Technical Note 1975-38

L. K. DeSize

Measured Characteristics of Variable Power Dividers

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LEXINGTON, MASSACHUSETTS

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FOR THE COMMANDER

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MEASURED CHARACTERISTICS OF VARIABLE POWER DIVIDERS

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Group 61

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ABSTRACT

A multiple-beam antenna system for Defense Satellite Communication System satellites offers an increased flexibility in controlling pattern shape for the suppression of interfering signals as well as providing narrow high-gain beams. One method of controlling the patterns of such an antenna system is to use a beam-forming network consisting of variable power dividers which are electronically controlled. It is then of interest to determine the characteristics of these power dividers. This note presents some measured characteristics of a particular variable power divider that uses non-reciprocal, latching, ferrite phase shifters to obtain electronic control of the amplitude at each of the beam ports of a multiple-beam antenna system.

Measured Characteristics of Variable Power Dividers

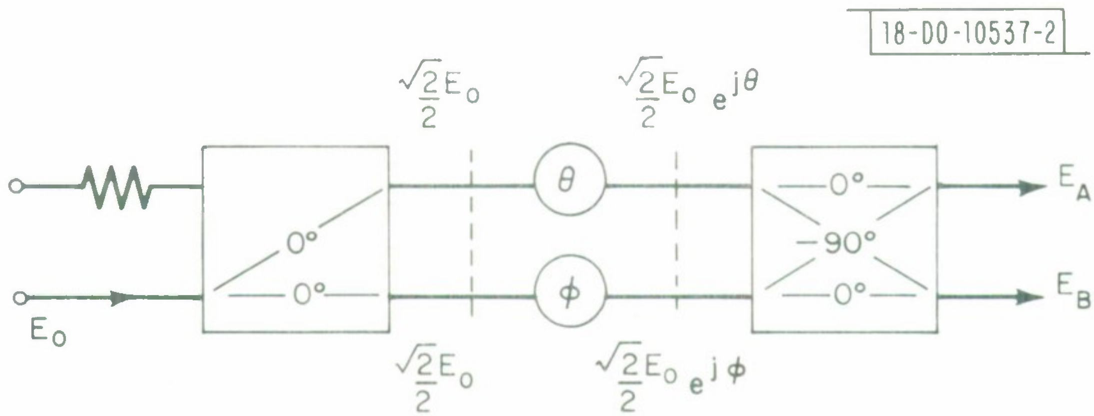
I. Introduction

A previous note [1] presented some characteristics of a communication satellite multiple-beam antenna. Included in that note was a discussion of the use of variable power dividers (VPD's) to form the network for feeding the antenna system. The purpose of this note is to present some measured characteristics of these variable power dividers as well as the non-reciprocal ferrite phase shifters that are used as part of the variable power dividers. Of particular significance are the similarity of the performance characteristics of the individual ferrite phase shifters as well as how these characteristics change with temperature. The first section of this note presents a brief discussion of the operation of a variable power divider and the second section presents the measured characteristics.

II. Operation of Variable Power Divider (VPD)

The operation of a variable power divider can best be understood by referring to Fig. 1. An input signal is applied to the sum port of a magic tee where it is split into two in-phase, equal amplitude signals. Each signal is then passed through a phase shifter into a short-slot hybrid which provides two in-phase outputs, whose amplitudes are proportional to the sine and cosine of the difference in phase setting of the two phase shifters, with the total insertion phase being proportional to the sum of the phase settings of the two phase shifters.

If the two phase shifters have a differential phase shift range from 0 to 90 degrees then the power into the input can be arbitrarily divided



$$E_A = \frac{E_o}{2}\left[e^{j\theta} + e^{j(\phi+90°)}\right] = E_o \sin\left(\frac{\phi - \theta}{2} + \frac{\pi}{4}\right) \exp\left[j\left(\frac{\phi + \theta}{2} - \frac{\pi}{4}\right)\right]$$

$$E_B = \frac{E_o}{2}\left[e^{j\phi} + e^{j(\theta+90°)}\right] = E_o \cos\left(\frac{\phi - \theta}{2} + \frac{\pi}{4}\right) \exp\left[j\left(\frac{\phi + \theta}{2} - \frac{\pi}{4}\right)\right]$$

Fig. 1. Schematic representation of variable power divider.

between the two output ports in any desired ratio, which is only dependent upon the ability to set the phase shifters to a prescribed value of differential phase shift (assuming ideal input and output hybrids). It is also possible to set the phase shifters so that the insertion phase through the device is independent of the power division. For a more detailed discussion of the operation of a variable power divider the reader is referred to [1].

The specific variable power divider that will be discussed in this note uses non-reciprocal, latching, ferrite phase shifters. The phase shifters as well as the input and output hybrids are constructed in WR-112 half-height waveguide (inside dimensions 1.122 x .250 inches) and the VPD's are designed to operate from 7.25 - 7.75 GHz. Lithium Ferrite is used in the phase shifters. A photograph of a complete VPD is shown in Fig. 2.

The phase shifters used in the VPD of Fig. 2 are of the flux transfer type [2], i.e., a reset current pulse is first applied to a latching wire which passes through the toroid. This results in the ferrite being saturated in either a positive or negative reference state depending upon the direction of the current pulse with respect to the flow of RF energy. A second current pulse of opposite polarity is applied to drive the ferrite out of saturation (reference state) into an intermediate remanent state. The section of ferrite loaded waveguide then exhibits a differential phase shift with respect to the reference state. In actual practice the current pulses are supplied by means of driver circuits which take a fixed voltage, fixed width pulse as the reference or <u>reset</u> pulse and a fixed voltage, variable width pulse as the intermediate state or <u>set</u> pulse. The width of the set pulse is then proportional.

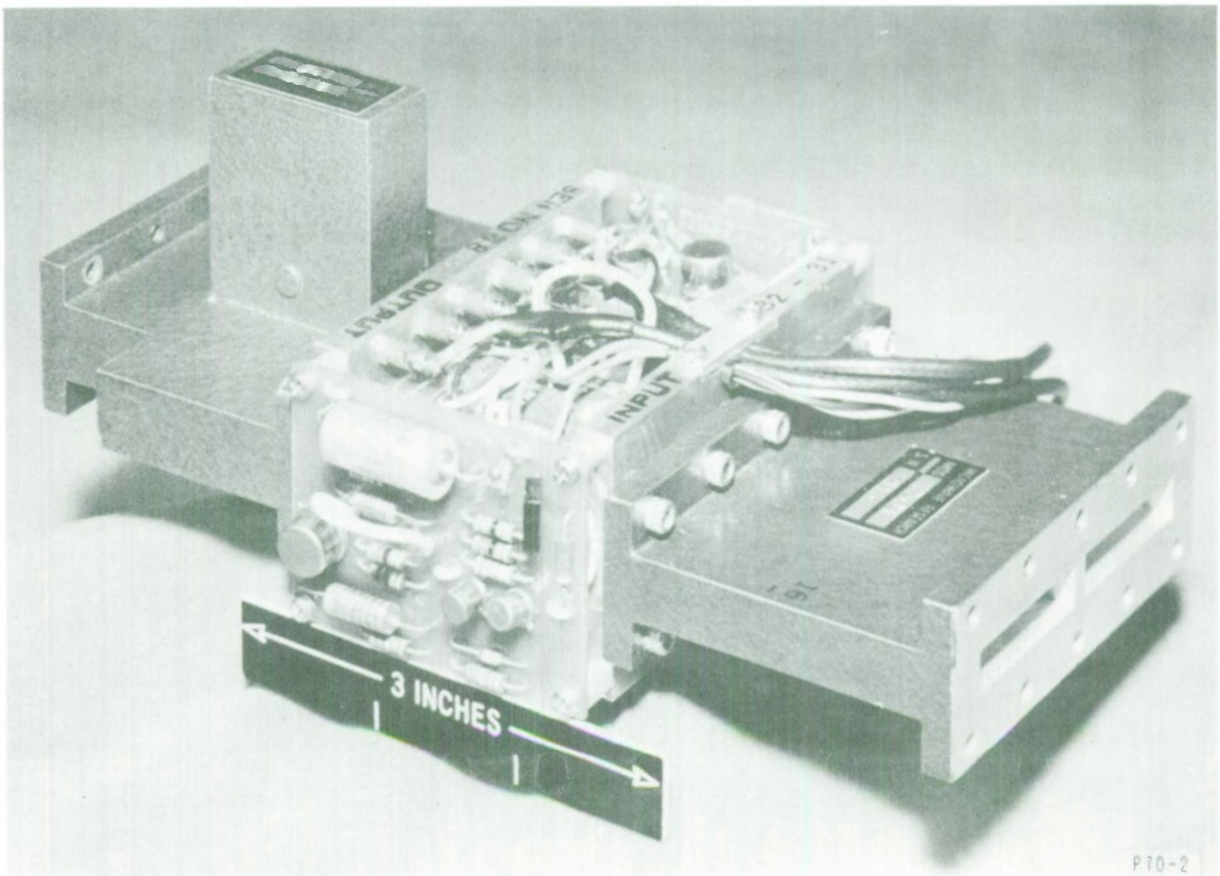


Fig. 2. Experimental variable power divider.

to the differential phase shift. The advantage of this method of operation, as compared to one in which ferrite cores are driven into positive or negative saturated states is that, to first order, a fixed amount of flux is induced in the ferrite, independent of the variation of its characteristics with temperature, so that the phase shift tends to be insensitive to temperature variation. It has been shown that the long reference state (longest electrical length of phase shifter) is more temperature-stable than the short reference state [2], thus both of the phase shifters in the VPD are reset to the long state. A single driver serves to perform this function for both phase shifters, with each phase shifter having its own separate set-pulse driver.

On the basis of the above discussion it is then obvious that to obtain a given power division between the two output ports each phase shifter must be set with a different pulse width (equal power division being the exception). This is illustrated in Fig. 3 which gives the measured amplitude characteristics of a VPD of the type shown in Fig. 2. The pulse width applied to phase shifter A increases from 0.05 to 5 μsec while the pulse width applied to phase shifter B decreases from 5 to 0.05 μsec. The fact that equal power division does not occur when the pulse widths on each phase shifter are equal is due to either the phase shift characteristics of each phase shifter being slightly different or the insertion phase of each phase shifter being different due to manufacturing tolerances or a combination of the two. In addition to the amplitude, the total insertion phase through the VPD can be expected to be reasonably constant [1], since the differential phase on one phase shifter

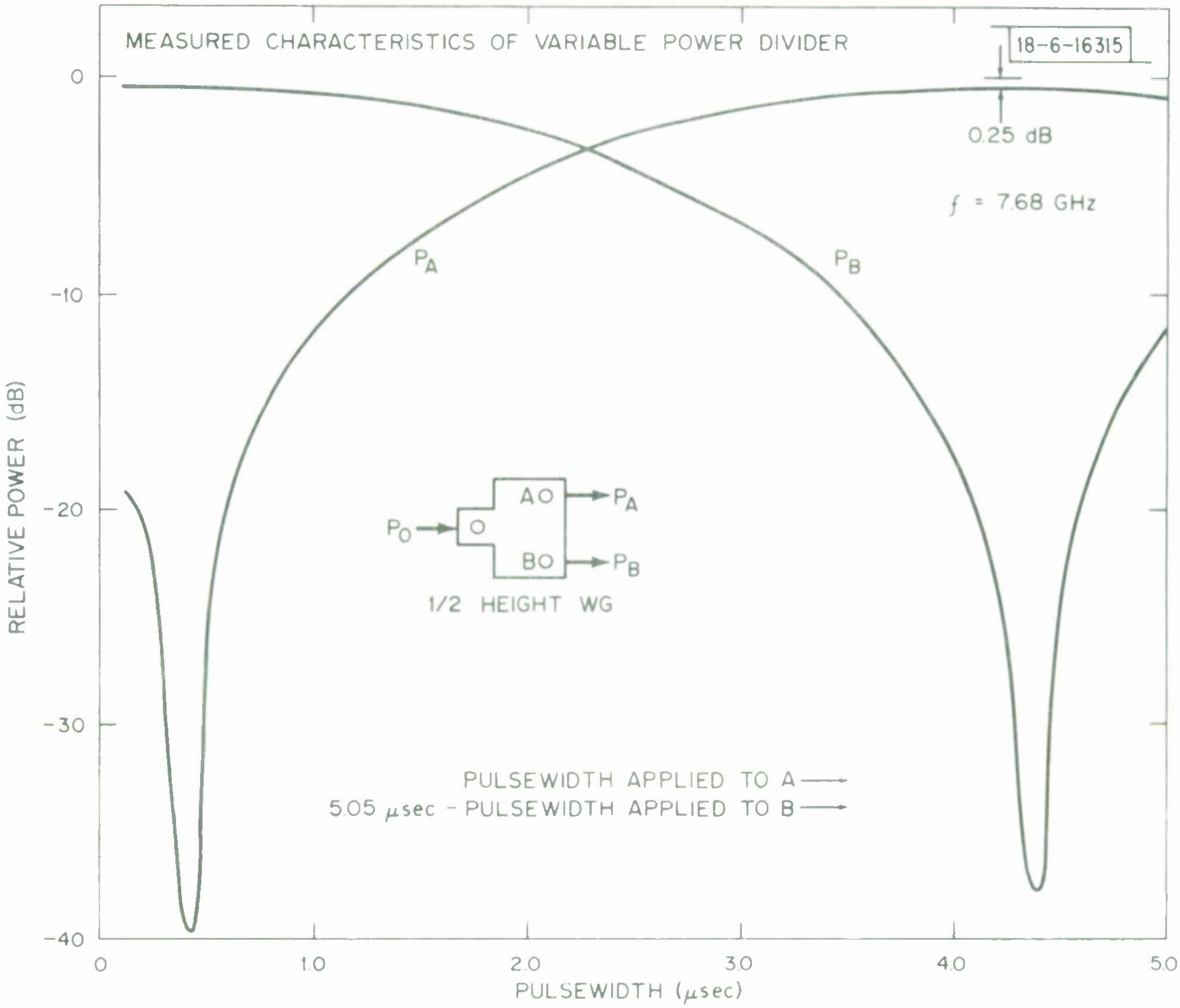


Fig. 3. Measured characteristics of variable power divider.

is decreasing and the differential phase on the other phase shifter is increasing; thus the operation attempts to maintain the sum of the two phase shifts constant.

The following section will discuss some of the measured characteristics of the 40 phase shifters (20 VPD's) that were utilized in the multiple-beam antenna program. Eighteen of the VPD's form the beam-forming network for the 19-beam antenna system, with the remaining two VPD's being spares.

III. Measured Characteristics of Variable Power Dividers

A. Similarity of Phase Shifters

The variation in the phase shift characteristics of the 36 phase shifters used in the beam-forming network was obtained by measuring the phase shift vs pulse width of the units at a frequency of 7.68 GHz. The six units with the largest deviations were neglected, and the data from the remaining 30 units was used to compute a mean phase shift vs pulse width curve. Deviations from this curve were then computed for each of the 30 units and are plotted in Fig. 4. Note that the measured insertion phase of the phase shifters is within $\approx \pm$ 15 degrees of the mean; for 26 units the insertion phase is within $\pm$ 10 degrees of the mean. The deviations in the insertion phase are thought to be due to material differences in the toroids, manufacturing tolerances, and driver characteristics. In particular if the driver circuits were fabricated to match the individual characteristics of each ferrite device, the measured insertion phase of each unit would be closer to the mean of all units.

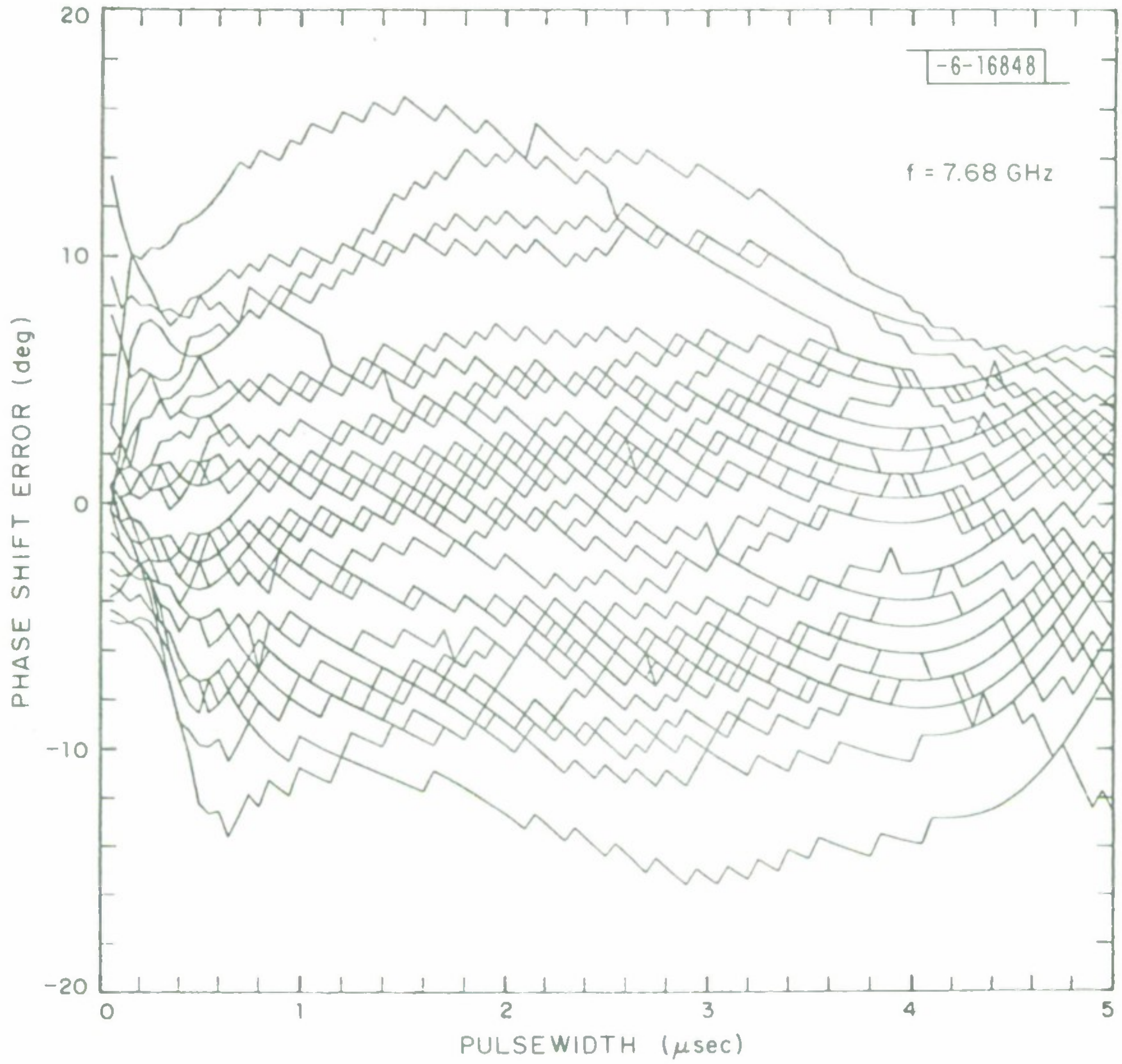


Fig. 4. Deviation of phase shifters from mean phase shift (30 phase shifters).

B. Temperature

The effect of temperature on the phase shift characteristics of the ferrite phase shifters is shown in Fig. 5. Note that, as was pointed out previously, the variation of phase shift with temperature is much less when the phase shifter is reset into the long state as compared to the short state. However the variation of phase shift ($\approx 15°$ over the linear portion of the curve) with temperature when the phase shifter is operated in the long state may still be of sufficient magnitude to warrant operation in a controlled temperature environment or the investigation of compensating techniques such as a driver whose characteristics vary with temperature in such a way as to compensate for the phase shift variation.

Since both phase shifters in the VPD are varying in the same way, there tends to be partial compensation for the phase variation when one looks at the amplitude variation of a VPD. Figure 6 shows the power division error as a function of temperature from a VPD when the power division at an ambient temperature of +20°C is used as a reference. The error for power division greater than -20 dB (with respect to the input power) is less than 1.5 dB; the error is slightly greater at -20°C than at +50°C. The variation in Fig. 6 does not mean the indicated isolation cannot be obtained, rather it indicates that the position of the minimum in the amplitude vs pulse width curve of a VPD (see Fig. 3) occurs at a different pulse width at different temperatures.

The data of Figs. 5 and 6 were obtained at each value of temperature by first applying a reset pulse to the phase shifter(s) and then applying a set pulse to give a prescribed phase shift. In an operational communications

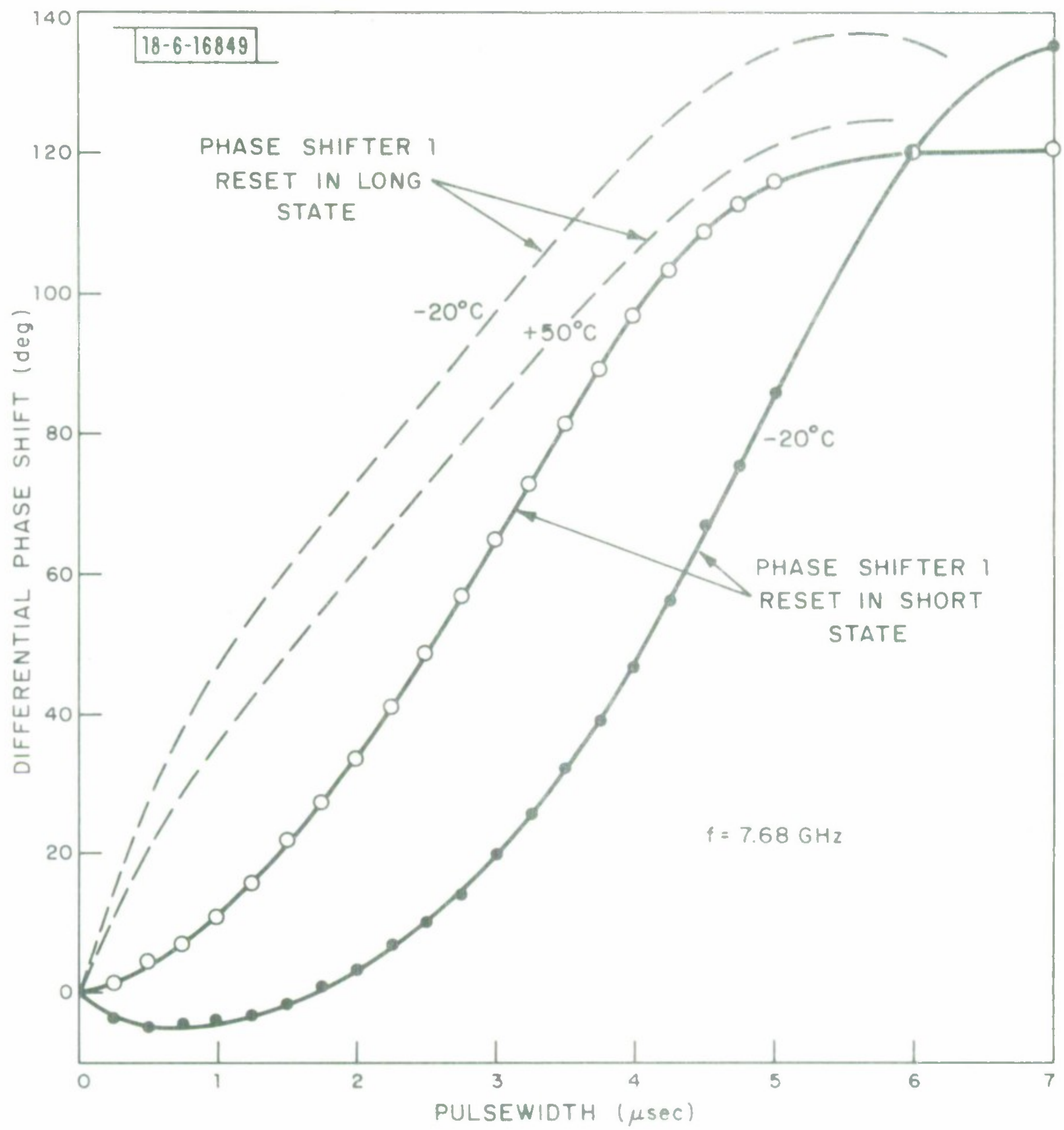


Fig. 5. Differential phase shift vs. pulse width for ferrite phase shifter at temperature extremes.

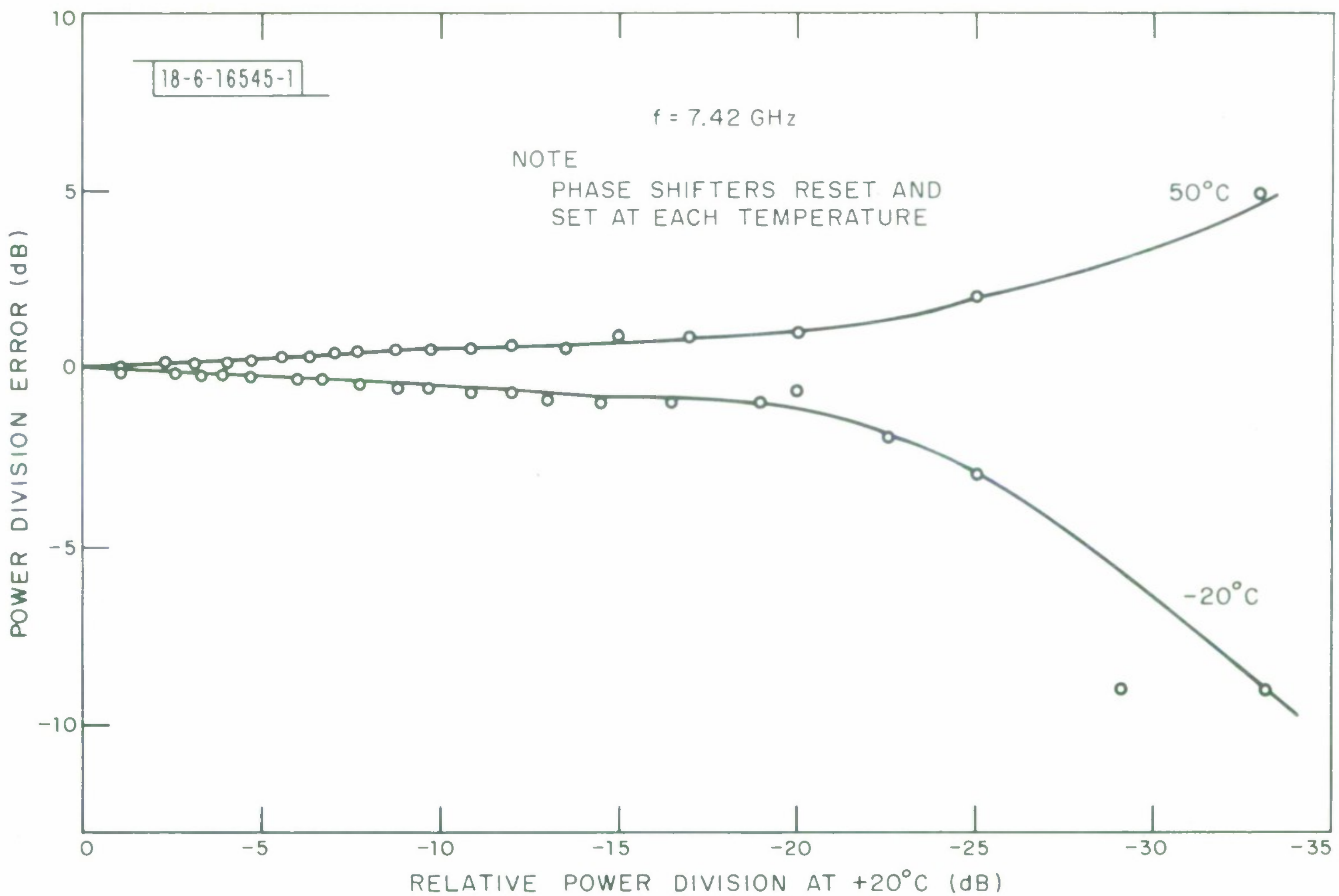


Fig. 6. Deviation of power division in variable power divider as a function of temperature.

system, the beam-forming network may be set to give a particular antenna radiation pattern and then allowed to remain in this state for a time of sufficient length that the ambient temperature might change significantly. It is of interest to examine the variation in insertion phase and power division as the temperature varies. Figures 7, 8 and 9 show some measured results.

Figure 7 shows the insertion phase variation between the input and say port A of a VPD when both phase shifters are in reset (long state). The insertion phase variation is $\approx \pm 6^\circ$ over three full cycles of temperature. This rather small variation illustrates the point made above that the insertion phase of the phase shifter is relatively constant when reset in the long state. The fact that the insertion phase does not repeat exactly is attributed to measurement error ($\approx 1^\circ$) and/or equipment drift over the six-hour span of the measurements. Figure 8 shows the amplitude and insertion phase change when the VPD is initially set for -10.6 dB at say port A and at +20°C. For this case the amplitude variation is $\approx$ 2.5 dB and the insertion phase variation $\approx 30^\circ$. Note that the insertion phase variation is much larger as compared to the reset condition. Figure 9 shows the amplitude variation when the VPD at -20°C is set for a minimum power out of one port (say P_A) and the temperature then allowed to rise. No attempt was made to measure the variation in insertion phase because of the difficulty of measuring phase in a null. As the temperature increase 70°C, P_A increases $\approx$ 18 dB; however when the phase shifters are reset and then set at +50°C (the temperature of maximum amplitude deviation from that at -20°C) the power at port A, P_A, returns to within $\approx$ 5 dB of its original value. This is a demonstration of the flux transfer properties of the phase shifter and demonstrates that one can expect better performance

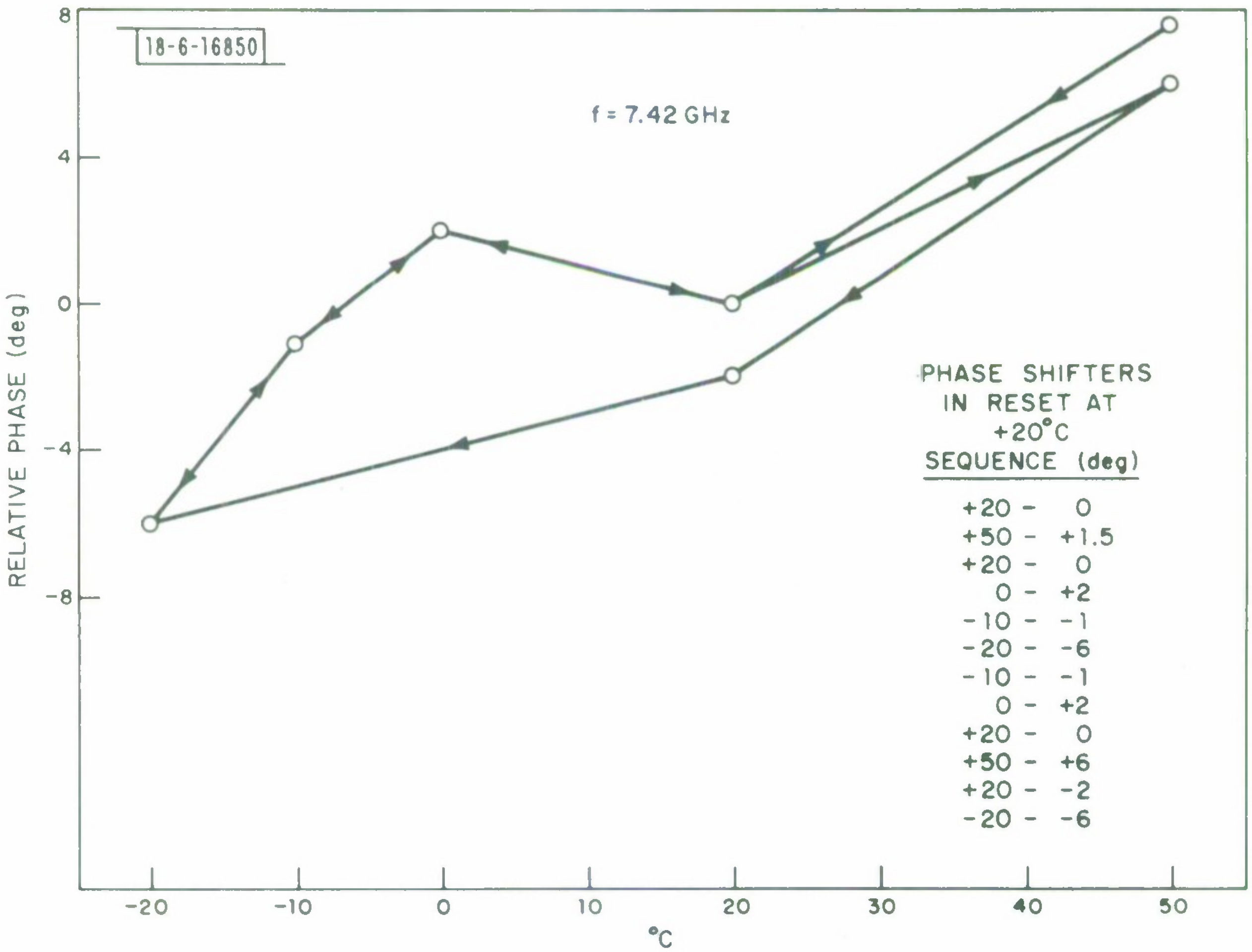


Fig. 7. Insertion phase variation of variable power divider as a function of temperature (reset state).

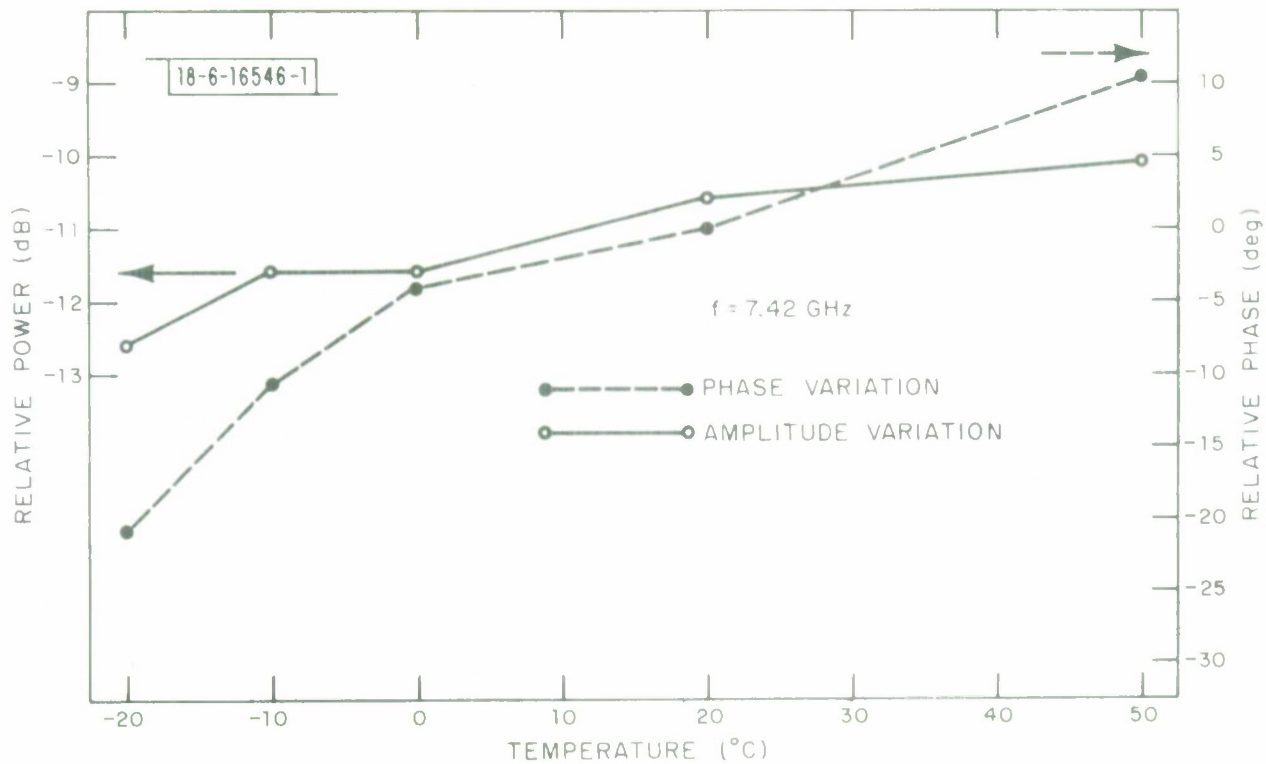


Fig. 8. Variation of insertion phase and amplitude of variable power divider as a function of temperature when phase shifters are reset and set at +20°C for a power division of -10.6 dB.

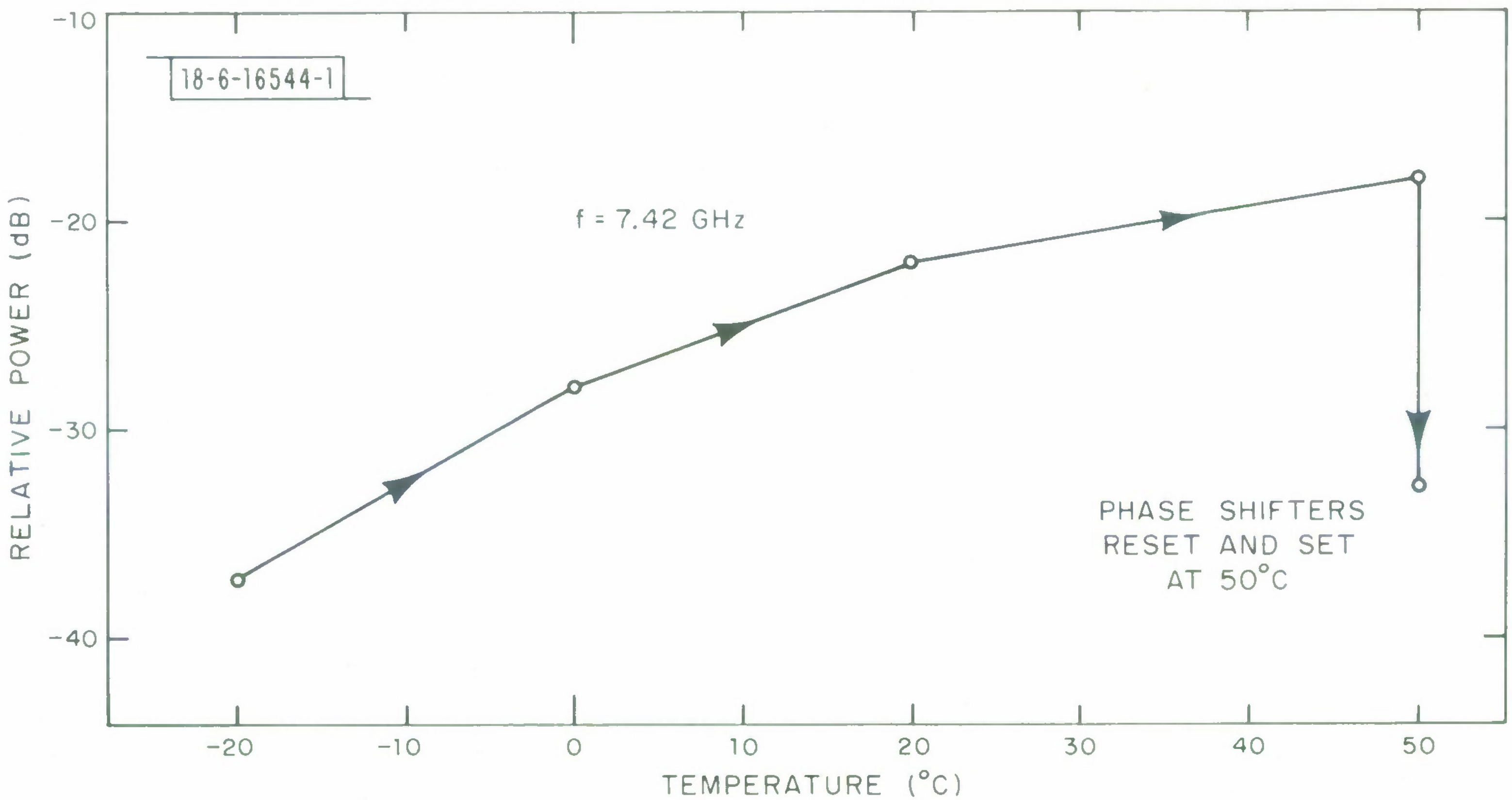


Fig. 9. Change in amplitude of variable power divider in switched position when phase shifters are set at -20°C.

from a VPD if it is reset and then set at different temperatures.

One VPD was also cycled in temperature five times (-20°C to +50°C). Comparing the measured amplitude characteristics, before and after the cycling, showed no significant changes.

C. Variation of Power Without Resetting

In some communications systems it may not be desirable to change the antenna radiation pattern by resetting and setting the phase shifters since the rapid phase and/or amplitude variations caused by resetting and setting could cause a short interruption (≈ 10 μsec) in service to some users. In view of the results discussed in the previous section it is of interest to determine if the power variation and insertion phase variation of a VPD can be controlled without resetting the phase shifters.

In order to demonstrate this technique it was necessary to modify one of the VPD's. If we refer back to Fig. 3 it can be seen that in the normal operation of the VPD both phase shifters are reset in the long saturated state and a short pulse is applied to phase shifter A and a long pulse to phase shifter B with the sum of the two pulses being 5.05 μsec. If the pulse on phase shifter A were increased and the pulse on phase shifter B decreased the power changes as indicated in the figure. Since the reset pulse placed the phase shifters in their long state these pulses decrease the electrical length of phase shifter A and increase the electrical length of phase shifter B, hence maintaining the total insertion phase through the VPD reasonably constant. To retain this property (of constant insertion phase) and operate the phase shifters without resetting it would be necessary to apply a positive incremental pulse to phase shifter A and a negative incremental pulse to phase shifter B.

Unfortunately the drive circuitry available prevented the generation of negative pulses. Therefore, phase shifter B was modified (reversing the leads of the latching wire) to operate out of the short reset state, resulting in an increase of the electrical length of phase shifter B by the application of a positive incremental pulse.

The operation of the VPD in this configuration is shown in Fig. 10. Both phase shifters were reset and then set with a pulse width of 1.4 μsec, both phase shifters were then pulsed with a 0.2-μsec pulse 20 times with the amplitude and insertion phase measured for each incremental pulse. The entire sequence was then repeated using a 0.3-μsec incremental pulse. In the first case the amplitude varied from -24 dB to -3 dB on the port being measured and in the second case the amplitude varied from -24 dB to full power. In both cases the insertion phase variation was < 10°. The other port of the VPD would of course exhibit the inverse amplitude variation. On the basis of the above results the width of the incremental pulse can be used as a parameter in determining the number of incremental pulses (and thus the total time) to change the power by a given amount.

The use of the incremental pulse technique raises the question of how repeatable the results are in view of the amplitude and insertion phase variations with temperature and the fact that the new setting of the phase shifter will depend on its previous magnetic history. Thus it appears necessary to have a method of monitoring the ports of a VPD for both amplitude and phase so that information is available to the pulse controller. No attempt to discuss such monitoring methods will be presented here other than to mention that

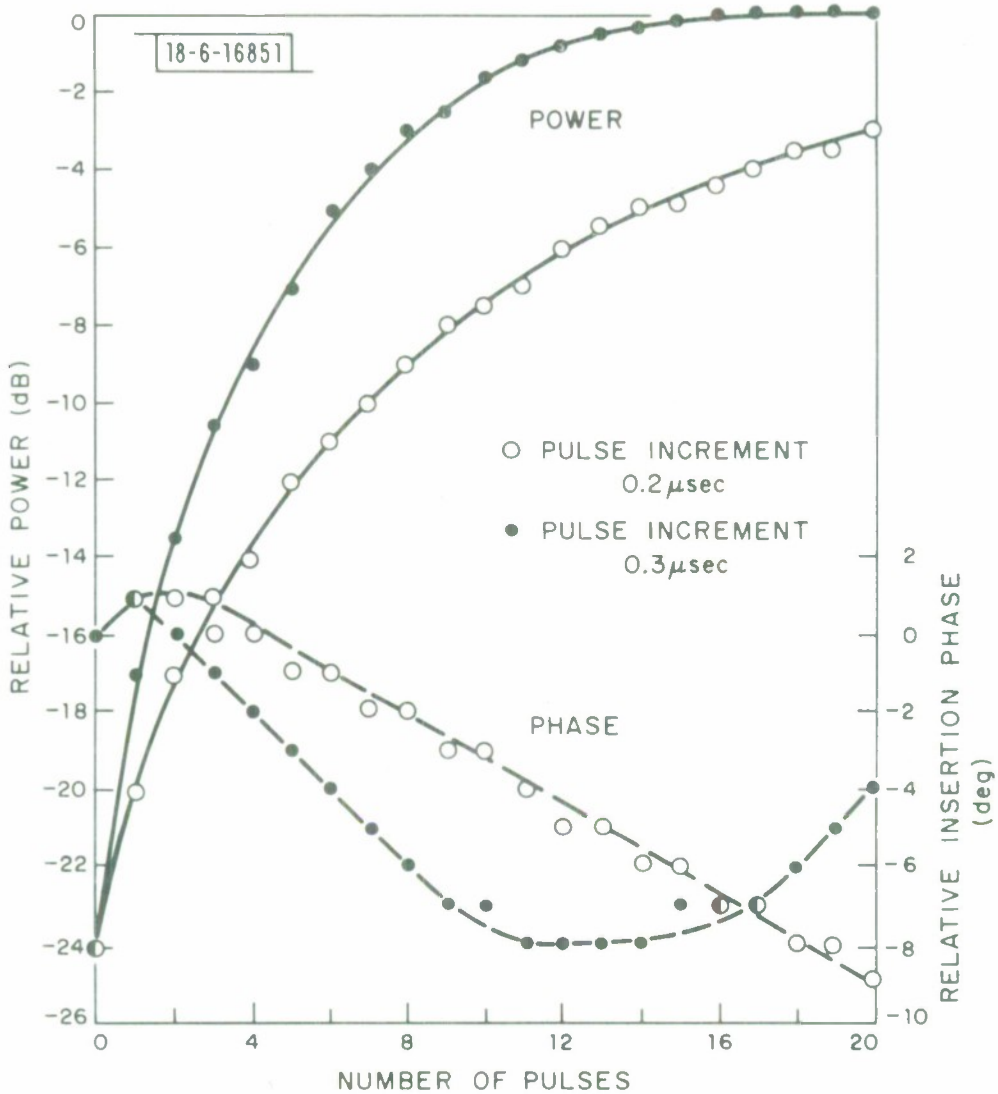


Fig. 10. Power and insertion phase variation of VPD as a function of the number of applied constant-width pulses.

there are several approaches to this problem and that a monitoring system may be required for other reasons, such as a routine check that the beam-forming network is functioning.

D. Resettability of Phase Shifters

The resettability of the phase shifters was measured by resetting and then setting the phase shifters 100 times at selected pulse widths. The 100 values of phase shift were then used to determine the mean and standard deviation of the measured phase shift. In no cases did the standard deviation exceed 0.5 degree.

E. RF Power

Two of the phase shifters were evaluated for phase shift and insertion loss characteristics as a function of RF input power up to 75 watts. No significant change in characteristics was noted.

F. Intermodulation Products

Third- and fifth-order intermodulation produces were measured on four phase shifters using the experimental setup described in [1]. Introducing two 7.5-watt signals separated by 375 MHz into the phase shifters the level of the third-order intermodulation product was $\sim$ -99 dBm and that of the fifth-order was $\sim$ -113 dBm. Extrapolating these results to two 20-watt signals allows one to estimate that the beam forming network would have a third-order IM of -77 dBm and a fifth-order IM of -83 dBm. However, as currently planned, the DSCS III satellite will only use a 40w and a 10w transmitter simultaneously through the beam-forming network (equivalent to a maximum of a 5w and a 20w signal through a single phase shifter). In addition the frequency plan is such that the 10-watt transmitter is at a higher frequency than the 40-watt transmitter. The above factors result in a 12-dB reduction in the level of the third-order IM and an 18-dB reduction in the level of the fifth-order IM. Thus the IM level out of the beam-forming network can be expected to be $\sim$ -89 dBm for the third-order and $\sim$ -101 dBm for the fifth-order. It should be noted that the proposed frequency plan for DSCS III is such that only IM products of the fifth and higher orders will be present in the receive band. For further details on the IM measurements the reader is referred to [1].

Acknowledgments

The measurements reported in this note could not have been made without the benefit of an accurate pulse controller to actuate the phasers. Special thanks is given to S. Srivastava, who designed the controller, and A. Alves who was responsible for its fabrication. The large number of measurements necessary to evaluate the VPD's were performed by J. Perry and C. Slotta. Their patience and attention to the details required for accurate measurements made the results reported in this note possible.

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A multiple-beam antenna system for Defense Satellite Communication System satellites offers an increased flexibility in controlling pattern shape for the suppression of interfering signals as well as providing narrow high-gain beams. One method of controlling the patterns of such an antenna system is to use a beam-forming network consisting of variable power dividers which are electronically controlled. It is then of interest to determine the characteristics of these power dividers. This note presents some measured characteristics of a particular variable power divider that uses non-reciprocal, latching, ferrite phase shifters to obtain electronic control of the amplitude at each of the beam ports of a multiple-beam antenna system.

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