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X-BAND SOLID STATE SIGNAL SOURCE

SPECIAL REPORT

15 JANUARY 1965

Contract NAS8-5205
(Modification No. 6)
Prepared for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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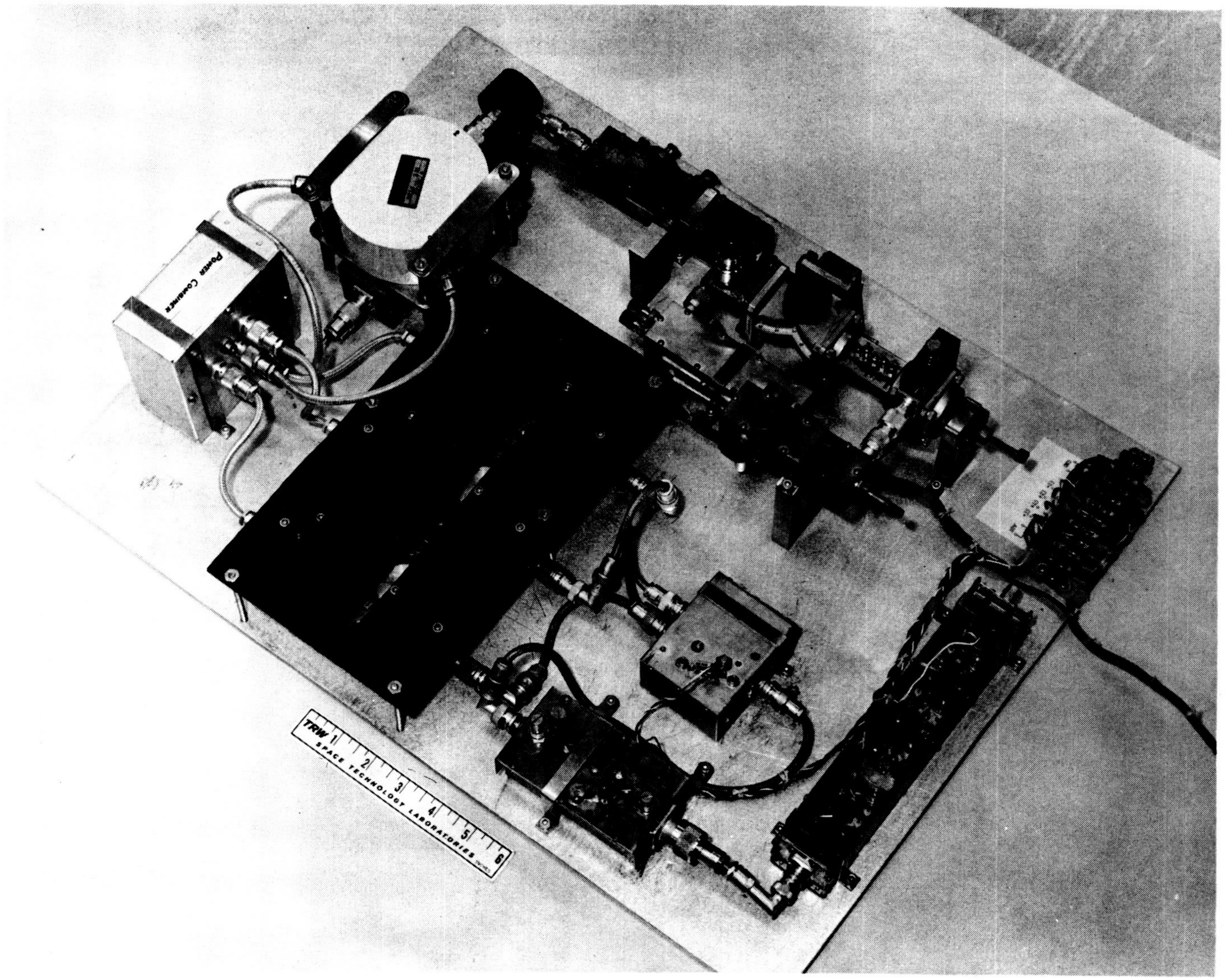

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X-Band Solid State Signal Source

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1. INTRODUCTION AND SUMMARY

1.1 BACKGROUND

During the years intervening since the feasibility of all solid-state microwave sources was first demonstrated, continued effort has been directed toward obtaining greater amounts of r-f power at ever increasing frequencies. To date, the solid state device most suited for use in obtaining these higher power levels is the varactor. Other devices such as the charge-storage, or snap-off, diode have various advantages in the generation of lower levels of r-f power; however, none are known that are equivalent to varactors in obtaining the higher levels of microwave power at maximum efficiencies.

More recently, varactor technology has reached a point where it has become feasible to generate a watt or more of r-f power at X-band frequencies. Probably the single most significant factor that has contributed to the higher performance of varactors has been an improved package type that permits a greatly reduced thermal resistance between the varactor junction and varactor case. Because varactor efficiency normally decreases as its junction temperature increases, the lower thermal resistance permits high efficiencies to be maintained while relatively large amounts of r-f power are being dissipated in the junction. Junction heating is regenerative in that it causes lower efficiencies which in turn causes greater heat dissipation. For this reason, the significance of low thermal resistance to high power operation is great.

Another major factor contributing to high power varactor signal source operation has been the development of circuit techniques whereby more than one varactor may be used in parallel. Many advancements have been made in this area for varactor frequency multipliers operating below L-band; comparable strides had not been made at the higher frequencies. It is in this latter area that significant contributions have been made as a result of this program — a series of balanced frequency doublers, each employing two varactors, has been developed to operate through X-band; efficiencies closely approaching theoretical limits have been achieved.

1.2 REVIEW OF PROJECT TASKS AND SUMMARY

The design and development of the Solid State X-Band Signal Source was accomplished in fulfillment of Contract NAS 8-5205, Modification 6, dated 18 May 1964. The objective of the contract was to design, develop, fabricate, test, and deliver a working model of a solid state X-band signal source having an output of approximately one watt insofar as this could be accomplished with currently available components. The period of performance was to be approximately seven months.

The project was accomplished using catalog listed components such as varactors and transistors in circuits employing advanced techniques. A ground rule followed in the selection of applicable varactors, for example, was that they be of a type available from at least two different manufacturers. This tended to preclude the use of unproven "breakthrough" devices, many of which have appeared on the market recently. It is our experience that greater success has been attained using devices of certain manufacturers and advantage was taken of this fact in making the selection of varactors to be used.

In addition to the use of varactors of repute, circuits of advanced design are needed to ensure maximum output and reliability of performance. In this regard, new circuit techniques were developed for the frequency doublers operating from L-band through X-band. These coaxial and waveguide multiplier circuits were synthesized from low frequency balanced networks employing dual active elements, and displayed those advantages usually associated with balanced circuits; that is, frequency separation by symmetry, doubled power handling capability, and less susceptibility to input and output line impedance fluctuations. Because similarly configured circuits had not been seen elsewhere, patent disclosures were submitted for each of the frequency doublers operating from 1.3 gc through 10 gc.

The optimum location of the power amplifier within the multiplier chain was carefully analyzed at the beginning of the program, and the decision was made to operate at 324 Mc in order to achieve a higher overall efficiency and to maintain the lowest possible power dissipation in each of the active devices. A RCA transistor having the requisite performance characteristics had been in production for some months and was selected for use in the amplifier. Two or three other transistor types are being developed which will have superior characteristics relative to the requirements and are expected to be available by early 1965. At the time of contract initiation, TRW Semiconductors was developing a transistor to provide an output of greater than 10 watts at 324 Mc; this unit was to be available during the latter part of 1964. It was thus surmised that optimum potential existed for the solid state source if the power amplifier operated near 300 Mc rather than at the 100 to 200 Mc level as is currently popular. The analysis showing the advantage of operating at 324 Mc is presented in Section 2.

A summary of the X-Band Solid State Signal Source operating characteristics is shown in Table 1. This data was taken in an ambient temperature environment of approximately 25^{O}C.

Table 1. X-Band Solid State Signal Source Operational Characteristics

Input Signal Frequency	108 Mc
Input Signal Power Level	0 dbm
Output Signal Frequency	10, 368 Mc
Output Signal Power Level	30 dbm
Multiplication Factor	96
Overall d-c to r-f Efficiency	1. 05 percent
r-f Bandwidth	0. 42 percent
Spurious Level	$>$ 25 db below the carrier

Temperature tests were performed on the two highest frequency doublers of the signal source. Limited testing was performed on the S- to C-band frequency doubler; the results displayed a change in the output power of 0.55 db when the ambient temperature was varied from -45 to +71^{O}C. Fairly extensive temperature tests were performed under NAS 9-2938 for the Manned Spacecraft Center on a reproduction of the C- to X-band doubler and a report entitled "Temperature Study of Varactor Diodes" prepared. Results of this temperature test indicated a variation of 0.5 to 0.6 db for a varactor case temperature variation of -39 to +72^{O}C. None of the remaining submodules was temperature tested.

The personnel at TRW Space Technology Laboratories responsible for the design and development of the submodules comprising the X-Band Solid State Signal Source were as follows:

Mr. R. Steinberg assisted by Messr. P. Quartarolo and R. Pitcher	X3/Power Amplifier
Mr. J. Habra assisted by Messrs. B. Gililland and F. Fowler	324 Mc to 10.4 gc Frequency Doubler Circuits
Mr. A. B. Blau assisted by Mr. F. Fowler	Low Loss Circulator and Bandpass Filter

2. DESCRIPTION OF EQUIPMENT

2.1 INTRODUCTION

This section presents a discussion of the arrangement and power budget of the submodules comprising the X-band Solid State Signal Source and of the design, development, and test results of each submodule. Schematics, photographs, and component descriptions are provided so that a complete understanding of the equipment can be attained.

A block diagram of the solid state signal source showing the signal powers and frequencies at various points of the system is present in Figure 1. The power levels predicted at the beginning of the program, and those actually obtained are each shown to provide some insight into first, the accuracy of the various efficiency relationships presented later in this section, and second, the extent to which the performance of the various doublers can be improved by further circuit refinements. For example, it is apparent that all but two of the frequency doublers have efficiencies within a few tenths of one db of the theoretical value. The conversion loss of the 0.648 to 1.3 gc frequency doubler exceeds the predicted value by over 1 db and also is more than 1 db higher than would be expected by interpolating the efficiencies of the adjacent doublers. This would indicate that the unit is excessively lossy and could be improved by about 1.5 db. This improvement could result in either a correspondingly higher output, or about a 1.0 to 1.5 db decrease in prime power as the power amplifier output may be decreased accordingly.

The conversion efficiency of the C- to X-band doubler exceeds the theoretical value by over 1 db. This indicates that an assumption made in connection with the conversion loss equations was incorrect, specifically that the constant relating the degree to which the varactor was driven was pessimistic, or that the thermal resistance of the varactor was lower than anticipated.

The three section bandpass filter originally intended for inclusion in the multiplier chain was omitted when it was found that its use contributed negligibly to the spurious signal rejection. The largest amplitude spurious signals measured at the output were displaced approximately ±30 Mc from the carrier and were about 25 db down from the carrier.

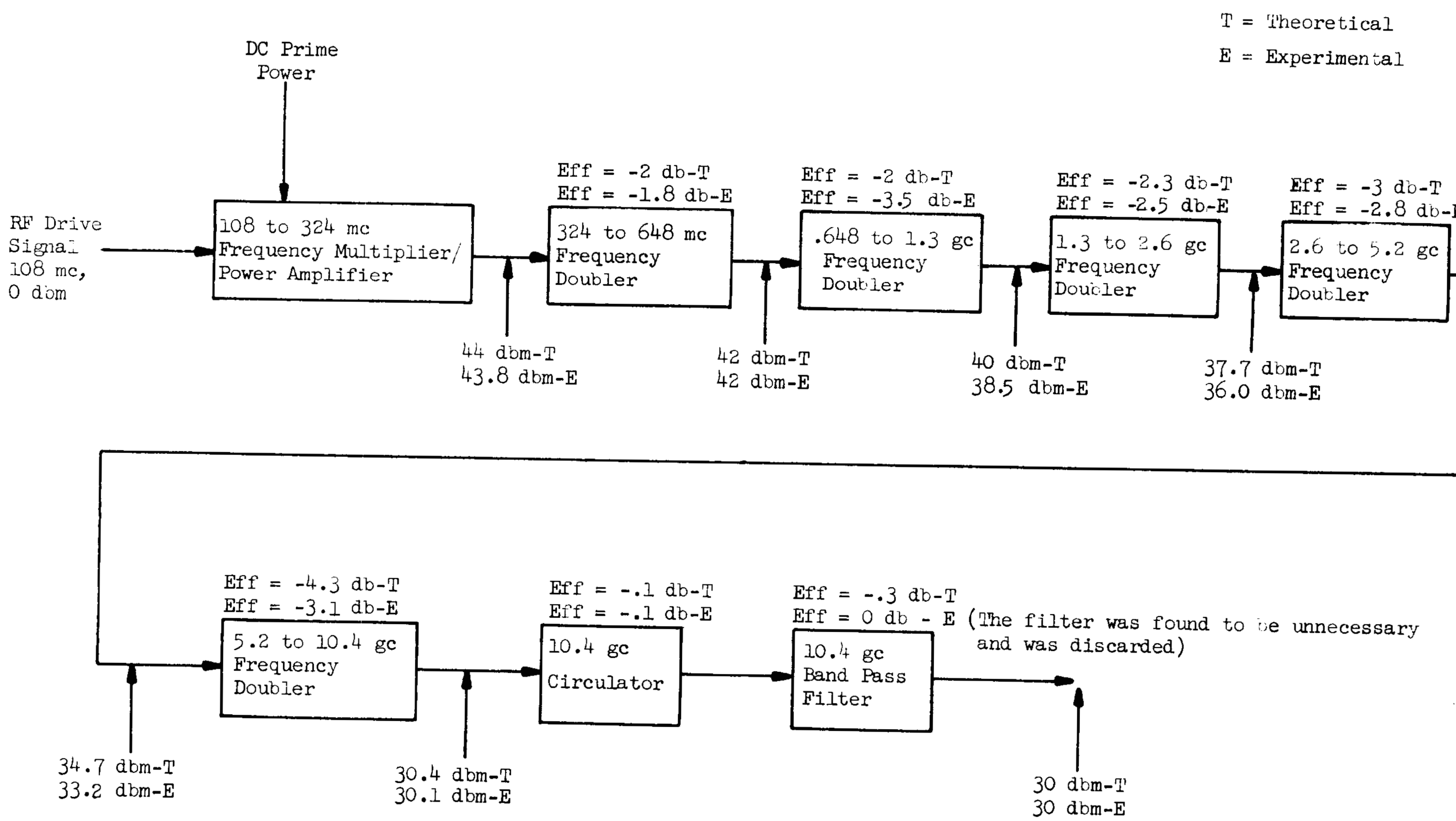

Figure 1. X-Band Solid State Signal Source Block Diagram

These were within the passband of the filter and hence were not appreciably attenuated. The filter had a subsidiary passband near twice its design center frequency as it offered little rejection to signals near 20 gc, which were about 44 db below the carrier. At half the output frequency, the filter would be an aid in further attenuating the spurious signals already about 33 db down; however, a short length of X-band waveguide would accomplish the same function and would probably be used with the signal source.

The next sections present the analyses performed on the blocks indicated in Figure 1. The presentation commences with the 108 to 324 Mc Frequency Multiplier and Power Amplifier.

2.2 108 TO 324 Mc FREQUENCY MULTIPLIER/AMPLIFIER

2.2.1 Module Arrangement for Maximum Efficiency

One of the main objectives in the design of the 1-watt, X-band, solid-state signal source was to obtain the highest possible d-c to r-f conversion efficiency so as to minimize the power consumption if used in a space mission. An analysis was prepared to aid in determining the optimum placement of the power amplifiers in the X-band signal source multiplier chain. In summary, the analysis indicated the power amplifiers should be placed at the highest frequency at which the individual transistors of the amplifier could furnish a minimum gain of 5 db and possess a minimum power conversion efficiency of approximately 0.45. When these criteria are imposed on the RCA 2N3375 transistors used in the power source, they result in the placement of the power amplifiers at the output of the varactor multiplier tripler, i.e., at 324 Mc.

The technique followed to determine the optimum placement of the power amplifier was to calculate the overall efficiencies of the frequency tripler/amplifier section for three different arrangements, each consisting of three amplifiers and one frequency tripler. Each of the amplifiers was assumed to possess the same efficiency, defined as the r-f output power divided by the d-c input power, and thus the same number of amplification stages. The efficiency of each amplifier was assumed independent of the two frequencies involved; this is obviously not true, however, the errors introduced do not change the conclusions. The three submodule arrangements, or cases, considered are as follows:

a) All transistor amplifiers are located before the varactor multiplier chain at 108 Mc, Figure 2.

b) Only the final power amplifier stage is located after the varactor tripler at 324 Mc, Figure 3.

c) The driver amplifier and power amplifier stages are located after the varactor tripler, Figure 4.

<u>Case 1</u>

Assume that the three amplifiers precede the frequency tripler, Figure 2, and that each amplifier has a power conversion efficiency of η_o. The power required from the d-c supply is

$$P_{d-c} = \frac{P_{pa} + P_d + P_a}{\eta_o}$$

where

P_{pa} = Output power of the power amplifier

P_d = Output power of the driver amplifier

P_a = Output power of the amplifier preceding the driver

In terms of the power delivered at the output frequency, P''_o

$$P_{d-c} = \frac{\frac{P''_o}{L} + \frac{P''_o}{LG'_p} + \frac{P''_o}{LG'_p G'_d}}{\eta_o}$$

where

L = Varactor multiplier conversion efficiency

G'_p = Gain of the power amplifier

G'_d = Gain of the driver amplifier

The overall power efficiency, η_{t_1}, at the output frequency for this case is

$$\eta_{t_1} = \frac{P''_o}{P_{d-c}} = \frac{\eta_o}{\frac{1}{L} + \frac{1}{LG'_p} + \frac{1}{LG'_p G'_d}} = \frac{LG'_p G'_d \eta_o}{G'_p G'_d + G'_d + 1}$$

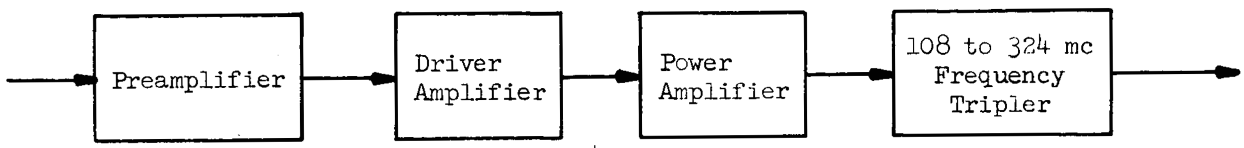

Figure 2. Case 1—Determination of Power Amplifier Location

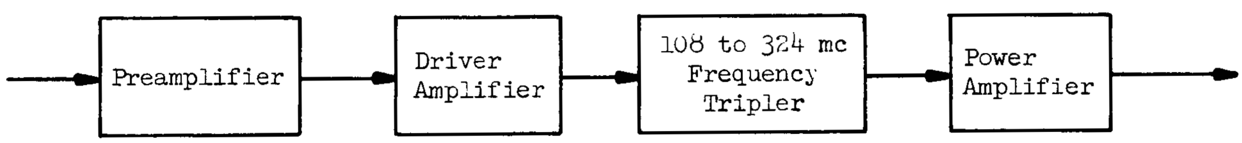

Figure . Case 2—Determination of Power Amplifier Location

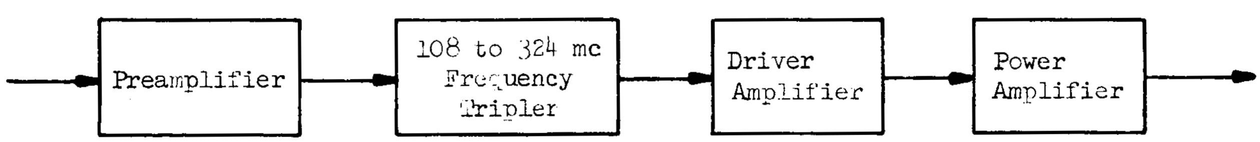

Figure 4. Case 3—Determination of Power Amplifier Location

This can be approximated by

$$\eta_{t_1} \cong L\eta_o,$$

since L is less than 1, and G'_p and G'_d are each normally greater than 10.

Case 2

In a similar way, it can be shown that the overall power efficiency for Case 2, Figure 3

$$\eta_{t_2} = \left[\frac{1}{1 + \frac{1}{G''_p L} + \frac{1}{LG''_p G'_d}}\right]\eta_o$$

$$= \left[\frac{G''_p G'_d L}{G''_p G'_d L + G'_d + 1}\right]\eta_o,$$

where the double primes indicate the output frequency power gain.

Case 3

The overall power conversion efficiency for Case 3, Figure 4, is

$$\eta_{t_3} = \frac{\eta_o}{\left[1 + \frac{1}{G''_p} + \frac{1}{G''_p G''_d L}\right]}$$

$$= \left[\frac{G''_p G''_d L}{G''_p G''_d L + G''_d L + 1}\right]\eta_o$$

Upon inspection of the efficiency expressions for the different cases, it is evident that the overall efficiency for Case 2 and 3 approaches the efficiency of the last stage as the gain of the last stage increases. This would indicate that as transistors become available with gains greater than 10 db at 322 Mc, the overall efficiency of the power amplifier/ frequency tripler section could approach 50 percent or more. This, of course, assumes an efficiency of the last stage of 50 percent, which should be typical, and a tripler conversion loss in the neighborhood of 2.5 db, which is also believed typical.

The expression for Case 1, on the other hand, indicates that the overall efficiency is limited to the product of the efficiency of the tripler and of the amplifier preceding it, again assuming a gain of 10 db or more for the amplifier. A realistic limit for overall efficiency in this case is about (0.6)(0.562) = 0.34 assuming a typical amplifier efficiency of 60 percent and a tripler efficiency of 0.562 (= -2.5 db).

At the present time, the best known transistor that is considered a shelf item only has a gain of about 5 db at 324 Mc. Based upon the fact that the power gain of a single transistor amplifier operating in the ultra-high frequency spectrum region falls off at a rate of 6 db per octave, the gain of this same transistor at one-third the frequency would be about 10 db higher, or 15 db. If the efficiencies of Case 1, 2, and 3 were calculated using this transistor, and assuming an amplifier efficiency of 50 and 60 percent at 324 Mc and 108 Mc, respectively, the overall efficiencies would be approximately equal. It should be noted that the numerical difference in efficiencies at 108 Mc and 324 Mc would be probably less than 10 percent, thus indicating a slightly higher overall efficiency for Case 2 and 3 than for Case 1.

In summary, as the gain of available transistors increases above 5 db, the advantages of configuring the amplifier/tripler as Case 2 or 3 becomes more pronounced, irrespective of the amplifier efficiency at 108 Mc being slightly greater than at 324 Mc.

At this time, the RCA 2N3375 silicon N-P-N planar transistor is the only known "off the shelf" solid state device that can furnish the gain and the minimum power conversion efficiency required for a power amplifier operating at 324 Mc. As an unneutralized Class C power amplifier with a gain of about 5 db, the output power capability of this transistor exceeds 4 watts.

The block diagram of the X-band power source through 324 Mc, as illustrated in Figure 5, is arranged for maximum efficiency, according to the analysis and for minimum power dissipation in any one active device. Directly paralleling more than two transistors at a time is cumbersome, hence, the technique of paralleling the final amplifiers was adopted. A photograph of this section of the solid state signal source is shown in Figure 6.

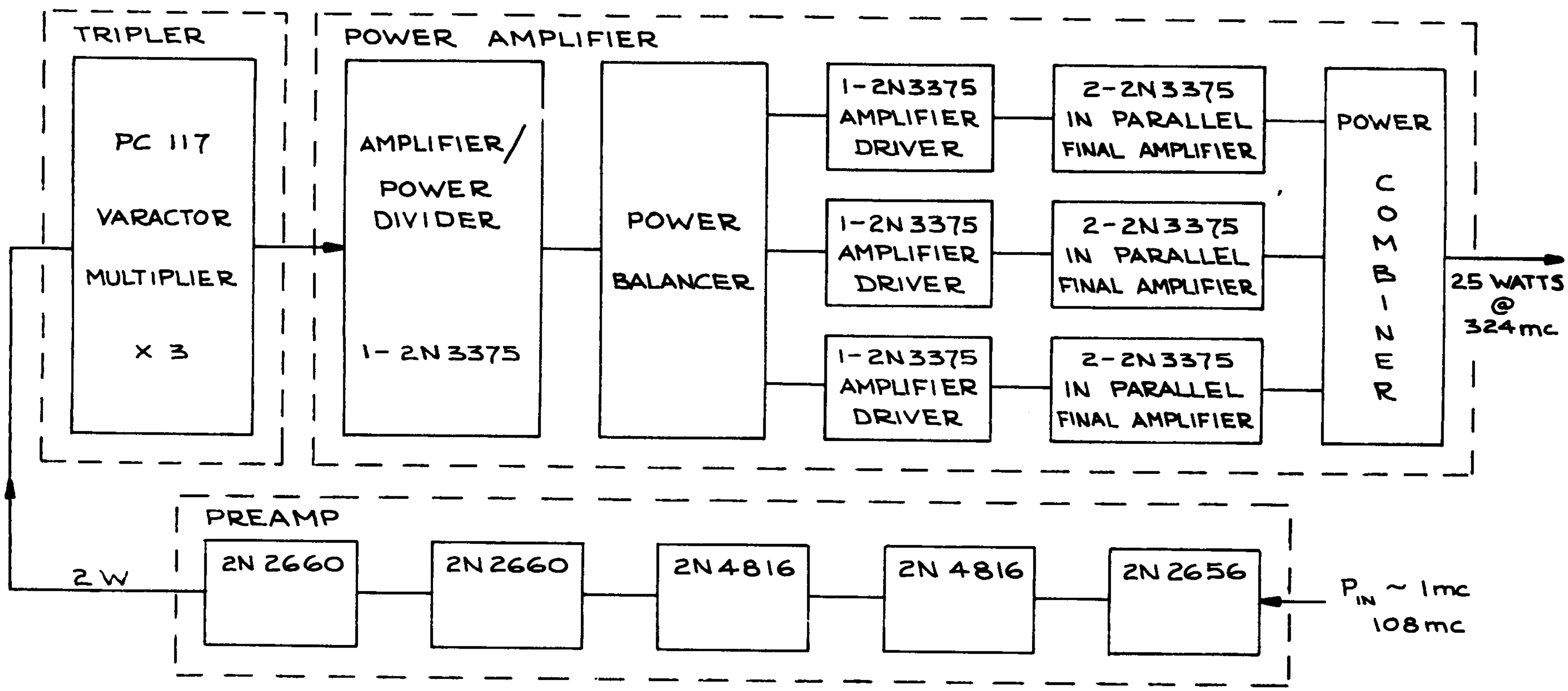

Figure 5. Block Diagram of the UHF Component Configuration for the X-Band Solid State Signal Source

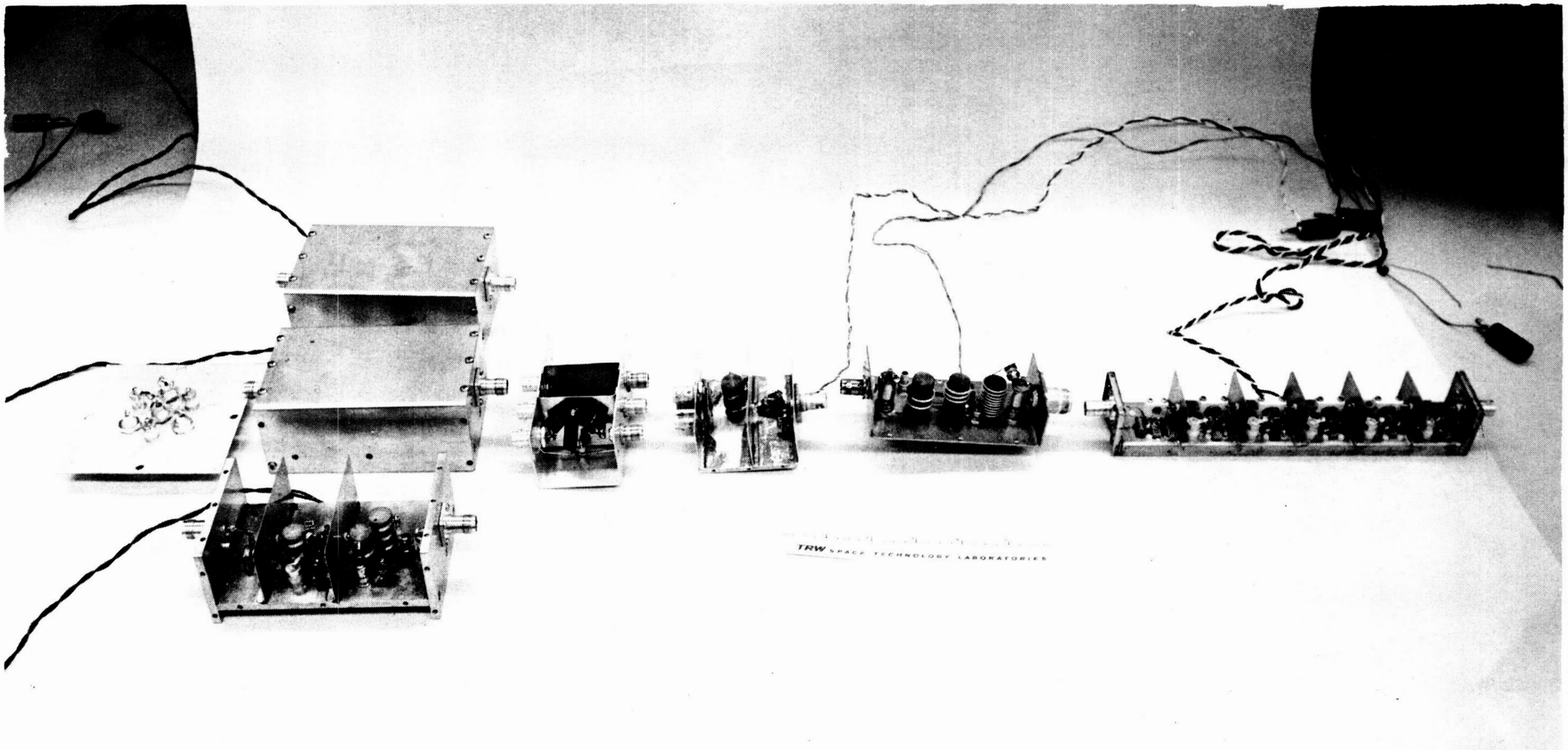

Figure 6. Power Amplifier Section, X-Band Solid State Signal Source

The gains and output power levels of each of the units were slightly over-designed to minimize the effects of interface degradation that might have occurred when the units were interconnected. A margin of safety against component parameter variation with age and replacement was also furnished in this manner. All amplifiers employ the common emitter configuration which provides the most gain for a given stability factor against regeneration. In addition, all amplifiers are implemented with interstage shielding.

2.2.2 Preamplifier Design and Development

As illustrated in the block diagram, Figure 5, the preamplifier furnishes approximately 2 watts to the X3 varactor multiplier when driven from a 1 milliwatt 108 Mc source. The preamplifier uses one 2N2656, two 2N4816, and two 2N2660 transistors connected in cascade (see Figure 7).

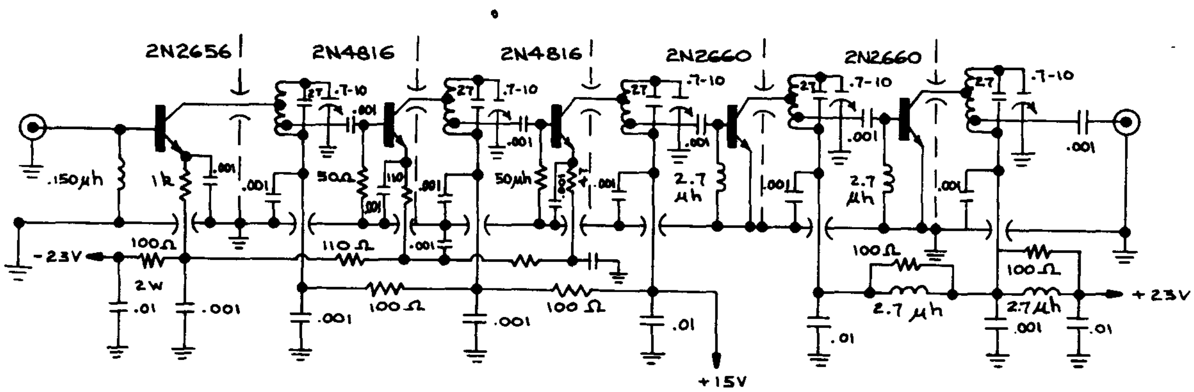

Figure 7. Schematic Diagram, 2 watt, 108 Mc Preamplifier

The 2N2656 is biased for class "A" operation and provides approximately 10 db gain. The collector dissipation is about 150 mw whereas the allowable dissipation at 25°C free air ambient is 360 mw. Since the case is heat sinked to the chassis, the transistor power dissipation derating factor exceeds two. The base of the 2N2656 transistor is connected to ground through a 50-ohm resistor to maximize the stability of the amplifier stage against oscillations. The preamplifier second and third stages make use of a PT4816 PSI transistor which is rated at 800 mw power dissipation at 25°C free air ambient, or 3 watts for a case temperature of 25°C.

The power rating at free air ambient assumes that no heat sink is provided, all cooling being by radiation from the transistor case. The power rating at 25°C case temperature assumes that the case temperature is always maintained at a temperature of 25°C via a suitable heat sink. The d-c current drawn by each transistor is approximately 35 ma, causing a collector dissipation of 520 mw. The transistors are heat sinked to the chassis and are therefore derated by a factor of two or more. A 50-ohm resistor is connected from the base to ground of each transistor; this is used in preference to a choke for enhancing the stability of the stages against oscillation.

The last two stages of the preamplifier employ PT2660 PSI transistors. For a case temperature of 25°C the transistors are rated at 10 watts power dissipation each and 1 watt at 25°C free air ambient, providing a power dissipation derating factor in excess of two.

The preamplifier has been tested and operated over long periods of time with good results. Changing the bias on the amplifiers for the purpose of increasing the amplifier gain has not resulted in regenerative behavior of the amplifier. A photograph of the preamplifier is shown in Figure 8.

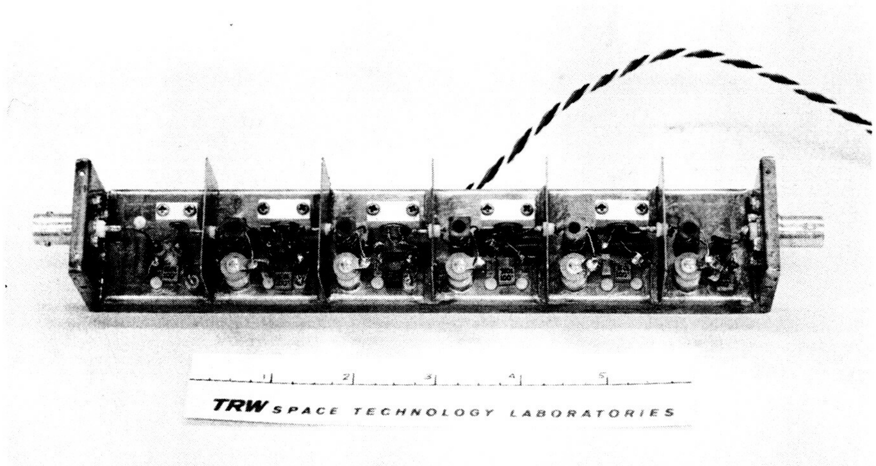

Figure 8. Working Model, 2 watt, 108 Mc Preamplifier

2.2.3 108 to 324 Mc Frequency Tripler

In designing the frequency tripler following the preamplifier, consideration was given to the fact that with a transistor multiplier, the base-emitter junction acts in some respects as a diode multiplier with the resulting signal amplified in a normal way. The conversion efficiency of diodes is generally less than that of varactors, thus it is more efficient to use a varactor multiplier and a transistor amplifier preceding or following it than employing a transistor multiplier directly. As a result, the low frequency tripler in the solid state signal source incorporates a varactor to perform the tripling process.

Because of the relatively low frequency at which the tripler operates and the comparatively low efficiency requirement (as previously noted the overall efficiency will be almost entirely determined by the last amplifier stages), an inexpensive readily available PC117 varactor was selected. The following analysis establishes the optimum drive power level, the conversion efficiency, the dissipated power, and the requisite input and output impedances of a frequency tripler employing this varactor.

The cutoff radian frequency, ω_c, of the PC117 varactor, is given by

$$\omega_c \triangleq \frac{S_{max} - S_{min}}{R_S} = \frac{10^{11} - 10^{10}}{0.5} = 1.8 \times 10^{11} \text{ rad/sec}$$

where

S_{max} = Maximum susceptance of the PC117

S_{min} = Minimum susceptance of the PC117

R_S = Equivalent series resistance of the PC117

For the design condition in which no forward bias current is drawn from the varactor at any portion of its cycle, the optimum varactor input power, P'_{in}, is

$$P'_{in} = 0.0242 \frac{\left(V_B - V_{min}\right)^2}{R_S} \times \frac{\omega_o}{\omega_c} = 1.68 \text{ watts}$$

where

V_B = Diode reverse bias breakdown voltage, 100 volts

V_{min} = Minimum reverse bias voltage reached during the fundamental frequency cycle, 0.5 volt

ω_o = Fundamental frequency, 678×10^6 rad/sec

The input impedance to the varactor at ω_o, R_{in}, is

$$R_{in} = 0.126 \frac{S_{max}}{\omega_o} = 18.5 \text{ ohms}$$

The output impedance at the third harmonic, R_3, is

$$R_3 = 0.168 \frac{S_{max}}{3\omega_o} = 8.26 \text{ ohms}$$

The power dissipated by the varactor

$$P_{diss} = 0.849 \frac{\left(V_B - V_{min}\right)^2}{R_S} \left(\frac{\omega_o}{\omega_c}\right)^2 = 0.24 \text{ watt}$$

The power output from the varactor is

$$P'_o = 1.68 - 0.24 = 1.44 \text{ watts}$$

At room temperature the PC117 is capable of handling 500 mw. Hence, the power derating factor is D = 500/240 = 2.08.

Assuming the output circuit efficiency $\cong$ 0.9, then the actual output power from the tripler will be

$$P_o \cong 1.44 \times 0.9 = 1.3 \text{ watts}$$

If the input circuit efficiency were also 0.9, then

$$P_{in} = \frac{P'_{in}}{0.9} = \frac{1.68}{0.9} = 1.87 \text{ watts}$$

Equivalent input and output circuits of the varactor for 108 Mc and 324 Mc, respectively, are shown in Figure 9.

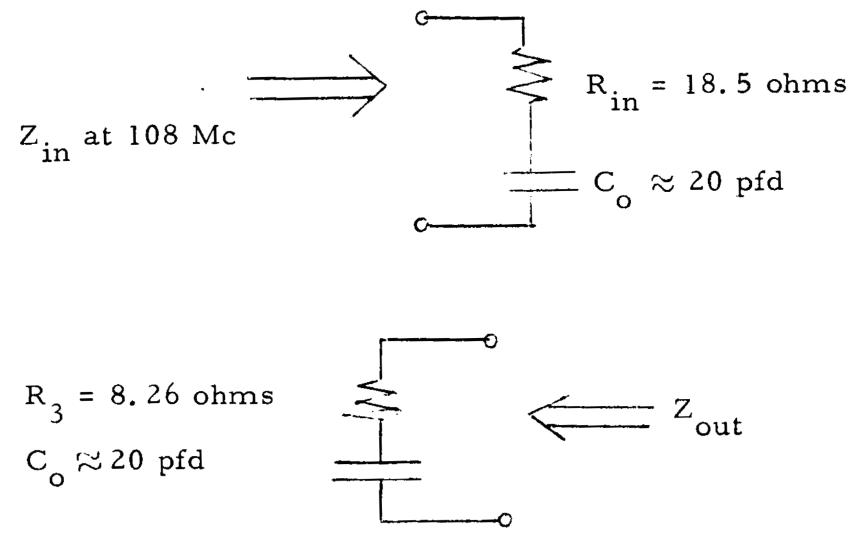

Figure 9. Equivalent Varactor Impedences

The circuits employed to match the input and output impedances of the varactor to 50 ohms are shown in the electrical schematic of Figure 10. The series resonant circuit across the varactor to ground is the idler circuit for the second harmonic.

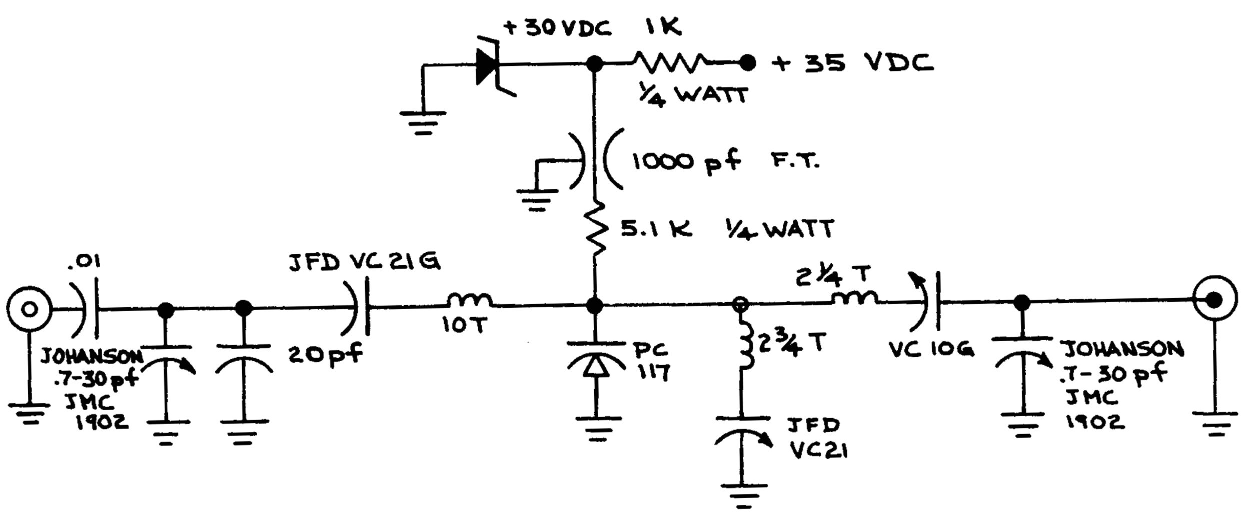

Figure 10. 108 To 324 Mc Varactor Multiplier

The measured multiplier characteristics closely matched the calculated performance. 1.2 watts was achieved from the varactor multiplier at a frequency of 324 Mc, working into a 50 ohm load, for an r-f drive of 2 watts at 108 Mc; this gave an overall conversion efficiency of 60 percent. A photograph of the frequency tripler working model is shown in Figure 11.

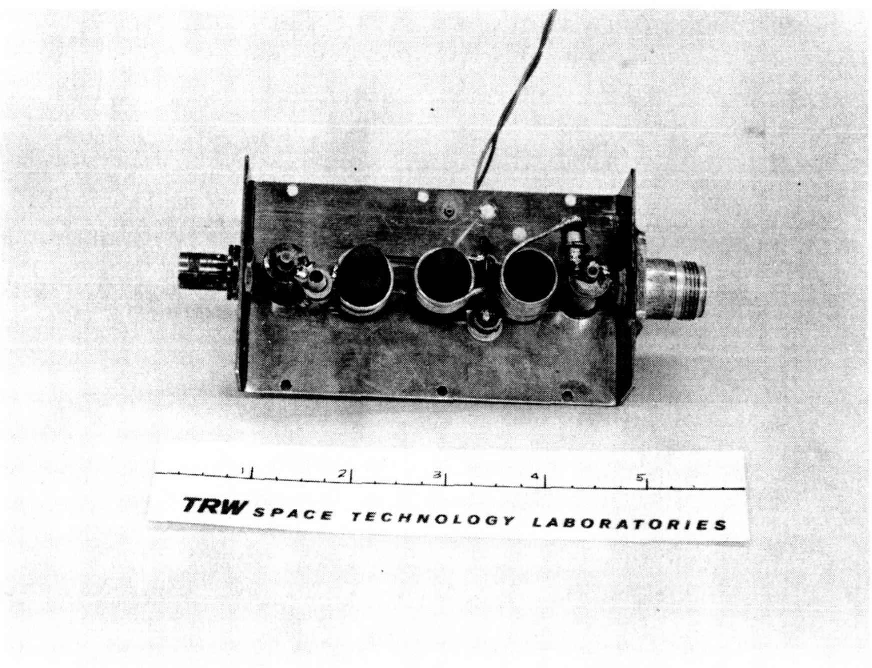

Figure 11. Working Model, 108 to 324 Mc Frequency Tripler

2.2.4 Power Amplifier

The power amplifier, shown in the block diagram of Figure 5, consists of an amplifier/power divider, a power balancer, three output power amplifiers, and a power combiner. Each of these sections of the power amplifier were individually packaged for the solid state signal source working model; however, they would be packaged as one submodule in a flight configuration.

The amplifier/power divider employs a single RCA 2N3375 power transistor in a common emitter configuration operating in the Class B mode. The power dissipation rating of this transistor at a case temperature of

25°C is 11.6 watts. The amplifier/power divider draws 200 ma or less from the 28 volt d-c supply and dissipates 3.6 watts or less; which is well within the rating of the transistor. The amplifier provides 1 watt into 50 ohms at each of its three outputs when driven from 1 watt source at an impedance level of 50 ohms.

The transistor input impedance of the amplifier/power divider approximate 13 ohms in series with an inductive reactance of about 8 ohms. This input impedance is transformed to a 50 ohm resistive impedance by the capacitor network at the base of the transistor, as illustrated in Figure 12. The collector capacitance of the transistor is resonated with the output coil. The output coil is also used to transform to 50 ohm load to about 140 ohms at the collector, the required value for maximum power conversion efficiency.

The amplifier driver stage driven by each output of the power divider has the same design as the amplifier/power divider. One watt into this stage furnishes 3 watts to the final stage of power amplification.

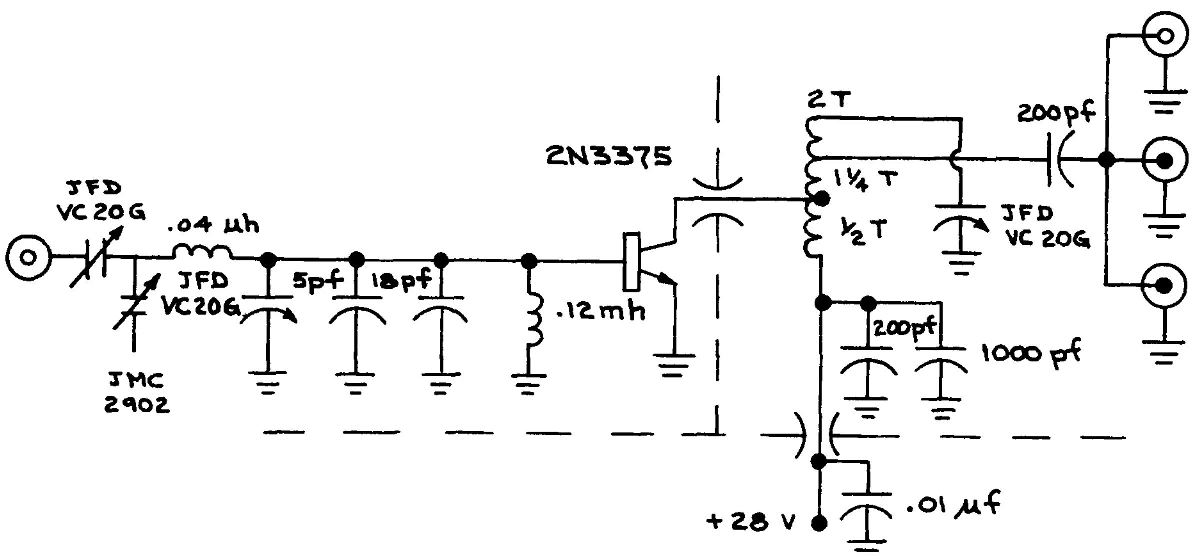

Figure 12. 2 Watt, 324 Mc Power Divider

Each of the three final stages of power amplification, Figure 13, makes use of two 2N3375 transistors connected in parallel to provide an output power of approximately 9 watts. Each transistor draws no more than 400 ma from the 28-volt d-c supply, hence the collector power dissipation is no greater than 8.2 watts per transistor which is within the transistor rating of 11.6 watts. The 50-ohm output load is transformed to reflect the optimum collector load impedance by use of a pi-matching network in the output circuit. A photograph of the final amplifier working model is shown in Figure 14.

TRW Semiconductors is developing a power transistor, expected to be available in sample quantities by mid-1965, that will be capable of delivering 10 watts at 500 Mc while displaying a 10-db gain and 50 percent collector efficiency. The use of this transistor would probably result in an overall amplifier efficiency exceeding 32 percent and would permit the volume of the flight packaged configuration to decrease to several cubic inches. The power divider and combiner would be eliminated, since only 2 transistors operating in parallel would be capable of providing the required power at 324 Mc; this same function now takes six transistors and appreciable additional circuitry.

The power combiner shown schematically in Figure 15 is actually a reactive power divider operated in reverse, i.e., with inputs and outputs interchanged. For a matched three port power divider a single input signal divides into three output signals, each having a precise phase and amplitude relationship with the other two. For a power combiner, then, these same phase and amplitude relationships are maintained between each of the three input signals so that they add, losslessly, to form a single output. The power combiner is designed as a standard power divider would be: each of the three 50 ohm output impedance are transformed to 150 ohms, and then paralleled to present a matched 50 ohm "input." A photograph of the power combiner, and the power balancer, is shown in Figure 16.

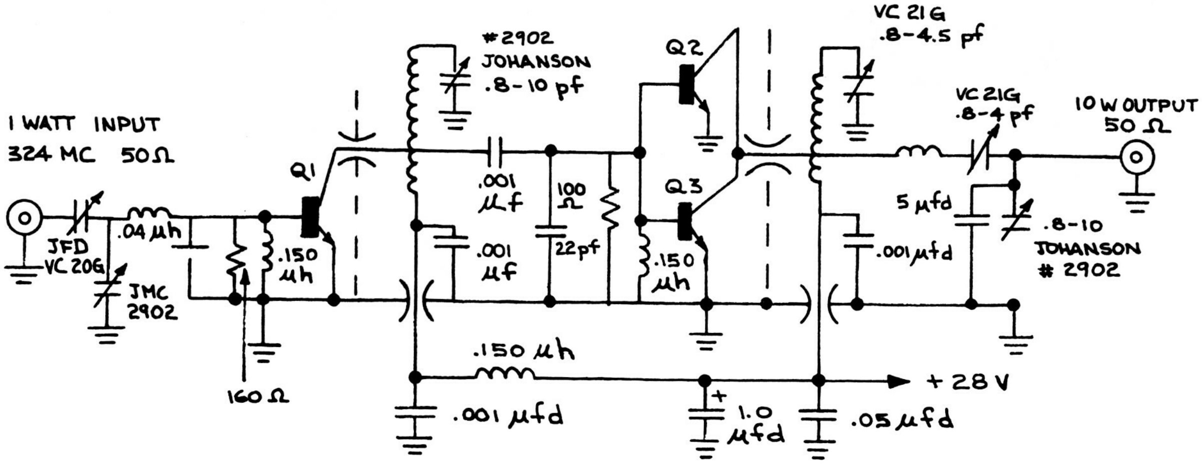

Figure 13. 10 Watt, 324 Mc Power Amplifier—
Schematic Diagram

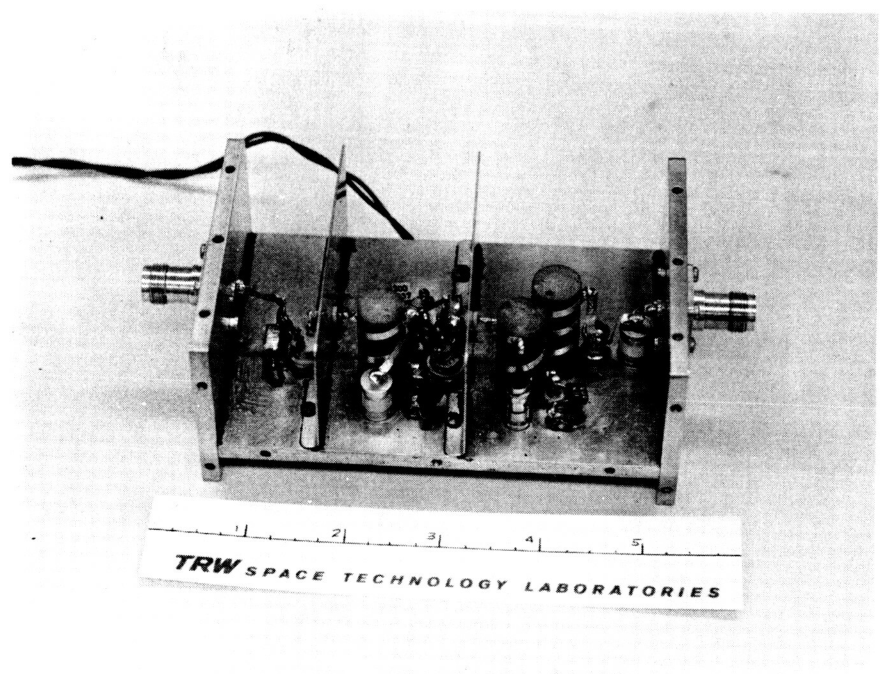

Figure 14. 10 Watt, 324 Mc Power Amplifier—
Working Model

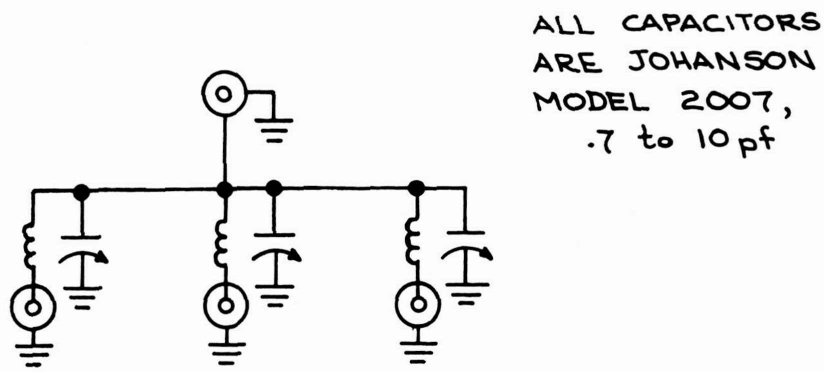

Figure 15. 324 Mc Power Combiner

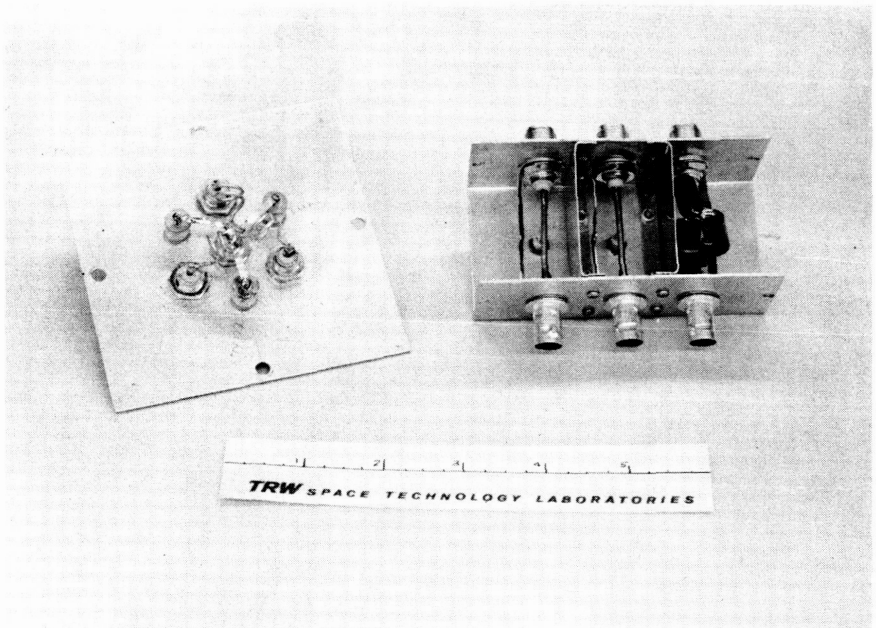

Figure 16. 324 Mc Power Combiner, Left
108 Mc Power Balancer, Right
Working Models

2.3 324 MC TO 10.4 GC FREQUENCY DOUBLER CHAIN

2.3.1 General Analysis

During the preliminary design phase of the frequency doublers in the X-Band Solid State Signal Source four significant design parameters had to be evaluated. The following questions were raised as a result:

- At what power level would each doubler operate?
- What type of varactor would operate most efficiently at the required frequency and power level?
- Should balanced or single ended multiplier circuits be used?
- What circuits should incorporate discrete components and which should utilize distributed constant techniques?

The determination of the r-f power levels were discussed in Section 2.1, and the predicted values shown in the block diagram of Figure 1. Varactor selection was accomplished by first computing the desired parameter values for each doubler, then obtaining, as nearly as possible, varactors possessing the same parameters. The selection of the balanced frequency doubler circuits was based primarily upon power requirements and a consideration of available varactor characteristics. Balanced circuits were adopted throughout the chain (from 324 Mc to 10,368 Mc) due to the possibility of excessive power dissipation in the single-ended type doublers, especially at higher ambient temperatures. It was decided that the first doubler, 324 to 648 Mc, should utilize lumped circuit elements; the second (624 to1248 Mc) should have the input circuit built in lumped circuit elements and the output circuit in distributed circuit elements; all other doublers from 1.3 gc to X-band should utilize distributed circuit elements. This decision was based upon size and weight considerations, upon the Q's of applicable lumped components, and upon the fact that lumped components have been used successfully at frequencies approaching 650 Mc. The resulting chain is believed to be a definite advancement in the state-of-the-art of varactor multipliers.

The schematic representation of the balanced circuit configuration used is shown in Figure 17 and has the following advantages:

- Improved operation over extreme temperatures
- Increased power handling capability without sacrifice of operating efficiency
- Reduction of power dissipation in each varactor
- Separation of even and odd harmonics by circuit symmetry.

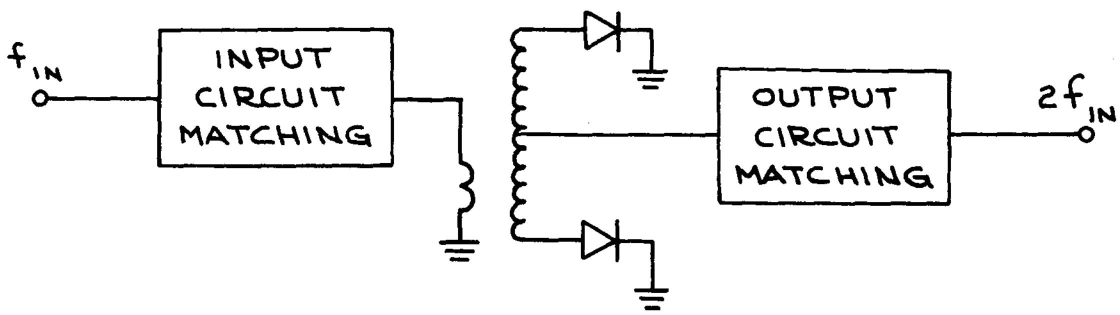

Figure 17. Balanced Frequency Doubler Circuit

Next consider the operating level of the multipliers. The drive power of the frequency multipliers at which maximum efficiency is obtained is given by the following expression:*

$$P_{in} = Bf_{in} C_{min} V_B^2$$

P_{in} = RF drive power

f_{in} = Multiplier input frequency (1)

C_{min} = Minimum varactor capacitance (at V_B)

V_B = Varactor breakdown voltage

B = Constant

*Robert P. Rafuse, "Recent Developments in Parametric Multipliers," Proceedings of the National Electronics Conference, 1963.

The value of B is a function of the multiplication factor, the degree to which the varactors are pumped, i.e., fully pumped or overdriven, and upon the varactor junction type. For the multipliers of interest, the multiplication factor is two, the varactors are overpumped in order to obtain maximum efficiency, and diffused junction varactors are used throughout. These conditions result in a value of 0.4 for B. This value was determined empirically at STL during the development of several multipliers and is used throughout the calculations in this report. Other values of B have been published by Rafuse for different pumping levels and for different junction types and are listed below for comparative purposes.

Table 2. Values of B for Different Junctions and Drive Levels

Constant	Fully Pumped, Abrupt	Overdriven, Graded	Overdriven, Abrupt	Fully Pumped, Graded
B	0.18	0.43	0.43	0.074

The efficiency of a times-two multiplier that is optimally pumped can be calculated from varactor parameters by the following expression:

$$\epsilon = 1 - A \frac{f_{in}}{f_{c_{max}}} \tag{2}$$

where

ϵ = Varactor efficiency

A = Constant

f_{in} = Input frequency to multiplier

$f_{c_{max}}$ = Maximum cutoff frequency of varactor

The value of A = 15 was determined empirically at STL during previous frequency multiplier development, Again, for comparative purposes, values for A published by Rafuse are shown in Table 3 (they are valid only for $f_{out} < 0.1\ f_c$). As with the Constant B, the value of A that was used in the calculations is slightly more conservative than the corresponding value in the table.

Table 3. Values of A for Different Junction Types and Drive Levels

Constant	Overdriven, abrupt	Fully pumped, abrupt	Overdriven, graded	Fully pumped, graded
A	15.0	19.90	14.0	25.6

Varactor capacitance is given at different arbitrary voltages, normally -6 volts or zero volts, by different manufacturers. In order to obtain the minimum capacitance, C_{min}, that occurs at voltage breakdown, the following relation can be used:

$$C_{(v)} = C_{case} + C_{min} \left[\frac{V_B + \theta}{V + \theta}\right]^{\gamma}$$

where

C_v = Junction capacitance at voltage V

C_{case} = Case capacitance

C_{min} = Junction capitance at V_B

V_B = Junction breakdown voltage

ϕ = Contact potential, $\approx$ 0.5 volt

V = Bias voltage

γ = 1/2 for abrupt junctions
= 1/3 for graded junctions

Because the characteristics of diffused junctions are similar to those of graded junctions over the greater part of the capacitance—voltage curve, a value for γ of 1/3 was used to determine C_{min}. As mentioned previously, diffused junction diodes were used for each of the frequency doublers. Values of case capacitance, C_{case}, were normally found to range between 0.45 and 0.75 picofarads for the varactors utilized.

When determining the optimum type of varactor to use in a particular situation, Equation (1) was used to establish the relationship between C_{min} and V_B at the specified drive power. With this information and catalog data of avilable varactors, all of the requisite information, except power dissipation capabilities, existed for a proper choice of varactor. Equation (3) aided in converting junction capacitance at bias points other than breakdown voltage, as given in many catalogs, to minimum capacitance at breakdown voltage while Equation (2) established the conversion efficiency of the varactor alone.

In addition to power losses within the varactors, losses also occur within the multiplier input and output filtering and impedance matching circuitry. These losses amount to about 0.3 to 0.5 db per doubler when the doublers are interconnected with coaxial cable. When the doublers are directly coupled, the losses are reducible.

Another varactor parameter whose influence is particularly significant in the design of high power frequency multipliers is thermal resistance, a measure of the heat transfer property of the diodes. Thermal resistance, in conjunction with efficiency, determines the r-f power handling capability of varactors, thus its characterization is essential in the choice of the devices.

It should be noted that the efficiency of varactors is directly dependent on junction temperature which in turn is a function of the thermal resistance and power dissipated. A rule of thumb used during the design of the X-band Solid State Signal Source was that the varactor cutoff frequency decreases to half values for a $100^{\circ}C$ increase in junction temperature. Typical levels of efficiency degradation due to increased junction temperature range up to one db for the frequency doublers in the X-band Solid State Signal Source.

When considering the efficiency degradation attributable to increasing junction temperature, the power handling advantage of a balanced over a single ended configuration becomes apparent. This is particularly true when the regenerative action of dissipated power-versus-efficiency is recognized This attribute results in a very rapid fall-off in efficiency after a critical level of dissipated power is reached. Further study of the decrease in efficiency versus dissipated r-f power is being carried out at STL under NAS 9-2938.

The power dissipated in the varactor can be expressed by the following relation

$$P_{diss} = \eta_1 P_{in} (1 - \epsilon) \quad (4)$$

where

η_1 = Efficiency of the doubler input coupling circuit

ϵ = Varactor efficiency

P_{in} = Doubler input power

P_{diss} = Dissipated power in the varactor

It is clear from the expression that P_{diss} would be minimized if ϵ, which is directly related to the cutoff frequency of the varactor, is maximized. The expression relating the varactor junction temperature and the dissipated power is

$$T_J = T_{amb} + \left(R_{T_{diode}} + R_{T_{mult}}\right) P_{diss}, \qquad (5)$$

and the rise in junction temperature due to the dissipated power is:

$$\Delta T_J = \left(R_{T_{diode}} + R_{T_{mult}}\right) P_{diss} \qquad (6)$$

where

$R_{T_{diode}}$ = Thermal resistance from junction to case of the varactor in $^{\circ}C$/watt

$R_{T_{mult}}$ = Thermal resistance from the varactor case to the multiplier body in $^{\circ}C$/watt

P_{diss} = Dissipated power per varactor (watts)

The value of $R_{T_{mult}}$ used in the design of the Solid State Signal Source was $5^{\circ}C$/watt. This value was obtained empirically during prior multiplier design. The thermal resistance of varactors, $R_{T_{diode}}$, typically decreases with increased capacitance and breakdown voltage from a maximum value of about $60^{\circ}C$/watt for higher power varactors. This is caused by the fact that higher capacitance and breakdown voltage units have larger junction diameters which result in a larger heat conducting area.

From relation (5) the importance of low thermal resistance for high power varactors is apparent. This parameter is of considerable importance in high power multiplier technology and its improvement will result directly in improved multiplier performance at higher power levels and/or temperatures.

In the remaining paragraphs of Section 2-4, the frequency doubler parameters that were calculated, using the techniques and equations just described, are presented. In addition, the type of varactors used and the experimental test data for each doubler are given. It is interesting to compare the measured characteristics with the predicted characteristics for each doubler in order to obtain insight into the accuracy of the various expressions.

Each doubler employs a dual varactor balanced configuration. The input and output circuits are tuned to the fundamental and output frequencies respectively, and perform functions of filtering and impedance matching. For each doubler, the varactors are symmetrical, physically as well as electrically, causing approximately equal currents to flow in each varactor, and nearly equal powers to be dissipated.

2.3.2 324 to 648 Mc Frequency Doubler

The schematic of the balanced 324 to 648 Mc frequency doubler is shown in Figure 18 and a photograph of the final unit is shown in Figure 19.

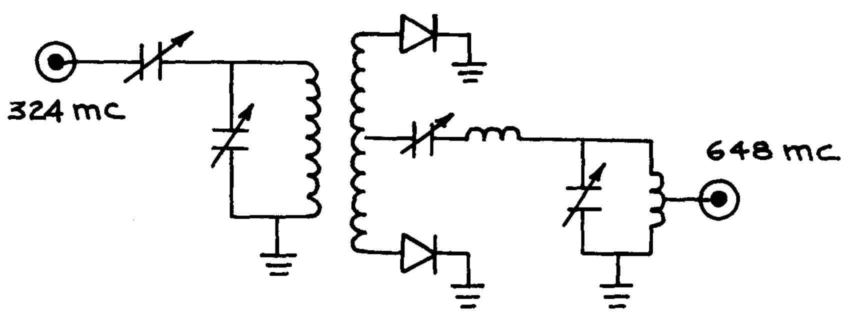

Figure 18. Schematic Diagram of the 324 to 648 Mc Frequency Doubler

Using the power and efficiency relations given in Section 2.3-1, the computed parameters are

$$C_{min} = 5.7 \text{ pf}$$

$$f_c = 30 \text{ gc}$$

$$V_B = 120 \text{ volts}$$

$$\text{Conversion loss} = 1.9 \text{ db}$$

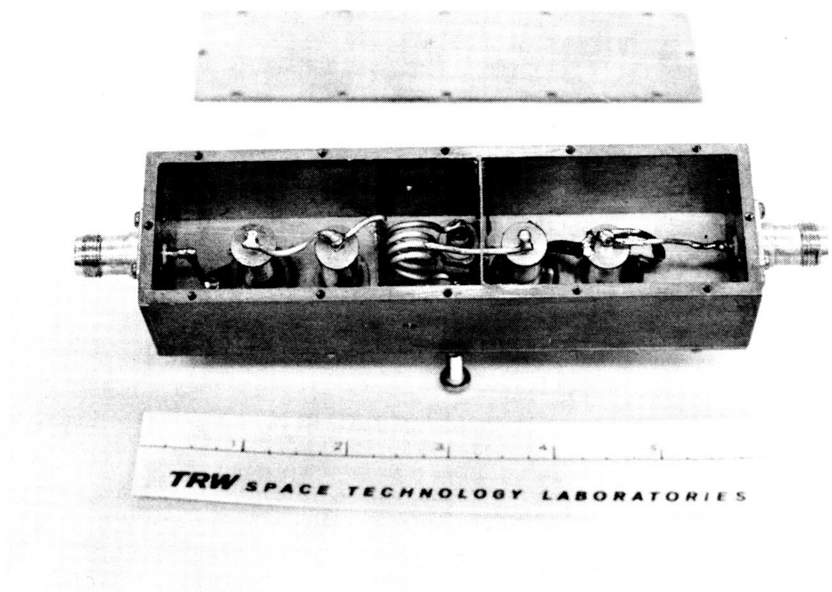

Figure 19. 324 to 648 Mc Frequency Doubler

The published parameters of the varactors used are

Varactor No. 1 (MA 4061A)	Varactor No. 2 (MA 4061A)
C_{min} = 7.7 pf	C_{min} = 7.5 pf
V_B = 130 volts	V_B = 128 volts
f_c = 30.7 gc	f_c = 29 gc
R_T = 6°C/watt	R_T = 6°C/watt

The measured data of the final model are:

P_{in} = 43.8 dbm (24 watts)

P_o = 42.0 dbm (15.85 watts)

Loss = 1.8 db

2.3.3 <u>648 to 1296 Mc Frequency Doubler</u>

The schematic of this balanced doubler is as shown in Figure 21; a photograph of the final configuration is presented in Figure 20.

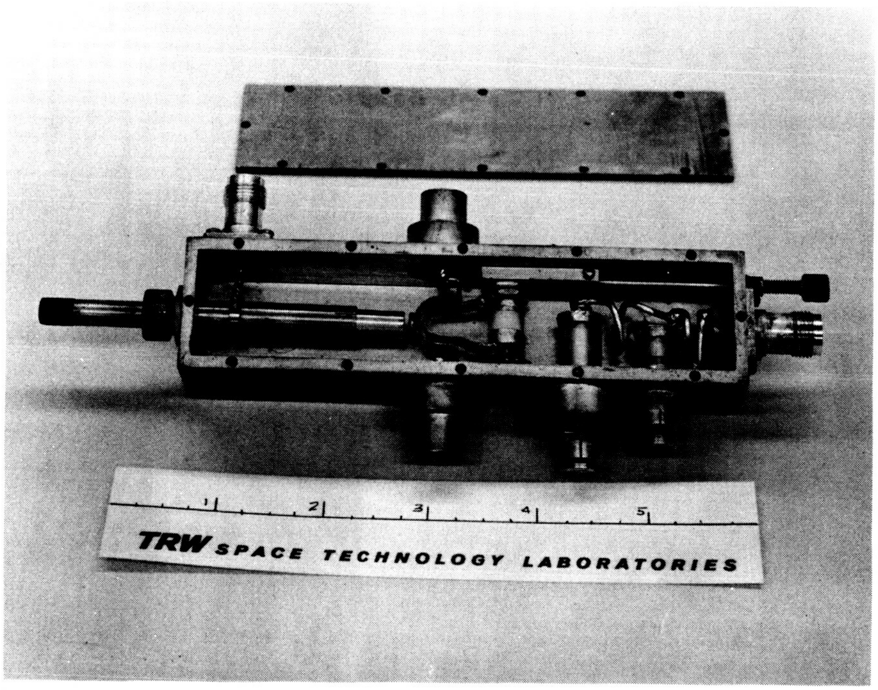

Figure 20. 648 to 1296 Mc Frequency Doubler

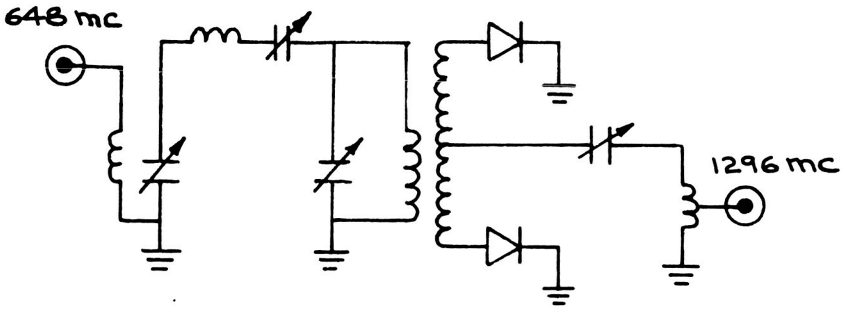

Figure 21. Schematic of the 648 to 1296 Mc Frequency Doubler

Using the relations previously given, the computed parameters are

$$C_{min} = 1.35 \text{ pf}$$

$$f_c = 120 \text{ gc}$$

$$V_B = 150 \text{ volts}$$

$$\text{Conversion loss} = 1.8 \text{ db}$$

The parameters of the varactors used are

Varactor No. 1 (RCA V6000)	Varactor No. 2 (RCA V6000)
$C_{min} = 2.0$ pf	$C_{min} = 2.8$ pf
$V_B = 146$ volts	$V_B = 176$ volts
$f_c = 115.3$ gc	$f_c = 132$ gc
$R_T = 20^{\circ}C/\text{watt}$	$R_T = 20^{\circ}C/\text{watt}$

The measured data are

$$P_{in} = 42 \text{ dbm } (15.85 \text{ watts})$$

$$P_o = 38.5 \text{ dbm } (7.07 \text{ watts})$$

$$\text{Loss} = 3.5 \text{ db}$$

2.3.4 1.3 to 2.6 gc Frequency Doubler

A photograph of the 1.3 to 2.6 gc doubler is shown in Figure 22. The computed parameters for this doubler are:

$$C_{min} = 0.50 \text{ pf}$$

$$f_c = 100 \text{ gc}$$

$$V_c = 135 \text{ volts}$$

$$\text{Conversion loss} = 2.2 \text{ db}$$

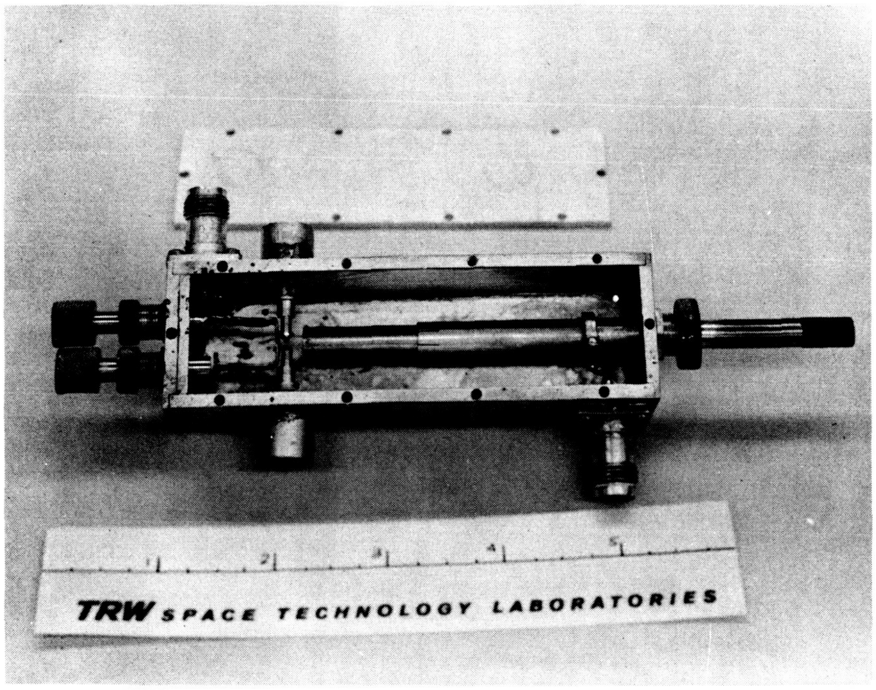

Figure 22. 1.3 to 2.6 gc Frequency Doubler

The parameters of the varactors used are

Varactor No. 1 (Sylvania D4800)	Varactor No. 2 (Sylvania D4800)
$C_{min} = 0.64$ pf	$C_{min} = 0.64$ pf
$V_B = 137$ volts	$V_B = 138$ volts
$f_c = 108$ gc	$f_c = 106$ gc
$R_T = 27^{o}C/watt$	$R_T = 27^{o}C/watt$

The measured data are

$$P_{in} = 38.5 \text{ dbm } (7.07 \text{ watts})$$

$$P_o = 36 \text{ dbm } (4.0 \text{ watts})$$

$$\text{Conversion loss} = 2.5 \text{ db}$$

2.3.5 <u>2.6 to 5.2 gc Frequency Doubler</u>

This doubler is a balanced doubler exactly like the third doubler, except for the input and output resonant cavities which are scaled to higher frequencies. A photograph of this double is shown in Figure 23.

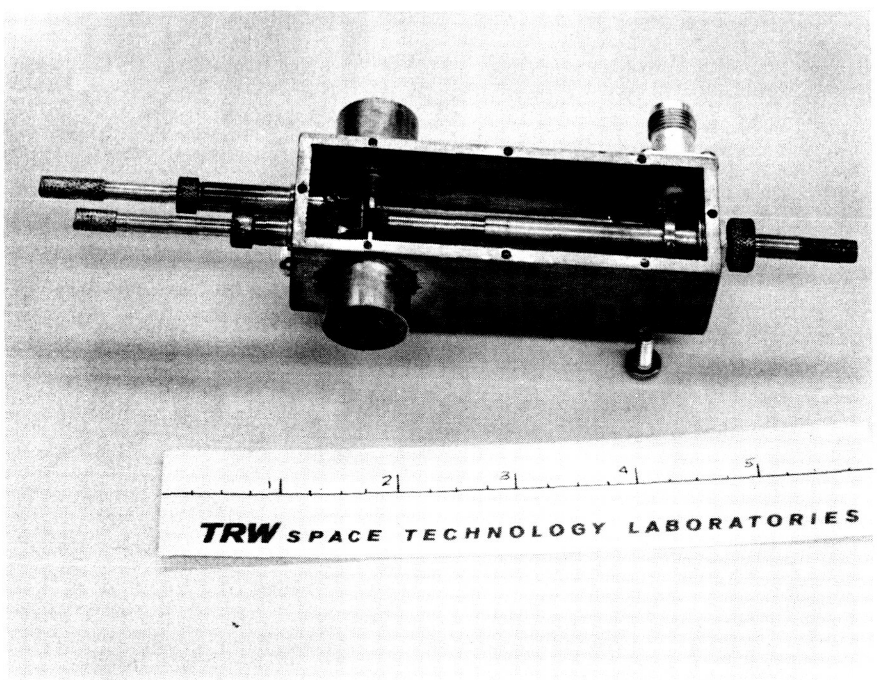

Figure 23. 2.6 to 5.2 gc Frequency Doubler

The computed parameters for this doubler are

$$C_{min} = 0.43 \text{ pf}$$
$$f_c = 130 \text{ gc}$$
$$V_B = 75 \text{ volts}$$
$$\text{Conversion loss} = 2.7 \text{ db}$$

The parameters of the varactors used are

Varactor No. 1 (Sylvania D4800)	Varactor No. 2 (Sylvania D4800)
$C_{min} = 0.47$ pf	$C_{min} = 0.43$ pf
$V_B = 75$ volts	$V_B = 75$ volts
$f_c = 150$ gc	$f_c = 138$ gc
$R_T = 43^{\circ}C/\text{watt}$	$R_T = 43^{\circ}C/\text{watt}$

The measured data are

$$P_{in} = 36 \text{ dbm } (4.0 \text{ watts})$$
$$P_o = 33.2 \text{ dbm } (2.10 \text{ watts})$$
$$\text{Conversion loss} = 2.8 \text{ db}$$

2.3.6 5.2 to 10.4 gc Frequency Doubler

This doubler stage consists of two varactors mounted on opposite sides of a square waveguide, shown in Figure 24, supporting two TE_{10} modes. Coupling is accomplished with a resonant cavity situated at the top and tuned to 5.2 gc. A bias voltage of about minus 10 volts is applied to the two varactors from a small connector located at the bottom of the doubler. A waveguide short circuit matches both varactors to the square waveguide. Tuning screws at the output match the doubler to the output circulator.

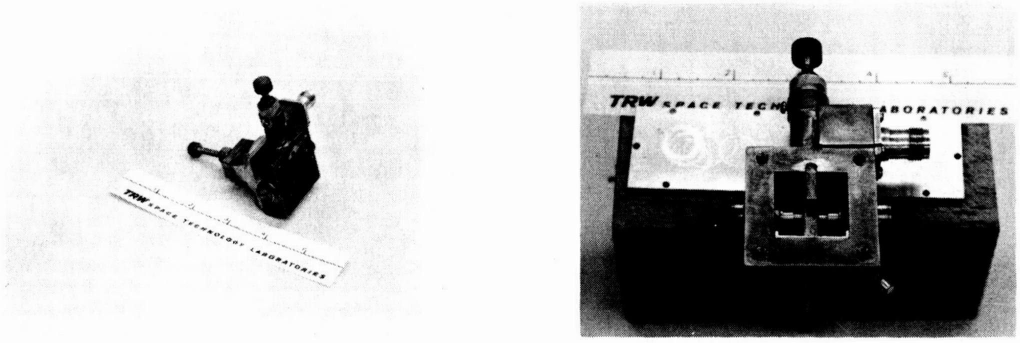

Figure 24. 5.2 to 10.4 gc Frequency Doubler

Temperature tests under NAS9-2938 are being conducted on this doubler at this time. Preliminary results are exceptionally good; the output power variation in an ambient temperature ranging from -25°C to +71°C was approximately 0.5 db.

The computed parameters for this doubler are

$$C_{min} = 0.30 \text{ pf}$$

$$f_c = 200 \text{ gc}$$

$$V_B = 45 \text{ volts}$$

$$\text{Conversion loss} = 4.3 \text{ db}$$

The parameters of the two varactors used are

Varactor No. 1 (Sylvania D4800)	Varactor No. 2 (Sylvania D4800)
$C_{min} = 0.43$ pf	$C_{min} = 0.42$ pf
$V_B = 47$ volts	$V_B = 46$ volts
$f_c = 214$ gc	$f_c = 200$ gc

The measured data are

$$P_{in} = 33.2 \text{ dbm } (2.10 \text{ watts})$$

$$P_o = 30.1 \text{ dbm } (1.023 \text{ watts})$$

$$\text{Conversion loss} = 3.1 \text{ db}$$

2.4 CIRCULATOR

The circulator was designed to present a good impedance match to the final frequency doubler over the band from 8 to 12 gc. The functions of the circulator are two-fold; first, it isolates any mismatches which may detune the final doubler stage; second, the wideband characteristics of the circulator tend to promote stabler operation by effectively damping out spurious oscillations.

The wideband characteristic of the circulator was achieved by using a triangular ferrite element with triangular matching structures. The unit was built into a moderately sized package so that the desired wideband characteristics could be attained; much smaller units are available but have degraded bandwidth characteristics. Curves of the VSWR, isolation, and insertion loss characteristics are shown in Figure 25.

2.5 SYSTEM TEST RESULTS

This section presents a series of curves plotted from data taken during tests of the signal source. The tests were performed at room temperature, thus are indicative of operation at an ambient temperature of approximately 25°C. Due to insufficient heat sinking of the signal source, two small fans were used to cool the power amplifier and the 1.3 to 2.6 gc frequency doubler during the tests. It can be noted from Figure 21 that the 1.3 to 2.6 gc frequency doubler was excessively lossy which accounts for its need for cooling.

All measuring instruments used during the performance of the tests had been recently calibrated against a secondary standard in the STL metrology laboratory. The types of instruments used for the tests are included in the recommended equipment list, Section 3.3.

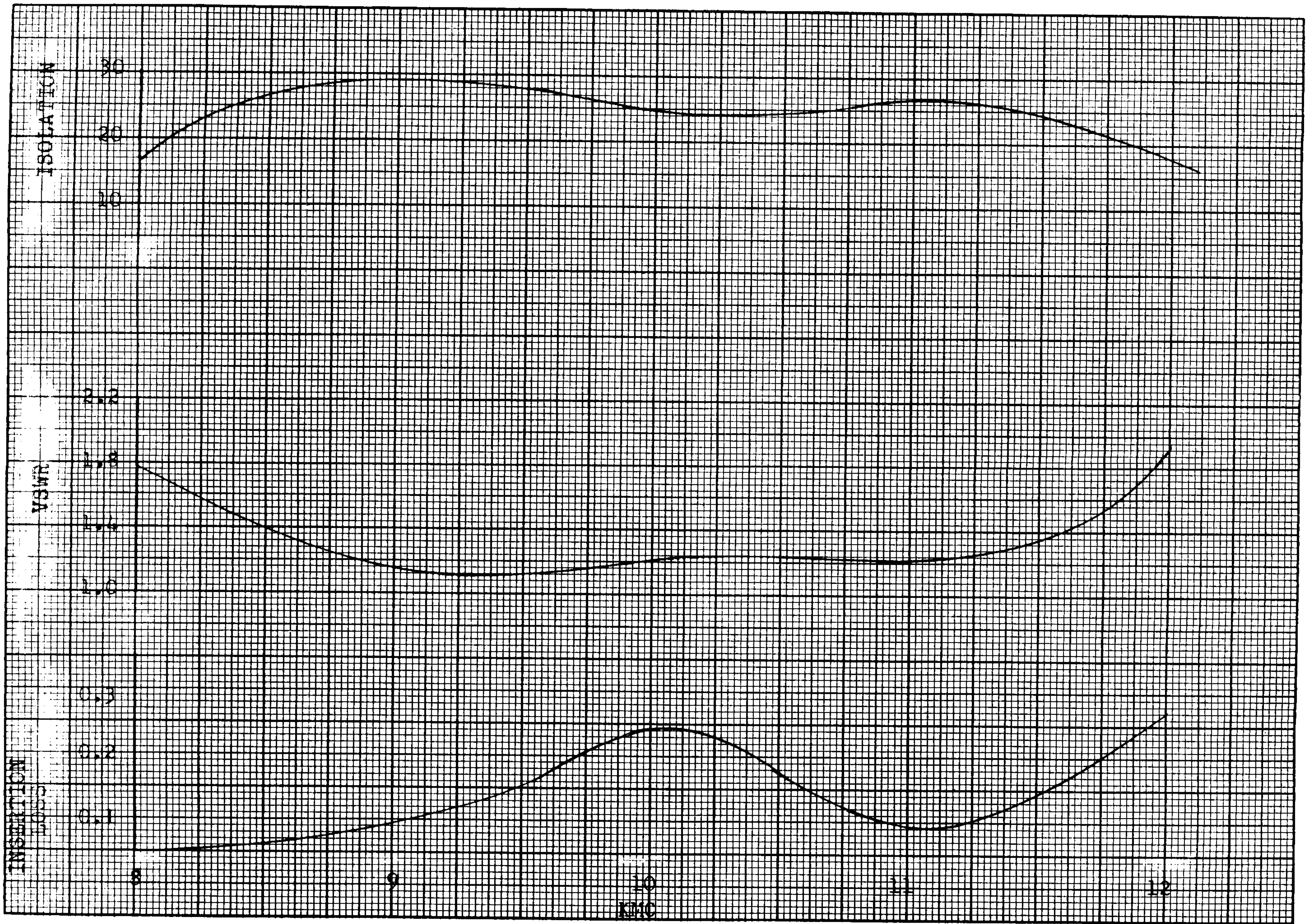

Figure 25. X-Band Waveguide Circulator Characteristics

Table 4 presents typical operating characteristics of the X-Band Solid State Signal Source. The data for the table was obtained after the Signal Source had operated continuously for about 24 hours at room temperature.

Table 4. Typical X-Band Solid State Signal Source Operational Characteristics

Input Frequency	108.000 Mc
Output Frequency	10,368 Mc
RF Power Input	0 dbm
RF Power Output	30.0 dbm
Average Amplifier Case Temperature	47°C (with external fan)
Harmonics	
10.4 gc	0 db (reference)
20.8 gc	-44 db
5.2 gc	-33 db
All others	-25 db*
DC Input Power	
Preamplifier	
+23 volts at 295 ma	
-23 volts at 92 ma	
+15 volts at 86 ma	
X-3 Multiplier	
+35 volts at 10 ma	
Power Amplifier	
+28 volts at 3.025 amps	

*These "harmonics" are modulation sidebands of the X-band carrier; they are believed generated in the power amplifier section.

The modulation sidebands present in the output spectrum were separated from the carrier by about 25 to 30 Mc, and were approximately 25 db below the carrier level. Their origin was traced to the 324 Mc power amplifier section, and it is believed they were generated by spurious oscillations occurring within one of the three final power amplifiers. The condition could be corrected, however due to the relatively low amplitude of the sidebands with respect to the carrier, and because of scheduling considerations, no effort was expended in this direction.

Figure 26 depicting the curve of output versus input power, illustrates the automatic gain control characteristic designed into the preamplifier. This automatic gain control action, obtained by driving the preamplifier near saturation, was intended to reduce the sensitivity to the r-f drive level. The curve indicates that over 29.6 dbm of output power can be obtained for an r-f drive level variation of from -4 dbm to +4 dbm; 30 dbm or over of output power can be obtained from a drive level varying from 0 to + 4 dbm.

Figure 27 is a plot of the bandwidth characteristics of the signal source; it displays a bandwidth of about 0.42 percent. Although the bandwidth is relatively narrow, it is nevertheless sufficiently wide so that frequency drifts in the laboratory instruments used during checkout do not inhibit successful operation.

Figures 28, 29, and 30 provide a measure of the sensitivity of the source to fluctuations of the various power supplies. The only power supply whose variation over a 10 percent limit appreciably affects the output power is the one providing the 28 volt prime power to the final amplifier. Of course, the C-to X-band frequency doubler is also fairly sensitive to fluctuations in its bias. It should be noted that no particular effort was made to isolate the various submodules from power supply fluctuations. The various measurements were made with each power supply, except the one being varied, set to its correct level.

As is apparent from Figures 31, 32, and 33, the levels of the spurious harmonics at the X-band output are essentially independent of variations in input signal frequency, input r-f power, and any power supply fluctuations. As in the preceding paragraph, the powers supplies were varied one at a time while the others remained at their correct level.

Finally, no hystersis effects were apparent during the performance of the various tests. Hystersis effects describe the phenomenon occurring when the output power does not come back to its normal level, or does not come back at all, after the signal source has been turned off and then back on.

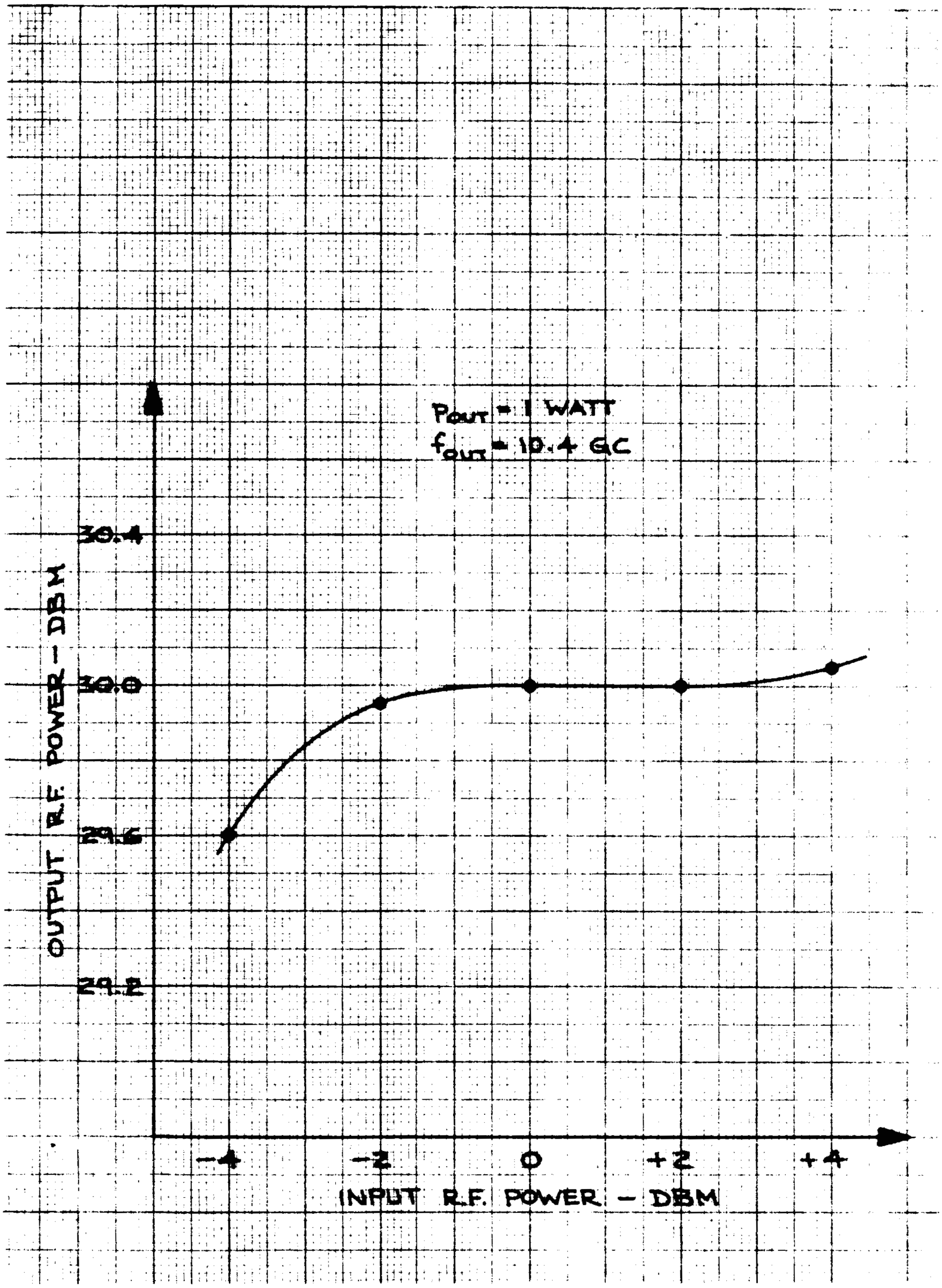

Figure 26. Output RF Power Versus Input RF Power of X-Band Solid State Power Source

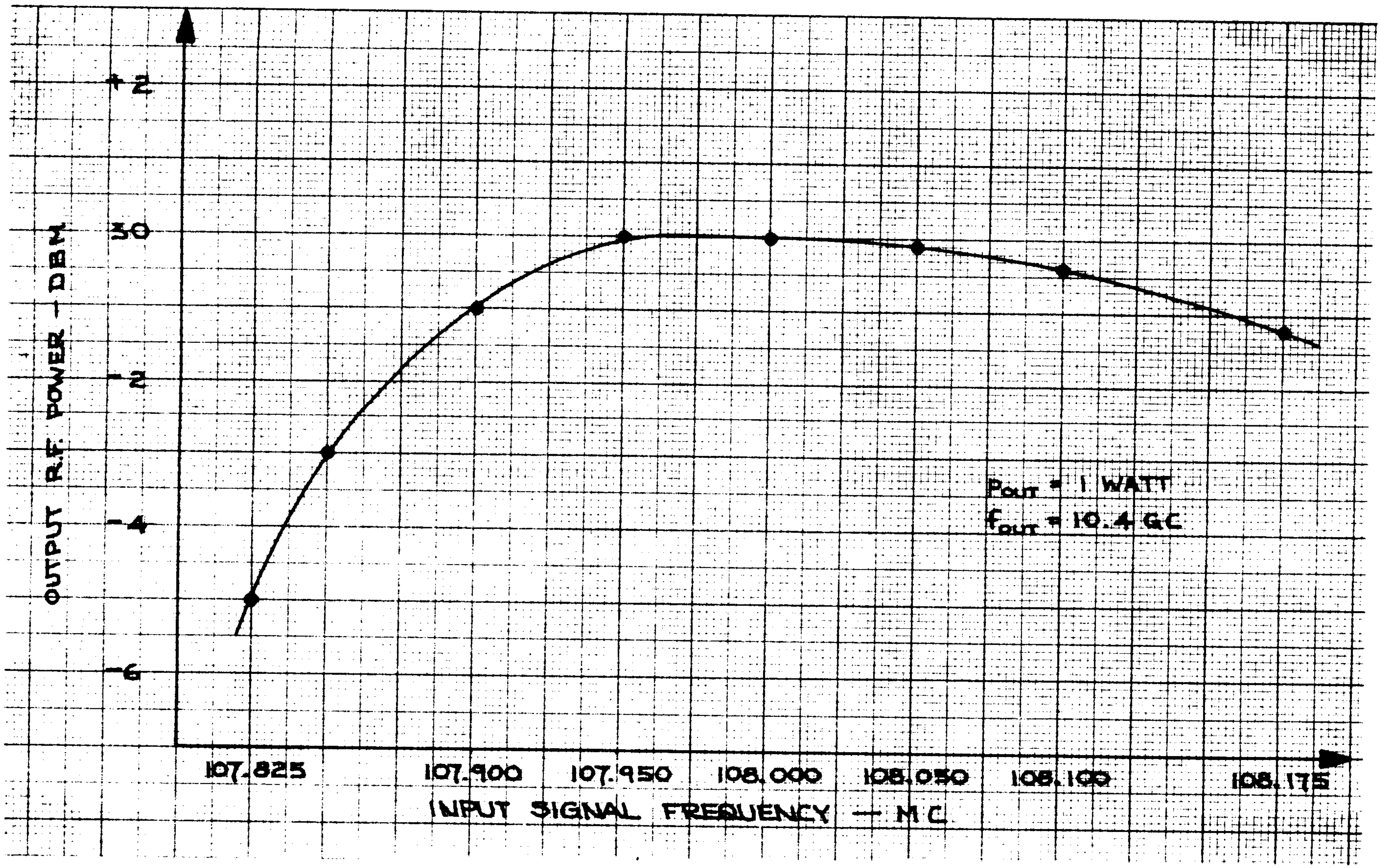

Figure 27. Output RF Power Versus Input Signal Frequency of X-Band Solid State Power Source

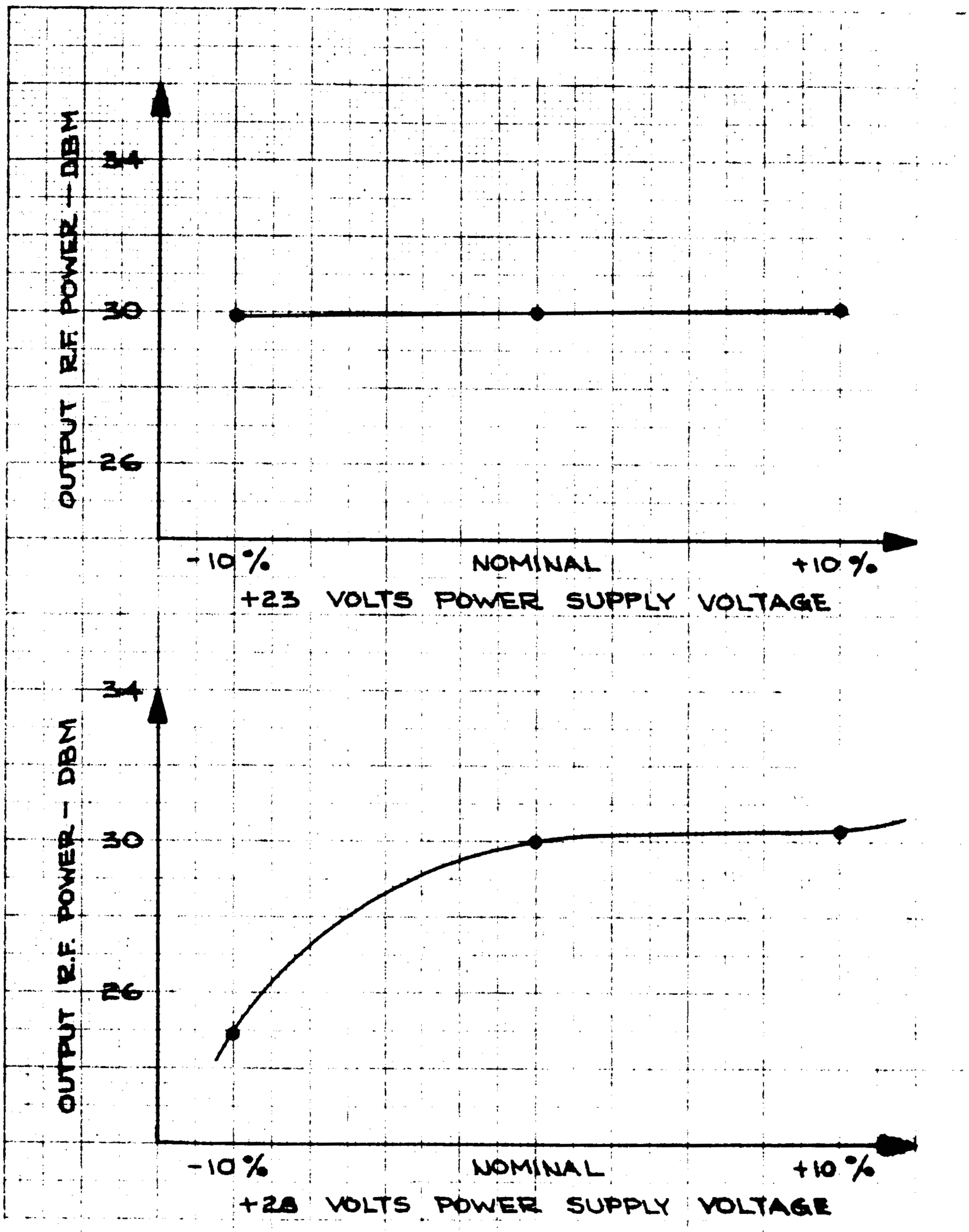

Figure 28. Output RF Power Versus Power Supply Voltage of X-Band Solid State Source

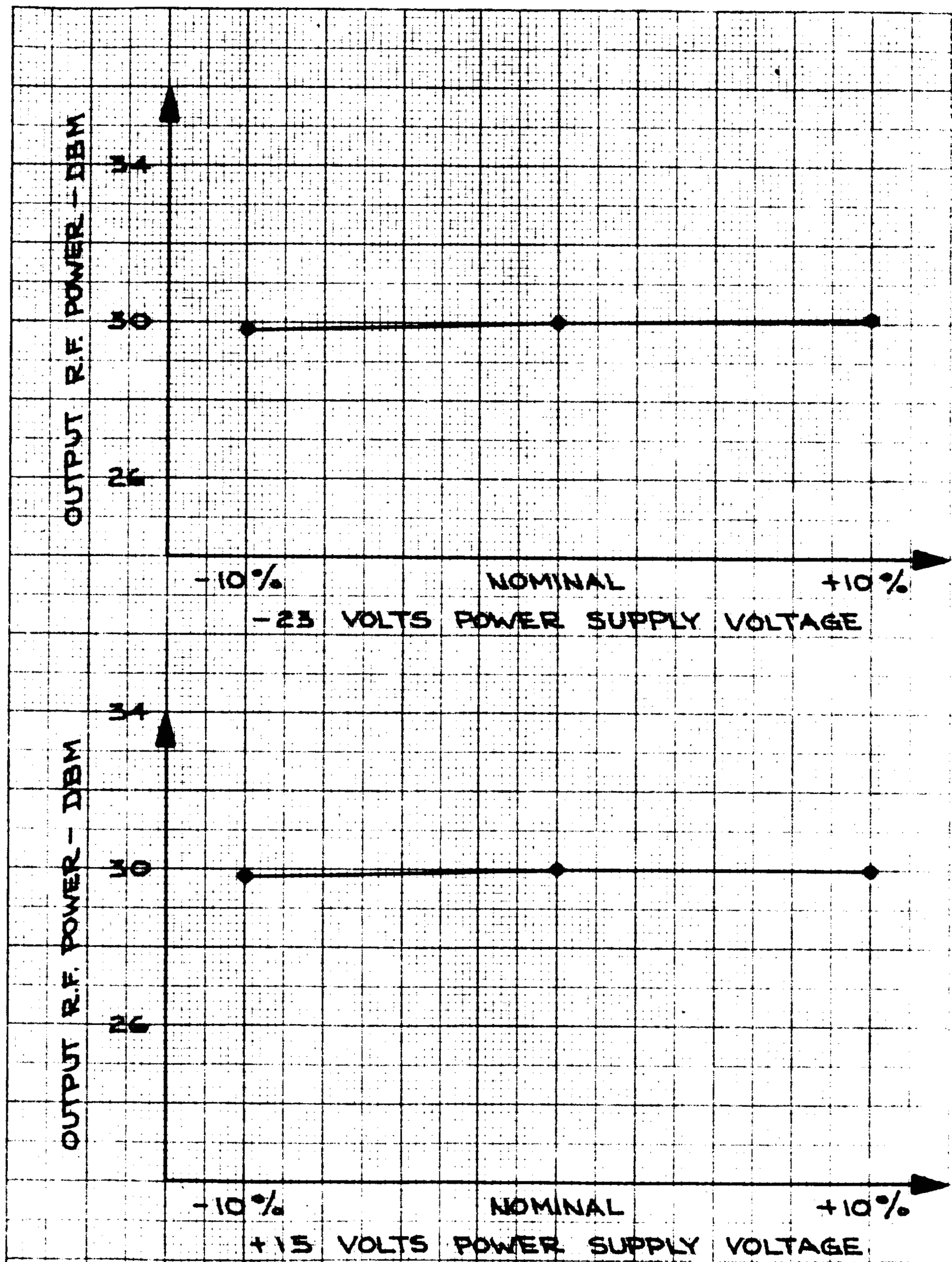

Figure 29. Output RF Power Versus Power Supply Voltage X-Band Solid State Source

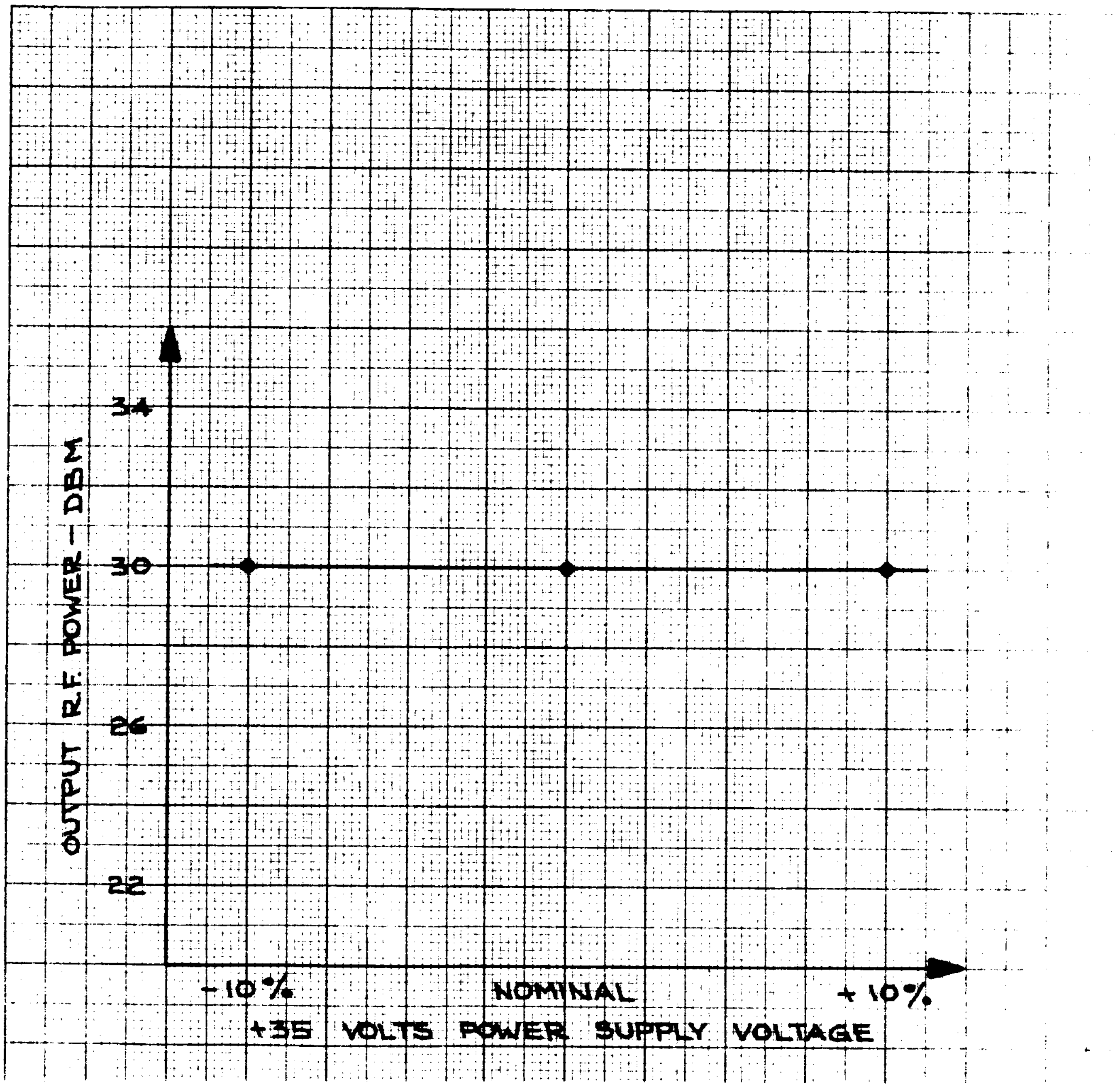

Figure 30. Output RF Power Versus Power Supply Voltage X-Band Solid State Source

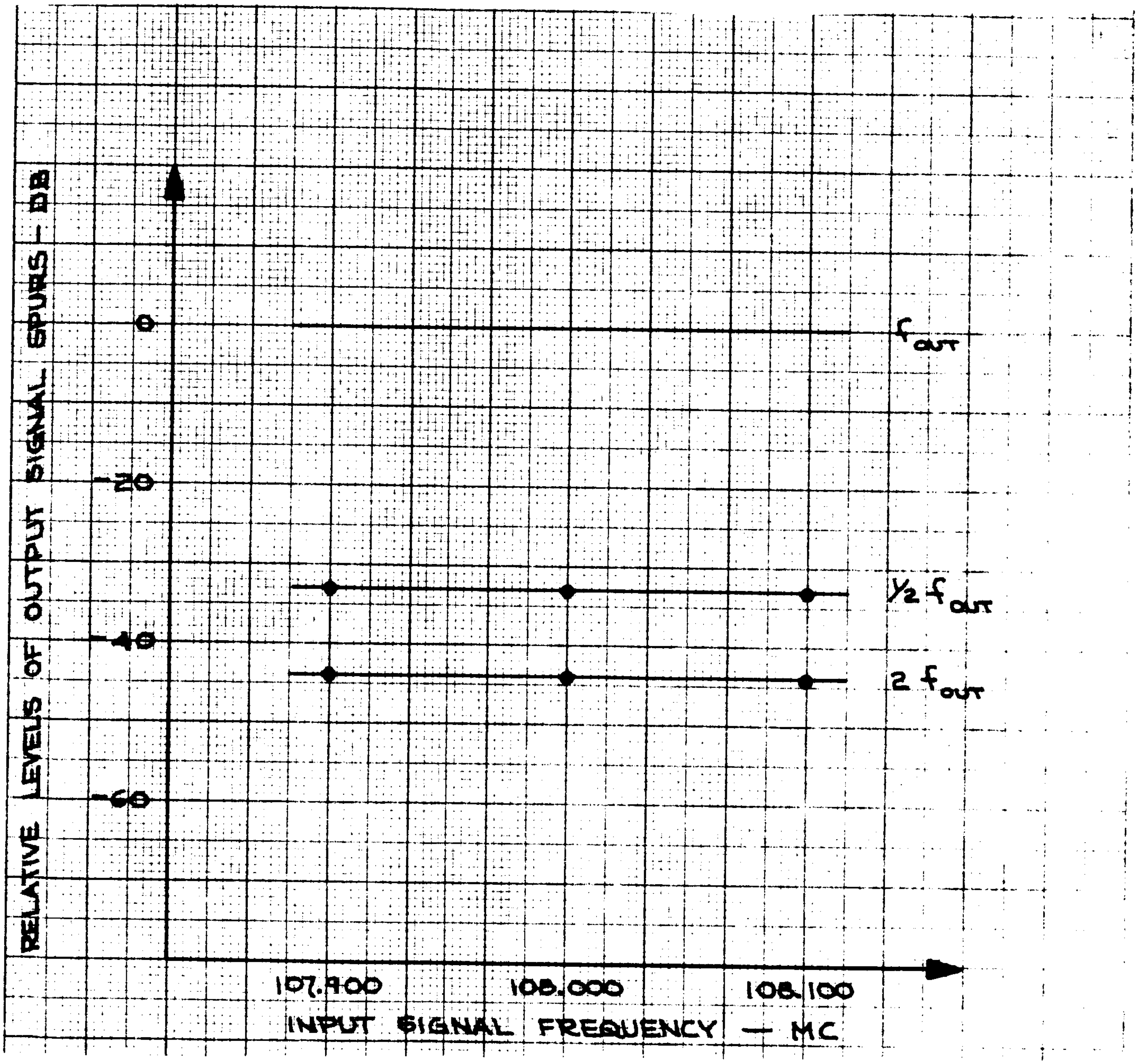

Figure 31. Output Signal Spurs Versus Input Signal Frequency X-Band Solid State Source

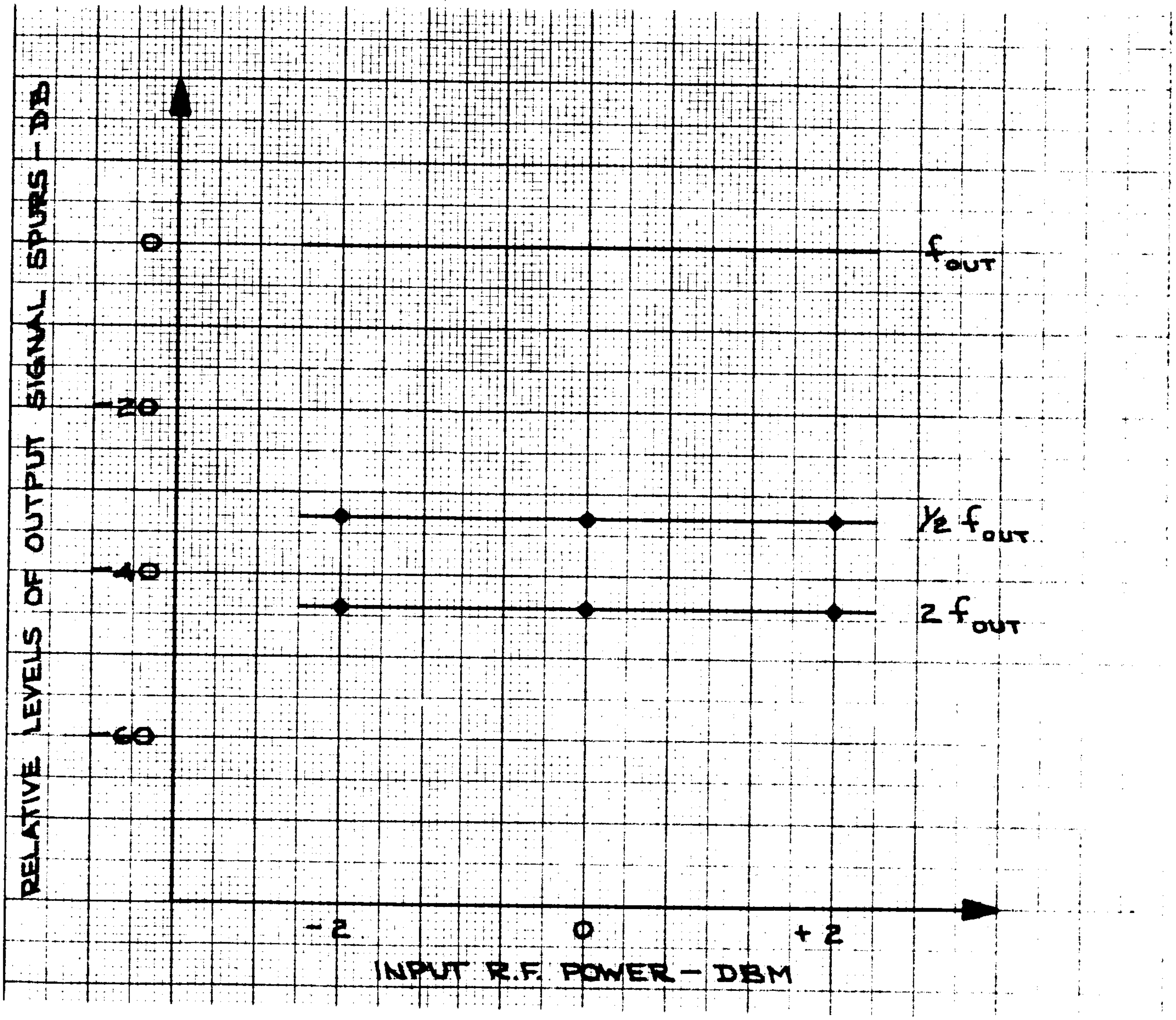

Figure 32. Output Signal Spurs Versus Input RF Signal X-Band Solid State Source

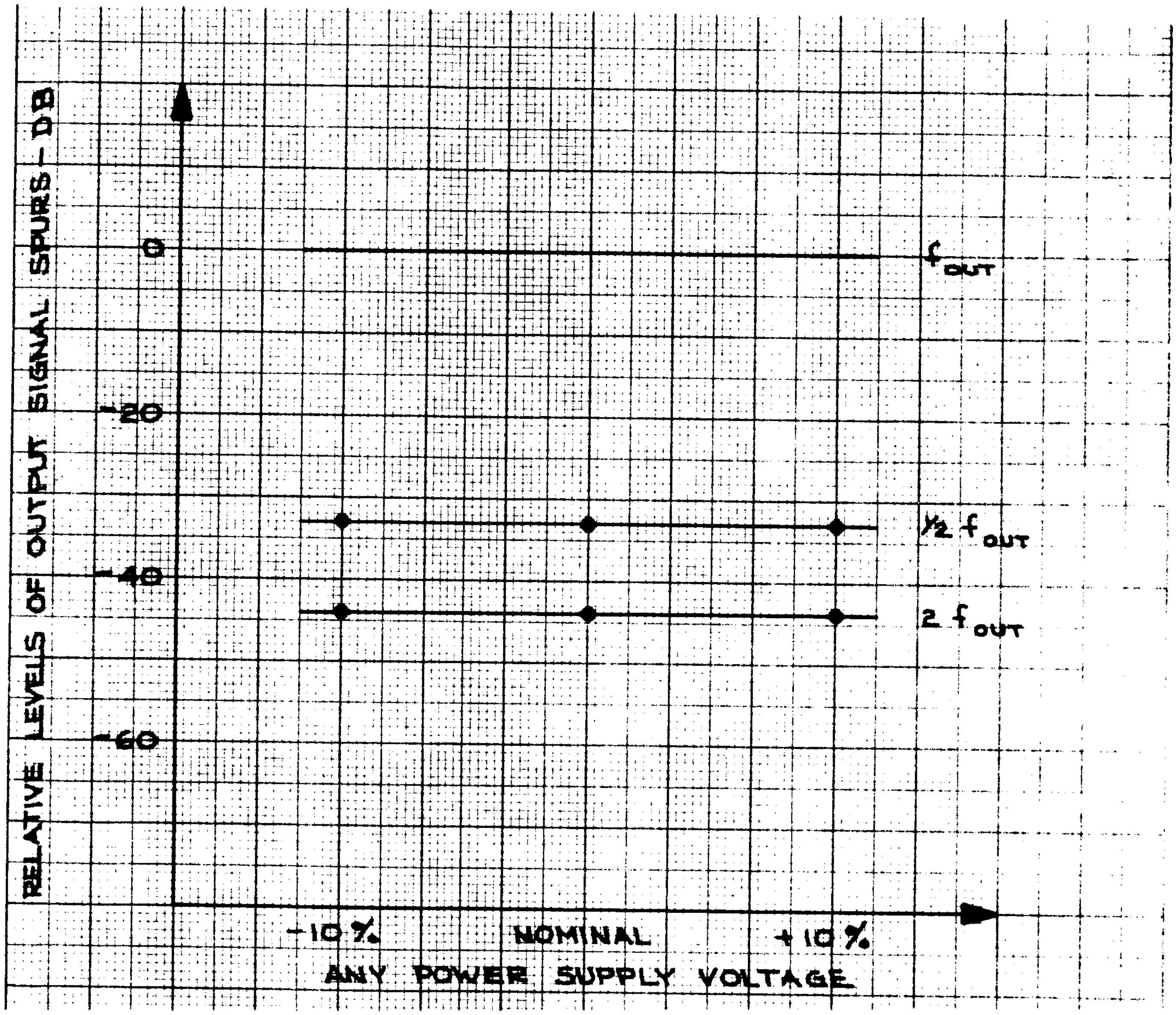

Figure 33. Output Signal Spurs Versus Power Supply Voltage of X-Band Solid State Source

3. OPERATION AND ALIGNMENT PROCEDURE

3.1 INTRODUCTION AND SUMMARY

This section presents the procedure for operating the X-Band Solid State Signal Source. In addition, pertinent techniques and recommended laboratory test equipment for aligning each component subsystem as well as the complete subsystem are given.

Each frequency doubler operating from 324 Mc through X-band is tuned in the same manner, thus the alignment procedure for all doublers is common. In every case, the amplifier and frequency multiplier modules are tuned synchronously.

A degree of independence from the drive level and output impedance variations has been designed into the Solid State Signal Source. The former feature was attained by incorporating a small amount of automatic gain control capability into the 108 Mc preamplifier. Sensitivity to output impedance variations has been almost totally reduced by incorporating a circulator to function as a load isolator. It is to be expected that these features will permit a simpler setup procedure, and provide appreciable operational stability.

3.2 OPERATION

The X-Band Solid State Signal Source working model requires six different d-c voltages, each regulated as well as standard laboratory supplies. The inputs for these voltages are marked on the signal source base plate and are apparent in the photograph of the source shown in the frontis piece; they are also noted on the source block diagram, Figure 34. The voltage and nominal current ratings are shown in Table 5.

The r-f drive required is 1 mw at about 108 Mc. The tolerable deviation in drive power is about ±4 db with the resulting degradation in operating characteristics discussed in Section 2.5. Because the high Q circuits are all synchronously tuned, the bandwidth for satisfactory operation is restricted to about 400 kc at 108 Mc. The output signal characteristic as a function of drive frequency is also discussed in Section 2.5.

Table 5. Prime Voltage and Current Ratings

Voltage	*Approximate Current
+23	295 ma
-23	92 ma
+15	86 ma
+35	10 ma
+28	3.025 amps
-10	1 ma

*These currents are applicable when r-f drive is applied.

Due to laboratory instrumentation tolerances, it is recommended that when operating the Solid State Signal Source, the frequency of the drive be roughly set initially, then carefully swept after connection to the source, until the correct output power level is obtained. By this means, accurate frequency measurements become unnecessary.

The X-band output of the Solid State Signal Source is designed to operate into a poor match with any reflected power being absorbed in the terminated arm of a circulator; however, for maximum output power, the source should operate into a well matched RG52/u waveguide load or the equivalent.

It is important that all d-c voltages be preset to the specified values before application to the source. Once set, it is recommended that the voltages and r-f drive signal be applied in the sequence shown in Table 6 below. If the suggested sequence isn't followed there is some risk that a failure will occur.

Ideally, the r-f drive should be increased from zero to the proper operating level, 1 milliwatt, however, application of powers up to several milliwatts will not cause damage; they will saturate the pre-amplifier and may result in degraded operation.

Table 6. Recommend Sequence for Application of Prime Powers and r-f Drive

Step	Function
1-	Collector voltages ($+15^V$, $+23^V$, $+28^V$)
2-	Bias voltages (-23^V, $+35^V$, -10^{V*},)
3-	r-f drive

*The -10 bias for the C to X-band frequency doubler should be slightly readjusted for maximum power output after all voltages and the r-f drive signal have been applied.

Because of the exclusion of satisfactory heat sinking provisions, it is definitely recommended that a small blower or fan be used to cool the power amplifiers. It would also be advisable to cool the 1.3 to 2.6 gc frequency multiplier due to its slightly excessive conversion loss; however, this is not necessary.

3.3 ALIGNMENT PROCEDURE

This section contains a list of recommended test equipment, block diagrams of test setups, comments regarding alignment techniques, and applicable submodule operating characteristics. It is expected that alignment will only arise from further experimentation on the source, or result from a submodule failure. In either case, the task will probably be directed first toward an individual submodule and then toward the integrated signal source.

Table 7 lists recommended types of laboratory test equipment. Those types of test equipment common to most laboratories, such as multimeters and d-c power supplies are excluded. In many cases, submodules in the signal source chain are recommended as drivers; when this occurs, it is so noted.

Table 7. Recommended Test Equipment List

	Preamplifier	
Signal Source	Hewlett Packard	HP608D
Power Meter w/ Thermistor Mount	Hewlett Packard	HP430C w/HP477B
Impedance Bridge and VHF Detector	Hewlett Packard	HP803A and HP417A
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-1
Attenuators	Empire Devices	AT58-10 and AT58-15
	108-324 Mc Frequency Tripler	
Signal Source	STL	Preamplifier
Power Meter w/ Thermistor Mount	Hewlett Packard	HP430C w/HP477B
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/ Model STU-1
Attenuators	Empire Devices	AT58-10 and AT58-15
Impedance Bridge and VHF Detector	Hewlett Packard	HP803A and HP417A
	Power Amplifier	
Signal Source	STL or Airborne Instruments Laboratory	Type 124C
Power Meter w/ Thermistor Mount	Hewlett Packard	HP430C w/HP447B
Attenuators	Empire Devices	2 each AT58-10, AT58-15
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-1
Impedance Bridge and VHF Detector	Hewlett Packard	HP803A and HP417A

Table 7. Recommended Test Equipment List (Continued)

	Power Combiner	
Signal Source	Hewlett Packard	HP608D
Impedance Bridge and VHF Detector	Hewlett Packard	HP803A and HP417A
50 ohm Termination, 3 each	Empire Devices	TE-80-2
	324 to 648 Mc Frequency Doubler	
Generator	STL	Power Amplifier
Input Filter	Telonic	TCF 324-100-4-CD
Output Filter	Telonic	TCF 648-100-4-CD
Isolator	E and M Labs	Model U25Y
Directional Coupler	Narda	Model 3000-20
Impedance Bridge and VHF Detector	Hewlett Packard	HP803A and HP417A
Input Tuner	Weinschel	DS190L
Output Tuner	Weinschel	DS190L
Attenuator	Empire Devices	4 each AT58-10
Power Meter w/ Thermistor Mount	Hewlett Packard	Model 340C w/HP477B
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-1
	648 to 1296 Mc Frequency Doubler	
Generator	Airborne Instrument Labs	Model 124C
Input Filter	Telonic	TCF-648-100-4-CD
Output Filter	Telonic	TCF-296-200-5-CD
Isolator	Mel Labs	Model XH 825
Directional Coupler	Narda	Model 3001-20
Input Tuner	Weinschel	Model DS190L
Output Tuner	Weinschel	Model DS190L

Table 7. Recommended Test Equipment List (Continued)

Attenuators	Empire Devices	2 each AT58-10 1 each AT58-15
Power Meter w/ Thermistor Mount	Hewlett-Packard	HP430C w/HP477B
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-2A
	1.3 to 2.6 gc Frequency Doubler	
Generator	Airborne Instrument Labs	Model 124C
Input Filter	Telonic	TCF 1296-200-5-CD
Output Filter	Microlab	Highpass Model HA-20N Lowpass Model FL3001
Isolator	STL	———
Directional Coupler	Narda	Model 3002-20
Input Tuner	Weinschel	Model DS190L
Output Tuner	Weinschel	Model DS190L
Attenuators	Weinschel	3 each Model 210-3 2 each Model 210-10
Power Meter w/ Thermistor Mount	Hewlett Packard	Model 430C w/HP477B
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-2A
	2.6 to 5.2 gc Frequency Doubler	
Generator	Hewlett-Packard	Model 616A
TWT Amplifier	Alfred	Model 5-6868
Input Filter	Microlab	Highpass Model HA-20N Lowpass Model FL3001
Output Filter	Microlab	Highpass HA-50N Lowpass LA-60N
Isolator	STL	
Input Tuner	Weinschel	Model DS190L
Output Tuner	FXR	Model N300A

Table 7. Recommended Test Equipment List (Continued)

Attenuators	Empire Devices	3 each Model 210-3 2 each Model 210-10
Power Meter w/ Thermistor Mount	Hewlett-Packard	Model HP430C w/HP477B
	Alfred	
TWT Amplifier	Alfred	Model 5-6868
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-3A
	5.2 to 10.4 Mc Frequency Doubler	
Generator	Hewlett-Packard	Model 618B
TWT Amplifier	Huggins	Model 405D
Input Filter	Microlab	Highpass Model HA-50N Lospass Model LA-60N
Output Filter	STL	
Isolator	STL	
Directional Coupler	Narda	Model 3044-10
Input Tuner	FXR	Model N300A
Output Tuner	Hewlett Packard	Model 870A Slide Screw Tuner
Attenuators	Weinschel	1 each Model 210-3 2 each Model 210-10
Power Meter	Hewlett Packard	Model 430C
Spectrum Analyzer w/ Plug-In	Polarad	Model TSA w/Model STU-3A
	Bandpass Filter	
Signal Source	Hewlett Packard	HP620A
Slotted Line	Hewlett Packard	HP809B w/HP 810B; HP440A
VSWR Meter	Hewlett Packard	HP415D
Attenuator	Weinschel	2 each Model 210-3
Bolometer-Mount	PRD	Type 628A

Pertinent techniques for aligning each submodule of the signal source are described in the following paragraphs. Step-by-step procedures for alignment of the submodules are considered standard, thus are not individually presented. The techniques involved in aligning each of the frequency doublers operating from 324 Mc through X-band is essentially the same, thus, the doublers are discussed collectively rather than individually.

Figure 34 illustrates how to properly interconnect the supply voltages and the power amplifier section of the X-band Solid State Signal Source. The only required d-c supply voltage not shown is the -10 volt bias for the C- to X-band doubler.

3.3.1 108 Mc Preamplifier

When properly operating, the preamplifier should draw the approximate currents listed in Table 5 when r-f drive is applied. Its output power should be approximately 2 watts for a 1 mw input at 108 mcps when driven from a 50 ohm source. All interstage tuning capacitors should be adjusted for synchronous tuning at an input frequency near 108 Mc.

The negative voltage supply may be adjusted to control the gain of the preamplifier. Increasing this voltage increases the quiescent emitter current of the first three stages and thereby increases the amplifier gain. Decreasing the negative supply voltage has the opposite effect.

3.3.2 108 to 324 Mc Frequency Tripler

The proper bias for the X3 multiplier is +35 vdc. With the specified input of 2 watts at 108 Mc, the output at 324 Mc should be approximately 1.2 watts. The input and output of the multiplier should each be matched to 50 ohms. The combination of the series resonant circuit across the varactor to ground and the varactor should resonate at the 2nd harmonic frequency of 216 Mc. The series resonant circuit at the input should be tuned with the varactor to the fundamental 108 Mc frequency; the series resonant circuit of the output circuit should be resonated with the varactor at the third harmonic, 324 Mc. The variable capacitors in shunt with the input and output of the multiplier should be adjusted to match the input

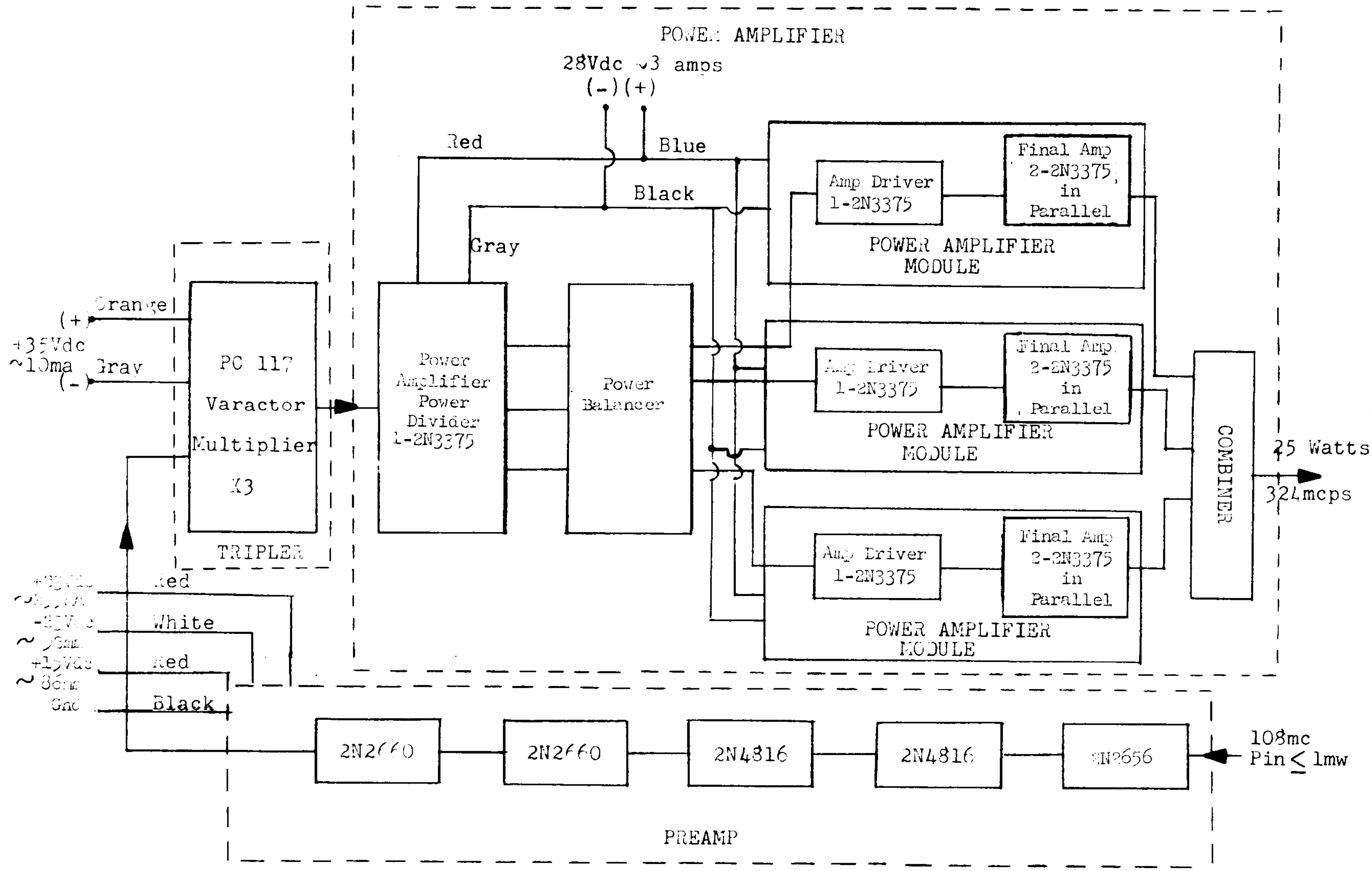

Figure 34. UHF Section, DC Supply Voltage Interconnection Diagram

and output impedances to 50 ohms. When adjusting the multiplier, a frequency selective indicator should be used to continuously monitor the output signal to prevent spurs and other harmonics from being generated.

3.3.3 Power Amplifier

The power amplifier should be powered only by the +28 vdc supply. With the X3 multiplier output connected to the input of the power amplifier and the output of the amplifier properly terminated in a 50 ohm load, the 28 vdc supply should draw approximately 3 amps.

The first stage of the power amplifier is a power divider as well as a power amplifier and is packaged in a separate chassis. For proper operation, the tuning capacitor of the divider should be adjusted for maximum power delivered at 324 Mc to the three separate 50 ohm loads connected to its three outputs. Each output should measure approximately 1 watt. The outputs of the divider feed three separate power amplifiers in parallel. Each of the power amplifiers should be synchronously tuned to deliver approximately 9 watts each into three 50 ohm loads connected to their respective outputs.

3.3.4 Power Combiner

The power combiner can be aligned by unsoldering two of the input matching networks and adjusting the third. A 50 ohm termination should be connected to the third input terminal and the output impedance of the combiner set to 150 ohms by tuning the variable shunt capacitor. The second input network should be reconnected and terminated in 50 ohms, and the output impedance of the combiner set to 75 ohms by tuning the second input variable shunt capacitor. After reconnecting the third input matching network and terminating it in 50 ohms, the output impedance of the combiner should be adjusted for 50 ohms by using the variable shunt capacitor of the third network.

3.3.5 Frequency Doublers

Each of the frequency doublers should be tuned individually in a similar fashion. That is, all tuners whether Johanson capacitors or machined plunger capacitors, should be synchronously tuned for maximum output power when the specified r-f signal is applied. Typical values of input and output powers, and of conversion losses of each doubler are given in Table 8; these values should be used as a guide when tuning the individual doublers. It should be noted that conversion efficiency is a function of drive level, thus it is important that drive levels agree with those in the table.

Table 8. Frequency Doubler Performance Data

Doublers	Power Input dbm	Power Output dbm	Conversion Loss db
1	43.8	42	1.8
2	42	38.5	3.5
3	38.5	36.0	2.5
4	36.0	33.2	2.8
5	33.2	30.1	3.1

If the proper power output cannot be obtained, either the varactors are at fault or the circuit is not functioning properly. Some of the causes of failures that have occurred during development are dirty components, broken components, or poor contacts. The latter fault is particularly prevalent with the plunger capacitors.

A block diagram of a test setup recommended for aligning the individual frequency multipliers is shown in Figure 35. In the test setup, the isolator following the signal generator facilitates tuning the doubler by minimizing interaction between the generator and doubler. The directional coupler is used to monitor the input power so that a constant value can be maintained. The output filter assures that only the desired harmonic frequency is optimized. A tuner is incorporated at the input and output of each doubler to permit correct impedance matching between it and the respective transmission line. The function of the calibrated attenuators is to decrease the r-f power by a known amount so the power can be measured with a low power meter. The actual power levels in dbm are the sum of the db's of attenuation and the meter reading in dbm.

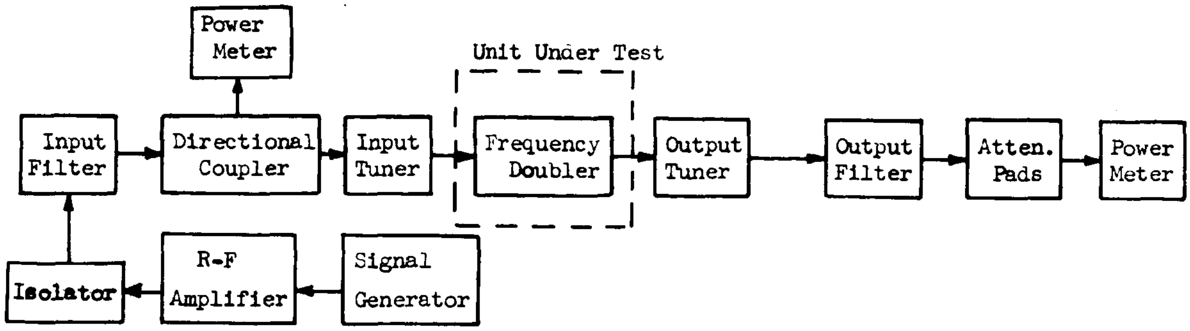

Figure 35. Block Diagram of a Typical Frequency Doubler Test Setup

After each doubler has been individually aligned, the 324 to 648 Mc frequency doubler should be connected to the power amplifier and properly matched by slightly readjusting the capacitors of the doubler for maximum output. The other doublers can subsequently be cascaded in turn; each time a doubler is added all previous tuners should be rechecked for maximum power output. When the 5.2 to 10.4 gc frequency doubler is tuned, its bias should be set to about -10 volts and then adjusted slightly for maximum power output. The -10 volt bias voltage will change slightly if different varactors are used in the final doubler.

A precaution to observe in tuning the doublers separately or in cascade is that each capacitor or tuner adjustment range is broad and does not have any extremely sharp peaks. A nonsensitive tuning condition is essential to insure satisfactory performance over a nominal ambient temperature range.

3.3.6 Ferrite Circulator

The ferrite circulator was designed so that the matching elements form part of the waveguide structure, thusthe circulator has no provisions for adjustments. The magnets used in the circulator are composed of a ceramic material that does not readily change in magnetic strength when placed in the vicinity of other magnetic objects. The magnetic field can however, be diverted somewhat by nearby magnetic materials, causing very slight changes in circulator characteristics. The circulator will readily return to its original characteristics when the magnetic material in the vicinity is removed.

4. CONCLUSIONS AND RECOMMENDATIONS

The accomplishment of this contract has definitely proven the feasibility of obtaining 1 watt at X-band from an all solid state signal source. In addition, hardware has been developed which has the advanced characteristics necessary for a flight packaged, flight proofed high power solid state signal source.

Although only minor effort was directed toward the power amplifier design, some significant factors were achieved. First, the final amplifier was built at 324 Mc, a frequency two to three times higher than normal. This feature particularly illustrates the advancements in transistor technology, and indicates that in the near future, amplifiers will be built at even higher frequencies, thus effecting further increases in solid state signal source d-c to r-f conversion efficiency. A second significant achievement was the successful adding of the output powers from three separate amplifiers. This technique could be used satisfactorily for obtaining power levels much in excess of the 25 to 30 watts obtained during this project. Of course, neither the operation of the amplifiers at the higher frequencies, nor the paralleling of the amplifiers were accomplished for the first time in connection with this project, however, it is believed that each represents current technology limits.

No particular effort was made to keep the 108 to 324 Mc frequency tripler/power amplifier package small, as is probably apparent. Based on packaging densities achieved for similar circuitry, it is estimated that the tripler/power amplifier package could be packaged in a volume of no more than 32 cubic inches. When transistors become available that are now being developed, this package size can undoubtedly be reduced even more.

It is believed that the most significant advancement in circuit technology resulting from this project was in the area of the frequency doublers operating from L- through X-band. The balanced configuration of these units, discussed previously, is believed to be a definite advancement in the state-of-the-art. The multipliers permit operation at twice the power levels of corresponding single ended multipliers, and appear to provide much less tuning sensitivity. During the fairly extensive temperature tests performed on a reproduction of the C- to X-band frequency doubler under NAS 9-2938, it was noted that considerable harmonic rejection was inherent in the basic doubler design.

Each of the frequency doubler packages were designed commensurate with the nucleus of a flight packaged solid state signal source. Of course, considerable progress could still be made in reducing the doubler sizes, perhaps by a factor of two or more. If this were accomplished, and the power amplifier packaged as described, then it is estimated that the entire X-Band Solid State Signal could be packaged within a volume of 90 cubic inches.

It is interesting to notice that in addition to furnishing 1 watt at X-band, parts of the Solid State Signal Source could be used for any of the following:

- 324 Mc, 25 watt signal source
- 648 Mc, 15.8 watt signal source
- 1.3 gc, 7.7 watt signal source
- 2.6 gc, 4.9 watt signal source
- 5.2 gc, 2.5 watt signal source

In view of the performance achieved with the X-Band Solid State Signal Source to date, it is recommended that a follow-on effort be continued to flight package the source and/or a program be initiated to increase the r-f power capability, possibly to 2 or more watts. Follow-on effort would entail development of an engineering model packaged in a flight configuration. Extensive temperature and high vacuum tests would be performed on this model, and necessary modifications made to improve its operation. As mentioned in the final report on the "Temperature Study of Varactor Diodes," prepared under NAS 9-2938, a distinct trade-off exists between the maximum operating ambient temperature and the maximum operating power levels in varactors. This trade-off would be exploited. Any multipactor action incurred during high vacuum tests could be corrected, probably using techniques established in connection with high power microwave tube development.

Upon completion of the engineering model, significant techniques and information would exist so that only minimal effort would be required to obtain a fully flightproof model of a 1 watt solid state signal source. Perhaps more important, a definite advance in technology would have been made and recorded regarding the high power operation of varactors in temperature and vacuum extremes.

If the task were undertaken to extend the power at X-band to 2 or more watts, the power at C-band to 5 or more watts, or the power at any of the other available signals to at least double their present value, it is believed that the same basic frequency doubler circuits would still be optimum. The power amplifier would require fairly extensive modifications, however one of a number of advanced transistors presently being developed would probably be available for the task at that time. New and improved varactors would be researched and would be of possible aid in accomplishing the goal. It is believed that the principal effort in obtaining two or more watts at X-band, however, would be directed toward further refinements of the present X-Band Solid State Signal Source.