Tradeoff Between Complexity and Performance in Measurement Systems for Large Antenna Arrays

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Abstract

In this paper different calibration methods for large antenna arrays subject to random errors in position and phase are compared. The results shows that the gain loss is reduced when more sophisticated calibration systems are used while the beam is broadened if the position error is measured using one probe.

1. Introduction

When designing a large antenna array for operation in arctic environments it is important to consider both complexity and performance of the associated monitoring system. On the one hand, the environment will cause a degradation of the performance of the array due to both temperature variations and precipitation in the form of snow and this can be mitigated using a sophisticated measurement system. On the other hand, a simpler measurement system cost less and might therefore facilitate the design of a larger antenna array which in turn can tolerate larger errors. This tradeoff will be studied in the present paper.

The antenna array considered here is the planned EISCAT_3D incoherent scatter radar [1] which is an upgrade of the existing tristatic EISCAT UHF radar in northern Scandinavia. The system will consist of multiple sites with a baseline of 90-280 km where each site have a transmit- or receive antenna array with up to 16000 antenna elements. The radar system will operate in the 210-240 MHz frequency band.

Since this radar system is expected to operate continuously under arctic conditions it is important to carefully assess the effect of the environment during the design process. In particular the arctic environment can be expected to affect the antenna elements due to the large seasonal temperature variations, which can affect both the timing system and the physical position of the antenna elements. Also, abundant snowfall can be expected during wintertime. This has previously been found to have a large impact on the performance on antenna arrays and at times even cause the antennas to be non-operational [2], [3]. For multistatic radar systems it is crucial to know the pointing direction of each antenna array in absolute numbers. Without calibration, this might be difficult in cases when snow accumulates unevenly on the aperture [4].

To mitigate the effect of the climate some measurement system will be needed. Traditionally, the properties of large aperture antennas is measured using distant radio sources [5]. In this paper it is assumed that radio sources are used for calibration and that these remove all systematic errors. The remaining part is then a random error of the type studied in [6]. The paper focus on how much a more sophisticated measurement system will improve the performance of the antenna array when it is subject to random errors in both position and phase.

2. Mitigation Methods

This paper is limited to study the effect of the random errors on the array factor. Each antenna element is thus assumed to be a isotropic point source which does not couple to the nearby elements. Also, the errors in position and phase of the antenna elements are assumed to be Gaussian distributed with a zero mean. Three different types of measurement systems were studied: Only removal of the systematic errors, a timing system that mitigates the phase error, and a timing system combined with a probe in the vicinity of the array which mitigates the position error in one dimension. A method for calibrating for timing errors can be found in [7] and a method for estimating the phase offset due to snow accretion can be found in [8]. If probes are available, the position can be estimated using a GPS-like approach where the distance to each antenna element is measured.

In the ideal case, the array factor of the antenna array is given by

$$AF(\hat{\mathbf{r}}) = \sum_{n}^{N} \mathbf{G}_n(\hat{\mathbf{r}}) e^{jk\hat{\mathbf{r}}\cdot\mathbf{r}_n} \tag{1}$$

where $\hat{\mathbf{r}}$ is the pointing direction of the array, k is the wave number, and $\mathbf{r}_n$ is the coordinate of antenna element n in the array, and $\mathbf{G}_n$ is the active far-field radiation pattern of the antenna element n.

The far-field radiation pattern, $\mathbf{G}_n$, can be written as

$$\mathbf{G}_n(\hat{\mathbf{r}}) = \mathbf{G}_{n0}(\hat{\mathbf{r}}) e^{jk(\Delta\mathbf{r}_n\cdot\hat{\mathbf{r}} + \Delta\phi_n)} \tag{2}$$

where $\mathbf{G}_{n0}(\hat{\mathbf{r}})$ is the far-field gain in direction $\hat{\mathbf{r}}$ without any errors, $\Delta\mathbf{r}_n$ is the position error of the antenna element, and $\Delta\phi_n$ is a constant phase error on the antenna element. The latter could for example be a timing error or due to snow loading of the antenna. Here it is assumed that all components of $\Delta\mathbf{r}_n$ and $\Delta\phi_n$ are independent, white, Gaussian with zero mean.

A significant error will be a phase error on each antenna element. This can be due to both snow loading of the antennas and timing errors due to temperature variations affecting the length of the cables in the time distribution system. In this paper it is assumed that the phase error can be removed entirely and a noise term, $\varepsilon_{\phi,n}$, is added which depends on the quality of the timing system. The far field pattern in (2) now becomes

$$\mathbf{G}_n(\hat{\mathbf{r}}) = \mathbf{G}_{n0}(\hat{\mathbf{r}}) e^{jk(\Delta\mathbf{r}_n\cdot\hat{\mathbf{r}} + \varepsilon_{\phi,n})} \tag{3}$$

where $\varepsilon_{\phi,n}$ is the noise induced in antenna n by the timing system.

In the case where one probe is available the position error will be reduced in one direction. This can be done by measuring the distance between the antenna element and the probe. The corrected array factor will then be

$$\mathbf{G}_n(\hat{\mathbf{r}}) = \mathbf{G}_{n0}(\hat{\mathbf{r}}) e^{jk\left(\Delta\mathbf{r}_n\cdot\hat{\mathbf{r}} - (\Delta\mathbf{r}_n + \boldsymbol{\varepsilon}_{\mathbf{r},n})\cdot\hat{\mathbf{r}}_{np} + + \varepsilon_{\phi,n}\right)} \tag{4}$$

where $\boldsymbol{\varepsilon}_{\mathbf{r},n}$ is the noise induced on antenna n by the positioning system and $\hat{\mathbf{r}}_{np}$ is the unit vector pointing from antenna element n to the probe. In the plane perpendicular to the vector $\hat{\mathbf{r}}_{np}$ the position error will not be reduced. If the probe is located in the near-field of the array, the error will mitigated in different directions for each antenna element.

To mitigate the position error in all directions and the phase offset at least four probes will be needed. This type of system will give the best performance of the array but will require substantial infrastructure. It is in this paper used a a reference when evaluating the other approaches.

3. Simulation Results

In this section, the performance of the measurement systems described in the previous section are evaluated for a large antenna array. The array considered have a circular aperture with a diameter of approximately 120 m and 16210 antenna elements ordered in a triangular grid. The antenna elements are assumed to be isotropic point sources and the array is phased pointing in the zenith direction. Also, all systematic errors are removed entirely, i.e. the errors in position and phase are assumed to be Gaussian distributed with a zero mean. The measurement system are assumed to be noise free.

The cases considered are the same as the ones described above:

1. Only removal of the systematic errors. There are random errors on both the position and phase of the antenna elements.

2. Only timing system. There are random errors on the position of the antenna elements but the error in phase is removed.

3. Timing system and position calibration in one direction. The probe is located in the center of the array at an altitude of 100 m and removes the position error in the direction from the antenna element to the probe.

Each of these cases was run 2000 times for noise ranging from a standard deviation of 0λ to 0.2λ. The results from the simulation is shown in Fig. 1. The variables of interest are gain reduction compared to the error free case and the beam width. Both the mean value and the standard deviation is analyzed. The reduction of the gain is clearly smaller for the cases when a calibration system is used. Even though the probe in case 3 is located directly above the array there is a small reduction in gain for the higher noise levels. This is due to the fact that the error is corrected in the direction from the antenna element to the probe and not in the direction perpendicular to the plane of the array. If the probe instead is located in the far-field of the array the whole error would be mitigated in the direction of the probe. This was verified but is not plotted in figure since it is nearly identical to the error-free case. The standard deviation is following the same pattern for both the gain and the beamwidth, i.e. the standard deviation is largest for case 1 is largest and smallest for case 3.

The mean value of the beamwidth shows a different, and interesting, behavior. Here the beamwidth for case 3 is considerably larger than for case 1 and 2. This is due to the fact that in case 3 there will be a tapering effect since the errors in the upward pointing direction is larger for the elements at the edges of the array than in the middle of the array, where the pointing direction of the array is the same as the vector pointing from the element to the probe. For applications where the beamwidth is a critical parameter it may thus be more advantageous to have a simpler calibration system.

4. Discussion and Conclusions

Three different approaches to calibrate the elements in a large antenna array have been compared: no calibration, only time calibration, and both timing and one probe for position calibration. Having a timing system increases the performance of the system over not having any calibration (except the distant radio sources). The case where one probe is used improves the performance in terms of gain but also broadens the beam. The type of measurement system chosen therefore depends on the specific requirements of the application of the array. Properties that have not been studied here but should be studied further are in particular the sidelobe levels and the scan angle.

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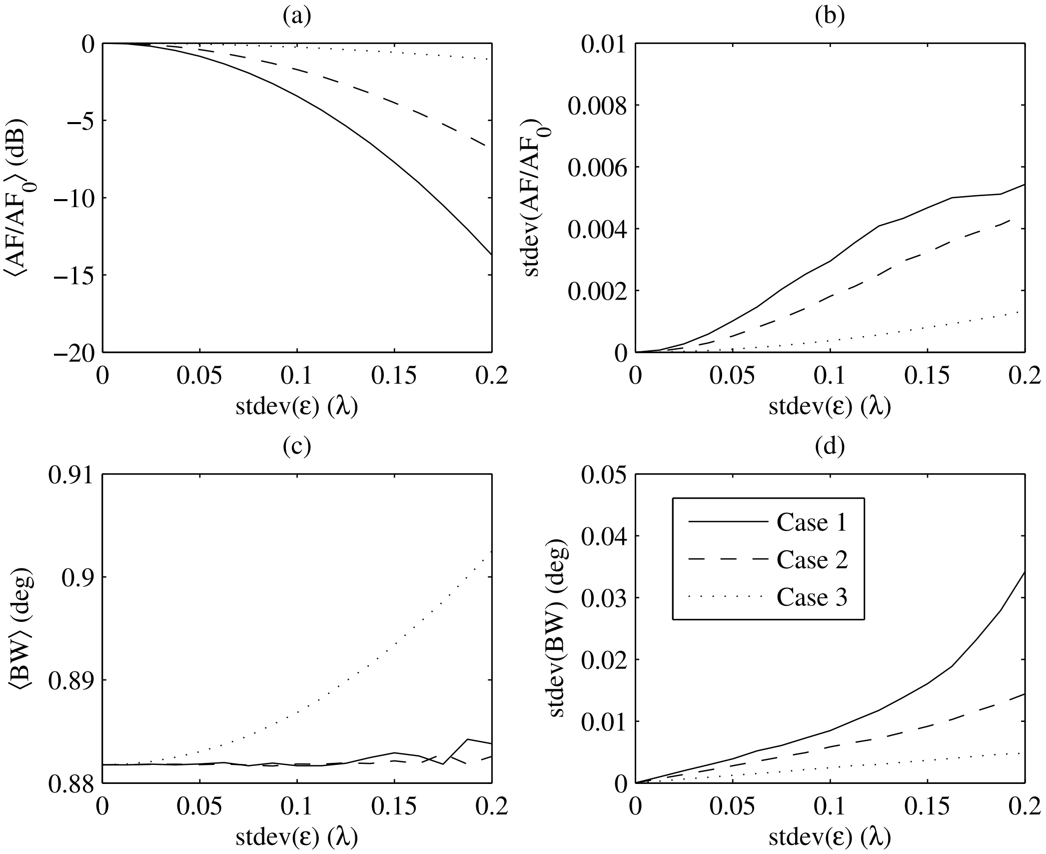

Figure 1: The performance of an antenna array subject to random position and phase errors with different calibration methods. In (a), the average of the gain loss is shown, (b) shows the standard deviation of the gain loss, (c) shows the average beamwidth, and (d) the standard deviation of the beam width.

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