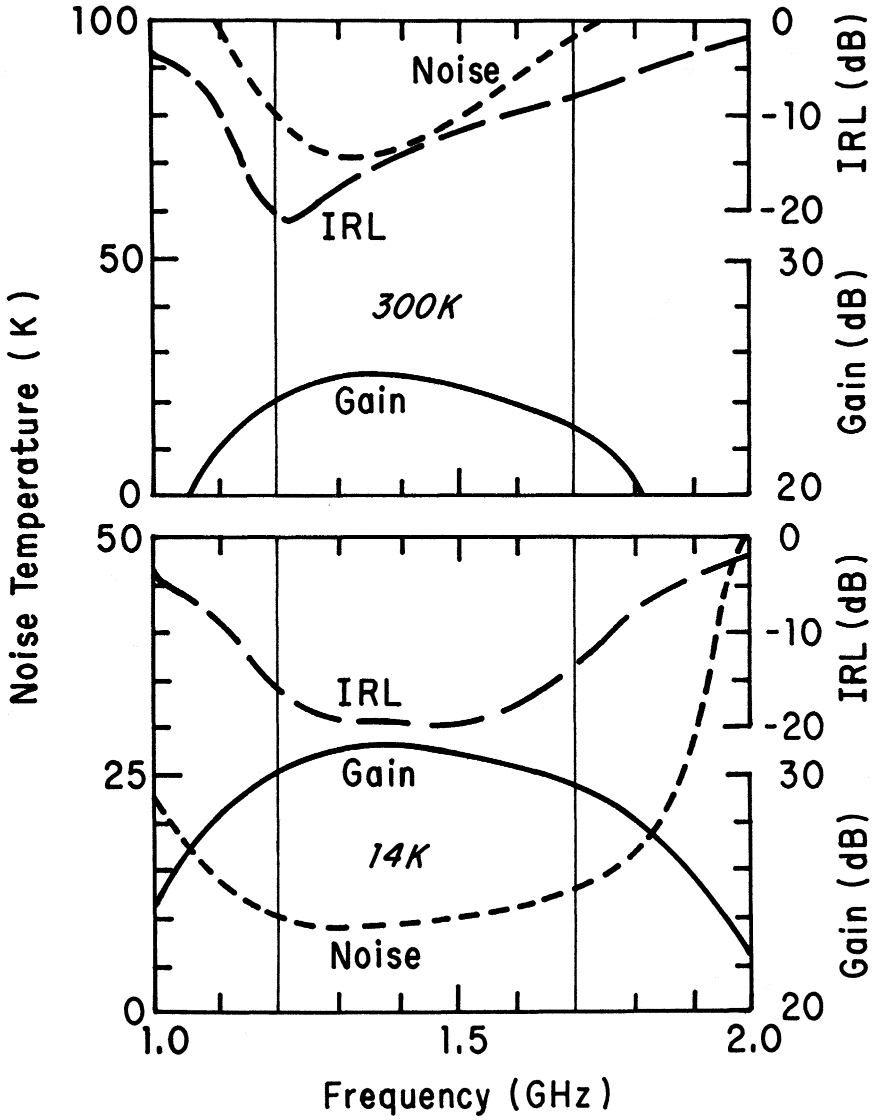


Fig. 6. Input return loss (IRL), gain, and noise temperature of amplifier #74 at 300K (top) and 14K (bottom). Note scale change for noise temperature.

bias voltage changes necessary to keep drain current in an optimum noise range. To some extent the input match change can be compensated by pre-tuning at 300K for the triangle shape shown in Figure 6. This is often not satisfactory and iterations of tuning and cooling may be necessary. Tuning of the amplifiers attached to a copper block in liquid nitrogen has been a useful procedure; little change in input match occurs between 77K and 20K.

V. Results

Amplifiers are tested for input return loss and gain utilizing a scalar network analyzer [19]. For the return-loss measurement, test signal power level at the amplifier input is -25 dBm and is somewhat critical; a higher level causes an error due to second-stage overload and a lower level gives insufficient reflected power for the reflectometer bridge sensitivity. For gain measurement, the input signal level is -45 dBm.

Noise temperature and also gain are measured with the test setup shown in Figure 7. The amplifier is mounted in a vacuum dewar and is thermally connected to a cryogenic refrigerator. The amplifier input is connected to the dewar exterior thru a very low loss (.08 dB, later reduced to .04 dB) coaxial line with APC 3.5 connectors and length 8.5 cm. This line has crystalline quartz inner conductor supports to form a vacuum seal and to insure that the amplifier end of the inner conductor is at the refrigerator temperature; the line will be described in detail in a future report.

Noise from a semiconductor-diode noise source [20] is coupled to the amplifier input thru the side arm of a 20 dB directional coupler. The main arm of the coupler is connected to a cold termination in the dewar to increase accuracy by preventing addition of a large room temperature noise to the

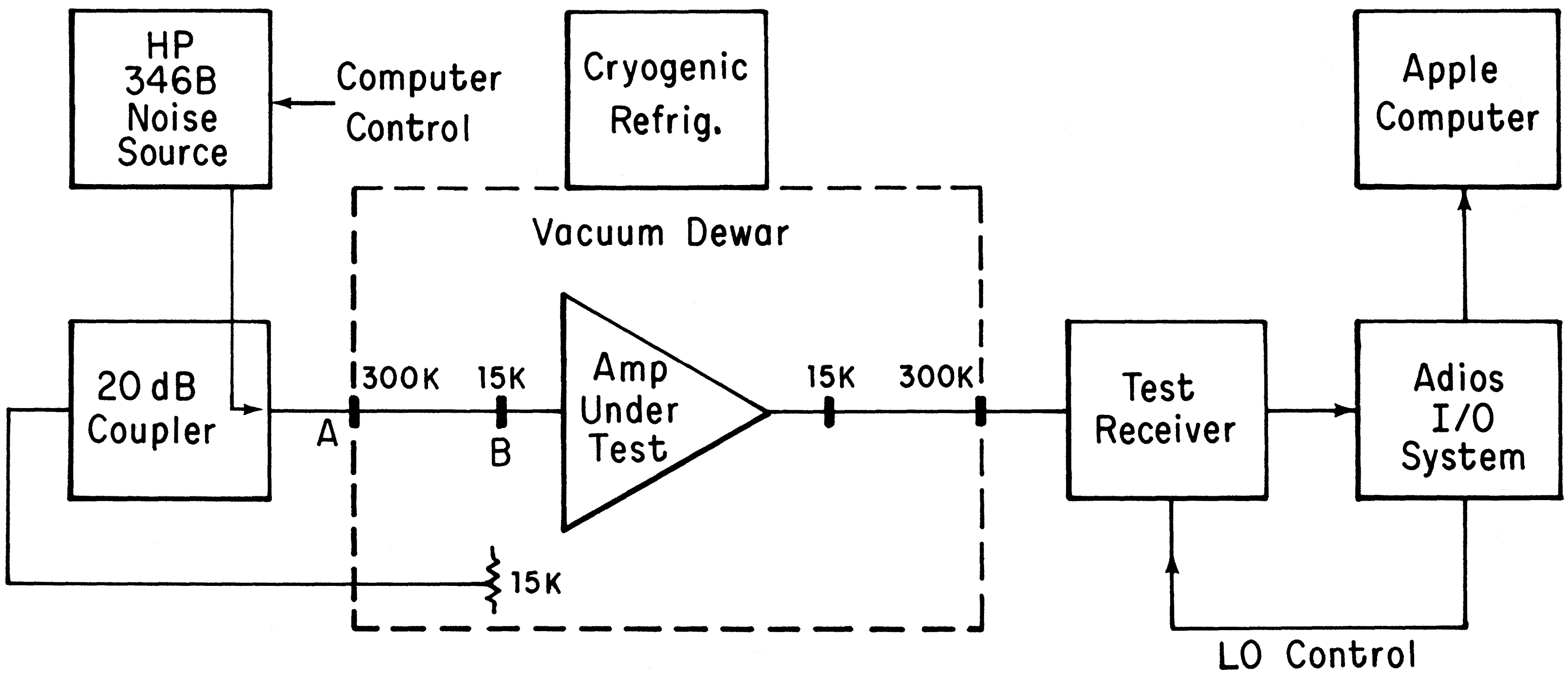


Fig. 7. Test setup for amplifier noise and gain measurements. Very low loss coaxial-line transitions were developed for connection, A to B, to the amplifier.

small amplifier noise. By replacing the coupler output, point A in Figure 7, with hot and cold noise temperature standards, the noise temperature at point A with diode off, 28.8K, and diode on, 94.1K to 123.7K dependent upon frequency, was calibrated. The noise diode was then turned on and off as receiver local-oscillator was scanned to give a swept-frequency measurement of noise temperature. A prior scan with the amplifier bypassed allows computation of the amplifier noise temperature, corrected for test receiver noise, and also the amplifier gain. This procedure is performed by an Apple II computer.

At the time of this writing, 16 amplifiers have been constructed. All amplifiers are stable for a sliding short of any phase connected to input or output. Oscillation of an amplifier can be detected either by observation of a bias value change or by observing the output of a broadband detector connected to the amplifier input or output port.

Noise temperature, gain, and input return loss for one amplifier are shown in Figure 6; this amplifier had the lowest noise temperature, 7.2K, but is typical in gain and input match. The noise temperature is referred to the cold amplifier input connector and is believed to be accurate within $\pm$ 0.5K; a value of 8.3K was measured at point A, outside of the dewar. Characteristics of four additional amplifiers are given in Table III; the noise temperatures of these amplifiers are only known to an accuracy of $\pm$ 2K and are also referred to the amplifier input connector.

TABLE III - PERFORMANCE OF FIVE AMPLIFIERS

UNIT NUMBER		74	75	83	84	86
AMBIENT TEMP °K		14	17	14	14.1	15.4
STAGE 1 BIAS,	V_D	5V	5V	5.5V	5.5V	5.5V
	I_D	10.7 mA	10 mA	12.4 mA	10.1 mA	6.7 mA
	V_G	-.713	-.592	-.598	-.750	-.684
NOISE TEMP*	MIN	7.2K	8.6K	9.0K	8.4K	11.6K
	f_{MIN}	1260	1320	1320	1360	1360
FREQS FOR						
INPUT RETURN	f_L	1160	1220	1150	1260	1300
LOSS > 15dB	f_H	1640	1720	1620	1625	1800
GAIN	MAX	25.5 dB	33.5 dB	30.4 dB	30.8 dB	31.2 dB
-3 dB	f_L	1150	1190	1050	1150	1100
-3 dB	f_H	1850	1820	1850	1750	1950

* Noise temperature referred to amplifier input connector at 15K. Values at room temperature connector are 1.1K to 3.0K higher.

REFERENCES

[1] Model 2 Cryogenic Refrigerator, Cryosystems, Inc. Westerville, OH.

[2] B. M. Oliver and J. Billingham, "Project Cyclops," Design Study Report CR114445, NASA Ames Research Center, Moffett Field, CA.

[3] D. R. Williams, W. Lum, and S. Weinreb, "L-Band Cryogenically-Cooled GaAs FET Amplifier," Microwave Journal, Vol. 23, No. 10, October 1980, pp. 73-76.

[4] L. Nevin and R. Wong, "L-Band GaAs FET Amplifier," Microwave Journal, Vol. 22, No. 4, April 1979, p. 82.

[5] Model LTE 1102, Passive Microwave Technology, Canoga Park, CA 91304.

[6] RT/Duroid 6010, .050" Dielectric, 2 oz., 2 Side Copper, Rogers Corp., Chandler, AZ.

[7] S. Weinreb, "Low-Noise Cooled GASFET Amplifiers," IEEE Trans. on Microwave Theory and Tech., Vol. MTT-28, No. 10, October 1980, pp. 1041-1054.

[8] R. Pucel, H. Haus, and H. Statz, "Signal and Noise Properties of Gallium Arsenide Microwave Field-Effect Transistors," Adv. in Electronics and Electron Physics, Vol. 38, L. Morton, Ed., New York: Academic, 1975.

[9] Type PCAW-10, KDI Pyrofilm, Whippany, NJ.

[10) D. Fenstermacher, Electronics Division Internal Report No. 217, National Radio Astronomy Observatory, Charlottesville, VA.

[11] Type SN62 Solder, 179°C, Multicore Solders, Westbury, NY.

[12] Type 20E2 Solder, 100°C, Alpha Metals, Jersey City, NJ.

[13] Type 30 Supersafe Flux (water soluble), Superior Flux and Mfg. Co., Cleveland, OH.

[14] Type 2156 Bellows, Servometer Corp., Cedar Grove, NJ.

[15] Indalloy No. 4 Solder, 157°C, Indium Corp. of America, Utica, NY.

[16] Eccosorb Type MF-124, Emerson and Cummings, Canton, MA.

[17] Type 97-500G Finger Contact Strip, Instrument Specialties Co., Delaware Water Gap, PA.

[18] Type T10-6 Ferrite Core, Micrometals Inc., Anaheim, CA.

[19] Type 560 Scalar Network Analyzer, Wiltron Inc., Palo Alto, CA.

[20) Type 346B Noise Source, Hewlett-Packard Co., Palo Alto, CA.

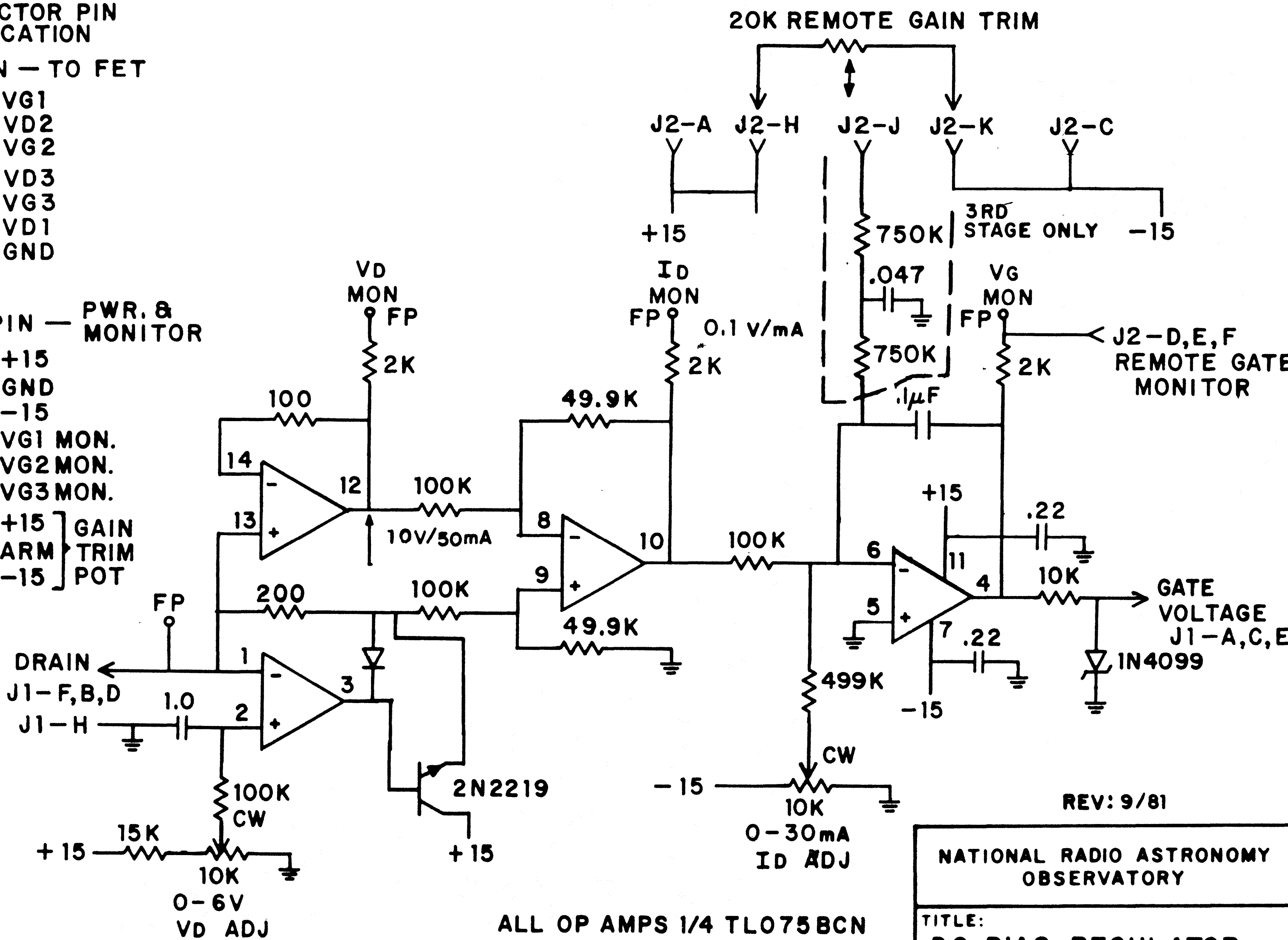
CONNECTOR PIN ALLOCATION

J1 — 7 PIN — TO FET

A	VG1
B	VD2
C	VG2
D	VD3
E	VG3
F	VD1
H	GND

J2 — 9 PIN — PWR. & MONITOR

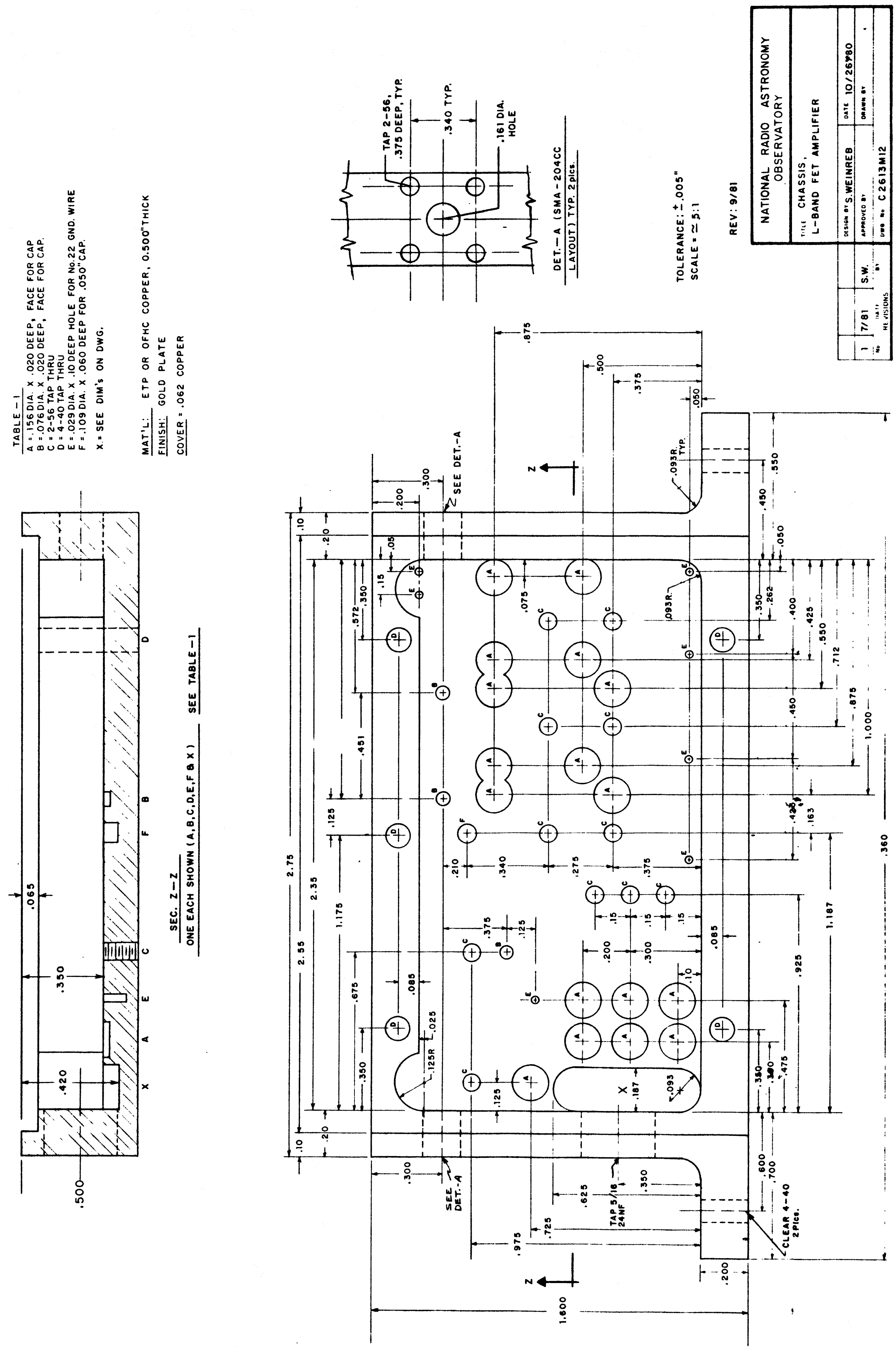
A	+15	
B	GND	
C	−15	
D	VG1 MON.	
E	VG2 MON.	
F	VG3 MON.	
H	+15	GAIN TRIM POT
J	ARM	
K	−15	



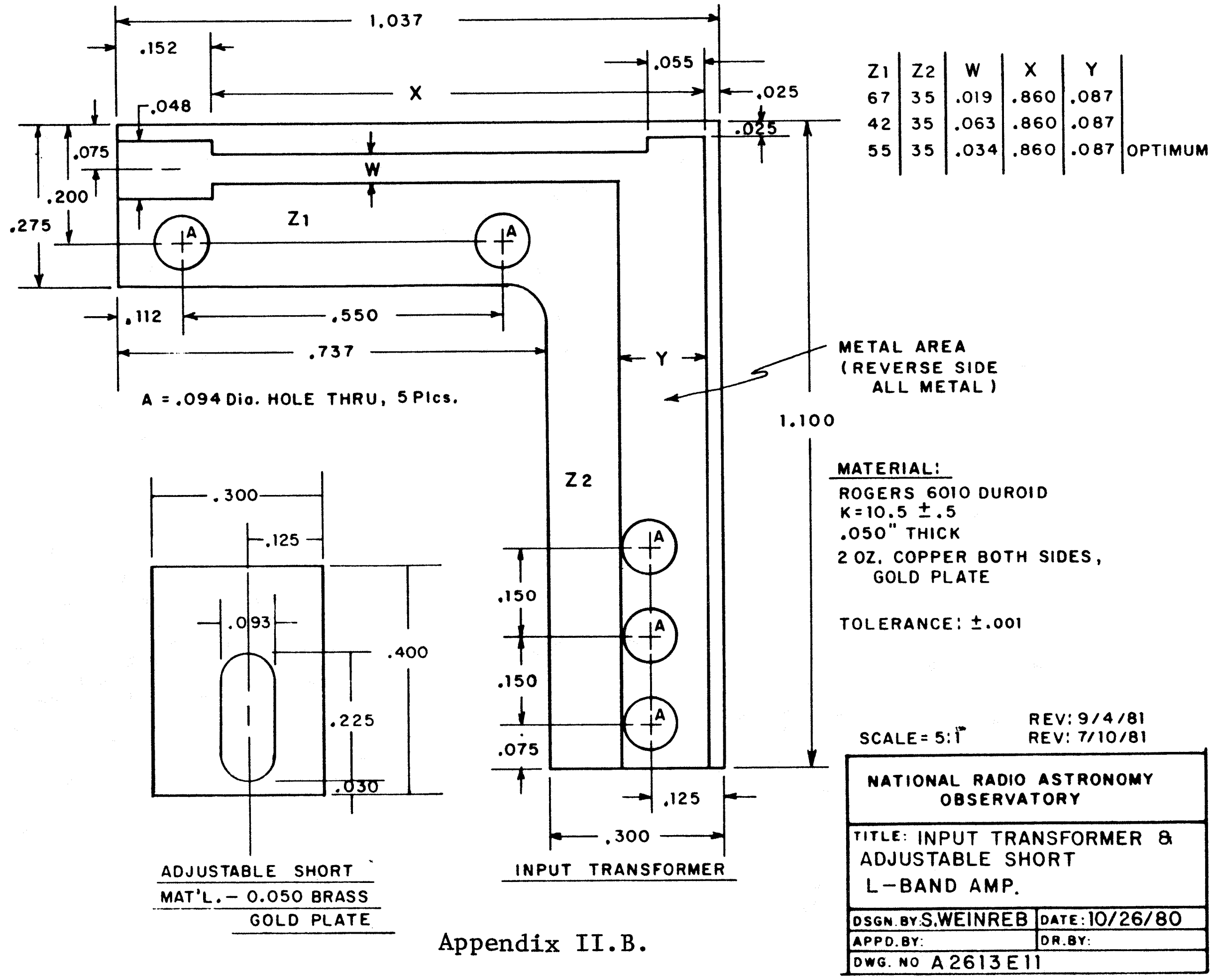
CONSTANT CURRENT FET SUPPLY
SYSTEM USE, 3 STAGE, WITH REMOTE
GATE VOLTAGE MONITOR & GAIN ADJUST

REV: 9/81

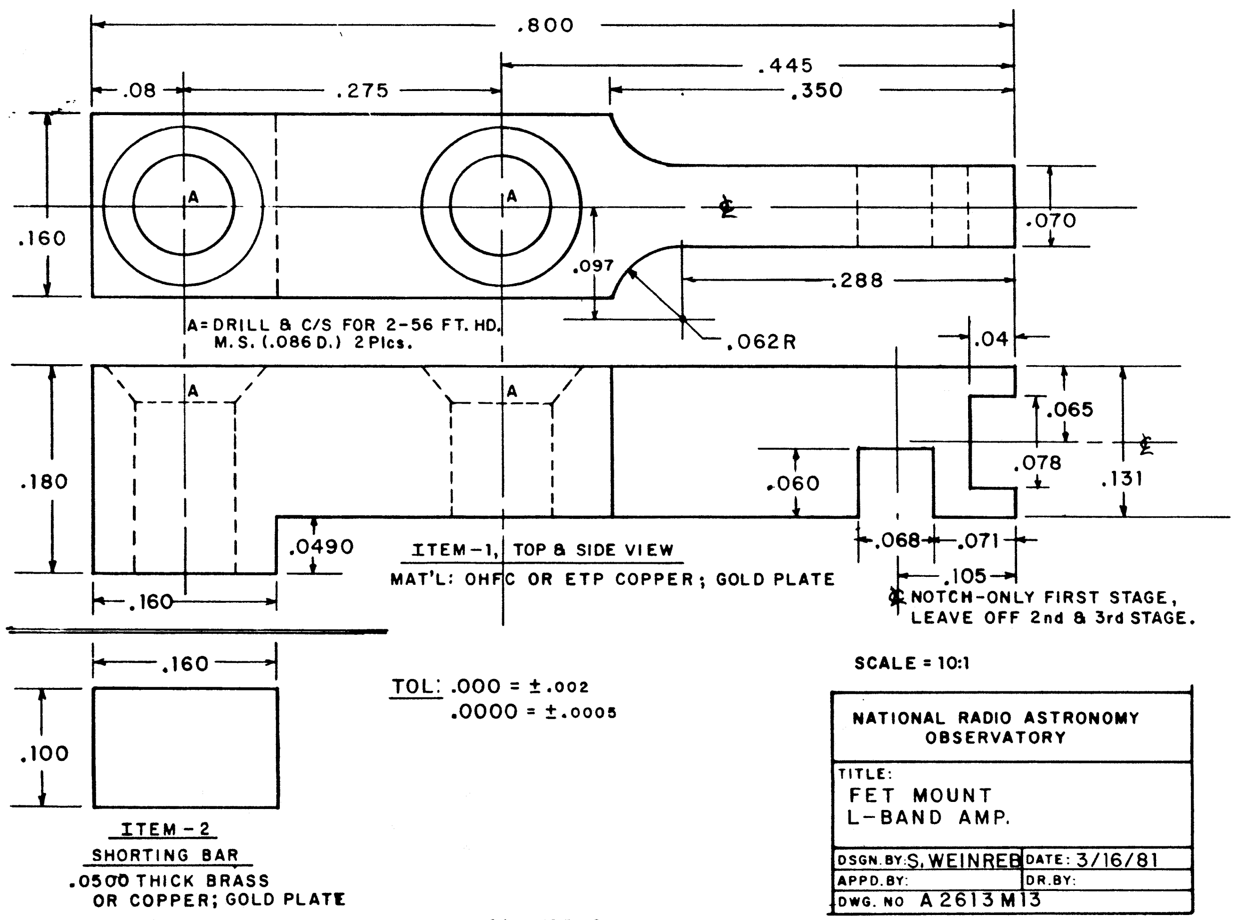
NATIONAL RADIO ASTRONOMY OBSERVATORY	
TITLE: DC BIAS REGULATOR	
DSGN. BY: S. WEINREB	DATE: 6/19/80
APPD. BY:	DR. BY:
DWG. NO. A2613 E16	



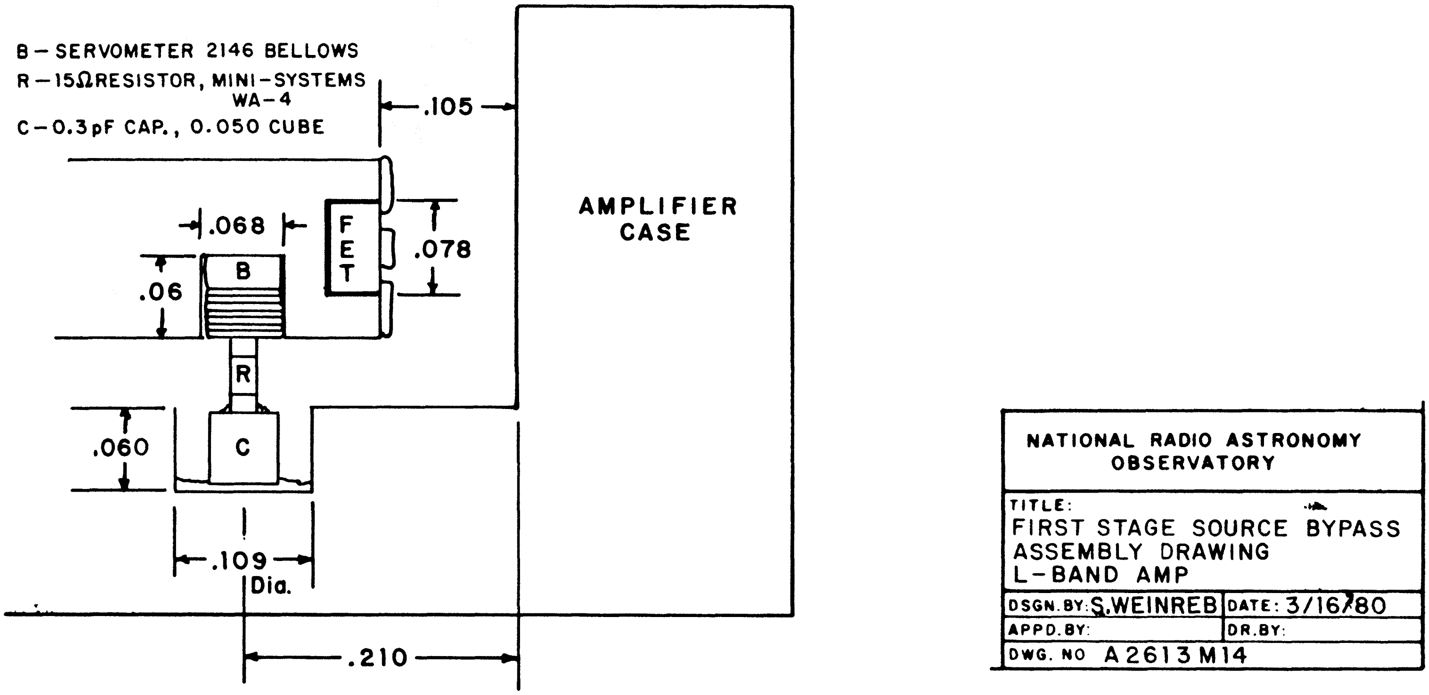
Appendix II.A



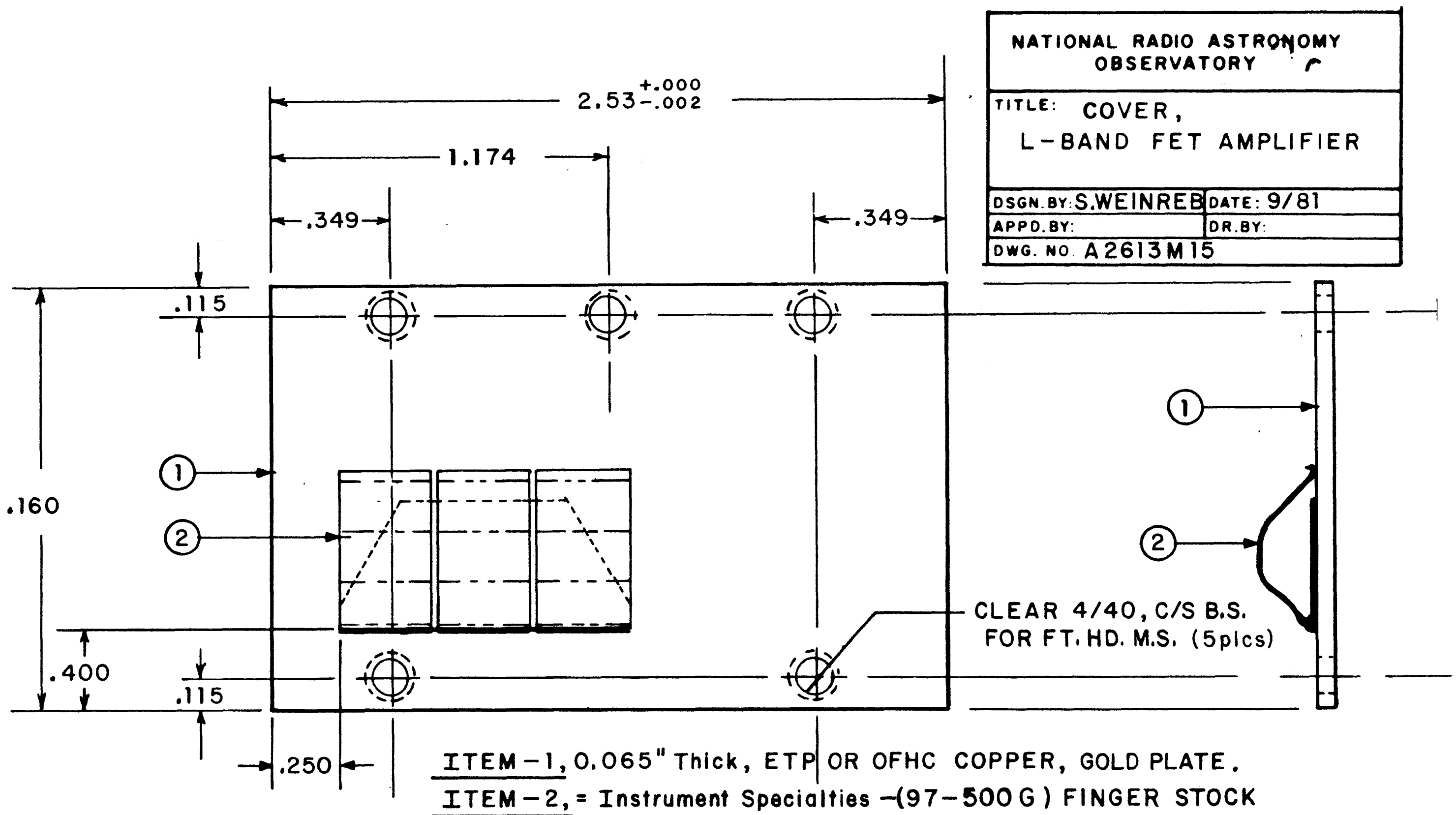
Appendix II.B.



Appendix II.C.



Appendix II.D



Appendix II.E

PARTS LIST L-Band FET Amplifier DATE 9/3/81 REVISION

ITEM	QUANTITY	REF. DESIG.	DESCRIPTION	MFG.	PART NUMBER
1	1		Chassis	NRAO	A2613M12
2	1		Cover	NRAO	A2613M15
3	1		Input Short	NRAO	A2613E11
4	3		FET Mount and Ground Shim	NRAO	A2613M13
5			Finger Stock Material	Instrument Specialties	97-500G
6			Microwave Absorber	Emerson-Cumming	MF-124
7	4		Toroid	Micro-Metals	T10-6
8	1		Bellows	Servometer	2146
9	1		Microwave Circuit Board, E=10.5, .050" dielectric, 2 oz. 2 side copper	Rogers	6010-.050
10	5		4-40 x 1/4" Flat Head Screw, S.S.	All-Metal Screw Products	
11	6		2-56 x 1/4" Flat Head Screw, S.S.	All-Metal Screw Products	
12	10		2-56 x 1/8" Binding Head Screw, S.S.	All-Metal Screw Products	
13	1		2-56 x 1/4" Binding Head Screw, S.S.	All-Metal Screw Products	
14	2		SMA Female Flange Connector	Omni-Spectra	204-CC
15	1		7-Pin Power Connector	Micro-Tech	ER-7S-6

PARTS LIST L-Band FET Amplifier DATE 9/3/81 REVISION

ITEM	QUANTITY	REF. DESIG.	DESCRIPTION	MFG.	PART NUMBER
16			Solder, B20E2, .032 diameter	Alpha Metals	B20E2-.032
17			Solder, 60/40, Rosin Flux	Ersin	Sn60
18			Solder, 100% Indium	Indium Corp.	Indalloy 4
19			Solder, 2% Silver	Ersin	Sn62
20			Flux, Supersafe	Superior Flux & Mfg.	#30
21			Flux, Rosin Liquid	Kester	#1544
22			Hookup Wire, #30 Enamel	Belden	8055
23			Hookup Wire, Tinned #24	Belden	8022
24			Wire, Phosphor-Bronze, .008" dia., gold-plated	California Fine Wire	
25			Wire, #32 Copper	Any	
26	1		Attenuator, Chip, 10 dB	KDI Pyrofilm Corp.	PCAW-10
27	2	Q1, Q2	FET	Mitsubishi	MGF-1412
28	1	Q3	FET	Mitsubishi	MGF-1402
29	12	C13 thru C24	Chip Capacitor, 680 pf, 100 mil	ATC	ATC-100-B-681-K-P
30	5	C7, C8, C9 C11, C12	Chip Capacitor, 22 pf, 100 mil	ATC	ATC-100-B-220-M-P

PARTS LIST L-Band FET Amplifier DATE 9/3/81 REVISION

ITEM	QUANTITY	REF. DESIG.	DESCRIPTION	MFG.	PART NUMBER
31	3	C2, C3, C4	Chip Capacitor, 16 pf, 50 mil	ATC	ATC-100-A-160-K-P
32	2	C1, C10	Chip Capacitor, 22 pf, 50 mil	ATC	ATC-100-A-220-K-P
33	2	C5, C6	Chip Capacitor, 1 pf, 50 mil	ATC	ATC-100-A-1R0-B-P
34	1	C25	Chip Capacitor, .3 pf, 50 mil	ATC	ATC-100-A-0R3-B-P
35	2	R1, R2	Chip Resistor, 50 ohm	Mini-Systems	WA4PG-500J-S
36	1	R9	Chip Resistor, 15 ohm	Mini-Systems	WA4PG-150J-S
37	3	R6, R7, R8	Resistor, 1000 ohm	Corning	RLR05C-1001-FR
38	2	R3, R4	Resistor, 49.9 ohm	Corning	RLR05C-49R9-FR
39	2	R5, R10	Resistor, 100 ohm	Corning	RLR05C-1000-FR
40	3	CR1, CR2, CR3	Diode, Zener	Motorola	1N4099
41	3	CR4, CR5, CR6	Diode, Zener Reference	Motorola	1N821

VENDOR LIST

Manufacturer/Vendor

All Metal Screw Products
9051 Baltimore National Pike
Ellicott City, MD 21043
(301) 461-3434

Alpha Metals/Q. C. Electronics
16 Highwood Avenue
Englewood, NJ 07631
(201) 569-0975

American Tech Ceramics (ATC)
1 Norden Lane
Huntington Station, NY 11746
(516) 271-9600

Belden/Virginia Radio Supply
715 Henry Avenue
Charlottesville, VA 22901
(304) 296-4184

California Fine Wire
P. O. Box 446
Grover City, CA 93433
(805) 489-5144

Corning/Milgray-Washington
11820 Parklawn Drive
Rockville, MD 20852
800-638-6656

Emerson-Cuming
59 Walpole Street
Canton, MA 02021
(617) 828-3300

Ersin/Techni-Tool, Inc.
5 Apollo Road
Plymouth Meeting, PA 19462
(215) 825-4990

Indium Corp. of America
1676-1680 Lincoln Avenue
Utica, NY 13502
800-448-9240

Instrument Specialties
P. O. Box A
Delaware Water Gap, PA 18327
(717) 424-8510

Manufacturer/Vendor

KDI Pyrofilm Corp.
60 S. Jefferson Road
Whippany, NJ 07981
(201) 887-8100

Kester/Virginia Radio Supply

Micro Metals
1190 N. Hawk Circle
Anaheim, CA 92807
(714) 630-7420

Micro Tech, Inc.
1420 Conchester Highway
Boothwyn, PA 19061
(215) 459-3566

Mini-Systems, Inc.
20 David Road
North Attleboro, MA 02761
(617) 695-0203

Mitsubishi Electronics/America, Inc.
1230 Oakmead Parkway, Suite 206
Sunnyvale, CA 94086
(408) 730-5900

Motorola/Hamilton Avnet
6822 Oak Hall Lane
Columbia, MD 21045
800-638-1772

Omni-Spectra
21 Continental Boulevard
Merrimack, NH 03054
(603) 424-4111

Rogers Corp.
P. O. Box 700
Chambler, AZ 85224
(602) 963-4584

Servometer Corp.
501 Little Falls Road
Cedar Grove, NJ 07009
(201) 785-4630

Superior Flux & Mfg. Co.
95 Alpha Park
Cleveland, OH 44143
(216) 461-3315