A SPACE-FED LOCAL OSCILLATOR FOR SPACEBORNE PHASED ARRAYS*

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ABSTRACT

Lightweight, spaceborne phased arrays require both local oscillator signal distribution and compensation for mechanical deformations that dynamically occur in orbit. These array deformations are expressed by a sum of the time and amplitude weighted characteristic mechanical modes of the array structure, and their effects on the array pattern differ from the effects of random phase perturbations assumed in classical antenna tolerance theory. A space-fed local oscillator concept can partially compensate the effects of array deformations to reduce array pattern degradation. This concept also offers potential weight reduction of the array design and reduced deployment complexity. This concept uses a local oscillator radiator on the back side of the array along with a series of local oscillator pickup elements connected to the array elements.

INTRODUCTION

Future satellite applications require lightweight, deployable phased array antenna designs. Technology for these array designs is presently being developed with significant emphasis on array element modules and large structures for space deployment. Practical array designs demand very lightweight construction techniques, and consequently the array is no longer a rigid structure. These arrays dynamically deform in orbit as a result of attitude control thrusting, thermal loading, etc. These dynamic deformations are typically expressed by a sum of the characteristic mechanical modes of the array; the rates of these modes is relatively slow, typically less than 1/10 Hz. In operation, the mechanical deformation of the array radiating surface results in a time-varying deformation of the array phase distribution that degrades the array radiation pattern.

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The rates with which these deformations occur are sufficiently slow that the array surface may be considered frozen for purposes of examining the pattern distortion. The pattern degradation caused by the mechanical deformation (1 and 2) differs from the results predicted by the classical antenna tolerance theory (3).

Many of these array designs will also require a large number of elements, and conventional transmission line distribution networks for the local oscillator signal have a significant weight. Moreover, the presence of these distribution networks further complicates the array surface folding required by deployment.

CONCEPT DESCRIPTION

A space-fed local oscillator concept, shown in Fig. 1, provides partial compensation

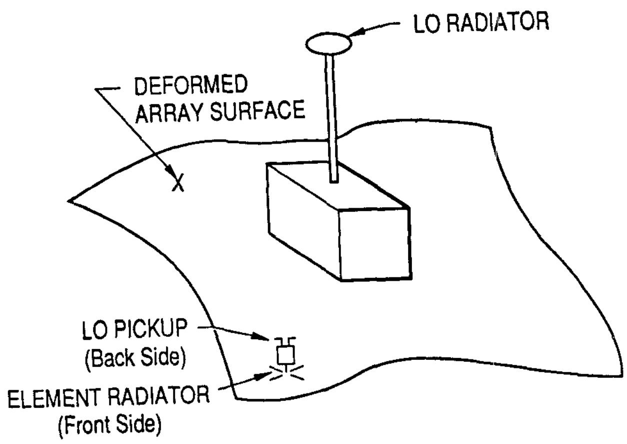

Fig. 1. Space-fed Local Oscillator Concept

for the mechanical deformations. In operation, the local oscillator signal is transmitted by the central radiator mounted above the back side of the array. A variety of designs, such as one recently

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described (4), might be used for this radiator. The transmitted local oscillator signal is received by pickup elements located on the back side of the array. These pickup elements can be used either with individual array elements or a group of array elements. In practice, the size of the group that can be serviced by a single pickup element is limited by the uniformity of compensation for deformation required. Because the pickup elements are on the back side of the array rather than the earth-facing side, the blockage from the array provides protection from ground-based interference.

The ability of the space-fed local oscillator to partially compensate the effects of array deformation can be visualized from Fig. 2. When the array surface is displaced towards the local oscillator radiator, the phase of the local oscillator signal is advanced relative to the phase received at the design array surface. However, the phase of the signal radiated by the array element is also retarded by the displacement from the design array surface. Similarly, if the array surface is displaced away from the local oscillator radiator, the phase of the local oscillator is retarded and the phase of the field radiated by the array element is advanced. The compensation is partial rather than exact because the local oscillator height is finite and the local oscillator frequency differs from the frequency used by the array.

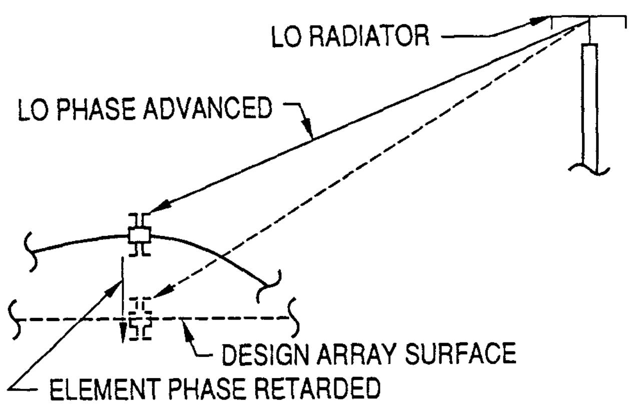

Fig. 2. Partial Compensation Capability

ANALYSIS

Presently, several structural techniques for deployable array designs are being investigated and these designs differ in their stiffness and mechanical mode patterns. In addition, the pattern control requirements differ with application and the tolerable mechanical deformation also depends on operating frequency. For example, in Fig 1, the central area represents the main structure of the spacecraft which would be more rigid than the portions of the array deployed from the central spacecraft structure. Rather than dwell on a specific design, the array will be modeled mechanically as a uniform square plate, whose mechanical modes are well known. Because the deformation is slowly varying, the corresponding degradation of the radiation pattern will be computed for an array surface with a fixed mechanical deformation.

The classical theory for tolerance effects on antennas (3) assumes random perturbations of the design phase distribution. This theory physically applies to deformations such as the manufacturing tolerance of reflector antennas. However, the deformations in deployable arrays follow a deterministic form rather than a random model, and the effects of these deformations differ from those predicted by a random model (1 and 2). For example, mechanical modes with odd symmetry result in shifts of the main beam direction, an effect not found in the random model.

The analysis proceeds by calculating the phase perturbation for both the local oscillator signal and radiated field caused by a mechanical displacement from the design array surface. This phase perturbation is calculated for all points on the array surface. The principal sensitivity in the radiated pattern results from element displacements normal to the beam direction; the radiation pattern is relatively insensitive to small displacements in the array plane.

The patterns in array designs are typically separable in orthogonal coordinates. In addition, the simple mechanical modeling of the array surface as a uniform plate results in a separation of the individual mechanical modes as well. The result is that the array pattern can be collapsed into a line source for pattern computations of arrays having individual mechanical mode deformations. This line source model of the array provides an easy computational means to demonstrate the effects of mechanical deformations and the partial compensation provided by the space-fed local oscillator concept. These simplifying assumptions may not be valid for practical array designs, but the extension to a two-dimensional array computation is straightforward.

With the above simplifications, the array pattern without the space-fed local oscillator compensation is given by

$$V(\theta) = \int_{-L}^{L} A(x)\ \exp[jk_0(\pm x\sin\theta + z(x)\cos\theta)]dx$$

Similarly, the array pattern with the space-fed local oscillator compensation is given by

$$V(\theta) = \int_{-L}^{L} A(x)\exp\left\{ \pm jk_0\ x\sin\theta + jk_0(x)\left[\cos\theta - \frac{f_{LO}/f_0}{\sqrt{1+(x/H)^2}} \right] \right\} dx$$

In these expressions, $A(x)$ is the amplitude distribution of the array, the mechanical deformation at a given instant of time is given by $z(x)$, k_o is the free space wave number, the width of the array is $2L$, H is the height of the local oscillator radiator above the array surface, f_{LO} is the local oscillator frequency, and f_o is the RF frequency used by the array. The second term in the brackets in eq. 2 is the compensation provided by the space-fed local oscillator.

In general, these expressions cannot be written in a closed form, and the pattern computations are obtained by numerical integration. While the mechanical deformation is generally a sum of the characteristic modes of the structure, the computations were performed for a single mode. In this way, the sensitivity of the array to particular mechanical modes can be observed and if mechanical control devices are to be used in the array design, the effect of control point locations can be observed.

Example pattern calculations are presented in Figs. 3 and 4 for the first order even and odd modes, respectively. These patterns are plotted as a function of u, where $\pi u = k_oL \sin\theta$ is used so that the spatial patterns are independent of array size. The amplitude distribution in these computations is assumed to be uniform. The peak mechanical deformation in both cases is 0.2 wavelengths. Both figures contain the pattern without error (short dashes), the pattern without compensation (long dashes), and the pattern with the space-fed compensation (solid). The even mechanical modes in Fig. 3 generally result in gain loss, increased sidelobe levels, and null-filling, similar to the effects of random phase error. With the space-fed local oscillator compensation, the pattern and gain levels are quite similar to the error-free pattern. The odd mechanical modes result in a boresight shift, less gain loss than the even mechanical modes, and an unsymmetric sidelobe structure.

These computations were performed with a relatively short local oscillator height, namely $H/2L = 0.2$. As the height of the local oscillator radiator increases, the partial compensation of the phase errors improves. However, an increase in the height of the local oscillator radiator also imposes further deployment burdens and greater stiffness in the boom structure supporting the local oscillator radiator. These issues need to be evaluated in a specific design.

The ratio of the local oscillator frequency to the RF frequency used by the array is unity in these computations. At microwave frequencies, where the mechanical deformations significantly degrade the patterns of deployable arrays, this ratio is close to unity. Other computations were performed with ratios that differ from unity. These computations indicate that the partial compensation provided by the space-fed local oscillator concept is not particularly sensitive to the ratio of the frequencies within the range of choice for practical applications. The effect of this ratio can be examined for a specific design.

CONCLUSIONS

A space-fed local oscillator concept for deployable spaceborne phased arrays has been described. This concept provides partial compensation for the dynamic deformations that occur on-orbit when lightweight deployable array designs are used. This analysis differs from the results predicted based on the random phase perturbations used in the classic antenna tolerance theory. The space-fed local oscillator concept provides effective compensation for peak array deformations that are as large as 0.3 wavelengths. The compensated patterns are comparable to those achieved by conventional local oscillator distribution techniques with about 0.1 wavelength peak mode distortion. Thus, the structural requirements for the array are reduced by the space-fed local oscillator compensation with the benefit of potential weight reduction.

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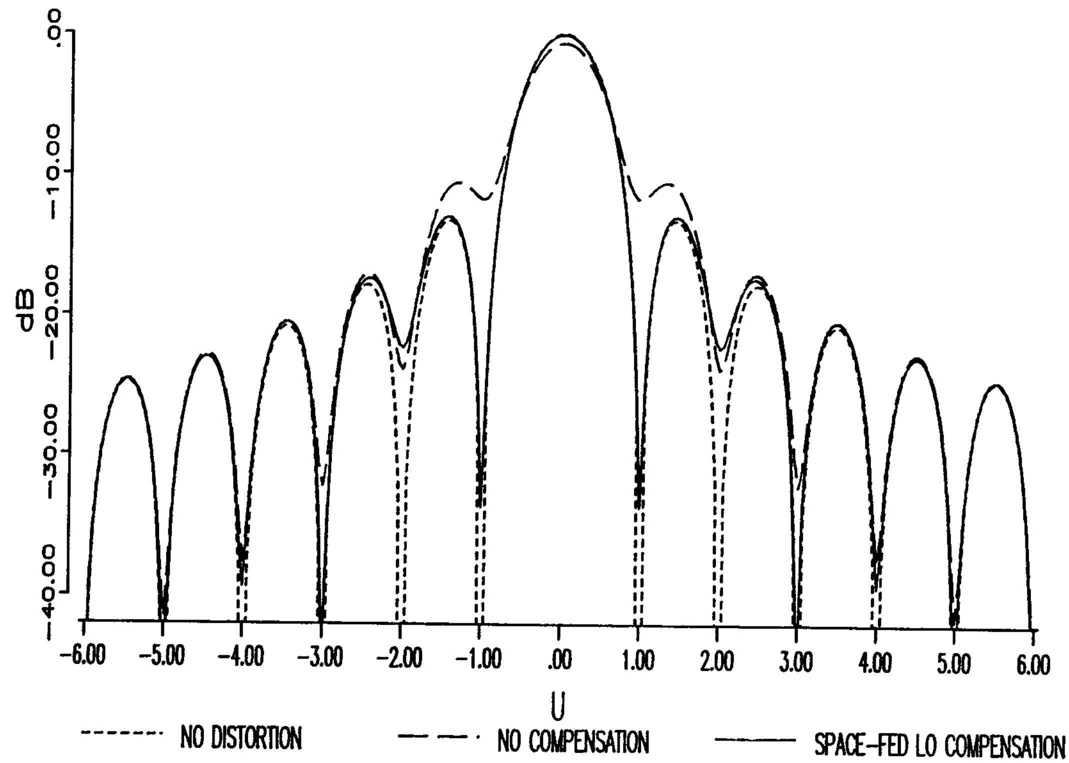

Fig. 3 Array Patterns for First-Order Even Mechanical Mode

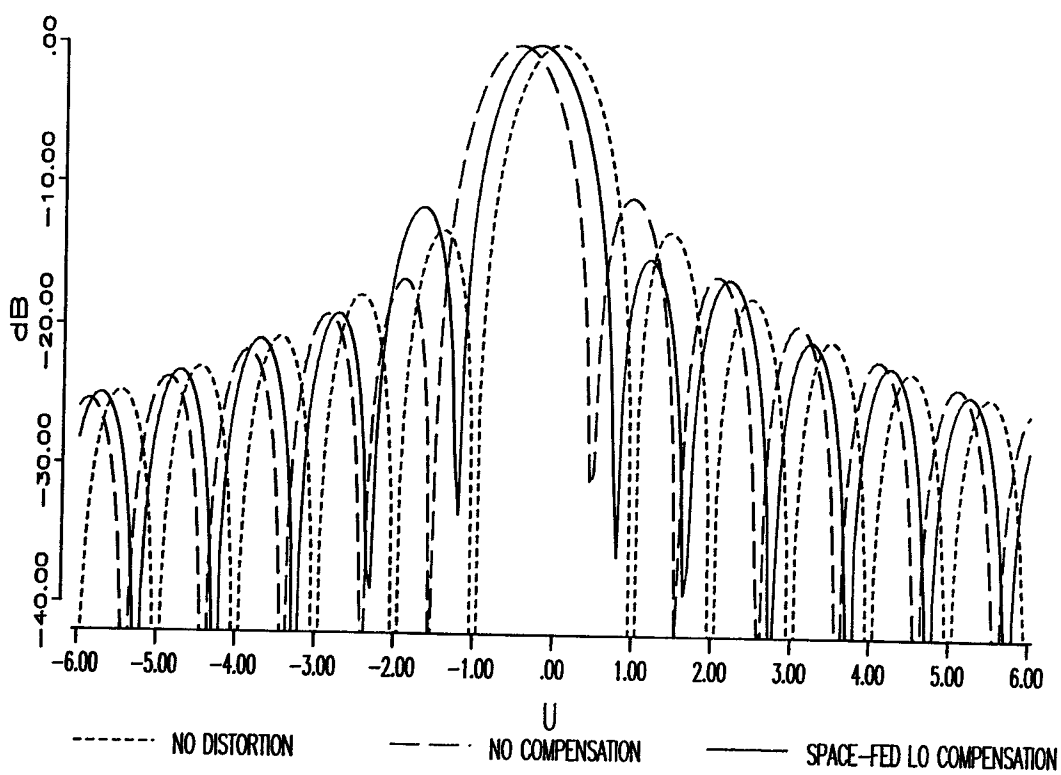

Fig. 4 Array Patterns for First-Order Odd Mechanical Mode