ISSUES FOR THE AUTOCALIBRATION OF PHASED ARRAY RADARS

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Abstract

It has been recognised for some years that the advantages of active phased array radars, such as flexible beam formation and efficient use of solid-state transmitters, could be made available to a much wider range of radars than is possible at present, if the arrays could be made cheaper. The work described here has been studying how targets of opportunity might be used to calibrate the array, simplifying the process of calibrating it and of maintaining that calibration, with the aim of reducing the element cost. The importance of sources or targets at known bearings, in order to remove bias errors, is also highlighted. Targets in the radar's environment can be used for calibration as can astronomical sources, such as the sun. The intrinsic stability of modern arrays means that the dynamic calibration problem is simpler than worst-case calculations might previously have suggested, and is a practical proposition.

Keywords: Phased Array, Radar, Calibration

Introduction

Phased array radars have long been a subject for research and have been used in the past for specialized applications, because of their ability to provide very large power-aperture products and to rapidly change the beam pointing direction(s). The latter advantage would be useful to a very wide range of radars if it could be achieved at moderate cost. If an active phased array is used, i.e. one which has individual transmit and receive amplifiers for each array element, then the reduced power of each element, compared with the whole radar, also provides an attractive way of providing solid-state power generation, with improved reliability and stability.

One obvious complication which is caused by the use of an active phased array is the need to match the signal paths through all the elements, so that the desired beam pattern is formed. Another requirement is to reduce the cost of the many, often several thousand, elements which comprise the array. This paper describes work which has been performed under funding from the Electro-Magnetic Remote Sensing Defence Technology Centre, on a project to look at ways of reducing the cost of calibrating the array, i. e. measuring the differential phase and amplitude between the different paths through the different elements. The ideas which have been studied use targets of opportunity in the external environment as reference signals with which to perform the calibration. The term 'autocalibration' has been used to characterise these techniques by analogy with the 'autofocus' techniques used to improve the focusing of synthetic aperture radar images by using the data in the images themselves. This approach potentially eliminates the need to provide extra calibration paths or external near-field calibration sources. This will in itself reduce the cost of the arrays. If it is practical to update the calibration information in the field, then the system will be able to cope with changes in the characteristics of the paths through the elements, due for examples to changes in temperature, ageing or mechanical distortion, reducing the need for the array to be so stable.

The first stage of this work has been to define the issues which are actually significant for the calibration of modern, active-element, phased array radars in the different applications for which phased array radars might be used and to identify suitable autocalibration schemes which can be applied. It is intended that subsequent work will prove the viability of these schemes, first by simulation and then in a real array.

Calibration Requirements

The requirements for calibrating the array must be studied first, as these requirements will drive the decision as to which of the potential calibration schemes would actually solve real problems.

The key measures of the accuracy of the calibration are associated with the antenna patterns which the array produces. There are three quantitatively-different characteristics of the pattern which must be considered: the most obvious issue is that of forming the beam, i.e. providing the correct beamwidth and gain - if the former is correct then, since, for a transmitter, the radiation has been constrained into the required directions, the gain will necessarily be correct. The well-known Rayleigh criterion is that the phase errors should be less than 45°. Figure 1 shows the antenna pattern of an ideal one-dimensional array with a cosine-squared weighting and of the same array with a phase error of 45° r.m.s. As expected, the gain is reduced by about three decibels, but the sidelobe level is very high. The elements have a spacing of half a wavelength.

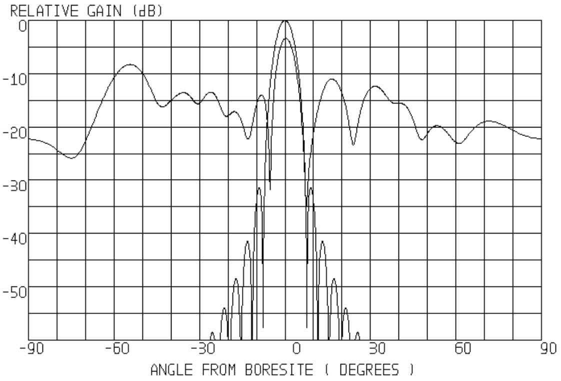

Figure 1: Illustrating Phase Errors Required to Destroy the Beam

The large dynamic range of radar targets means that for most radar applications the antenna sidelobe levels are also important. An additional requirement for many military radars is that low antenna sidelobes are also needed as an Electronic Counter-Counter Measure (ECCM) technique to reduce the ability of an opponent either to detect radiation emitted through the sidelobes or to inject jamming through them. providing low sidelobes needs more accurate control of the array than does forming the beam. An estimate of the allowable phase error is $\delta\phi = \sqrt{(GS)}$, where G is the antenna gain and S is the required mean sidelobe level. Transmitters can either be designed to have low sidelobes, or else higher sidelobes can be tolerated for the sake of maximising the gain. It is more common to make the receive sidelobes low, but, of course, if a common antenna is used for both functions, as is usually the case for a mechanically-scanned antenna, or if the beam pattern cannot be switched rapidly between 'transmit' and 'receive,' then the same pattern is needed for both. As a typical example, with 30dB gain and -40dB sidelobe levels the allowable phase error would be 18°. If the contribution to the sidelobe level due to amplitude errors is the same as that due to the phase errors, the allowable phase errors would be reduced by a factor of √2, to 13° and the allowable amplitude error would be about 3dB. The phase tolerance required to control the array sidelobes becomes tighter as the array gain is reduced, i.e. for smaller arrays. Figure 2 shows the effect of 18 degrees r.m.s phase error on a nine hundred element array (30 x 30) elements. The sidelobe levels of the imperfect array, as expected, are at about -40dB.

Figure 3, by contrast, shows the effect of 3° r.m.s. phase errors on a 30-element array, showing roughly the same sidelobe level, illustrating, as expected, how the smaller array is generally more sensitive to errors in the phases of the individual elements. In respect of sidelobe control, it should be noted that most calibration schemes need only be sensitive enough to detect errors at the required level within the main beam, to allow the sidelobes to be calibrated by 'dead reckoning,' and do not require the sidelobes actually to be measured.

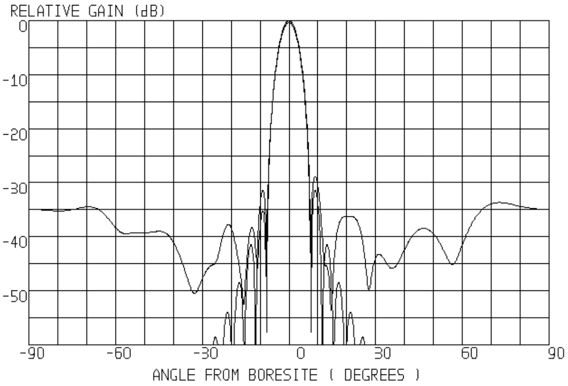

Figure 2: Illustrating Phase Errors Required to Degrade the Sidelobes - Large Array

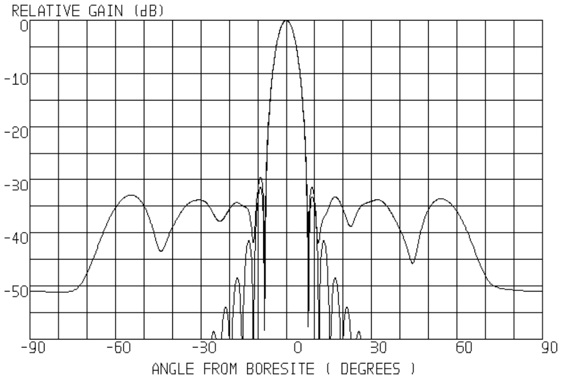

Figure 3: Illustrating Phase Errors Required to Degrade the Sidelobes - Small Array

The third set of errors which need to be corrected are the bias errors. The individual errors in the elements can be considered to add up as a 'random walk' across around the desired wavefront, resulting in a net error in the pointing direction, even if there is no inherent bias within the array. This error will be much less than the beamwidth, but many radars, including almost all high-performance radars, measure target positions more accurately than that, using monopulse etc.

A systematic error of $\delta\phi_0$ radians from one element to the next will lead to an error in the array pointing direction of

$$\delta\theta = \lambda\delta\phi_0/(2\pi\delta x), \qquad (1)$$

where λ is the wavelength and δx is the element spacing. If the element spacing is half a wavelength, i.e. the maximum value which will still allow the grating lobes to be suppressed, this simplifies to

$$\delta\theta = \delta\phi_0/\pi. \qquad (2)$$

Hence a pointing accuracy of 0.1° requires a phase accuracy of about 0.3°. Systematic pointing errors can usually be removed at the design stage, but the net effect of the 'random walk' due to all the random errors must also be considered. If the array contains N elements each with a random phase error of $\delta\phi$ the mean error per element due to the random walk will be

$$\delta\phi_0 = \delta\phi/\sqrt{N} \tag{3}$$

and the error in the predicted pointing direction will then be expected to be

$$\delta\theta = \delta\phi/(\pi\sqrt{N}). \tag{4}$$

It should be noted that the above calculation is optimistic if the errors are due to the corporate feeds, since the construction of the feed may lead to errors which are common to a number of elements and which will therefore not be 'averaged out.' It will be noticed that, like the calibration accuracy required to control the sidelobes, that required to control the bias errors become tighter for smaller arrays.

The Array Problem

The complexity of the calibration problem increases if factors which are dependent on the element state or on the steering direction become important. In the simplest case, all that needs to be considered is a constant path length (phase) error which will be independent of the beam pointing direction, and which should be a predictable function of frequency. The next stage of complexity is when the errors in the phase setting of the individual elements become significant, since these may be functions of the phase state and frequency for each element.

The worst case can occur, for example, when the inter-element coupling is significant. This will, in general, be different for each element pair and, what is worse, a function of frequency and of the phases of the both elements. With a thousand elements, a thousand beam positions and three frequencies, and separate measurements being required for the 'transmit' and 'receive' directions, there are six million calibrations which must then be performed.

If each calibration takes, ten milliseconds (to obtain enough averaging to obtain a reasonable sensitivity to the measurements), then the calibration process would take sixteen hours, even if the array was not required to do anything else, which would not be acceptable.

A second problem with the worst-case problem is that one would have, in theory, to find suitable targets of opportunity in all possible directions, and for calibration, targets at known positions in all directions.

Practical Simplification

A way out of this problem has been indicated by a study of the design of microwave phased arrays. This has shown that the errors which are most significant are those associated with the feed paths. The phase errors on modern microwave phase shifters will be accurate within +/-3° and thus within the allowable tolerances discussed above. The feed structures which are used for microwave arrays reduce the inter-element coupling to an acceptable level, so that, at least for larger arrays, these effects can be ignored when defining the beam position. The use of amplifiers between the phase shifters and the array faces, on either the 'transmit' or 'receive' side, also isolates the leakage level from the changes in the phases of the signals.

This is a very important conclusion. The most obviously consequence is that the number of measurements is reduced. In our example above it is reduced to 6000 if the measurements must be made at three frequencies across the band and separately for transmit and receive, or only 1000 if the significant paths are the same for transmission and reception, and if the frequency effects can be predicted, compared to the much larger number quoted above. We are now talking about a calibration time of between ten seconds and a minute. Possibly as significant is that since the errors are now independent of pointing direction, the errors can be estimated by scanning the antenna across a known source. Also, the effects which lead to the biases are independent of the scan direction so only one calibration source is needed.

Proposed Solutions

The techniques which we are studying for obtaining the required calibration solutions fall into two general groups. The first is those whereby measurements are made on the array elements one at a time, and the second type involves deducing the element responses from measurements of the antenna patterns.

Element-By-Element Techniques

The most basic calibration technique is either to illuminate a target of opportunity, or detect the signal from a known source, In an ideal case, where the signals from each element are digitised separately, the amplitude and phase at each element is measured. Knowing that the measurements should give a flat, uniform, phase front, the measurements will reveal the errors. If the true direction of arrival of the sources is known, then the bias can also be measured. There are a number of variations on this technique:

- If the signals are not digitised at the element level, then all but one element can be switched off at a time, and the signal from that element can be measured.

- Similarly, if the array is to be calibrated in transmit, one element at a time may be switched on and all the elements used for reception

- Targets at known location, or sources at known locations, such as man made or natural (extraterrestrial) sources can be used to correct for the bias errors.

Another technique, which can be used while the array is scanning, is to switch off each element in turn, and the difference between that signal at the signal received when all the elements are switched on gives the signal due to that element.

Scanning Past the Target

These techniques can be used for arrays with arbitrarily-complex errors, i.e. given the availability of appropriate targets and sources arrays with direction-dependent errors can be calibrated, given time. Since we know that for practical microwave arrays the significant errors are not dependent on the steering direction, the array can also be calibrated by scanning past the targets and inverting the measured antenna pattern. This technique can also be used whilst the radar is performing its normal calibration routines, and is a simplification of that which is used to measure the errors in radio telescopes (see, for example, Brenner et. al (1)).

Conclusions

It is concluded that the intrinsic stability of current microwave arrays makes calibration using targets of opportunity a practical proposition, but the set of calibration sources should include at least one object at a known position in order to be able to correct for bias errors.

Reference

1. Brenner, M. J., Elldér, A. J. and Zarghamee, M. S., 1194, 'Upgrade of a Large Millimeter-Wave length Radio Telescope for Improved Performance at 115GHz, Proc IEEE 82, 734-42.