

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.

Note: This document applies to 2.4 GHz BLE standards for EFR32MG22 and EFR32BG22 devices.

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. Introduction

AoA relies on a single-antenna transmit beacon with continuous tone extension 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.

2. General Antenna 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:

- Single antenna dimensions
- Distance between single antennas
- Position of antenna feed points
- Hybrid coupler dimensions
- Trace lengths and widths between the couplers and the switches
- PCB dimensions (length, width, thickness)
- PCB layer stack-up

If the antenna array structure is 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, as different PCB form factor, different PCB dielectric constant or a nearby dielectric (such as plastic case) might detune the antenna. Similar antenna impedance is expected across the different antennas of the antenna array, which is why checking antenna impedance on one single antenna is sufficient. If antenna mismatch occurs, section [5. 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. Silicon Labs has a 3x3 antenna array as well as a few other options under development. The 4x4 array was chosen as the reference based on the most optimal system performance for smallest array size. If the 4x4 antenna array designed by Silicon Labs cannot be copied to a custom design, contact [Technical Support](#) for more details on other antenna array developments.

3. Antenna Array Parameters in the Firmware for Direction Finding

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

Currently, only the 4x4 array can be selected for the array type as other antenna array types are still in the development phase. 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.

Angle estimation performance strongly depends on other algorithm input parameters such as trace length (phase shift) or PCB dielectric constant. The radiation pattern is not unified across the individual antennas of the array; this information is an input parameter for the calculator as well. Users do not have the capability of adjusting the input parameters (trace length/phase shift, dielectric constant, antenna pattern); those 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 design board (dimensions, stack-up, and dielectric constant). If any of these parameters are changed, a custom firmware might be necessary, in which case, contact [Technical Support](#).

4. Properties of the 4x4 Antenna Array for Direction Finding

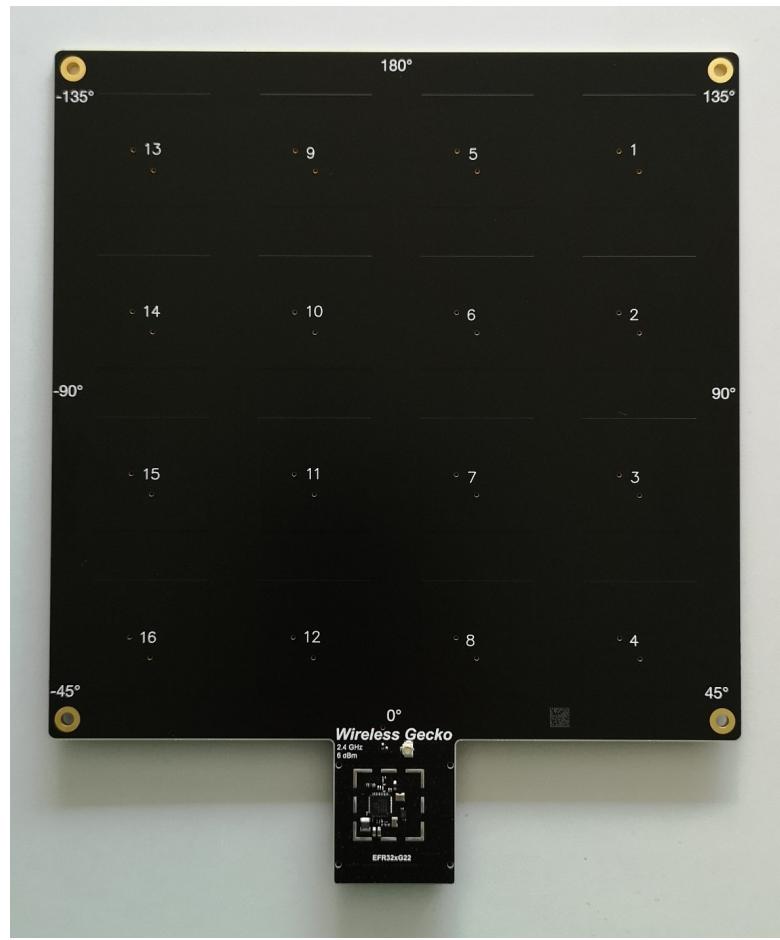


Figure 4.1. BRD4185A Radio Board (4x4 Antenna Array)

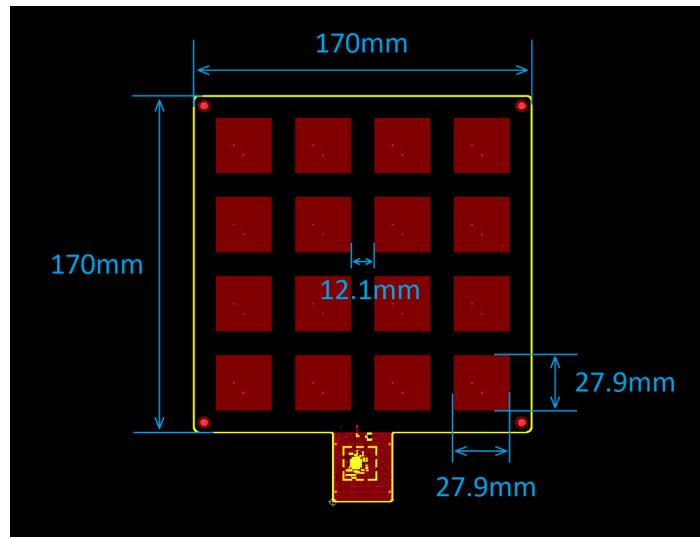


Figure 4.2. BRD4185A Radio Board Top Layer (4x4 Antenna Array)

The 4x4 array consists of rectangular patch antennas with 27.9×27.9 mm size placed 12.1 mm away from each other. The resulting antenna array dimension is 170 x 170 mm.

4.1 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.

4.2 Antenna Type: Rectangular Shape Patch Antennas

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.

4.3 Polarization: Circular Polarized Antenna

Circular polarization is needed so that the antenna will not be sensitive to the polarization of the incoming signal.

Circular polarization is realized with a Hybrid Coupler (see [Figure 4.4 Hybrid Coupler on page 7](#)), which creates two signals with 90° phase difference. These signals are connected to the antenna feed points. Angle estimation accuracy strongly depends on circular polarization, therefore, it is critical to maintain circular polarization across the entire 2.4 GHz Bluetooth band. Due to the Hybrid Coupler solution, circular polarization bandwidth is far exceeding the 2.4 GHz Bluetooth band, thus a slight detune of the antenna will not affect circular polarization nor angle estimation accuracy.

4.4 Single Antenna

All elements in the antenna array are identical. The single antennas are rectangular shape patch antennas with two feed points. The feed point locations for the antennas are chosen so that the antenna impedance at both points are 50 Ω.

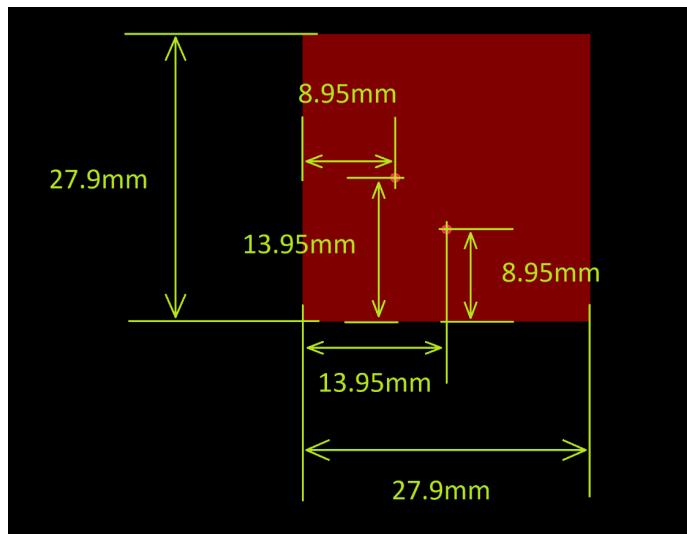


Figure 4.3. Single Antenna Top Layer

4.5 Hybrid Coupler

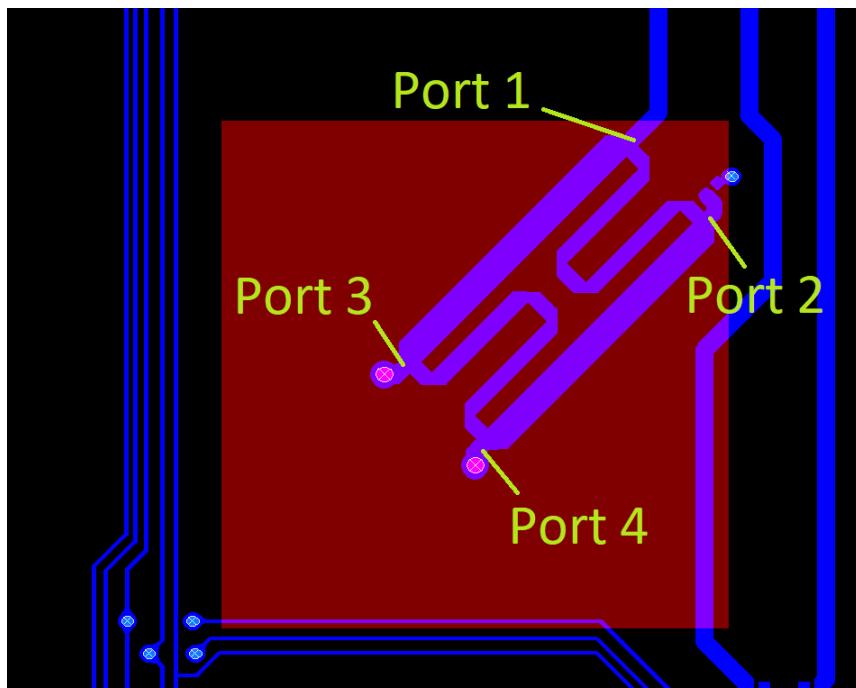


Figure 4.4. Hybrid Coupler

The hybrid coupler should be routed on the bottom layer (opposite layer as the patch antennas). The optimal trace impedance for the coupler is set by the trace lengths, trace width, and the distance between the bottom layer and the ground layer beneath the coupler.

Port 1 is connected to the RF switch, port 3 and port 4 are connected to the antenna feed points, while port 2 is terminated by a $50\ \Omega$ resistor to the ground. The $\lambda/4$ transmission line between ports 3 and 4 creates a 90° phase shift between the antenna feed points, which allows for circular polarization.

For ideal operation of the hybrid coupler, it is recommended to copy the structure as it is shown on the PCB4185A layout (especially for transmission line length and width, and the distance between the bottom layer and the inner ground layer).

4.6 Antenna Return Loss, Radiation Pattern

Individual antennas of the array are expected to be similar in terms of antenna impedance and return loss:

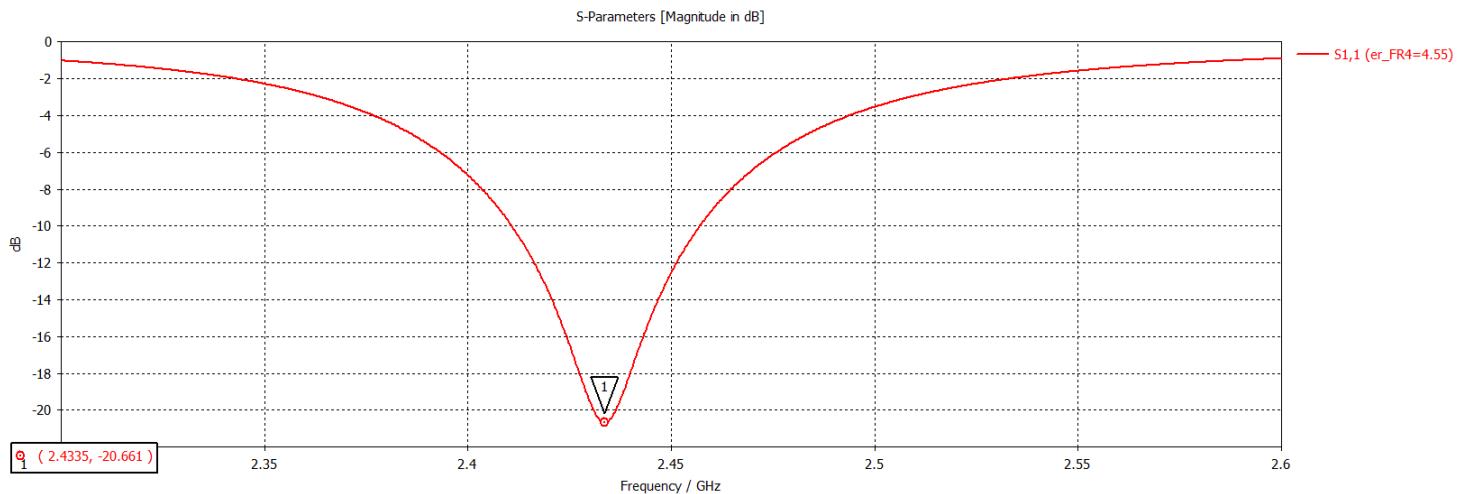


Figure 4.5. Single Antenna S11

As shown in the figure above, the antenna resonance is around 2.43 GHz. Antenna impedance should be optimized on a custom design so that the resonance is around the middle of the Bluetooth band (2.402-2.48GHz).

Antenna radiation pattern, however, is not unified across the antenna array elements. The response of center and edge elements of the array are different. This information is stored for each antenna and used as an input for the calculator.

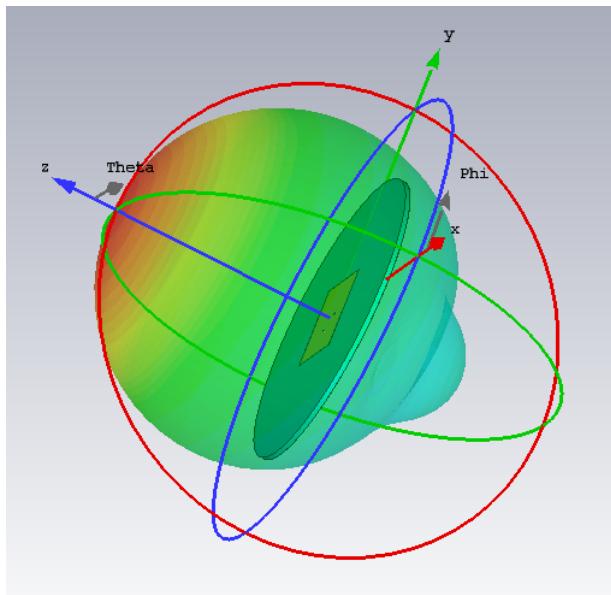


Figure 4.6. 3D Radiation Pattern for Single Antenna

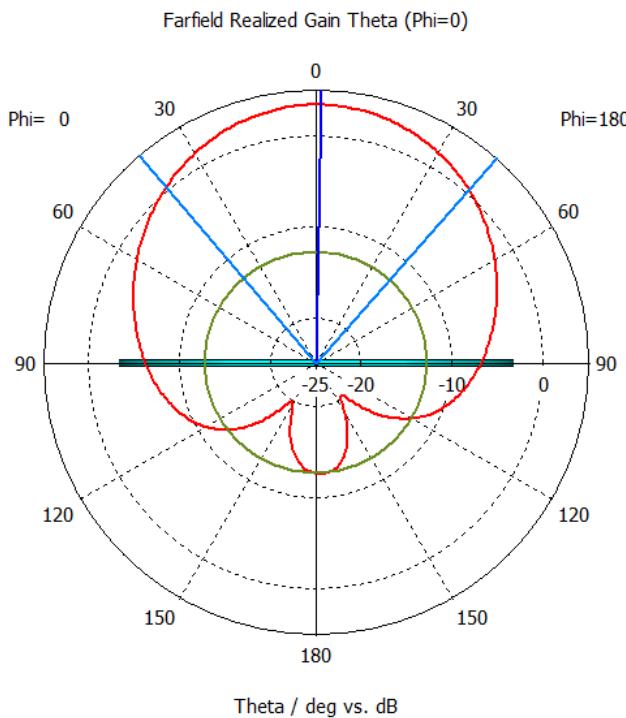


Figure 4.7. 2D Radiation Pattern for Single Antenna

Note: Despite the solid ground metal layer below the antenna array, the antenna radiation pattern has side lobes from the bottom side. To eliminate wrong position calculations, place the tag above the plane of the top side of the PCB.

4.7 PCB Material, Thickness, Relative Dielectric Constant

The 4x4 antenna array is designed on an FR-4 PCB with 2.34 mm thickness in order to extend the BW for the narrowband patch antenna. The relationship between the PCB thickness and antenna BW for rectangular patch antennas is:

$$BW \approx \frac{f}{Q} \approx \frac{4f^2 h}{c\sqrt{\epsilon_r}}$$

Where f is the frequency, Q is the Q factor of the antenna, h = 1.675 mm is the distance between the antenna and PCB Layer 3 (ground), c is the speed of light, and ϵ_r is the PCB relative permittivity.

The recommended relative dielectric constant is 4.55. The effect of dielectric constant variation is detailed in section [4.11 Effect of Relative Dielectric Constant Variation](#).

4.8 PCB Layer Stack-up

- Top layer: Patch antennas are designed on this layer
- Inner layer 2: No trace or ground metal should be added on this layer in the antenna array area
- Inner layer 3: Unified GND metal plane
- Bottom layer: $50\ \Omega$ RF traces, hybrid coupler, RF switches and switch control signal traces (GPIOs) are routed on this layer.

Note: Silicon Labs antenna array reference design uses blind vias to connect the bottom layer ground to the common ground of Layer 3. Make sure to not connect the top layer patch antennas to the ground.

L1	===== =====	35 um Cu (ca) After plating
- - - -	PREPREG - 7628-45 - - -	180 um
- - - -	ETCHED INNER FR4 UK 0.2	200 um
- - - -	PREPREG - 7628-45 - - -	180 um
L2	===== =====	35 um Cu
- - - -	High Tg 1.08mm 35um/35um	1080um - - CENTER - -
L3	===== =====	35 um Cu
- - - -	PREPREG - 7628-45 - - -	180 um
- - - -	ETCHED INNER FR4 UK 0.2	200 um
- - - -	PREPREG - 7628-45 - - -	180 um
L4	===== =====	35 um Cu

Figure 4.8. BRD4185A Radio Board PCB Layer Stack-Up

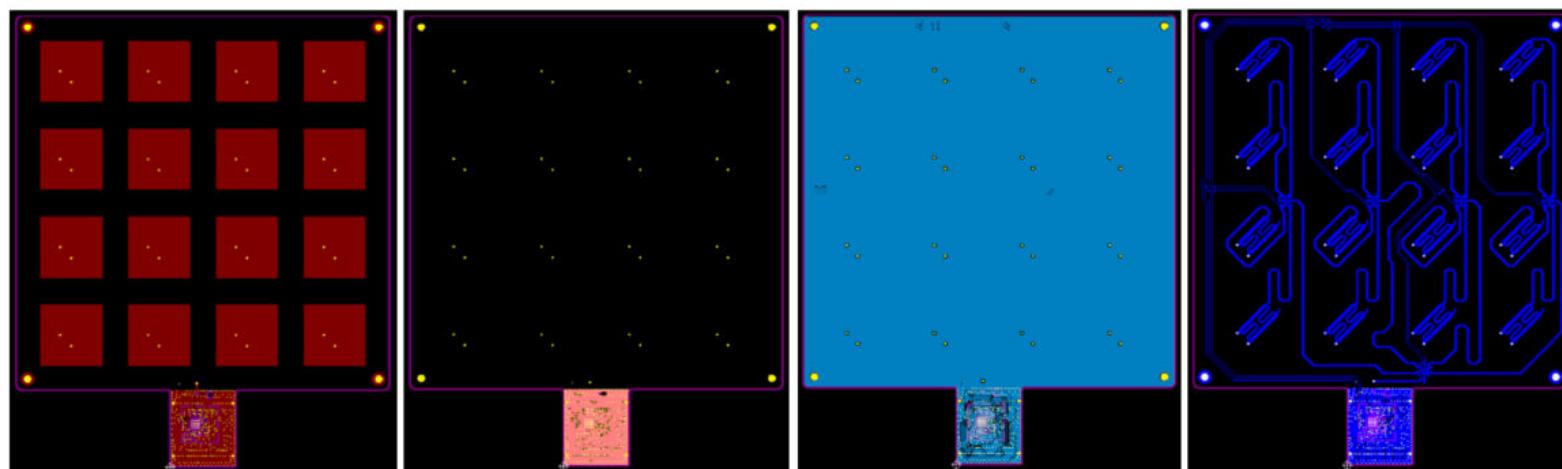


Figure 4.9. BRD4185A Radio Board PCB Layers

4.9 RF Switch Type

RF switches in the 4x4 antenna array reference design are SP4T type. The number of switches in the antenna array is $4 + 1$. Each individual switch needs to be controlled by two GPIOs; the overall number of GPIOs for controlling the switches is four (the switches connected directly to the single antennas are controlled simultaneously).

The type of RF switch is SKY13575-639LF from Skyworks, which was selected carefully for switching speed and termination impedance parameters.

4.10 Plastic Case Effect on Antenna Impedance and Radiation Pattern

Typical applications utilize a plastic box around the antenna array; therefore, the effect of a nearby plastic case should be investigated carefully.

The distance from the antenna array bottom layer is not critical as the bottom layer of the PCB is covered with ground metal. However, the plastic case distance from the top (antenna) layer can influence antenna impedance and radiation pattern.

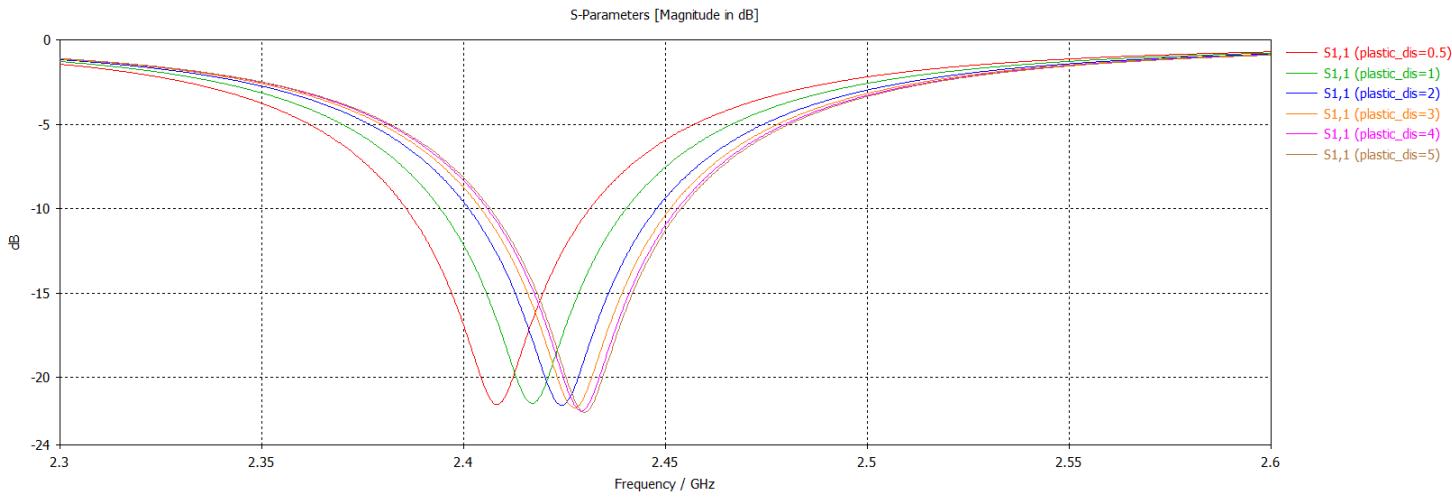


Figure 4.10. Plastic Case Distance (dimension: mm) vs. Antenna S11

As the figure above shows, antenna impedance is detuned only if the plastic case is placed closer than 2-3 mm to the antennas. Above 2-3 mm distance, S11 variation is negligible.

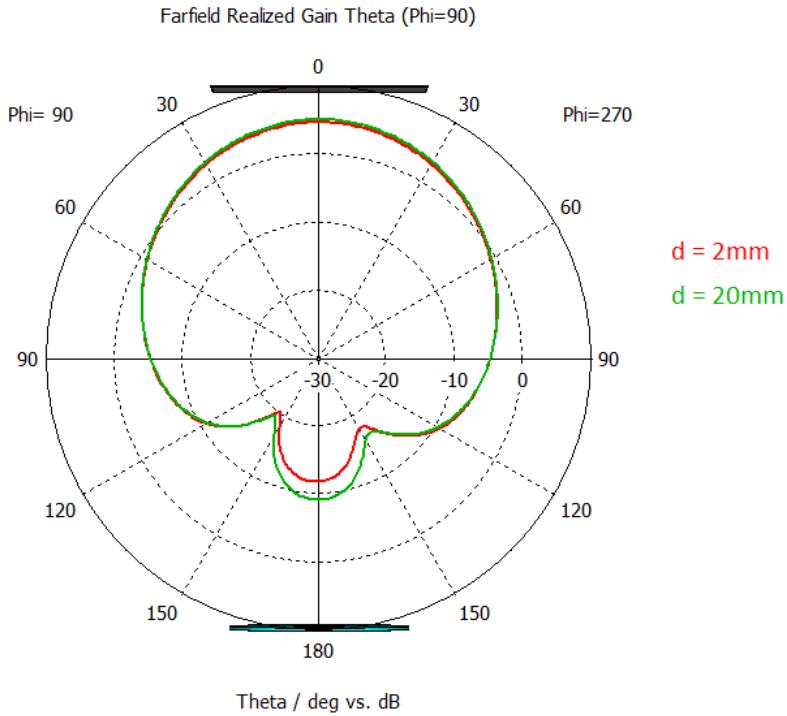


Figure 4.11. Antenna Pattern of a Single Antenna (2 mm vs. 20 mm Separation)

As the figure above shows, the plastic case distance from the antenna array has minimal effect on the antenna pattern.

General recommendation for plastic case placement: Keep 5 mm distance from the antenna array minimum. It is important that the plastic distance should be the same for each antenna element, so that the potential effect on each antenna is similar.

General recommendation for any other dielectric placement near the antenna array: Keep 20 mm distance from the antenna array minimum.

4.11 Effect of Relative Dielectric Constant Variation

The figure below shows how PCB FR4 dielectric constant has a direct effect on the antenna resonance frequency.

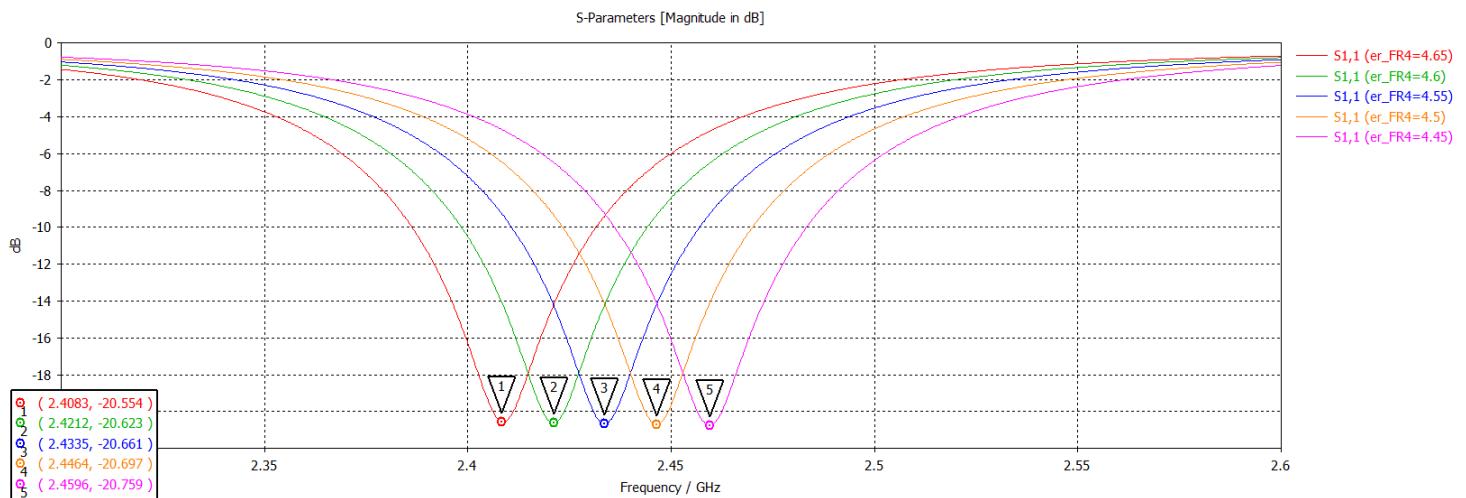


Figure 4.12. S11 vs FR4 Dielectric Constant

Based on the above figure, ϵ_r dielectric constant variation is acceptable between 4.45 and 4.6 in order to minimize mismatch loss at channel edges.

5. Antenna Impedance Measurement and Tuning

As mentioned in section [2. General Antenna Recommendations](#), it is recommended to verify antenna impedance of the single antennas on a custom design. Antenna impedance should be measured at one of the antenna feed points on the bottom side of the PCB due to the symmetrical locations of Feed point 1 and Feed point 2 within a single antenna. Similar antenna impedance is expected across the individual antennas, therefore, it is sufficient to check antenna impedance only on one antenna.

Two modifications are necessary on a custom design compared to the antenna array on the BRD4185A reference board to measure antenna impedance of a single antenna:

1. The bottom side of the antenna array does not utilize any ground copper, therefore, a small piece of ground copper (~3x3 mm) with a ground via should be added near the antenna feed points on the bottom layer during the PCB layout design (shown with green on [Figure 5.1 Antenna Impedance Measurement Point on page 13](#)). This small piece of ground will not affect the antenna parameters or angle estimation accuracy but allows for connecting the ground reference of the coaxial cable used for antenna impedance measurements. Because the measurement is required only on one antenna, adding the small piece of ground near the antenna feed points is required for only one of the antennas.
2. It is important to disconnect the hybrid coupler near the antenna feed point to avoid its effect on impedance measurement. Basically, there are two options to disconnect the hybrid coupler:
 - Cutting the trace between the feed point and the coupler (yellow line on the figure below).
 - Adding a $0\ \Omega$ resistor to connect the feed point to the coupler by design, and removing this resistor during the impedance measurement.

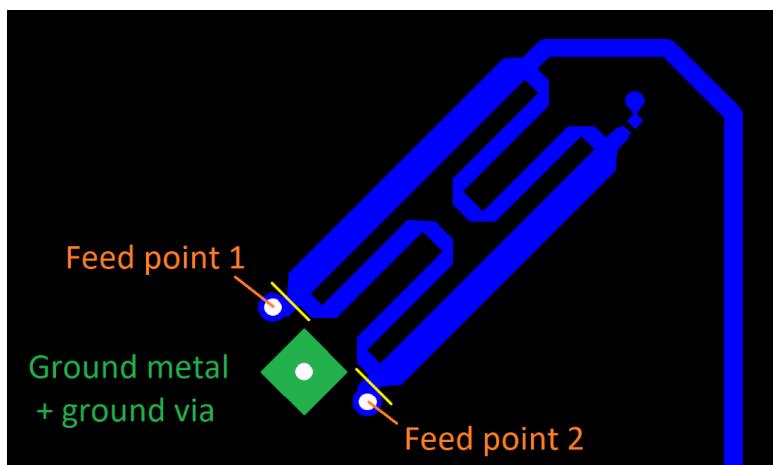


Figure 5.1. Antenna Impedance Measurement Point

As detailed in section [4.10 Plastic Case Effect on Antenna Impedance and Radiation Pattern](#), antenna impedance can be sensitive to nearby metal or plastic objects, that is why it is strongly recommended to measure antenna impedance in the way it will be used in the final application (with plastic case, battery, etc.)

A detuned antenna resonance frequency can be compensated by adjusting the following parameters:

- Keep the minimum recommended distance for dielectrics as described in section [4.10 Plastic Case Effect on Antenna Impedance and Radiation Pattern](#).
- Keep the PCB relative permittivity in the recommended region of 4.45 and 4.6 as described in section [4.11 Effect of Relative Dielectric Constant Variation](#).
- Adjust patch antenna dimensions.

If adjusting patch antenna dimensions is needed to achieve optimal antenna resonance frequency, contact [Technical Support](#).

6. 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 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 3.1 and RTL library API: SL_RTL_AOX_MODE_REAL_TIME_BASIC.

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

- Locator: BRD4185A Rev A01
- Tag: BRD4184A Rev A02 (except for section [6.3 Environment 3 \(1 tag, 6 locators, static measurement\)](#) where the tag was BRD4182A Rev B05)

6.1 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 m²
- 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

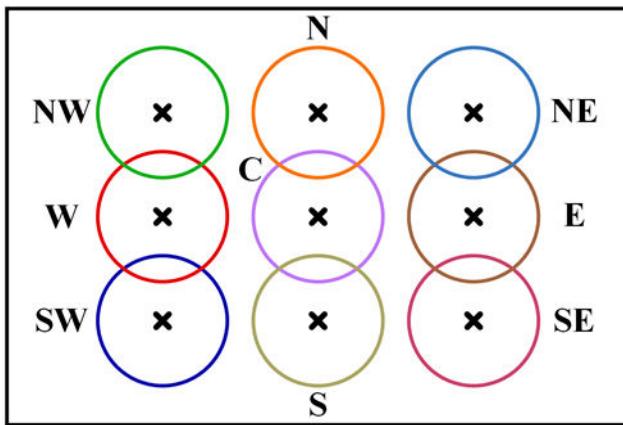
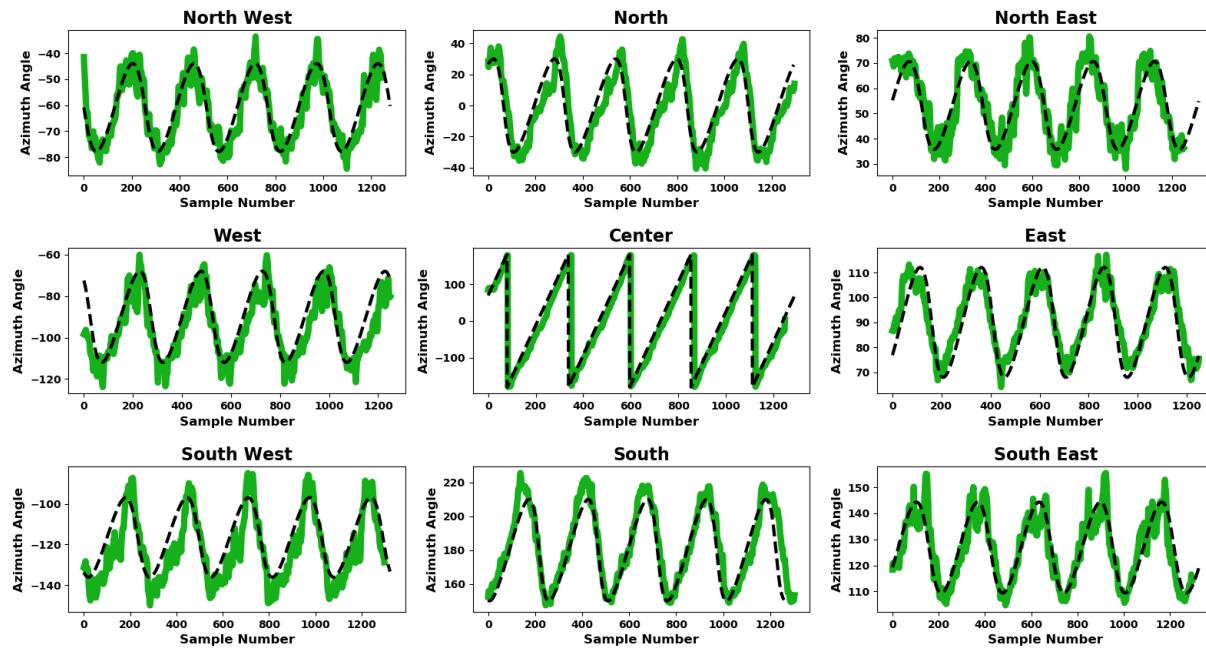


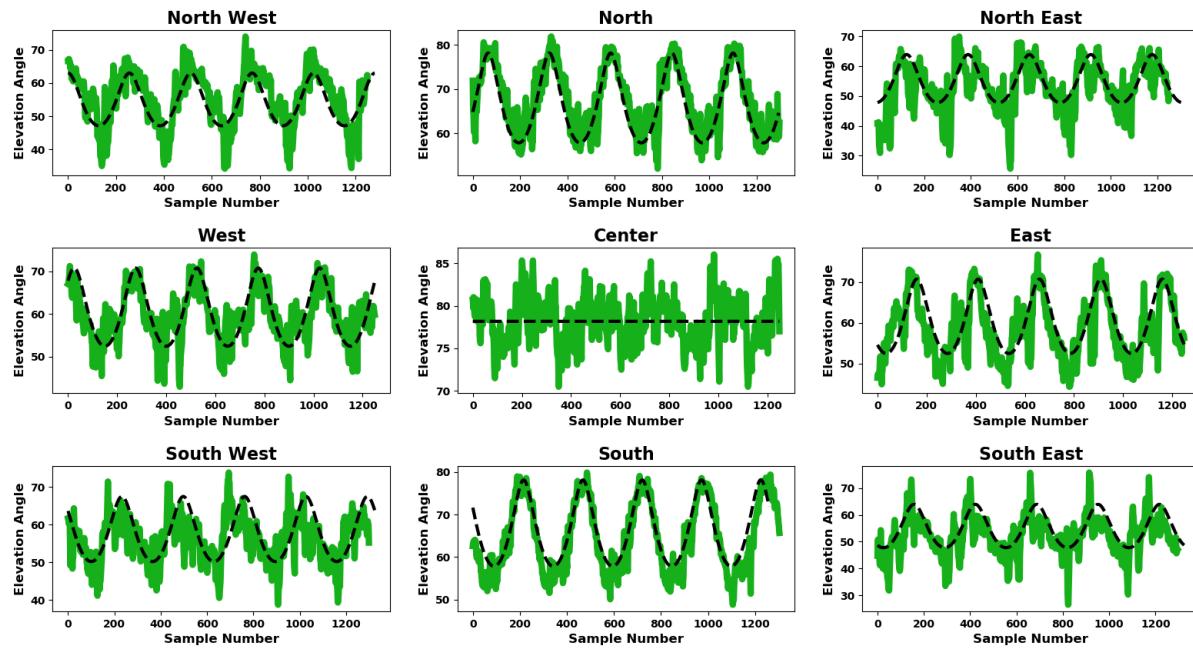
Figure 6.1. Turntable at 9 Different Positions

Azimuth Angle Measurement Results:

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

Figure 6.2. Azimuth Angle Measurement Results**Elevation Angle Measurement Results:**

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

**Figure 6.3. Elevation Angle Measurement Results**

6.2 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: 27 m²
- Tag position is fixed
- Locator in the middle of a turntable
- Locator is rotated with the turntable
- Average azimuth error: +/- 3°
- Average elevation error at 3.5 m away from the locator: +/- 7°

6.3 Environment 3 (1 tag, 6 locators, static measurement)

- Location: Office environment, open space, lots of desks, shelves, and cubicles in the measurement area
- Locator height from floor: 2.8 m
- Tag height from floor: 1.5 m
- Testing range: 120 m²
- Average azimuth error: +/- 3.8°
- Average elevation error at 5 m away from the locator: +/- 7.2°
- Average elevation error at 13 m away from the locator: +/- 3.7°

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

6.4 Environment 4 (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 m²
- Distance between locators and tag is varying between 2 and 3 meters
- Average azimuth error: +/- 5.5°
- Best and worst-case azimuth errors: +/- 1.1° and +/- 11.3°
- Average elevation error: +/- 3.9°
- Best and worst-case elevation errors: +/- 2.6° and +/- 4.9°

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

6.5 Environment 5 (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 m²
- 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
- Average azimuth error: +/- 17.8°
- Best and worst-case azimuth errors: +/- 5.5° and +/- 39.3°
- Average elevation error: +/- 7.6°
- Best and worst-case elevation errors: +/- 5.2° and +/- 9.5°

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

6.6 Environment 6 (1 tag, 1 locator, locator on turntable)

- Location: anechoic chamber, no multipath
- Testing range: 24 m²

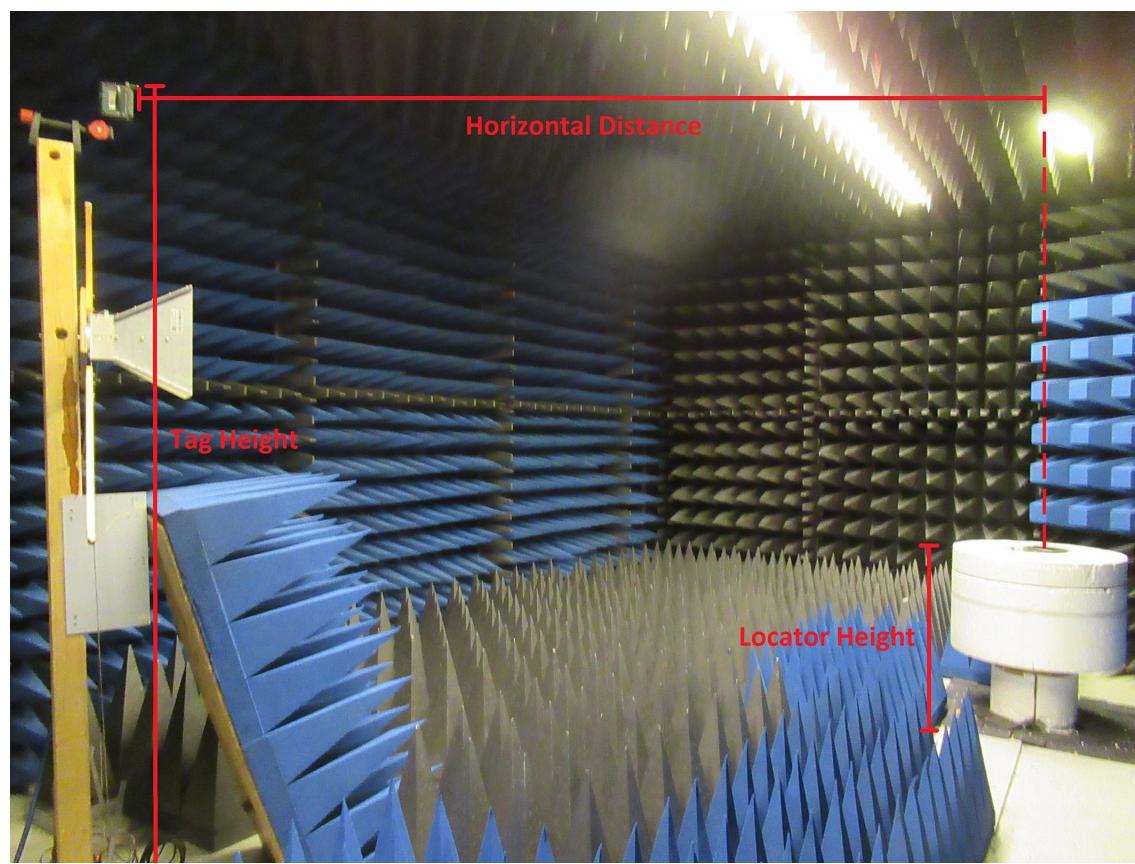


Figure 6.4. Azimuth Angle Measurement Setup

Azimuth Angle Measurement Method:

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

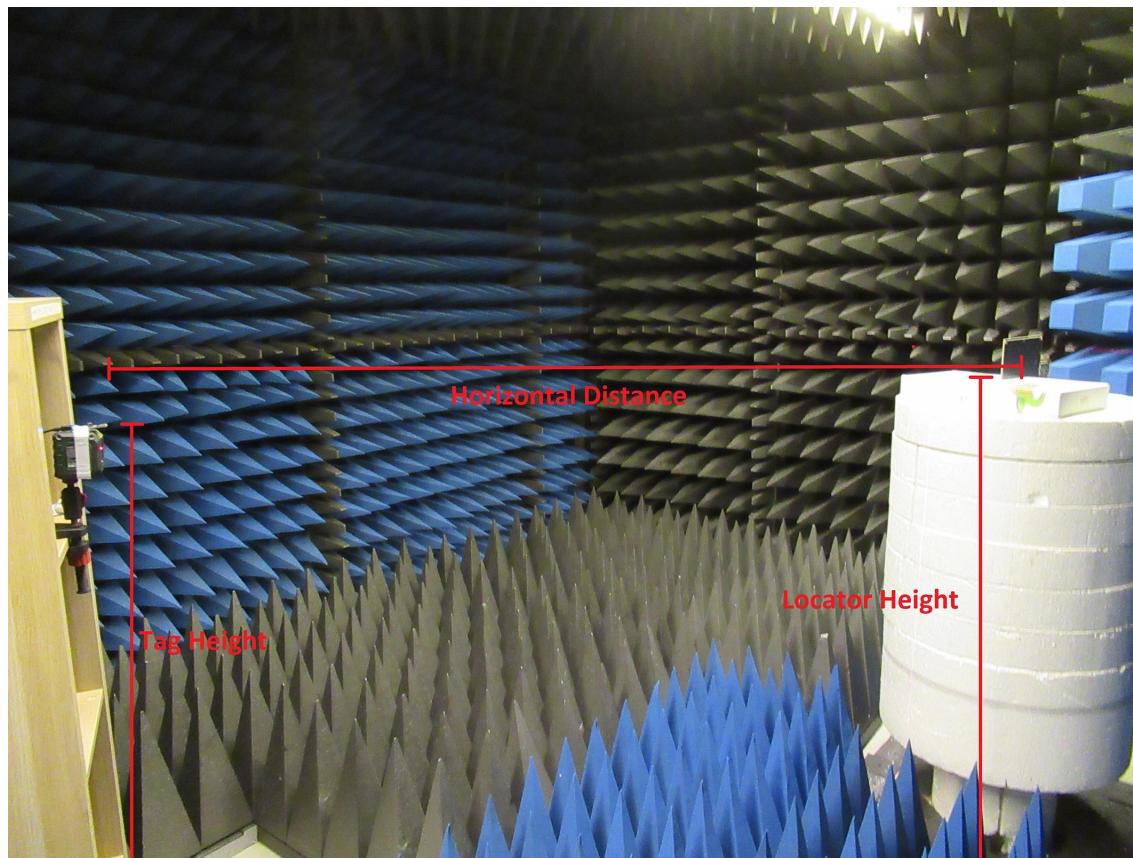


Figure 6.5. Elevation Angle Measurement Setup

Elevation Angle Measurement Method:

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

6.6.1 Azimuth Angle Measurement - Tag in Vertical Polarization

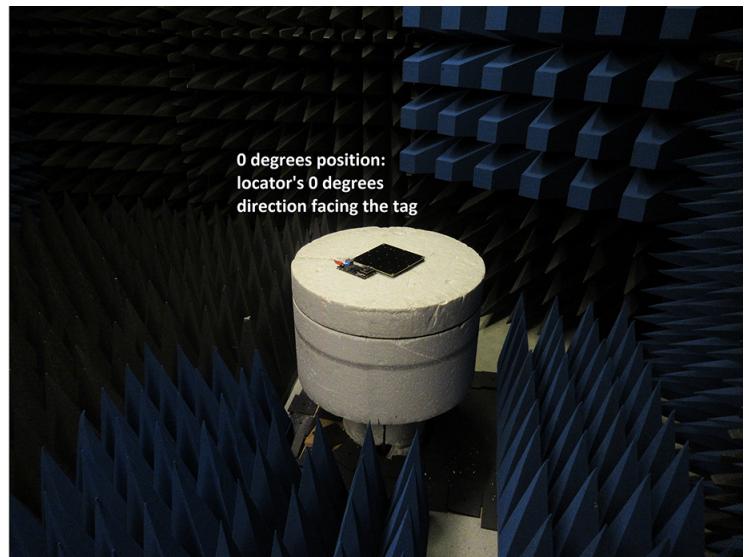
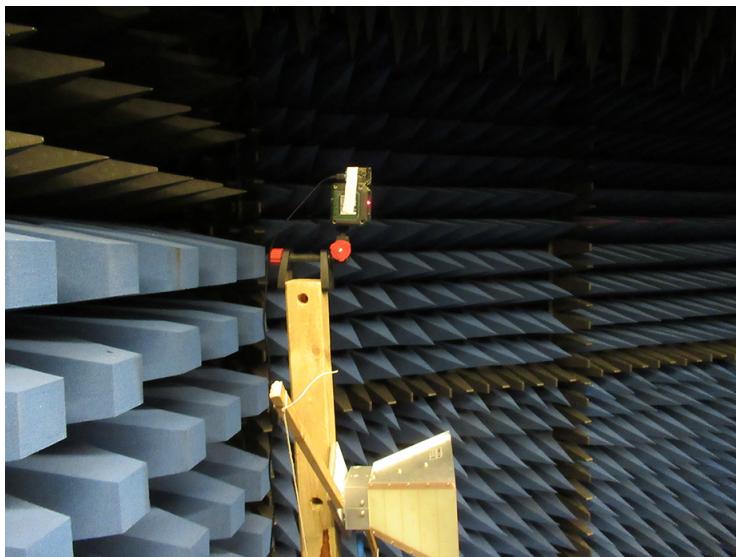


Figure 6.6. Azimuth Angle Measurement - Tag in Vertical Polarization

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Distance between tag and locator: 3 m

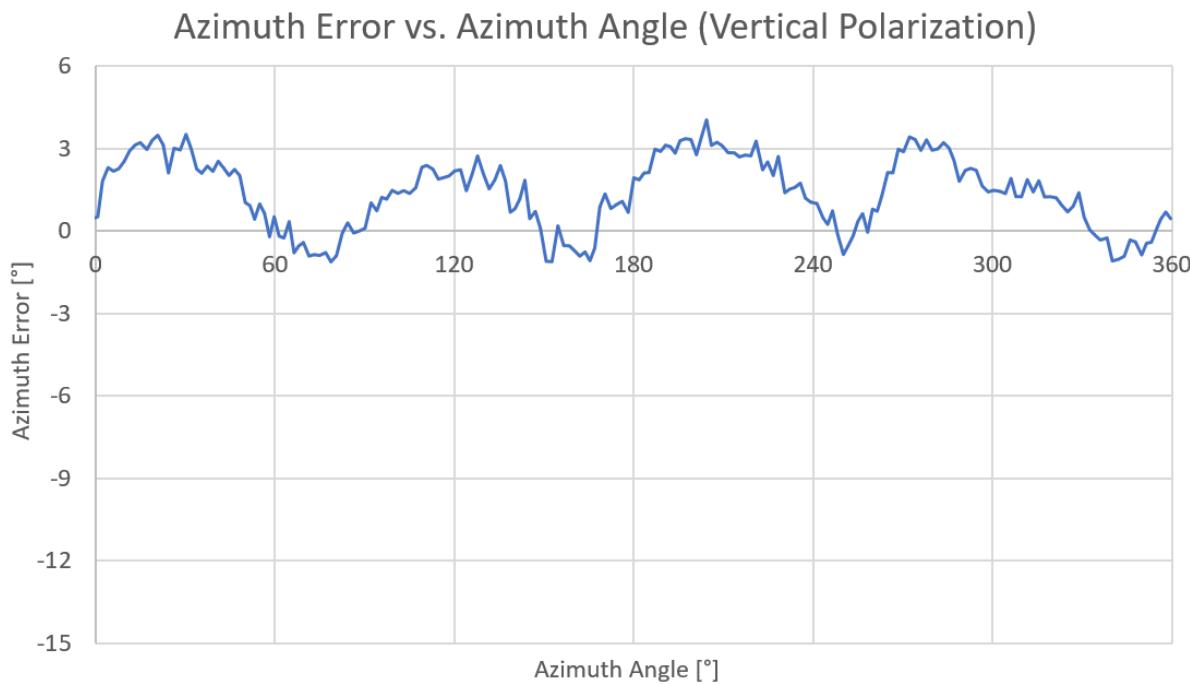


Figure 6.7. Azimuth Error vs. Azimuth Angle - Tag in Vertical Polarization

- Average azimuth error (Tag in Vertical polarization): +/- 1.6°
- Best and worst-case azimuth errors: +/- 0° and +/- 4°

6.6.2 Azimuth Angle Measurement - Tag in Horizontal Polarization

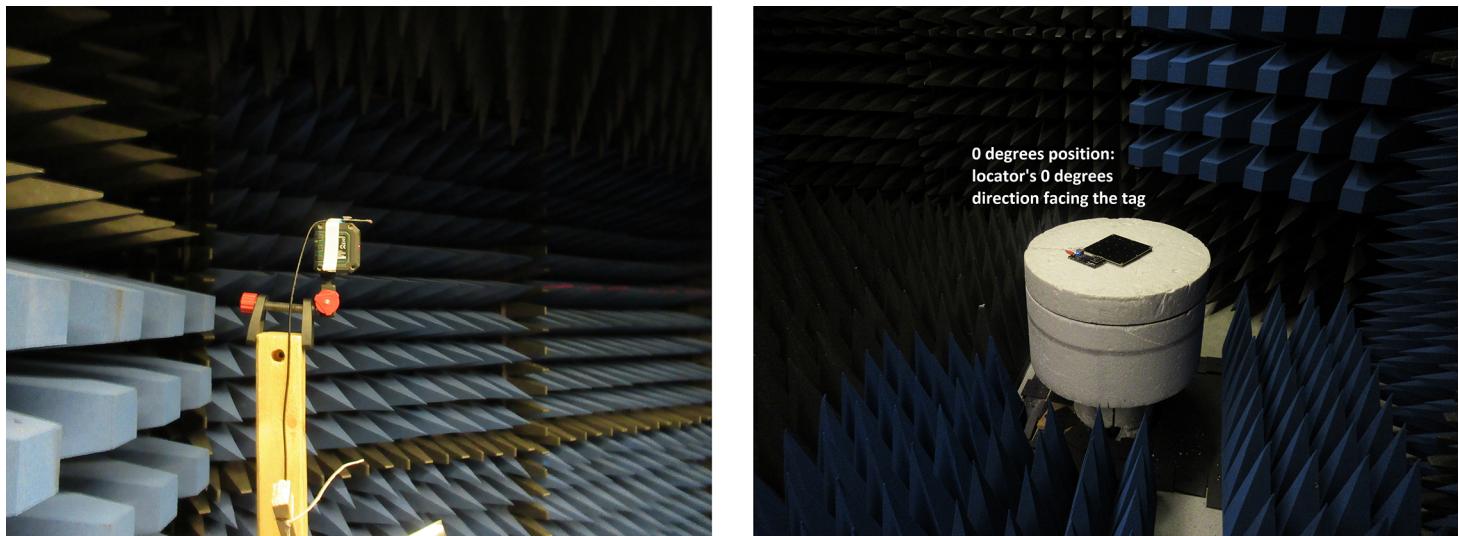


Figure 6.8. Azimuth Angle Measurement - Tag in Horizontal Polarization

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Distance between tag and locator: 3 m

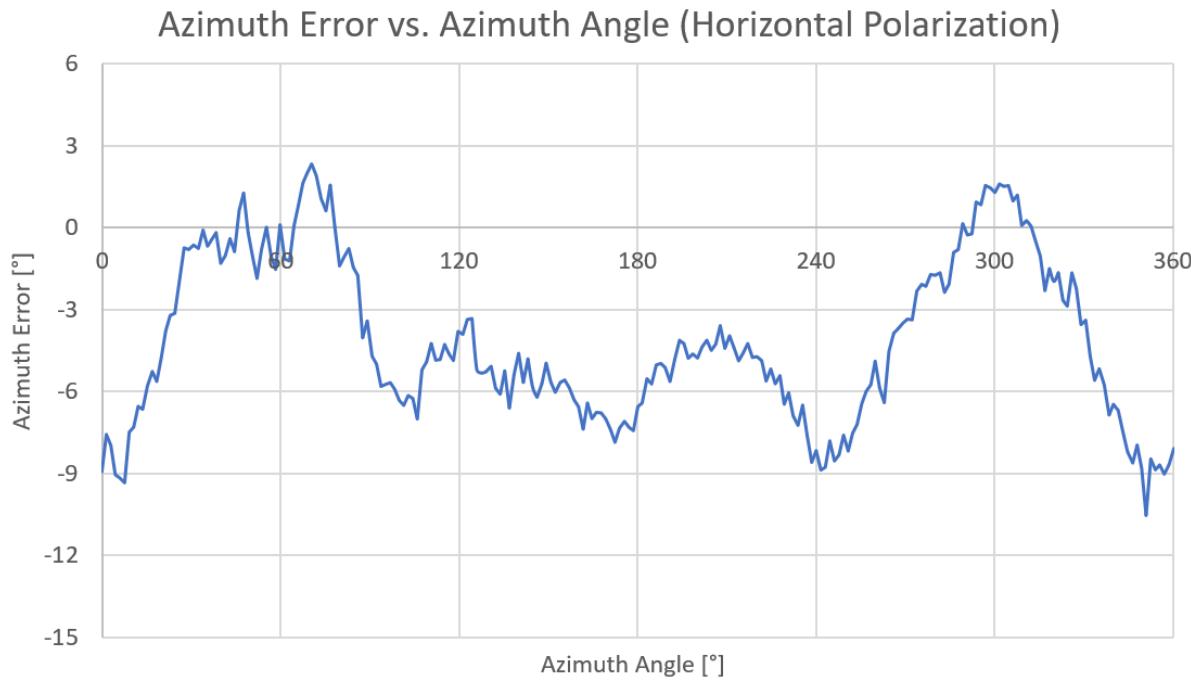


Figure 6.9. Azimuth Error vs. Azimuth Angle - Tag in Horizontal Polarization

- Average azimuth error: +/- 4.4°
- Best and worst-case azimuth errors: +/- 0° and +/- 10.5°

6.6.3 Azimuth Angle Measurement - Tag in 45° Orientation (between Horizontal and Vertical positions)

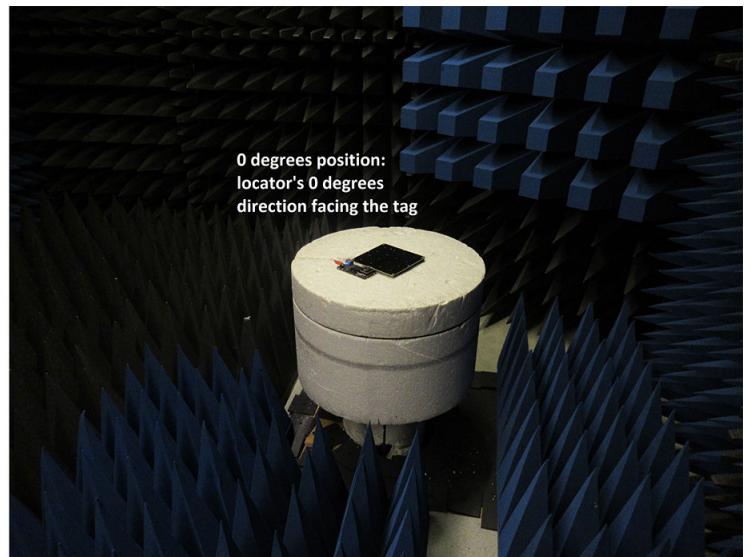
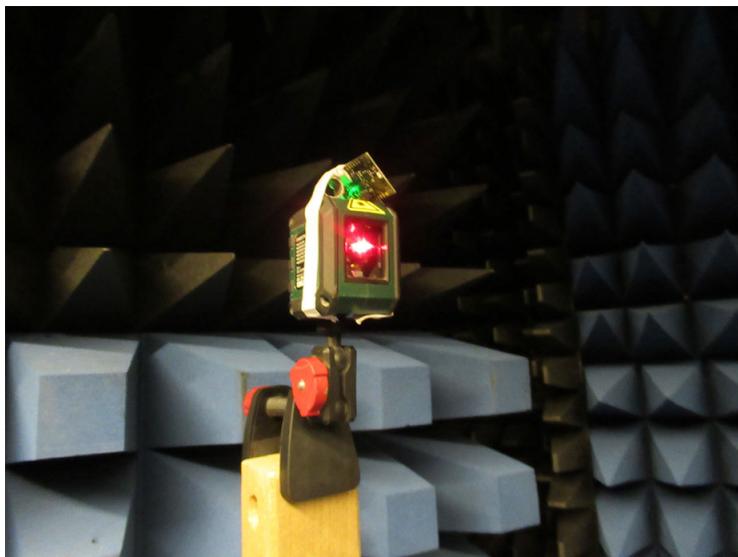


Figure 6.10. Azimuth Angle Measurement - Tag in 45° Orientation

- Locator height from floor: 0.7 m
- Tag height from floor: 1.8 m
- Distance between tag and locator: 3 m

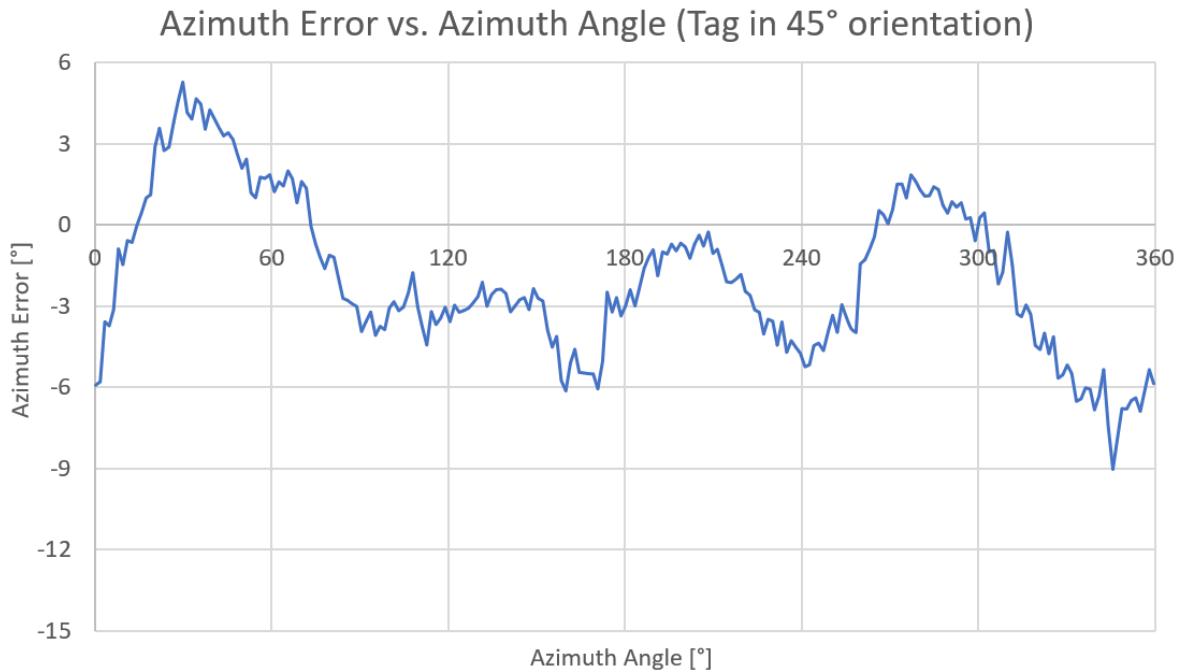


Figure 6.11. Azimuth Error vs. Azimuth Angle - Tag in 45° Orientation

- Average azimuth error: +/- 3.1°
- Best and worst-case azimuth errors: +/- 0° and +/- 9°

6.6.4 Azimuth Angle Measurement - Summary

- Average azimuth error (average of Horizontal, Vertical and 45° tag orientation): +/- 3°
- Best and worst-case azimuth errors: +/- 0° and +/- 10.5°

6.6.5 Elevation Angle Measurement - Tag in Vertical Polarization

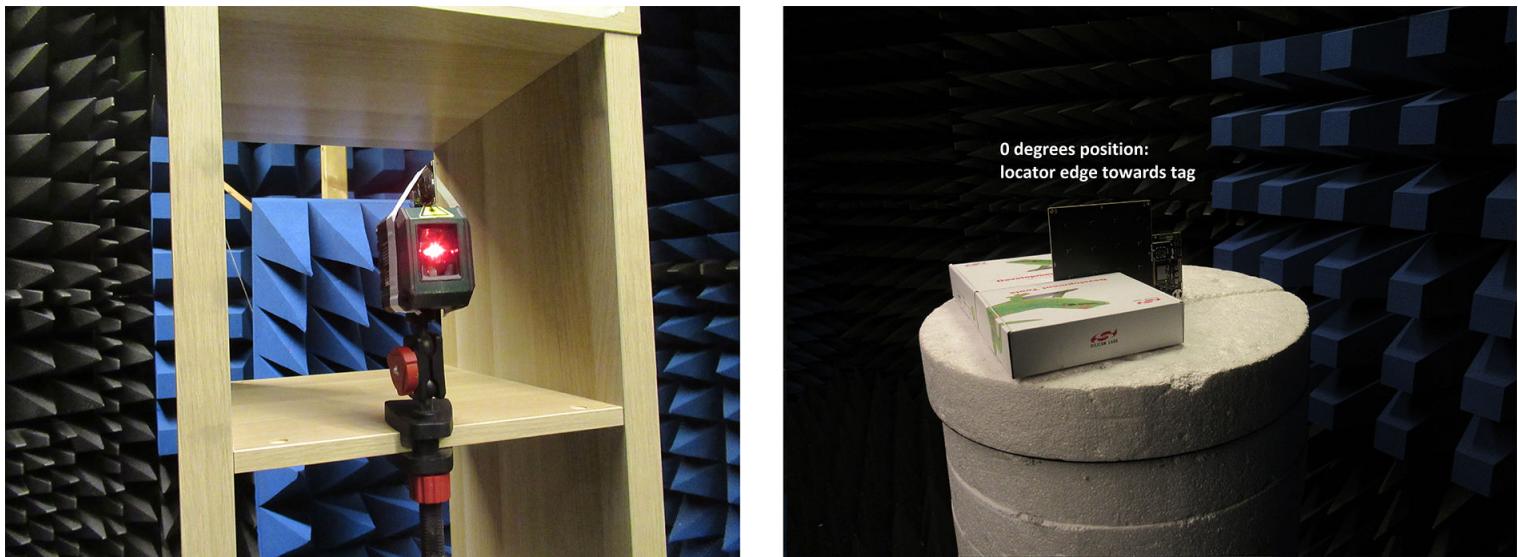


Figure 6.12. Elevation Angle Measurement - Tag in Vertical Polarization

- Locator height from floor: 1.2 m
- Tag height from floor: 1.2 m
- Distance between tag and locator: 2 m

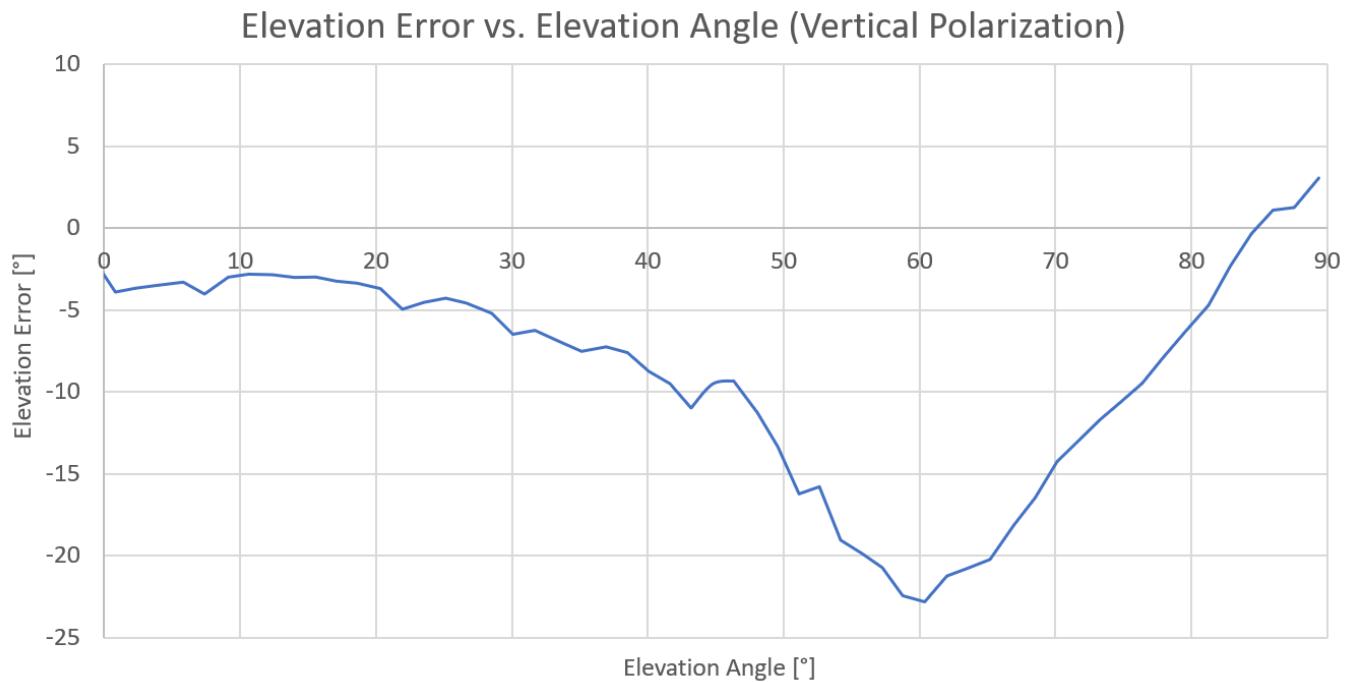


Figure 6.13. Elevation Error vs. Elevation Angle - Tag in Vertical Polarization

- Average elevation error: +/- 8.7°
- Best and worst-case elevation errors: +/- 0.3° and +/- 22.8°

6.6.6 Elevation Angle Measurement - Tag in Horizontal Polarization

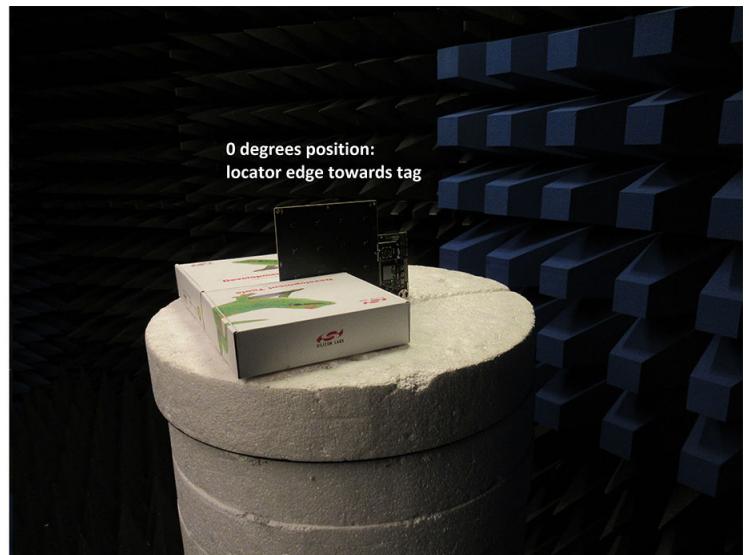


Figure 6.14. Elevation Angle Measurement - Tag in Horizontal Polarization

- Locator height from floor: 1.2 m
- Tag height from floor: 1.2 m
- Distance between tag and locator: 2 m

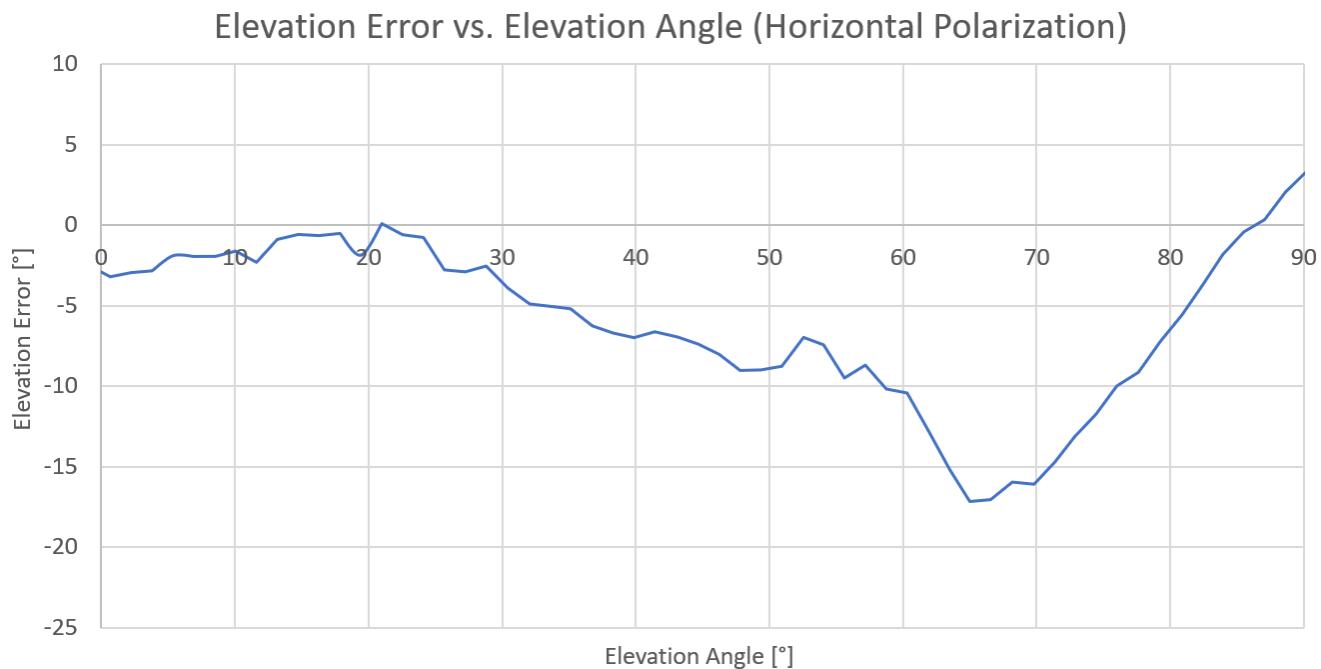


Figure 6.15. Elevation Error vs. Elevation Angle - Tag in Horizontal Polarization

- Average elevation error: +/- 6.1°
- Best and worst-case elevation errors: +/- 0.1° and +/- 17.1°

6.6.7 Elevation Angle Measurement - Summary

- Average elevation error (average of Horizontal and Vertical tag polarizations): +/- 7.4°
- Best and worst-case elevation errors: +/- 0.1° and +/- 22.8°

7. Revision History

Revision 0.3

December 2020

- Updated antenna array accuracy measurement results for section [6. Antenna Array Accuracy](#).

Revision 0.2

June 2020

- Update to reflect antenna array changes.

Revision 0.1

January 2019

- Initial Revision.

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