AN1195: Antenna Array Design Guidelines for Direction Finding

In January 2019, the Bluetooth SIG announced support for Angle of Arrival (AoA) and Angle of Departure (AoD) in the Bluetooth 5 specification. AoA and AoD can be used for building RF-based real-time locationing systems and applications, based on phase-based angle estimation algorithms. Application use cases for the Internet of Things (IoT) are tracking of assets and people, as well as indoor locationing and wayfinding.

The purpose of this application note is to provide hardware design guidelines specific to the antenna arrays required for the direction finding implementations.

KEY POINTS

- Describes general direction finding use cases
- Provides general antenna recommendations for a direction finding antenna array
- Details 4x4 antenna array properties and insight into antenna tuning and items which affect the antenna

1. Device Compatability

This application note applies to 2.4 GHz Bluetooth Low Energy (BLE) standards for the following devices:

EFR32 Gecko Series 2:

- EFR32BG22, EFR32MG22
- EFR32BG24, EFR32MG24

The antenna array board presented in this application note (BRD4191A) is designed with EFR32BG22 SoC, but it is applicable to each of the EFR32 families listed above. Refer to the device data sheets for the complete list of supported part numbers.

2. Introduction

AoA relies on a single-antenna transmit beacon with continuous tone extension (CTE) appended to a Bluetooth packet transmission and a locator receiver device to measure the arrival angle of the signal using an array of antennas. Each antenna in the array sees phase differences due to different line of sight distances to the beacon device. The antennas in the array are switched during continuous tone extension, resulting in IQ samples with phase information for each antenna. This IQ-data is fed to an angle estimator algorithm. In this AoA use case, the receiving device tracks arrival angles for individual transmit beacon objects.

AoD is similar to AoA but the beacon and receiver roles are swapped. The AoD use case relies on a single-antenna mobile receiver and multi-antenna transmitter beacons. The mobile receiving device can calculate its own position in space using angles from multiple beacons and their positions.

Angle calculation is based on phase information from the individual antenna elements of the antenna array. The arrays utilized for this purpose are uniform rectangular arrays. The number of channels/antennas affects the overall angle estimation accuracy. A larger number of antennas also helps with multipath effects. Other types of arrays could be used for AoA/AoD, such as linear arrays, circular arrays, and non-uniform arrays. However, custom array development requires significant simulation and test efforts. For this reason, we recommend utilizing the array discussed in detail in this application note. The sections to follow outline general and specific recommendations related to the antenna array design.

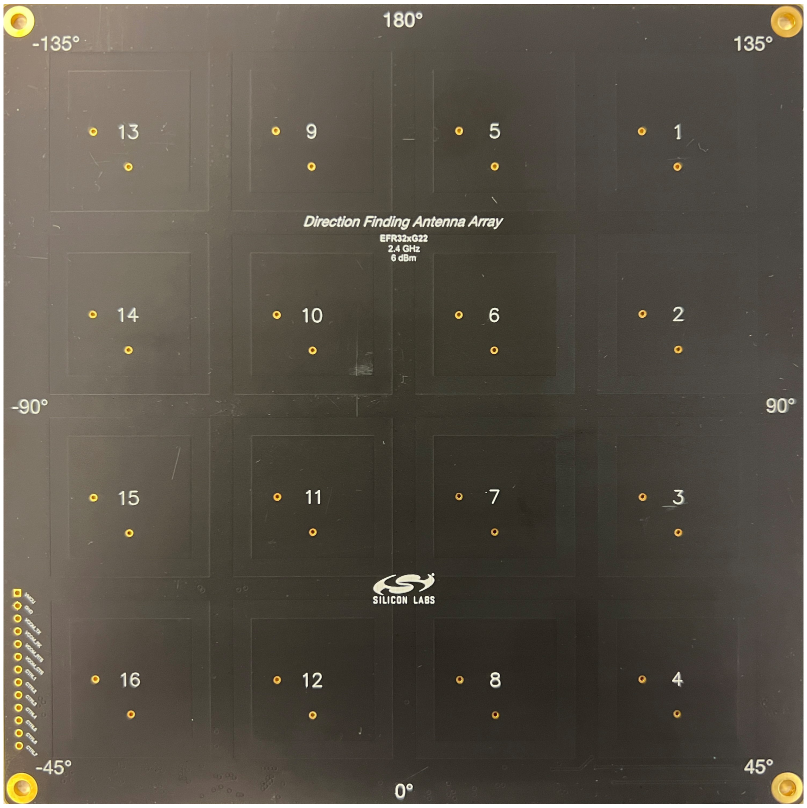


Figure 2.1. BRD4191A – 4x4 Antenna Array (Top View)

3. General Antenna Array Recommendations

Silicon Labs recommends copying the antenna array structure from the reference design as is, in order to minimize any issues caused by improper antenna design. The antenna array should be copied carefully, especially for the following parameters:

- Antenna building block dimensions
  - Single antenna dimensions
  - Distance between single antennas
  - RIS (Reactive Impedance Surface) dimensions
  - GND guard ring dimensions
  - Position of antenna feed points
- Hybrid coupler dimensions
- Coplanar transmission line lengths and widths
- Stitching vias around the coplanar transmission lines
- PCB dimensions (length, width, thickness)
- PCB layer stack-up + laminate type + laminate construction

If the antenna array structure and parameters are copied properly, the angle estimation performance should be very similar to the performance of the reference design board.

However, antenna impedance should always be checked on a custom board, since even if all the recommendations are followed carefully, some amount of variation is expected between PCB samples, PCB builds and PCB vendors. Similar antenna impedance is expected across the different antennas of an antenna array, which is why checking antenna impedance on one single antenna is sufficient. If antenna mismatch occurs, 6. Antenna Impedance Measurement and Tuning provides guidelines on how to measure and optimize antenna impedance on the antenna array.

The default recommended antenna array uses 4x4 antennas. The 4x4 array was chosen as the reference based on the most optimal system performance for smallest array size.

4. Antenna Array Parameters in the Firmware for Direction Finding

The firmware for direction finding allows users to select antenna parameters such as antenna array type or calculation mode.

The direction finding firmware allows selection of the 4x4 antenna array only, however, within the standard 4x4 array configuration, there is an option to select sub-arrays such as 3x3 or 1x4. These configurations eliminate data samples from the unnecessary antennas to test performance of a 3x3 or a 1x4 antenna array.

The 4x4 antenna array is designed to have equal transmission line length from the individual antennas to the EFR32BG22 device in order to have zero phase shift between the antenna paths. The direction finding firmware has input parameters for trace length and PCB dielectric constant, however due to the equal transmission line paths the trace length parameter for all antenna paths is set to zero and in this case PCB dielectric constant parameter is not used in the calculator.

The magnitude and phase radiation pattern are not unified for a given antenna, neither across the individual antennas of the array; these information are input parameters for the estimator as well. The manifold compensation is disabled by default, but if enabled manually in the application, it can be disabled by calling *sl_rtl_aox_set_antenna_pattern(&libitem, NULL);* or by removing the function call *sl_rtl_aox_set_antenna_pattern* from the application.

The BLE real-time location services supporting BRD4191A in Gecko SDK Suite 4.1 and Real-Time Locating Library 4.0.0.0 GA release is Alpha quality. BRD4191A sometimes shows elevation and azimuth "sticking" issues at 0-20 degrees elevation or around 90 degree elevation when using manifold compensation. When sticking occurs, the angle estimate does not change until the true angle changes more than several degrees. If the issue occurs and degrades angle accuracy when compensation is enabled, compensation should be disabled. Evaluation is recommended with manifold compensation disabled. The issue will be corrected in a future firmware release.

Users do not have the capability of adjusting trace length, dielectric constant or antenna radiation pattern parameters, as they are fixed in the firmware for direction finding. Therefore, it is important to copy the antenna array layout as it is and use the same PCB parameters as the reference board design (see 3. General Antenna Array Recommendations).

5. Properties of the 4x4 Antenna Array

The following sections are going to provide details about the properties of the 4x4 Antenna Array board BRD4191A. This board is available as part of the Silicon Labs Direction Finding development kit, while the design files are available for customers and should be used as a reference for a custom antenna array design.

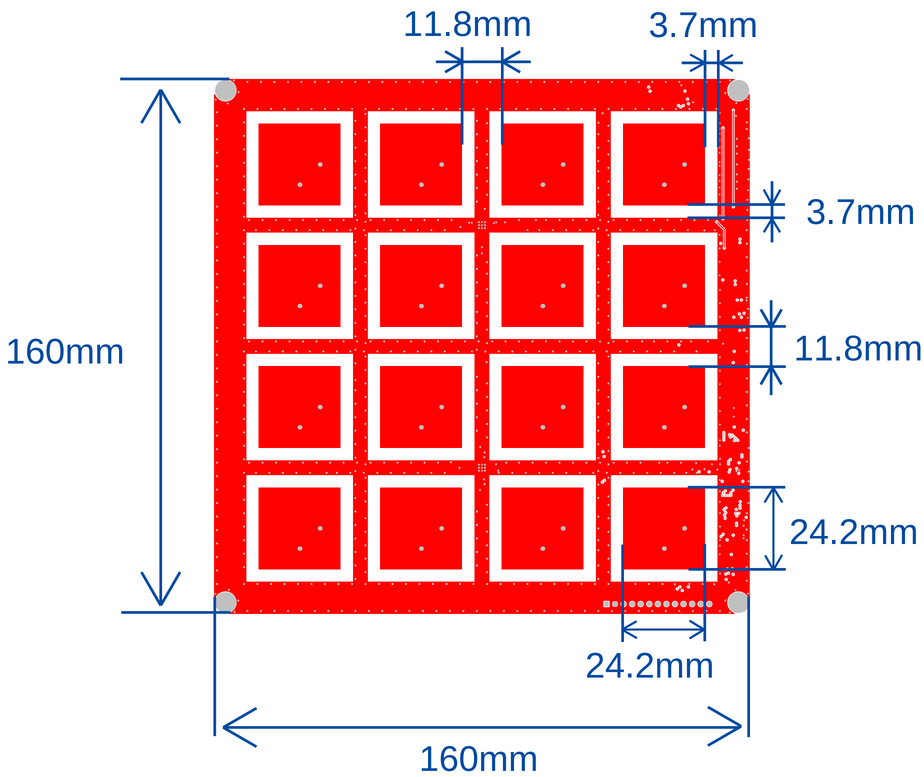


Figure 5.1. BRD4191A Antenna Array Dimensions

5.1 Array Type: Patch Antenna Array

As phase-based angle estimation is dependent on slightly differing path lengths, multiple antennas are needed in an array. Uniform two-dimensional rectangular arrays are preferred for simplicity. The greater the number of antennas, the better accuracy for positioning.

5.2 Antenna Type: Rectangular Shape Patch Antennas with RIS Cells and GND Guard Rings

The antenna array utilizes a 4x4 matrix of rectangular shape patch antennas with two feed points. Monopole or chip antenna types cannot work well in a direction finding application, as coupling between antennas through the ground could result in false phase information. The patch antenna also has the advantage of a better radiation pattern with a main lobe extending perpendicular to the board surface, whereas monopole antennas have a null in this direction.

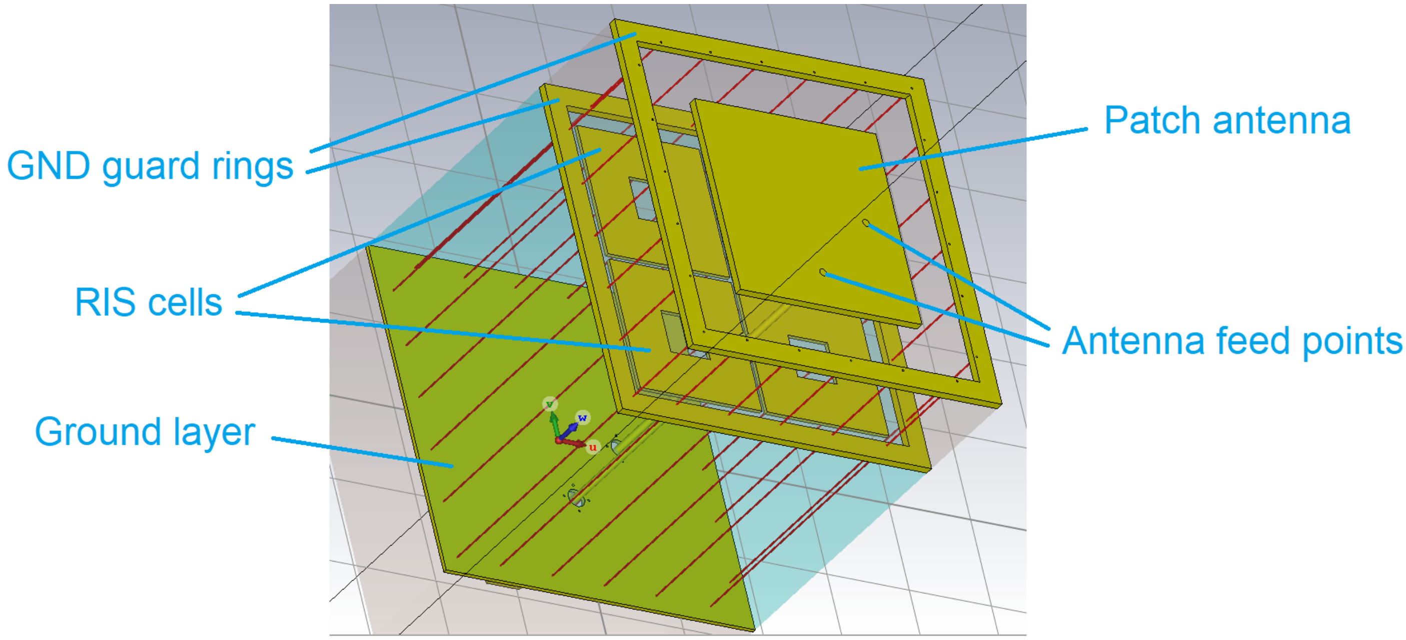


Figure 5.2. Antenna Building Block (exploded view)

The figure of exploded view above shows the build-up of one antenna building block. The rectangular shape patch antenna is placed on the PCB Top layer.

The next layer beneath the patch antenna is a so called RIS (Reactive Impedance Surface) / metamaterial layer. The main purpose of this layer is to increase the effective relative permittivity of the PCB, therefore allow for smaller patch antenna size and smaller overall antenna array dimensions, while improving important antenna parameters which allows for better AoA angle estimation accuracy. Each patch antennas have 4 individual rectangular RIS cells under the antenna with a rectangular keepout in the middle of the cells.

Both the patch antennas and the RIS cells are surrounded by the so called GND guard rings, which help unifying the radiation pattern of the middle and outer antennas of the array. The patch antenna and RIS layer need proper ground reference for optimal operation, this is realized with a complete ground layer on a separate PCB layer.

The theory of RIS cells is not scope of this application note and will be discussed in detail in a separate document.

5.3 Polarization: Dual Polarized Antennas with Option for Circular Polarization

Each individual antenna has 2 input ports which allow for receiving both horizontal and vertical polarized signals. The AoA algorithm calculates azimuth and elevation angles based on the phases received by the dual-polarized antennas.

However, the antenna array provides option for reception of circular polarized signals on 2 antennas in order to have an accurate estimation for the optimal AGC (Automatic Gain Control) value in the receiver. Circular polarization is realized by a hybrid coupler, which combines the two linear polarized signals while creating 90° phase shift between them. For additional details on hybrid coupler options, refer to 5.6 RF Feedline Blocks. Switching between circular polarized and dual-polarized modes is controlled by RF switches.

5.4 PCB Layer Stack-Up, Laminate Type and Construction

The following figure illustrates layer consistency on the PCB layout of BRD4191A Radio Board:

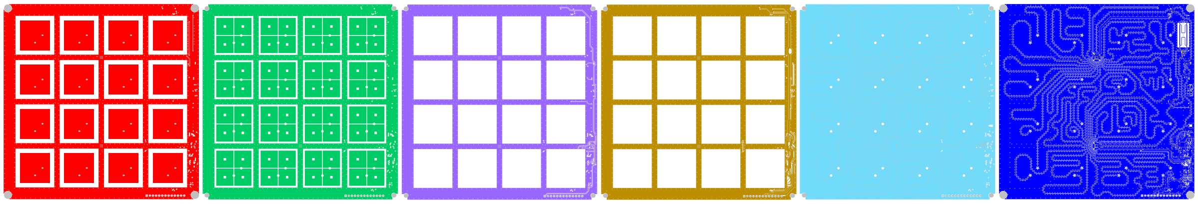


Figure 5.3. BRD4191A PCB stack-up (Top, Inner 1, Inner 2, Inner 3, Inner 4, Bottom)

- Top layer: Patch antennas
- Inner layer 1: RIS cells
- Inner layer 2: Signal layer + keepout under the RIS cells
- Inner layer 3: Signal layer + keepout under the RIS cells
- Inner layer 4: Ground layer
- Bottom layer: EFR32BG22, matching network, RF switches, transmission lines, hybrid coupler

During the investigations of the antenna array with metamaterials, it was identified that the antenna resonance frequency is sensitive to not only PCB stack-up variations, but to PCB laminate type and PCB laminate construction differences as well. Therefore, Silicon Labs recommends using one of the 3 laminate options provided below, which were tested and optimized extensively.

Table 5.1. Recommended Laminate Types for the Antenna Array PCB

Laminate manufacturer	Laminate type	Sample to Sample variation [MHz]	Build to Build variation [MHz]	PCB Vendor to PCB Vendor variation [MHz]
Jiangsu Lianxin	JL-2800	± 8-10	4	TBD
ITEQ	IT-180A	± 6-7	2	14
Isola	IS400	± 4-5	3	TBD

- Sample to sample variation = the maximum antenna resonance frequency variation between samples from the same build from the same PCB vendor compared to the center frequency
- Build to build variation = the difference between the average antenna resonance frequencies across a number of samples from different builds from the same PCB vendor
- PCB vendor to PCB vendor variation = the difference between the average antenna resonance frequencies across a number of samples from different PCB vendors

The 4x4 antenna array board BRD4191A is built with JL-2800 laminate type, but antenna array prototypes were built, optimized and tested extensively with IT-180A and IS400 laminates as well. The table below shows the recommended RIS cell dimensions for the various laminate types.

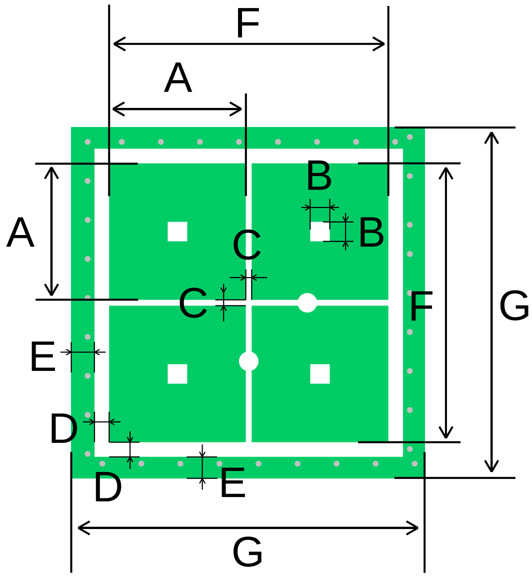


Figure 5.4. RIS Cell Dimensions

Table 5.2. Recommended RIS Cell Dimensions for Various Laminate Types

Laminate manufacturer	Laminate type	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]
Jiangsu Lianxin	JL-2800	14.0	2.0	0.6	1.5	2.2	28.6	36.0
ITEQ	IT-180A	14.05	2.05	0.6	1.2	2.45	28.7	36.0
Isola	IS400	14.4	2.4	0.6	1.2	2.1	29.4	36.0

As the table above shows, the overall size of one RIS cell block (G = 36.0 mm) and so the overall size of the antenna array is fixed for all 3 laminate manufacturers and laminate types. Besides the RIS cell dimension changes listed in the table above, no other parameters in the antenna array should be adjusted regardless of the selected laminate type. This means that all parameters mentioned in 3. General Antenna Array Recommendations should remain the same except for the RIS cell parameter changes shown in the table above.

The recommended PCB build-up for the various laminate types are shown below.

```
BUILD UP              :

                      Blind vias  L5-L6

                      L1 ===== | |=========================  35 um Cu (ca) After plating
                         - - - | |- Core - JL-2800- - - - -  200 um
                      L2 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 2x2116-47 - -  240 um
                         - - - | |- PREPREG - 7628-45 - - -  180 um
                      L3 ===== | |=========================  18 um Cu
                         - - - | |- Core - JL-2800- - - - -  200um  - -  CENTER - -
                      L4 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 7628-45 - - -  180 um
                         - - - | |- PREPREG - 2x2116-47 - -  240 um
                      L5 ==| |= | |=========================  18 um Cu
                         - | |- | |- Core - JL-2800- - - - -  200 um
                      L6 ==| |= | |=========================  35 um Cu (ca) After plating

                        Jiangsu Lianxin JL-2800 shall be used as base
                        material. Core dielectric constant shall be as
                        close to 4.3 at 2.4 GHz as possible.
```

Figure 5.5. PCB Build-Up – JL-2800

```
BUILD UP              :

                      Blind vias  L5-L6

                      L1 ===== | |=========================  35 um Cu (ca) After plating
                         - - - | |- Core - IT-180A- - - - -  200 um
                      L2 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 2x2116-53 - -  226 um
                         - - - | |- PREPREG - 7628-43 - - -  186 um
                      L3 ===== | |=========================  18 um Cu
                         - - - | |- Core - IT-180A- - - - -  200um  - -  CENTER - -
                      L4 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 7628-43 - - -  186 um
                         - - - | |- PREPREG - 2x2116-53 - -  226 um
                      L5 ==| |= | |=========================  18 um Cu
                         - | |- | |- Core - IT-180A- - - - -  200 um
                      L6 ==| |= | |=========================  35 um Cu (ca) After plating

                        ITEQ IT-180A shall be used as base material.
                        Core dielectric constant shall be as close to 4.3
                        at 2.4 GHz as possible.
```

Figure 5.6. PCB Build-Up – IT-180A

```
BUILD UP              :

                      Blind vias  L5-L6

                      L1 ===== | |=========================  35 um Cu (ca) After plating
                         - - - | |- Core - - IS400- - - - -  200 um
                      L2 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 2x2116-53 - -  240 um
                         - - - | |- PREPREG - 7628-41 - - -  180 um
                      L3 ===== | |=========================  18 um Cu
                         - - - | |- Core - - IS400- - - - -  200um  - -  CENTER - -
                      L4 ===== | |=========================  18 um Cu
                         - - - | |- PREPREG - 7628-41 - - -  180 um
                         - - - | |- PREPREG - 2x2116-53 - -  240 um
                      L5 ==| |= | |=========================  18 um Cu
                         - | |- | |- Core - - IS400- - - - -  200 um
                      L6 ==| |= | |=========================  35 um Cu (ca) After plating

                        Isola IS400 shall be used as base material. Core
                        dielectric constant shall be as close to 4.1
                        at 2.4 GHz as possible.
```

Figure 5.7. PCB build-up – IS400

Prior to PCB manufacturing the following parameters should be defined to the PCB manufacturer:

- Laminate type: JL-2800 / IT-180-A / IS400
- Core dielectric constant: 4.3 / 4.1
- Prepreg layer laminate types: 2116-ab / 7628-cd ('ab' and 'cd' numbers refer to the resin content of the laminate)

5.5 Antenna Return Loss and Phase Radiation Pattern

As Table 5.2 Recommended RIS Cell Dimensions for Various Laminate Types on page 9 shows, by utilizing proper dimensions for the RIS cell parameters, all 3 laminate types can be optimized to have the antenna resonance frequency centered for the 2.4 GHz Bluetooth band, which allows for the most accurate angle estimation performance.

The figures below show the measured S11 curves for the various laminate types. All figures show 8 curves measured on 2 ports for a given antenna across 4 PCB samples.

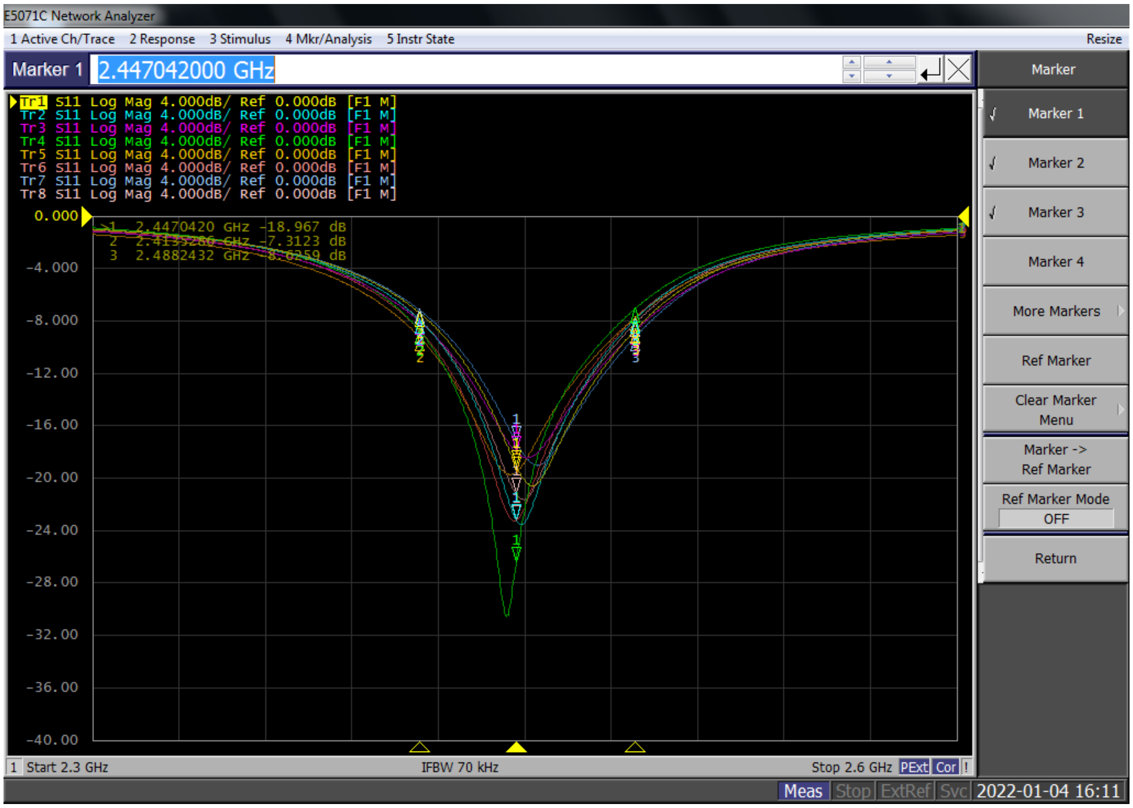


Figure 5.8. Antenna Return Loss for Inner Antenna (JL-2800 laminate)

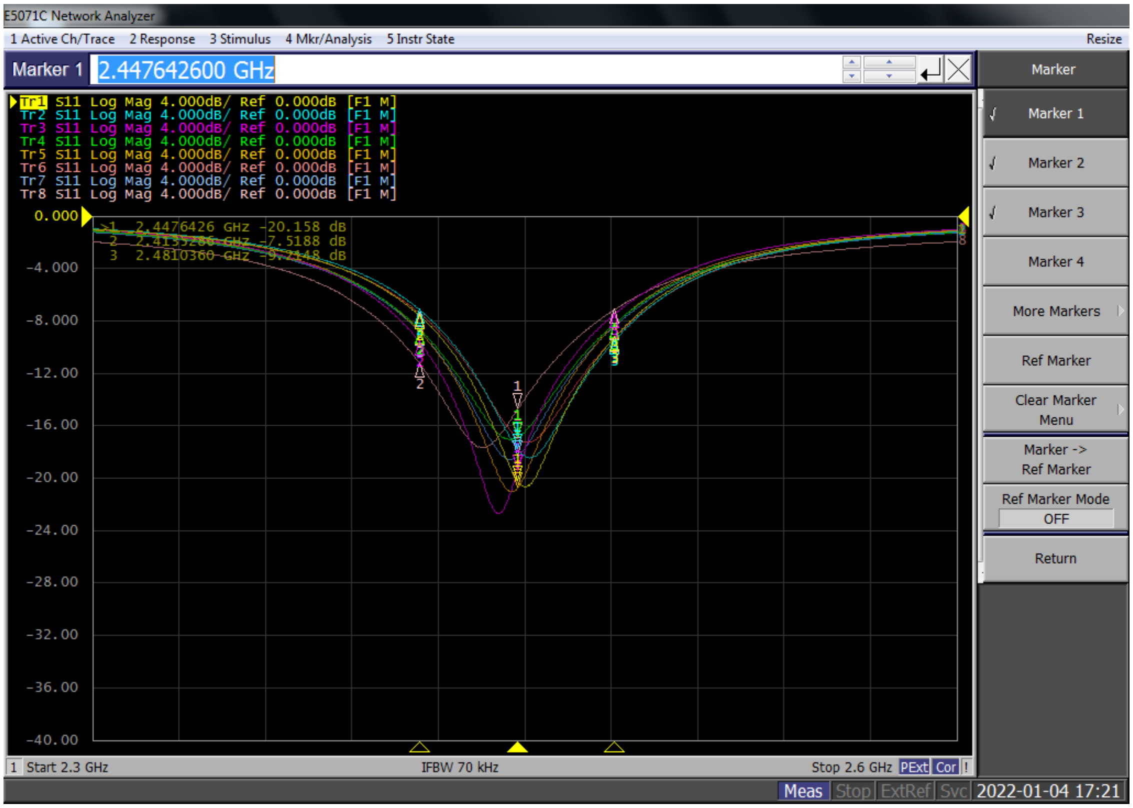


Figure 5.9. Antenna Return Loss for Outer Antenna (JL-2800 laminate)

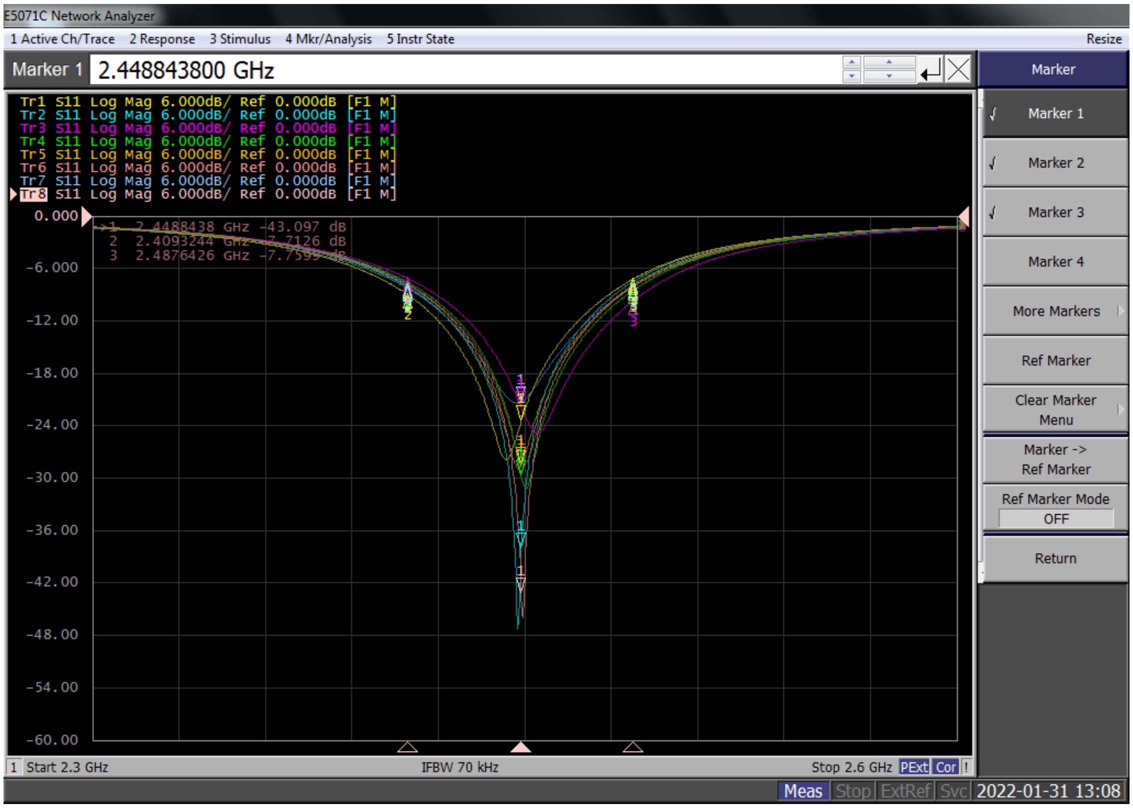


Figure 5.10. Antenna Return Loss for Inner Antenna (IT-180A laminate)

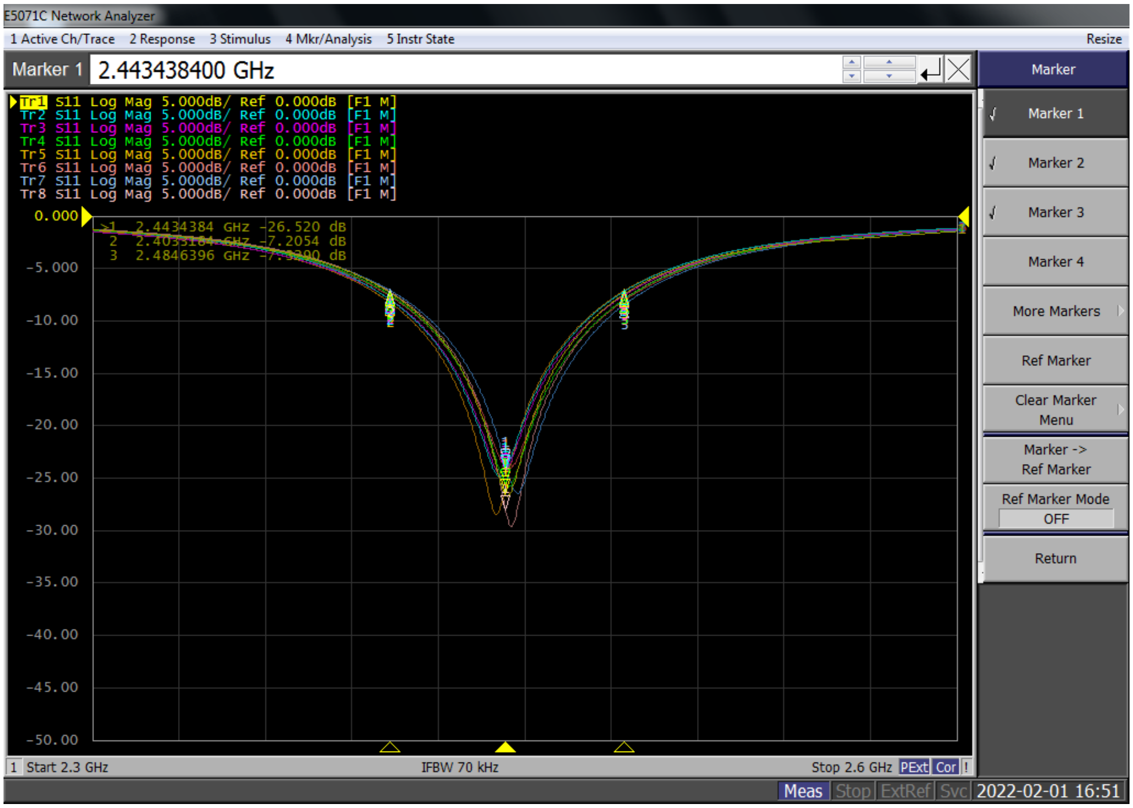


Figure 5.11. Antenna Return Loss for Outer Antenna (IT-180A laminate)

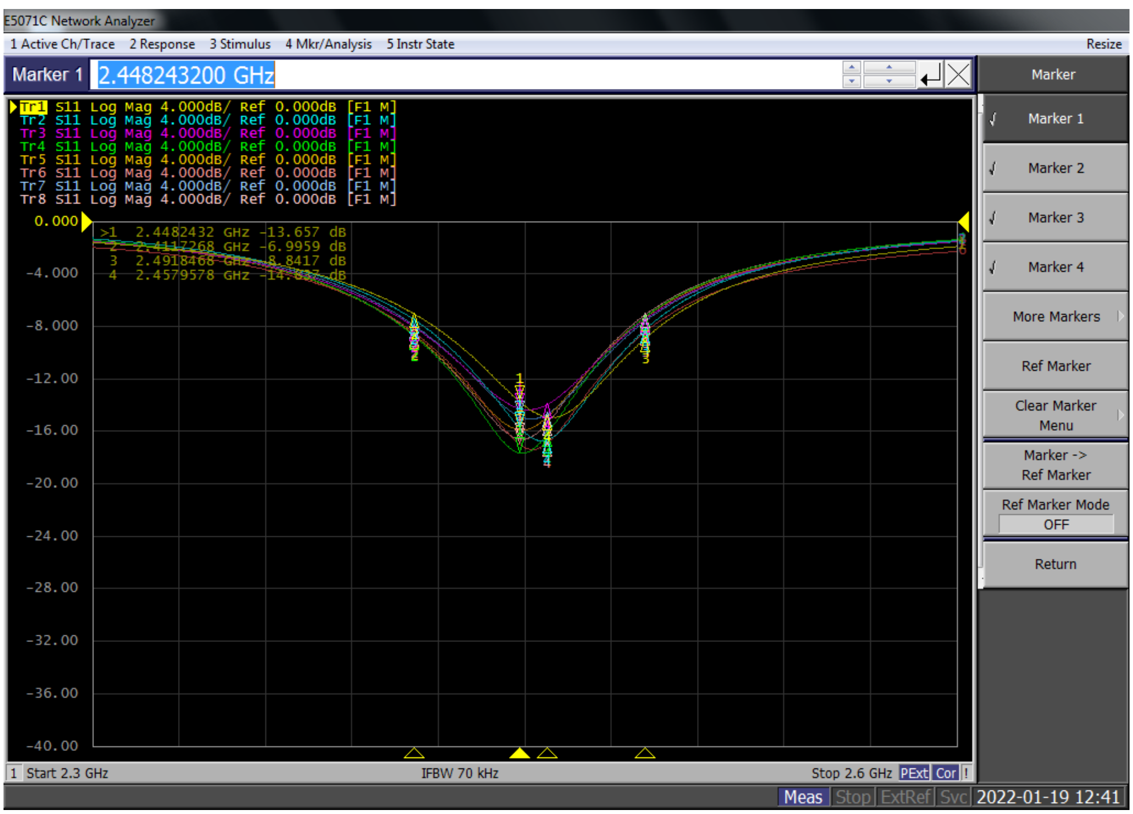


Figure 5.12. Antenna Return Loss for Inner Antenna (IS400 laminate)

From Direction Finding point of view, the phase of the radiation pattern carries important information. Simulation results of the phase radiation pattern for an inner antenna with 2 different polarizations (Theta, Phi) are shown below. Theta and Phi are coordinates of the spherical coordinate system.

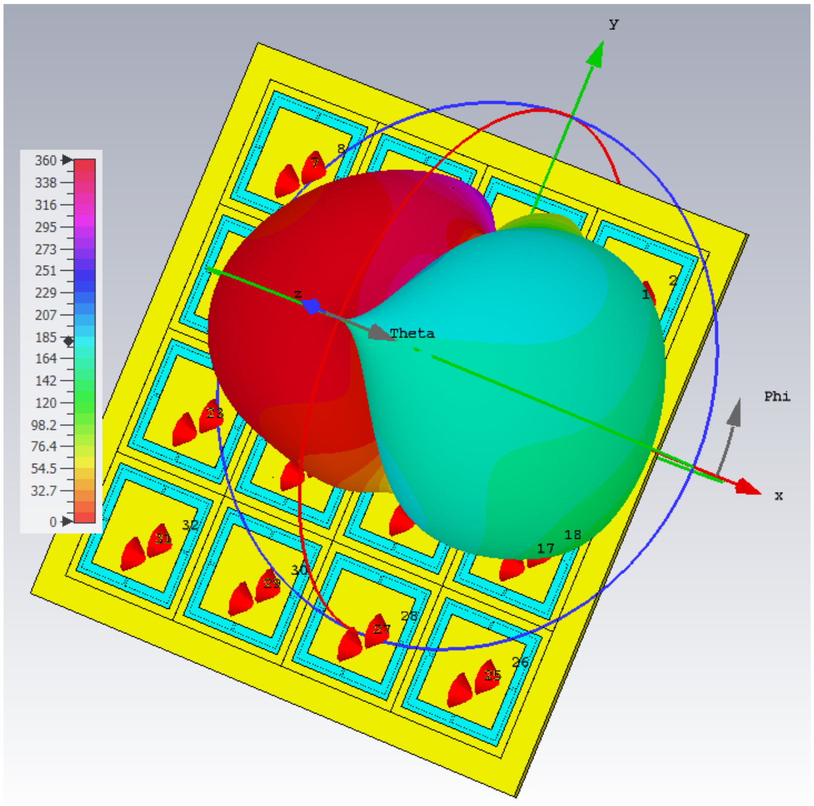


Figure 5.13. Phase Radiation Pattern (Inner patch, Vertical port, Phi polarization)

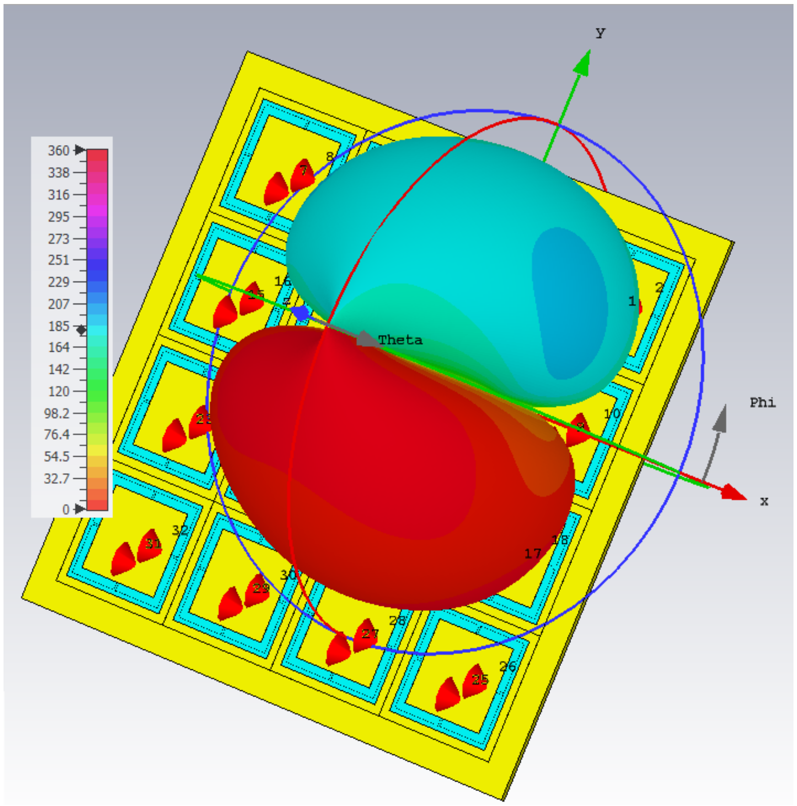


Figure 5.14. Phase Radiation Pattern (Inner patch, Vertical port, Theta polarization)

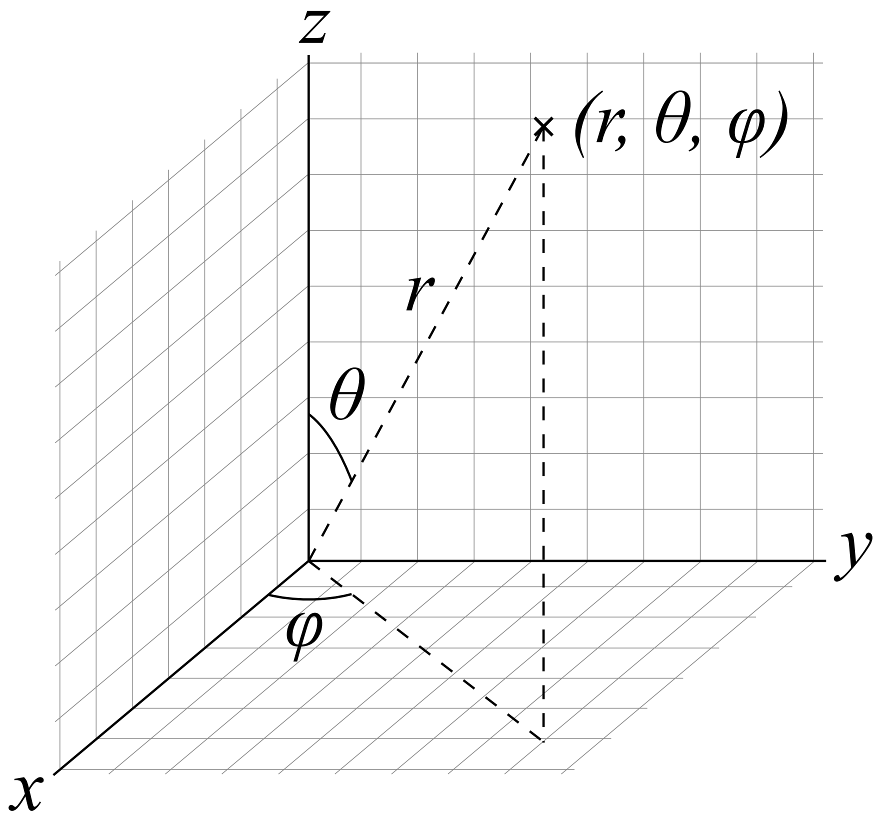


Figure 5.15. Spherical Coordinate System

Note: In the simulations the antenna array is located in the XY plane. Theta (θ) is measured from the z-axis, while elevation angle is measured from the XY plane. The connection between theta and elevation angle:

Elevation = 90° - theta

As figures Figure 5.13 Phase Radiation Pattern (Inner patch, Vertical port, Phi polarization) on page 15 and Figure 5.14 Phase Radiation Pattern (Inner patch, Vertical port, Theta polarization) on page 15 show, the phase characteristic is not unified across the individual lobes. The phase and magnitude characteristic data of the antenna radiation patterns are input parameters for the Direction Finding algorithm and this manifold compensation is used to maximize angle estimation accuracy in all directions.

5.6 RF Feedline Blocks

The 32 ports of the antenna array are connected to the EFR32BG22 device using multiple RF switches:

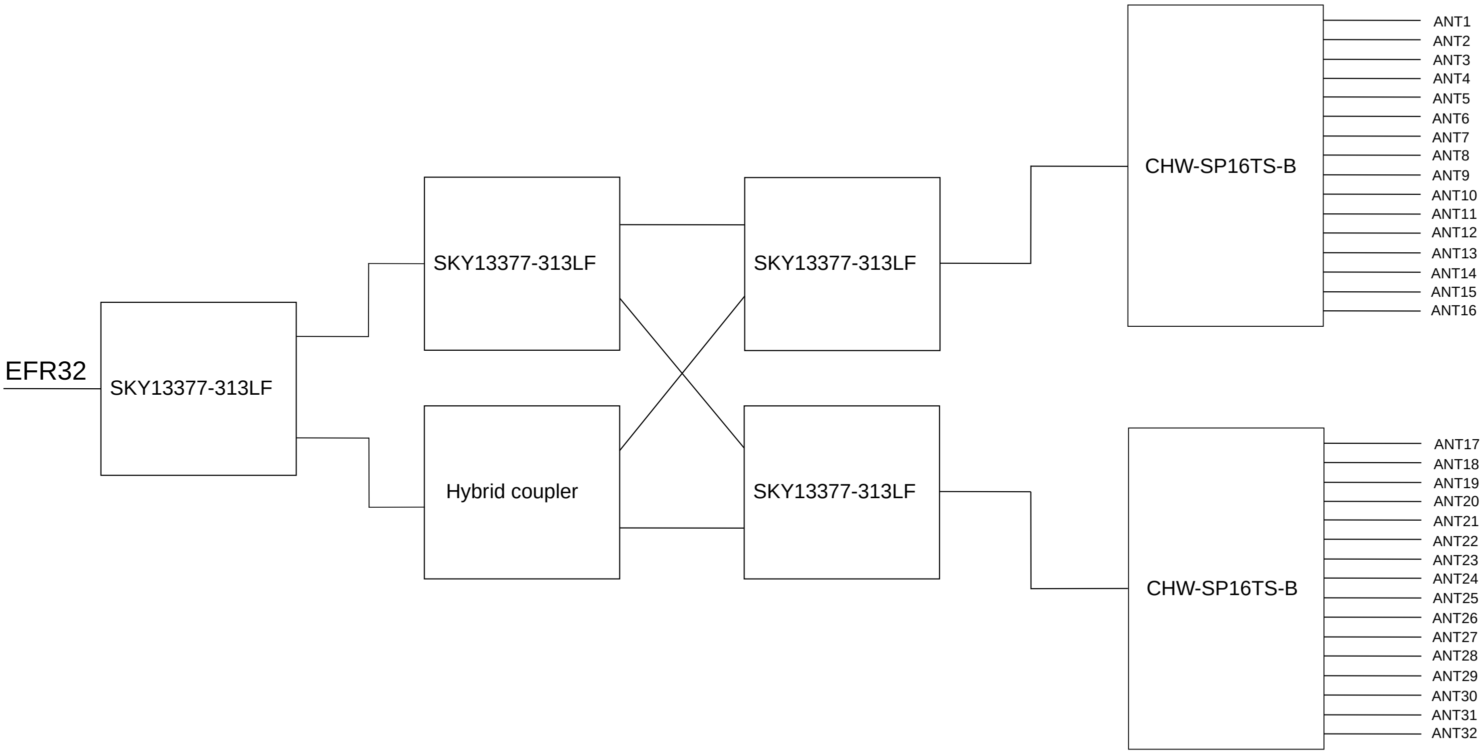


Figure 5.16. RF switch structure in the Antenna Array

As discussed in 5.3 Polarization: Dual Polarized Antennas with Option for Circular Polarization, the antenna array allows for reception of circular polarized signals on 2 antennas for accurate AGC value setting. The circular polarization is realized with a hybrid coupler, for which the BRD4191A design provides two options:

- Planar hybrid coupler (default)
- Discrete hybrid coupler (optional, not embedded)

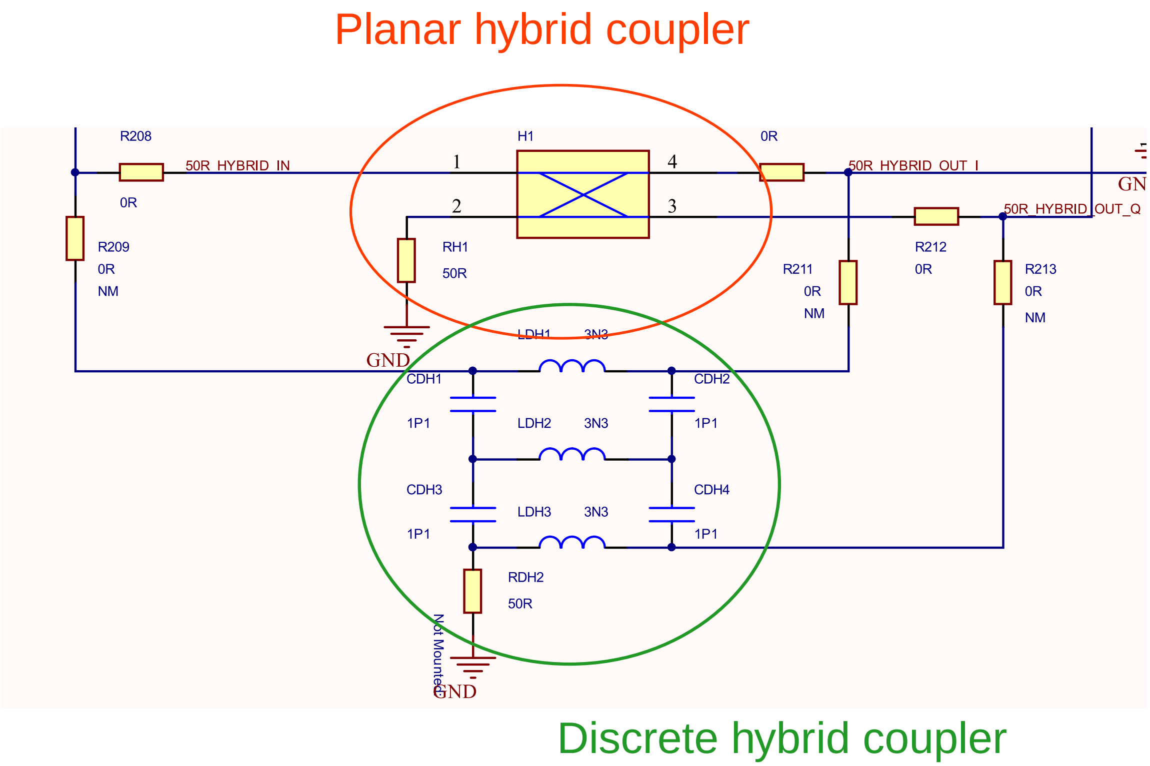


Figure 5.17. Schematic of Planar + Discrete Hybrids

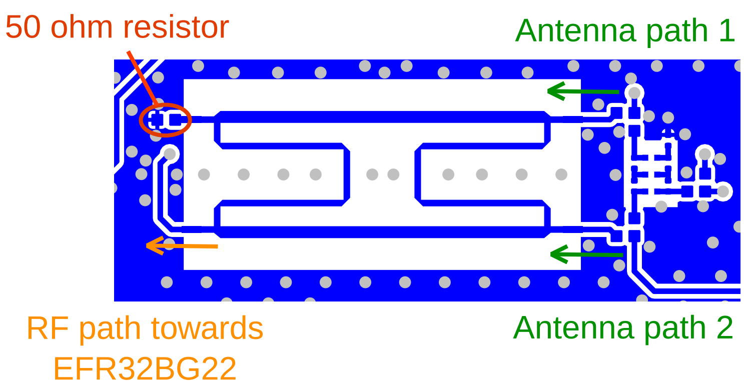


Figure 5.18. PCB layout of Planar Hybrid

Both the planar and discrete hybrid coupler work in a similar way: they combine the two linear polarized signals while creating 90° phase shift between them.

5.7 Effect of Back Metal, Back Concrete and Plastic Case on Antenna Return Loss and Phase Characteristics

Simulations were performed to determine the minimum required keepout between the antenna array and various materials. The minimum keepout values were determined separately for the back, front and side areas.

A typical use case of a Direction Finding application is when the antenna array is mounted on a ceiling to track position of tag(s), while the antennas are facing towards the ground and the back of the array is facing the ceiling. The minimum required keepout from the back of the antenna array was determined assuming metal as the base material behind the array, but simulations were performed also with concrete as base material.

The minimum required gaps from the array on the front and the sides were determined with plastic as base material.

5.7.1 Effect of Back Metal

It is assumed that the outer antennas of the array are more sensitive to a nearby metal behind the array, therefore this section investigates both an outer antenna (port 1) and an inner antenna (port 11).

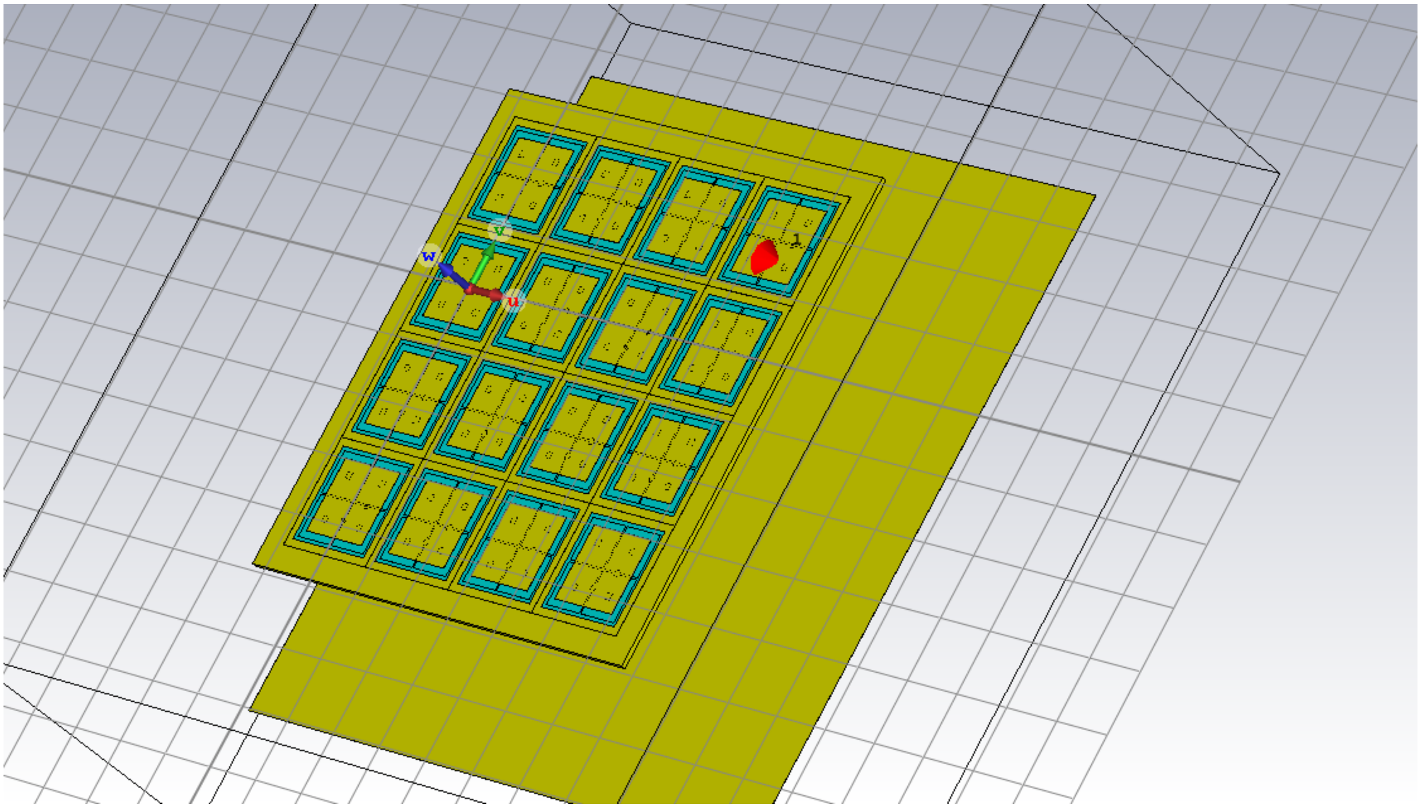


Figure 5.19. Metal Plane Behind the Array (Vertical Port 1)

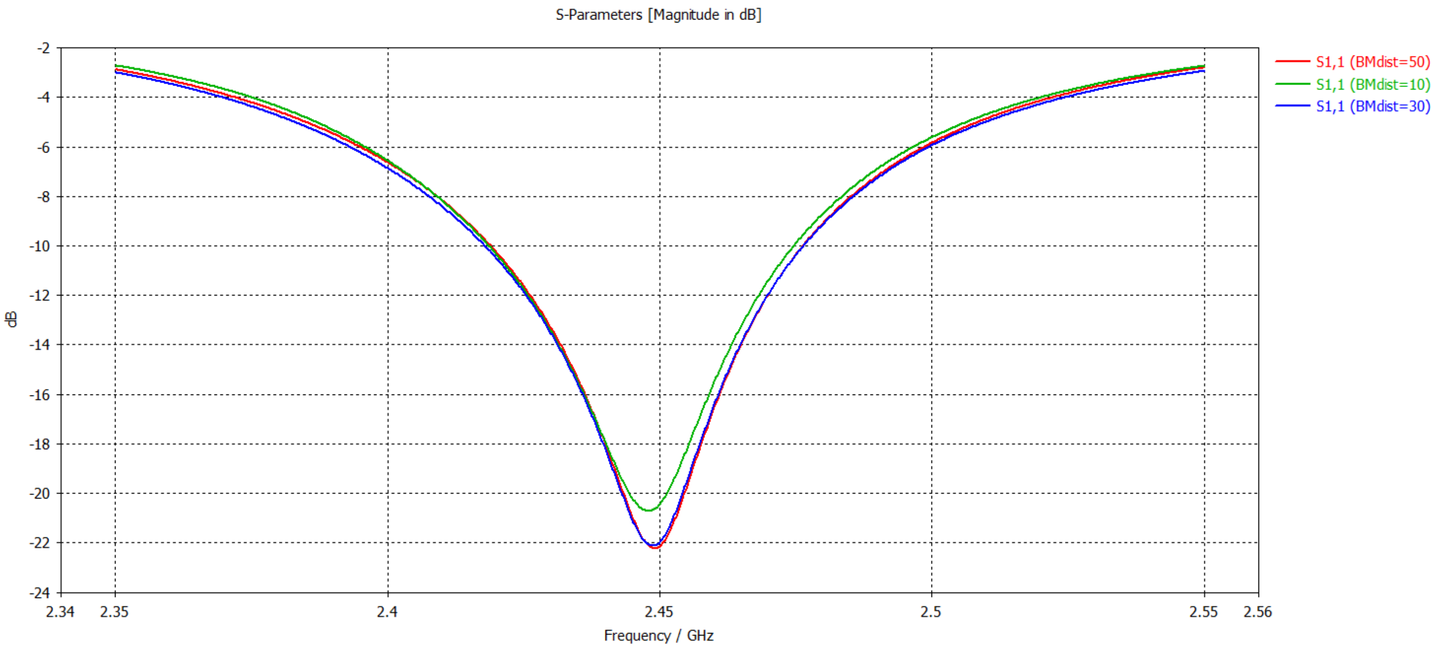


Figure 5.20. S11 vs. Back Metal Distance [mm] (Vertical Port 1)

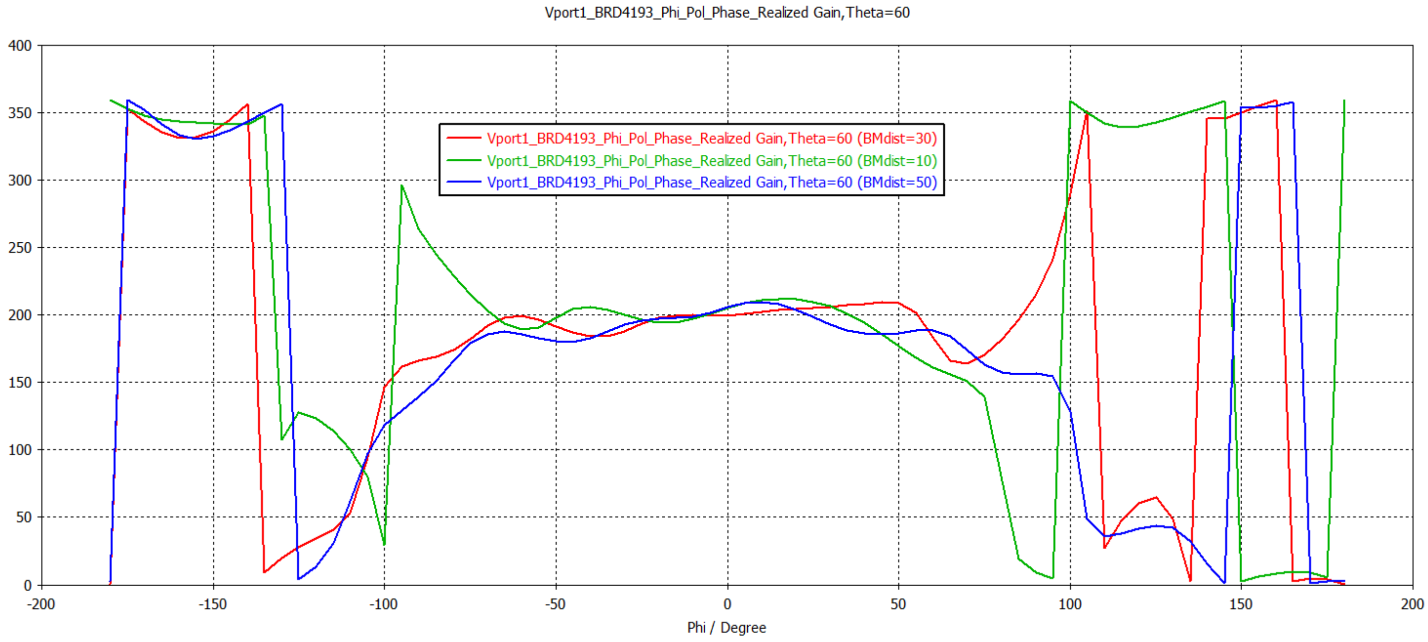


Figure 5.21. Phase vs. Back Metal Distance [mm] (Vertical Port 1, Phi polarization, Theta = 60°)

Note: Some sudden jumps can be seen at the edge of the phase curves, which is due to the phase value being limited to the 0-360° region.

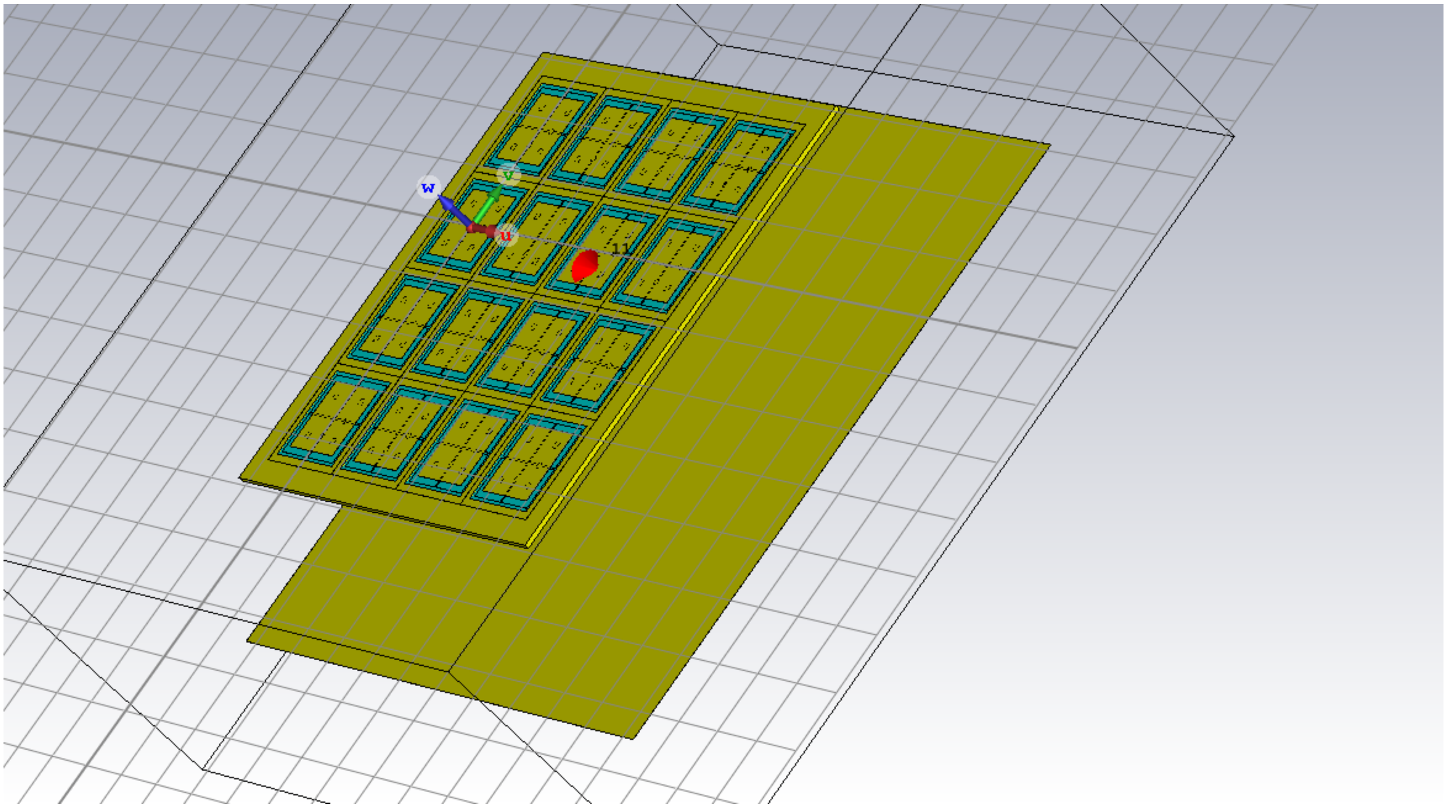


Figure 5.22. Metal Plane Behind the Array (Vertical Port 11)

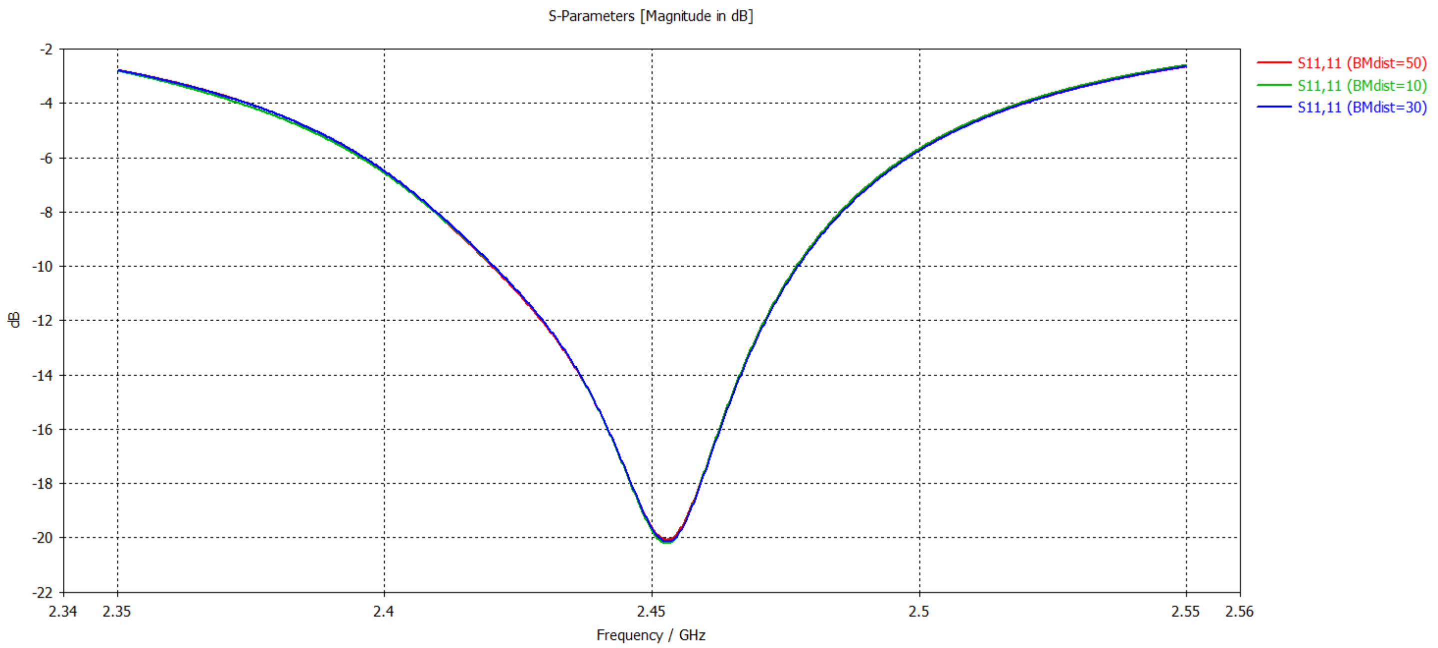


Figure 5.23. S11 vs. Back Metal Distance [mm] (Vertical Port 11)

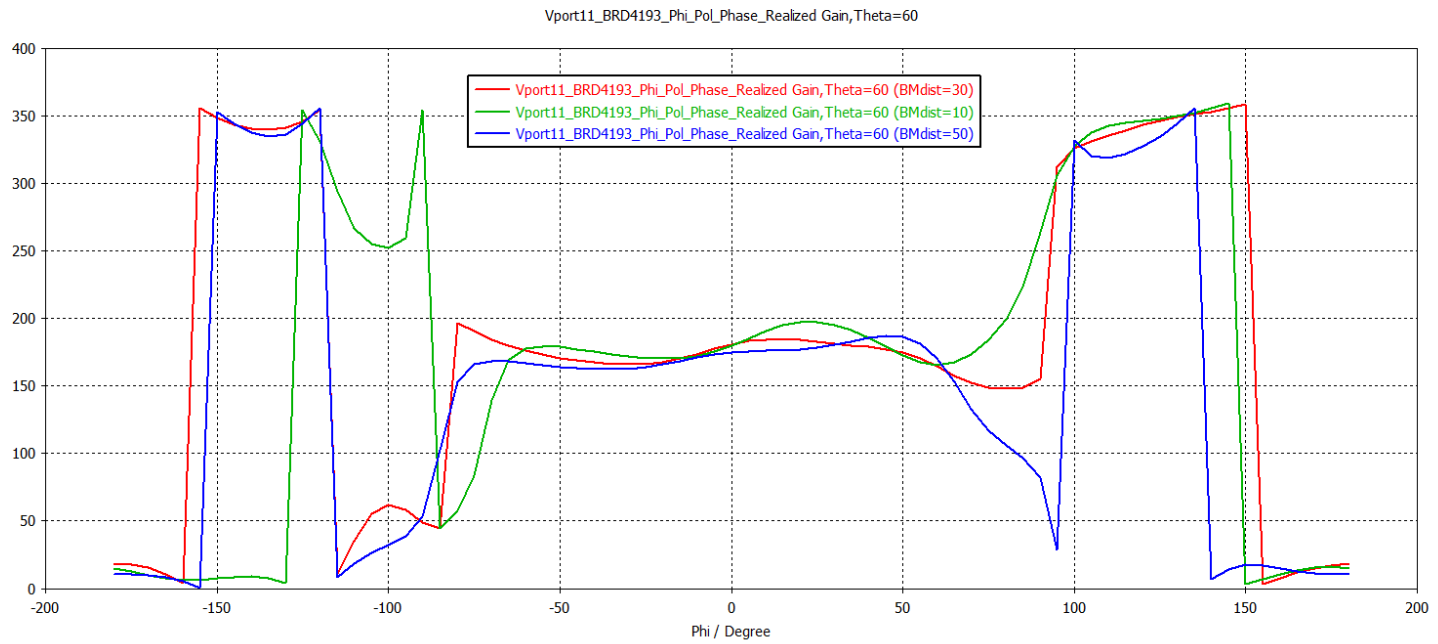


Figure 5.24. Phase vs. Back Metal Distance [mm] (Vertical Port 11, Phi polarization, Theta = 60°)

Note: Some sudden jumps can be seen at the edge of the phase curves, which is due to the phase value being limited to the 0-360° region.

Based on the S11 and phase curves vs. back metal distance, the minimum recommended gap for any metal behind the array is 30 mm.

5.7.2 Effect of Back Concrete

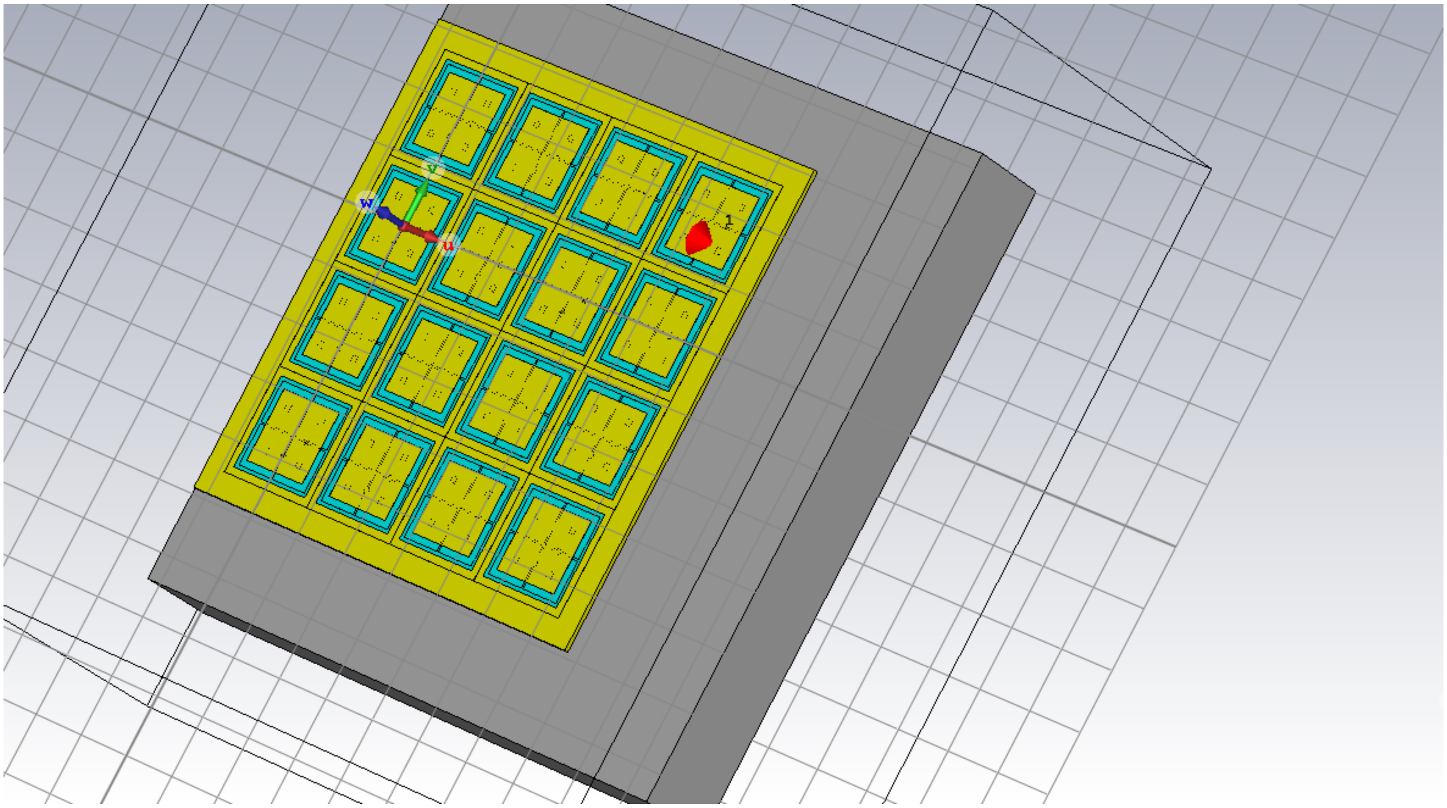


Figure 5.25. Concrete Behind the Array (Vertical Port 1)

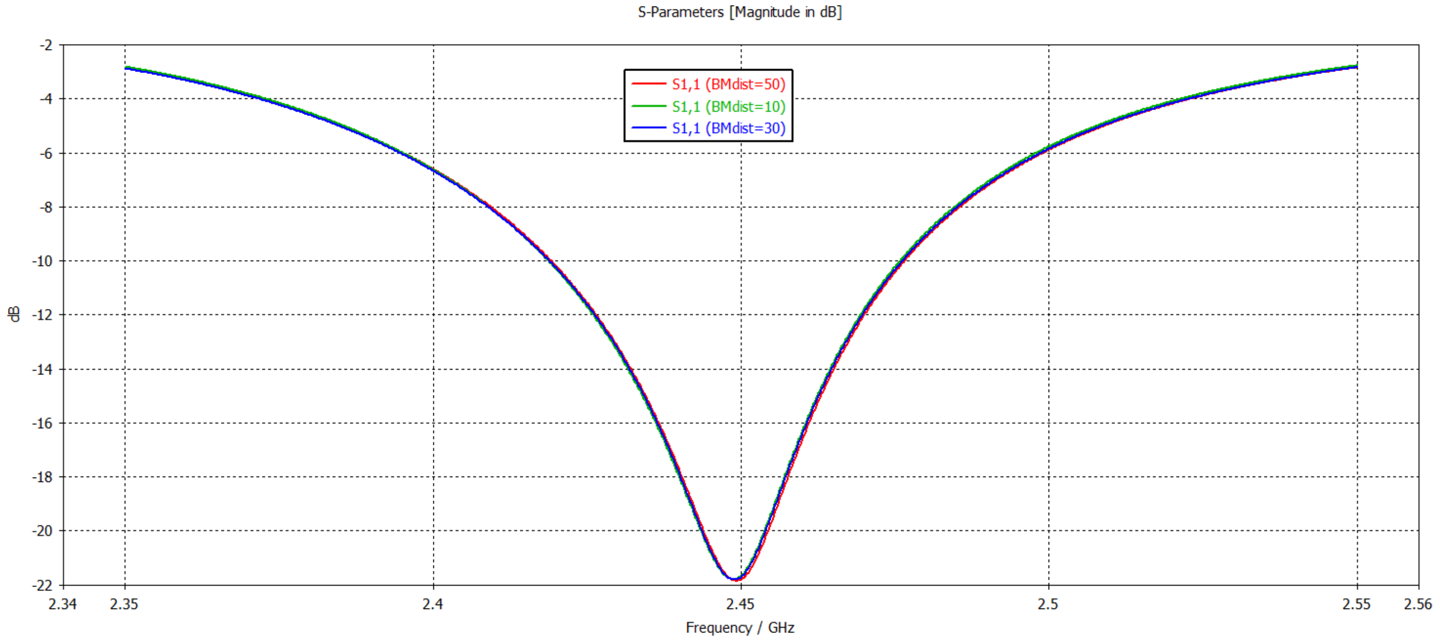


Figure 5.26. S11 vs. Back Concrete Distance [mm] (Vertical Port 1)

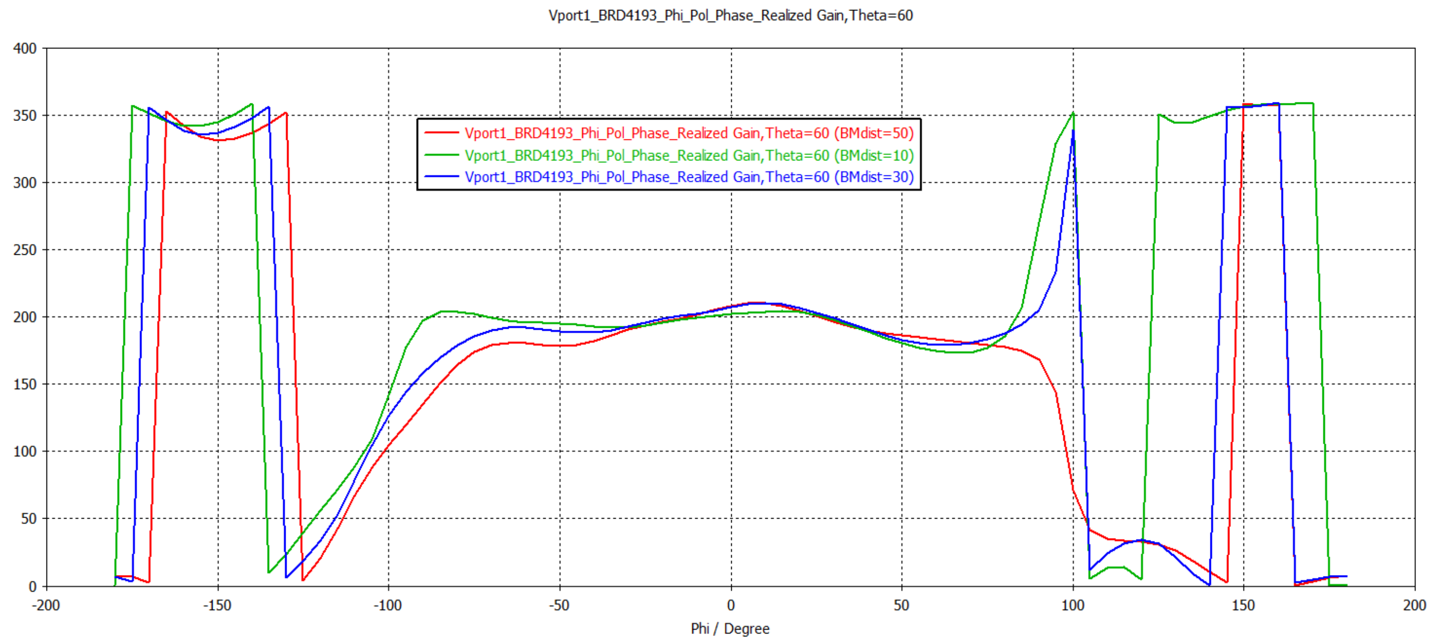


Figure 5.27. Phase vs. Back Metal Distance [mm] (Vertical Port 1, Phi polarization, Theta = 60°)

Note: Some sudden jumps can be seen at the edge of the phase curves, which is due to the phase value being limited to the 0-360° region.

As the figures above show, the effect of a concrete behind the antenna array is less significant compared to a metal behind the array. Still, it is recommended to keep the 30 mm distance from any concrete to avoid the deterioration of the angle estimation performance due to unknown metal inside the concrete.

5.7.3 Effect of Plastic

The effect of plastic was investigated to determine the minimum required plastic keepout from the antenna array in the front and side directions. During the simulation the array was surrounded with plastic in all directions, while the following parameter sweeps were run:

- Front gap sweep (1-5 mm), while the side gap was fixed to 1 mm and the back gap was fixed to 30 mm
- Side gap sweep (0-10 mm), while the front gap was fixed to 3 mm and the back gap was fixed to 30 mm

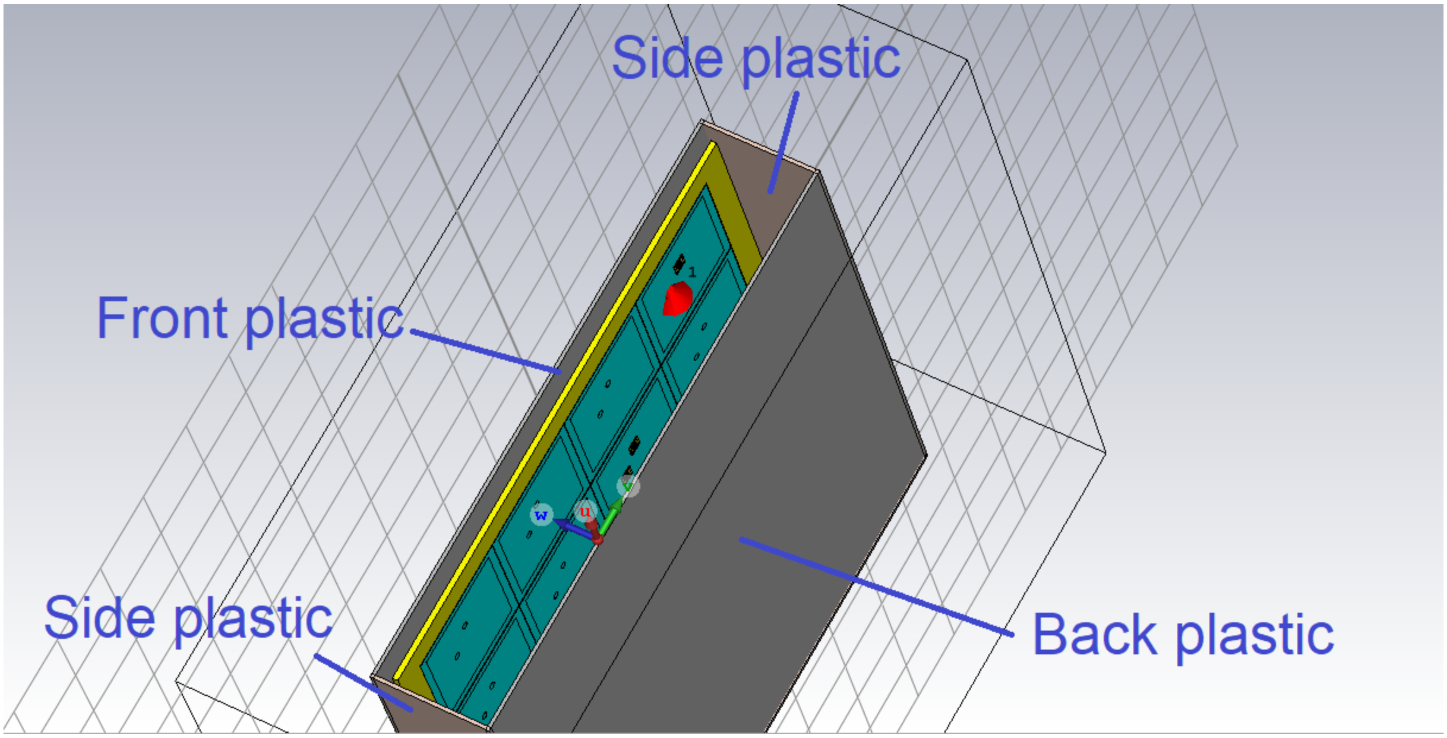


Figure 5.28. Plastic Around the Array (Vertical Port 1)

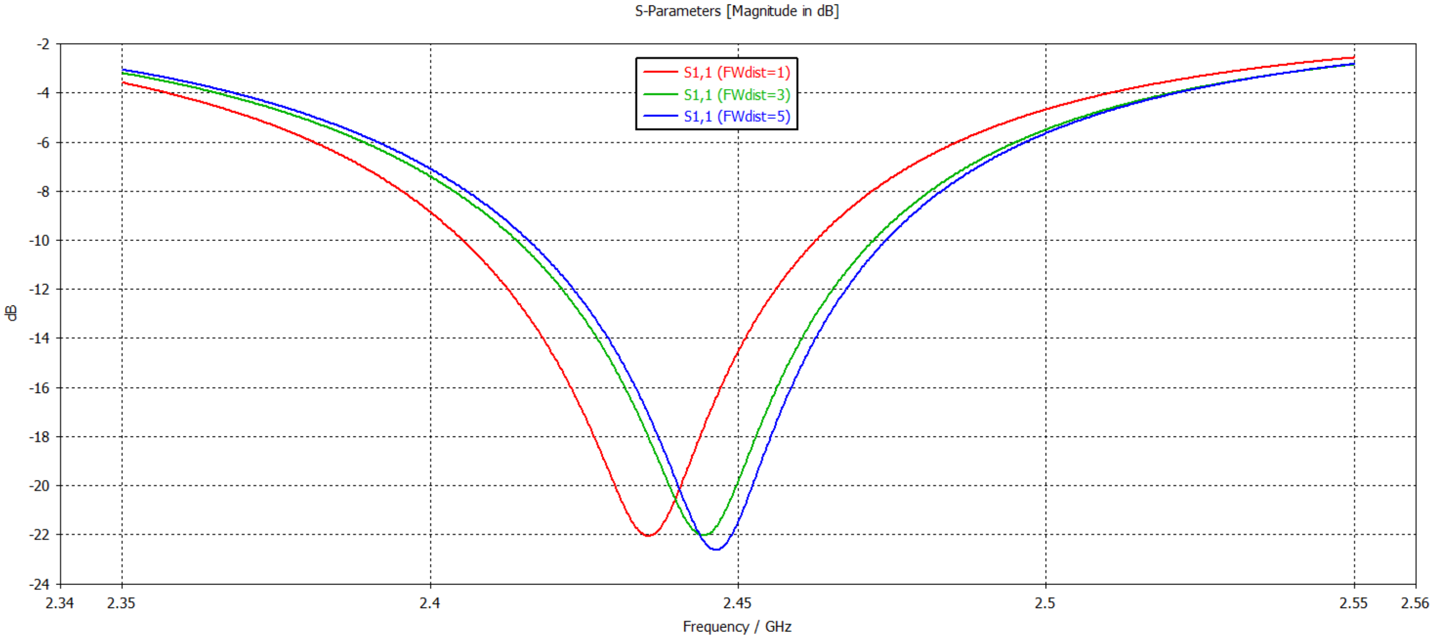


Figure 5.29. S11 vs. Front Gap Distance [mm] (Vertical Port 1)

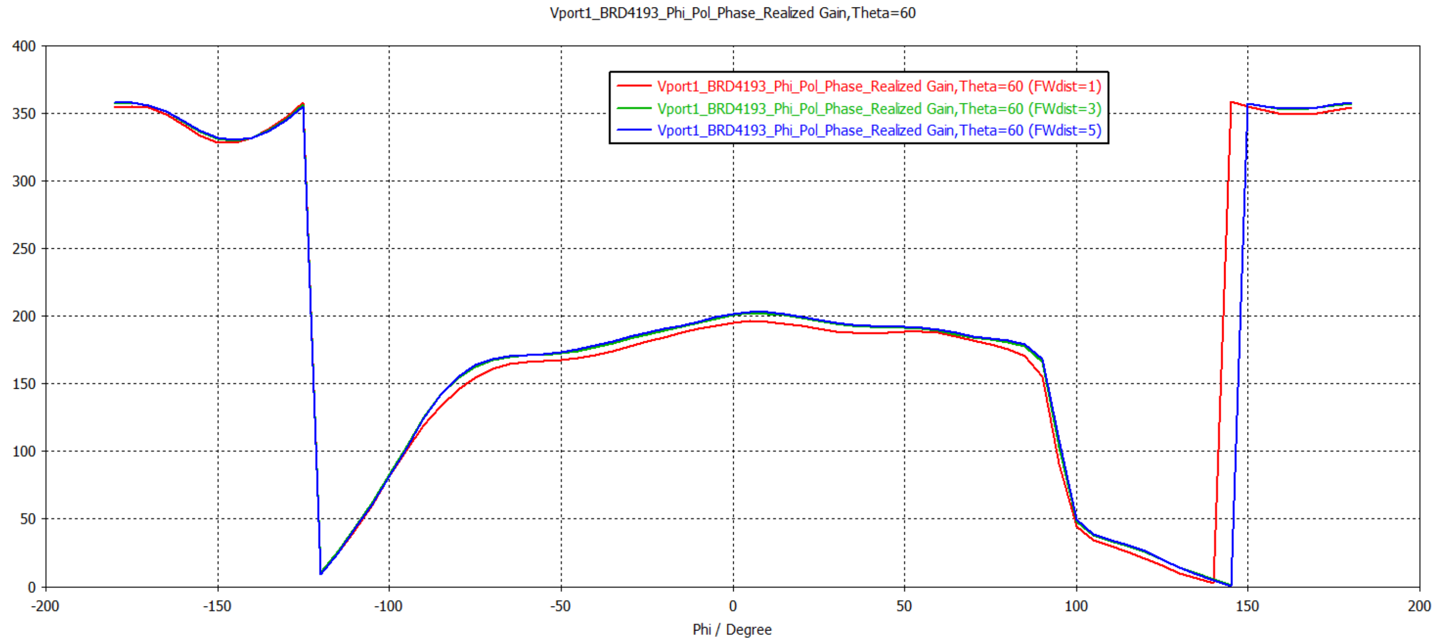


Figure 5.30. Phase vs. Front Gap Distance [mm] (Vertical Port 1)

Note: Some sudden jumps can be seen at the edge of the phase curves, which is due to the phase value being limited to the 0-360° region.

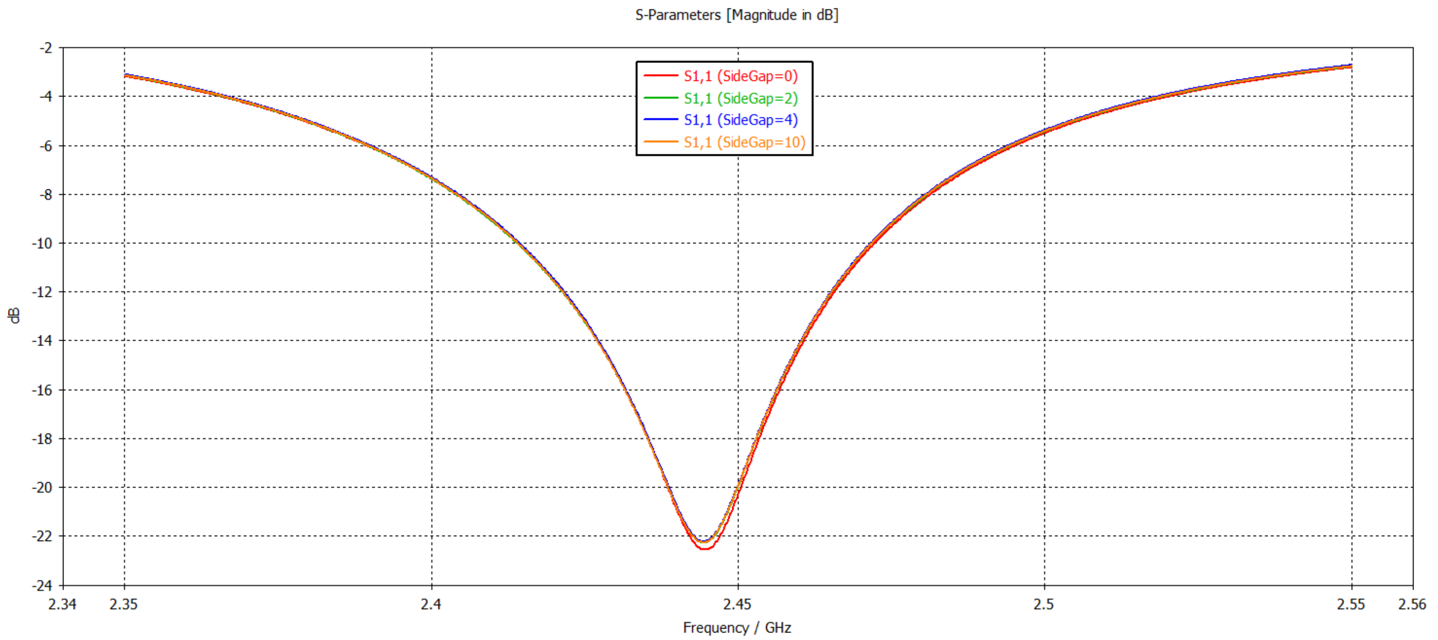


Figure 5.31. S11 vs. Side Gap Distance [mm] (Vertical Port 1)

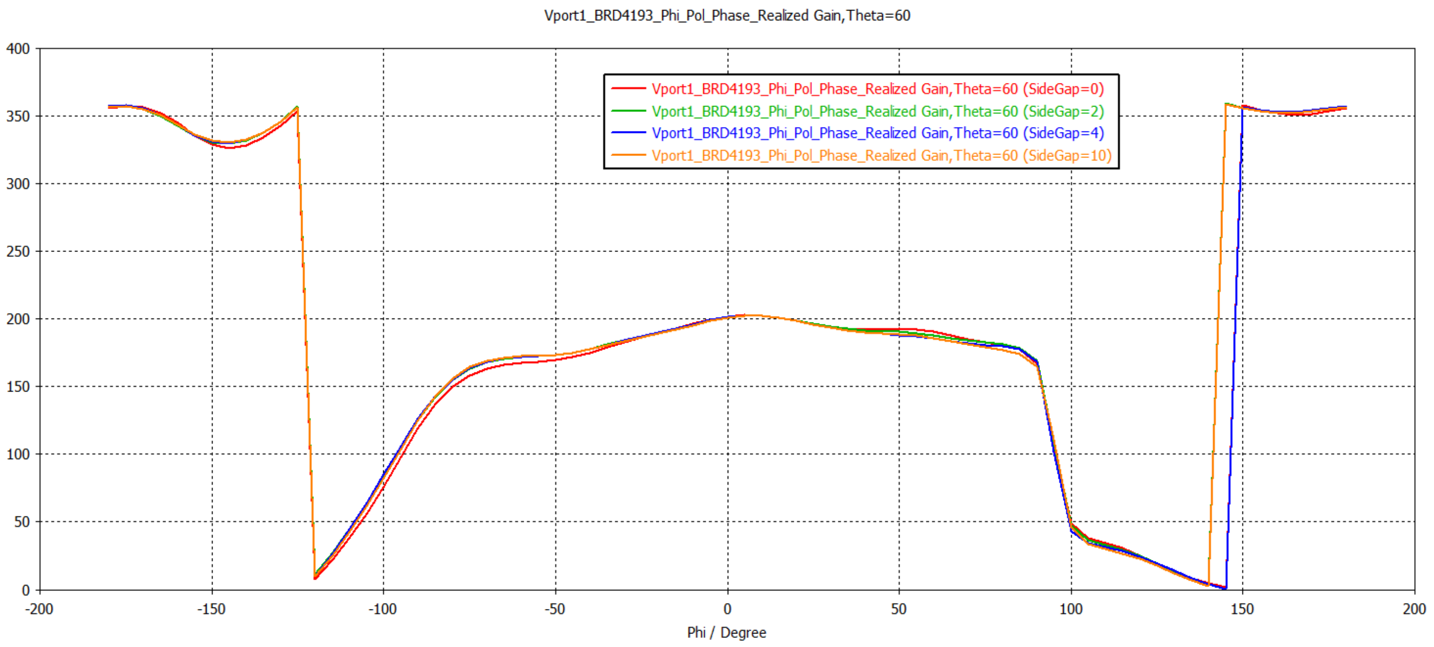


Figure 5.32. Phase vs. Side Gap Distance [mm] (Vertical Port 1)

Note: Some sudden jumps can be seen at the edge of the phase curves, which is due to the phase value being limited to the 0-360° region.

Based on the figures above, the recommended plastic clearance around the antenna array in the various directions:

- Front gap: min. 3 mm
- Side gap: min. 1 mm (side gap distance does not have effect on S11 and phase curves, therefore a min. 1 mm distance is recommended for mechanical reasons)
- Back gap: min. 30 mm (the plastic will create the required clearance for any metal or concrete behind the array)

6. Antenna Impedance Measurement and Tuning

6.1 Antenna Impedance Measurement

As mentioned in 3. General Antenna Array Recommendations, it is recommended to verify antenna impedance of the single antennas on a custom design. Similar antenna impedance is expected across the individual antennas and across the 2 feed points of a specific patch antenna, therefore it is sufficient to check antenna impedance only on one port on one patch of the antenna array.

For accurate antenna impedance measurement on one antenna port of the antenna array, the steps below should be followed carefully:

- Antenna impedance should be measured using an SMA pigtail cable: the inner conductor should be connected to one of the antenna feed points on the Bottom PCB layer, while the cable ground should be connected to the Bottom PCB layer ground near the antenna feed point (solder mask should be removed from the ground copper area).
- The antenna feed line should be cut on the Bottom PCB layer close to the antenna feed point.

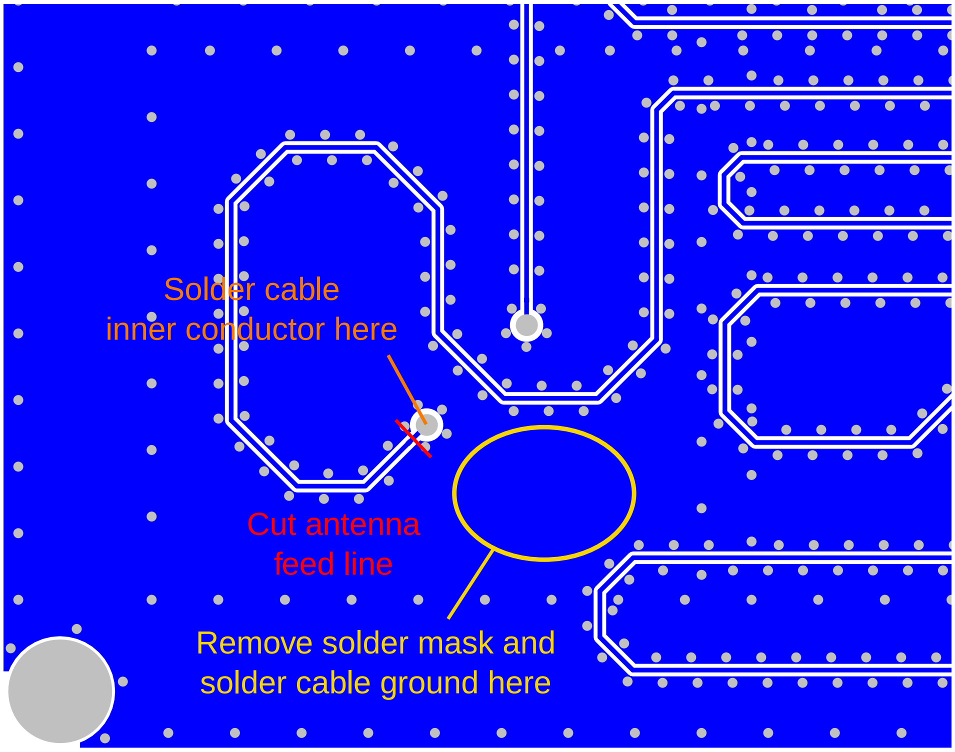


Figure 6.1. Antenna Impedance Measurement on the Bottom PCB Layer

The target resonance frequency of the antenna is the middle of the Bluetooth band (2402-2480 MHz): ~2440 MHz.

6.2 Antenna Impedance Tuning with RIS Cell Size Adjustments

One option to compensate for the detuned antenna resonance is to adjust the RIS cell dimensions. Investigations showed that larger RIS cell size decreases the antenna resonance frequency, while smaller RIS cell size causes a frequency shift upwards in frequency.

If one intends to optimize antenna resonance frequency by adjusting RIS cell dimensions, Silicon Labs recommends to create 3 different PCB prototypes from the same laminate type with different RIS cell sizes, then select the best candidate based on the antenna impedance measurement on all 3 variants.

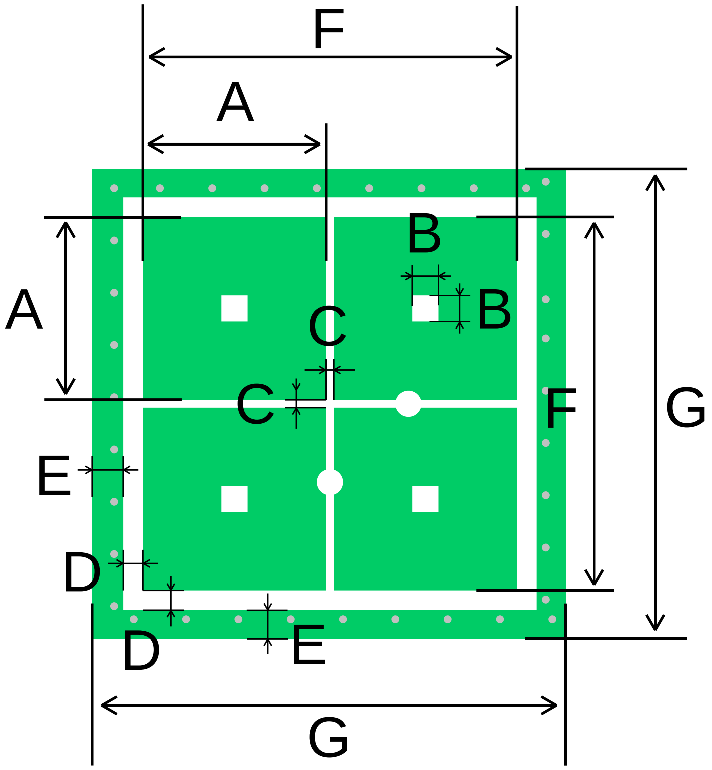


Figure 6.2. RIS Cell Dimensions

The recommended RIS cell dimensions (including the default and 2 corner cases) for the 3 recommended laminate types are shown in the tables below.

Table 6.1. Recommended RIS Cell Dimensions for JL-2800 Laminate

Laminate manufacturer	Laminate type	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]
Jiangsu Lianxin	JL-2800	13.9	1.9	0.6	1.5	2.3	28.4	36.0
		14.0	2.0	0.6	1.5	2.2	28.6	36.0
		14.1	2.1	0.6	1.5	2.1	28.8	36.0

If JL-2800 is the selected laminate type, create PCB prototypes with all 3 RIS cell dimensions as shown above, and select the final production variant based on antenna impedance measurements.

Table 6.2. Recommended RIS Cell Dimensions for IT-180A Laminate

Laminate manufac-turer	Laminate type	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]
ITEQ	ITEQ	13.95	1.95	0.6	1.2	2.55	28.5	36.0
		14.05	2.05	0.6	1.2	2.45	28.7	36.0
		14.15	2.15	0.6	1.2	2.35	28.9	36.0

If IT-180A is the selected laminate type, create PCB prototypes with all 3 RIS cell dimensions as shown above, and select the final production variant based on antenna impedance measurements.

Table 6.3. Recommended RIS Cell Dimensions for IS400 Laminate

Laminate manufactur-er	Laminate type	A [mm]	B [mm]	C [mm]	D [mm]	E [mm]	F [mm]	G [mm]
Isola	IS400	14.3	2.3	0.6	1.2	2.2	29.2	36.0
		14.4	2.4	0.6	1.2	2.1	29.4	36.0
		14.5	2.5	0.6	1.2	2.0	29.6	36.0

If IS400 is the selected laminate type, create PCB prototypes with all 3 RIS cell dimensions as shown above, and select the final production variant based on antenna impedance measurements.

6.3 Antenna Impedance Tuning with External SMD Components

Another option to compensate for the detuned antenna resonance is to add discrete components (inductors, capacitors) prior to the antenna feed point.

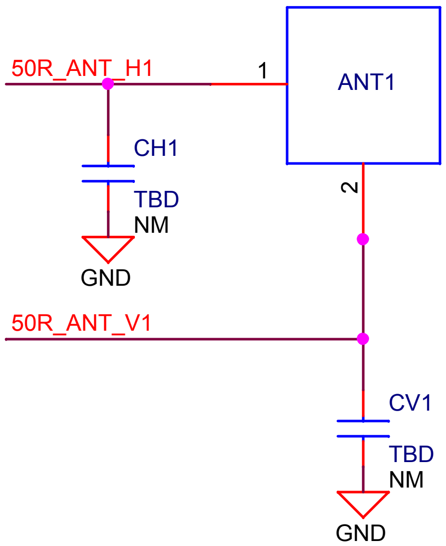


Figure 6.3. Antenna Tuning with SMD Components – Schematic

Investigations showed that by adding one shunt element close to the antenna feed point, antenna resonance can be shifted according to the following:

- Shunt inductor: shifts frequency upwards
- Shunt capacitor: shifts frequency downwards

If antenna tuning with discrete SMD components is desired, make sure to add such a component to all 32 ports of the 16 antennas.

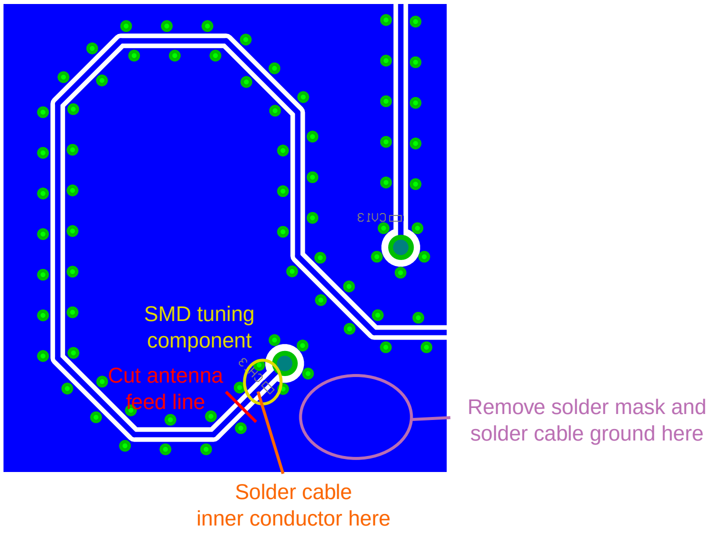


Figure 6.4. Antenna Tuning with SMD Components – Layout

Also, make sure to place this component as close to the antenna feed point as possible. In this case, the inner conductor of the measurement cable should be soldered to the other side of the SMD component instead of to be soldered on the antenna feed point.

7. Antenna Array Accuracy

Direction finding accuracy depends strongly on the amount of different phase information in the receiver. The number of channels/antennas affects the overall angle accuracy. However, increasing the number of antennas requires more and more memory for the calculations and increases PCB size as well.

The dual-polarized 4x4 array was chosen as the reference based on the most optimal system performance for smallest array size.

Silicon Labs has performed real environment testing on the 4x4 array with the following results. The measurements were performed using Gecko SDK 4.1 and RTL library 4.0.0.0 GA AoX Estimator Mode: SL_RTL_AOX_MODE_REAL_TIME_BASIC.

The following devices were used for all antenna array accuracy measurements in this section:

- Locator: BRD4191A Rev A01
- Tag: BRD4184A Rev A02

7.1 Environment 1 (1 locator, 1 tag, tag on turntable)

- Location: Indoor, open space, objects outside measurement area
- Locator height from floor: 2.7 m
- Tag height from floor: 0.5 m
- Testing range: 27 m^2
- Tag on the edge of a turntable with 0.5 m radius
- Turntable moved to 9 different locations
- Tag is rotated with the turntable in all 9 locations
- Locator position is fixed at center
- Manifold compensation: disabled

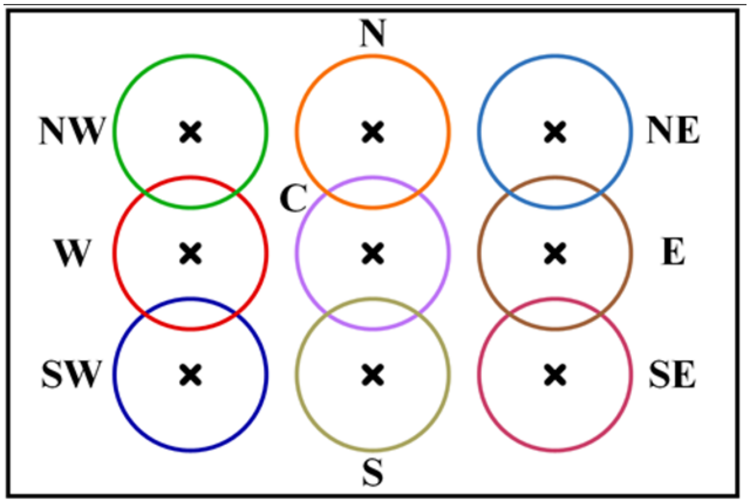


Figure 7.1. Turntable at 9 Different Positions

Azimuth Angle Measurement Results:

- Black dotted line: Expected ideal angle
- Green line: Measured azimuth angle

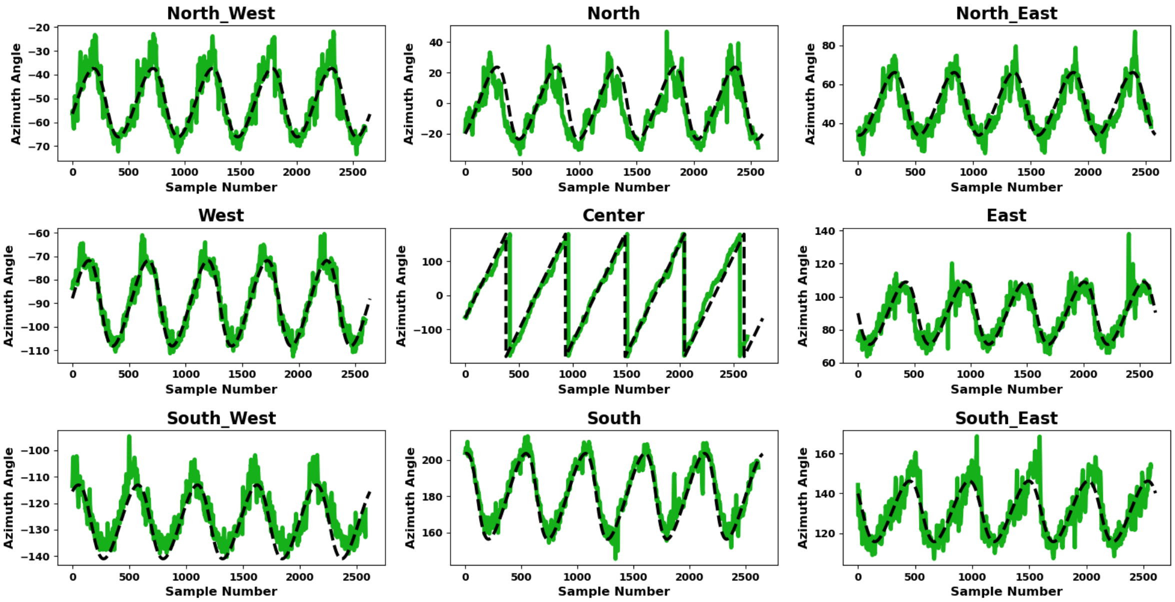


Figure 7.2. Azimuth Angle Measurement Results

Elevation Angle Measurement Results:

- Black dotted line: Expected ideal angle
- Green line: Measured azimuth angle

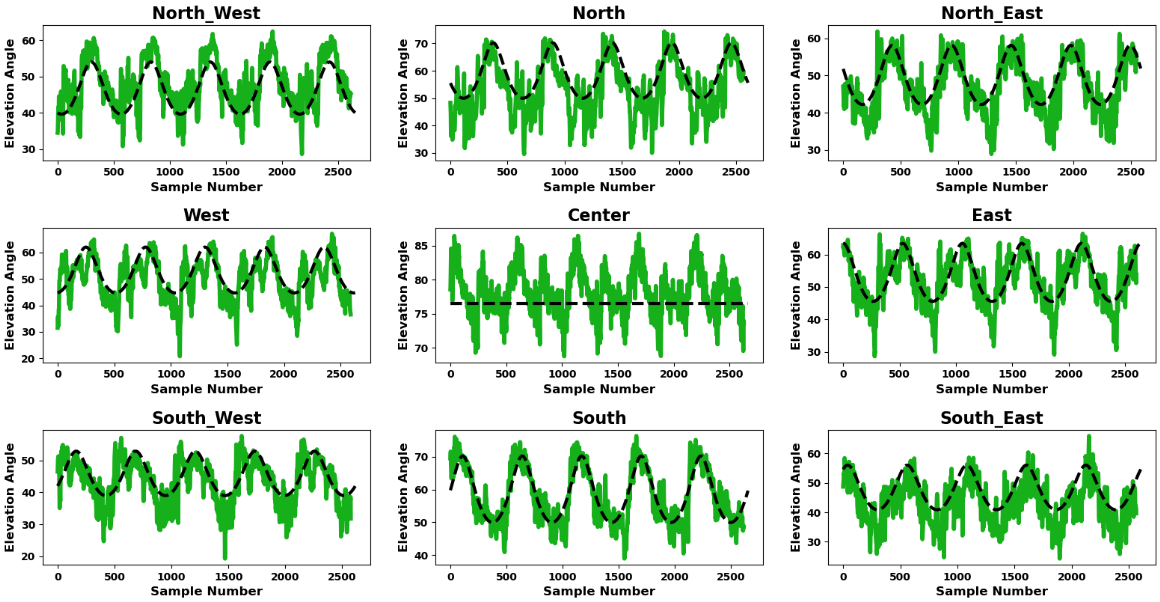


Figure 7.3. Elevation Angle Measurement Results

7.2 Environment 2 (1 locator, 1 tag, locator on turntable)

- Location: Indoor, open space, plenty of objects in the measurement area
- Locator height from floor: 0.5 m
- Tag height from floor: 2.4 m
- Testing range: 30 m^2
- Tag position is fixed
- Locator in the middle of a turntable
- Locator is rotated with the turntable
- Manifold compensation: enabled
- Average azimuth error: ±1.97°
- Average elevation error at 3.5 m away from the locator: ±4.22°

7.3 Environment 3 (1 tag, 4 locators, static measurement)

- Location: Indoor, open space, some objects in the measurement area
- Locator height from floor: 2.9 m
- Tag height from floor: 1.5 m
- Testing range: 10 m^2
- Distance between locators and tag is varying between 2 and 3 meters
- Manifold compensation: disabled
- Average azimuth error: ±3.8°
- Best and worst-case azimuth errors: ±2.9° and ±6.25°
- Average elevation error: ±5.8°
- Best and worst-case elevation errors: ±2.5° and ±8.9°

Note: The total average azimuth and elevation errors represent an average error value from the four individual locators.

7.4 Environment 4 (1 tag, 4 locators, tag moving with a known path)

- Location: Indoor, open space, heavy multipath due to nearby walls and windows, some objects in the measurement area
- Locator height from floor: 2.9 m
- Tag height from floor: 1.5 m
- Testing range: 10 m^2
- Tag position is moving slowly with constant speed 5 cm/s
- Four locators around the tag's path
- Distance between locators and tag is varying between 2 and 3 meters
- Manifold compensation: disabled
- Average azimuth error: ±4.0°
- Best and worst-case azimuth errors: ±0.1° and ±13.5°
- Average elevation error: ±7.1°
- Best and worst-case elevation errors: ±0.06° and ±27.6°

Note: The total average azimuth and elevation errors represent an average error value from the four individual locators.

7.5 Environment 5 (1 tag, 1 locator, locator on turntable)

- Location: anechoic chamber, no multipath
- Testing range: 24 m^2

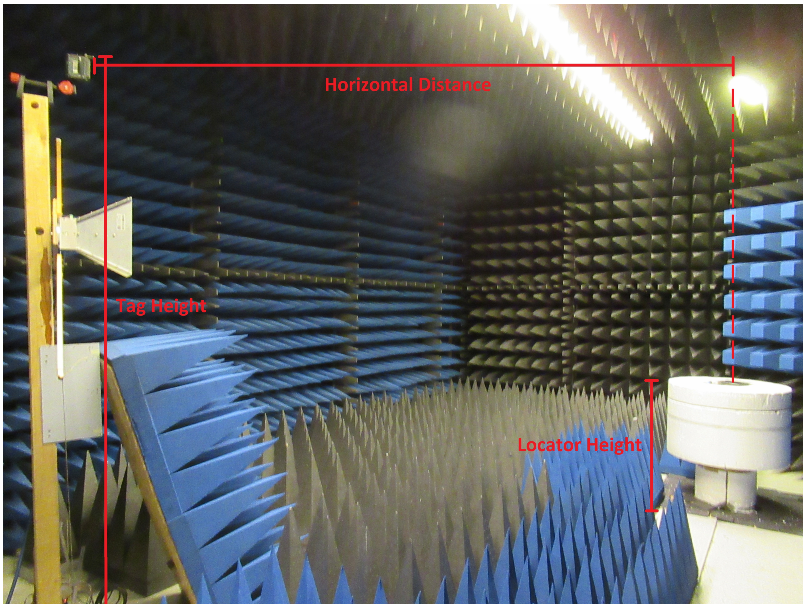


Figure 7.4. Azimuth Angle Measurement Setup

Azimuth Angle Measurement Method:

- Tag position is fixed
- Locator placed on a turntable horizontally
- Locator rotated between 0-360°

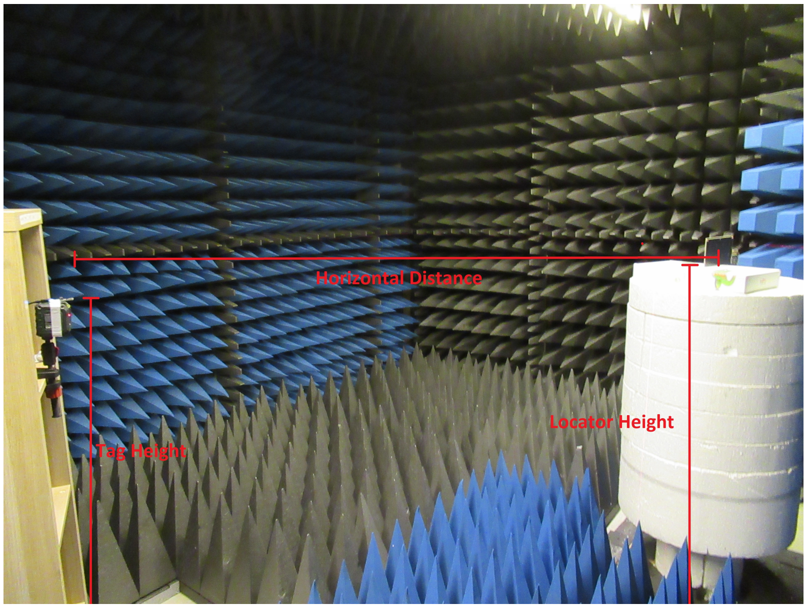
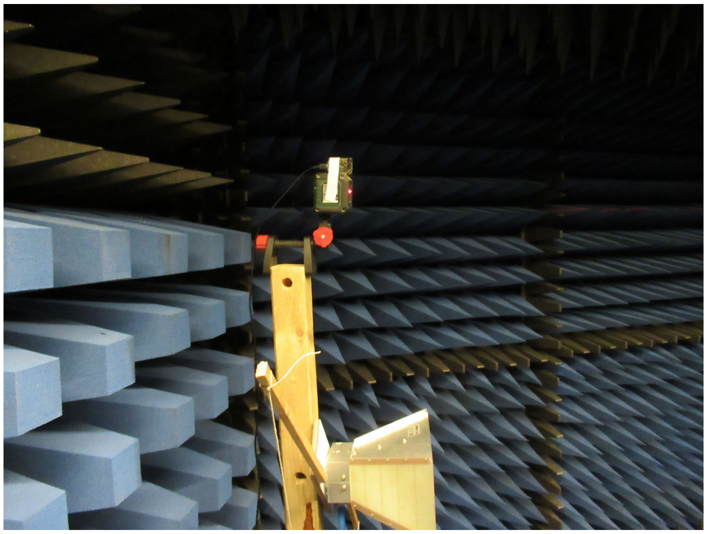


Figure 7.5. Elevation Angle Measurement Setup

Elevation Angle Measurement Method:

- Tag position is fixed
- Locator placed on a turntable vertically
- Locator rotated between 0-90°

7.5.1 Azimuth Angle Measurement: Tag in Vertical Polarization



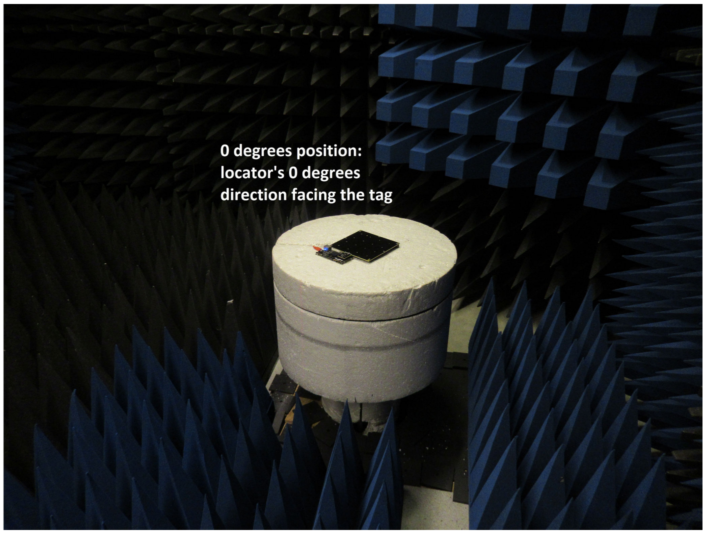


Figure 7.6. Azimuth Angle Measurement: Tag in Vertical Polarization

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Horizontal distance between tag and locator: 3 m
- Manifold compensation: disabled

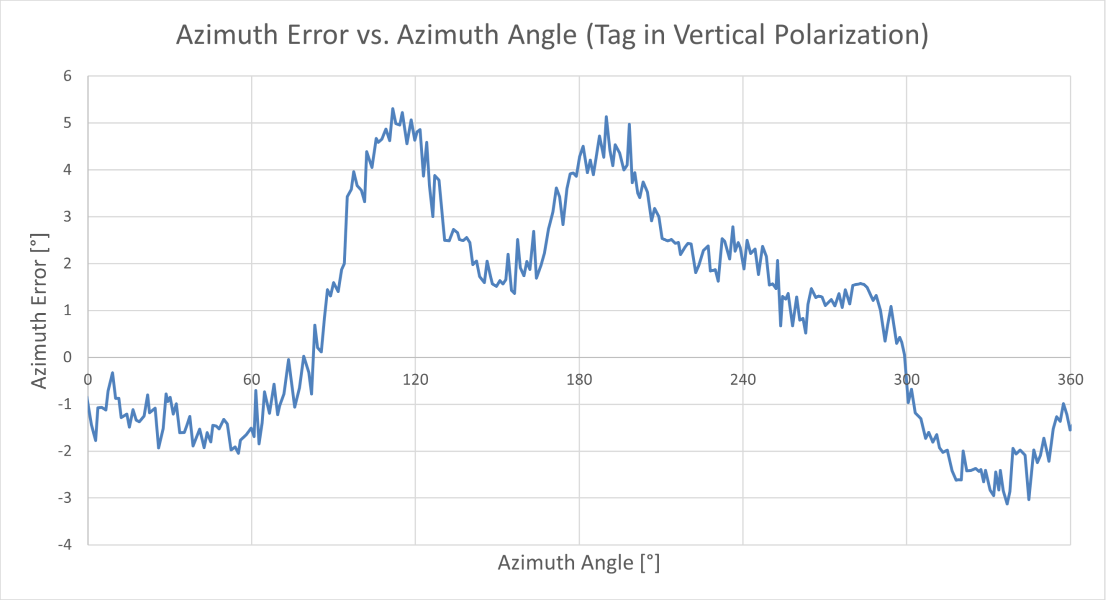


Figure 7.7. Azimuth Error vs. Azimuth Angle: Tag in Vertical Polarization

- Average azimuth error: ±2.2°
- Best and worst-case azimuth errors: ±0.02° and ±5.3°

7.5.2 Azimuth Angle Measurement: Tag in Horizontal Polarization

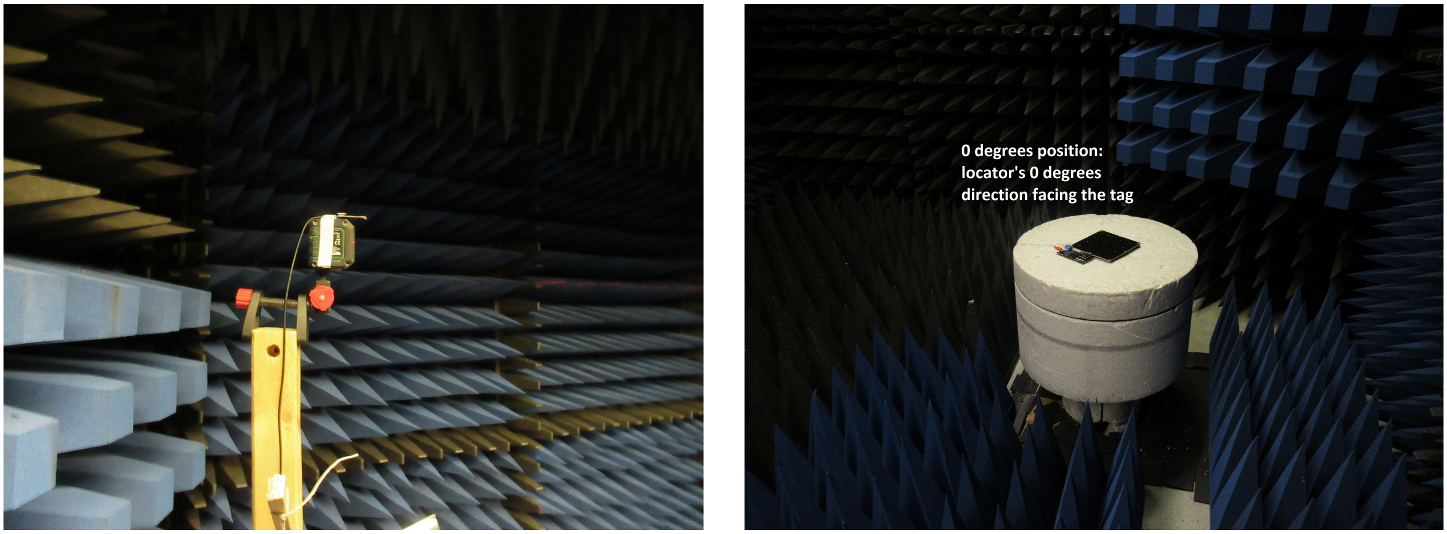


Figure 7.8. Azimuth Angle Measurement: Tag in Horizontal Polarization

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Horizontal distance between tag and locator: 3 m
- Manifold compensation: disabled

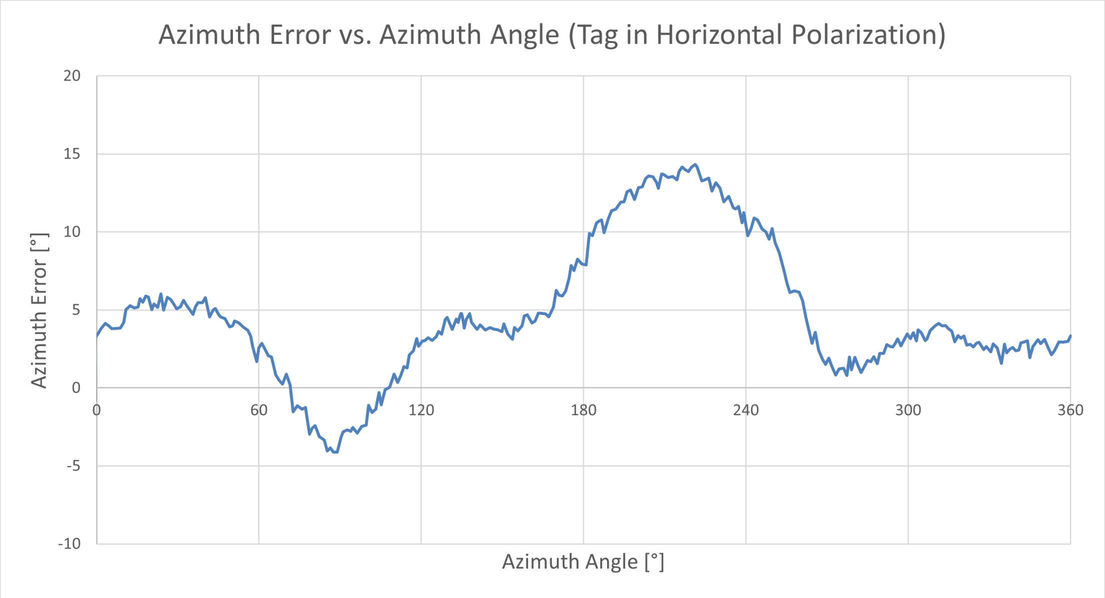
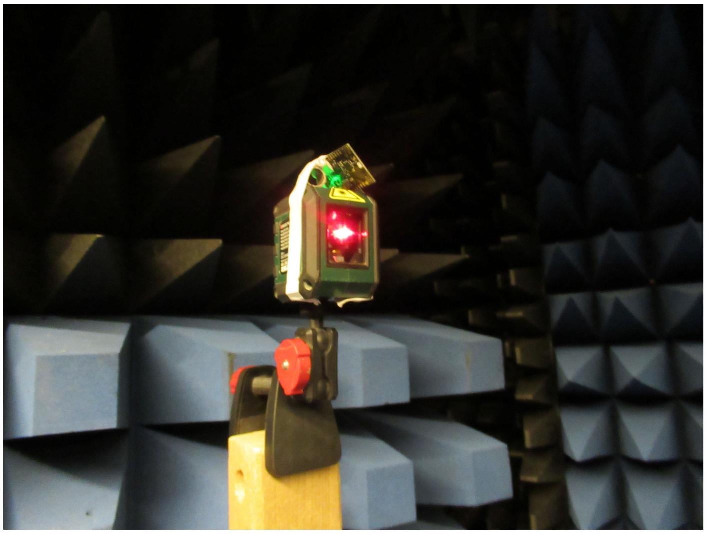


Figure 7.9. Azimuth Error vs. Azimuth Angle: Tag in Horizontal Polarization

- Average azimuth error: ±5.1°
- Best and worst-case azimuth errors: ±0.05° and ±14.3°

7.5.3 Azimuth Angle Measurement: Tag in 45° Orientation (between Horizontal and Vertical Positions)



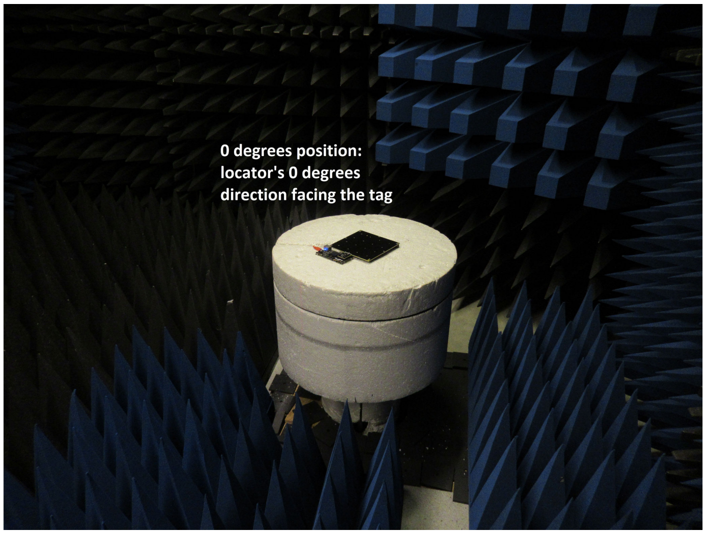


Figure 7.10. Azimuth Angle Measurement: Tag in 45° Orientation

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Horizontal distance between tag and locator: 3 m
- Manifold compensation: disabled

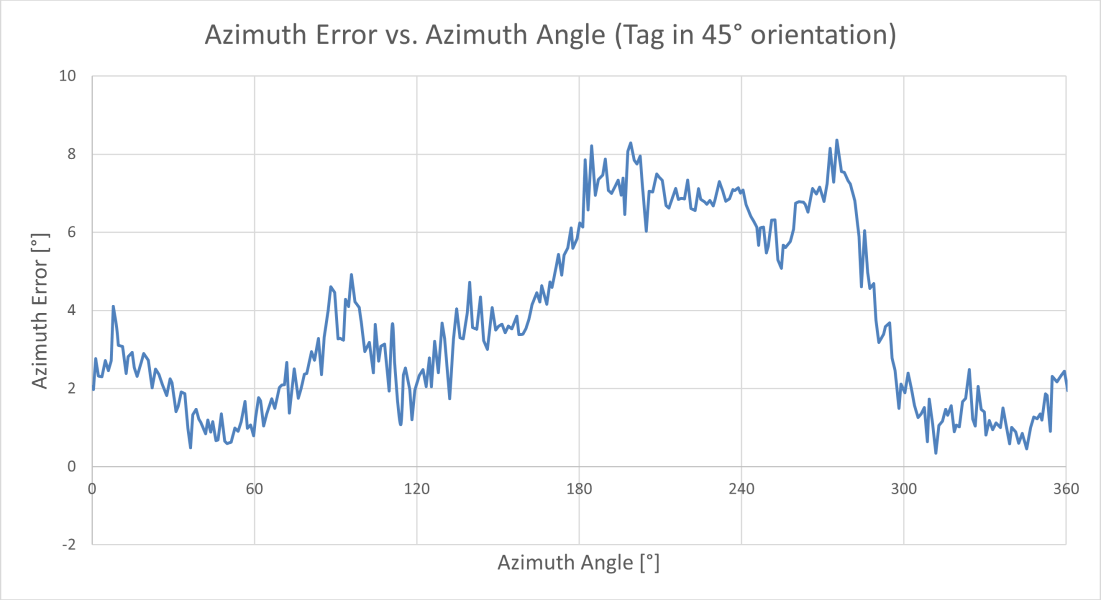


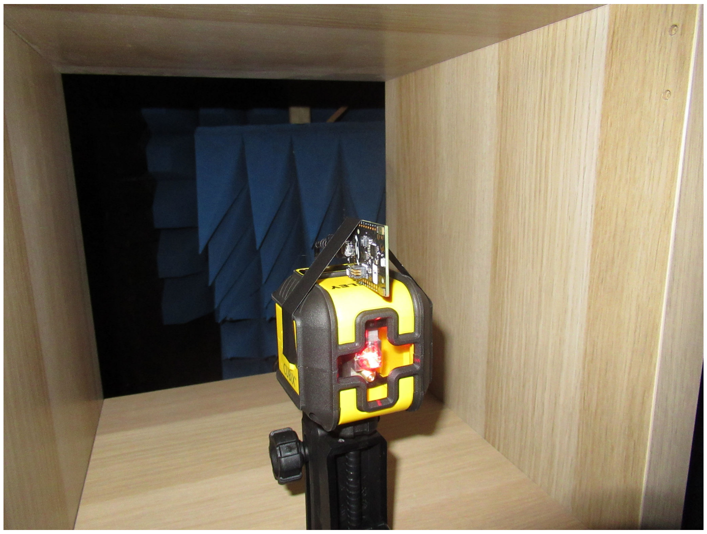
Figure 7.11. Azimuth Error vs. Azimuth Angle: Tag in 45° Orientation

- Average azimuth error: ±3.7°
- Best and worst-case azimuth errors: ±0.3° and ±8.3°

7.5.4 Azimuth Angle Measurement: Summary

- Average azimuth error (average of Horizontal, Vertical and 45° tag orientation): ±3.66°
- Best and worst-case azimuth errors: ±0.02° and ±14.3°

7.5.5 Elevation Angle Measurement: Tag in Vertical Polarization



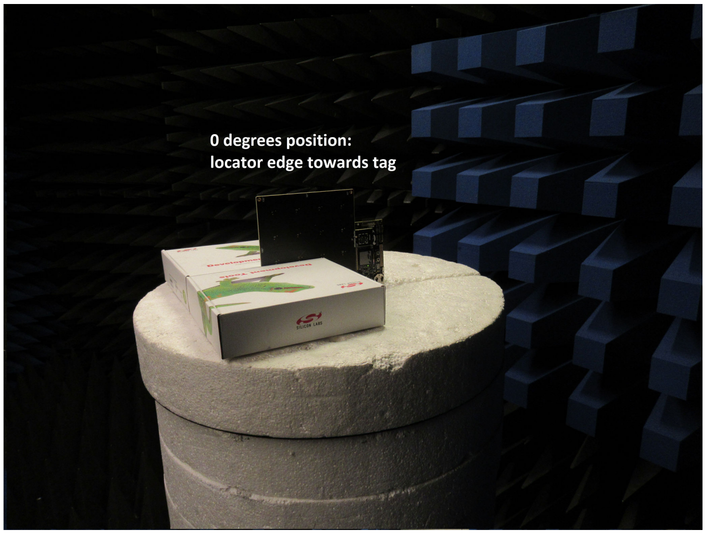


Figure 7.12. Elevation Angle Measurement: Tag in Vertical Polarization

- Locator height from floor: 1.2 m
- Tag height from floor: 1.2 m
- Horizontal distance between tag and locator: 2 m
- Manifold compensation: disabled

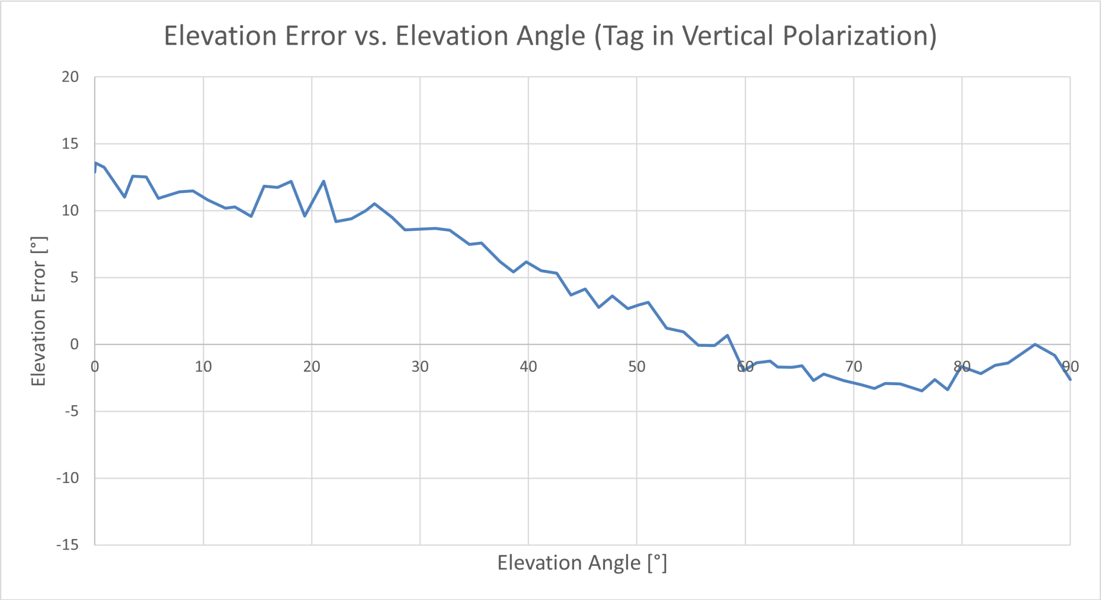


Figure 7.13. Elevation Error vs. Elevation Angle: Tag in Vertical Polarization

- Average azimuth error: ±5.8°
- Best and worst-case azimuth errors: ±0.02° and ±13.6°

7.5.6 Elevation Angle Measurement: Tag in Horizontal Polarization

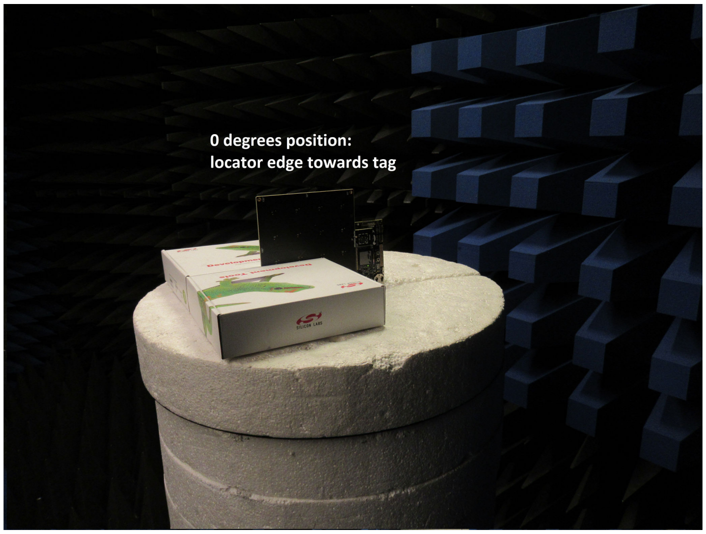


Figure 7.14. Elevation Angle Measurement: Tag in Horizontal Polarization

- Locator height from floor: 1.2 m
- Tag height from floor: 1.2 m
- Horizontal distance between tag and locator: 2 m
- Manifold compensation: disabled

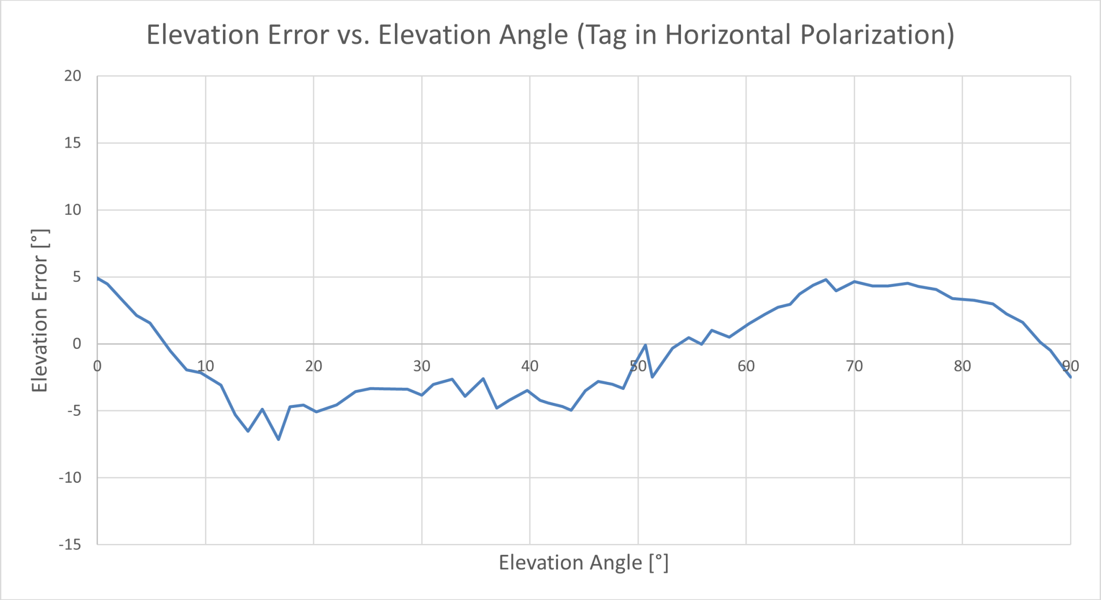


Figure 7.15. Elevation Error vs. Elevation Angle: Tag in Horizontal Polarization

- Average azimuth error: ±3.2°
- Best and worst-case azimuth errors: ±0.02° and ±7.1°

7.5.7 Elevation Angle Measurement: Tag in 45° Orientation (between Horizontal and Vertical Positions)

Figure 7.16. Elevation Angle Measurement: Tag in 45° Orientation

- Locator height from floor: 1.2 m
- Tag height from floor: 1.2 m
- Horizontal distance between tag and locator: 2 m
- Manifold compensation: disabled

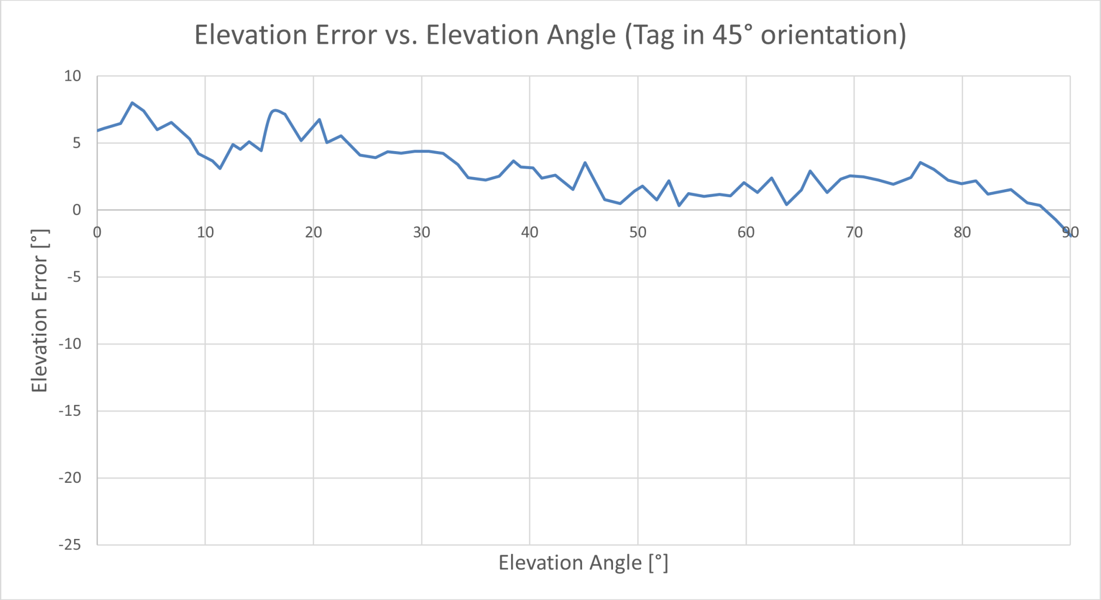


Figure 7.17. Elevation Error vs. Elevation Angle: Tag in 45° Orientation

- Average azimuth error: ±3.0°
- Best and worst-case azimuth errors: ±0.3° and ±8.0°

7.5.8 Elevation Angle Measurement: Summary

- Average elevation error (average of Horizontal, Vertical and 45° tag orientation): ±4.0°
- Best and worst-case elevation errors: ±0.02 ° and ±13.6°

8. Revision History

Revision 0.4

June 2022

- Update to show the 4x4 antenna array with RIS cells.

Revision 0.3

December 2020

- Updated antenna array accuracy measurement results for section 6.1 Antenna Impedance Measurement.

Revision 0.2

June 2020

- Update to reflect antenna array changes.

Revision 0.1

January 2019

- Initial Revision.

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