# Practical Failure Compensation in Active Phased Arrays

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***Abstract*—A practical failure compensation technique for active phased arrays is presented. It is suitable for real-time applications and is applicable to any distribution of the failures across the array. It is independent of the external signal environment and is capable of achieving substantial performance improvement across broad selectable angular sectors at the expense of some additional performance degradation in other less important sectors.**

***Index Terms*—Active arrays, phased arrays.**

## I. Introduction

ACTIVE phased arrays are different from passive phased arrays in that they contain an active transmit/receive (T/R) module behind each radiating element.[1] Since the number of such active modules, all operating in parallel, is vastly greater than the number of transmitters and receivers in passive array architectures, the probability of some module failure tends to be correspondingly higher. However, in contrast to the passive array, a module failure in an active array does not have catastrophic consequences. The effects of such failures are usually expressed in terms of corresponding degradation of the antenna pattern and possible losses of some transmit power. The amount of degradation depends on the number and types of failures and on their location within the array. Increased module age and excess temperature will contribute to such failures.

As the number of failed modules increases, the pattern gradually worsens until at a certain point it becomes unacceptable. The array is then considered to have failed. The precise degradation level required to declare an array failure depends, of course, on system specifics. When this point is reached, the array should have modules replaced or be scheduled for overhaul.

To increase the mean-time-between-failures (MTBF) of an active array—thereby increasing its availability—it is necessary both to maximize the average lifetime of a T/R module through appropriate manufacturing and maintenance processes and to mitigate the effects of module failures through the implementation of reasonably effective autocompensation techniques. Such techniques modify the illumination function across the remaining "healthy" elements so as to best compensate for the pattern degradation caused by the failures. Beside extending the array's MTBF, a successful implementation of an autocompensation technique will also ensure that the user will obtain the best possible performance out of the array over any given time interval. An effective autocompensation will, therefore, be important not only to control cost, but also to ensure that when simple repair and recalibration is not within reach, the degradation of an error-compensated array will be slow and graceful.

Prior works in the field known to these authors consist either of complex syntheses of new "optimal" antenna patterns using the remaining elements after multiple failures (see, e.g., [1]–[3]) or of compensation techniques geared toward improved performance in the presence of specific external interference sources [4], [5].

In this work, the chief concern was to develop an autocompensation technique of a practical—as opposed to optimal—nature. The goal was to achieve significant improvements in the patterns of arrays with failures across broad selectable solid-angle sectors, independently of the external environment and without having to incur unduly lengthy and complex computations. We required from the start that our technique be very simple and that it should adapt easily to any failed element configuration—no matter how complex. The next section describes our approach. Validation results are given in Section III.

## II. Technical Approach

The radiation pattern of a phased-array antenna is a properly weighted linear superposition of its individual element patterns. In a similar vein, we require that the compensation adjustment for a composite failure in an active phased array be constituted of a linear superposition of individual single failed element adjustments. (Throughout this paper, we use the terms "failed module" and "failed element" interchangeably—always implying that it is the active module behind the radiating element that failed.)

We first assume that separate built-in-test/fault-isolation-test (BIT/FIT) circuits are in place to detect each module failure. We next require that in each offending module, the responsible channel be turned off in such a way that the radiating element will remain connected to a matched load. This is done in order to avoid having to address the specific nature of each failure. Another implicit assumption is that the interelement coupling across the array will not be disturbed when an element is switched into its "off" state. The array architecture should be supportive of these capabilities.

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[1] This technique was developed under Small Business Innovation Research (SBIR) Contract F19628-95-C-0225 for the USAF Rome Laboratory under the direction of Dr. R. A. Shore.

After the above steps have been taken, we proceed to implement our failure compensation technique as described in the following sections. Though, in principle, failure compensation techniques can be employed both on transmit and receive, we choose to focus our present effort on the receive path. We consider this path to be the more important because to conserve transmit power active arrays usually implement much lower sidelobe patterns on receive than on transmit. Also, because oftentimes the solid-state power amplifiers employed in active phased arrays are designed to operate in a saturated mode, the indicated autocompensation technique would necessarily be different in some respects than that to be employed on receive, e.g., it would not include amplitude compensation.

### *A. Single-Element Failure Compensation*

We divide the compensation process for a single-element failure into two complementary steps. The one step restores performance at and near the pattern's azimuth plane; the other step recovers parts of the lost performance in the pattern's elevation and intercardinal planes.

Relative to the ensuing discussion, it will be borne in mind that the so-called "principal azimuth" and "principal elevation" planes are defined in relation to the antenna pattern. Their actual orientations depend on the locations of the main-beam axis and the array's elevation axis (i.e., its $y$ axis.) The pattern's principal elevation plane always contains these two vectors and, therefore, even when steering with the main beam in azimuth, it always remains vertical in relation to the array coordinates' azimuth plane. The pattern's principal azimuth plane, though always perpendicular to the array's elevation plane, also contains the main beam's axis. Therefore, it only coincides with the array coordinates' azimuth plane when the main beam's axis is also in that plane. In what follows, we will frequently refer to the pattern's principal or cardinal planes simply as the "azimuth" and "elevation" planes.

Since air and surface-borne arrays are usually mounted at close to vertical orientations, the pattern's principal planes can often be loosely associated with the azimuth and elevation planes as defined by the local earth coordinates. It will be seen that this association is important to the understanding of the potential operational significance of the autocompensation technique to be described.

### *B. Pattern Compensation in the Azimuth Plane*

*1) A General Description:* In the principal azimuth plane, the far-field pattern is defined by a one-dimensional azimuth illumination function. It is obtained from the two-dimensional array illumination function by collapsing every column illumination into the sum of its individual-element component weights. When an element in a given column fails, it influences the azimuth pattern through the decrease of the scalar amplitude sum that corresponds to this column. This pattern can be easily repaired by increasing the amplitudes of other elements in the column by the total margin necessary to offset this shortfall.

Fig. 1(a) shows a rectangular grid array in which one element has failed. The failed element is indicated, together with its immediate neighbors in the column. Fig. 1(b) shows the way that the three corresponding electric field vectors add up in the principal azimuth plane—before the failure, after the failure, and after amplitude compensation has been applied. Fig. 1(c) shows the corresponding antenna patterns in the principal azimuth plane. The prefailure and postfailure compensation patterns are identical.

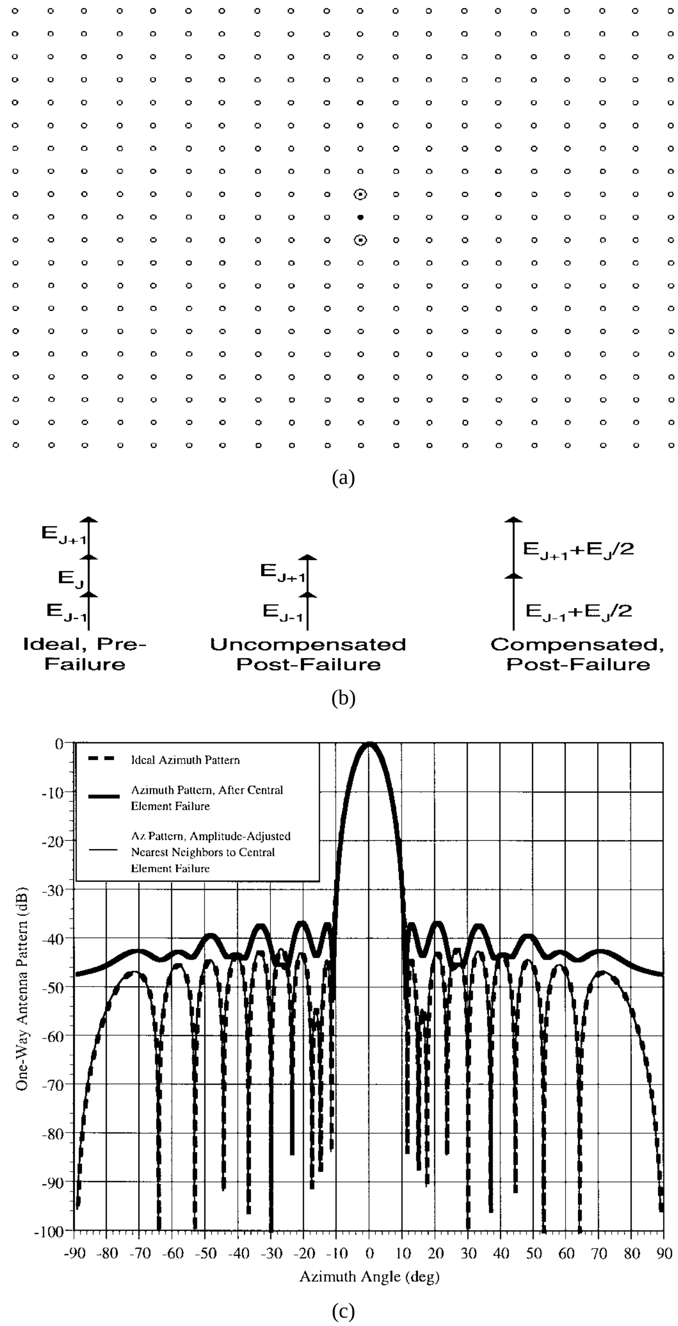



Fig. 1. (a) Rectangular array with central element failure and compensating elements highlighted. (b) Amplitude compensation for element failure. (c) A pattern compensation in the azimuth plane via amplitude adjustments to the near column neighbors.

As long as the compensating elements are selected strictly within the failure's own column, the principal azimuth pattern at the carrier frequency is precisely restored. The effect of such compensation schemes on the pattern behavior in other planes

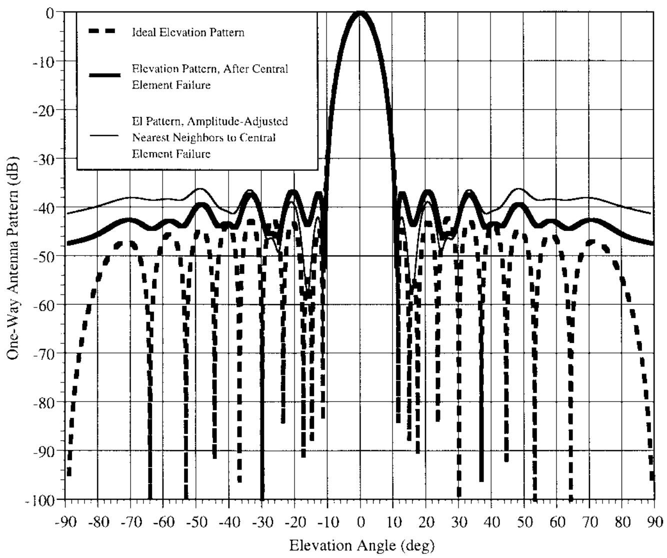



Fig. 2. Effects of amplitude compensation scheme on elevation plane pattern.

is always less than perfect. The specifics of this behavior depend on how the compensation is implemented within the column.

*2) Compensation Options and Selection:* There is generally a multitude of options as to how to select compensating elements within a failure column. Their relative impacts can be best understood by comparing the two extreme options. Of these, one confines the compensating action to the failure's two immediate neighbors. The other spreads it throughout the entire column.

When the two nearest neighbors are used, each will have its amplitude increased by half the amplitude of the failed element. Clearly, in the principal azimuth plane, the illumination function will thereby be completely restored. However, as we begin to depart from the azimuth plane the thus compensated illumination function will also begin to depart from the illumination ideal for these planes. This is because the projections of the compensating elements' locations onto planes other than the principal azimuth plane are different from that of the failed element. Since the elements used are nearest to the failure, this departure will normally be quite small near the azimuth plane. In the neighborhood of the principal elevation plane substantial additional pattern degradation is expected because there the departure will be maximal.

This additional degradation near the elevation plane can be avoided by using the entire column to compensate for the failure. When this is done, the failed element's amplitude can be spread across the remaining elements in the proportions dictated by the illumination function prevailing in the column. Performance in the principal azimuth plane is thus perfectly restored without introducing an additional degradation into the principal elevation plane.

Fig. 2 shows principal elevation plane patterns for the array in Fig. 1. Shown are the prefailure pattern, the uncompensated postfailure pattern, and the compensated postfailure pattern. The amplitude compensation is identical to that shown in Fig. 1(b). Its degrading effect on the principal elevation pattern is evident. When the amplitude compensation is spread across the entire column, as per the prevailing illumination function, it does not degrade from the postfailure elevation pattern.

Though this second scheme is superior in relation to performance in the two principal planes, extensive simulations showed that overall it was the inferior option. The reason was that due to the large spread of the correction across the column, the illumination began to depart very rapidly from ideal even for slight deviations from the principle azimuth plan. Thus, the effect of the correction was confined to a very narrow region immediately adjoining this plane. This was clearly in opposition to our goal set forth in the introduction of achieving significant pattern improvement over wide angular sectors. A general conclusion in this respect, borne out by our results in Section III, was that to remain consistent with this goal it would be necessary to confine all single-element compensation manipulations to the failed element's immediate neighbors in the column. The element patterns of these neighbors possess the phase centers nearest to that of the failed element and can remain in approximate phase with it across wider angular sectors than other element patterns. Therefore, we selected the nearest neighbor compensation as our standard azimuth compensation scheme. We accepted the resulting degradation near the principal elevation plane as an additional margin to be handled by our elevation compensation scheme to be described next.

### C. Compensation in the Elevation Plane

If we were to compensate for the failed element in the principal elevation plane using the same amplitude technique, it would be necessary to increase the amplitudes of some elements within the failed element's row. This would upset the illumination function balance already obtained in the azimuth plane and degrade the now perfect azimuth pattern in that plane. What we need instead is a degree of freedom that could be used to improve the elevation pattern without introducing adverse effects into the azimuth pattern. Next, we show that phase is such a parameter and describe its utilization in connection with elevation pattern compensation.

*1) Phase Compensation Within the Failure Column:* Fig. 3(a) shows three adjacent elements labeled $j-1$, $j$, and $j+1$ in an array's column. Behind each element is a phase shifter that can be used to modify the phase response of this element independently of all the others. When the beam is steered to a given elevation via these phase shifters, the space about it is divided into three regions [see Fig. 3(b)]: the "horizontal" beam-axis plane and "upper" and "lower" hemispheres. When the beam points horizontally and the array columns are vertical, the "horizontal" beam-axis plane is horizontal and these hemispheres are upper and lower—also in the local earth coordinates sense.

Fig. 3(c) shows how the three corresponding electric field vectors add up in each of the three regions. In the beam plane they are parallel and add up linearly. In the "lower" hemisphere they add up with a relative phase gradient in one sense. And in the "upper" hemisphere they add up with a relative phase gradient in the opposite sense. The size of each

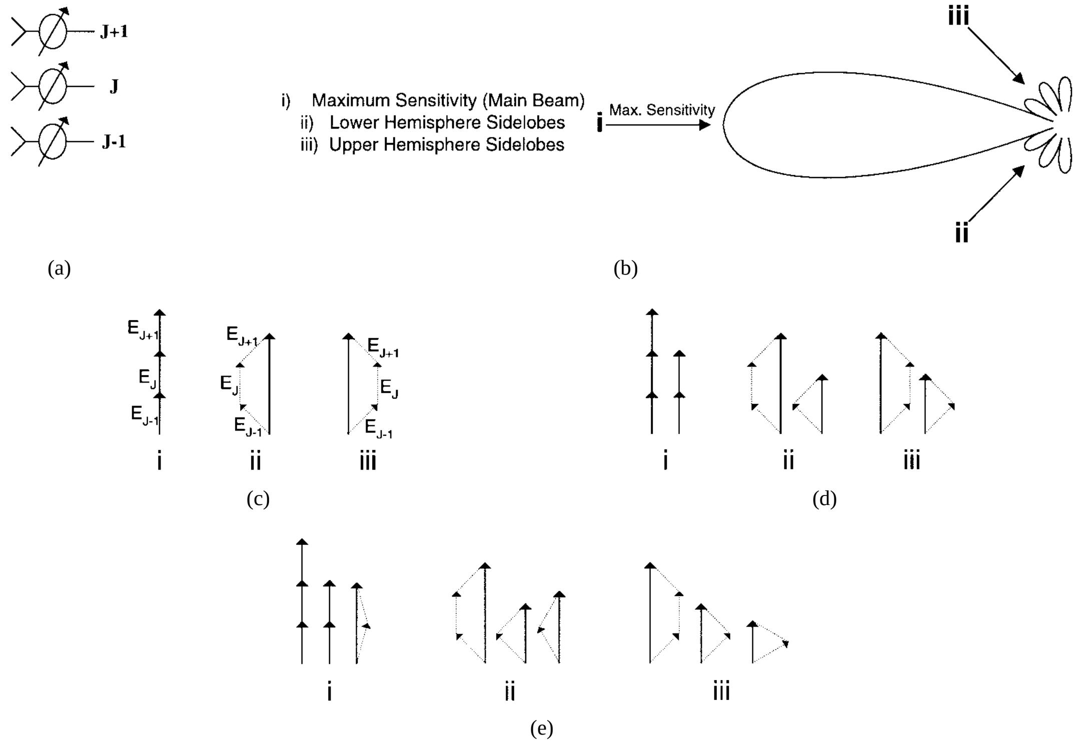



Fig. 3. (a) Three adjacent column elements together with their phase shifters. (b) Three directions of arrival. (c) Composite $E$-field phasors due to three elements at three directions of arrival. (d) Three element $E$-field phasors before and after middle element failure at three directions of arrival. (e) Three element $E$-field phasors before failure, after uncompensated central element failure, and after phase rotation compensation at three directions of arrival.

gradient depends on how far from the beam plane the signal originates.

When the middle ($j'$th) element fails the sum is affected in each of the three cases. Fig. 3(d) shows the vector sum before and after failure for each case. In the lower and upper hemispheres—the differences between the pre and postfailure vector sums—accounts for sidelobe degradation. In the main beam it accounts for reduced gain. To compensate for sidelobe degradation, it is necessary to bring the vector sum of the remaining neighbors as closely as possible to the original prefailure three-element, sum. (This is because, when the sidelobe level is low, the remainder of the column produces a resultant electric field that is nearly the exact opposite of the prefailure three-element field.)

Fig. 3(e) shows that we can achieve a correction in one hemisphere by rotating the phases of the two remaining elements in such a way as to make them more collinear. The effect of any given rotation on the antenna pattern depends on the viewing angle relative to the main beam. The same figure also shows that the sense of corrective rotation, which improves performance in one hemisphere and degrades it in the other hemisphere. By reversing the sense of our corrective rotation, we reverse the hemispherical preference.

To minimize undesirable rotations to the overall electric field vector, the corrective rotations applied to the two vectors must be such as to reproduce the original prefailure direction of the resultant three-element field in the principal elevation plane. Given the proximity of the two correcting elements, their original amplitude weightings would often be nearly equal. Whenever this is the case, their respective rotations should be nearly equal in magnitude but opposite in sign. (When the failure occurs far enough from the center of the column, the amplitudes of the two neighbors can become less equal due to the array taper. When this is the case, the entire effect is also weighted down via the same taper.)

The magnitude of the corrective rotations should be selected based on the overall behavior across the two hemispheres. Since azimuth correction requires that both vectors' amplitudes be increased this must be included in the process of determining which phase rotation produces the best overall sidelobe performance.

Fig. 4(a) shows the composite process of amplitude and phase compensation, as seen from the principal azimuth plane. Fig. 4(b) shows the corresponding antenna patterns in the principal elevation plane. It is seen that after phase compensation, the elevation pattern improves considerably in one "hemisphere" while undergoing some additional deterioration in the other "hemisphere." Fig. 4(c) shows a corresponding cut in the 45° intercardinal plane.

*1) Further Considerations Pertaining to Phase-Rotation Compensation:* At any point in space, the antenna pattern is the normalized phasor sum of all the single elements in the array. In the main beam, the phasors are nearly parallel. In the sidelobes they add up to small residual values. If the array is divided into any two mutually exclusive groups of elements; then, in the sidelobe region they will be nearly complementary, i.e., they will form phasor sums of nearly equal magnitudes but nearly opposite directions. A given element and its immediate neighbors, can be viewed as one such group. The remainder of the array forms its complementary group. When the element

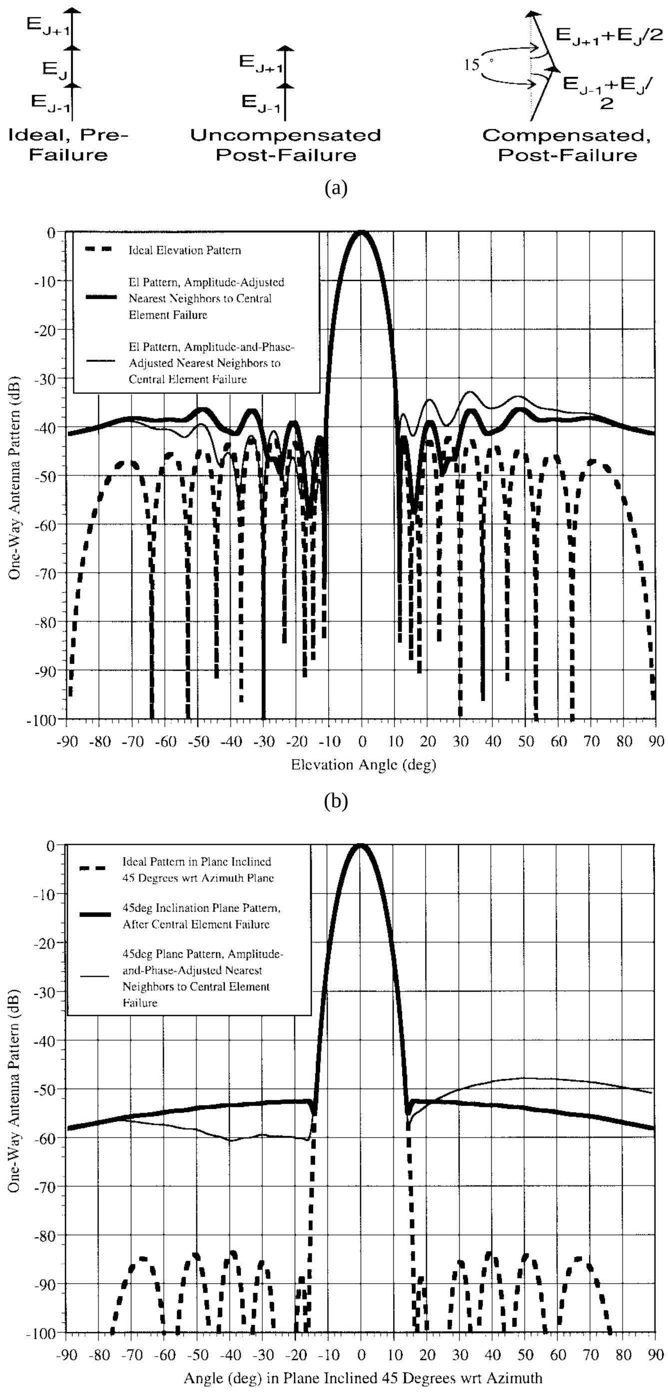



Fig. 4. (a) Description of the compensation, as seen from the principal azimuth plane. (b) Effects of phase rotations in the two hemispheres: principal elevation plane. (c) Effects of phase rotations in the two hemispheres: 45° inclination plane.

fails, the array sidelobe performance can be partially restored by modifying its neighbors' phasor contributions, so as to bring the group's total (as nearly as possible) to its original prefailure phasor sum. We have previously introduced both amplitude- and phase-based methods, whereby such corrections can be partially achieved. We shall now discuss the phase-rotation method in more detail and expose some of its properties and limitations.

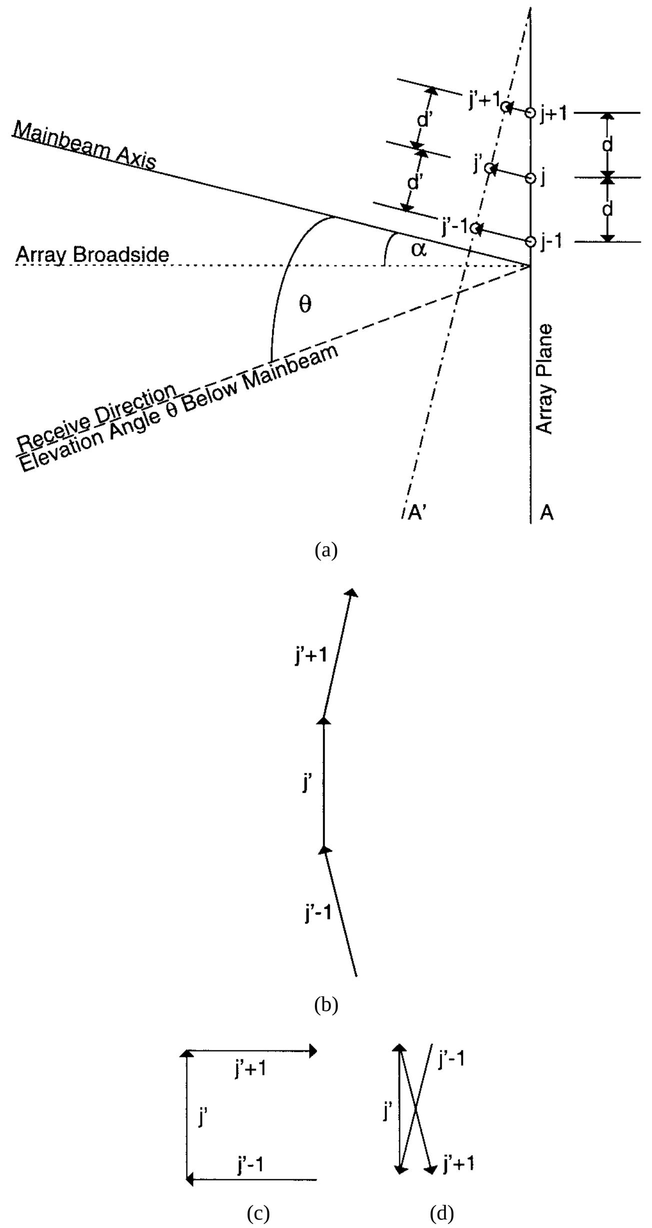



Fig. 5. (a) Array receive geometry. (b) Phasor sum near the mainbeam. (c) Phasor sum near 30° below the mainbeam axis. (d) Phasor sum near the lower end-fire direction.

Fig. 5 shows an array's receive geometry in which the main beam is steered in elevation to $\alpha$ radians above the array broadside. The element spacing in a column is given as "$d$." A failed element is shown in the column position "$j$." Due to phase steering, the projections of the failed element and its immediate column neighbors "$j-1$" and "$j+1$" are equiphase in the plane $A'$, perpendicular to the main beam. Their respective projections in $A'$ are shown as "$j'-1$," "$j'$," and "$j'+1$." The separation between the neighbors' projections in $A'$ is given as

$$2d' = 2d\cos\alpha$$

which is less than, or equal to, the original $2d$ separation in the array column.

The relative path delay to the $j-1$, $j+1$ elements along the receive direction shown ($\theta$ radians below the main beam axis) is

$$\Delta = 2d\,\sin(\theta-\alpha).$$

The received phase differences in the array due to a plane wave incident from this direction is

$$\Delta\varphi = \varphi_{j-1} - \varphi_{j+1} = \frac{2\pi}{\lambda}(\Delta + 2d\sin\alpha).$$

Along the main beam axis, $\theta$ is zero and the received signals are equiphase [see Fig. 3(c.i)]. Immediately above and below the main beam axis the phase difference changes sign [see Fig. 3(c.ii) and (c.iii)]. As $\theta$ increases, $(\varphi_{j-1} - \varphi_{j+1})$ can eventually reach a full cycle (i.e., $2\pi$) at which point the orientation changes again, e.g., from that of Fig. 3(c.ii) to that of Fig. 3(c.iii). When $\alpha = 0$, this happens at

$$\sin\theta = \frac{\lambda}{2d}.$$

When $\alpha = 0$ and $d = \lambda/2$, $\theta = \pi/2$, i.e., along the low-elevation end-fire direction. At $\alpha \neq 0$, this condition will happen at other angles. Because of the above, the phase-rotation method is truly effective in one hemisphere, while having a deleterious effect in the other. Furthermore, when the amplitude of the phasor sum is increased via rotation, as per Fig. 3(e.ii), it continues to exceed the original, unrotated amplitude across most of the favored hemisphere, so long as $\alpha$ is close to zero.

In the favored hemisphere, the pattern sensitivity to reasonably sized—i.e., 10–20° phase rotations, is not high near the main beam or near end-fire [see Fig. 5(a) and (c)]. This is because in these regions the phasors are already nearly parallel or antiparallel to the sum. The highest sensitivity is obtained when the phasors are perpendicular to the sum [see Fig. 5(c)]. When $d = \lambda/2$ and $\alpha = 0$, this happens at $\sin\theta = 1/2$ or $\theta = 30°$.

The above observations are supported by Fig. 4(b). In this figure, it is shown that the region of best sidelobe improvement is centered about an elevation angle of $-30°$ and that the effect of the correction becomes negligible as the bottom end fire ($\theta = -90°$) is approached.

In this work, the specific correction used for all failure conditions was a single fixed amplitude adjustment and a single fixed phase rotation. It was selected based on results from a detailed off-line array simulation that incorporated different levels of multiple random failures and computed the effects of the correction in every plane of the pattern. The on-line application is straightforward. Above all, it requires no computations. For the arrays under study, rotations close to 15° were generally found to be the best for beam elevations near the array broadside. They were determined from the off-line simulation by generating various levels of random failures, applying different corrections, and comparing results. In practical applications, different corrections can be selected off-line as per elevation steering sector.

The following argument is given in support of the 10–20° range of the optimal rotation: in the receive direction most sensitive to the rotational correction, the phasors from the adjacent column neighbors are antiparallel [see Fig. 5(c)]. Assume that their average amplitude is close to that of the failed element's. Then, if each respective amplitude is increased by one half the failed element's amplitude, a 20° rotation would approximate the original prefailure phasor total in this region. When we spread our rotation compensation scheme across additional neighbor pairs, as per Section II-C-2 below, the value becomes closer to about 15°. Our extensive numerical simulations have borne this out.

The subjects of correcting outside the principal planes and of implementing corrections for multiple failures, are discussed throughout the remainder of this paper.

*2) The Compensative Properties of Phase Rotations:* We briefly summarize some key properties of the phase rotation technique.

1) The effects on overall sidelobe behavior in the upper and lower hemispheres are opposite. An overall improvement in one hemisphere implies an overall degradation in the other and vice versa. Therefore, this technique can only be useful in radar or communication systems in which the sidelobe performance in one hemisphere is much more critical than in the other. Airborne surveillance and fire control radars are examples of systems in which performance in the lower hemisphere is far more critical than that in the upper hemisphere—especially near its uppermost reaches. Shipborne radars are examples of systems in which sidelobe performance in the upper hemisphere is far more important than that in the lower hemisphere.
2) For any given compensative rotation, the local effectiveness will be a function of the viewing angle relative to the main beam's elevation. The specific performance values will depend on the array spacings, the carrier wavelength, and the ideal prefailure illumination function.
3) The contiguous region size, over which improvement can be attained, depends on the interelement elevation spacing measured in carrier wavelengths. The smaller the spacing is, the wider this region can be made. Spacings on the order of half-wavelength generally yield improvement regions of acceptable widths.
4) The effects of this technique tend to be less significant in the immediate neighborhood of the principal azimuth plane. This is because in these regions, the three vectors are nearly parallel to begin with so that not much increase in overall length can be accomplished by rotation. The missing performance, however, is partially recovered through the azimuth correction, which is effective in the low-elevation region.
5) In the intercardinal planes, the performance will vary depending on the inclination angle of the plane. This is because the projection of the elevation spacing between the correcting elements depends on this inclination angle. It is not always easy to generate adequate compensations that are evenly spread across an entire hemisphere using only the two elements above and below. In the next section, we will address this issue.

*2) Phase-Compensation Spread Across Six Immediate Neighbors:* It is possible to achieve an equivalent compensation in the elevation plane by spreading the rotational correction across the three nearest element pairs, which straddle the failed element's position in the column. [See Fig. 6(a) and (b) for a hexagonal grid example. In these figures, the failed element is represented by a different symbol. It has no significance beyond denoting failure.] The magnitude of the rotation, of course, may have to be adjusted to reflect the new scheme. As long as attention is confined strictly to the elevation plane, the two schemes are perfectly equivalent. However, in every other plane, the compensative behavior is quite different. In the azimuth plane, the compensation will no longer be perfect because the amplitude sum in the neighboring columns has changed.

In the intercardinal planes the behavior will be more balanced than before. This can best be seen by observing the three element pairs indicated in Fig. 6(a) and (b). (It is easier to perceive the point if we group these pairs along the three diagonals of the hexagon, as shown, instead of by columns.) As the inclination angle grows, the projected spacings of the failure column pair and of one diagonal pair decreases in this plane. For the third pair, however, the projected spacing becomes larger. This provides a more balanced overall behavior.

When the array has a hexagonal geometry, as in the case shown in Fig. 6, there is the additional advantage that the elements of the two neighboring pairs are spaced closer together than the corrective pair within the failure column. This broadens their contiguous elevation region of effectiveness. All of this has been proven through a detailed simulation and through several compact antenna range measurements.

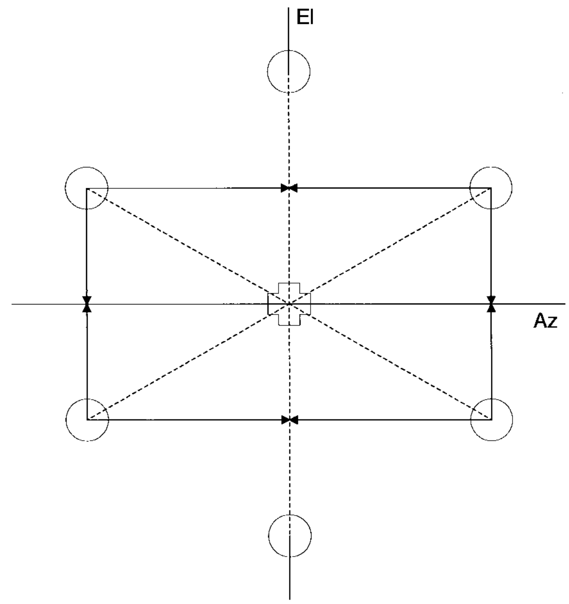
### D. Multiple Failure Compensation

The compensation mechanism for multiple failure is linear superposition. It is described below.

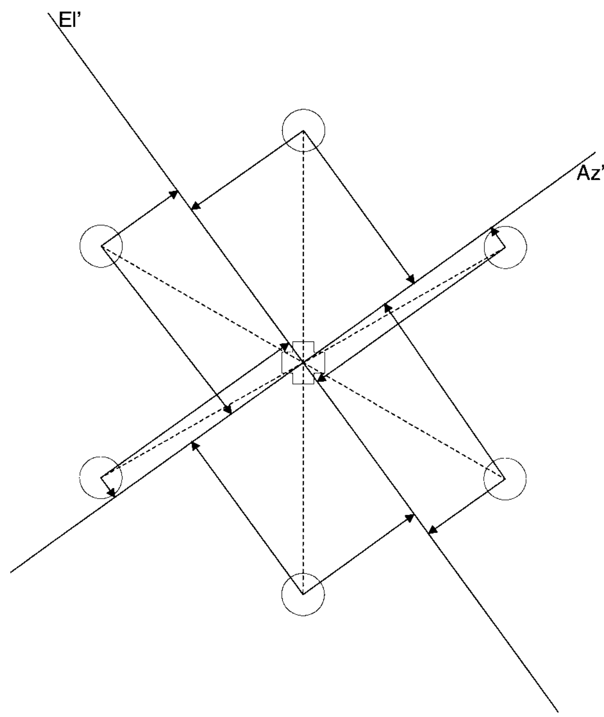
*1) Pattern Compensation via Superposition:* When several elements fail in an active phased array, each receives the same amplitude and phase correction described in the preceding sections. Amplitude compensations are applied through the two immediate neighbors in each failure's column. In a hexagonal array, phase compensations are applied through the three element pairs, which constitute the six immediate neighbors of each failure. In a rectangular array, it can be applied either through the single nearest neighbor pair within each failure's column or through the three nearest neighbor pairs that straddle each failure's row.

The specific rotation to be used is derived only once via a detailed array simulation and is used without alterations thereafter. Possible refinements could be attained through the optimization of separate corrections, say, for different percent failures, etc. In our simulation work, we found that even when we used a single corrective rotation for all possible failure extents and distributions, we still obtained substantial improvements in our sectors of interest.

Following this approach, the overall compensation is achieved via the superposition of individual failure compensations. This is the same mechanism that accounts for the formation of the overall antenna pattern and for the aggregate failure pattern.




(a)




(b)

Fig. 6. (a) Diagonal pairing of compensative elements in neighboring columns. (b) Projection of compensative element positions onto an intercardinal plane.

*2) Required Provisions in the Presence of Closely Spaced Failures:* The above described superposition technique applies in a straightforward way only as long as the failures are far enough removed from each other to preclude overlapping of their immediate neighborhoods. When failures occur close enough together that some of their immediate neighbors are shared among them, each of these neighbors has to compensate for more than one failure. When failed elements are themselves immediate neighbors, ideal compensations cannot be implemented because elements that are to compensate for other element failures may have failed themselves. Failed elements at the array edges experience similar problems because they do not have full complements of neighbors.

Simple rules can be used to modify the compensation technique in such situations. While the performance still deteriorates, enough can be salvaged to make the operation worthwhile. Such a set of rules is described below. It was used throughout the examples detailed in Section III.

*Rules for Handling Closely Spaced Failures:*

1) *Shared Neighbors:* When an element is to compensate for two or more failures, both its amplitude and phase manipulations will consist of the linear sum of the individual per-failure amplitude and phase compensations.
2) *Failed or Missing Neighbor-Amplitude:* When one of the immediate neighbors of a failed element has also failed, its paired element will assume its original amplitude correction independent of this failure. (In our current scheme we didn't attempt to compensate for this failure. This was done in the interest of simplicity. In principle, this can be improved upon.) The same approach applies when a paired element is missing due to an array edge.
3) *Failed or Missing Neighbor-Phase:* When one element of a compensative pair is missing due to failure or due to proximity to an array edge, the remaining element will not execute compensative phase rotations. This is so as to minimize unwanted overall rotations. Stated differently, phase rotations are only acceptable when they come in balanced pairs.

## III. Simulated and Measured Results

We first present the results of a multiple failure simulation, following the above-described technique. The array was as shown in Fig. 7. It was octagonal in shape, had a hexagonal lattice, and contained approximately 2000 elements. In one test case, 4% of the elements were failed by a random draw. The failed element distribution across the array is also shown in Fig. 7.

Fig. 8 shows three performance curves. The bottom curve represents the ideal root-mean-squared (rms) sidelobe level of the array prior to any failure computed in various planes. The horizontal coordinate is the inclination angle of the rms sidelobe plane given in degrees with respect to the horizontal, i.e., azimuth, plane. The azimuth plane is thus represented by the coordinate "0" and the elevation plane by 90. The abrupt behavior of the curve is due to the relatively coarse, 5° step used by the simulation. The top coarsely-dashed curve represents the uncompensated rms sidelobe level after failure. The intermediate curve shows the rms sidelobe behavior after amplitude compensation only, using the nearest neighbors. In the principal azimuth plane the correction is perfect. It remains near perfect for another 10° on either side of this plane and thereafter begins to deteriorate.

Fig. 9 shows the effects of a composite amplitude and phase compensation. The compensation shown in this figure is confined to the immediate neighbors of each failure within its column. The intermediate curve of Fig. 8 is here replaced by two curves. One, representing the compensated behavior in the favored (here lower) hemisphere and the other representing the compensated behavior in the other hemisphere. The improved behavior in the favored hemisphere manifests itself through the better sidelobe behavior throughout the entire hemisphere. In the other hemisphere, the compensated behavior only becomes significantly degraded in planes inclined more than 30° in relation to the azimuth plane. Still, the improvement in the

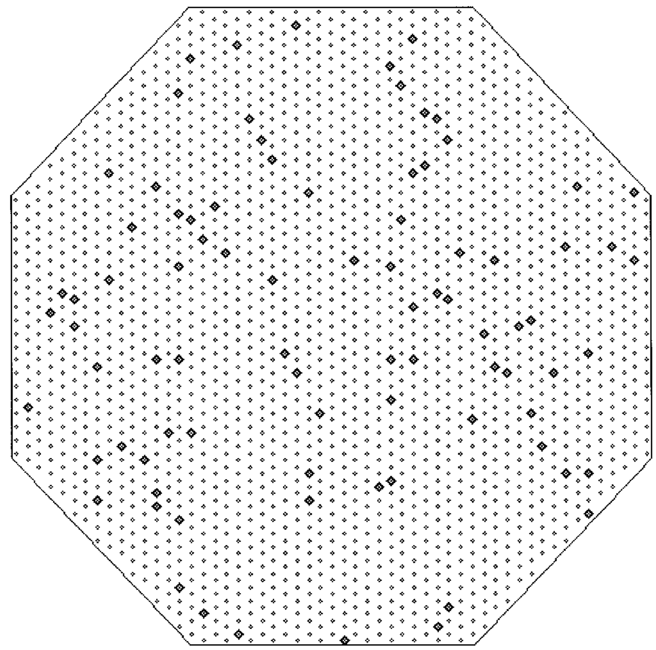


Fig. 7. Randomly selected 4% of elements failed.

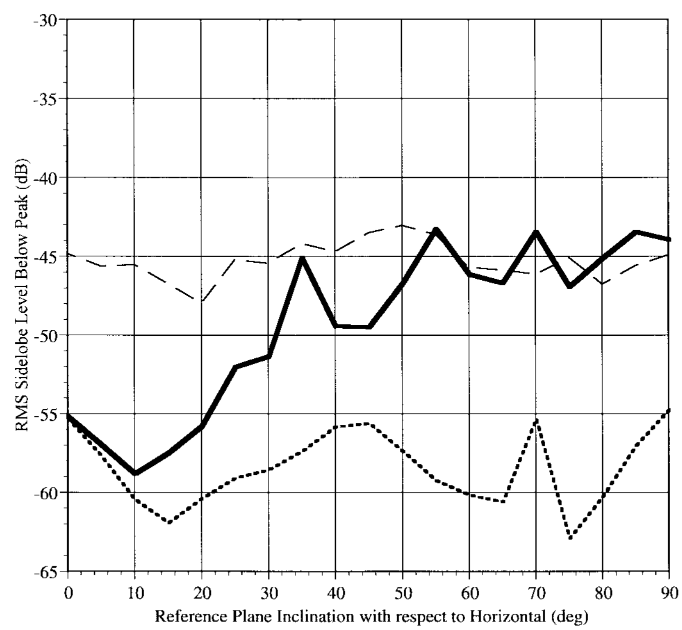



Fig. 8. RMS sidelobe level versus reference plane inclination after 4% failure corrected by applying half-amplitude compensations to two cocolumnal elements nearest failures.

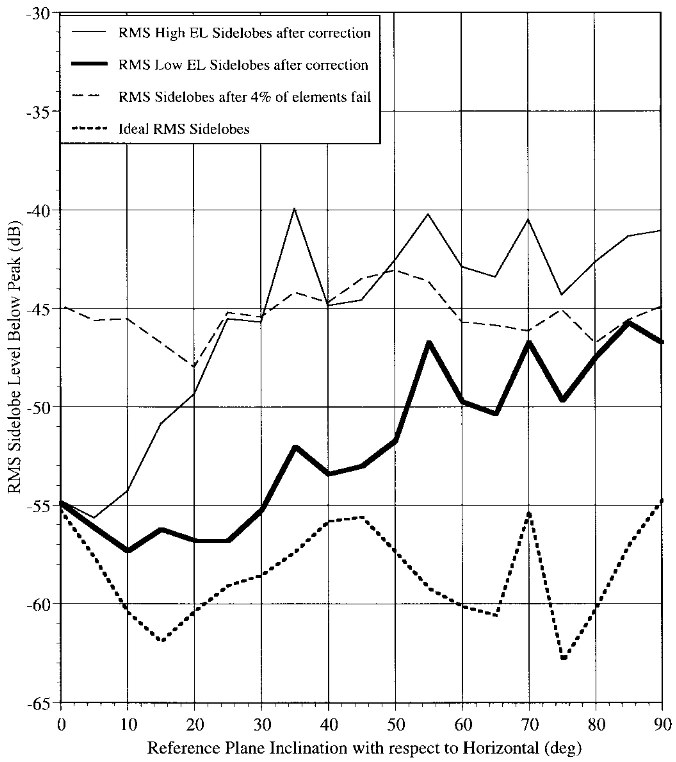



Fig. 9. RMS sidelobe level versus reference plane inclination after 4% failure corrected by applying half-amplitude 15° phase compensations to two cocolumnal elements nearest failures.

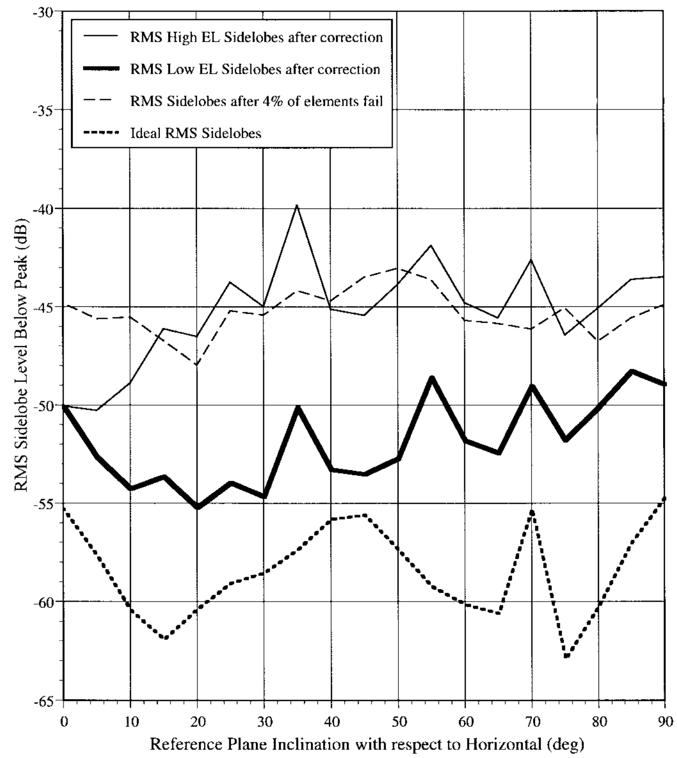



Fig. 10. RMS sidelobe level versus reference plane inclination after 4% failure corrected by applying one-sixth amplitude 15° phase compensations to hexagons surrounding failed elements.

favored hemisphere is not large at high inclination angles, i.e., near the elevation plane. Attempting to improve it by controlling the phase rotation only resulted in corresponding degradation elsewhere in the coverage.

Fig. 10 shows how greater improvement can be obtained in such planes by spreading both the amplitude and the phase corrections across the nearest six neighbors. The cost is incurred at and near to the azimuth plane, where performance is now far less than perfect. This is due to the amplitude distortion introduced into the neighboring columns.

A more satisfactory solution is shown in Fig. 11. Here the amplitude compensation is confined to the immediate neighbors in the failure column, whereas the phase compensation is spread among the nearest six. The behavior is now quite good near the azimuth plane and continues to maintain a significant improvement throughout the entire hemisphere. Furthermore, improvement is realized also in the other hemisphere, throughout the first 30° of inclination. The sharp deterioration shown at higher inclination angles constitutes the cost of the improvement. In a high-flying surveillance aircraft, the large sidelobes at high elevation angles do not usually matter. Conversely, in a shipboard radar, where the upper hemisphere would be favored, sidelobe degradation would be seen at large depression angles. Returns from such angles are normally short enough in range to be eclipsed by the transmit pulse.

Figs. 12–14 show the same information for 2%, 6%, and 12% random failure. It is seen that even in the case of 12% failure, where substantial clumping routinely happens, significant improvements still obtain. The deterioration observed near

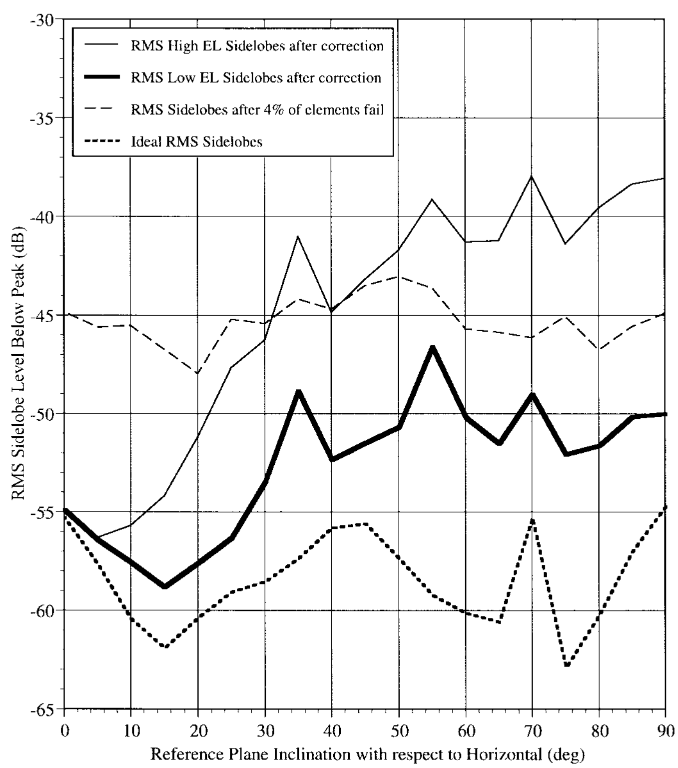



Fig. 11. RMS sidelobe level versus reference plane inclination after 4% failure corrected by applying half-amplitude compensations to two cocolumnal elements nearest failures and 15° phase rotations to hexagons surrounding failed elements.

the azimuth plane is one result of such clumping. (It will be recalled that to preserve simplicity and practicality when one

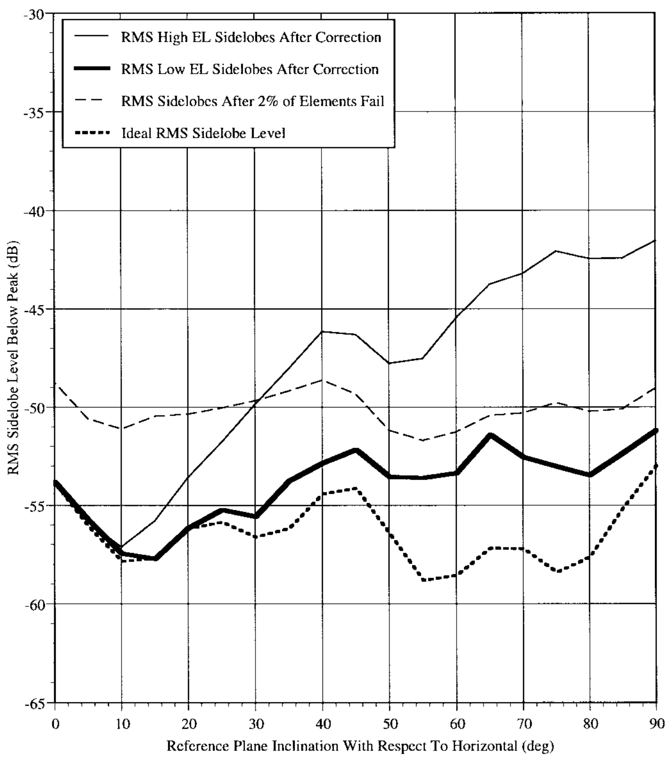



Fig. 12. RMS sidelobe level versus reference plane inclination after 2% failure corrected by applying half-amplitude compensations to two cocolumnal elements nearest failures and 15° phase rotations to hexagons surrounding failed elements.

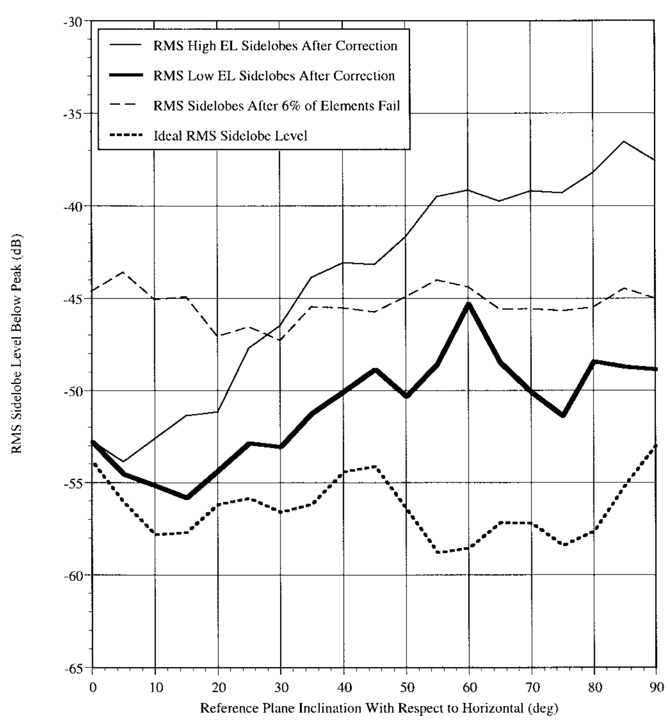



Fig. 13. RMS sidelobe level versus reference plane inclination after 6% failure corrected by applying half-amplitude compensations to two cocolumnal elements nearest failures and 15° phase rotations to hexagons surrounding failed elements.

neighbor in the column is also a failure, the element only receives one half of the required compensation. When both neighbors fail, no amplitude compensation was applied.)

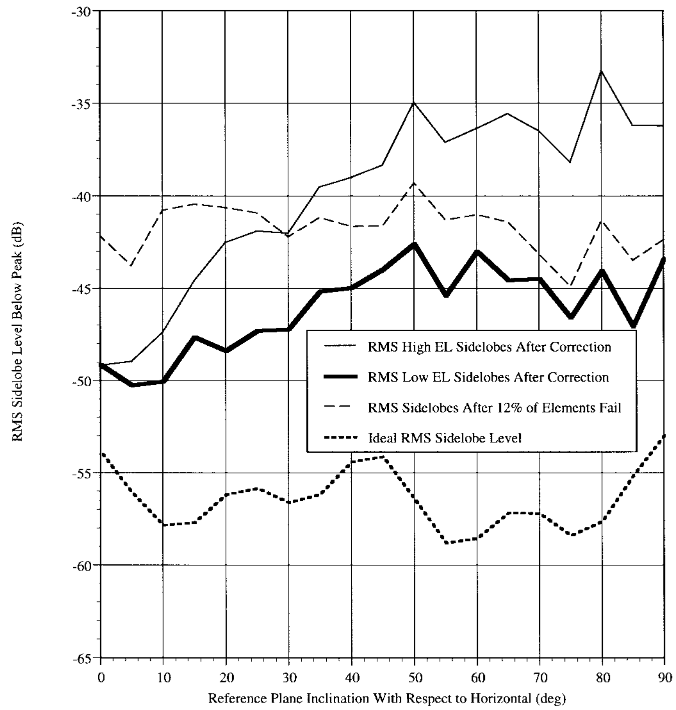



Fig. 14. RMS sidelobe level versus reference plane inclination after 12% failure corrected by applying half-amplitude compensations to two cocolumnal elements nearest failures and 15° phase rotations to hexagons surrounding failed elements.

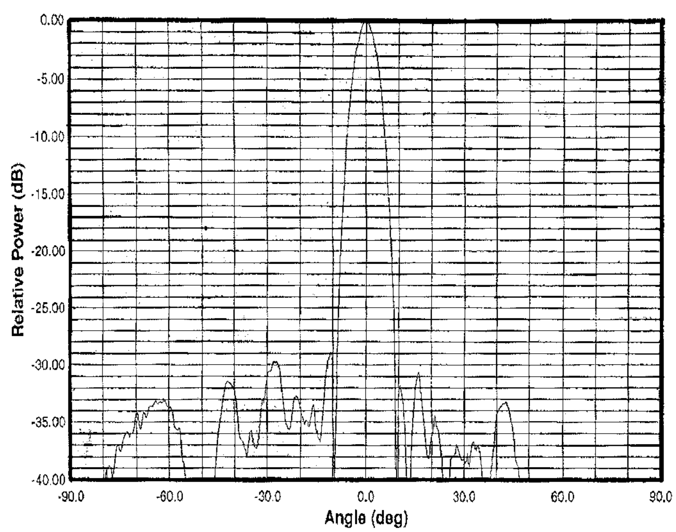



Fig. 15. Measured ideal (full array) elevation plane pattern.

Fig. 15 is the elevation plane pattern of a 40-element stick antenna as measured at a Northrop Grumman compact antenna range. The stick antenna consisted of two adjoining columns of 20 elements each. Fig. 16 shows the correspondingly degraded pattern after a single central element was failed. Fig. 17 shows the resulting elevation pattern after the amplitudes of the adjoining neighbors in the column were increased by one half the failed element's amplitude. Due to the specifics of this case (element spacing geometry and illumination function details), a significant pattern improvement was realized at this stage alone. When phase rotation was added, the improvement in the

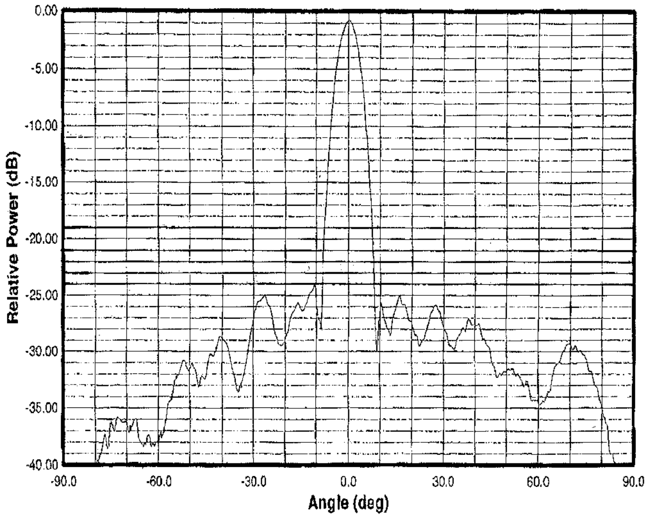



Fig. 16. Measured elevation plane pattern after single uncompensated central element failure.

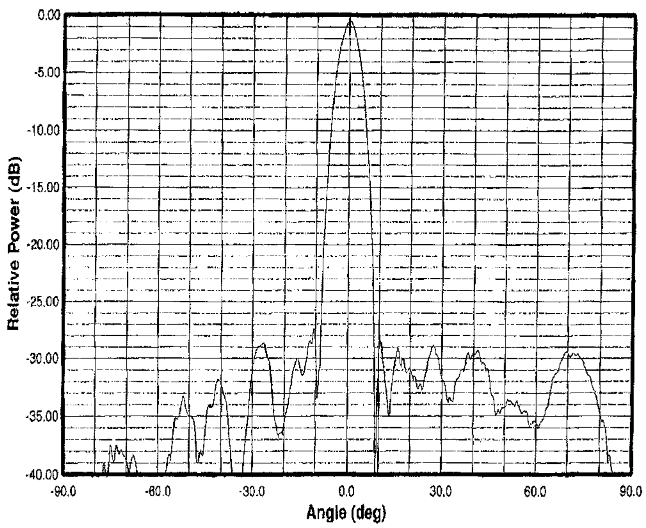



Fig. 17. Measured elevation plane pattern after half-amplitude compensations applied for single central element failure.

preferred hemisphere increased further whereas performance in the other hemisphere degraded (Fig. 18).

## IV. Conclusions

A failure compensation technique has been introduced for active phased arrays. It is simple to implement and is compatible with real-time requirements. It does not depend on the external environment and consists of a linear superposition of individual failure compensations, each of which is applied through the immediate neighbors of the failed element in question. It utilizes a combination of amplitude and phase operations. The amplitude operation role is chiefly to effect pattern compensation at and near to the principal azimuth plane. The phase operation role is to effect compensation elsewhere. It is inherently asymmetrical. Whereas it provides significant improvement in one hemisphere, it degrades performance in the other—especially in regions far removed from the principal azimuth plane. This property is found to

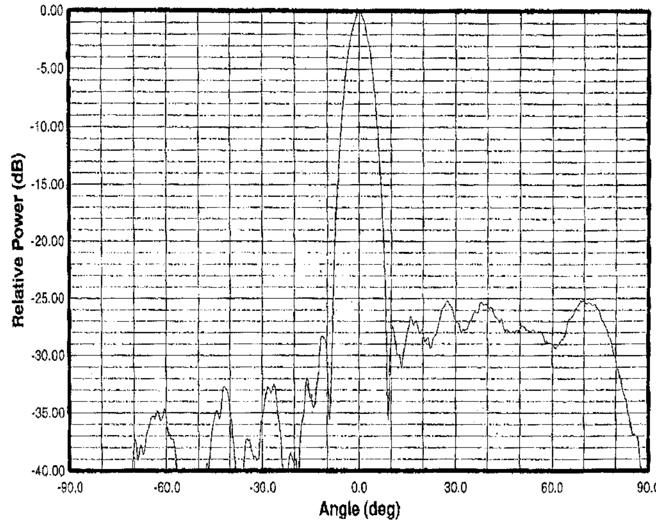



Fig. 18. Measured elevation plane pattern after half-amplitude 15° phase rotation compensations applied for single central element failure.

be compatible with the operational requirements of many airborne and surface based radar systems. It is particularly effective at small elevation steering angles. The above has been demonstrated via detailed simulations and some compact antenna range measurements.

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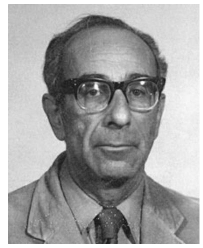

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