Weather-Robust Systems for Outdoor Acoustical Measurements

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ABSTRACT

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An improved microphone configuration for making outdoor sound measurements has been studied. This configuration, nicknamed the Compact Outdoor Unit for Ground-based Acoustical Recordings (COUGAR), consists of an inverted microphone placed above a circular plastic plate and covered with a dome wind screen. The second generation of COUGAR, known as COUGARxt, follows the same general design but with a thinner plastic plate and a thicker wind screen. These two configurations, COUGAR and COUGARxt, along with an Elevated microphone configuration, have been tested in the BYU large anechoic chamber at various elevation and rotation angles relative to a noise source. The COUGAR and COUGARxt configurations have been tested on field tests involving rocket motor noise. Results indicate that both configurations record reliable acoustic data. Compared to COUGAR, COUGARxt is shown to vary less with rotation relative to the sound source and to reduce more low-frequency wind noise. As expected, the Elevated microphone configuration is shown to experience multi-path interference at all tested elevation angles when placed on a hard reflecting surface.

Keywords: Outdoor, Acoustic, COUGAR, COUGARxt, Weather, Measurements, Rocket, Anechoic, Jet Noise, Rocket Noise, Sonic Boom

ACKNOWLEDGMENTS

I would like to thank the Brigham Young University Department of Physics and Astronomy for requiring their students to produce a senior thesis. Participating in research has easily been the highlight of my undergraduate experience at Brigham Young University. I would go so far as to say that I may have learned more during my three years of undergraduate research than I did throughout all of my core physics classes, and the reason I feel confident in my education is because of the skills I've learned as I have performed and published research.

I would like to thank Dr. Kent Gee for taking me on three years ago as his student and encouraging me to actively participate along with the other students, even though at the time I hardly knew what I was doing. He has always treated his students as competent individuals who can be productive and start working on meaningful research the moment they join.

I would like to thank my parents for supporting me in my decision to pursue my education. Their encouragement and support throughout my elementary, junior high, high school, and college experience has helped me to continue to study when I felt that I wasn't capable and guided me gently down a path that I know will help me provide for my own family.

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Chapter 1

Introduction

1.1 Relevance

Supersonic flight over land is a dream that came true, and then disappeared. The great Concorde aircraft was the first supersonic passenger aircraft and was ultimately retired, in part, because the sonic boom was so intense that it became illegal for it to fly over land. Ever since then the ban on supersonic flight over land has remained in force, and now efforts are underway to lift it. The National Aeronautics and Space Administration (NASA) is developing the X-59 Quiet Supersonic Technology (QueSST) aircraft as a way to create certification standards for future supersonic aircraft that will be allowed to fly over land. This aircraft is designed to have a quiet sonic boom known as a "Sonic Thump" [1] and acoustical measurements must be taken outdoors. As part of this endeavor, Brigham Young University (BYU) has been funded by NASA to create a weather-robust system for making acoustical measurements outdoors in preparation for testing the NASA X-59 aircraft. The measurement system developed by BYU must be able to withstand wind, rain, and intense temperatures. This thesis will focus on the design and testing of the physical microphone configuration as part of this overall project.

1.2 Outdoor Sound Measurements

Two impacts on outdoor acoustics are the ground [2] and the weather [3]. The ground is a complicated absorptive and reflective surface. Previous work shows that if the ground is made of a soft material, like sand, then at shallow angles the soft surface absorbs a lot of the high-frequency sound. On the contrary, if the ground is made out of a hard material then that effect disappears completely [2]. The weather creates a dynamic problem, affecting the direction that sound travels over long distances. The wind also acts as a loud low-frequency acoustic source and can wash out data at low frequencies [4]. All of these issues contribute to error in the acoustical measurements.

The physical location of the microphone relative to the rest of the measurement setup and the ground contribute additional noise. The most easily-understood example of this noise is the interference due to the height of the microphone. Sound waves bounce off of hard surfaces, and if the microphone is elevated then it will actually receive at least two signals: a direct signal, and a reflected signal, which will cause interference nulls to appear in a spectral analysis. In a seemingly backwards result, the best way to avoid the effects of ground reflections is to put the microphone low to the ground, with the optimal height being half of the microphone diaphragm diameter above the ground plate [5]. Another, more subtle, interference effect occurs when the microphone is placed near the center of the ground board. When sound waves come in at normal incidence they divert over the surface of the plate, and when they reach the edges, they experience edge diffraction and reflect back towards the center, creating another interference null as a function of the diameter of the board.

1.3 Past Solutions

While striving to make outdoor measurements, many different microphone configuration designs have been presented. One such design is the NASA Supersonic Pressure Instrumentation Kit

Ensemble (SPIKE) setup [6]. This setup consists of a square plywood board and a half-inch microphone laid on its side inside a half-ball windscreen. One of the benefits of this setup is the shape of the ground board naturally discourages the same magnitude of edge-diffraction interference as would be experienced by a more commonly-used circular ground board. It also succeeds in getting the microphone low to the ground and shrouding it from the wind with a small wind screen. Another design, the Gulfstream Sonic Boom Unattended Data Acquisition System (SBUDAS) setup, consists of a microphone raised eighteen inches above the ground, also shrouded in a wind screen [7]. The benefit of this setup is that it is immune to small amounts of water flooding. The main drawback, as will be discussed later in Section 3.5, is that the height of the microphone above the ground leads to interference nulls at lower frequencies than the other setups. To overcome such multipath interference, additional work was done by The Boeing Company on flush-mounting microphones in convex ground boards [8]. They found that flush mounting the microphone eliminated multipath interference but still suffered from edge diffraction effects. This was solved by using an exponential flush disk design to eliminate sudden impedance changes and therefore reduce edge diffraction effects. Other potentially relevant work has been done on the azimuthal dependence of the configurations [2, 9] and creating systems for aircraft and sonic boom measurements [10].

1.4 Previous Work at Brigham Young University

To account for several of the known environmental factors while still acquiring valid outdoor acoustical data, BYU assisted in the devlopment of the Compact Outdoor Unit for Ground-based Acoustical Recordings (COUGAR) [11, 12]. This unit attempts to solves many of the previously-discussed issues surrounding outdoor acoustical measurements. The basic setup is similar to many other standard setups, consisting of a circular ground board with a microphone close to the ground [13], and is diagrammed in Figure 1.1. The microphone has a half-inch diameter diaphragm and is elevated one-quarter inch above the ground board, in accordance with previous research [5]. Adaptors are also available for quarter-inch microphones, which can then be placed one-eighth inch above the ground board. The microphone is held in place by a three-pronged mechanism known as the spider. One of the key differences between COUGAR and other designs is the use of a convex ground board rather than a flat board. The convex ground board aids during rainy weather; the water slides off the board rather than pooling on top of it, reducing potential microphone damage. To further protect the microphone from the elements, a large cylindrical wind screen made of polyurethane foam is placed over the microphone, and the microphone is closed on top by a dome also made of the same polyurethane foam. This wind screen tends to naturally draw water onto a path around the microphone, while also protecting the microphone from wind noise. In the event of excess rain, an optional plastic rain cap can be fixed to the underside of the dome to prevent water from dripping onto the microphone. This practice is discouraged whenever possible as a result of the data shown later in Section 3.2.2.

The successor to COUGAR, named COUGARxt [1, 11], was developed in 2019 and employs the same basic strategies to protect the microphone and enable high-fidelity acoustical recordings during outdoor tests. There are two main differences between the setups. The first difference is the thinner ground board used in COUGARxt, enabling the microphone to be even closer to the local ground. A thicker wind screen further discourages wind noise corruption in the acoustic signals.

1.5 Community Impact

This research helps to create better microphone configurations for testing supersonic vehicles. The goal of the measurements made with this technology is to open to door to supersonic flight over land. This research is relevant for anyone making outdoor sound measurements. For work on rockets and sonic booms, which tend to peak at low frequencies, the details about wind noise reduction will be

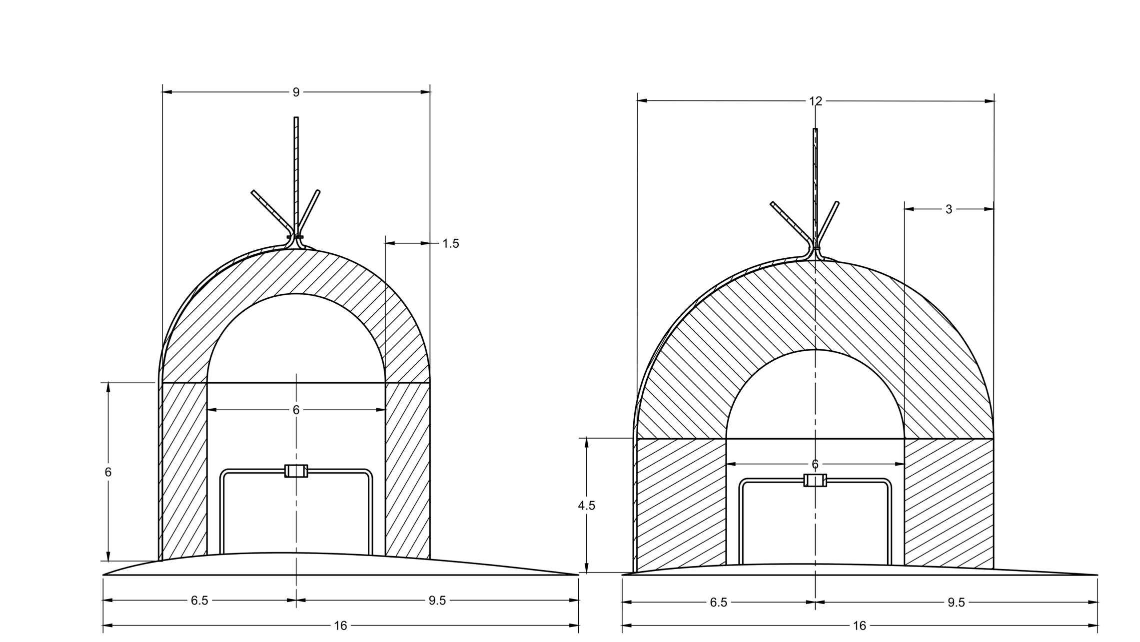


Figure 1.1 The COUGAR (left) and COUGARxt (right) microphone configurations.

useful. For work done on flight vehicle certification, where there are already standards in place [13], this work will help create designs that are more capable of determining the true acoustic signals the flight vehicle produces. For work done on outdoor soundscapes, this will help to show systems that are more weather-robust and can be left outdoors for longer, and even unattended in light rain [4].

1.6 Overview

The main goal of this thesis is to describe and examine several different microphone configurations and their acoustic responses. In Section 2 we will discuss the equipment and facilities that were used to obtain these data. Section 3 will present the results of the research including laboratory testing and field testing. The setups that were explored were COUGAR, COUGARxt, and SBUDAS. Note that from this point forward, the SBUDAS microphone configuration will be referred to as the "Elevated" microphone configuration because we are simply examining the microphone configuration rather than the entire SBUDAS data acquisition system. All of the setups succeeded in obtaining good acoustic data at low frequencies, and each have their own problems at higher frequencies. The ultimate result of this work is to improve outdoor sound measurements around the acoustics community by showing a few different microphone configurations and how they each respond to the acoustic signals they are measuring.

Chapter 2

Methods

2.1 Overview

This section discusses the measurements and techniques used to compare the microphone configurations. The laboratory testing was done in the BYU Large Anechoic Chamber using a large metal arc and a loudspeaker, as discussed in Section 2.2. To validate the findings in the laboratory, the configurations were also tested outdoors on two field tests where they measured two different solid rocket motors. The COUGAR and COUGARxt microphone configurations were also tested in heavy winds to determine the effects of the thicker wind screen used on COUGARxt. Outdoor testing is the subject of Section 2.3. Lastly, a tabular summary of the data that are shown in Section 3 is given in Section 2.4.

2.2 The Anechoic Chamber and the ARC

Laboratory experimentation was done in the BYU Large Anechoic Chamber, where environmental effects remained effectively constant. Using the chamber allowed the acoustic differences between the setups to be probed in a controlled environment. The chamber is rated as anechoic between 0.08

– 20 kHz and has interior dimensions 8.8 x 5.8 x 5.8 m.

To further reduce the variables, we used the Angular Recording Configuration (ARC). This structure let the sound source move to different locations relative to the microphones. It enabled angular resolution of five degrees in the elevation (up-down) angle and arbitrary resolution in the azimuthal (rotation) angle. A photograph of the entire setup is shown in Figure 2.1, with additional photographs indicating the elevation and azimuthal angles in Figure 2.2. The ARC was placed on several sheets of three-quarter-inch medium-density fiberboard (MDF), which is assumed to represent an acoustic surface similar to plywood, which is known to be a hard acoustic surface [2]. This simulates a hemi-anechoic environment similar to what would be experienced on an outdoor field test under an open sky. A reference microphone was placed to the side of the device under test and was present for all recordings. This reference microphone was used to validate the output of the speaker during recordings and showed that the speaker output was consistent. The speaker itself was a Mackie HR824mk2 speaker, and it was used to output white noise over all the frequencies shown in this thesis.

The ARC had to be used carefully because parts of it were thin and it was placed on a large wire mesh. After adjusting the ARC for each test, we had to wait several seconds for the mechanical oscillations to dampen. When placing a new microphone on the plywood for testing, we also made sure that the microphone for each setup was in the same place as for the other setups. The speaker was often cumbersome to handle and was sometimes difficult to mount it at the higher elevation angles.

Throughout this thesis, you will encounter many cases where data are shown relative to the baseline measurement. The baseline measurement was recorded by placing a quarter-inch microphone flat on the ground at the same location as the devices under test indicated in Figure 2.1. The purpose of this measurement is to attempt to capture the sound field at the location of the microphone configurations so we can compare the microphone configurations to an ideal recording.

This measurement serves an entirely different purpose than the reference microphone indicated in Figure 2.1, which was used simply to test for consistency in the speaker output, and which does not receive the same sound as the devices under test because it is placed to the side. Each time the ARC was set up, a new baseline measurement was recorded.

Measurements were performed over a little more than a year, with the ARC being set up on multiple separate occasions in the anechoic chamber. A few limited studies shown in Appendix A indicate that results are relatively consistent between times the ARC was set up.

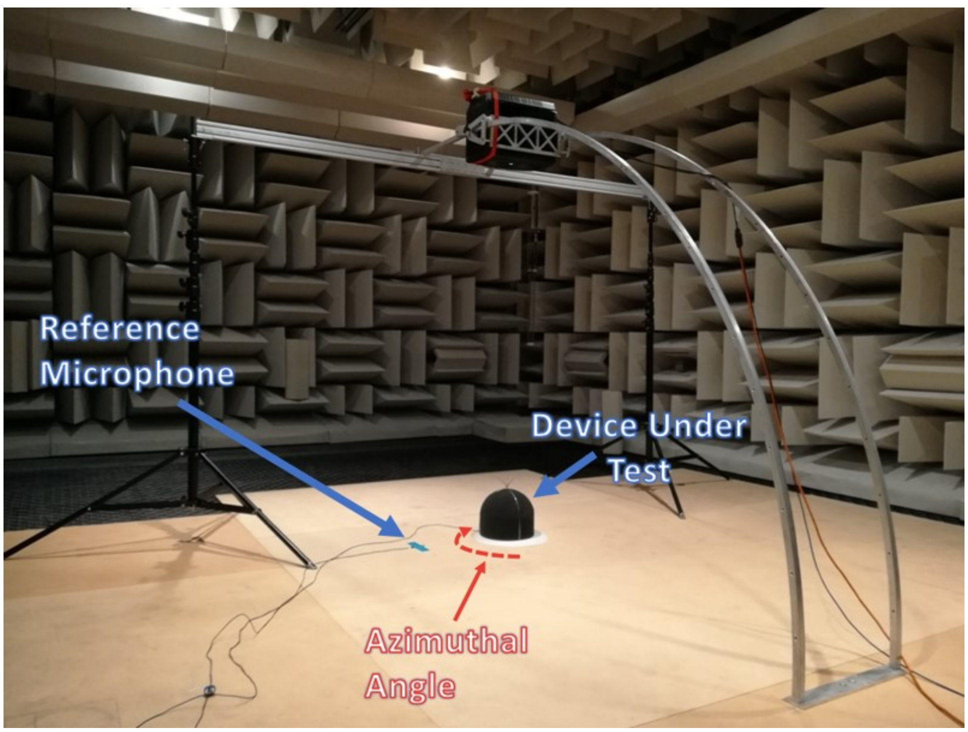


Figure 2.1 The ARC assembly in the BYU Large Anechoic Chamber. The speaker was able to move along the rails to provide a signal from many different elevation angles. A reference microphone was used to verify the speaker output between tests.

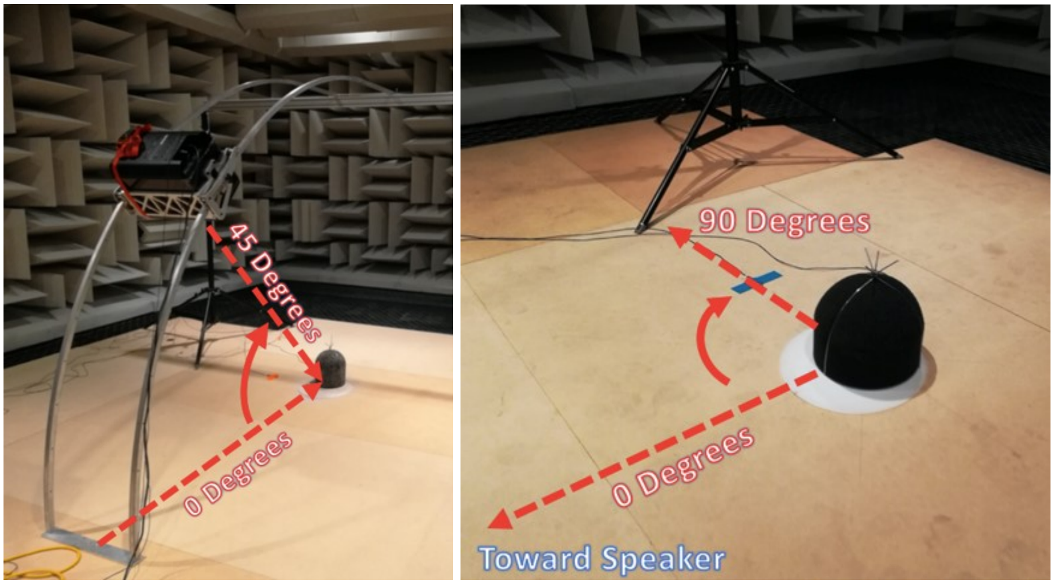


Figure 2.2 *Left:* The definition of the elevation angle in the experiment. *Right:* The definition of the azimuthal angle in the experiment.

2.3 Outdoor Testing

Each of the setups have been tested on field tests including QSF18, CarpetDIEM, and solid rocket motor static fire tests. These tests generally consist of multiple microphones located at one station so that direct comparisons can be made between the setups. Due to the secure nature of the work done at QSF18 and CarpetDIEM, no data are shown here but should become available in the future. A limited analysis from CarpetDIEM is shown in [11]. However, data from GEM-63 and CASTOR 300 rocket motor tests are shown in this thesis. These solid rocket motors are designed to be used as parts of larger rockets. These tests were performed at Promontory, Utah by Northrop Grumman, and a comparison of COUGAR and COUGARxt is drawn from the data. A photograph of a CASTOR series motor is shown in Figure 2.3.

COUGAR and COUGARxt have also been tested in wind-specific measurements to measure their difference in wind noise rejection. The data shown are taken from measurements performed near Provo Municipal Airport and the setup is shown in Figure 2.4. For this comparison, both

Figure 2.3 A close-up photograph of a CASTOR solid rocket motor test. The microphones were generally about 1-2 km away from the motor during testing.

configurations used a GRAS 47AC microphone and were connected to the computer through the same data acquisition card. Weather data were obtained using the airport weather station, which reported winds around 20 mph over the duration of the test [14]. The recording length is forty minutes.

2.4 Configurations Tested

This thesis focuses primarily on the COUGAR and COUGARxt microphone configurations. A list of presented results, including results for the Elevated configuration, is in Table 2.1. The anechoic measurements were performed in the BYU Large Anechoic Chamber using the ARC. Elevation testing varied the elevation angle of the sound source relative to the microphone configuration. Azimuthal testing varied the rotation of the physical microphone configuration relative to the sound source. The water and dirt tests refer to tests where the wind screen was either soaked in water or

Figure 2.4 The outdoor setup used to obtain comparative wind data for COUGAR and COUGARxt. In this figure, COUGAR is shown further away from the camera and COUGARxt is closer. The wind traveled from right to left in this photograph.

covered in sand before the measurement. Outdoor field testing was done using solid rocket motors as the sources. Outdoor wind testing was performed under windy conditions with no intentional acoustic source – just wind noise.

Table 2.1 All of the tests that are shown in this thesis. ‘Elevation’ refers to changes in the elevation angle of the sound source relative to the setup and ‘Azimuthal’ refers to rotations of the setup relative to the sound source. ‘Water/Sand’ refers to extreme environmental tests where the wind screen was soaked in water or covered in sand. ‘Field Test’ refers to outdoor field test data of rocket motor firings using a real acoustic source, and ‘Wind’ refers to an outdoor test with no source other than wind noise.

Configuration	Tests Performed				
	Anechoic			Outdoor	
	Elevation	**Azimuthal**	**Water/Sand**	**Field Test**	**Wind**
COUGAR	X	X	X	X	X
COUGARxt	X	X		X	X
Elevated	X			X	

Chapter 3

Results

3.1 Overview

This section displays the results of the laboratory and field testing done on the different microphone configurations. The laboratory testing for COUGAR, shown in Section 3.2, includes different ground board geometries, the wind screen, and azimuthal rotations of the configuration. The laboratory testing for COUGARxt is shown in Section 3.3. A comparison of COUGAR and COUGARxt for laboratory, field, and wind testing is then given in Section 3.4. The laboratory results for the Elevated configuration are shown in Section 3.5 and a summary of the results along with the conclusions is given in Section 3.6.

3.2 COUGAR

3.2.1 Influence of the Plate

Several different plate designs were tested to determine the effects of different plate geometries on the recorded acoustic signals. These include a standard COUGAR convex plate with the apex off-center, a variation with a thinner plate, and a third variation where the apex remained centered on the plate. The results presented in this subsection all had the wind screen removed, allowing us to investigate the effects of the plate design. The current COUGAR plate design shows reductions at mid-range frequencies up to 1000 Hz and lots of variation at higher frequencies, seen in Figure 3.1. Using a thinner plate (with the apex still off-center) shows less variation at these mid-range frequencies, but retains the high-frequency variation, seen in Figure 3.2. If the standard COUGAR plate is swapped out for a plate with the same thickness but with the apex in the center of the plate, we see that the overall shape of the results is similar, indicating that there is not much difference between a centered apex and an offset apex, seen in Figure 3.3.

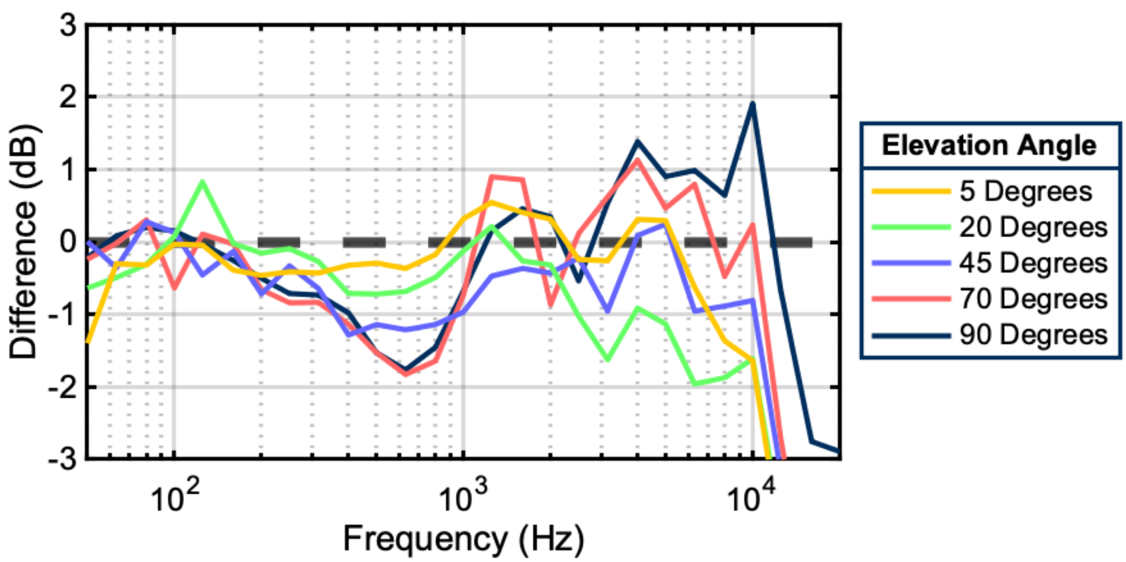


Figure 3.1 The recorded spectrum by a microphone in a spider and placed 0.25 inches above the convex COUGAR plate without the windscreen, relative to the baseline.

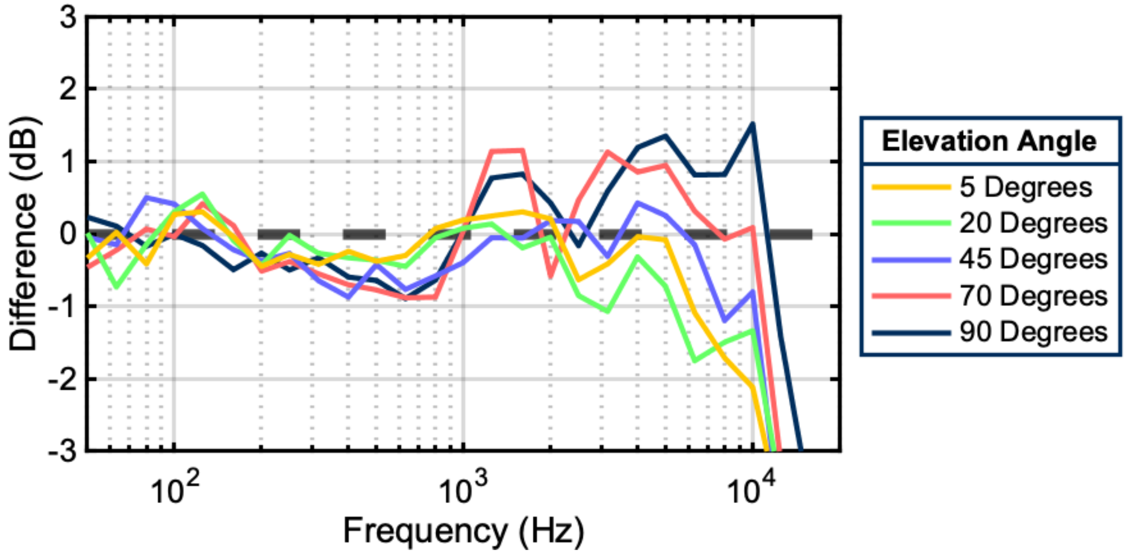


Figure 3.2 One-third octave spectrum (re: baseline) of COUGAR without windscreen and with a thinner plate.

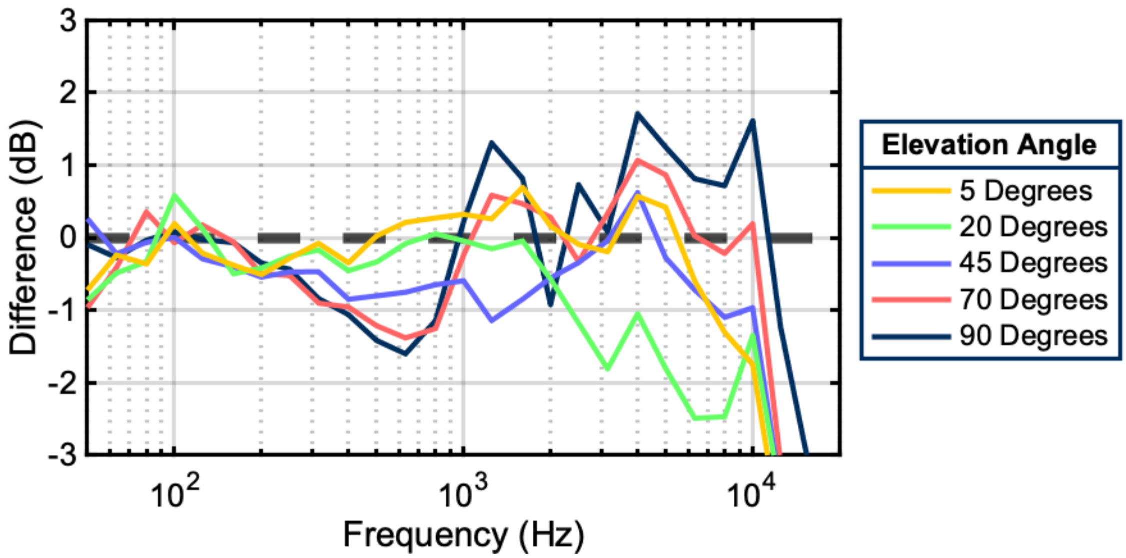


Figure 3.3 One-third octave spectrum (re: baseline) of COUGAR without windscreen and with a plate that has a centered apex.

3.2.2 Influence of the Wind Screen

The wind screen does affect the performance of the COUGAR configuration. Most of these effects are only noticeable at high frequencies (>1 kHz). This means that if the measurement will consist of primarily low frequency content, then COUGAR should return good acoustic data under a variety of different conditions. One of the effects is to decrease the amplitude of the higher frequencies, shown beginning at about 1 kHz in Figure 3.4. At low frequencies the effects of the wind screen are less than one decibel, especially at mid-range frequencies up to 1 kHz. An optional rain cap made of tent nylon can be attached to the underside of the dome to help keep water off the microphone. This does produce large changes in frequencies greater than 1 kHz, shown in Figure 3.5. To further investigate the effects of leaving COUGAR in the field during wet conditions, the wind screen was completely saturated with water and then tested relative to the dry case. These results, shown in Figure 3.6, indicate large losses at high frequencies when the wind screen is completely saturated with water. One possible side effect of wind is increased amounts of dirt blown through the air. To simulate this, we took a COUGAR wind screen and saturated it with sand several times. The most dramatic case is shown in Figure 3.7, where sand was also scattered on and around the COUGAR configuration. The effects are again appreciable at high frequencies greater than 1 kHz, indicating that if there is wind saturation the high frequencies will be the most affected. However, considerable effort was needed to truly saturate the wind screen because most of the sand passed through the mesh and therefore the measured effect is likely much stronger than would be experienced in the field.

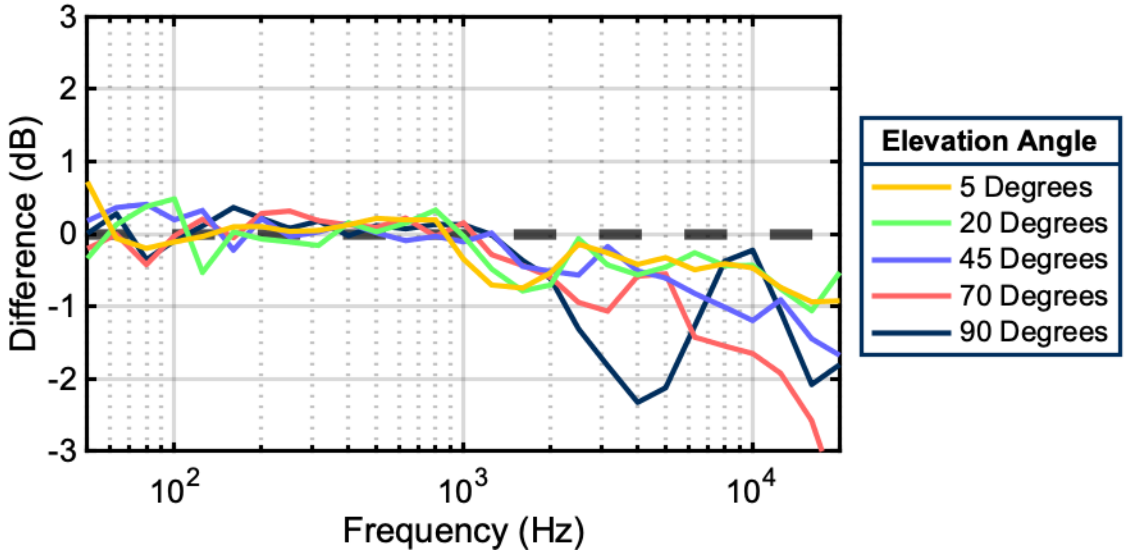


Figure 3.4 COUGAR with the wind screen relative to COUGAR without the wind screen. The rain cap was not used.

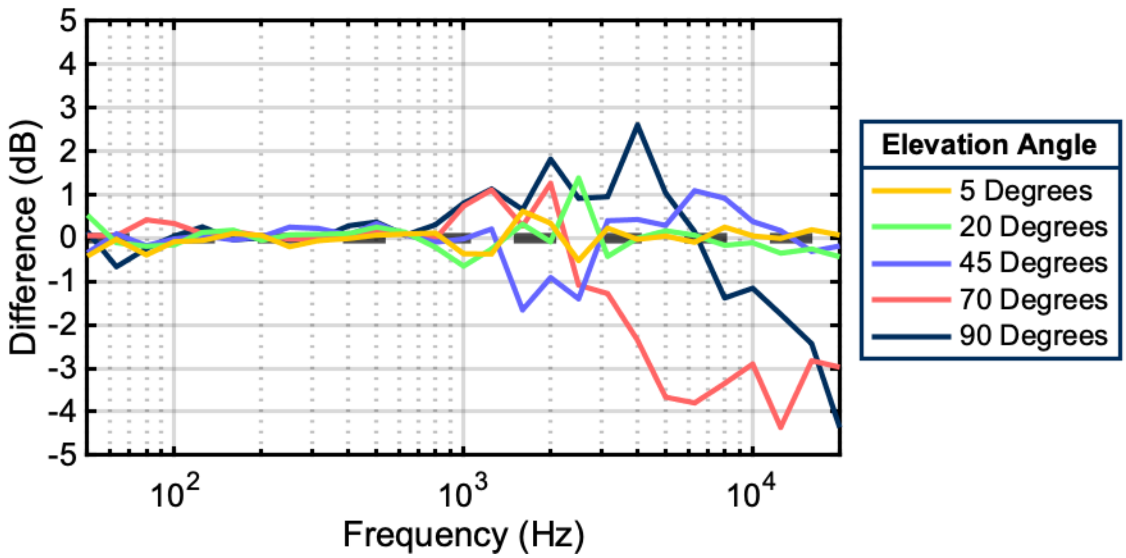


Figure 3.5 One-third octave spectra for the COUGAR configuration with a rain cap relative to a COUGAR configuration without a rain cap.

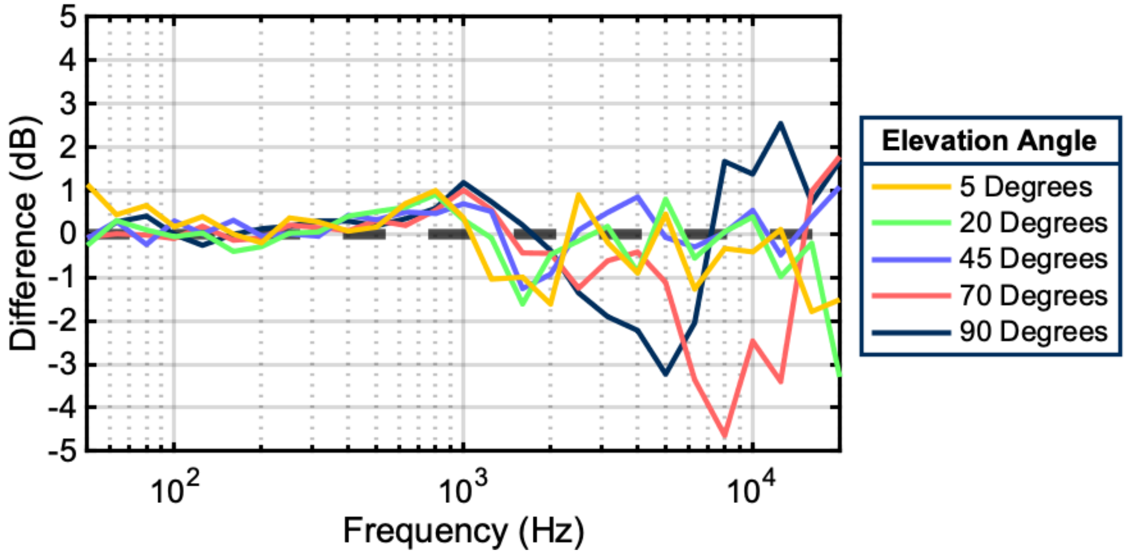


Figure 3.6 The recorded spectrum from a microphone in a COUGAR configuration with the wind screen saturated with water, relative to the dry case. The rain cap was used in both cases.

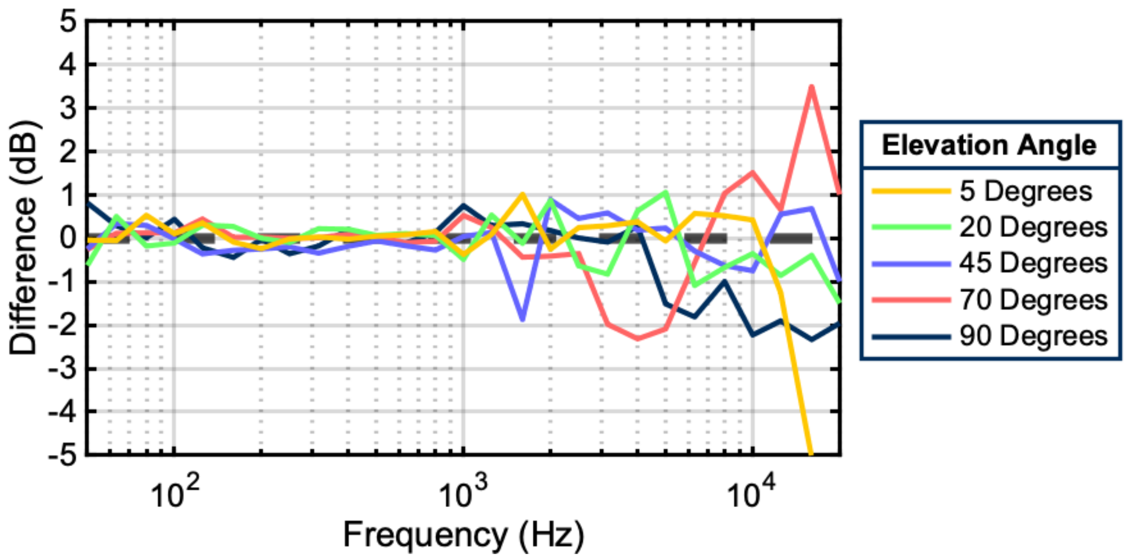


Figure 3.7 The recorded spectrum from a microphone in a COUGAR configuration with the wind screen saturated with sand, relative to the clean case. The wind screen was saturated with more sand than either of the other tests. Sand was also scattered on and around the ground.

3.2.3 COUGAR in Standard Configuration

COUGAR stays within about ± 2 dB relative to the baseline. The overall frequency effects are very similar to the tests without the wind screen, with some high-frequency attenuation (likely due to the wind screen) seen at frequencies greater than 1 kHz. The results of comparing the COUGAR configuration in standard orientation relative to the baseline are shown in Figure 3.8.

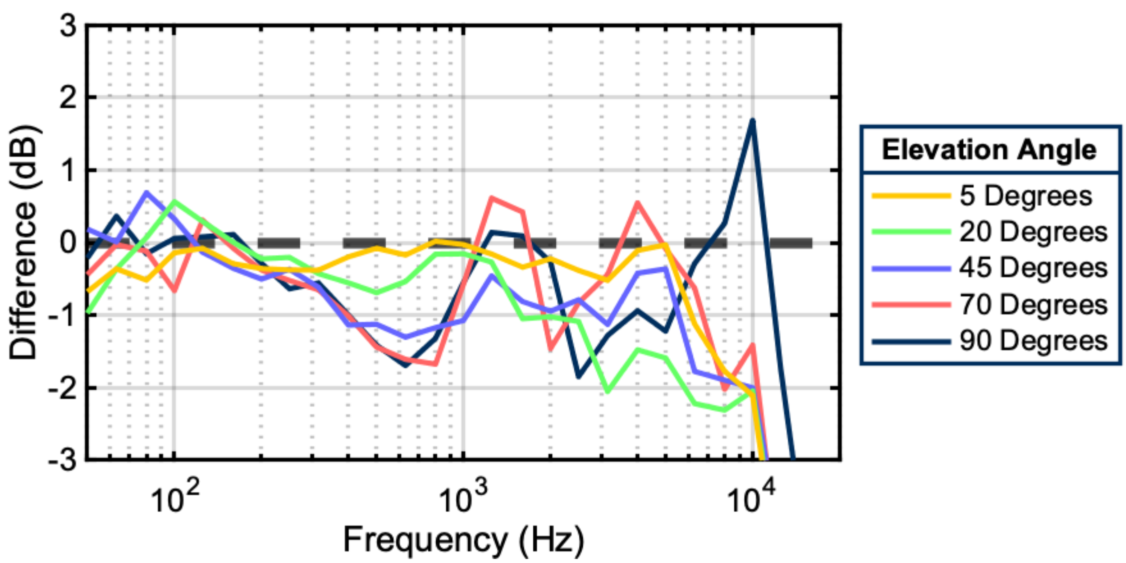


Figure 3.8 One-third octave spectrum (re: baseline) of COUGAR without additional rain cap.

3.2.4 Azimuthal Rotations

It is impossible to have the COUGAR configuration consistently in its standard configuration relative to the sound source. In many cases this is because the sound source is moving, or the sound may be originating in different locations relative to COUGAR. To investigate this issue, we tested COUGAR at different azimuthal (rotational) angles relative to the sound source. The results at grazing incidence are shown in Figure 3.9, indicating that the rotations induce a difference of less than ±1 dB. The effects are noticeably larger at an elevation angle of 45 degrees, but still remain within about the same limits as the grazing case and are shown in Figure 3.10. Lastly, at normal incidence the results are mostly flat, but with a noticeable increase toward the high frequencies, which is not yet well understood, and are shown in Figure 3.11. One peculiarity is the fact that the 90- and 270-degrees cases to not match. They were anticipated to match based on the symmetry of the entire setup, and one proposed reason for the mismatch is that the sound source was a speaker that output different frequencies from two different regions on its face, thus not being a symmetric sound source and potentially affecting the symmetry of the setup.

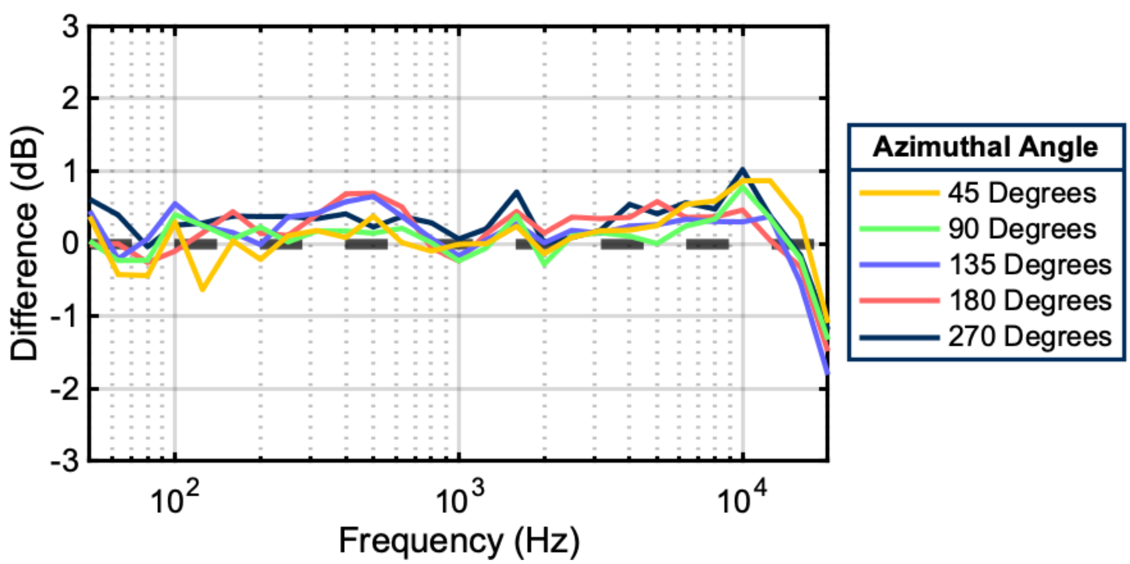


Figure 3.9 The recorded spectrum from a microphone in a COUGAR configuration, relative to the azimuth = 0 Degrees case. The physical COUGAR setup was rotated to each of the azimuthal angles indicated. Data were taken at an elevation angle of five degrees.

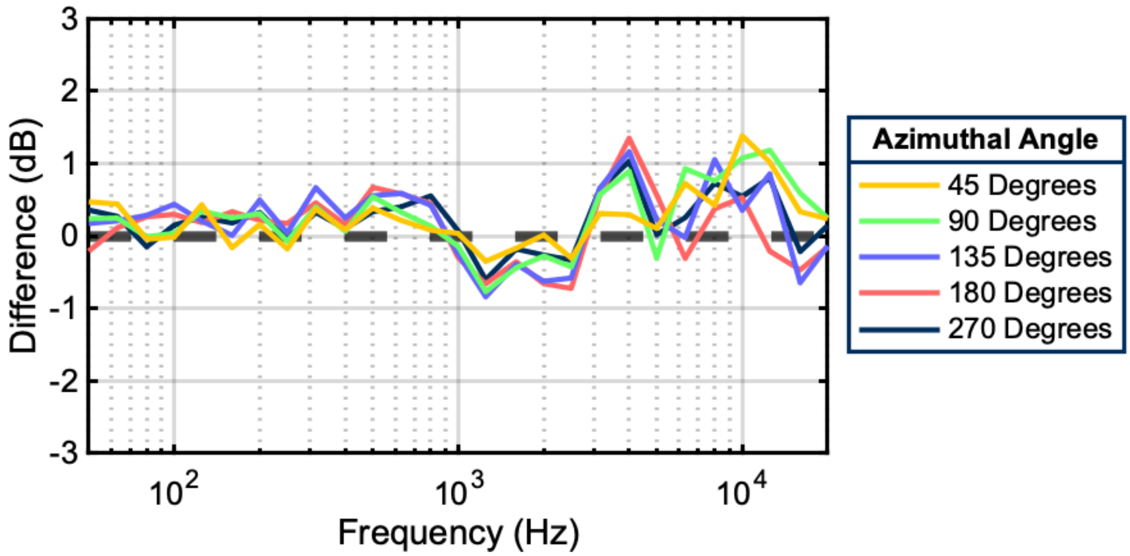


Figure 3.10 The recorded spectrum from a microphone in a COUGAR configuration, relative to the azimuth = 0 Degrees case. The physical COUGAR setup was rotated to each of the azimuthal angles indicated. Data were taken at an elevation angle of forty-five degrees.

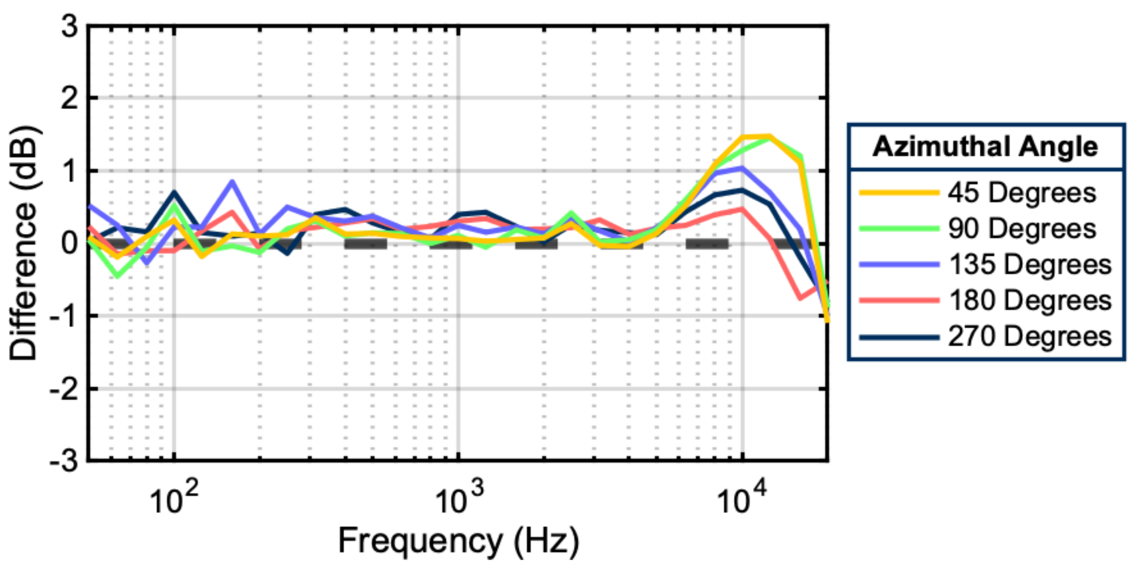


Figure 3.11 The recorded spectrum from a microphone in a COUGAR configuration, relative to the azimuth = 0 Degrees case. The physical COUGAR setup was rotated to each of the azimuthal angles indicated. Data were taken at an elevation angle of ninety degrees.

3.3 COUGARxt

3.3.1 COUGARxt in Standard Configuration

COUGARxt shows noticeable improvement over COUGAR. The difference relative to the baseline stays within approximately ±1.5 dB, with exceptions at 70- and 90-degrees incidence, as shown in Figure 3.12 We believe that the improvements are primarily due to the thinner plate used, which was shown to be an improvement on the previous plate design in Section 3.2.1. This result is important because it validates the use of COUGARxt over COUGAR from a purely acoustical standpoint.

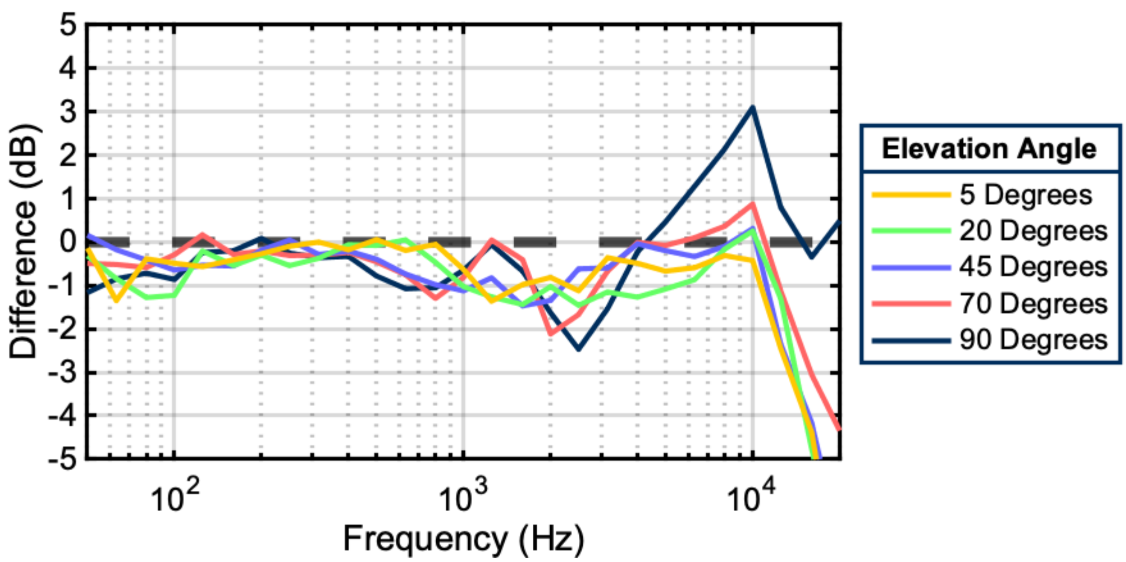


Figure 3.12 The recorded spectrum by a microphone in a COUGARxt configuration, relative to the baseline.

3.3.2 Rain Cap Effects

The same rain cap used for COUGAR was also tested on COUGARxt and yields similar results as it did for COUGAR. The differences are only noticeable at frequencies greater than 1 kHz, indicating that the rain cap would be acceptable for tests where the primary goal is measuring low frequencies.

This is shown in Figure 3.13.

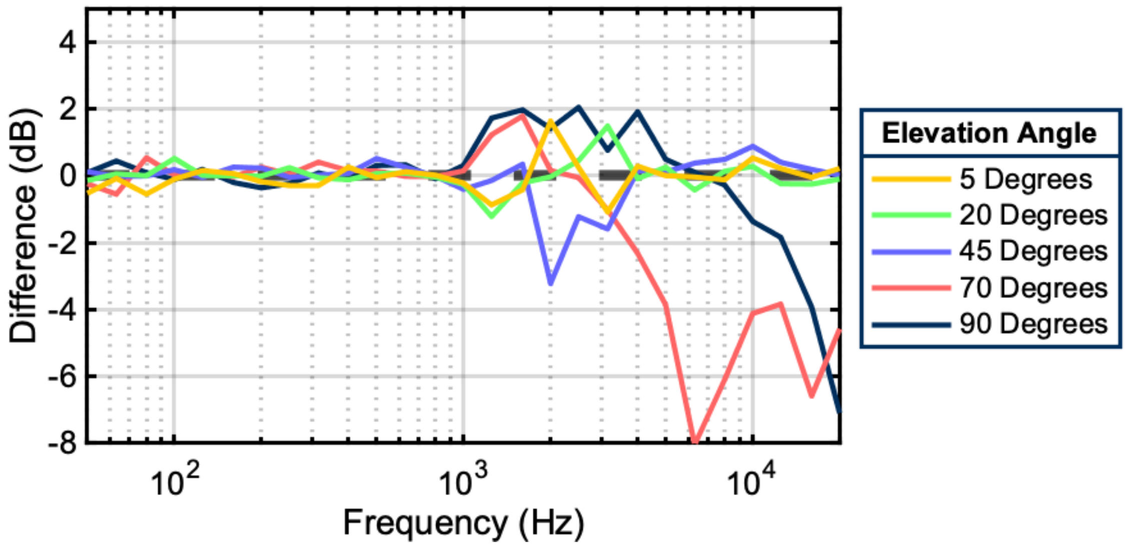


Figure 3.13 The recorded spectrum from a microphone in a COUGARxt configuration that had a thin plastic rain cap placed on the underside of the dome, relative to a COUGARxt configuration without a rain cap.

3.3.3 Influence of the Wind Screen

The COUGARxt wind screen, similar to the COUGAR wind screen, does impact the frequency response of the COUGARxt microphone configuration. Figure 3.14 shows the difference between the case where the wind screen is used and when it is not. The effect primarily impacts higher frequencies, as expected.

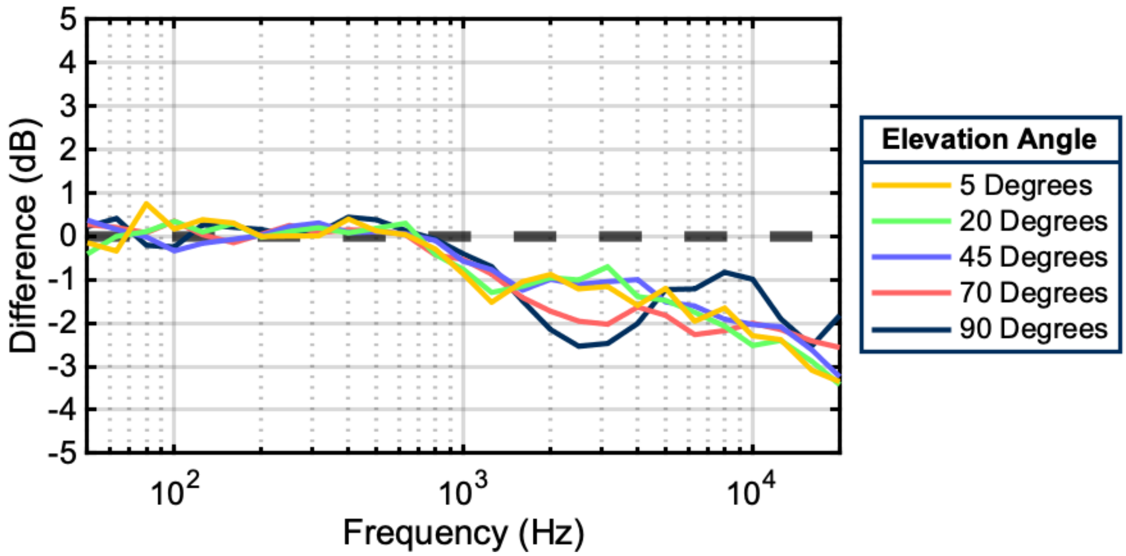


Figure 3.14 The effects of the COUGARxt wind screen. This shows the measurement with the wind screen relative to the measurement without the wind screen. Negative values indicate that the wind screen causes those frequencies to be diminished relative to the case where no wind screen is used. Note that this is the negative of the insertion loss of the wind screen.

3.3.4 Azimuthal Rotations

The same azimuthal analysis performed on COUGAR was performed on COUGARxt, where COUGARxt was shown to vary less with azimuthal angle, further validating its use over COUGAR. At grazing incidence, the results are consistently within ±1 dB of the standard configuration case (azimuth = 0 degrees), shown in Figure 3.15. At 45 degrees incidence a peculiar pattern is seen at all azimuthal angles at high frequencies, where the differences oscillate together about the standard case, beginning at about 1.1 kHz and shown in Figure 3.16. The best result is achieved at 90 degrees incidence, where the differences stay roughly within ±0.5 dB across the spectrum, shown in Figure 3.17.

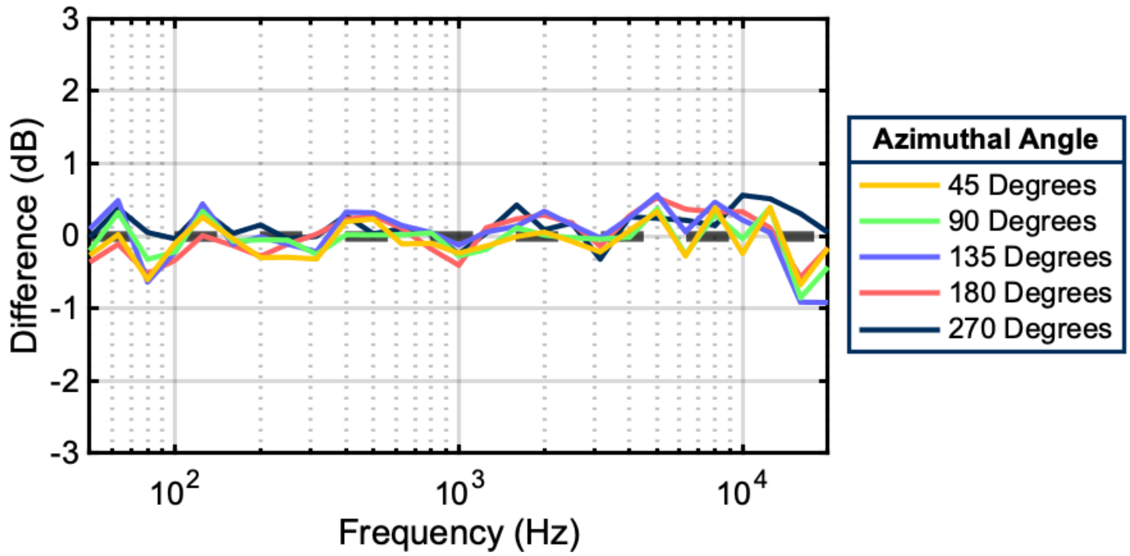


Figure 3.15 The recorded spectrum from a microphone in a COUGARxt configuration, relative to the azimuth = 0 Degrees case. The physical COUGARxt setup was rotated to each of the angles indicated. Data were taken at an elevation angle of five degrees.

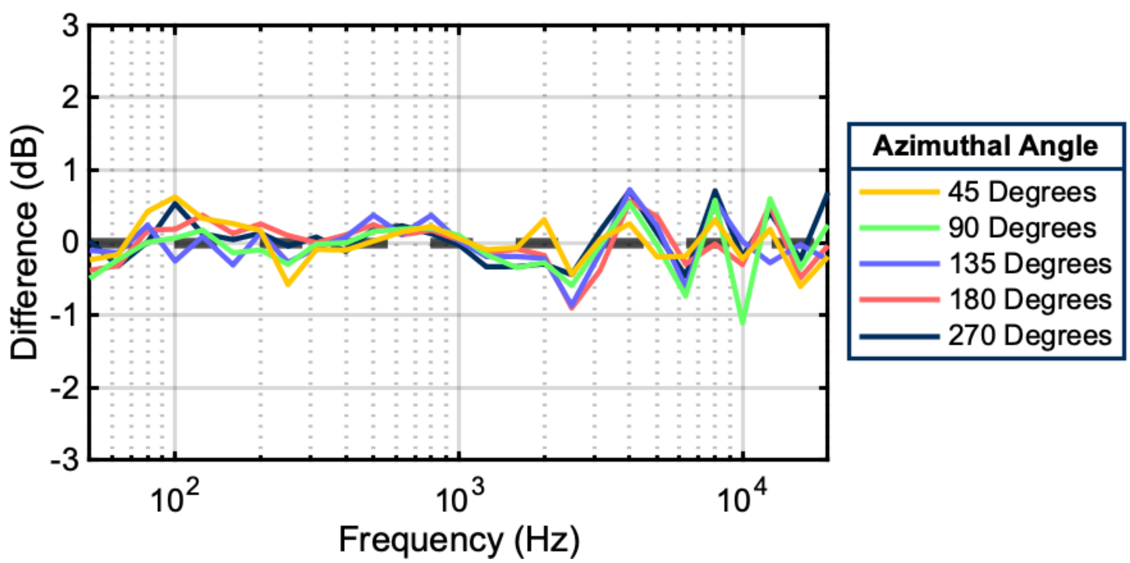


Figure 3.16 The recorded spectrum from a microphone in a COUGARxt configuration, relative to the azimuth = 0 Degrees case. The physical COUGARxt setup was rotated to each of the angles indicated. Data were taken at an elevation angle of forty-five degrees.

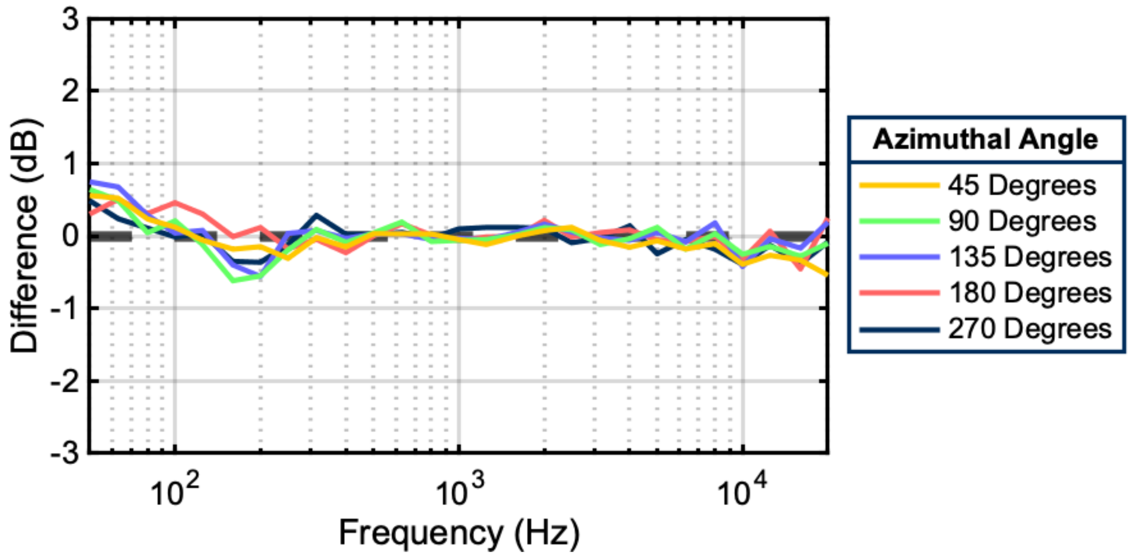


Figure 3.17 The recorded spectrum from a microphone in a COUGARxt configuration, relative to the azimuth = 0 Degrees case. The physical COUGARxt setup was rotated to each of the angles indicated. Data were taken at an elevation angle of ninety degrees.

3.4 COUGAR and COUGARxt Comparison

3.4.1 Laboratory Testing

COUGAR and COUGARxt are shown to be acoustically similar to within about ±1.5 dB up to 10 kHz at all elevation angles. The results in Figure 3.18 show that COUGARxt is greater than COUGAR between 100 Hz and 700 Hz. COUGARxt performs closer to the baseline in this frequency range while COUGAR fell below the baseline in this same range, thus resulting in a positive value for COUGARxt in this figure. The negative values shown here at higher frequencies may be the result of the thicker wind screen, which should attenuate the higher frequencies more than COUGAR does.

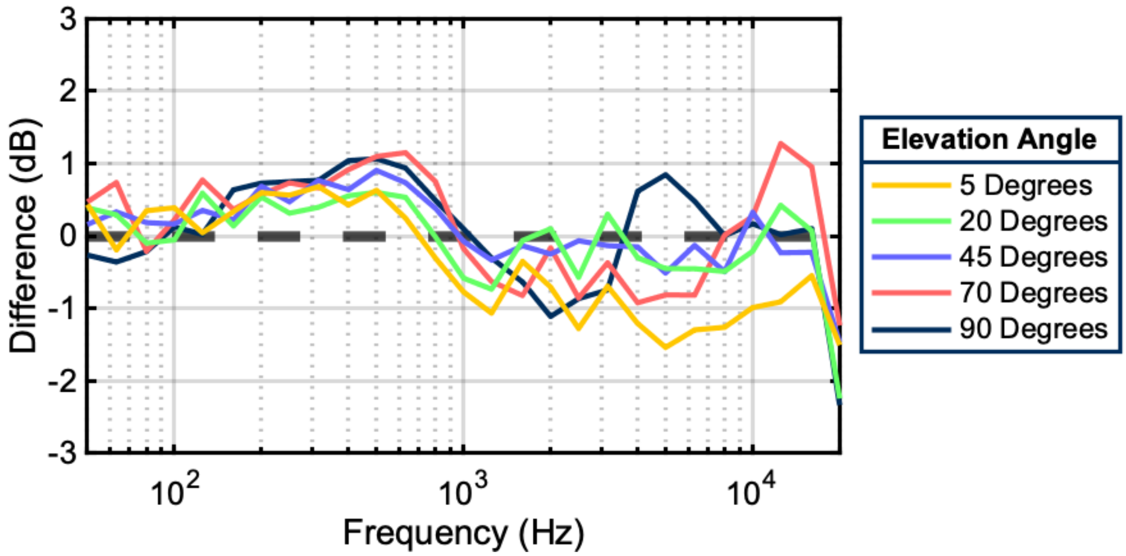


Figure 3.18 The recorded spectrum of a COUGARxt configuration relative to a COUGAR configuration.

3.4.2 Wind Testing

COUGARxt has a thicker wind screen to help reject more wind noise. To verify this, COUGAR and COUGARxt were both tested outdoors for forty minutes in wind at speeds consistently around 9 m/s (20mph). A difference plot between the two setups, shown in Figure 3.19 indicates that COUGARxt does reject more wind noise than COUGAR at low frequencies. This result is important because many outdoor tests involving rockets or sonic booms peak in this low frequency region. Under windy conditions, COUGARxt would be a better choice. For a deeper investigation into the particulars of wind noise and why COUGAR and COUGARxt are more efficient at rejecting wind noise than other standard configurations, see reference [4].

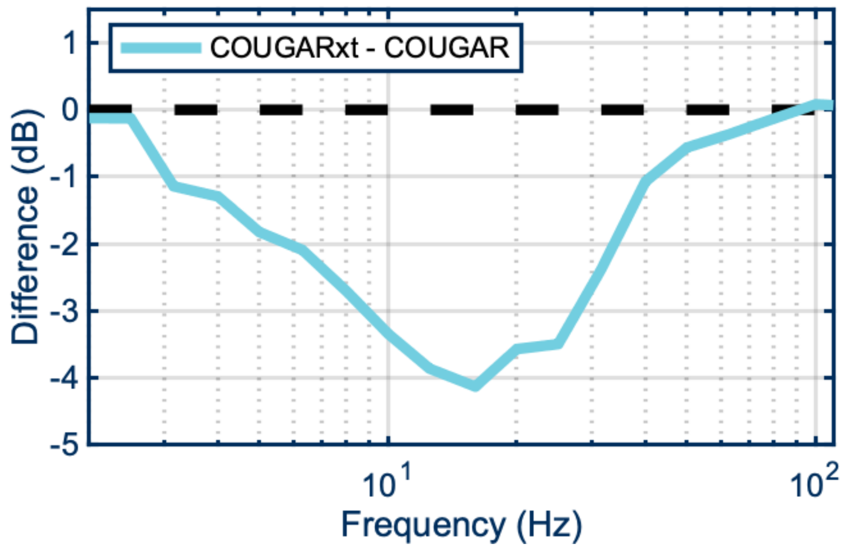


Figure 3.19 The results of the wind comparison between COUGARxt and COUGAR. We conclude that COUGARxt has superior wind rejection capability relative to COUGAR.

3.4.3 Rocket Static Fire Testing

Both configurations have been tested on two separate static rocket tests at Northrop Grumman in Promontory, Utah. The first test was a GEM-63 solid rocket motor designed to be a strap-on booster. The microphones were located at 45° relative to the nozzle at a distance of about 2 km. The results of this test are shown in Figure 3.20 and indicate that COUGARxt reports smaller amplitudes for the high frequencies, as anticipated because of its thicker wind screen. There is a spike at 250 Hz that has not been investigated but does remain within ±2 dB of COUGAR. The second test was a CASTOR 300 solid rocket motor designed to be the second stage of a rocket. The microphones were located at 77.5° relative to the nozzle of the rocket and were thus slightly downstream of the nozzle. These results, shown in Figure 3.21, show that COUGAR and COUGARxt are within about ±1 dB of each other over the entire spectrum up to 10 kHz. This is different from the GEM-63 result and therefore adds a further error margin to the true differences between COUGAR and COUGARxt and how accurately those differences can be predicted.

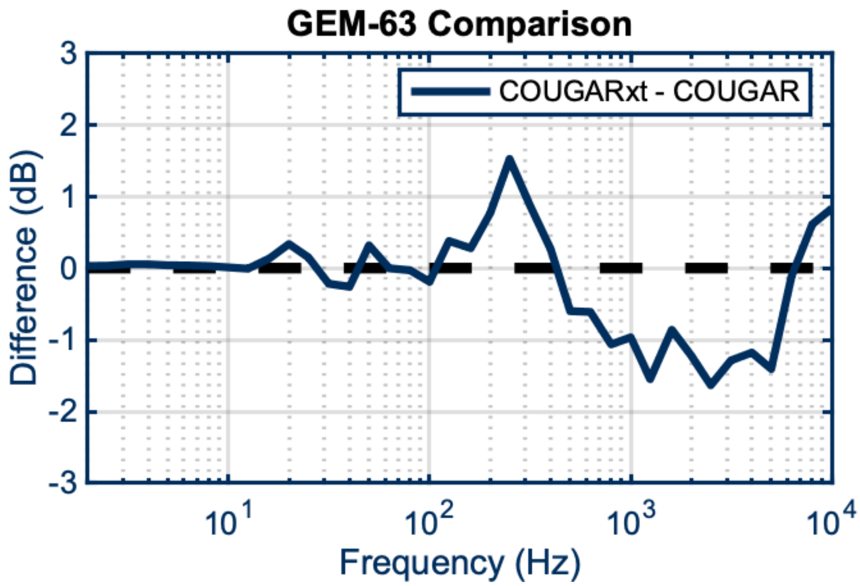


Figure 3.20 COUGAR and COUGARxt GEM-63 comparison. Comparison between the COUGAR and COUGARxt configurations during a twenty-second segment of a GEM-63 rocket motor test.

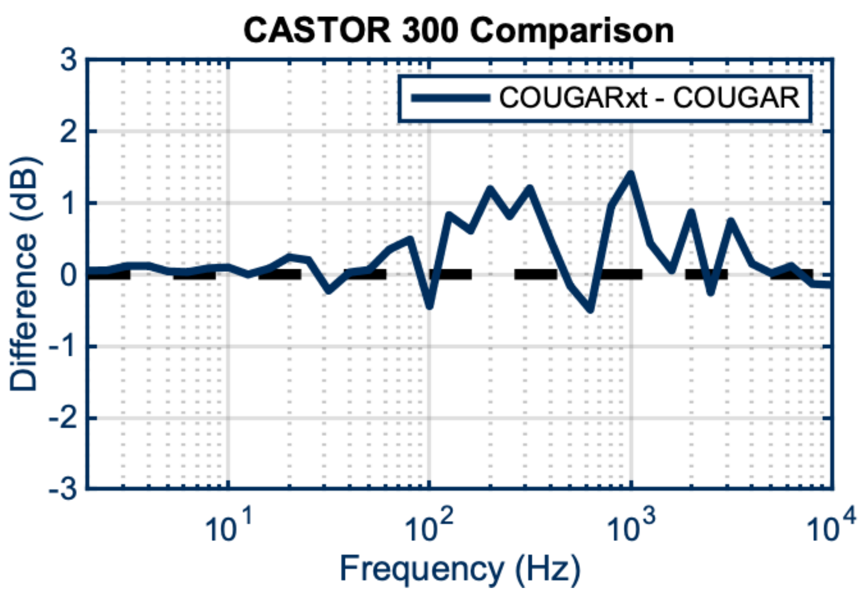


Figure 3.21 COUGAR and COUGARxt CASTOR 300 comparison. Comparison between the COUGAR and COUGARxt configurations during a twenty-second segment of a CASTOR 300 rocket motor test.

3.5 Elevated

The Elevated configuration shows deep interference nulls at all elevation angles and across the entire spectrum. These results are shown in Figure 3.22, and the locations of the interference nulls progress in order to lower and lower frequencies according to elevation angle. We believe these interference nulls are the result of reflections off the ground. Higher-order interference nulls are also seen. As a note, these elevation angles represent the angle measured relative to a point on the ground directly beneath the microphone. Additionally, bear in mind that the Elevated configuration used in the SBUDAS setup has the microphone oriented skyward, while these tests were performed with the microphone oriented horizontally, but still elevated eighteen inches above the ground.

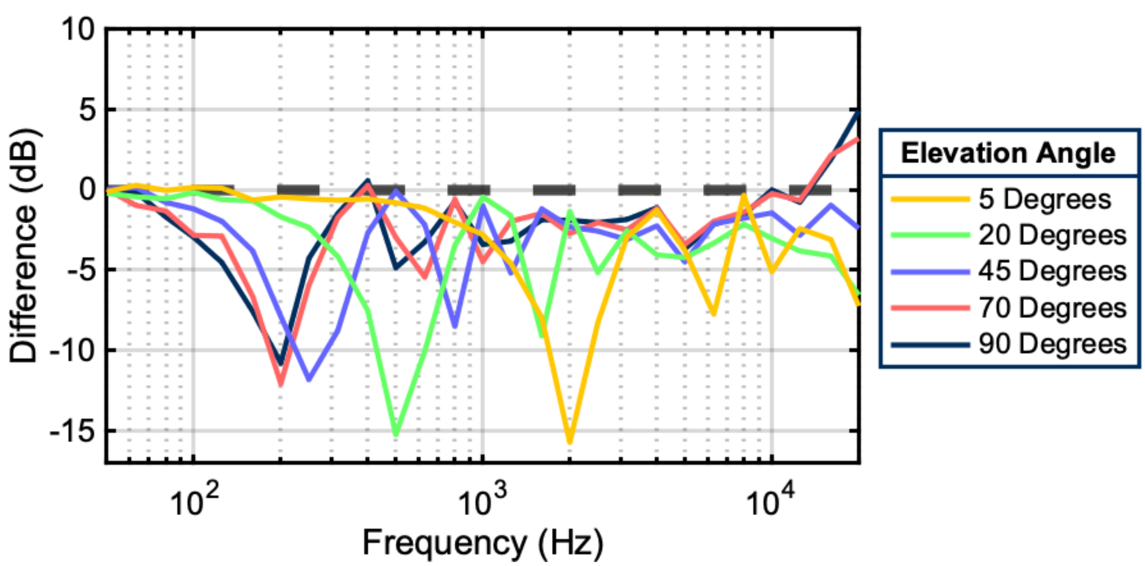


Figure 3.22 Elevated microphone results. Recorded spectrum from an Elevated configuration with the microphone oriented sideways (parallel to the floor), relative to the baseline. Note the different scale on the y-axis. The elevation angle is measured relative to the spot on the ground directly underneath the microphone.

3.6 Conclusion

COUGAR and COUGARxt are both microphone configurations that can record quality acoustic data to within ±2 dB at most frequencies. The results presented here show that COUGARxt is an improvement over COUGAR because of its thinner plate and thicker wind screen. Both the COUGAR and COUGARxt configurations outperformed the Elevated configuration, which shows large interference nulls at all elevation angles

During the COUGAR testing, the impact of the apex location on the plate was found to be small compared to the impact of the thickness of the plate. The thinner plate showed closer results to the baseline, and the thinner plate is used in the COUGARxt configuration. The wind screen attenuated the sound at high frequencies as expected, and when saturated with either water or sand proved to still be effective at low frequencies up to 1 kHz. The COUGARxt configuration has less azimuthal variation than COUGAR, showing that it is even more versatile because sound can come in from any azimuthal angle around the configuration and get recorded accurately, a useful result for flight testing. The rain cap was found to cause deviations in the measurements on the order of several decibels in both configurations. The COUGARxt configuration also reports lower wind noise levels than COUGAR by up to four decibels, likely due to its thicker wind screen.

In summary, both the COUGAR and COUGARxt microphone configurations record satisfactory acoustic data. COUGARxt outperforms COUGAR under windy conditions at low frequencies and also experiences less azimuthal variation.

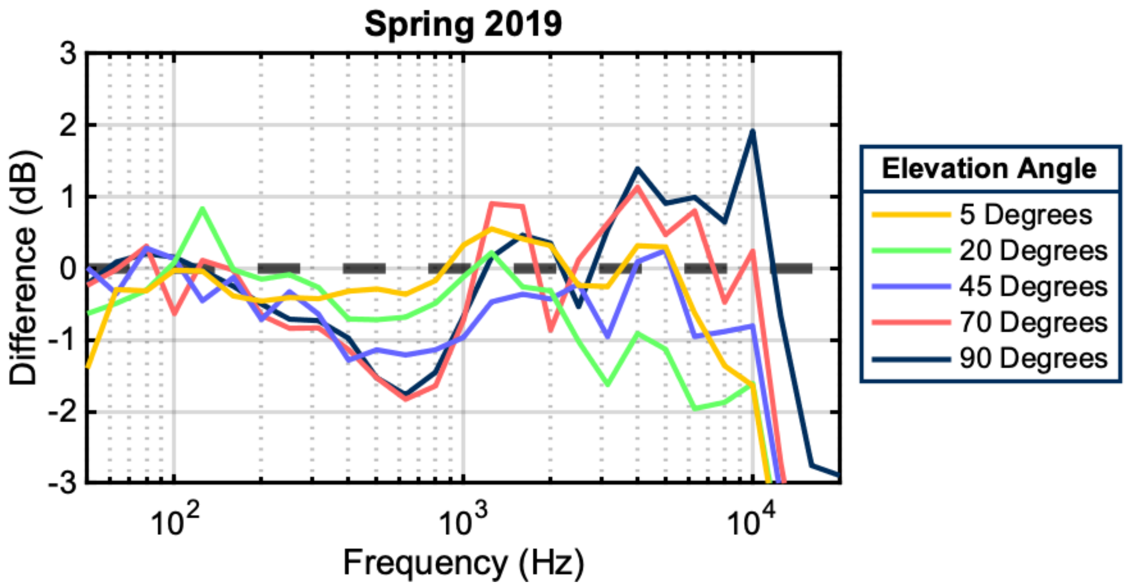
Appendix A

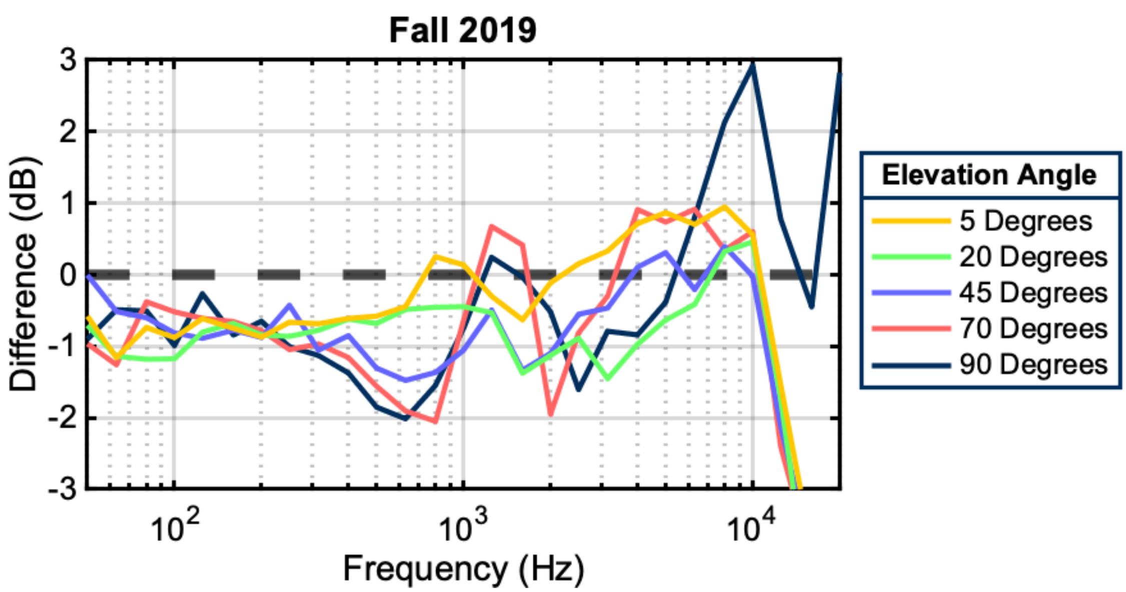
Repeatability Analysis

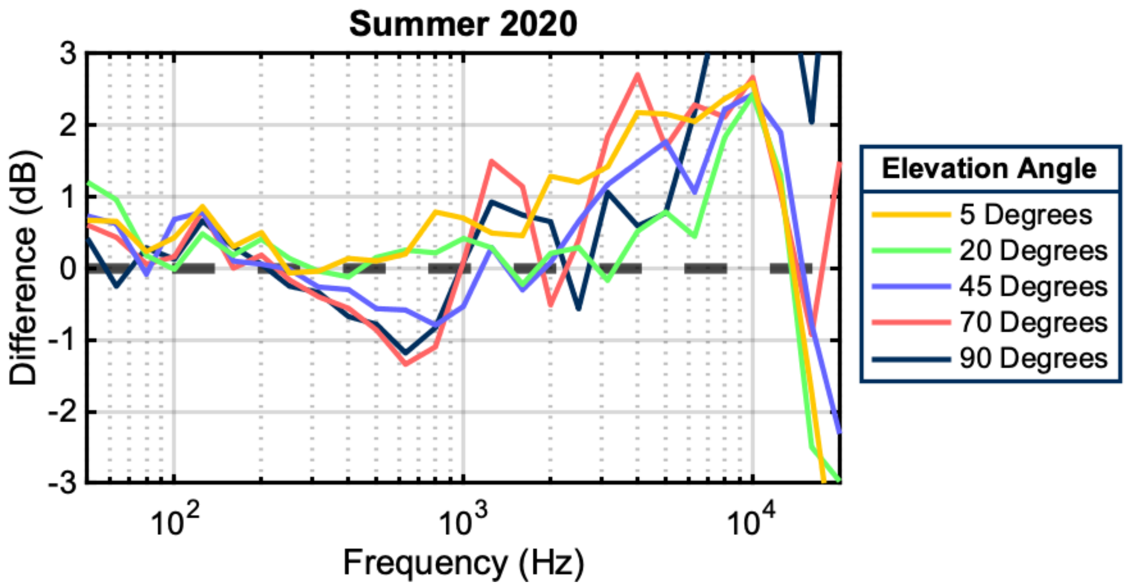
This appendix serves to show the amount to which these tests are repeatable. Several examples and general descriptions of tests performed will be given. Additional interpretation is left to the reader.

A.1 COUGAR in Standard Orientation

COUGAR was set up three times and tested in its standard configuration. These tests were performed without the rain cap and are shown relative to the baseline measurements for each respective test.

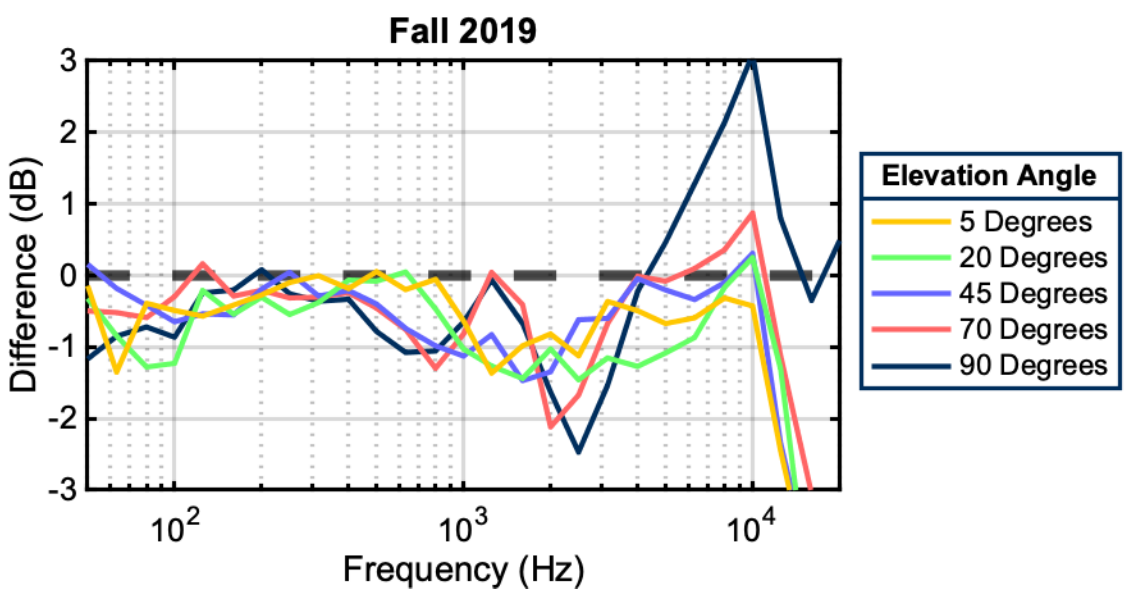

Spring 2019
Difference (dB)
Frequency (Hz)
Elevation Angle
5 Degrees
20 Degrees
45 Degrees
70 Degrees
90 Degrees

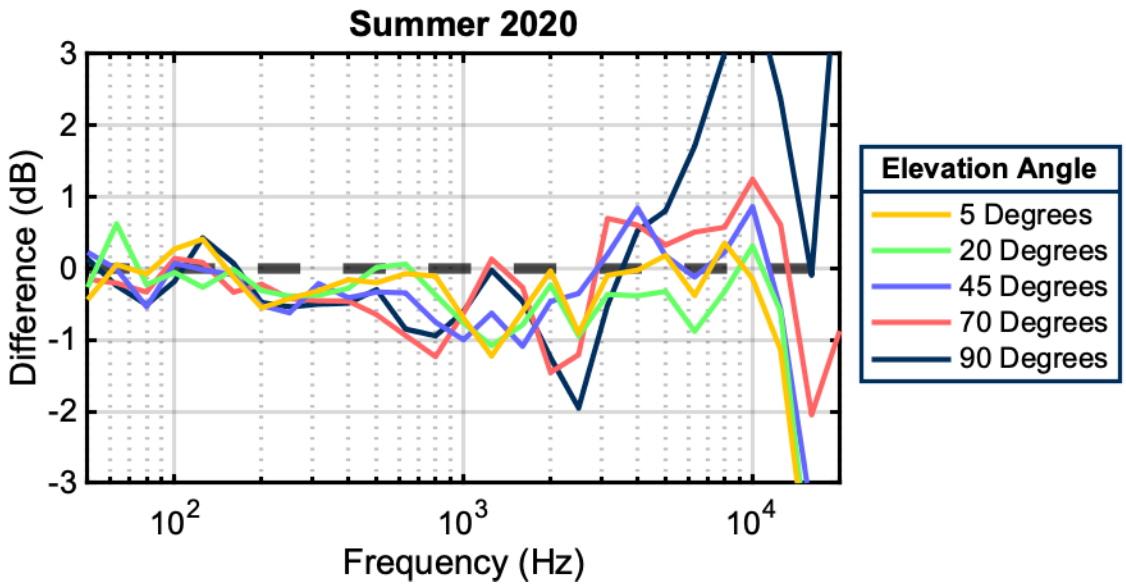

Fall 2019
Difference (dB)
Frequency (Hz)
Elevation Angle
5 Degrees
20 Degrees
45 Degrees
70 Degrees
90 Degrees



A.2 COUGARxt in Standard Orientation

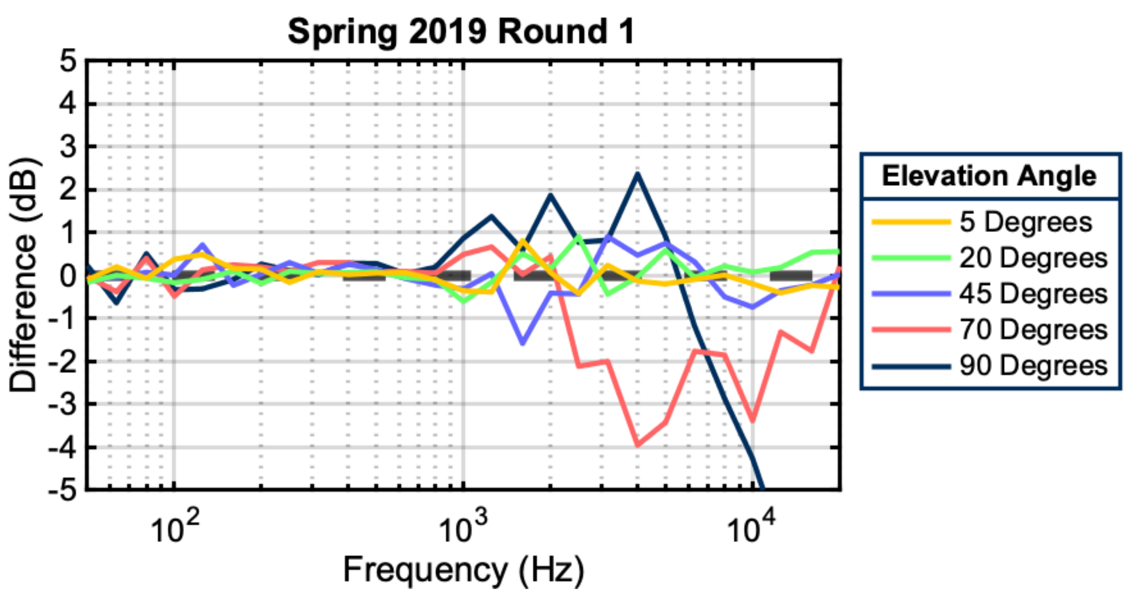
COUGARxt was set up twice and tested in its standard configuration. Tests were again performed without the rain cap and are shown relative to the baseline measurements for each respective test.

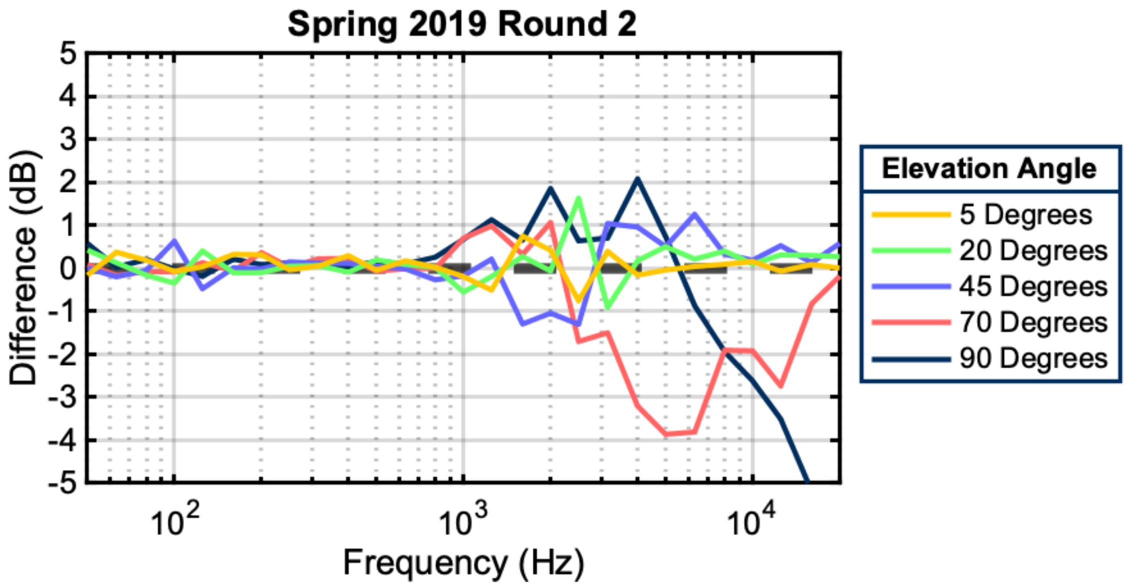


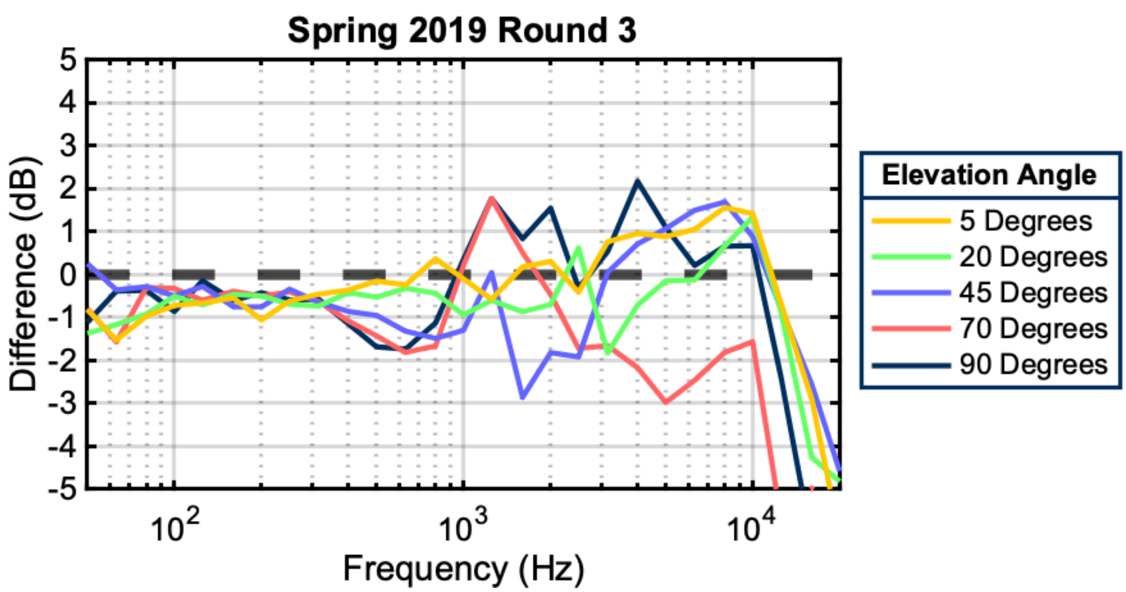


A.3 Rain Cap Effects

The rain cap was tested multiple times. The results below show the difference between the COUGAR with a rain cap and the COUGAR without a rain cap. Negative values indicate that the COUGAR without a rain cap reported higher values at that frequency.



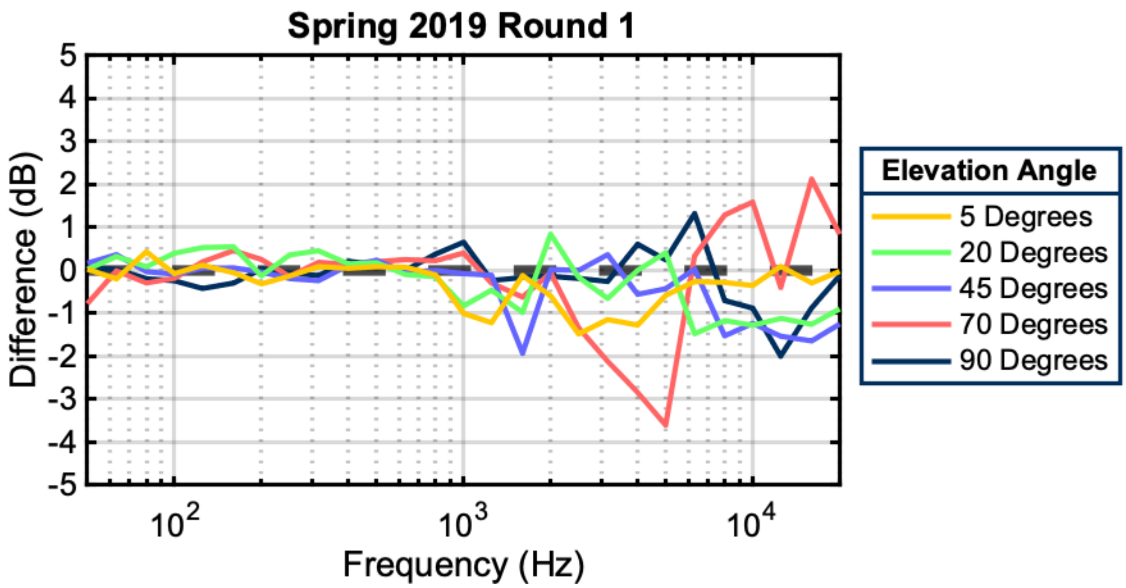


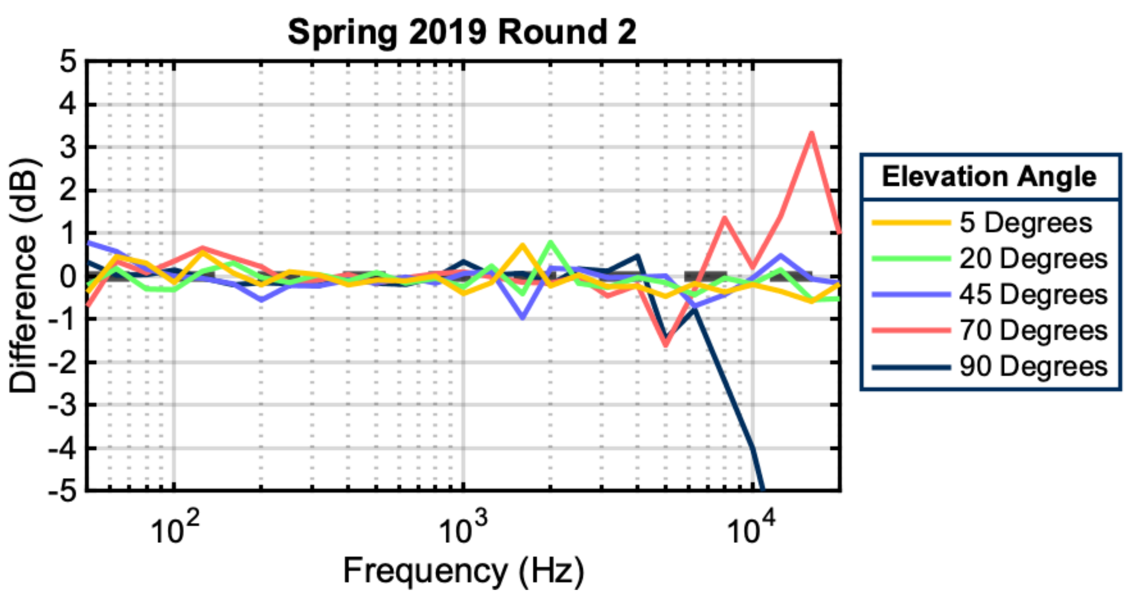


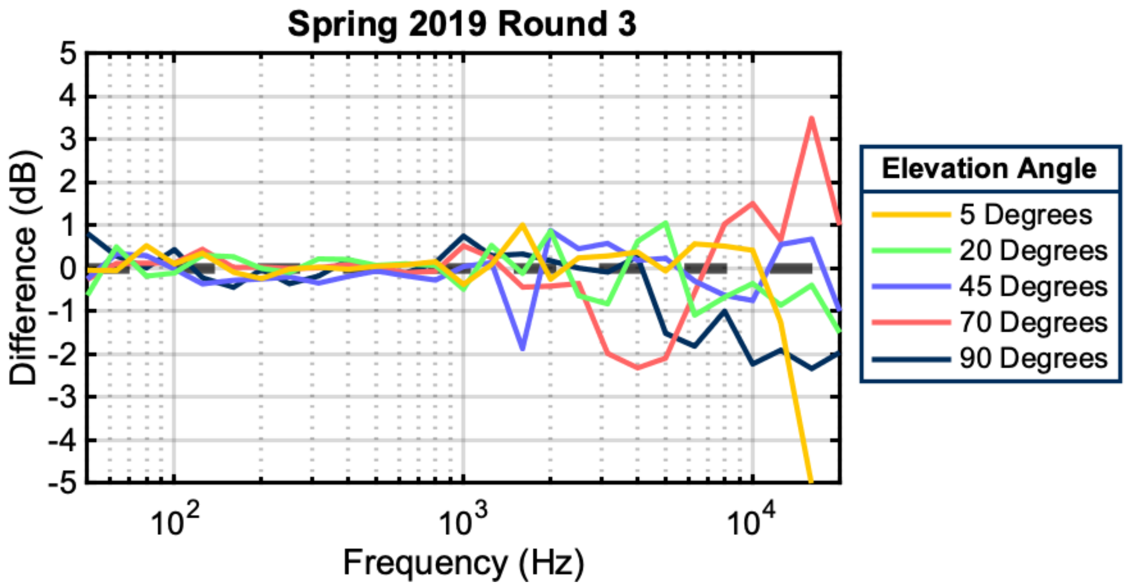
A.4 COUGAR Wind Screen Sand Saturation

Saturating the COUGAR wind screen with sand was done three times. These tests used the same COUGAR wind screen before and after sand saturation to ensure there were not effects due to using a different wind screen. Results show the difference between the saturated and clean cases.

Negative values indicate that the clean version reported higher values at that frequency.






Spring 2019 Round 3
Difference (dB)
5
4
3
2
1
0
-1
-2
-3
-4
-5
10^2
10^3
10^4
Frequency (Hz)
Elevation Angle
5 Degrees
20 Degrees
45 Degrees
70 Degrees
90 Degrees

Appendix B

Getting the Data and Code

- The raw data for this thesis are located on Box at:

  https://byu.box.com/s/ugvj7r1dpzmr58u7ilu15iot9zwbzpuk

- The code for this thesis is located at:

  https://github.com/Mark-C-Anderson/Senior_Thesis_Mark_Anderson_Code

  and depends on code located at:

  https://git.physics.byu.edu/acoustics/general/GeneralSignalProcessing

  https://git.physics.byu.edu/acoustics/general/ArrayAnalysis

  The particular commit IDs at which these repositories were at the conclusion of this thesis are indicated in the Manifest.csv file in the main repository. In case any of the code has since been modified, you can reach the code as it was at the time these figures were generated by looking for the v1.0.0 tag in the main repository.

  When attempting to reproduce the results, keep in mind that you may need to change some file paths.

- If you would like to access the repository containing the LaTeX code for this document, it can be found at:

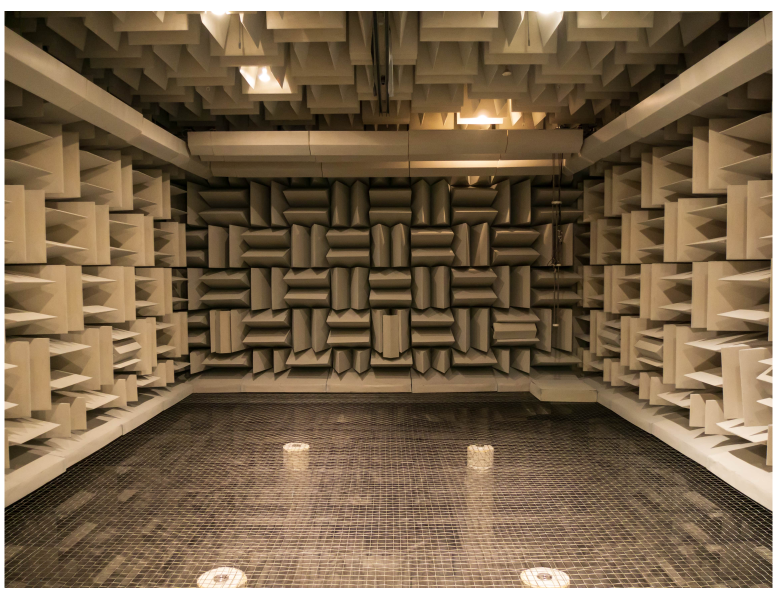
  https://github.com/Mark-C-Anderson/Mark_Anderson_Senior_Thesis_Document

Appendix C

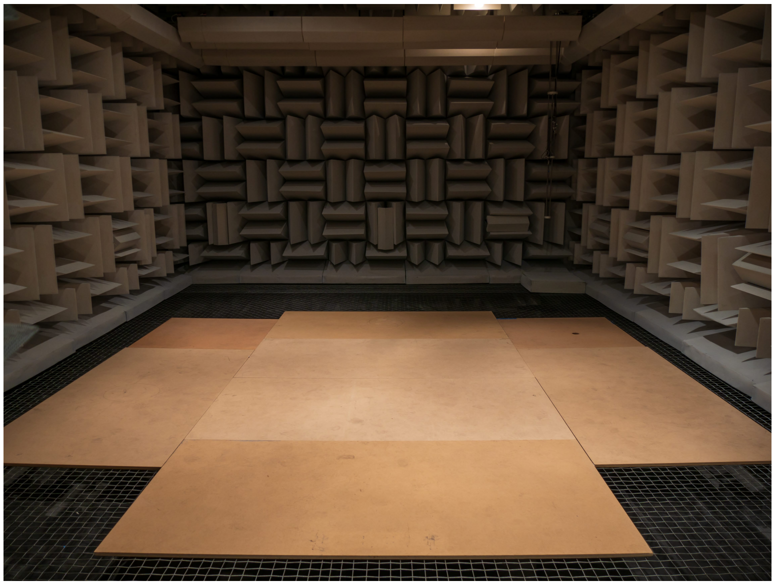
Setting Up The ARC

The goal of this appendix is to teach the reader how to set up the ARC. Pictures are shown for each key step.

1. Because the ARC is so large, make sure that the anechoic chamber is empty.

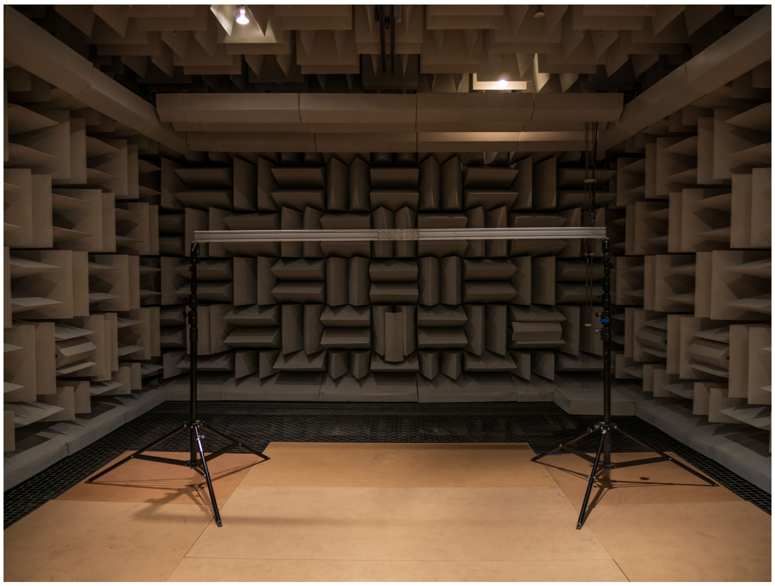


2. Place the MDF boards in the chamber as shown below.

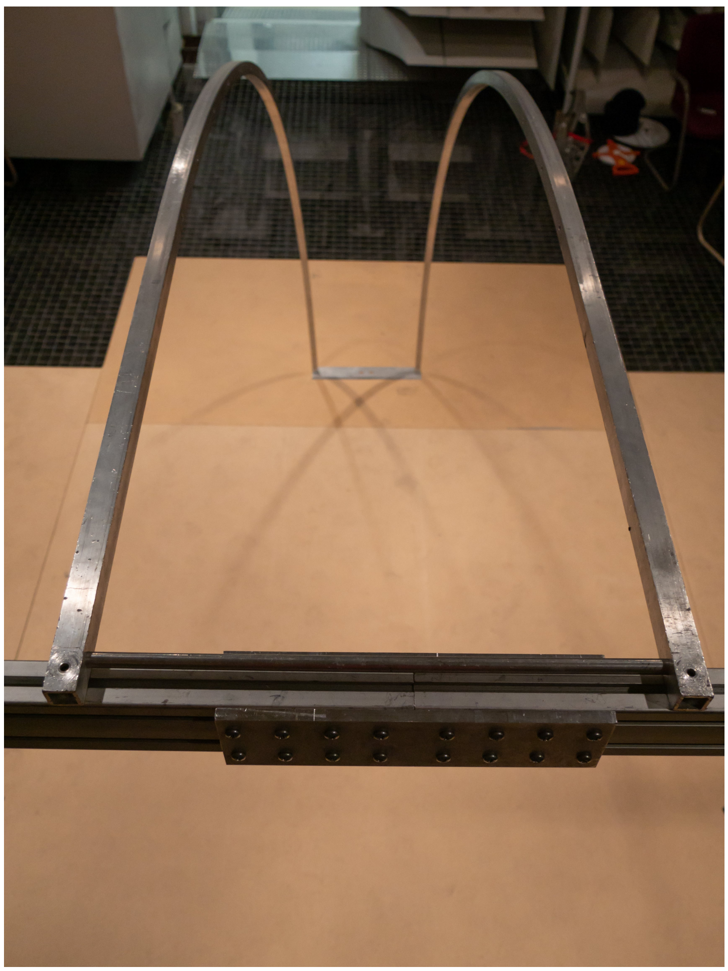


3. Put the tripods on the far end of the boards.

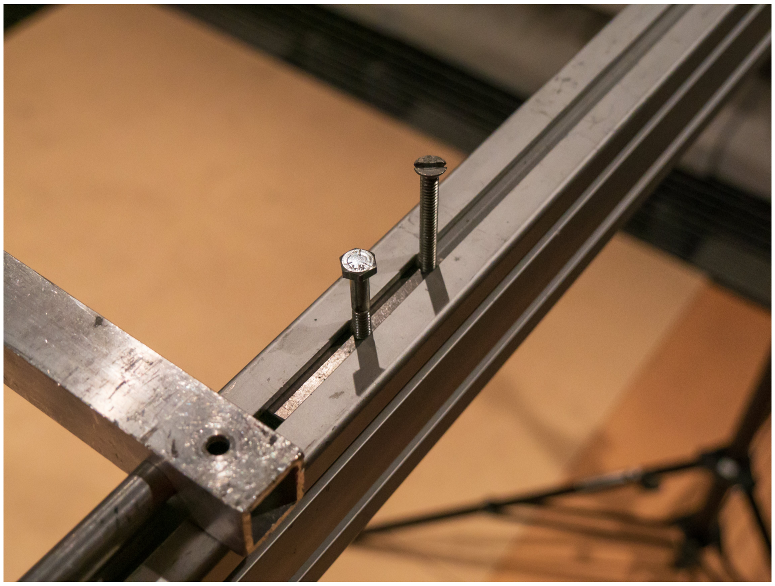
4. Bolt the two halves of the crossbar together. Each face of the crossbar required sixteen bolts. Note that one of the faces may only have fifteen due to issues with the threading. Either end of the assembled crossbar should have a metal dowel in it that inserts directly into the tops of the tripods.



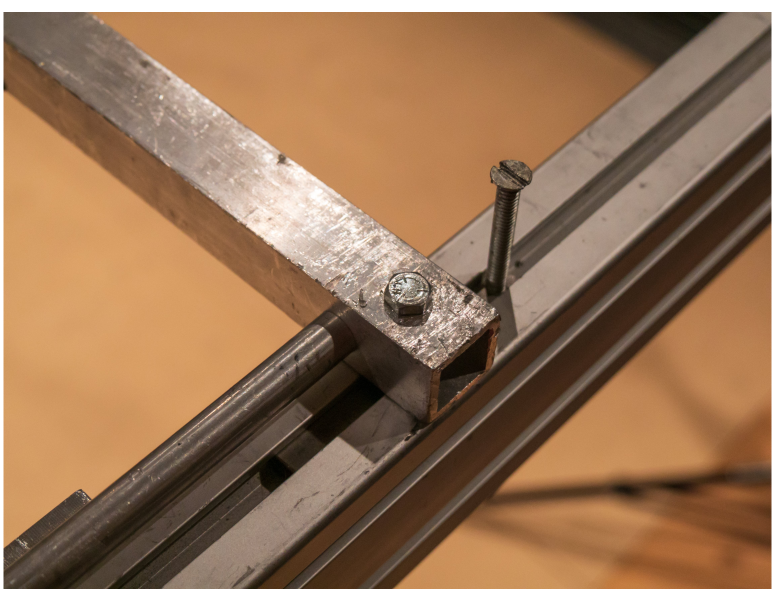
5. Assemble the two halves of the actual arc. Each one of the metal arcs comes in two pieces. There should be metal dowels that fit into each other. There is a metal base that both of the assembled arc pieces connect two via two metal dowels. A cylindrical metal piece connects the tops of the separate arc halves, with screws on either side to connect the two halves to it. Once complete, rest the arc on top of the crossbar. Adjust the height of the crossbar until the top of the arc is approximately flat, but don't worry about being too precise at the moment. An overhead view is shown below.



6. Take the peices that slide into the top of the crossbar (one for each side), screw the two screws into both of them, and slide them in towards the center of the crossbar near the arc halves.

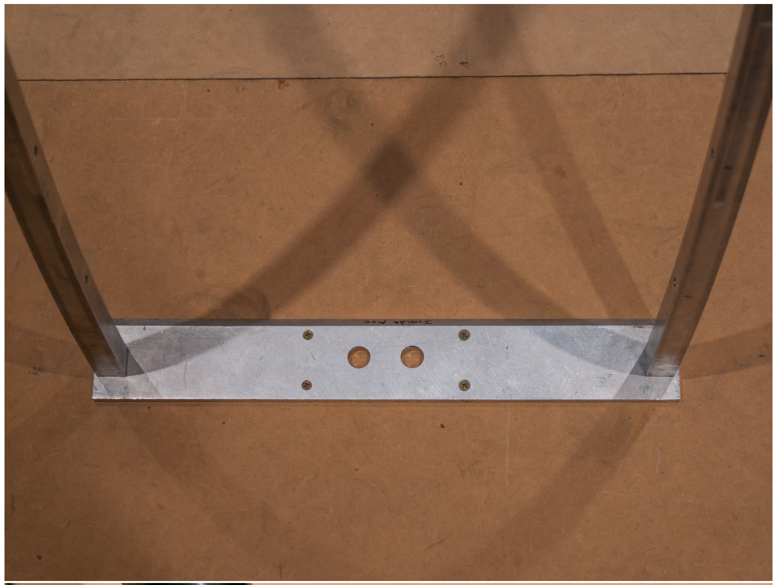


7. Unscrew the inside screw, shift the sliding metal piece that the screws attach to underneath the arc halves, and re-screw the inside screw into it through the hole in the top of the arc halves. This firmly connects the arc halves to the crossbar. This process can be tedious, but it does work so be careful not to cross-thread the pieces.

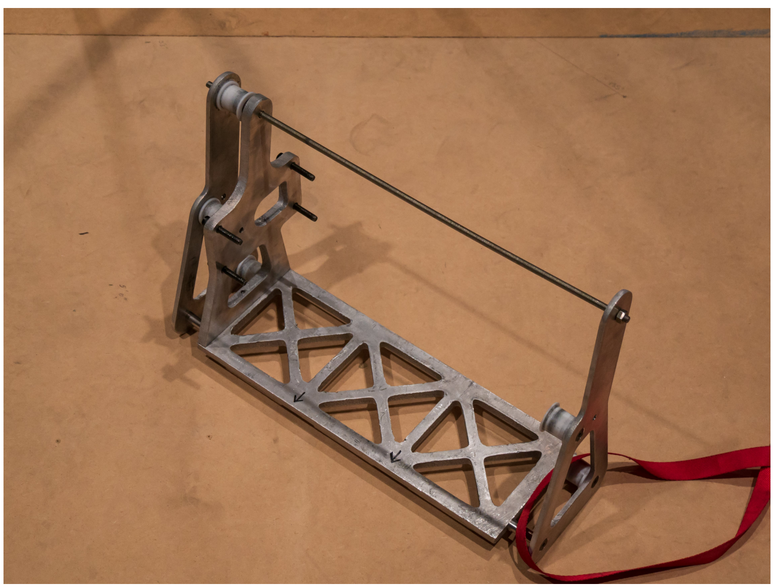


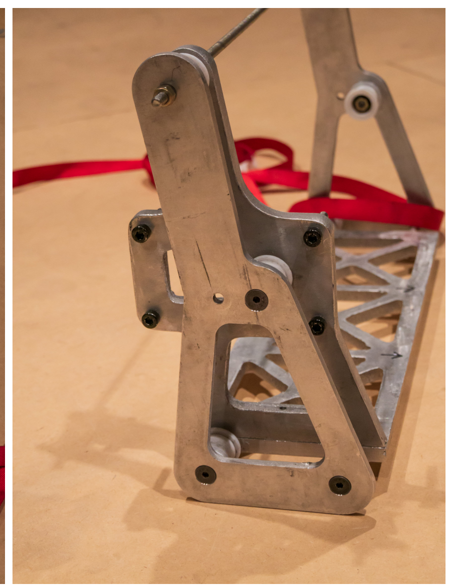
8. Now measure the crossbar height and bring it to a little under seven feet. Get a level and make sure that the center of the crossbar and the tops of the arc segments are all flat. This is likely to be an iterative process, especially if you are setting this up by yourself.

9. When you are satisfied with the heights, make sure to screw down the tripods and the base plate for the arc halves.

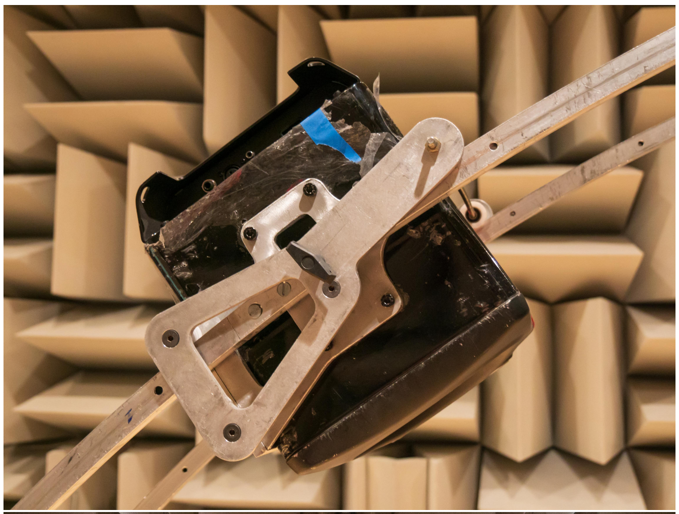


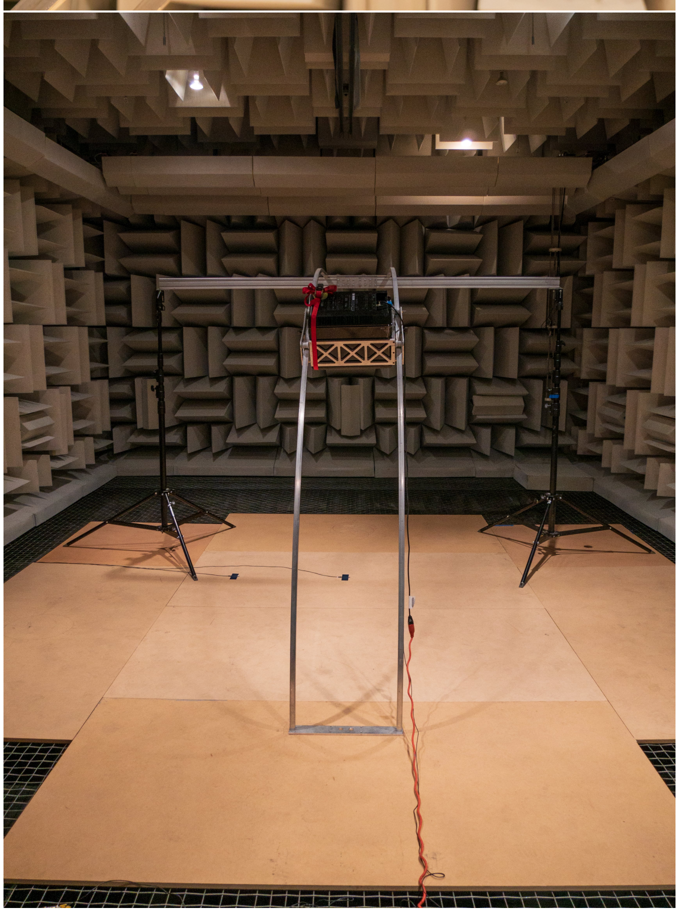
10. Locate the speaker holder. If it is not already assembled, then that is very unfortunate. However, if needed you can definitely assemble it. Detailed instructions are omitted from this thesis but help may be sought by reaching out to Mark Anderson at anderson.mark.az@gmail.com. I may not respond immediately but will help as needed. The four screws on one end of the holder screw directly into the bottom of an HR824mk2 speaker. Also note that this speaker has a known interference null at about 13 kHz that will not show up much on one-third octave plots but is easily spotted on narrowband spectra. This has been validated with two separate HR824mk2 speakers in two separate labs, one at BYU and one at NASA Langley Research Center.



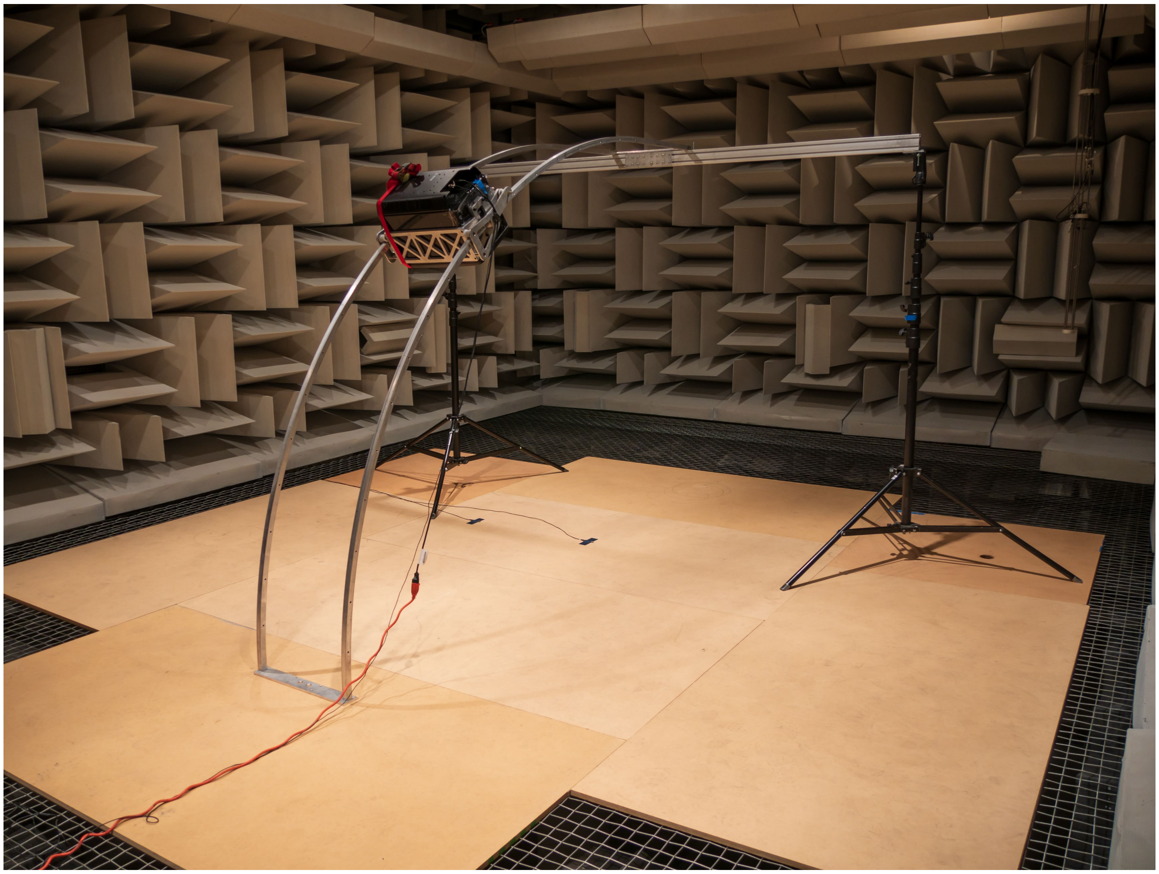


11. Connect the speaker to the speaker holder. You'll also want to secure the top of the speaker (the side not screwed in) by using the red ratchet strap. When doing so, make sure not to cover any sound-producing parts of the speaker (ie. the woofer or the tweeter).





12. The setup is now complete. Two pictures are shown below.



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