SPS SOLID STATE ANTENNA POWER COMBINER

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1. INTRODUCTION

Solid state dc-rf converters offer potential improvements in reliability, mass and low voltage operation, provided that anticipated efficiencies in excess of 80% can be realized. Field effect transistors offer the greatest potential in the SPS frequency band at 2.45 GHz. To implement this approach it is essential that means be found to sum the power of many relatively low power solid state sources in a low-loss manner, and that means be provided to properly control the phase of the outputs of the large number of solid state sources required.

To avoid the power combining losses associated with circuit hybrids it was proposed that the power from multiple solid state amplifiers be combined by direct coupling of each amplifier's output to the radiating antenna structure. The resulting savings in transmitter efficiency ranges from 4% to 10% depending upon the configurations being compared. The selected power-combining antenna consists of a unique printed (metalized) microstrip circuit on a ceramic type dielectric substrate which is backed by a shallow lightweight aluminum cavity which sums the power of four microwave sources. The antenna behaves like two one-half wavelength slot-line antennas coupled together via their common cavity structure. A significant feature of the antenna configuration selected is that the radiated energy is summed to yield a single radiated output phase which represents the average insertion phase of the four power amplifiers. This energy may be sampled and, by comparison with the input signal, one can phase error correct to maintain the insertion phase of all solid state power combining modules at exactly the same value. This insures that the insertion phase of each SPS power combining antenna module is identical even though the power amplifiers are fabricated to relatively loose (low cost) insertion phase requirements.

The concept, illustrated in Figure 1, shows two solid state power amplifier modules with two outputs each at 5 watts delivering power to the antenna. The power amplifiers derive their input from an integrated circuit which performs the function of phase error correction so that each module has the same insertion phase. The phase error correction circuit employs two probes to sample the phase of the of the radiated power. This phase is then compared with that at the module input. A ceramic substrate is proposed to dissipate the heat of the power amplifiers via radiation. The high thermal conductivity of the ceramic substrate and of the aluminum cavity and ground plane will spread the heat so that all surfaces will participate in the cooling process.

The material that follows describes an initial program to verify the suitability of this concept for SPS. An appropriate microstrip antenna is being developed which will be evaluated when driven from four solid state power amplifiers.

2. EXPERIMENTAL VERIFICATION PROGRAM

The objective of the program is to demonstrate the suitability of a 2.45 GHz power combining microstrip slot-line antenna, when fed by four solid state amplifiers, to the needs of a solar power satellite. The program entails the design and fabrication of a four feed microstrip antenna and a stripline antenna phasing network which will be integrated with four transistor amplifiers to demonstrate that the total solid state module (amplifiers plus antenna) will operate as an efficient power combining-radiating system. The antenna developed will be evaluated for gain, pattern and efficiency on the antenna range with and without the amplifiers. The amplifiers will be connected directly to the antenna without benefit of isolators so that their interaction via the antenna will be unimpeded. The combined output power of the amplifiers will be approximately 1/2 watt.

Figure 2 contains a sketch of the power combining microstrip antenna to be evaluated. The dielectric substrate is metalized on both sides. The underside, within the cavity, contains the four microstrip feed lines which are coupled to the two radiating slots on the top side via two narrow slotlines. In order to feed the antenna, two of the rf inputs are required to be 180° out of phase with the remaining two. An antenna feed network is thus required which will provide the four 0°-180° equal amplitude outputs.

The antenna feed network, the power amplifiers and the microstrip antenna will be connected as indicated in Figure 3a. The four cables connecting the amplifiers and the antenna are required to have equal electrical lengths as are the cables connecting the antenna feed network and the amplifiers. This is necessary to retain proper phasing of the antenna.

3. EXPERIMENTAL PROGRAM STATUS

3.1 FEED NETWORK

Three solid state antenna module feed networks have been assembled and measurements on all have been made. Two of the feed networks are needed to accomplish the antenna range tests. The stripline feed network, (Figure 4a), consists of two 0°-180° rat race ring hybrids fed by a single in-phase two-way power divider. The circuit metalization pattern was etched into the top circuit cover plate as a label for the finished feed. Figure 4b contains a photograph of the automatic network analyzer being used to measure the feed network performance.

The insertion loss and insertion phase measurements over a 500 MHz bandwidth indicate (Figure 5) that, at the design prequency, the insertion loss of all ports is nearly equal. The insertion phase error window at 2.45 GHz is 1.5° wide, or ± .75°. The measured results for all feed networks at 2.45 GHz are as follows:

Serial No.	Phase Balance	Loss Balance	Insertion Loss	Isolation & Return Loss
001	±.73°	±.03 dB	.154 dB	25 dB
002	±.39°	±.03 dB	.189 dB	25 dB
003	±.81°	±.015 dB	.172 dB	25 dB
GOAL	± 1°	±.05 dB	.2 dB	20 dB

The measured insertion phase to all ports of each network deviate from a mean value by less than one degree, which was the design goal. The measured loss was less than 0.2 dB for each of the units over and above the 6.02 dB that results from the four way power division. This value will be used again when the antenna efficiency is calculated. A more important parameter is loss balance, which is so small that it is hardly measurable (± .03 dB). Thus, the power delivered to all ports is within 0.7% of the mean value.

The isolation between the feed network output ports is greater than 25 dB for all units. This minimizes the interaction between amplifiers in the final configuration, by preventing reflected power from the input of each amplifier from reaching the input of one or more of the other amplifiers. Thus, the amplifiers are operated as if they were each driven from an isolated source. This is a particularly good operating procedure where one is primarily interested in how well the power combining antenna performs, and in how well the solid state amplifiers interact with each other within the antenna circuitry.

The impedance match realized at each port results in a VSWR <1.12, with a return loss greater than 25 dB. In actual operation, a low output VSWR and good isolation is only available if the input power to the feed network is derived from a well-matched source.

3.2 POWER AMPLIFIERS

The four 2.45 GHz power amplifiers have been supplied by Tron-Tech, Inc. of Eatontown, N. J. and, to date, have only been evaluated under small signal conditions. (Table 1) As can be seen, the amplifiers meet many of the specifications and are out on others. More tests are scheduled to determine how the amplifiers perform under the required drive condition needed to yield 1/8 watt of output power. Until these additional tests are completed, it is premature to speculate on the degree of suitability of the four amplifiers.

Table 1. AMPLIFIER SPECIFICATIONS & SMALL SIGNAL MEASURED VALUES

Parameter	Specification	Measured by Boeing (small signal)
Frequency	2.45GHz	2.45GHz
Power our @ 1 dB gain compression	+21 dBm	Not measured
Gain	6 dB min.	7.76 dB - 8.18 dB
Gain match	±.5 dB max.	±.21 dB
VSWR in:	2.5:1 max.	3.65:1 (one unit)
out:	1.5:1 max.	1.66:1 (two units)
Phase match	± 5° max.	± 2.4°
Phase control	± 10° min.	± 2° by varying B^+ according to Tron-Tech.
Gain Control	by varying B^+	Installed separate loss cont. which yields ± 1.5 dB according to Tron-Tech.
Infinite VSWR save at full power		verified by Tron-Tech.

The amplifiers were specified to be fail-safe under conditions of infinite VSWR at all phases. This was required to insure that the amplifiers wouldn't fail during test. Such a failure would preclude the collection of antenna data with the amplifiers attached. Since the amplifiers are designed to operate Class A, the small signal data exhibited in Table 1 may not change very much under large signal tests.

3.3 RADIATING ELEMENT

A four feed microstrip antenna has been developed which appears suitable for the task at hand. It evolved through a series of steps which began with a microstrip to slot-line coupler and graduated from a single feed slot line antenna to a dual fed slot-line antenna and finally, the four feed design illustrated in Figure 3b. Figure 3b shows the metalization pattern (actual scale) on each side of the microstrip dielectric substrate. The four microstrip lines (shown shaded) cross under and couple their energy to the four narrow slotlines which transport the signal to the wide radiating slots (shown in black). The antenna substrate is 2.6 inches square and is backed by a 2.5" x 2.5" x 0.30" cavity, which couples the radiating slots together.

The antenna, when fed by the feed network described earlier, exhibits a bandwidth at the 15 dB return loss points of approximately 100 MHz. A preliminary pattern taken with the antenna on the range is shown in Figure 6. The peak gain as measured is approximately 8 dB; however, not accounting for 0.43 dB of feed network and cabling losses. The pattern is well behaved with the first sidelobes approximately 23 dB down. A second "cleaned-up" model will now be fabricated to initiate full range testing with and without the power amplifiers.

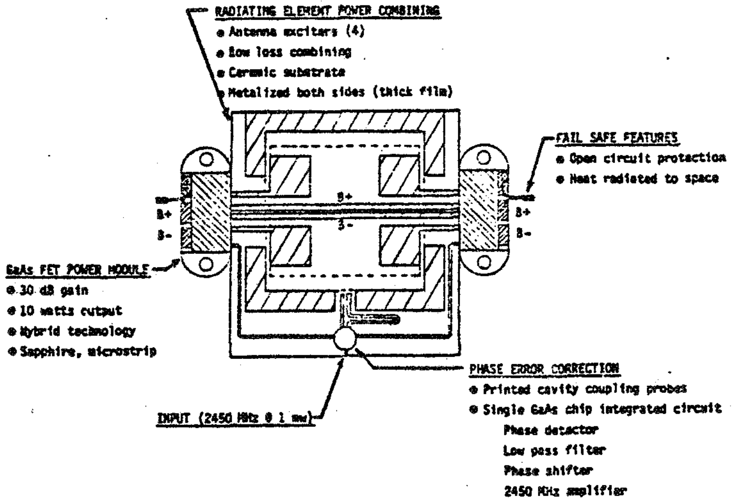
4. TEST PLAN

The primary purpose of the antenna range testing is to determine the efficiency of the four feed antenna with and without the amplifiers. The efficiency is derived by dividing the antenna gain G by the antenna directivity D. The antenna gain will be determined by a 3-antenna method in which antenna spacing is measured to better than 1/2%. This method is expected to yield gain accuracies of ± 0.3 dB.

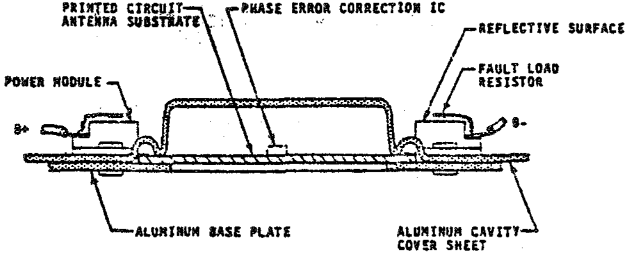
The antenna directivity D is defined as the ratio of the peak radiated power to the average isotropic radiated power (average power radiated over the unit sphere). To arrive at the average isotropic radiated power, one must measure and total up the radiated power over the spherical surface with the unknown antenna at its center, and average that value by dividing by the number of measurements. Typically, a 2° x 2° cell is employed which requires 16,200 measurements. The error associated with the directivity measurement is approximately ± .25 dB.

The antenna feed system insertion loss will be measured on the automatic network analyzer (HP 8542B), which is periodically certified by Hewlett-Packard using standards traceable to NBS to an accuracy of ± 0.15 dB (± 3.51%) for devices of low insertion loss. Thus, when the feed system insertion loss is subtracted from the measured gain, the feed system measurement uncertainty will be added to the previously stated uncertainties. The RSS value of the combined efficiency is thus. $\pm\sqrt{(.30)^2 + (.25)^2 + (.15)^2} = \pm .42\text{db} = \pm 10\%$ Cross-polarized radiation for the SPS application is considered wasted power, and therefore, it will also be measured and included when determining the antenna efficiency.

With the basic antenna characterized for gain, pattern and efficiency, antenna range measurements will then be made with the solid state power amplifiers inserted and operating with a combined output power of approximately one-half watt. The measurement of interest is the difference between the range received power with and without the inclusion of the solid state power amplifiers. The difference should be equal to the gain of the amplifiers. This difference will verify the degree in which the antenna sums the available power of the four amplifiers. Pattern measurements will also be taken to compare with those taken without the power amplifiers. As a final test to verify the entire procedure, the integrated amplifier-antenna system will be tested for directivity and gain, and the overall efficiency will be calculated.

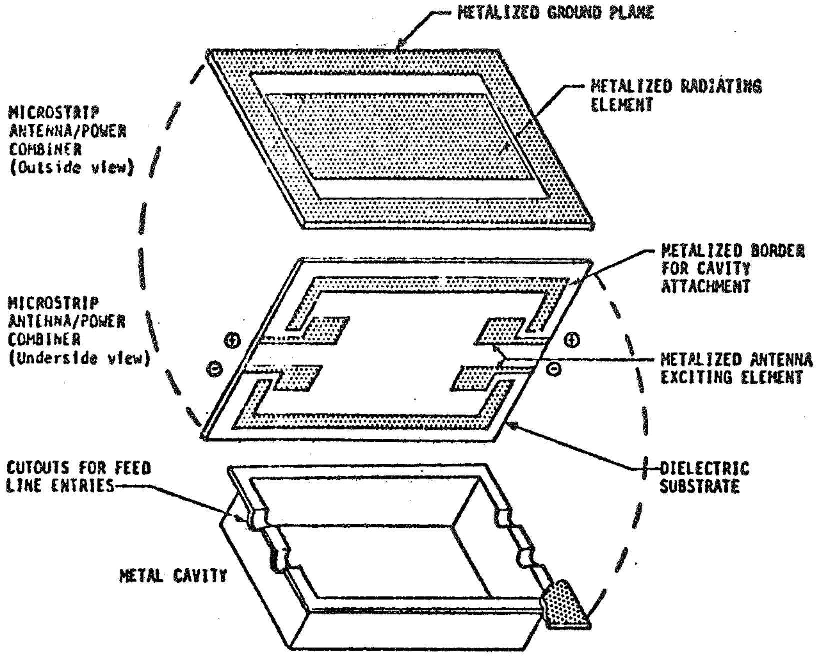


(a) PLAN VIEW

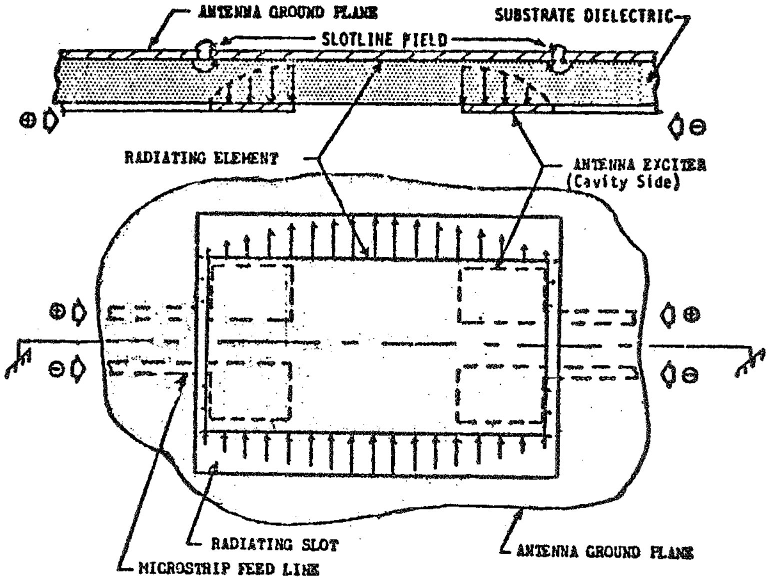


(b) CROSS SECTION

FIGURE 1 SOLID STATE POWER COMBINING MODULE CONCEPT (20 WATTS)



(a) BREAK-A-WAY VIEW



(b) "E" FIELD PROFILE

FIGURE 2 POWER COMBINING MICROSTRIP SLOTLINE ANTENNA

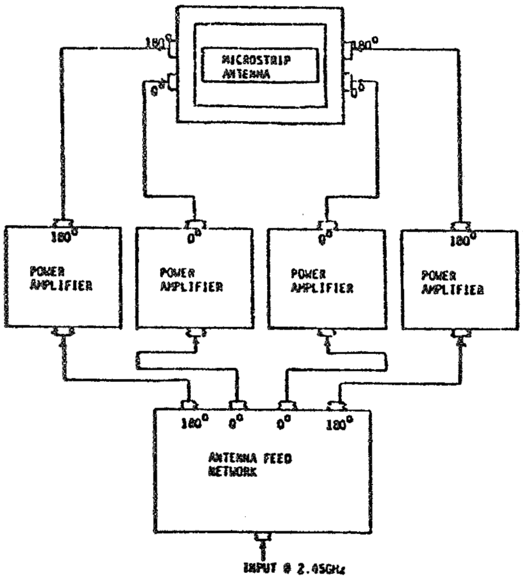


FIGURE 3a POWER COMBINING ANTENNA, FEED NETWORK & POWER AMPLIFIER BLOCK DIAGRAM

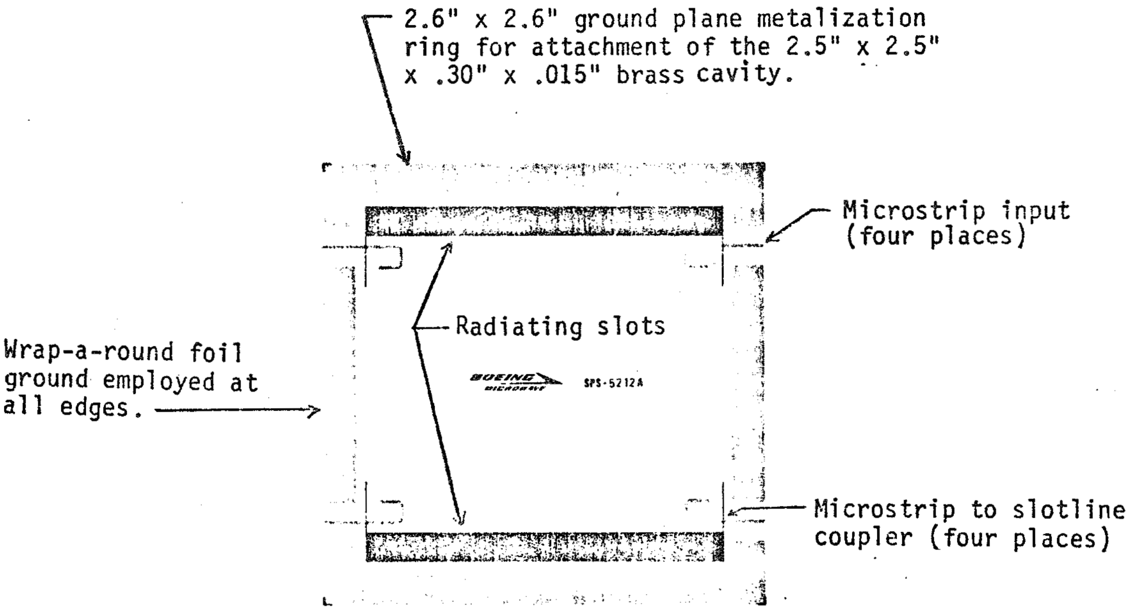


FIGURE 3b COPPER METALIZATION PATTERN FOR FOUR FEED MICROSTRIP ANTENNA

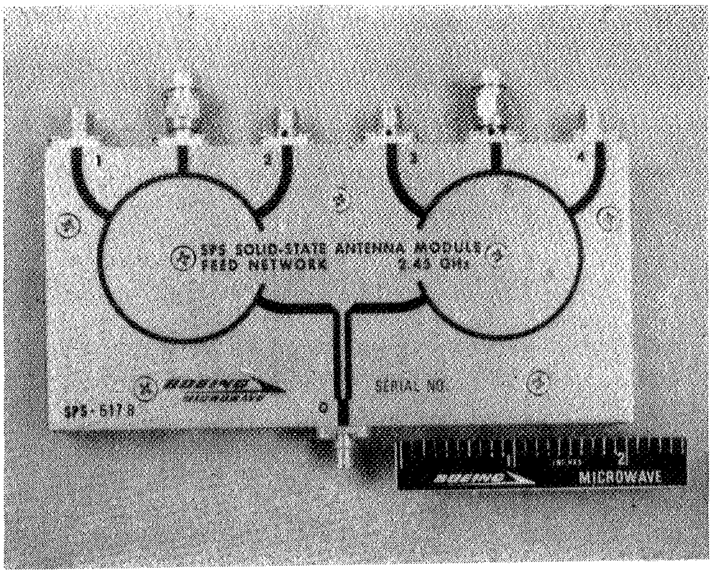


FIGURE 4a STRIPLINE FEED NETWORK

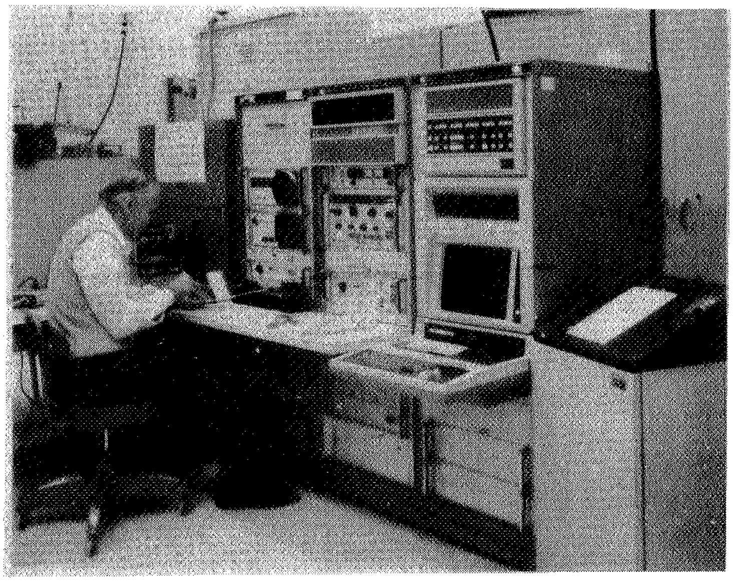
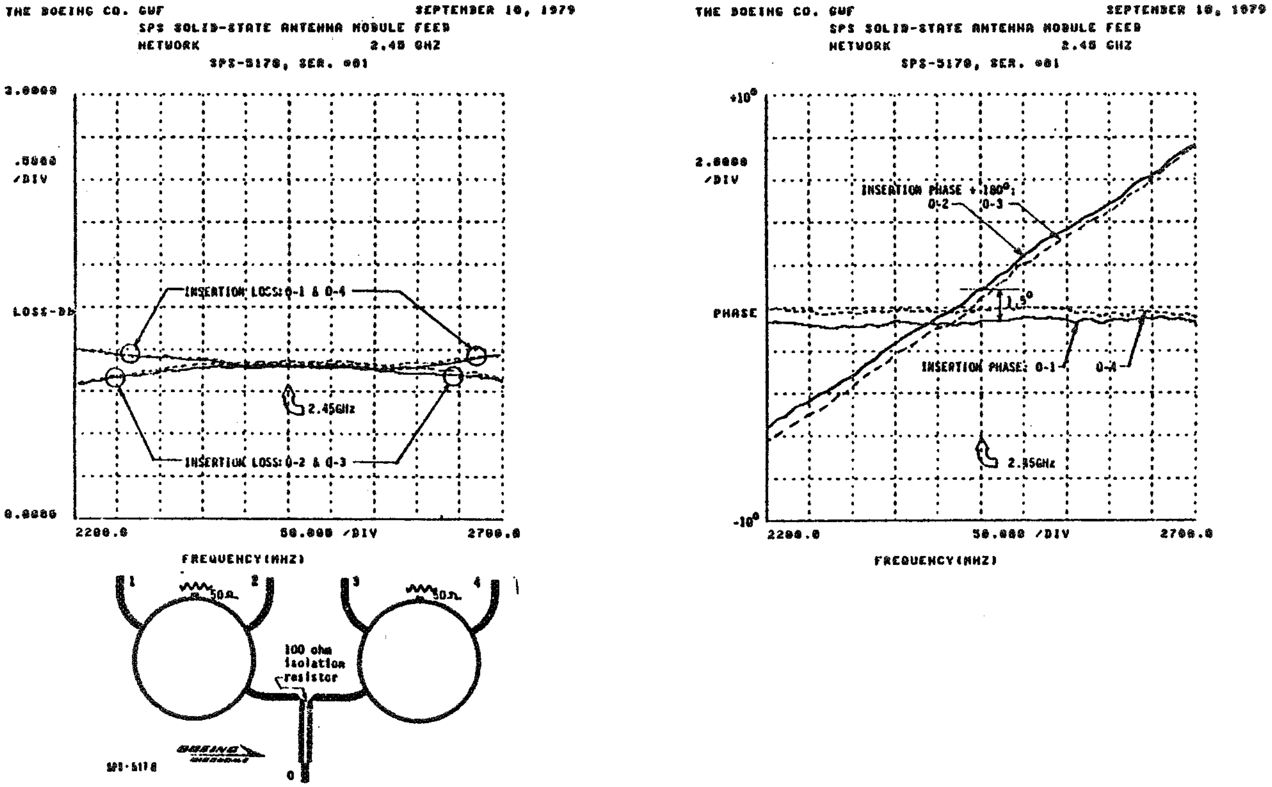


FIGURE 4b AUTOMATIC NETWORK ANALYZER



INSERTION LOSS

INSERTION PHASE

FIGURE 5 INSERTION LOSS AND INSERTION PHASE VERSUS FREQUENCY FOR THE STRIPLINE FEED NETWORK.

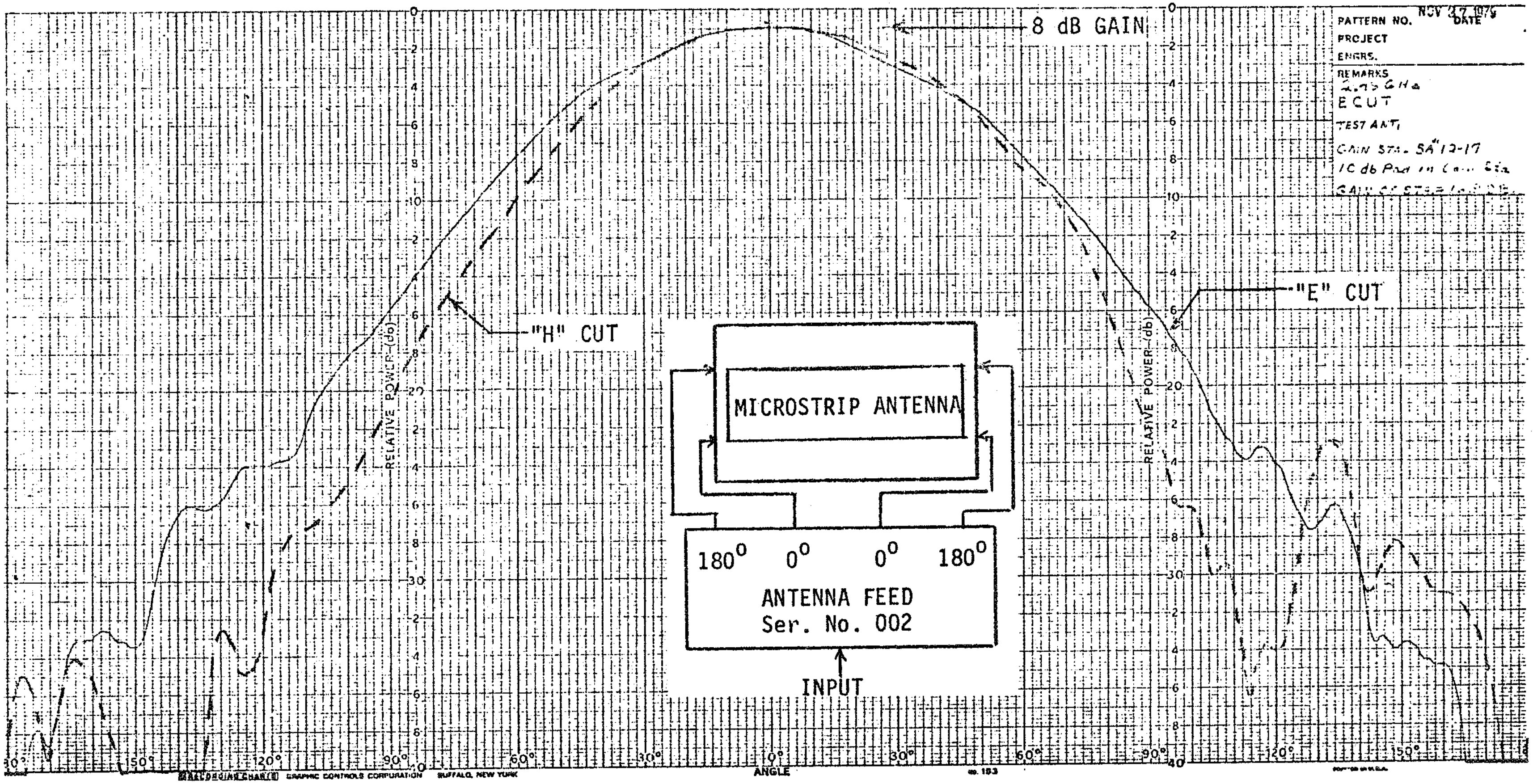


FIGURE 6 ANTENNA RANGE GAIN PATTERN FOR THE FIRST POWER COMBINING MICROSTRIP ANTENNA (FEED NETWORK NO. 2)