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A Prototype Automatic Phase Compensation Module

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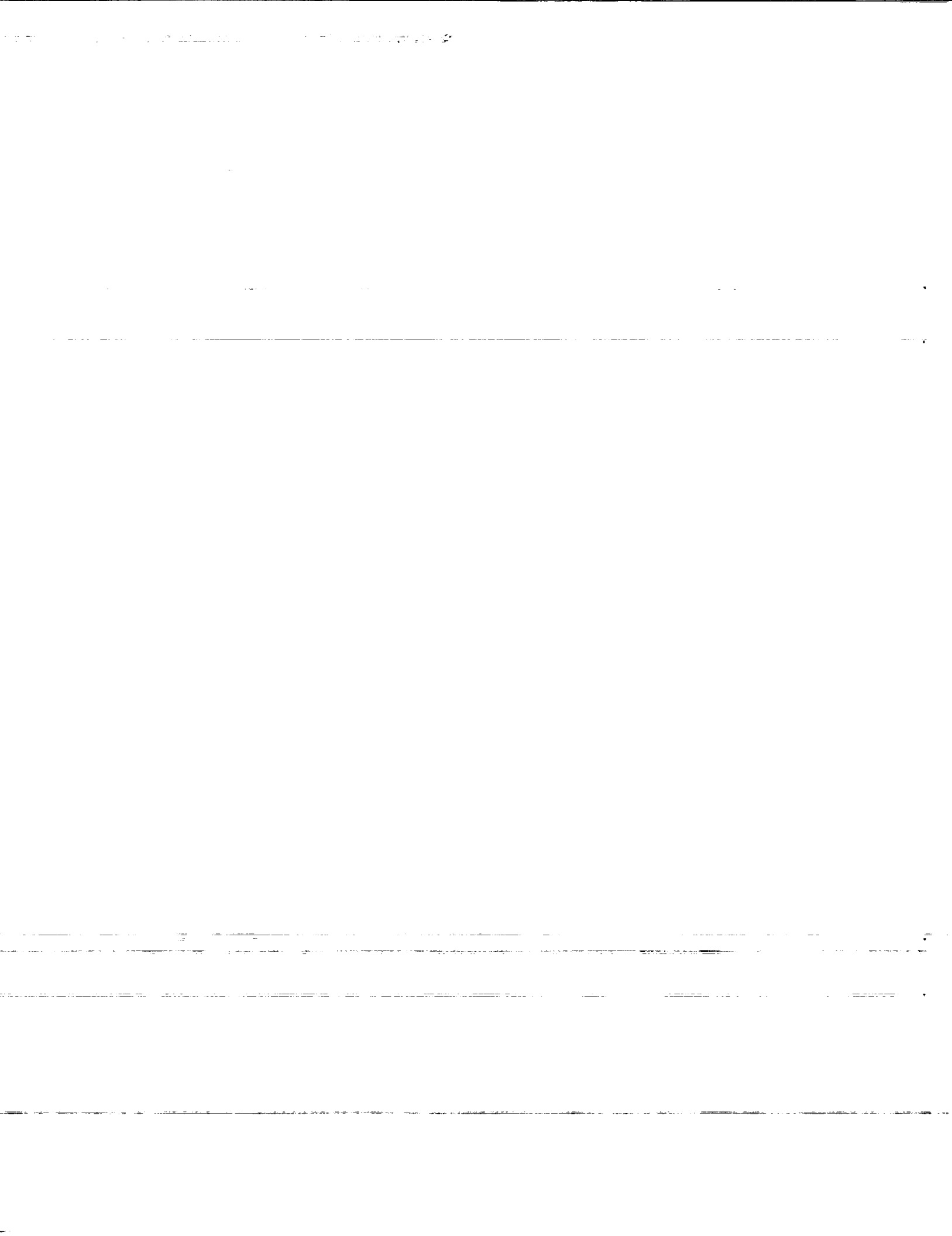*Lewis Research Center*
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A PROTOTYPE AUTOMATIC PHASE COMPENSATION MODULE

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SUMMARY

The growing demands for high gain and accurate satellite communication systems will necessitate the utilization of large reflector systems. One area of concern of reflector based satellite communication is large scale surface deformations due to thermal effects. These distortions, when present, can degrade the performance of the reflector system appreciably. This performance degradation is manifested by a decrease in peak gain, an increase in sidelobe level, and pointing errors. It is essential to compensate for these distortion effects and to maintain the required system performance in the operating space environment. For this reason the development of a technique to offset the degradation effects is highly desirable. Currently, most research is direct at developing better material for the reflector. These materials have a lower coefficient of linear expansion thereby reducing the surface errors. Alternatively, one can minimize the distortion effects of these large scale errors by adaptive phased array compensation. Adaptive phased array techniques have been studied extensively at NASA and elsewhere (refs. 1 to 3). Presented in this paper is a prototype automatic phase compensation module designed and built at NASA Lewis Research Center which is the first stage of development for an adaptive array compensation module.

INTRODUCTION

Advanced satellite communication systems employing large reflector antennas may require surface error compensation to maintain system performance. Previous studies have indicated that electronic compensation by independent amplitude and phase control of array feeds is a viable method of surface distortion compensation (refs. 1 and 5). In particular, extensive research has been conducted in examining the Focal Plane Conjugate Field Matching (FPCFM) (ref. 2). The basis for this concept is that the product of a phase distorted field and its complex conjugate is a plane wave. There are two ways of arriving at the focal plane field distribution: indirect and direct. Indirect FPCFM calculates the focal plane electric field produced by an incident uniform plane wave using the reciprocity principle. The incident uniform plane wave is generated by the feed array in transmit mode. Direct FPCFM measures the focal plane electric field distribution directly with the feed array in receive mode (figs. 1 and 2). The latter technique can more easily be implemented into an array controller module. With this in mind, a prototype automatic phase conjugate module based on the direct FPCFM technique was developed at NASA Lewis Research Center.

The "proof of concept" module was developed using discrete off-the-shelf components. The schematic drawing of the module is shown in figure 3. The incoming microwave signal is coherently detected and down converted to intermediate frequency (IF). The module performs a product integration of the IF signal with locally generated in-phase and quadrature IF signals. The results are used to estimate phase of the received signal. The operations are expressed mathematically below:

$$\beta_I = \int_0^T r_{IF}(t) * \gamma_I \, dt$$

$$\beta_Q = \int_0^T r_{IF}(t) * \gamma_Q \, dt$$

$$\theta = \tan^{-1}(\beta_Q / \beta_I)$$

where

$r_{IF}(t)$ coherently detected IF signal

γ_I locally generated in-phase IF signal

γ_Q locally generated quadrature IF signal

T $2 * \pi / \omega_{IF}$: period of the IF signal

β_I in-phase projection of $r_{IF}(t)$

β_Q quadrature projection of $r_{IF}(t)$

θ estimate of the phase of $r_{IF}(t)$

Experimental Procedures

Two experiments were conducted to test the automatic phase conjugate module. First, the phase measurement and conjugation capabilities of the system were tested. Next, a simple experiment was performed to demonstrate the ability of the system to correct phase distortion between two array elements.

Phase Measurement and Conjugation Verification

The first experiment was conducted using the test setup in figure 4. The test setup distributes a reference channel and test channel to each of two systems shown in the figure for phase difference measurements. The measurements from network analyzer was used as a standard against which the measurements from the phase compensation module were compared. To verify the phase measurement capabilities of the system, known phase delays were added in one of the signal paths, and the phase difference between the two channels was measured by both systems. However, before any phase measurements were taken, the systematic errors due to the cables and other accessory components were calibrated out.

Phases were measured at all possible phase settings by both systems and were compared, analyzed, and stored in files. Next, the stored data from the experiment above was used in the conjugation verification. Assuming uniform insertion losses at all phase settings, the conjugate is just the negative of the measured phase value.

The conjugation verification experiment was conducted by measuring known arbitrary phases set by the phase shifter and inverting the sign of the measured phase. Next, a look-up table of stored phase measurements was used to determine the closest phase setting corresponding to the negative of the measured phase. This phase setting, the conjugate of the measured phase, is set on the phase shifter. Plots of the measured phase and its conjugate were plotted from the screen of the network analyzer (see fig. 9.). This was repeated for several phase settings.

Phase Distortion Demonstration

The phase distortion demonstration was conducted using the test setup in figure 5. The demonstration is aimed at showing how phase distortions can corrupt the far-field pattern and how that can be compensated with the complex conjugate of the measured phase. This experiment is a simulation of errors due to large scale surface distortions. The demonstration consists of three steps: The first step is the measurement of the reference pattern. The second step is the measurement of the phase distorted pattern. The last step is the measurement of the compensated pattern.

The receive antenna is a two element linear array, and the transmit antenna is a standard gain horn. The distance which separates the two antennas is such that the receive array is in far-field zone of the transmit antenna, and the receive antenna is positioned at bore-sight. The transmit horn sends out a continuous-wave (CW) signal. The switch in figure 5 is set such that the receiver is connected to the receive antenna. The E-plane far-field pattern is then measured. This pattern is the reference case.

Next, a phase distortion element is added to one of the signal paths of the receive array, and the E-plane far-field pattern is measured. This pattern is the phase distorted case.

The switch is now set to the phase compensation system. The phase distortion is measured, and the conjugate is computed and set on the phase shifter. The switch is toggled back to the receiver, and the E-plane far-field pattern is again measured. This pattern is the compensated case.

RESULTS

The analysis of the data show that the phase measured by the automatic phase conjugation system was always within five degrees of the phase measured by the network analyzer. These results are the best the system can perform without averaging. This is a result of the random phase error which exists between the two synthesizers used in the system. The error appears to be uniformly distributed over a five degree interval.

Close inspection of the reference, distorted, and compensated patterns clearly show that the phase conjugation helps to compensate for the phase distortion. The compensated patterns are particularly impressive when one considers that the system was not optimized for phase distortions due to accessory components included in the experiment. More specifically, an IF amplifier-not shown in figure 5, was used to magnify the signals to levels within range of operation of the analog to digitial converters contained in the phase compensation module (fig. 3). The IF amplifier adds phase delays to the signal paths which are not present when the array antenna is connected to the receiver. Thus, the phase difference measured by phase compensation module has an additional error term contained in it. In addition, the insertion losses of the phase distortion elements were considered to be negligible which was not entirely a correct assumption. However, the impact of this assumption is not significant since the phase compensation module is insensitive amplitude variations within its range of operation, and the signals were amplified to ensure that they were always within the range operation of the module.

CONCLUSION AND FUTURE WORK

The results obtained from the automatic phase compensation module demonstrate that it is sufficient for implementation in an adaptive array compensation system. The mean phase error calculated for the module is less than five degrees. The error in the measured phase by the module is less than one

quantization level of a digital N bit phase shifter—where $n \leq 6$. Moreover, a phased array antenna using 6 bit phase shifters is sufficient to compensate surface distortions of the order of 200 mil or greater. Also, the results presented in this paper clearly demonstrate that complex feed array element weighing can reduce the effects of phase distortions on the far-field antenna pattern.

If one wishes to implement an adaptive phased compensation module in a satellite system, the size and weight of the module must be reduced. Toward this end, development of a miniaturized version of the module is planned. The system will be developed using MMIC devices rather discrete packaged off-the-shelf components as in this module. Furthermore, for large arrays, the phase distortions introduced by the different path delays of each feed array element will be significant. Thus, a four channel module is planned to investigate the problem. Finally, a demonstration with a distorted reflector fed by a phased array antenna is planned.

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Brennan, P.: An Experimental and Theoretical Study of Self-Phased Arrays in Mobile Satellite Communications. IEEE Trans. Antennas Propag., vol. AP-37, no. 11, Nov. 1989, pp. 1370-1376.

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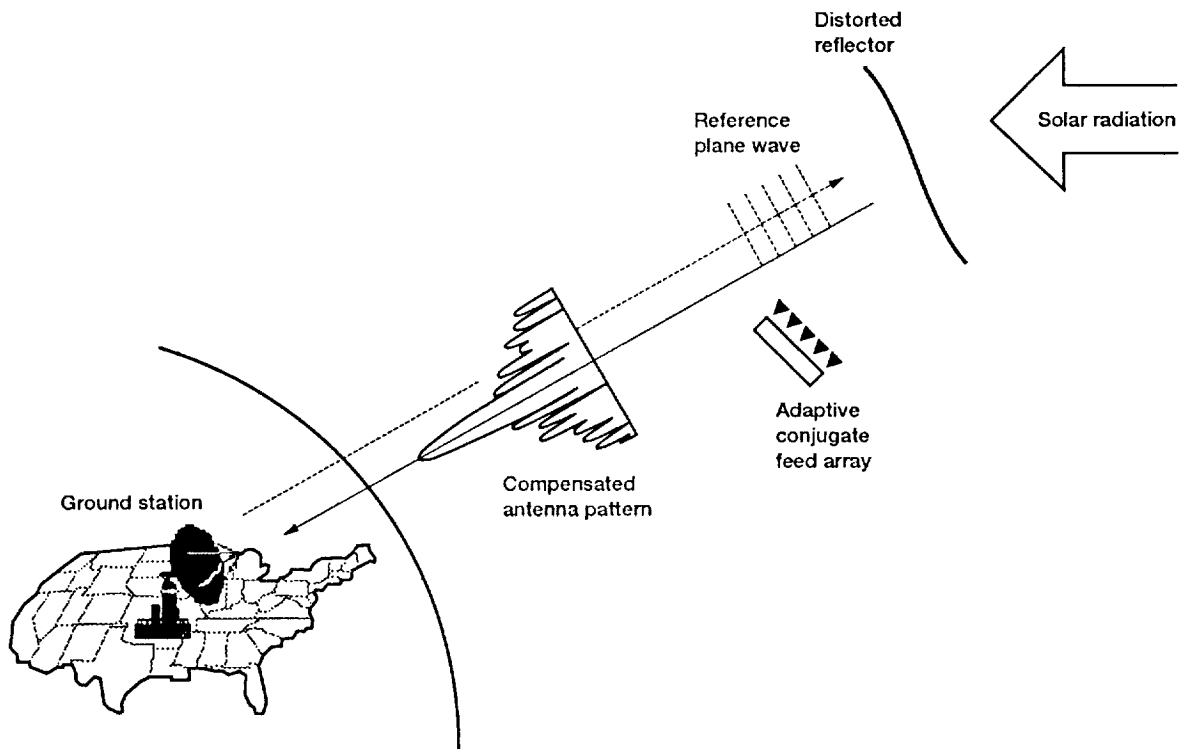
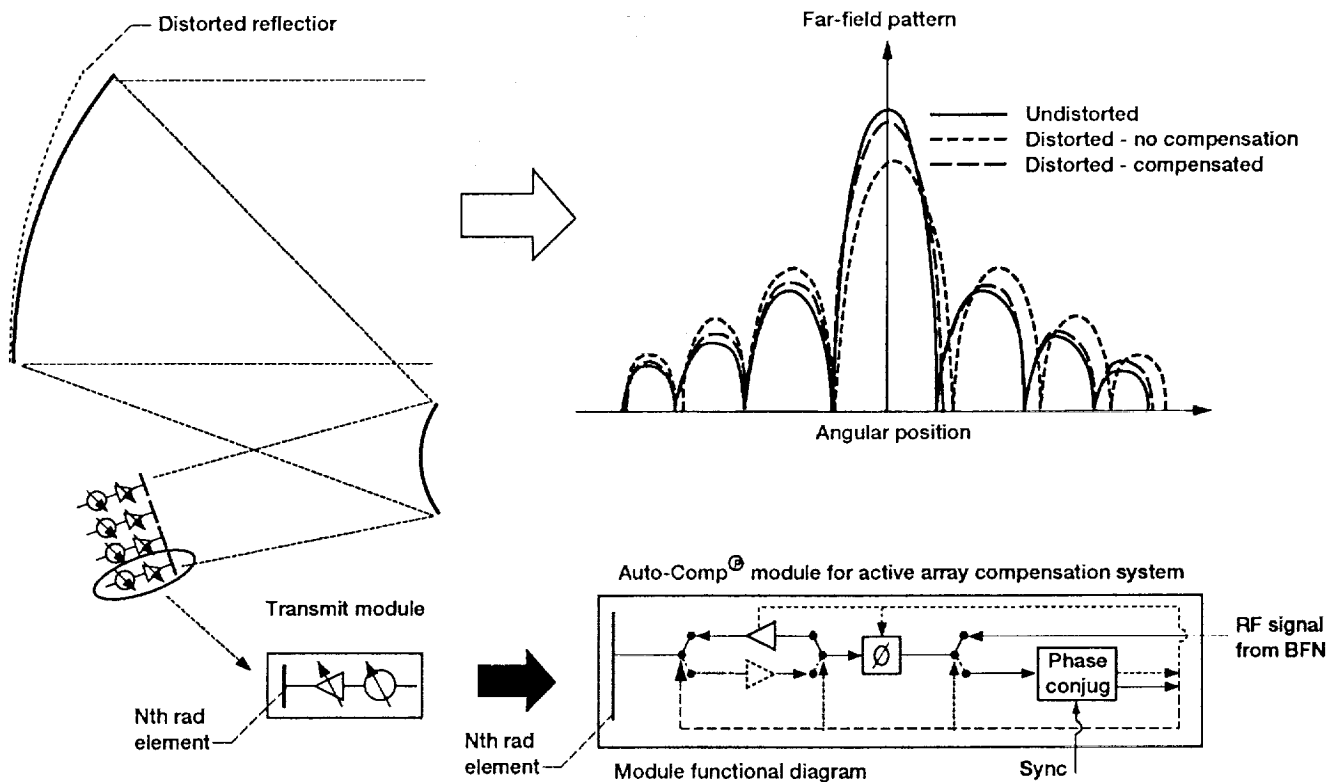Figure 1.—Adaptive conjugate feed array system.

Figure 2.—Automatic module for active feed array compensation.
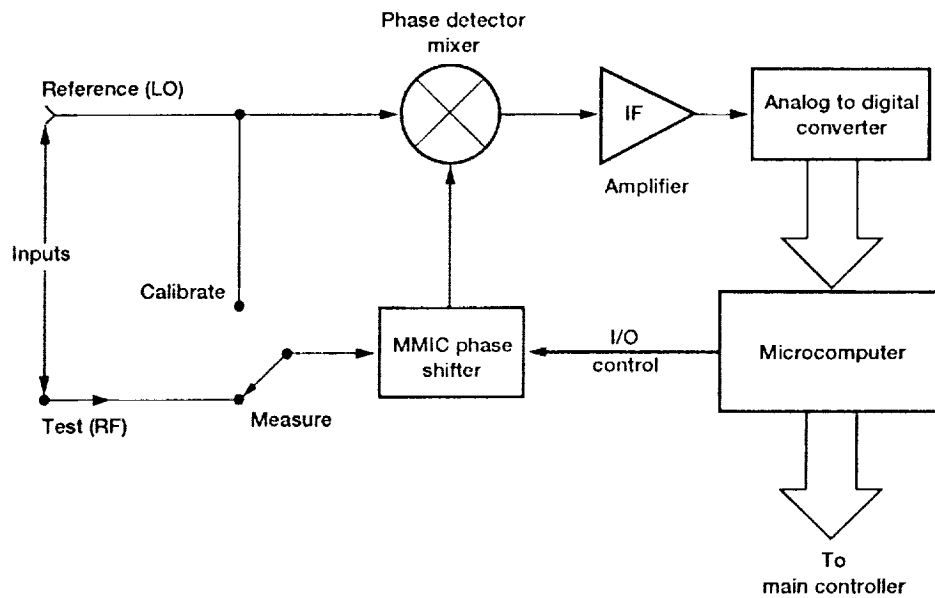
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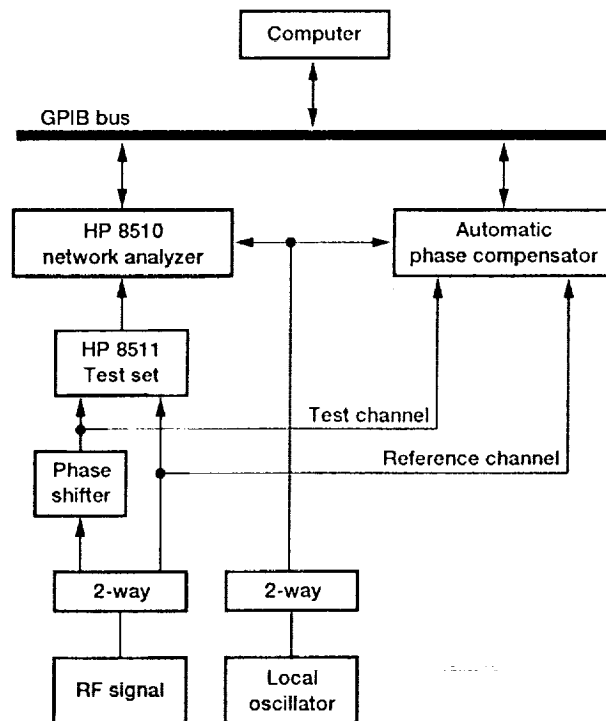Figure 3.—Automatic phase conjugation sub-module.

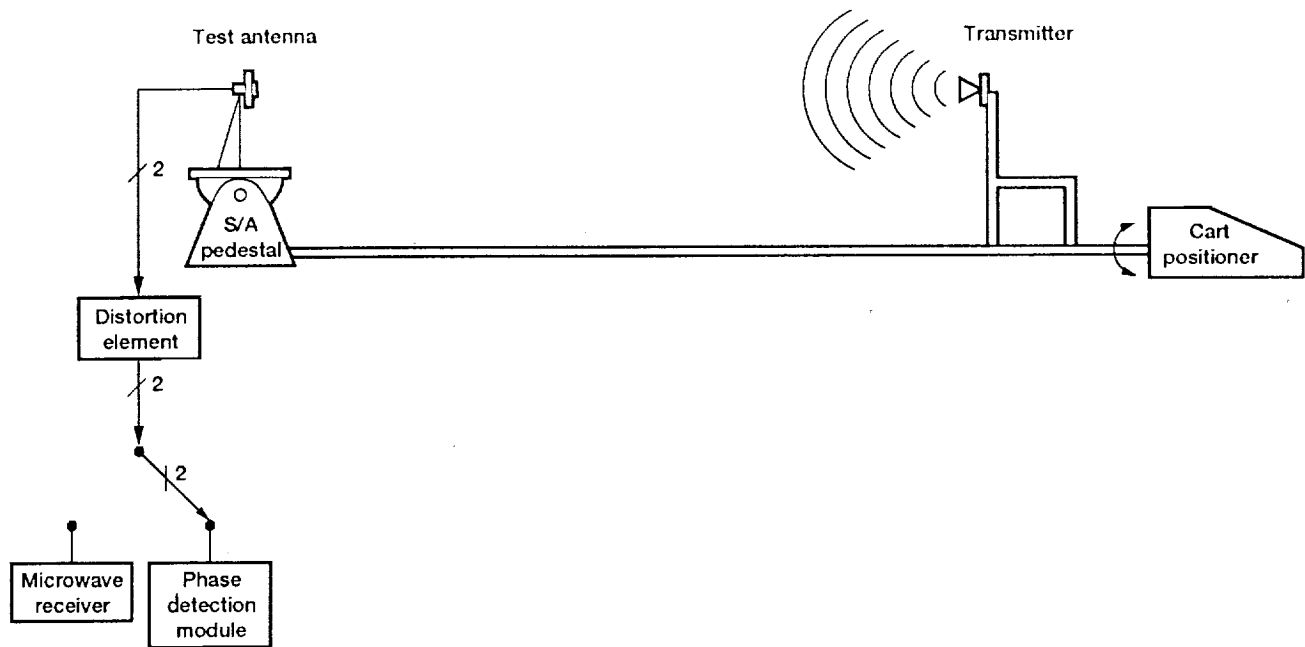Figure 4.—Phase measurement and conjugation experiment.

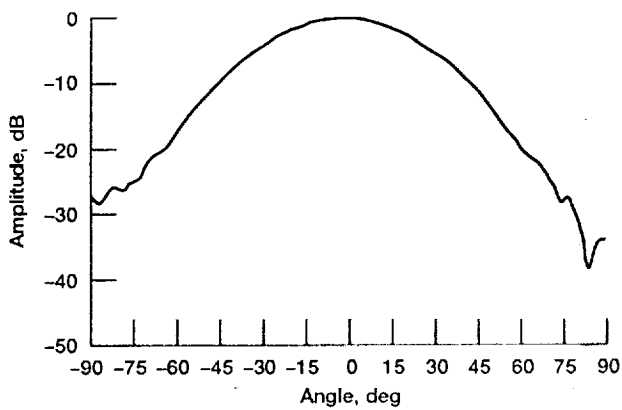Figure 5.—Phase distortion experiment.

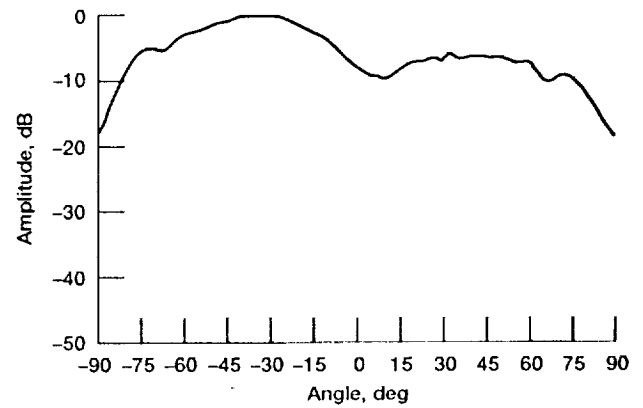Figure 6.—Undistorted far-field pattern.
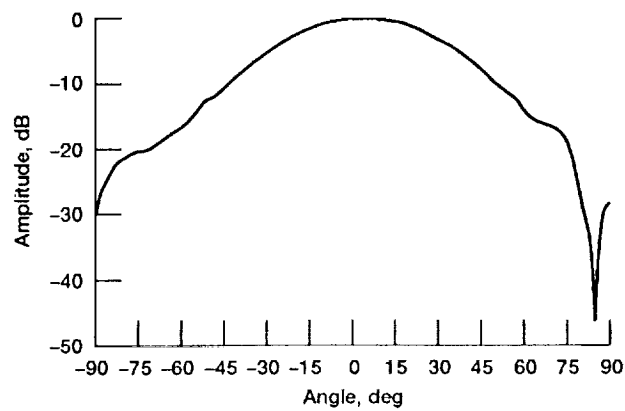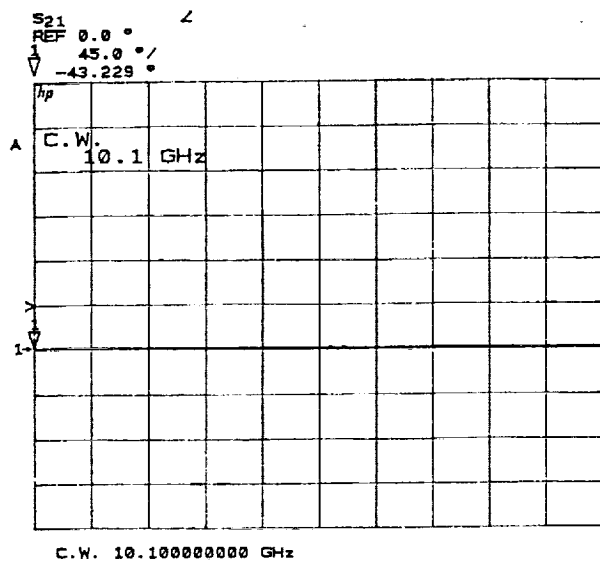

Figure 7.—Phase corrupted far-field pattern.
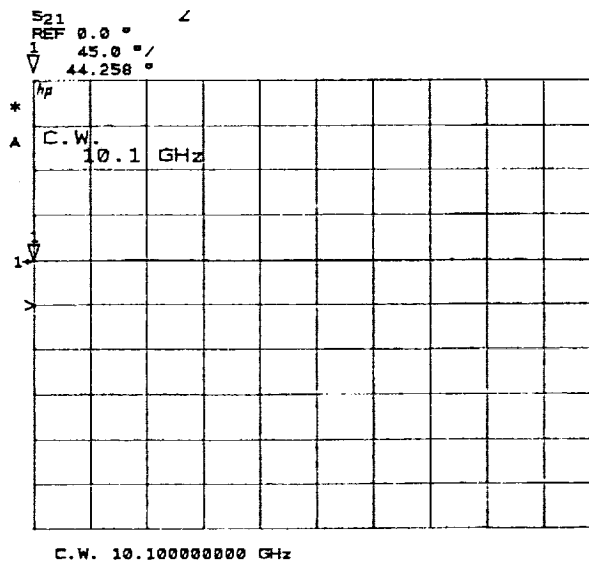

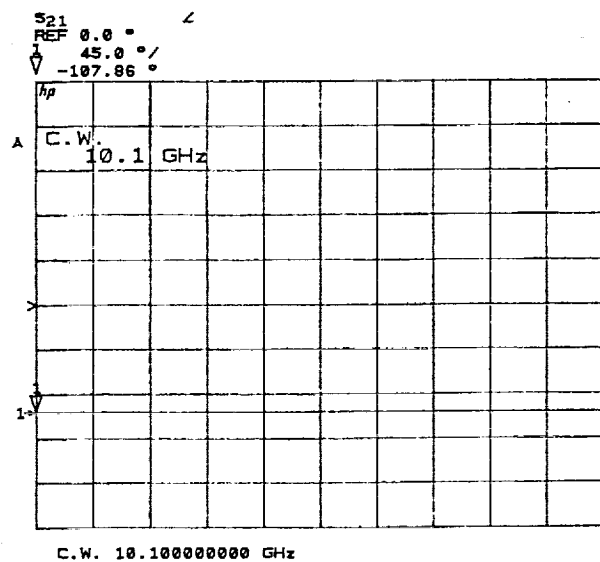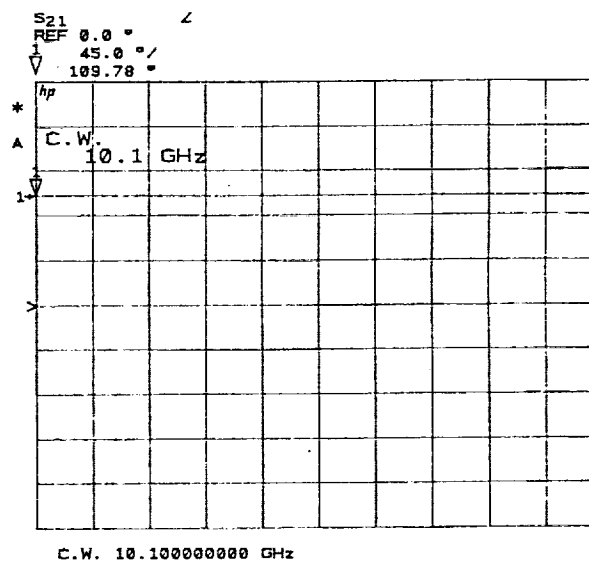Figure 8.—Compensated far-field pattern.

(a) Measured phase.

(b) Phase conjugate.

Case 1

(a) Measured phase.

(b) Phase conjugate.

Case 2

Figure 9.—Phase measurements and calculated conjugates.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

The growing demands for high gain and accurate satellite communication systems will necessitate the utilization of large reflector systems. One area of concern of reflector based satellite communication is large scale surface deformations due to thermal effects. These distortions, when present, can degrade the performance of the reflector system appreciably. This performance degradation is manifested by a decrease in peak gain, an increase in sidelobe level, and pointing errors. It is essential to compensate for these distortion effects and to maintain the required system performance in the operating space environment. For this reason the development of a technique to offset the degradation effects is highly desirable. Currently, most research is direct at developing better material for the reflector. These materials have a lower coefficient of linear expansion thereby reducing the surface errors. Alternatively, one can minimize the distortion effects of these large scale errors by adaptive phased array compensation. Adaptive phased array techniques have been studied extensively at NASA and elsewhere. Presented in this paper is a prototype automatic phase compensation module designed and built at NASA Lewis Research Center which is the first stage of development for an adaptive array compensation module.

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