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Switched-Beam Radiometer Front-End Network Analysis

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I. Introduction

Switched-beam networks offer the potential to fabricate electronically steered antennas with RF performance characteristics superior to mechanically steered configurations. This concept has been widely developed and employed for phased-array radars, but has not been thoroughly investigated for radiometer applications. The radiometer application is, in many regards, much more difficult for switched-beam networks than encountered in phased-array radars for a basic reason. In a radar a coherent signal is transmitted to a target and the return signal compared to the original to determine certain parameters of interest about the target, such as range, velocity, etc. The active signal is the main information carrier and since it's characteristics such as frequency, phase, and amplitude are known, it is only necessary to determine how the transmission path and target modify the signal to extract the information of interest. Noise acts to contaminate the signal, but primarily serves to place a limit upon the useful operating range of the radar. Radiometers, conversely, operate on a fundamentally different principle. They do not transmit a source signal, but measure the natural radiation emissions from the target scene. As such, they measure whatever radiation emissions are present within the antenna beamwidth. Noise generated within the path between the target scene and radiometer or within the antenna/network circuit will contaminate the desired radiometer signal. Since the instrument is basically measuring noise, it is, in general very difficult to differentiate between the path/system noise and the desired target emissions.

The noise contamination problem can be minimized by proper calibration procedures. In this manner it is possible to measure or calculate the characteristics of the noise generation mechanisms between the target scene and the instrument read-out. Once the noise characteristics are known, they can be subtracted from the composite signal to yield the desired target scene. As long as the unwanted signals are deterministic it is possible to improve the instrument performance by calibration. Unfortunately, certain signals are not deterministic and cannot be removed from the composite signal by calibration. These signals can prove very troubling and will present limitations to system sensitivity. Examples of this type of signal include anything that has a basically random performance characteristic. For example, a switch that alternates between two positions is deterministic only if it returns to exactly the same position every time it is activated. Since a physical switch will have tolerances associated with its operation, it will not have exactly the same characteristics every time it switches. The tolerances depend upon both mechanical and electrical parameters. The tolerance problem ultimately will define the sensitivity of a radiometer, since small variations in the device impedance will produce slight impedance discontinuities that will generate noise. The noise generated from the performance tolerances is not deterministic and cannot be calibrated out and will, therefore, place a limitation upon the radiometer sensitivity.

The problem is fundamental to the use of switched-beam networks for radiometers. The purpose of this study is to investigate this issue. Specifically, a particular combiner network is modeled and investigated in order to determine its noise performance. The network consists of a series of parallel delay lines with an ideal antenna element at one end and connected together by means of an ideal combiner. The noise performance of a lossy combiner and the use of such an element in switched-beam radiometer front-ends is also considered and reported. The effects of delay line fabrication were also considered and preliminary work directed towards investigation of the noise performance of example phase shift elements is reported.

II. *Delay Line Investigation*

For this investigation a series of delay lines fabricated from microstrip were simulated using the Hewlett-Packard Microwave Design System. The lines were operated for a band of frequencies centered at f_o = 4.3 GHz. The wavelength in free space corresponding to this frequency is λ = 2.75 inches or λ = 0.229 feet. Arrays with $2 \leq N \geq 16$ elements placed on $\lambda/2$ centers were simulated. The investigation considers one dimensional angular sweeps. The angle was allowed to vary from on-axis boresight (zero degrees) to +/- 45°. Since the array is symmetric, it is sufficient to consider only positive angles as the negative angles will be simple mirror images of the positive angle results. The angle is measured in terms of the free space distance between adjacent elements. This length is extended out to $\lambda/2$, which corresponds to an "end-fire" orientation of 90°. The results are presented so that the center of the plots corresponds to the 45° angular location. Narrow bandwidths of a few percent are considered so that dispersion has negligible effects upon the performance of the array. Although most of the work considered the use of microstrip transmission lines, other transmission media, including TEM transmission lines, were considered. The TEM transmission lines, however, are considered impractical for lengths of a few inches that are of interest for the frequency and array size investigated in this work.

Delay Line Implementation

The microstrip model used in the simulation is selected so that the signal is attenuated at a rate of 2.5 db/foot, which is significantly lossier than obtained with coaxial transmission lines. This is not restrictive, however, since the simulations predict that for small arrays the attenuation is negligible compared to other effects in the system. High attenuation rates result in the noise figure being dependent upon the steering angle, but this effect is not significant for losses up to about 5 db/foot. The delay lines are assumed to be switched by PIN diodes which introduce negligible noise compared to other effects in the system.

An alternative to delay lines are electrically controlled filters with specifically designed phase characteristics. In this type of network the delay is established primarily by varactor diodes, which can be tuned by bias to present the correct impedance to generate the desired delay. This operation is in contrast to the use of the varactor diodes as switches where they simply switch lengths of transmission line in or out of the network. The varactor diodes in the filter network will have reactance characteristics that are strongly determined by the electronic bias and the reactance tolerance will be directly dependent upon the bias tolerance of the source. Unless extremely stable bias sources are employed this type of network may contribute significant noise. The amount of noise will be a function of the diode resistance as well as the bias source stability. This type of network has the advantage of small size and easy integration, however, and may be useful for the switched beam application. Due to time limitations it was not possible to completely investigate these networks at this time, but they should be investigated in more detail due to the potential advantages offered.

Antenna Element Model

Several circuits were evaluated for the switched-beam radiometer front-end network. Two general models were investigated in detail. Both network models use arrays of delay lines with realistic loss and both use power combiners to combine the output from the delay lines into a 50 Ω load. The two models differed in the details of the method used to simulate the antenna and free space propagation. One model used power splitters to distribute the output of a source to lossless delay lines used to model free space propagation. That model was found to not accurately model the desired network for reasons that will be discussed. A model that accurately simulated the desired network was constructed by use of voltage-controlled voltage sources with specified phase. These elements permitted the free space wave to be simulated for any incident angle by control over the individual phase at each source. The resulting circuit for a 4 element network is shown in Fig. 1 and was used for this investigation.

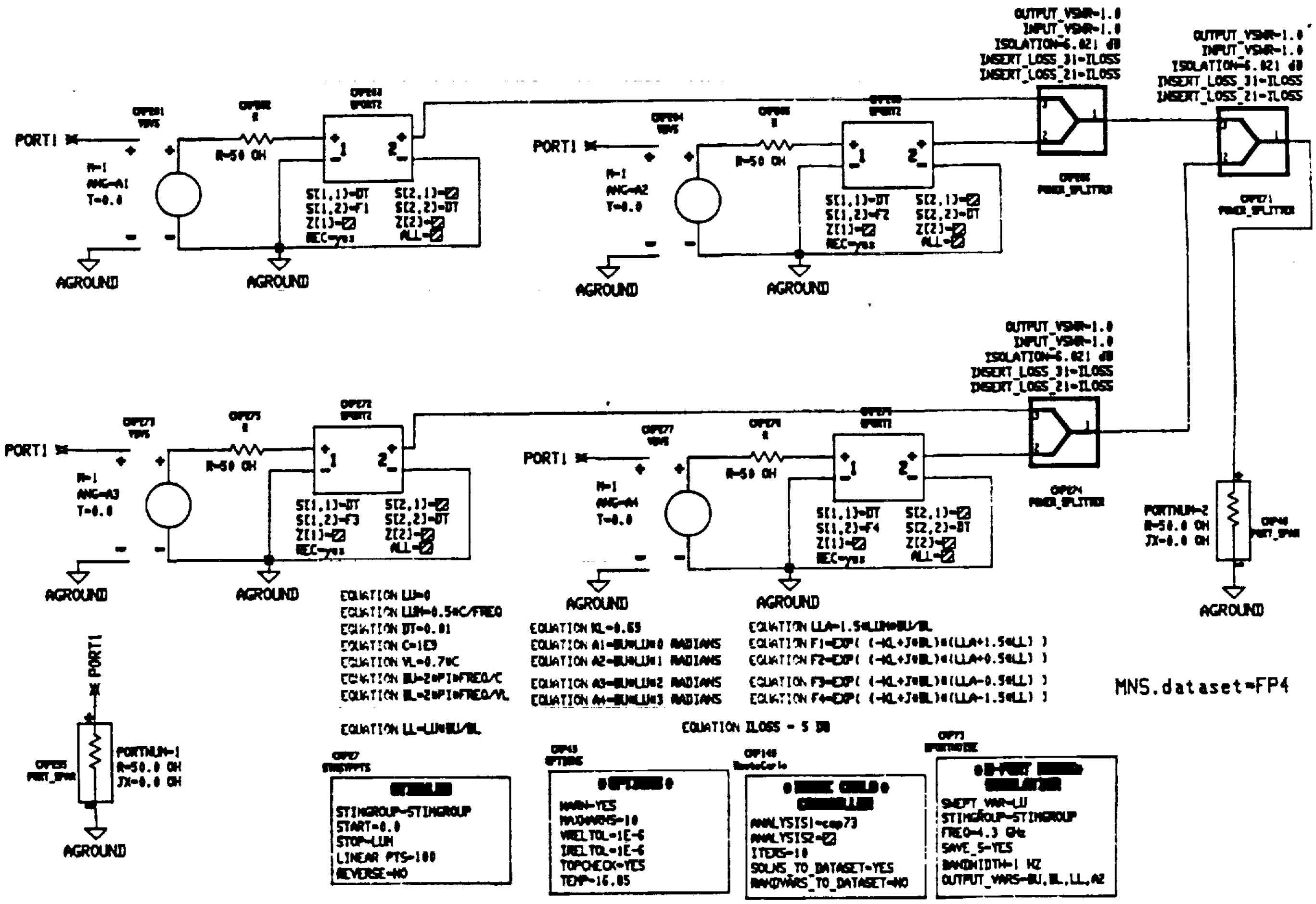

Fig. 1 Switched-Beam Network Model

Originally, attention was directed towards investigation of the noise performance of the delay lines and it was desired to isolate the delay line effects from those of the combiner. Therefore, the array was modeled with a series of delay lines connected by an ideal power splitter on the input and an ideal combiner on the output. The power splitter and combiner had no losses and contributed no noise to the network. When the noise performance of the network was calculated a very surprising result was obtained. It was observed that the lowest noise performance was obtained when the array was tuned to the extreme angular positions at the +/- 45° positions. This result is contrary to intuition since the extreme angle positions require longer delay lines with their corresponding loss. The extra length of lossy line should produce more noise so that the highest noise is expected at the extreme angle positions.

The reasons for this performance were investigated. It was discovered that the anomalous behavior was related to the model used in the simulation. The power splitter on the array input does not accurately model the performance of the desired network. In fact, the power splitter creates a simple parallel topology of delay lines, rather than a suitable model of a switched-beam network. When the array using the input power splitter is tuned to the extreme angle position the delay line on one end is tuned to maximum delay and the delay line on the other end of the array is tuned to zero delay. The array of delay lines operates as a group of parallel resistors and the noise performance is defined by the net equivalent resistance. Since the end line tuned to minimum delay has the lowest resistance it will, therefore, dominate the parallel combination and the minimum net resistance will be obtained when the array is tuned to extreme angle positions. Conversely, the largest net resistance (and the greatest noise performance) is obtained when all the delay resistors are the same, which occurs when the network is tuned to the zero angular position. This behavior explains the observed performance and indicates that the power splitter model is not an accurate representation of a switched-beam input network.

A suitable model for the switched-beam network is obtained by removal of the input power splitter and locating a voltage source on the input of each delay line element as shown in Fig. 1. The binary power combining strategy is also shown in Fig. 1 and demonstrated for an array of four delay line elements. Removal of the input power splitter eliminates the paralleling effect of the lossy lines. Each element is modeled as a voltage-controlled voltage source with a specified phase and an impedance of 50 Ω at the frequencies of interest around the center frequency of 4.3 GHz. The phase of the n^{th} element is

$$A_n = B_U \cdot L_U \cdot (n-1)$$

where $B_U = 2\pi f/c$ is the free space wave number which depends upon frequency $f = 4.3 \times 10^9$ and $c = 9.84 \times 10^8$ feet/sec. The attenuation coefficient of the microstrip delay line is $K_L = 0.69/foot$, which corresponds to *2.5 db/foot*.

Networks of varying complexity are formed by using a series of 2x1 combiners as shown in Fig. 1. By cascading the combiners network complexity will increase by a factor of two. That is, one combiner will have two lines. A network of 4 lines, however, will require the use of three 2x1 combiners. For this work combiners with loss are considered since the combiner will be a significant noise source as the number of lines increase. The attenuation of the power combiner is described in terms of the loss of a corresponding power splitter. This loss was varied from 3.1 db (3 db of ideal combiner loss and 0.1 excess resistive loss) up to 5 db loss (3 db ideal combiner loss and 2 db excess resistive loss) in order to determine the effects of the loss upon overall system performance.

Simulation Results

Three different simulation experiments were performed. First, two different delay line architectures were investigated and the noise figure performance of each was determined. Second, the dependence of noise figure on the loss in the power combiners was investigated. It is demonstrated that small losses in the combiners have a limiting effect upon the optimal size of the array. Third, the effect of uncertainties in the microstrip delay lines were considered. The effects of line tolerances were investigated by means of Monte Carlo simulation techniques. This effect is very significant in establishing radiometer sensitivity since the resulting noise is not deterministic and cannot be calibrated out, as previously discussed.

Delay Line Architecture

Two delay line architectures based upon the network shown in Fig. 1 were considered. The first is an arrangement in which there is no delay on axis and as the beam is steered to end-fire, delay is added to compensate the free space delay according to

$$L_L = \frac{B_U}{B_L} L_U$$

where L_U is the free space delay length, $B_U = 2\pi f/c$ is the free space wave number, $B_L = 2\pi f/v_L$ is the wave number in the microstrip, and $v_L=0.7c$ is the phase velocity in the microstrip. This results in low noise figure on axis and high noise figure off axis as shown in Fig. 2, which shows the noise figure performance for arrays fabricated using 6 db power combiners. The power combiners include 3 db of resistive loss. In Fig. 2 the horizontal scale is the delay line length in feet with the left hand side indicating zero delay and the right hand side indicating +90^{o} phase, which occurs at 0.116 ft. or 0.5λ for operation at 4.3 GHz. The vertical scale is the combiner noise figure with a maximum of 4 db indicated. Array sizes of 1, 2, 4, and 8 elements are shown. As indicated, the noise figure for the arrays increase with phase angle. At zero phase the arrays have only the 3 db ideal combiner loss. As delay line length increases more resistive loss is encountered and noise figure increases. As expected the maximum loss and greatest noise figure is encountered with the largest array size.

The second architecture is designed to reduce sensitivity of the noise figure to angle. The delay line lengths on axis are selected to be the average length value determined by

$$L_{average} = 0.5 \cdot L_{U,\max} \cdot \frac{B_U}{B_L}$$

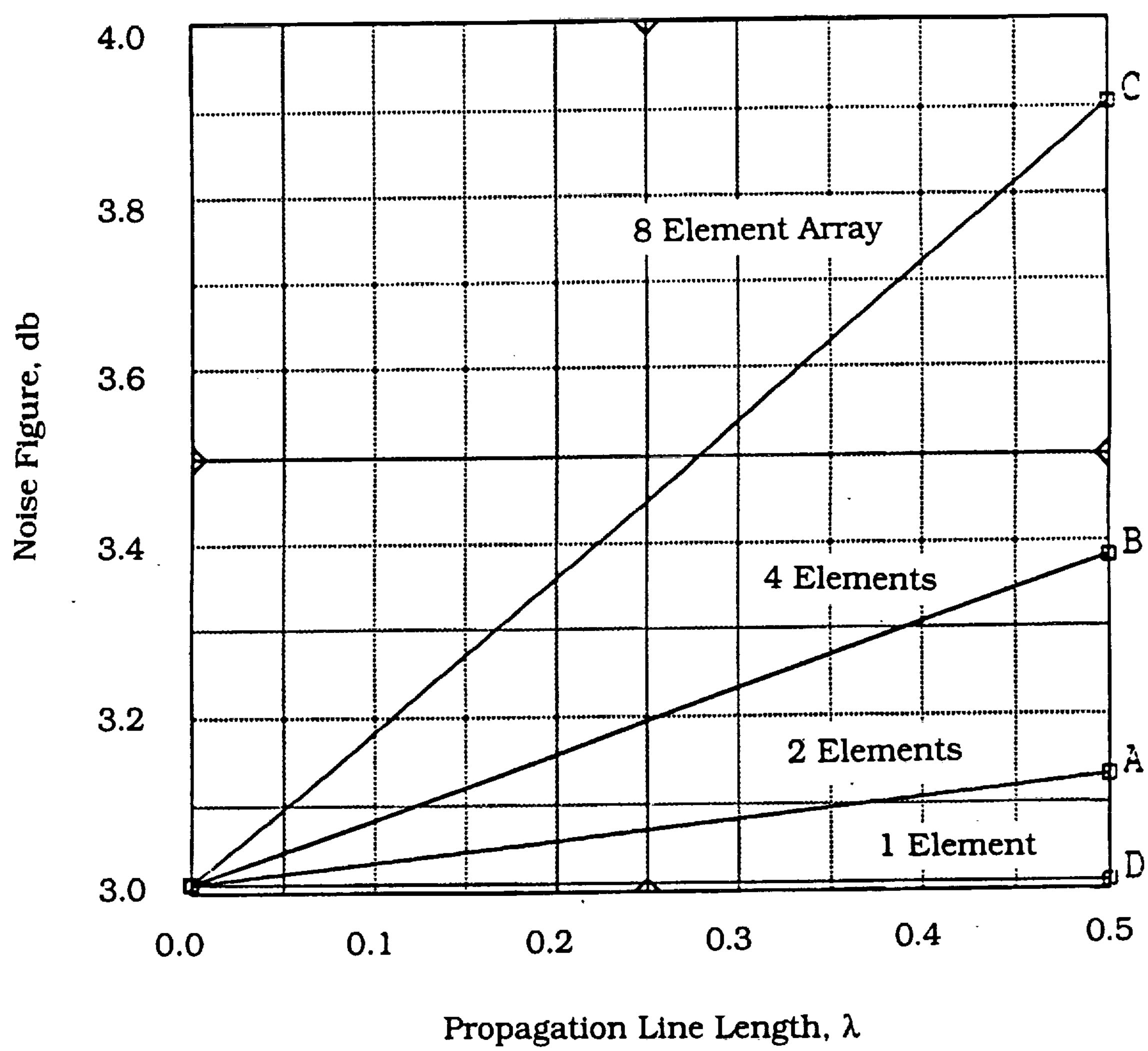

Fig. 2 Noise Figure for Combiner Arrays with Zero On-Axis Delay as the Beam is Swept From On-Axis to End-Fire (λ in free space = 0.116 ft. at 4.3 GHz)

and are either shortened or lengthened to steer the beam. As shown in Fig. 3, this increases the average noise figure compared to the other architecture, but essentially eliminates the angular dependence of noise figure for the arrays considered (i.e., $N \leq 8$).

Fig. 3 indicates that the noise figure of the second design falls slightly with increasing steering angle even though a comparison of the performances shown in Figs. 2 and 3 shows that the sensitivity of the network performance to steering angle is greatly reduced in the second design. For the first design the noise figure indicated in Fig. 2 rises rapidly with steering angle as expected. But for the second design with on-axis delay, there is a weak reverse dependence upon steering angle: the noise figure falls with angle, contrary to expectation.

For very lossy delay lines, this reverse dependence on steering angle is clearer, as shown in Fig. 4 where the noise figure for two 8 element arrays is presented. The arrays differ in the amount of loss. One array has a loss factor of $K_L = 0.69/foot$ and the other a loss factor of $K_L = 2.5/foot$. The second loss factor is much greater than expected in practice and is shown only for illustration purposes to indicate trends. It indicates that only for very lossy lines does the noise figure of the array depend significantly upon the beam angle. The maximum noise figure occurs on-axis. This result is explained in terms of simple circuit theory for parallel resistive circuits. However, the gain of the antenna is correspondingly reduced for large steering angles, so that the output signal is also lower at high angles.

For larger arrays, lossier lines, or lower frequencies, attenuation increases and more structure is obtained in the noise figure versus angle performance characteristics as shown in Fig. 5 for array sizes up to N=16. The noise figure dependence results from the excess losses in the power combiners. The optimal number of elements with respect to noise figure can be determined for various power combiner losses. For the largest array (N=16) the noise figure is greatest at the zero delay line length position and decreases as delay line length is increased.

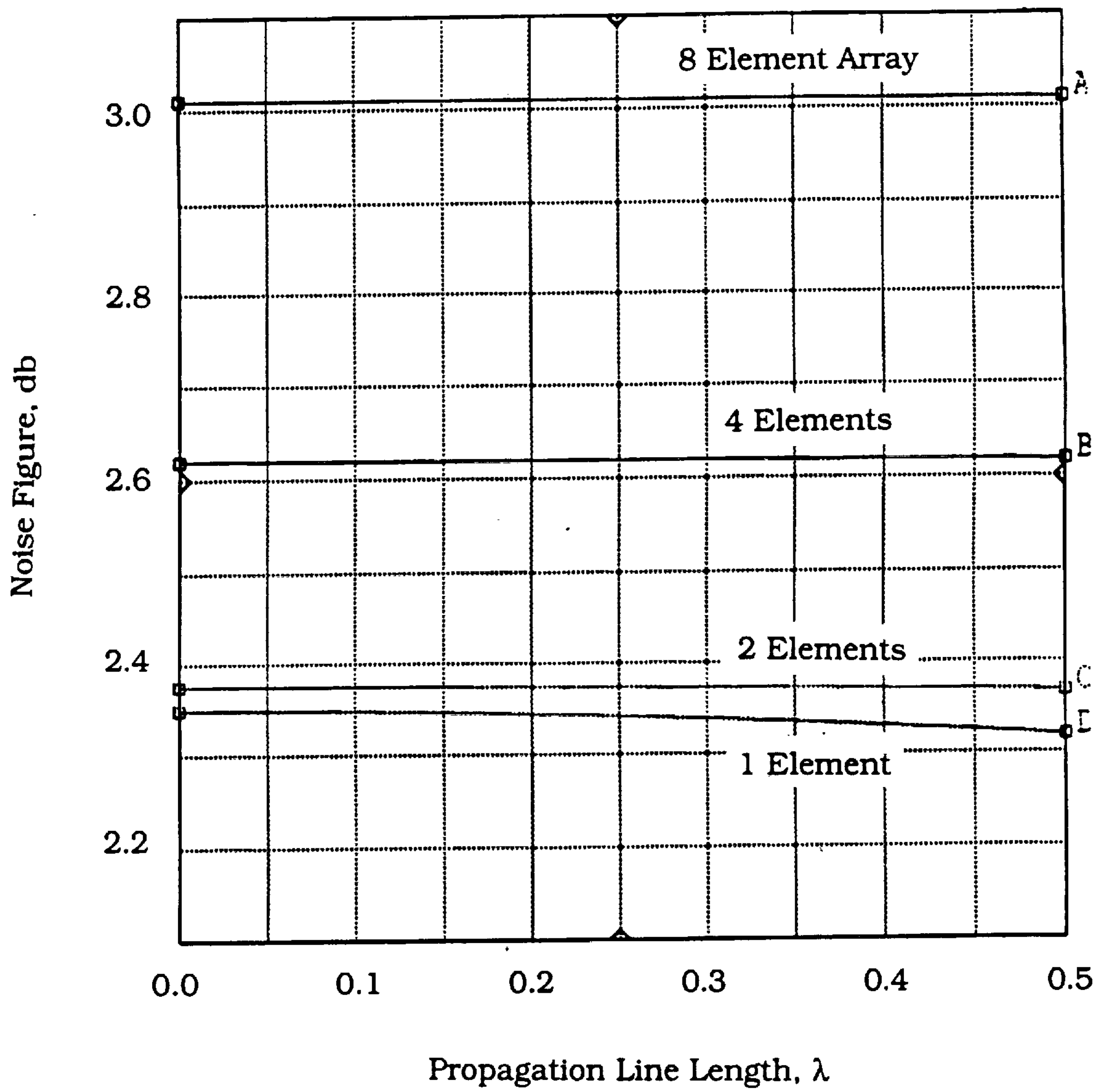

Fig. 3 Noise Figure for Combiner Arrays with On-Axis Delay Equal to the Average Delay as the Beam is Swept From On-Axis to End-Fire (λ in free space = 0.116 ft. at 4.3 GHz)

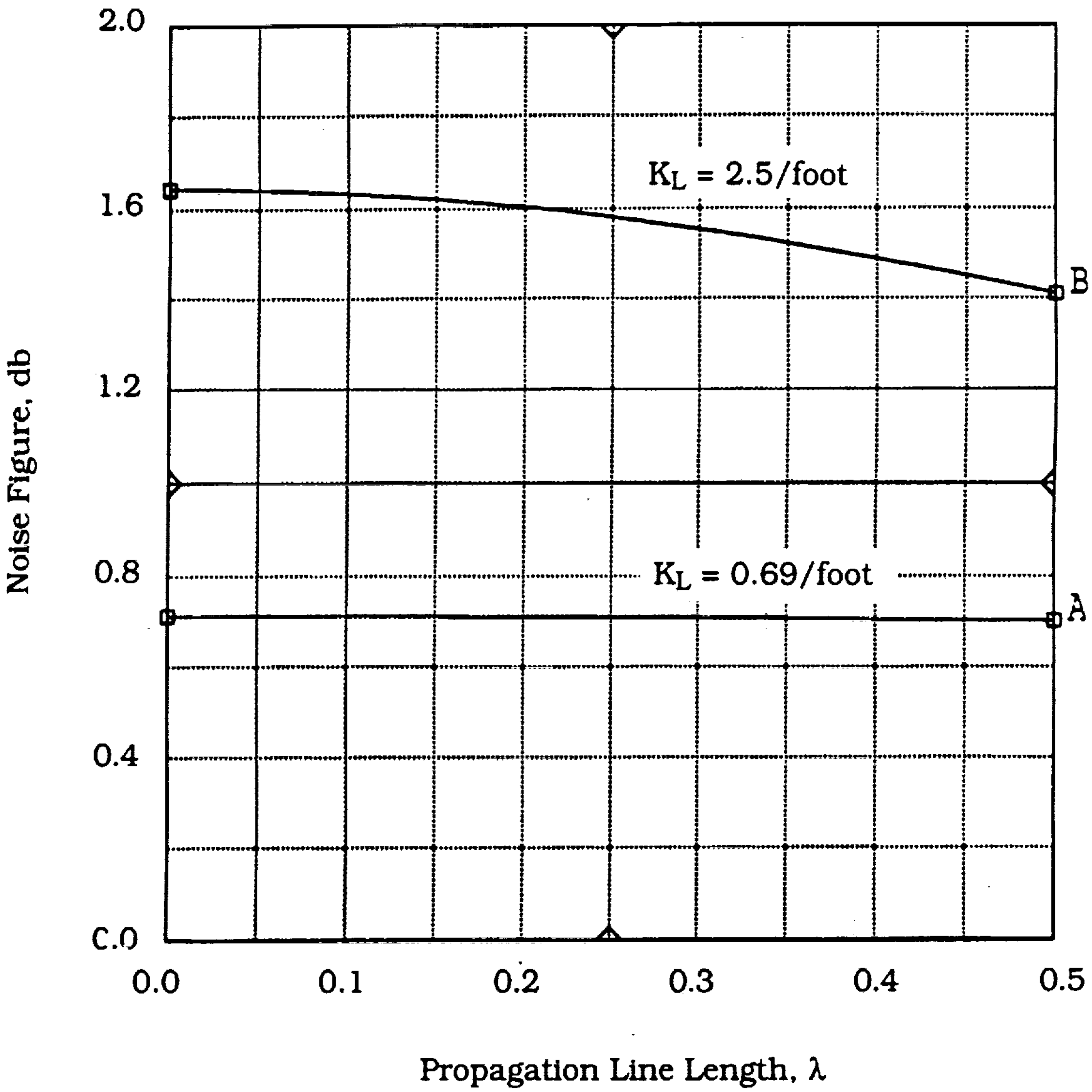

Fig. 4 Noise Figure for 8 Element Combiner Arrays with Loss Factors of K_L = 0.69/foot and 2.5/foot (λ in free space = 0.116 ft. at 4.3 GHz)

Noise Figure and Combiner Loss

The effects of combiner loss upon the network noise figure were investigated for array sizes up to 16 elements. The results of the simulations are shown in Fig. 5. The number of delay elements is shown on the horizontal scale and the network noise figure is indicated on the vertical axis. Noise figure was calculated for combiner resistive losses of 0.1 db, 1 db, 2 db, and 3 db. As indicated, the network noise figure is always reduced as array size increases for low resistive loss values. For example, for resistive loss of 0.1 db and array sizes up to N=16 the noise figure is still being reduced. As resistive loss increases an optimum array size is found to exist, with the optimum number of elements being reduced as loss increases. For resistive loss of 2 db the optimum array size is 4-8 elements. For resistive loss of 3 db, however, the minimum noise figure is obtained for the minimum array size (N=2 in this case).

Monte Carlo Tolerance Simulation

In order to investigate the sensitivity limitation imposed by component tolerances, a Monte Carlo approach was employed. Simulations on the on-axis delay line network were performed using component tolerances of 1%, 2%, 3%, 4%, 5%, and 6%. The actual line length for each angle was randomly selected to lie within the desired value to the allowed tolerance. The noise figure for the array was then calculated. The procedure was repeated until sufficient data was obtained to determine the resulting spread in network noise figure. This information is very important since the noise figure can not be resolved to accuracy greater than the resulting spread in network noise figures. Since this type of variation cannot be removed by calibration, it ultimately determines the sensitivity of the radiometer.

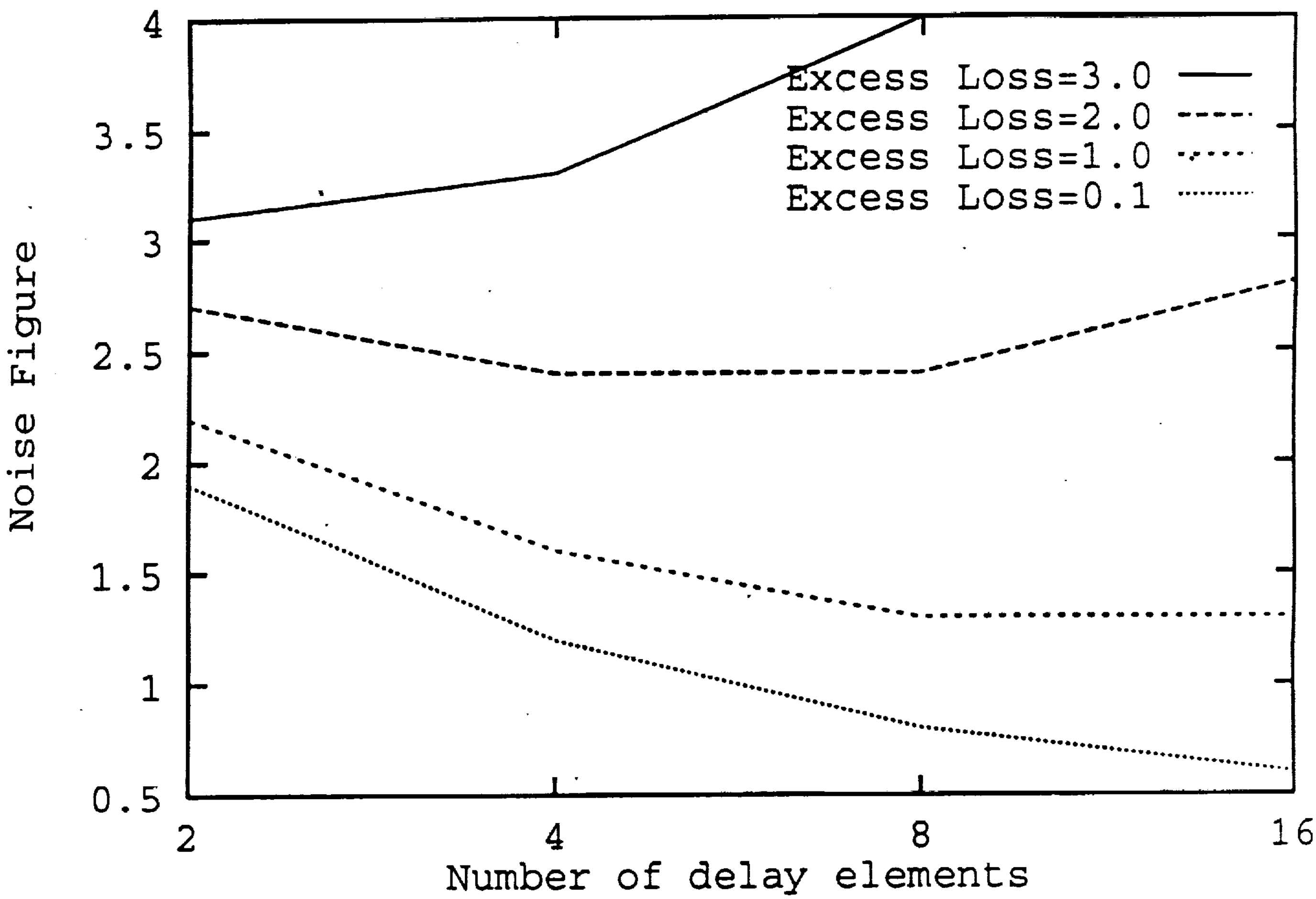

Fig. 5 Noise Figure as a Function of Number of Delay Lines for Several Values of Excess Loss in the Combiners (KL = 0.69/foot, Frequency = 4.3 GHz)

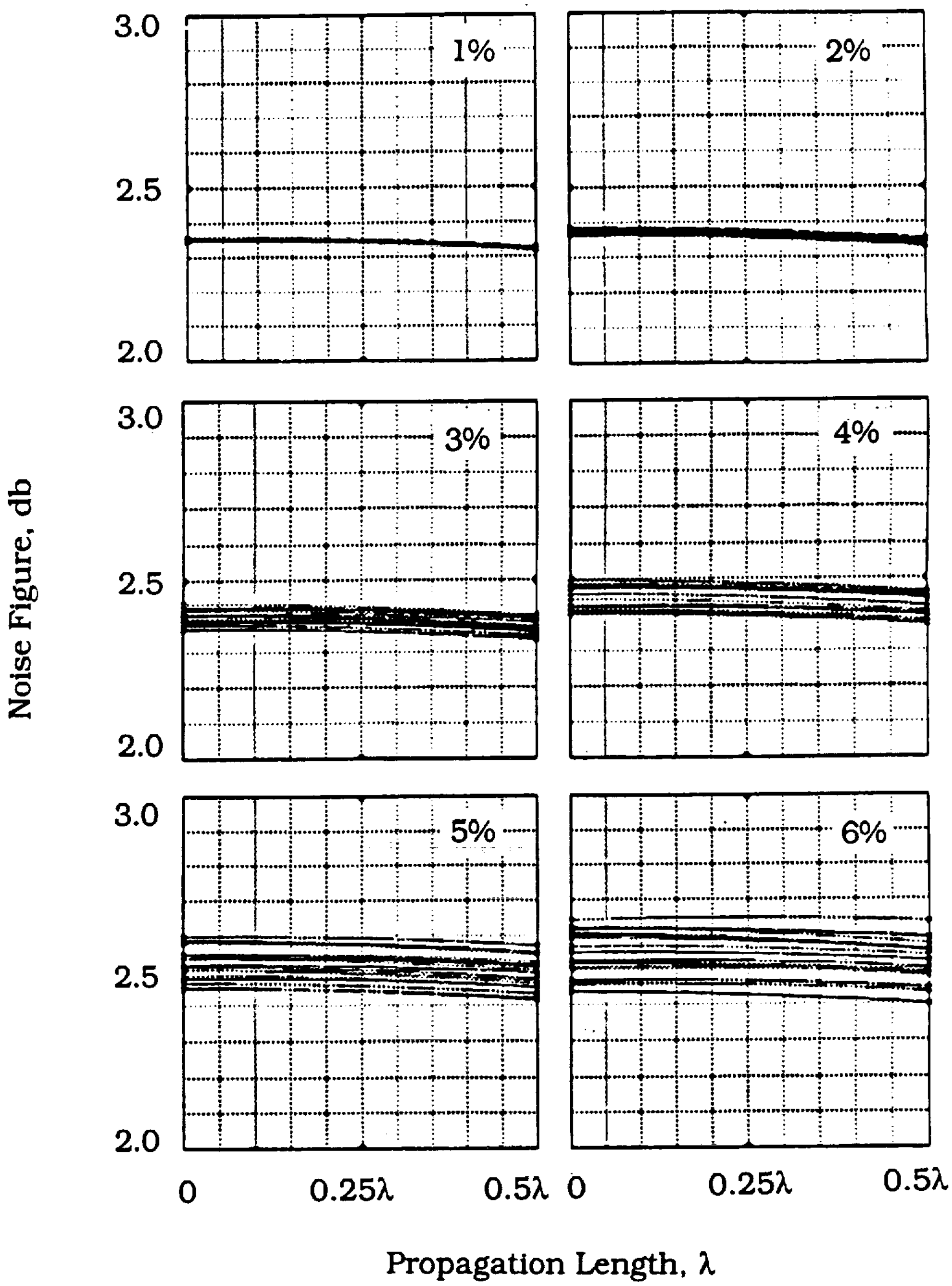

Fig. 6 Noise Figure Sensitivity as a Function of Delay Line Propagation Length for an 8 Element Combiner with Line Length Tolerances of 1-6 %.

The results of the simulations are shown in Fig. 6. The horizontal scale indicates delay line length in wavelength, and the vertical scale indicates network noise figure. The noise figure is calculated for an on-axis array of N=8 elements with a resistive combiner loss of 2 db. The non deterministic noise figure variation is indicated by the width (i.e., thickness) of the noise figure plots. The uncertainty in noise figure and resulting noise temperature is directly related to the line length tolerance and the results are indicated in Table 1.

Table 1
Uncertainty in Network Noise Figure and Noise Temperature due to Component Tolerance

Component Tolerance	Noise Figure Uncertainty	Noise Temp. Uncertainty
1%	0.01 db	0.67 °K
2%	0.025 db	1.67 °K
3%	0.06 db	4.03 °K
4%	0.1 db	6.75 °K
5%	0.16 db	10.88 °K
6%	0.2 db	13.67 °K

The significance of this result is that if the delay line lengths for this array could not be determined for each beam angle position to an accuracy tolerance better than the values indicated in the table, the network alone would limit the radiometer sensitivity to the temperatures indicated. The situation gets worse for greater tolerance variations. For this reason it is very important to use delay line elements with extremely repeatable characteristics.

III. Phase Shifters

The transmission delay lines create a phase shift function that allows the antenna beam to be electrically steered. Phase shifters can be fabricated in a variety of configurations, but generally require the use of switching elements to change the amount of phase delay. The delay, itself, can be generated using transmission lines or reactance devices. The most common switching element used is a PIN diode. The noise generated by the diode will vary, depending upon the state the switch is in. The resistance of the diode will vary from a low value in the forward bias, or 'on' state, to a very high value in the reverse bias or 'off' state. Since the switch is fundamental to phase shift networks it is important to understand it's noise characteristics. In this section the noise performance of three phase shift implementations is investigated. The phase shifters are fabricated in microstrip using a commercial PIN diode (MA47899-030). This diode is not necessarily the best diode to use, but is typical of devices commonly employed in phase shifters. The noise performance of the phase shifters is typical of experimentally obtained results.

The three phase shift implementations investigated consist of one reflection design and two transmission type (switched-line and loaded-line) phase shifters. The phase shifters were designed to operate at a center frequency of 4 GHz and were fabricated in microstrip using an alumina (AL_2O_3) substrate. The reflection phase shifter uses a hybrid 90° coupler in order to operate as a two-port device. All three phase shifters were designed to provide one bit 45° phase shift.

The equivalent circuit for the PIN diode is shown in Fig. 7. The equivalent circuit is applicable for both forward and reverse bias states. The equivalent circuit can be used for other PIN diodes by determination of the equivalent circuit parameters, which can be established by parameter extraction techniques from measured data. The phase shifter circuits are shown in Figs. 8a, 8b, and 8c, for the reflection-type, switched-line, and loaded-line phase shifters, respectively. The RF performance of the three phase shifters are shown in Figs. 9a, 9b, and 9c, respectively, for the three phase shifters. The RF performance is shown for a frequency band extending from 3 GHz to 5 GHz. The left hand side vertical scale indicates the return loss and insertion loss for the phase shifters, and the right-hand side vertical scale indicates the phase shift angle and noise figure. The RF performance characteristics for the three phase shifters are summarized in the following tables.

Table 2

RF Performance of the Three Phase Shifters

Phase Shifters	BW(%)	RL^0(db)	RL^1(db)	IL^0(db)	IL^1(db)
Switched-Line	20.0	-34	-36	-0.193	-0.194
Loaded-Line	11.0	-50	-43	-0.020	-0.082
Reflection-Type	6.8	-38	-32	-0.138	-0.287

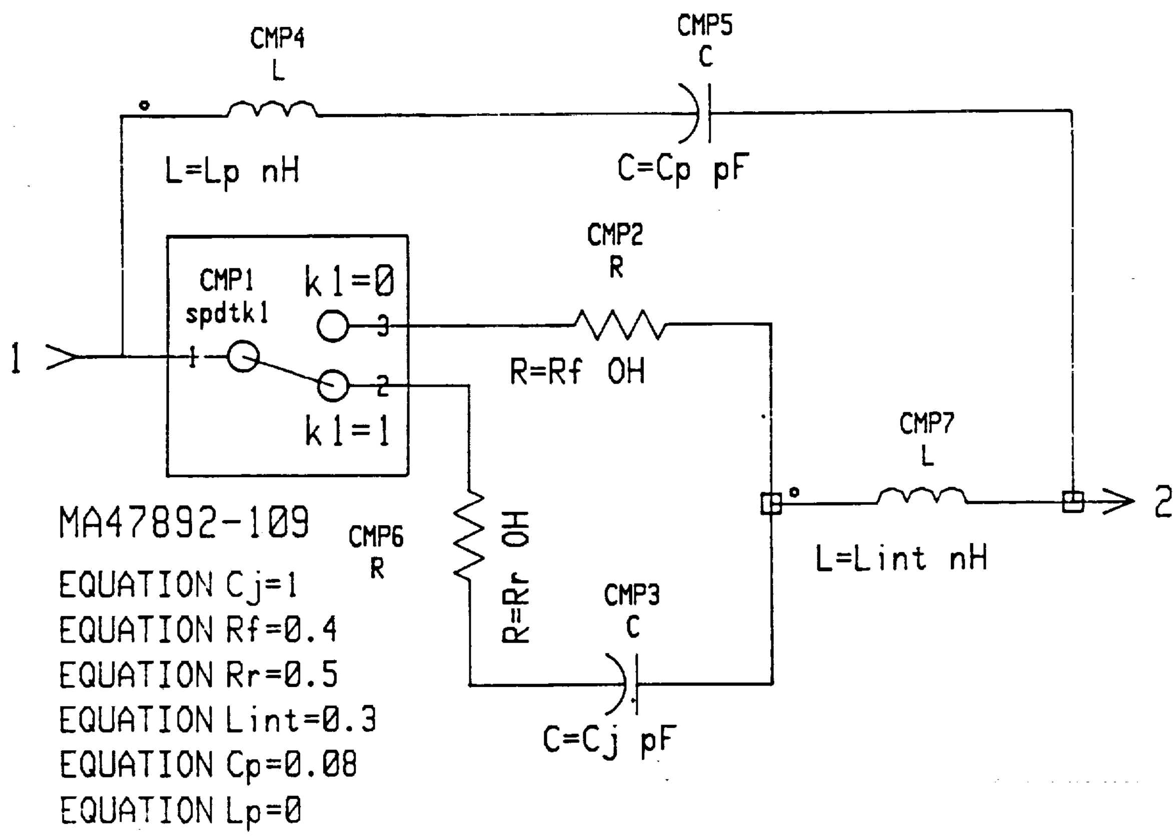

Fig. 7 PIN Diode Equivalent Circuit

Table 3

Noise Figure Performance of the Three Phase Shifters

Phase Shifter	NF^o(db) Center	NF^1(db) Center	NF^o(db) Max	NF^1(db) Max
Switched-Line	0.192	0.192	0.204	0.196
Loaded-Line	0.020	0.082	0.024	0.112
Reflection-Type	0.137	0.284	0.142	0.287

In Tables 2 and 3 the 'o' and '1' correspond to the two states of the phase shifter bit. The percent bandwidth is defined as the range of frequencies with phase shift error less than 10^o and return loss less than -20 db.

As indicated in the Figs. 9a, 9b, and 9c and summarized in the tables it is seen that the loaded-line phase shifter has superior noise performance over an acceptable bandwidth. The switched-line phase shifter has a considerably larger bandwidth, but the noise figure throughout the band is significantly higher. The reflection-type design provides the least desirable performance.

The offset between the noise figure values at different positions of the phase shift angle is an important consideration. In a phased array application the offset results in uncertainty in the noise figure of the network and serves to degrade system sensitivity in much the same way

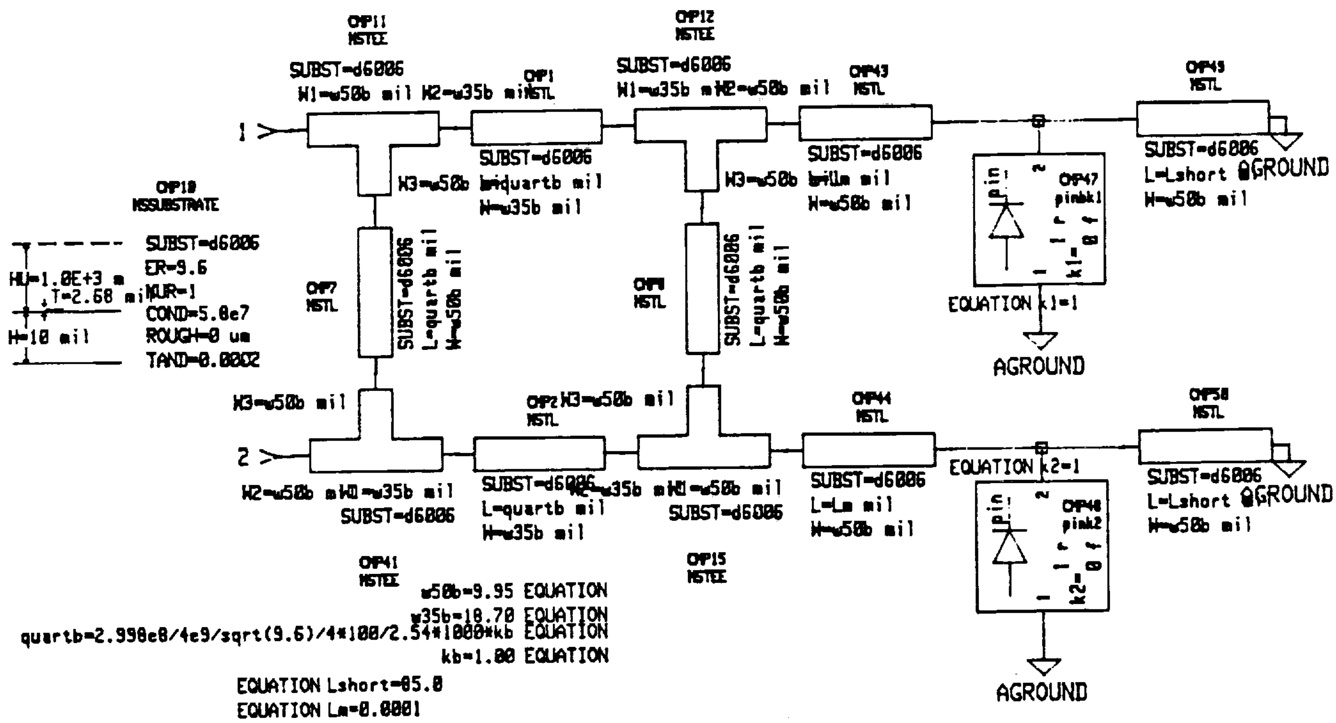

Fig. 8a Reflection-Type Phase Shifter

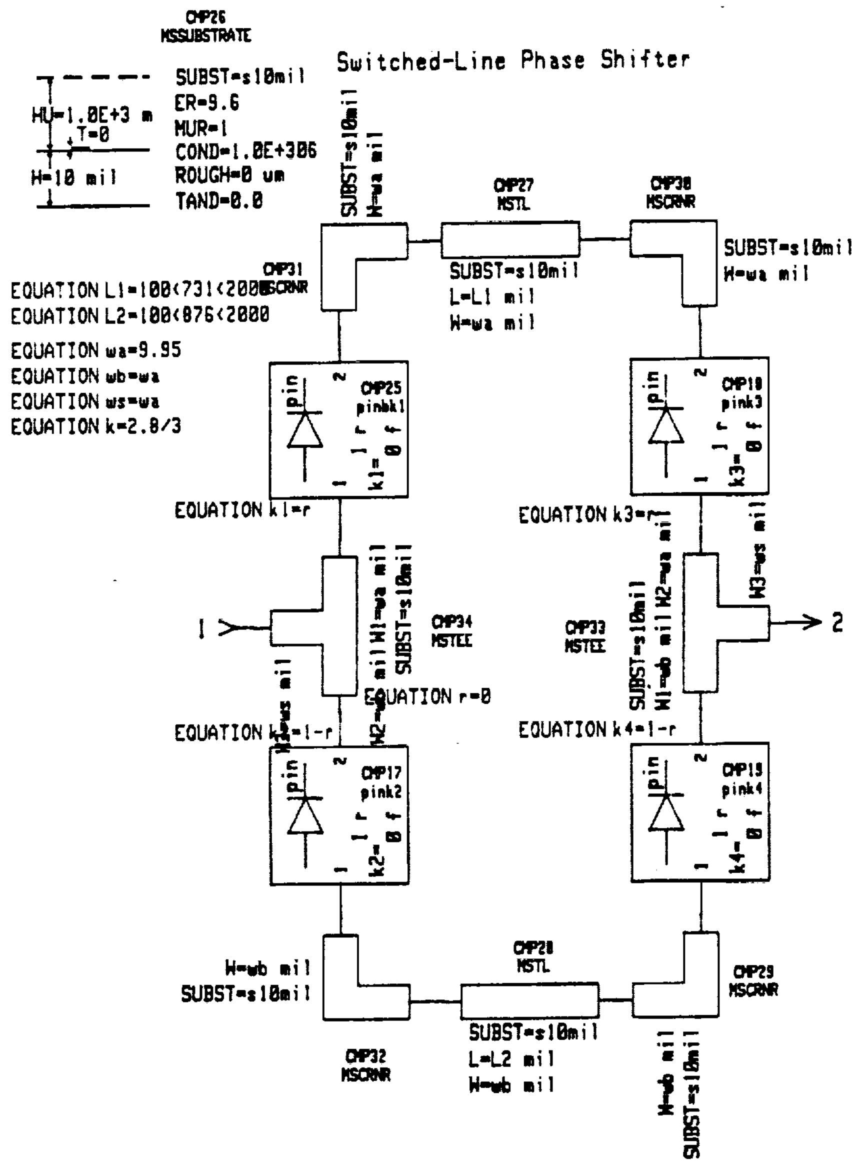

Fig. 8b Switched-Line Phase Shifter

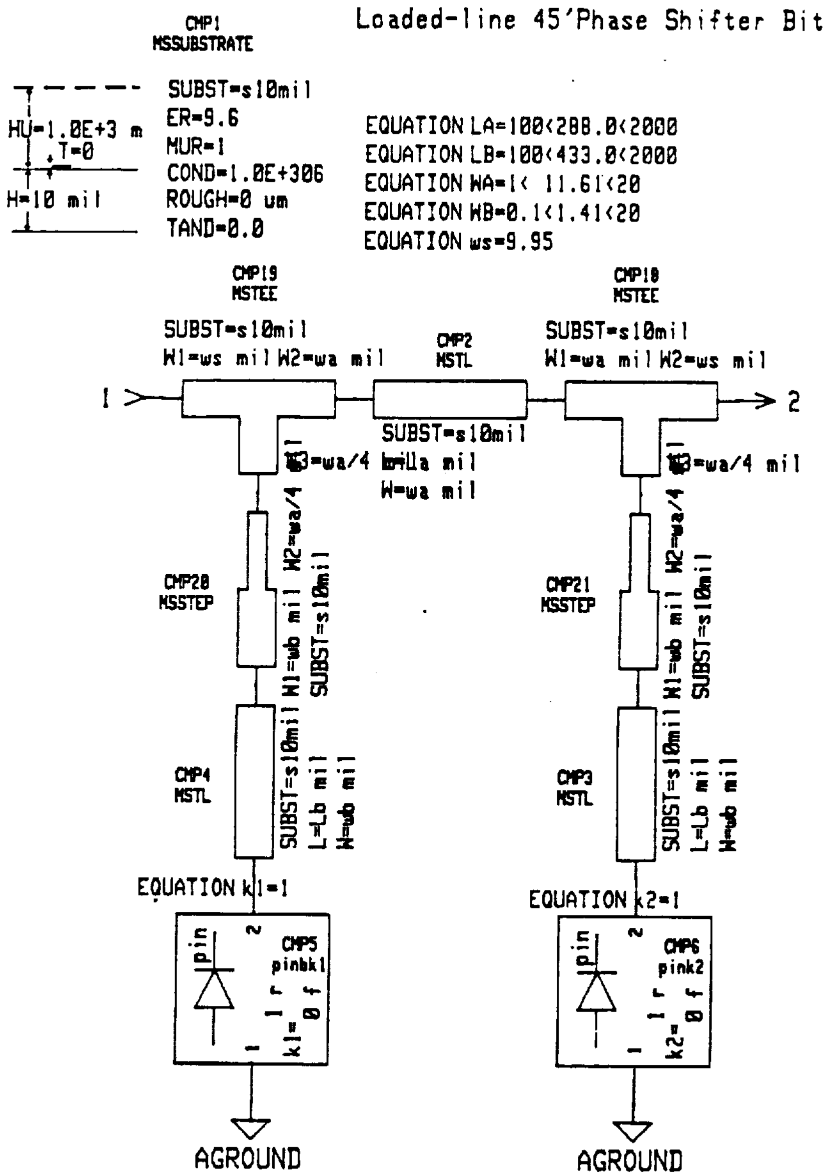

Fig. 8c Loaded-Line Phase Shifter

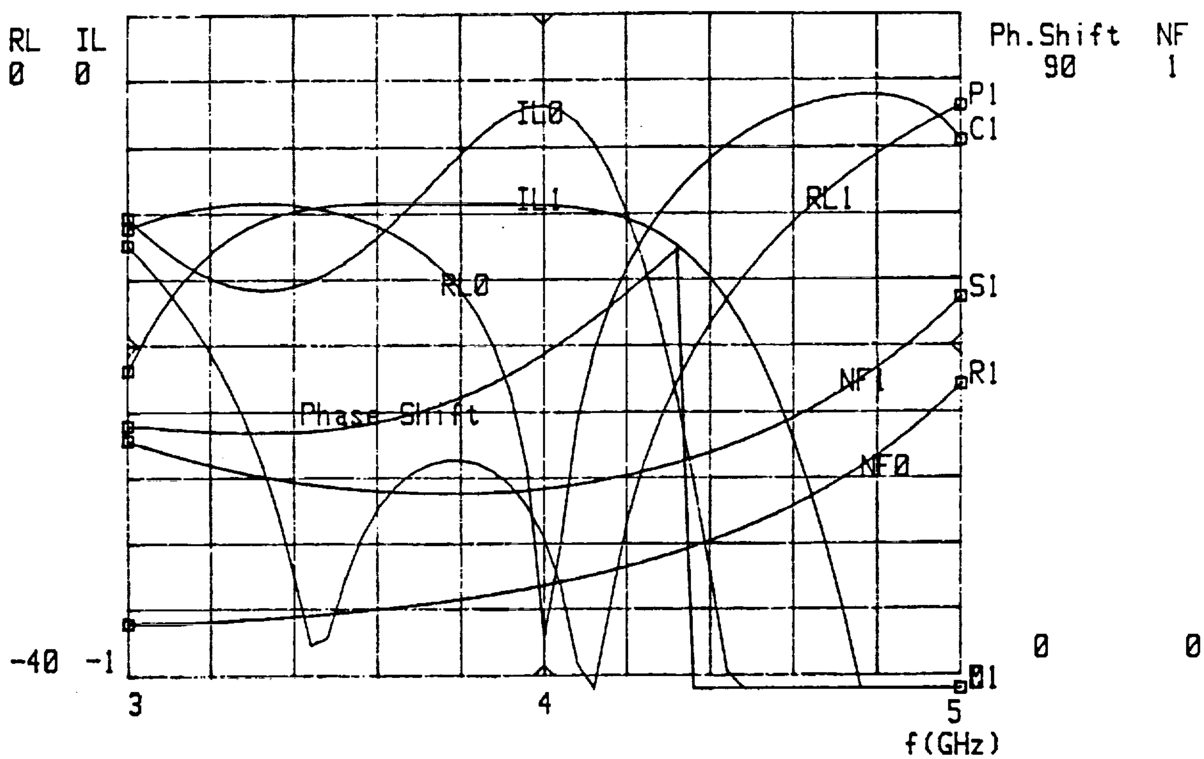

Fig. 9a Reflection-Type Phase Shifter Performance

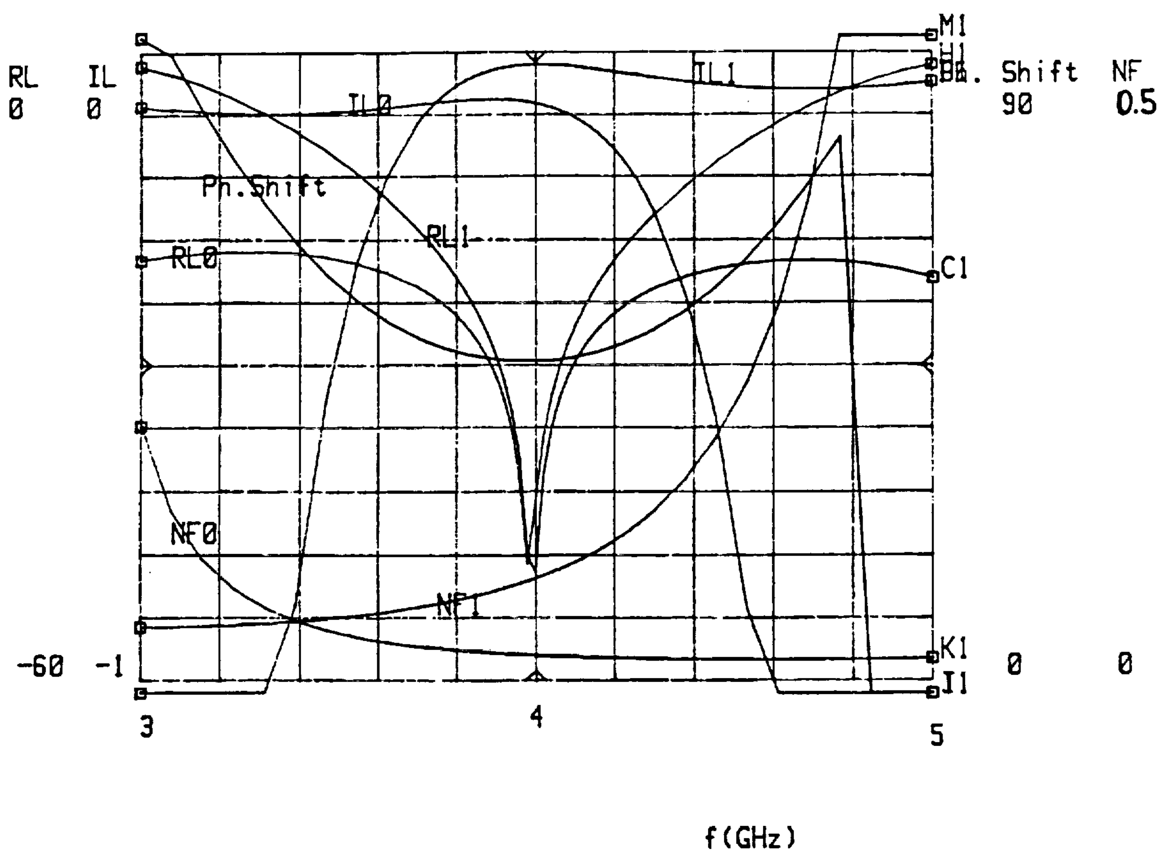

Fig. 9b Loaded-Line Phase Shifter Performance

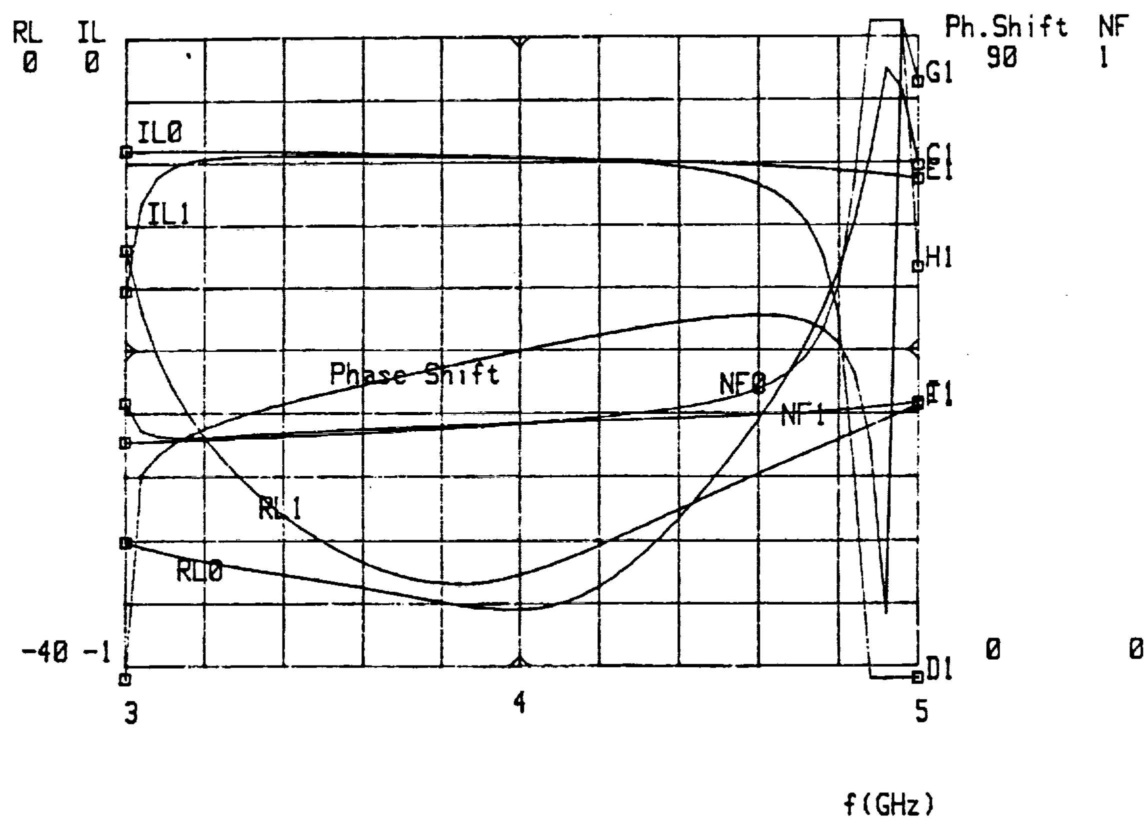

Fig. 9c Switched-Line Phase Shifter Performance

as discussed for the tolerance considerations. The switched-line phase shifter appears to have the most desirable characteristics in this regard.

IV. Conclusions

The noise figure performance of various delay line networks fabricated from microstrip lines with varying number of elements was investigated using a computer simulation. The effects of resistive losses in both the transmission lines and power combiners was considered. In general, it is found that an optimum number of elements exists, depending upon the resistive losses present in the network. Small resistive losses are found to have a significant degrading effect upon the noise figure performance of the array. Extreme stability in switching characteristics is necessary to minimize the non deterministic noise of the array. For example, it is found that a 6% tolerance on the delay line lengths will produce a 0.2 db uncertainty in the noise figure which translates into a 13.67 ^{o}K temperature uncertainty generated by the network. If the tolerance can be held to 2% the uncertainty in noise figure and noise temperature will be 0.025 db and 1.67 ^{o}K, respectively.

Three phase shift networks fabricated using a commercially available PIN diode switch were investigated. Loaded-line phase shifters are found to have desirable RF and noise characteristics and are attractive components for use in phased-array networks.

Switched-Beam Radiometer Front-End Network Analysis

Addendum

After submission of this report some additional calculations were performed. The purpose of these calculations was to investigate the uncertainty in the noise figure and noise temperature for a combiner structure that had lower loss than the combiner previously investigated and reported. The original calculations are described starting on page 13 in the ***Monte Carlo Tolerance Simulation*** section. The original calculations were performed for an N=8 combiner array with 2 db combiner loss. These calculations resulted in the the uncertainty values presented in Table 1 on page 16. As indicated in Table 1 the noise temperature uncertainty varies from 0.67 °K for 1% line length tolerance to 13.67 °K for 6 % line length tolerance.

The new calculations reported in this ***Addendum*** were performed for the identical combiner array, except that the combiner loss was reduced to 0.5 db. The results are presented in Table 4.

As indicated in Table 4, the decrease in the combiner loss from 2 db to 0.5 db produces a slight reduction in the uncertainty in the network noise figure and noise temperature. However, the reduction is not in proportion to the combiner loss reduction. For example, for 1% line length tolerance the noise temperature uncertainty is reduced from 0.67 °K to 0.58 °K, and for 6% tolerance the noise temperature uncertainty is reduced from 13.67 °K to 12.95 °K.

These calculations indicate that the line length variation due to the tolerances is far more significant in determination of the network noise temperature uncertainty than is the actual magnitude of the combiner loss. Since the uncertainty in the noise temperature cannot be removed from the system noise temperature by calibration, it represents a lower limit to radiometer sensitivity. It is believed that this issue is fundamental to understanding the use of switched-beam networks in radiometry. Although this study only considered a simple combiner network the physical principles revealed are significant and additional work should be performed to more clearly understand the problem.

Table 4

Uncertainty in Network Noise Figure and Noise Temperature due to Component Tolerances for an N=8 Array with 0.5 db Combiner Loss

Component Tolerance	Noise Figure Uncertainty	Noise Temp. Uncertainty
±1%	0.008 db	0.58 °K
±3%	0.04 db	2.89 °K
±6%	0.19 db	12.95 °K

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13. ABSTRACT *(Maximum 200 words)*

The noise figure performance of various delay-line networks fabricated from microstrip lines with varying number of elements was investigated using a computer simulation. The effects of resistive losses in both the transmission lines and power combiners were considered. In general, it is found that an optimum number of elements exists, depending upon the resistive losses present in the network. Small resistive losses are found to have a significant degrading effect upon the noise figure performance of the array. Extreme stability in switching characteristics is necessary to minimize the non-deterministic noise of the array. For example, it is found that a 6 percent tolerance on the delay-line lengths will produce a 0.2 db uncertainty in the noise figure which translates into a 13.67°K temperature uncertainty generated by the network. If the tolerance can be held to 2 percent, the uncertainty in noise figure and noise temperature will be 0.025 db and 1.67°K, respectively. Three phase shift networks fabricated using a commercially available PIN diode switch were investigated. Loaded-line phase shifters are found to have desirable RF and noise characteristics and are attractive components for use in phased-array networks.

14. SUBJECT TERMS
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