Calibration of Tactical Radar Antennas using the Sun - Simulation and Analysis

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Abstract

This paper describes how microwave noise from the sun can be used to calibrate active array antennas in the field. The sun can be used both to correct for errors in the pattern and for bias errors. The same technique can also be used to correct for alignment errors in mechanically-scanned antennas.

Keywords: Calibration, Phased Array, Radar, Sun

Introduction

Active phased array radars could be used in a much wider range of applications than is currently the case, if their cost can be reduced.[1]. One way of reducing the cost would be to provide simple calibration schemes, to dispense with dedicated calibration hardware and relax the requirements on the long-term stability of the array components.

This paper describes the results obtained during the second year of a project to look at ways of achieving this. The work performed in the first year [1] had established that the intrinsic stability of typical arrays is such that relatively simple techniques can be used to calibrate them. In particular, the dominant errors are not expected to change with scan direction, so the array can be scanned past the calibration source in order to measure the antenna pattern. The measured pattern can then be used to estimate, and thus to correct for, the errors.

The initial work had concentrated on using suitable point clutter as 'sources' from which the patterns could be measured, and had considered the use of the sun as a means of correcting for the bias in the antenna. The work described here concentrates further on the use of emissions from the sun to correct both bias errors and also the random errors which raise the array sidelobes.

Array Pointing Direction

Reference [1] included a simplified analysis of the bias in the array pointing direction arising from the 'random walk' due to the errors in the individual elements. A more sophisticated analysis of this effect is included below, which shows that the effect is less severe than had previously been thought.

The individual errors in the elements can still 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 techniques such as monopulse processing.

The following analysis is based on taking pairs of elements, estimating the mean phase slope between them and averaging this over all the pairs.

Consider an N element linear array with pitch δx and r.m.s. phase error $\delta\phi$ on each element, and uniform amplitude weighting. The beam pointing error is determined by the linear component of phase error across the array. Assuming for the moment that N is even, one way of estimating the linear component is to consider $N/2$ pairs of elements, each separated by $N\delta x/2$. For each pair, the r.m.s. gradient is

$$(\mathrm{d}\phi/\mathrm{d}x)_{pair} = \sqrt{2}\ \delta\phi\ /\ (N\delta x\ /2)$$

Averaging over $N/2$ pairs, there is a reduction in the estimated error gradient for a pair by a factor of $\sqrt{(N/2)}$ to give

$$(\mathrm{d}\phi/\mathrm{d}x)_{array} = 4\ \delta\phi\ /\ (\delta x\ N^{3/2}).$$

A more sophisticated analysis replaces the factor of 4 by $\sqrt{(12)}$, and shows that this applies for N odd or even. Thus the angular error for case where $\delta x = \lambda/2$ is:

$$\delta\theta \approx \sqrt{(12)}\ \delta\phi\ /\ (\pi\ N^{3/2}).$$

For example, if $\delta\theta = 0.1°$ and $N = 30$ (i.e. a linear array 15 wavelengths long), $\delta\phi \approx 15°$.

For a 2D array of N by M elements, $\delta\phi$ is replaced by $\delta\phi/\sqrt{M}$; i.e.

$$\delta\theta_2 \approx \lambda\sqrt{(12)}\ \delta\phi\ /\ (2\pi\ \delta x\ M^{1/2}N^{3/2}).$$

Note that $\delta\theta_2$ as defined above is in the plane containing N array elements.

For an array with $\delta x = \lambda/2$ and $M = N$; i.e. total number of elements $L = N^2$

$$\delta\theta_2 \approx \sqrt{(12)}\ \delta\phi\ /\ (\pi\ L).$$

Thus for $\delta\theta = 0.1$ degrees and $L = 900$, $\delta\phi \approx 90$ degrees.

The bias errors due to residual random errors in the array elements are therefore likely only to be significant for smaller arrays. On the other hand, it has become apparent that a method of checking the alignment of many existing mechanically-scanned antennas would be valuable, particularly if the technique could be used as a 'retro-fit' when higher absolute angular accuracy is needed in order to allow the radar to be used within a network of sensors.

Use of the Sun as a Calibration Source

The sun is preferred as a calibration source instead of point clutter targets because its availability is more predictable. It is often difficult, when designing a radar, to be sure that it will always be able to see large discrete clutter returns often enough to be able to keep the radar in calibration, and the need to ensure that the clutter returns really are point targets may complicate the processing.

It may be objected that the sun is only visible during daylight - although its microwave radiation can be detected through clouds and rain, it cannot be detected when the sun is below the horizon. On the other hand, for many systems such absolute calibrations need only be carried out once every 24 hours or even less frequently. The shorter-term variations in performance due to differential temperature changes within an array are probably better controlled by using temperature sensors.

Another possible objection to the use of the sun as a calibration source is that it can only calibrate the receive paths of the array. Against this it may be pointed out that the dominant error sources are frequently due to the corporate feed and the path lengths within the transmit-receive modules which are common to both the transmit and receive paths. In any case, the receiver is usually more sensitive to calibration effects than the transmitter - it is the receiver which must generally have the lowest sidelobe levels, to reduce the susceptibility to jamming, and which must be able to accurately place the 'null' in the centre of the monopulse antenna difference pattern for bearing estimation.

Sensitivity of the Radar to the Sun

The sensitivity of a radar to emissions from the sun is higher than might at first be thought. The signal to noise ratio received by a radiometer is

$$SNR = B\tau\, \Delta T^2/T_{sys}^2$$

where

SNR is the signal to noise ratio

B is the RF or IF bandwidth of the receiver,

τ is the integration time,

ΔT is the effective value of the temperature difference between the source and the background and

T_{sys} is the temperature of the receiver system.

In this case the signal to noise ratio is the ratio of the difference between the power received when looking at the source and when looking at the background to the variance in the noise level in the receiver.

Note that

$$T_{sys} = NT,$$

where N is the noise figure of the receiver and T is its physical temperature.

The effective temperature difference, ΔT is

$$\Delta T = (T_s - T_b)\eta\, \Omega_s / \Omega_r$$

where

T_s is the temperature of the source,

T_b is the temperature of the background,

η is the aperture efficiency of the antenna,

Ω_s is the solid angle extended by the source, in this case the sun, at the antenna and

Ω_r is the solid angle extended by the main beam of the antenna.

This formula is subject to the constraint that the maximum value of Ω_s / Ω_r is unity, beyond which the source becomes beam-filling.

Integration Time Required to Measure the Bias.

Following on from the previous formulae, the angular accuracy of a radiometer can be shown to be

$$\sigma_\theta = \theta NT\, \Omega_r /[\sqrt{(B\tau)}(T_s - T_b)\eta\, \Omega_s]$$

where σ_θ is the r.m.s. angular error and θ is the 3dB beamwidth of the antenna.

In a typical case we may wish to obtain an accuracy of 0.1° r.m.s. from an antenna with a natural beamwidth of 2°. We may use the following values for the parameters:

NT = 3000K (i.e. 10dB noise figure)
Ω_r = 2° × 2°
η = 0.5 and
Ω_s = 0.8° × 0.8°.

This latter value is 1.5 times the optical diameter of the sun, and is taken from [2], as being appropriate at microwave frequencies.

The effective temperature of the sun may be taken as 20000K at higher microwave frequencies, such as 9GHz [2]. The

background temperature of the sky can be neglected.
The required time-bandwidth product will then be $B\tau \approx 1400$. For example, if the receiver bandwidth is a (modest) 10MHz, the integration time required to measure the bias will only be 140μs, which means that the measurements will be quite practicable.

Measurement of Antenna Patterns

In order to measure sidelobe levels at, for example, 40dB below the peak of the pattern a signal to noise ratio of 40dB will be required against sun when it is on boresite. The time bandwidth product required to achieve this with the parameters chosen previously will be about 35000. With a bandwidth of 10MHz the integration time must then be 3.5ms, which is quite typical of radar dwell times.

To scan a whole hemisphere of 2πSr with a beamwidth of 1.2×10^{-3}Sr will take 18 seconds. This is a significant time, but even if the calibration had to be performed once per hour, it would not take a significant amount of the radar's time budget.

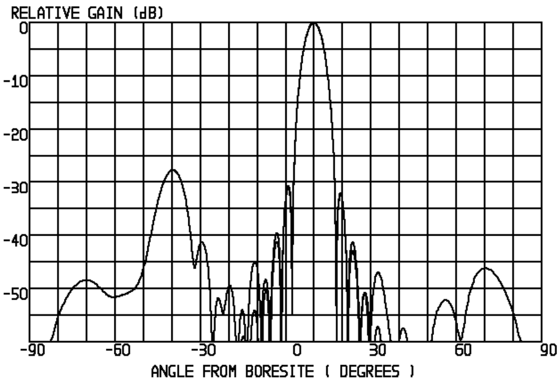
Practical Issues

The calculations presented in the previous section have indicated that there is sufficient power available from the sun to measure both the bias and the antenna pattern of a typical, relatively small, phased array radar. It is known that astronomical radio sources have been used to calibrate radio telescopes [3] and large radar antennas, but the calculations presented here show that with modern antenna design, the sun at least can also be used to estimate the characteristics of smaller, tactical scale, radar antennas, and, in particular, can be used to calibrate active arrays.

The first practical issue to be considered is the finite size of the sun. This can limit the accuracy with which the bias can be measured. If the sun were a uniform disk, then its finite size would not affect the bias measurements, but the presence of solar flares means that it is not a uniform source, and the radar will tend to measure the position of the flare rather than the centre of the disk. Multiple flares will tend to 'average out' the measurements, so a single flare is the worst case. Reference [2] suggests that although such flares are less powerful at microwave frequencies than at lower frequencies, their power and their rate of occurrence means that they will affect the bias measurement.

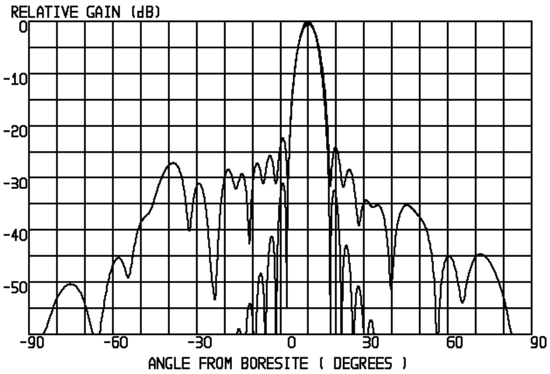
If the flares have a uniform distribution over the sun's disk, then their r.m.s. deviation from the centre of the disk will be $\phi/4$, where ϕ is the apparent width of the sun (effectively 0.8° at microwave frequencies). This suggests that the 'goal' accuracy of 0.1° will not be easily attainable, but that a single measurement will get within a factor of 2 of this. Averaging over many days would improve the estimate. This calculation is slightly optimistic since the flares are more concentrated near the centre of the disk. The upper bound of the error would occur if they were all concentrated along the equator in which case the error would rise to $\phi/\sqrt{12}$, so the original estimate of $\phi/4$ remains realistic.

The effect of the finite width on the estimation of the antenna sidelobes is a different matter, since here the uniform disk is the worst case. We might expect that the finite width of the disk would have only a minor effect provided that it was smaller than the beamwidth of the antenna. The following simulations show that this is indeed the case. The first figure is a simulation of the corrected pattern obtained from a 30-element array with an uncorrected sidelobe level of about -25dB, corresponding to about 10° r.m.s. phase error per element. The pattern is complicated by the fact that the correction data was assumed to be obtainable only over an angle of ±45° either side of the peak of the beam, i.e. not over the whole pattern. This lack of measurement data accounts for the higher sidelobes in the corrected pattern outside this range. The reduction in the sidelobe levels far from boresite is due to the natural cosinusoidal pattern of the elements. The combination of these effects has led to the relatively prominent sidelobe at about -40° from boresite (-50° from the peak of the steered pattern).



Pattern Corrected from Ideal Measurements over ±45°

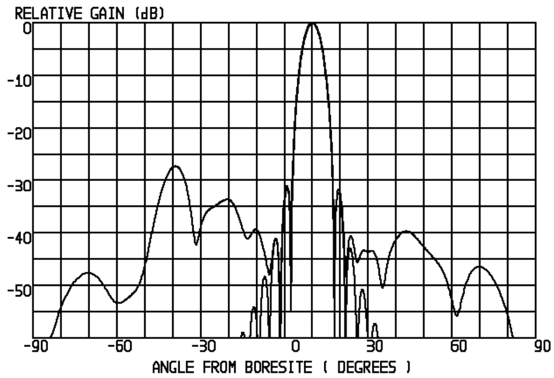
The second figure, by contrast, shows the corrected patterns obtained when the measured sidelobe pattern was convolved with a rectangular distribution of the same width as the antenna beamwidth. This corresponds to the limiting condition where we would expect the calibration scheme to fail.



Pattern Corrected from Measurements Smeared by a Beamwidth

As expected, the close-in sidelobe levels are now about -27dB. The 'ideal' sidelobe levels are also shown for reference.

The third figure shows that if the broadening is now reduced to 0.4 beamwidths, which is equivalent to the case of a sun with an effective width of 0.8° and an antenna beamwidth of 2°, the close-in sidelobe levels are much improved.



Pattern Corrected from Measurements Smeared by 0.4 Beamwidths

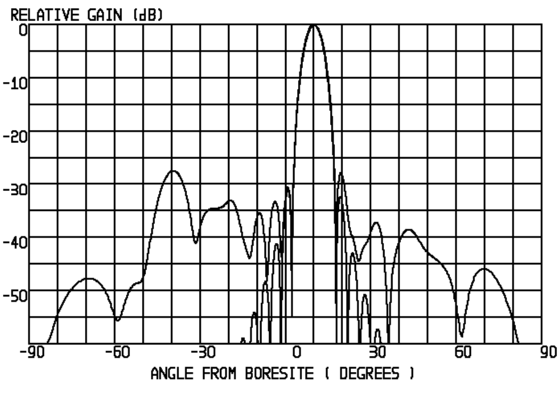
These results confirm the expectation that source widths less than a beamwidth have little effect on the calibration process.

The radioastronomical community generally do not use the sun as a source because of its variability and large apparent size, but other astonomical radio sources are too faint for the calibration of tactical phased arrays, i.e. the relatively small apertures mean that the required integration times would be too long to allow such calibrations to be interleaved with the normal operation of the radar.

Need for Coherency

A further issue affecting the practicality of using the sun as a calibration source is that if the antenna pattern is to be Fourier transformed, to determine the aperture distribution, and hence estimate the calibration errors, then the measurements must be coherent. This is not normally the case for simple pattern measurements. Once again, the radioastronomical community has shown that this is possible, using an auxiliary antenna to provide a reference channel[4]. An auxiliary channel will also be needed to correct for variations in the power from the sun.

In fact, the requirements on the accuracy of this phase reference can be quite modest. The following figure shows the effect on the corrected patterns of 45° r.m.s. phase errors on the measured patterns.



Pattern Corrected from Measurements with 45° Phase Errors

The sidelobe levels are still around -30dB, This is probably the limit at which the technqiue will still be useful, but corresponds to a very modest signal to noise ratio in the 'reference' channel, such as could probably be obtained from a guard channel or a single sub-array.

Conclusions

It is concluded that the sun is a suitable calibration source for correcting for both random and systematic errors in active phased array antennas, as well as for correcting for bias errors in mechanically-scanned antennas.

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