

Analysis of Current Electric Pickup Technology Utilized in Clarinet Performance  
and Investigation into Potential Improvements

by

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## ABSTRACT

Despite the growth of technology in music composition and performance, professional clarinetists maintain that air microphones are superior to piezoelectric pickups. Pickups offer increased mobility, isolation, and reduced feedback, but air microphones are used simply for the perceived sound quality. In this study a ported barrel pickup and a contact transducer pickup placed at various intervals on the clarinet were sampled and compared to a reference recording to determine how the sound differed for each method. In addition, the history of wind instrument pickups, the acoustics of the clarinet, and the basics of piezoelectricity were discussed to help examine the results. The pickups were examined in three ways: overall level in decibels, frequency cutoff, and overtone displacement. Through these results it was determined that the most accurate methods of clarinet pickup are the ported barrel pickup, contact transducers closer to the vibration of the reed such as the ligature or barrel surface, or a transducer placed at the end of the bell. These findings were consistent with the discussions regarding history, clarinet acoustics, and piezoelectricity. This study also produced a reference for the sounds associated with different pickup methods, as well as possible improvements for clarinet pickup design.

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# TABLE OF CONTENTS

	Page
LIST OF FIGURES.....	vi
CHAPTER	
1 INTRODUCTION.....	1
2 HISTORY.....	3
First Wave of Wind Instrument Pickup Systems.....	4
Moving Away from Pickups.....	9
The Second Wave of Modern Pickup Systems.....	13
3 CLARINET ACOUSTICS.....	16
4 PIEZOELECTRICITY.....	23
Basics of Piezoelectricity.....	23
Why Piezoelectricity?.....	27
5 COMPARATIVE STUDY ON CURRENT PICKUP METHODS.....	30
Explanation of Study.....	30
Difficulties of Study.....	31
Procedure.....	32
Analysis.....	41
Results.....	44
Sample Level in dB.....	45
Frequency Cutoff.....	48
Overtone Displacement.....	54
E7.....	55

CHAPTER	Page
B6 .....	56
G-sharp6 .....	57
E6 .....	59
B5 .....	60
G-sharp5 .....	61
E5 .....	63
B4 .....	64
G-sharp4 .....	66
E4 .....	68
B3 .....	70
G-sharp3 .....	72
E3 .....	73
Discussion.....	75
Empirical Listening.....	79
Possible Improvements.....	80
BIBLIOGRAPHY .....	82
 APPENDIX	
A NALBANTOV NCM 8X COMPARISON AND DATA.....	86
B LARGER GRAPHS FROM “OVERTONE DISPLACEMENT” .....	104
C SAMPLE DATA WAVEFORM dB .....	118
D SAMPLE DATA FULL SPECTROGRAM .....	130
E SAMPLE DATA E3 .....	142

APPENDIX	PAGE
F SAMPLE DATA E3 .....	154
G SAMPLE DATA G-SHARP3 .....	166
H SAMPLE DATA B3 .....	178
I SAMPLE DATA E4 .....	190
J SAMPLE DATA G-SHARP4 .....	202
K SAMPLE DATA B4 .....	214
L SAMPLE DATA E5 .....	226
M SAMPLE DATA G-SHARP5 .....	238
N SAMPLE DATA B5 .....	250
O SAMPLE DATA E6 .....	262
P SAMPLE DATA G-SHARP6 .....	274
Q SAMPLE DATA B6 .....	274
R SAMPLE DATA E7 .....	286

## LIST OF FIGURES

Figure	Page
4.1 Diagram from APC International Ltd. Illustrating Directions of Forces .....	25
4.2 Diagram from Piezo Technologies Showing Direction of Forces in a Disc.....	25
5.1 Ligature (LIG) Placement of Contact Pickup .....	34
5.2 Ported Barrel Pickup (BAR Port) by PiezoBarrel.....	35
5.3 Barrel Surface (BAR Surf) Placement of Contact Pickup.....	35
5.4 Barrel Surface Placement of Contact Pickup; Plastic Cover Removed (BAR NC)....	36
5.5 LefreQue Plates Spanning the Mouthpiece and Barrel Joint (LF MPB).....	36
5.6 LefreQue Plates Spanning the Barrel and Upper Joint Tenon (LF BUJ) .....	37
5.7 Upper Joint (UJ) Placement of Contact Pickup .....	37
5.8 Center Tenon (CTR) Placement of Contact Pickup .....	38
5.9 Lower Joint (LJ) Placement of Contact Pickup .....	38
5.10 Outside of Bell (BELL Out) Placement of Contact Pickup.....	39
5.11 End of Bell (BELL End) Placement of Contact Pickup .....	39
5.12 Strength of Fundamental in Decibels for each Pitch per Pickup Method.....	45
5.13 Spectrogram of Reference Gsharp-3 .....	48
5.14 Spectrogram of Ligature (LIG) Gsharp-3 .....	49
5.15 Spectrogram of LefreQue at Mouthpiece-Barrel (LF MPB) E3 .....	50
5.16 Spectrogram of Upper Joint (UJ) E3 .....	52
5.17 Spectrogram of Center Tenon (CTR) E3.....	52
5.18 Spectrogram of Lower Joint (LJ) E3 .....	53
5.19 Spectrogram of Outside of Bell (BELL Out) E3.....	53

Figure	Page
5.20 Spectrogram of End of Bell (BELL End) E3 .....	54
5.21 Frequency Response for E7 .....	56
5.22 Frequency Response for B6 .....	57
5.23 Frequency Response for G-sharp6 .....	58
5.24 Frequency Response for E6 .....	60
5.25 Frequency Response for B5 .....	61
5.26 Frequency Response for G-sharp5 .....	63
5.27 Frequency Response for E5 .....	64
5.28 Frequency Response for B4 .....	66
5.29 Frequency Response for G-sharp4 .....	68
5.30 Frequency Response for E4 .....	70
5.31 Frequency Response for B3 .....	71
5.32 Frequency Response for G-sharp3 .....	73
5.33 Frequency Response for E3 .....	74
A.1 Nalbantov NCM 8X Barrel Pickup with Included Barrel.....	88

## CHAPTER 1-INTRODUCTION

The integration of technology in music composition and performance throughout the 20<sup>th</sup> and 21<sup>st</sup> centuries has necessitated the amplification of the clarinet. Due to the prominence of the clarinet in contemporary literature, works requiring amplification, performance with tape, interactive electronics, or other multimedia have created this need. At first microphones were the only means to amplify the clarinet, but in the 1960s wind instrument pickups were developed that allowed the performer to amplify the instrument with less danger of feedback. Despite this apparent benefit and the explosion of works requiring amplification, pickups never gained wide popularity.

Most performers today choose air microphones when performing works requiring amplification if the natural acoustic sound of the clarinet is required; if pickups are used, it is due to the use of extensive processing or specialty sounds where the natural sound of the clarinet would be obscured. Thus, the first goal of this paper is to examine how and why pickups are considered to be inferior to air microphones in reproducing natural clarinet tone despite offering many performance benefits such as mobility, portability, and sound isolation.

Chapter 2 focuses on the historical context of pickup use, starting with the first wave of pickups introduced in the 1960s. Chapter 3 examines clarinet acoustics in order to build a basic model of sound production to understand how the two types of pickups, ported and surface mounted, interact with the acoustic system of the clarinet. Chapter 4 discusses the basics of piezoelectricity, how pickups work, and why clarinet pickups use piezoelectricity.

The main study conducted for this paper is outlined in Chapter 5, a comparison of multiple pickup methods to a reference recording in order to examine how current pickup systems differ from the natural acoustic sound of the clarinet. The samples are compared on the basis of three factors: overall level in decibels of the sample, frequency cutoff, and overtone displacement. Through these three factors, it can be seen how the sound captured by a pickup differs from the natural clarinet sound.

## CHAPTER 2-HISTORY

The history of barrel pickups is difficult to trace due to the relatively small niche that wind instrument pickups occupy in music history as a whole. The term barrel pickup is used to describe the style of pickup that captures sound directly from the bore, most commonly in the barrel of the clarinet. The first difficulty lies in the evidence available: outside of a handful of advertisements and price catalogues, most evidence is anecdotal. A small number of recordings were created where the use of early pickup systems is evident either through the title or the sound, but the relative lack of recordings brings up the second issue with pickup history: the professional perception surrounding early attempts at wind instrument pickups. Despite the availability for most wind instruments, both wind and brass, the use of pickups never took root among wind players for a variety of reasons, both artistic and economic.

The third difficulty is the short time in which wind instrument pickups were widely marketed. Wind instrument pickups came onto the scene in the mid- to late 60s, in reaction to the growing interest in electric instruments in pop culture. On the other end, the development of the Electronic Wind Instrument (EWI) and digital synthesis in the 1970s would for the most part provide all the benefits of the wind instrument pickup systems, and although the sound could be more artificial it was much cleaner, lacking the distortion and poor sound quality of pickup systems. Thus, wind instrument pickups only occupy the space of a decade before music all but moved on from them.

## The First Wave of Wind Instrument Pickup Systems

Barrel pickups for the clarinet first started to surface in the 1960's, with several brands marketing pickups including King/Vox, Gibson, Selmer, and Leblanc. These pickups differed little from the selections today, working in basically the same fashion, through a port in the barrel, mouthpiece, neck, or lead pipe of the instrument of choice. While these pickups were available individually, they were heavily marketed to be paired with an accompanying effects unit. Selmer's offering, the Varitone, was one of the first wind instrument pickups available from major music instrument makers and was mainly marketed toward saxophonists, being sold as both a pickup unit for retrofitting an existing instrument as well as a full instrument pre-fitted with the Varitone system. The Varitone consisted of a pickup mounted at the neck that was connected to a unit attached to the bell that allowed for adjustment of the volume and tone as well as echo, tremolo, and octave (-1) effects.<sup>1</sup> Two of the most notable names to use the Varitone are Eddie Harris and Sonny Stitt, both of whom used the Varitone saxophone on several records.

A cursory listen to the recordings using Varitone saxophone illustrates some of the problems that plagued early pickups: it was neither flexible enough to fully change the sound of the instrument appreciably, nor was it able to reproduce the sound as faithfully as a quality studio microphone.<sup>2</sup> The recordings by Harris showcase how the Varitone could enhance performance with the octave/timbre effects of the unit and use of outboard effects. However, the recordings produced by Stitt showcase the unfortunate

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<sup>1</sup> Mark Myers, "Sonny Stitt: Varitone Redux." *JazzWax* (blog), December 20, 2011, <http://www.jazzwax.com/2011/12/sonny-stitt-varitone-redux.html>.

<sup>2</sup> Ibid.

limitations of the system, mainly the thin and artificial sound. A representative list of albums by Harris and Stitt including the Varitone follows:<sup>3</sup>

Eddie Harris:

*The Tender Storm*, Atlantic (1478), 1966  
*Mean Greens*, Atlantic (1453), 1967  
*Plug Me In*, Atlantic (1506), 1968  
*The Electrifying Eddie Harris*, Atlantic (1495), 1968  
*Silver Cycles*, Atlantic (1517), 1969  
*High Voltage*, Atlantic (1529), 1969  
*Free Speech*, Atlantic (1573), 1970  
*Is It In*, Atlantic (1659), 1974  
*Bad Luck Is All I Have*, Atlantic (1675), 1975  
*The Reason Why I'm Talking Shit*, Atlantic (18165), 1975  
*This Is Why You're Overweight*, Atlantic (1683), 1976  
*Playin' With Myself*, RCA Records (AFL 1-3402), 1979  
*The Real Electrifying Eddie Harris*, Mutt & Jeff Records (MJ 5018), 1982

Sonny Stitt:

*What's New*, Roulette (R 25343), July 1966  
*I Keep Coming Back!*, Roulette (R 25346), 1966  
*Parallel-a-Stitt: Stitt on the Varitone*, Roulette (R 25354), 1967  
*Made for Each Other*, Delmark (DS 426), July 1968  
*Soul Electricity*, Prestige (PR 7635), September 1968  
*Little Green Apples*, Solid State (SS 18047), October 1968  
*Come Hither*, Solid State (SS 18057), 1968  
*Brothers 4*, Prestige (PR 7738), September 1969  
*Night Letter*, Prestige (PR 7759), October 1969  
*Turn It On!*, Prestige (PR 10012), January 1971  
*You Talk That Talk!*, Prestige (10019), February 1971  
*Just the Way It Was: Live at the Left Bank*, Label M (5703), March 1971  
*Black Vibrations*, Prestige (PR 10032), July 1971

Vox offered two types of pickups, the Uni-level and the Vari-level, with the Vari-level providing, “built-in instrument control range,” to be used with the Ampliphonic system—a system very similar to the Varitone in that the pickup connected to a separate

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<sup>3</sup> List compiled from: Myers, “Sonny Stitt,” <http://www.jazzwax.com/2011/12/sonny-stitt-varitone-redux.html>; Eddie Harris, “Discography,” accessed March 11, 2018, [eddieharris.com](http://eddieharris.com); record numbers from [discogs.com](http://discogs.com).

box with controls for volume and effects.<sup>4</sup> Three versions were created for use with a variety of instruments: the Ampliphonic I was intended for use with the clarinet, compared with the II (brass) and III (woodwinds), and gave the options for adding oboe (doubling the current octave with a different timbre), bass clarinet (one octave down) or contrabass clarinet (two octaves down).<sup>5</sup>

Barcus-Berry, a company created in 1963 between Les Barcus and John Berry, allegedly created the first piezoelectric transducer for use with musical instruments.<sup>6</sup> However, relatively little evidence apart from the anecdotal is available regarding the products created by the company during the initial boom in wind instrument pickups. A notable clarinetist to allegedly utilize a Barcus-Berry pickup was Bill Smith, who performed with Dave Brubeck in addition to his classical career, in which he was better known as William O. Smith. According to message boards dedicated to various instruments, many other musicians have utilized classic Barcus-Berry pickups as well, with mention of two designs for clarinet: one in the style of other pickups of the time that attached via a ported barrel, and another that was more similar to a simple contact transducer that was placed behind the reed. Unfortunately, any mention of these methods is purely anecdotal and cannot be substantiated beyond a picture of Smith performing with a barrel pickup.

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<sup>4</sup> *Ampliphonic Equipment Price List*, Vox Ampliphonic/Thomas Organ Company, June 23, 1968, available via North Coast Music, <http://www.voxshowroom.com/catalogs/TAA.html>.

<sup>5</sup> *Octavoice Clarinet I Owners Manual*, Vox Ampliphonic/Thomas Organ Company, 1968, available via North Coast Music, <http://www.voxshowroom.com/us/amp/octavoicel.html>.

<sup>6</sup> “History,” Barcus-Berry, accessed March 11, 2018, <http://barcusberry.com/history.cfm>.

Gibson's offering came along at the beginning of the 70s, offering the Maestro multi-effects unit. The Maestro was marketed to guitarists as well as woodwind players, likely the reason that of all the woodwind pickup units it is the most widely available today. The Maestro came supplied with a barrel fitted with a pickup and offered tremolo as well as various octave and timbre manipulations.<sup>7</sup> Richard Lockwood of the Australian band Tully recounts using the Maestro, "it was a room-shaking, monster of an instrument with a range of about seven octaves, including harmonics and *freak* notes, and screams and squeals effected by biting the reed."<sup>8</sup>

Unfortunately, by the mid-70s many of these devices were being phased out if not entirely dropped by their respective makers. One of the likely causes for the lack of success with these initial units was the cost. Wind instrument pickup systems were simply too expensive, especially when compared to the price for a guitar. A 1968 price list for the Vox Ampliphonic series shows the minimum cost to be around \$140.00, which would include the Uni-level pickup (\$29.50) and the least expensive Nova Amplifier (\$105.00), not to mention the additional cost of an instrument.<sup>9</sup> In comparison, price lists from Fender show that an electric guitar and amplifier could be had for as little as \$167.50.<sup>10</sup> In addition to the purchase price, another cost would be the retrofitting of

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<sup>7</sup> "Gibson Maestro W-1 Sound System for Woodwinds," Effects Database, submitted October 30, 2009, <http://www.effectsdatabase.com/model/maestro/w1#reviews>.

<sup>8</sup> "Insights," Richard Lockwood, Little Paper Boats, accessed March 11, 2018, [http://www.littlepaperboats.com/Richard\\_Lockwood.html](http://www.littlepaperboats.com/Richard_Lockwood.html).

<sup>9</sup> *Ampliphonic Price List*, Vox/Thomas, 1968, North Coast Music, [voxshowroom.com](http://voxshowroom.com).

<sup>10</sup> *Fender Musical Instruments Price List*, Fender Musical Instruments, October 1968.

the existing instrument to accept the pickup, a conversion that requires drilling into the bore of the instrument, which was likely seen as destroying the equipment.

Another issue with the early wind instrument pickups was the sound quality. As previously discussed, the Varitone had a sound that could be likened to a saxophone that had “swallowed a kazoo.”<sup>11</sup> The numerous anecdotal reports of using various types of pickups substantiate the claim that pickups did not have nearly as pleasing of a sound, but that it was acceptable for live sound applications; this sentiment can be tempered by the relative lack of surviving professional records or recordings utilizing the various pickup methods.

Finally, the new technologies of digital synthesis and the EWI started to be developed in the 70s and would offer all of the benefits of the pickup systems and more without the poor sound quality and destruction to the existing equipment. The EWI was invented by Neil Steiner as the woodwind version of his Electronic Valve Instrument (EVI) that was debuted in 1975, and enjoyed much more popularity among mainstream performers than any of the pickup systems.<sup>12</sup> The development of digital synthesis such as the GROOVE (Generated Realtime Operations On Voltage-controlled Equipment) system developed at Bell Laboratories in the late 1960s and many others would move music in another direction, away from wind instrument pickups.<sup>13</sup>

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<sup>11</sup> Myers, “Sonny Stitt.” *JazzWax*.

<sup>12</sup> “The Neil Steiner Homepage,” Patchman Music, updated September 18, 2017, <http://www.patchmanmusic.com/NyleSteinerHomepage.html>

<sup>13</sup> Thomas D. Rossing, F. Richard Moore, Paul A. Steiner, *The Science of Sound*, 3<sup>rd</sup> ed., (San Francisco: Addison Wesley, 2002): 628.

### Moving Away from Pickups

Despite most major music instrument manufacturers moving away from wind instrument pickups by the mid-1970s, the repertory of music for clarinet and tape or clarinet with electronic manipulation was about to expand greatly. Phillip Rehfeldt's book *New Directions for Clarinet* includes a representative list of works for clarinet and tape or other electronics; the list includes 68 works, 42 of which list the date of composition between 1973 and 1985 (the second edition released in 1994 updated the bibliography somewhat from the 1977 version, though it is still only representative), and the earliest listed at 1961.<sup>14</sup> Many clarinetists specializing in new and contemporary music were experimenting with electronic accompaniment either through composition or commission, most notably F. Gerard Errante and Burton Beerman. As music technology advanced and programs such as Max/MSP gave composers greater freedom and performance capabilities, so too did the repertoire for clarinet and electronics. Rachel Yoder's doctoral document on the performance practice of interactive music involving the clarinet contains a bibliography of over 100 pieces for clarinet and interactive electronics, with all from the 1990s or early 2000s.<sup>15</sup>

While it could be considered that the expansion of electronic applications in classical music for the clarinet was a niche market not significant enough to warrant continued production of pickup systems by major manufacturers, what is curious is not

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<sup>14</sup> Phillip Rehfeldt, *New Directions for Clarinet*, rev. ed. University of California Press, (Lanham: Scarecrow Press Inc., 1994): 138-139.

<sup>15</sup> Rachel Yoder, "Performance Practice of Interactive Music For Clarinet And Computer With An Examination Of Five Works By American Composers," (DMA diss., University of North Texas, 2010), 127-132.

that major manufacturers stopped producing pickups but rather that classical music sources barely recognize that pickups existed at all. Rehfeldt describes two specific pickups, the Barcus-Berry reed transducer and a barrel mounted pickup available from DEG Music Products, with no specific mention of the other pickups described in the previous section.<sup>16</sup> Dutch bass clarinetist Harry Sparnaay, a well-known commissioner of new music in the same timeframe being discussed (1970-2000s), writes extensively about the problems associated with all manner of electronics in pieces that he has performed in addition to the accomplishments of some of his students; despite the breadth he includes on the topic, he does not mention utilizing a pickup once.<sup>17</sup>

Yoder's dissertation includes a survey of nine clarinetists known for extensive performance with electronics, including F. Gerard Errante, Burton Beerman, Michael Lowenstern, and Laura Carmichael. Of the nine surveyed, only four used a pickup, and only for works where a pickup provided better sonic results.<sup>18</sup> All of the clarinetists surveyed claimed to use a microphone, citing the improved reproduction of the natural clarinet sound.<sup>19</sup>

The issue at the heart of the matter for classical clarinetists seems to be quality of sound. Rehfeldt corroborates the issue of sound quality, stating that although the benefits include reduced feedback, isolation, and improved response with certain effects, the

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<sup>16</sup> Rehfeldt, *New Directions*, 84.

<sup>17</sup> Harry Sparnaay, *The Bass Clarinet: A Personal History*, 3<sup>rd</sup> ed., (Barcelona: Periferia Sheet Music, 2010): 107-122.

<sup>18</sup> Yoder, "Performance Practice of Interactive Music," 73-124.

<sup>19</sup> Ibid.

disadvantage is “fairly low fidelity of the clarinet’s sound.”<sup>20</sup> This sentiment seems to carry over to composers of works for clarinet and electronics, where in examining a representative group of compositions for clarinet and electronics, none mention utilizing a pickup in performance, instead specifying a quality studio microphone. Though only a small minority of pieces were examined, the group consists of several standards for clarinet and electronics, such as *Passages of the Beast* (1978) by Morton Subotnick, *New York Counterpoint* (1985) by Steve Reich, and *Asana* by William O. Smith, as well as several more recent compositions.<sup>21</sup> It is conceivable Subotnick and Reich would not know of pickup systems for clarinet despite their experience in electronic music, but as discussed earlier there is evidence, albeit small, that Smith had previously used a pickup in performance.

Digging deeper into the survey conducted by Yoder, the choice of equipment for performers depends mainly on sound quality. Several of the performers surveyed mentioned using a microphone produced by Applied Microphone Technology Inc. (AMT) that features two gooseneck microphones that can be placed at both the middle tenon and at the bell.<sup>22</sup> The perception among the performers surveyed was that this placement captured the full range of the instrument in such a way that no notes stuck out and provided an accurate representation of their acoustic sound.<sup>23</sup> For those performers

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<sup>20</sup> Rehfeldt, *New Directions*, 84.

<sup>21</sup> Morton Subotnick, *Passages of the Beast for Solo Clarinet and an Electronic Ghost Score*, (New York: Schott Music Corporation, 1978); Steve Reich, *New York Counterpoint*, (Winona: Hal Leonard, 1986); William O. Smith, *Asana*, (Rome: Edipan, 1988); other scores listed in Bibliography.

<sup>22</sup> “AMT WS,” Applied Microphone Technology Inc., accessed March 11, 2018, <https://appliedmicrophoneshop.com/products/amt-ws>.

<sup>23</sup> Yoder, “Performance Practice Of Interactive Music,” 73-124.

that utilized pickups, the reasoning was either for “tracking” as Errante specified (likely referencing early pitch tracking devices), or for capturing a specific sound other than the natural acoustic sound of the clarinet. Laura Carmichael describes further the type of sounds that a ported pickup would give:

I have also used a small contact mic inside the clarinet mouthpiece, by using a mouthpiece in which I drilled a hole in the side, as close to the cork joint as possible. This was for special effects related to processing a lot of air and mouth sounds and wanting no acoustic room sound in the sound.<sup>24</sup>

Carmichael further specifies that, “if the sound coming out is very processed, in other words, we do not hear the clarinet as a clarinet so much anymore...close dynamic mics with plenty of gain on them can be reliable while preventing feedback issues.”<sup>25</sup>

Though most performers did not express dissatisfaction with barrel or contact microphones, timbral demands of a given piece create a clear differentiation in equipment choice. The perception seems to be that unless a piece greatly processes the sound so that the natural clarinet sound is obscured, ‘pickups’ or contact microphones are an inferior choice to traditional microphones. However, this sentiment is perhaps outdated, with the performers surveyed being already well-established prior to the 2010 publication of the Yoder dissertation; only the oldest performers of the group would have been performing during the first wave of pickup systems. The issues of the original pickups notwithstanding, evidence of pickup systems during the 30 years after the first wave of systems in the 1960s-70s is nearly nonexistent. Pickup technology was limited to the surviving units or custom devices which would likely not offer much improvement, such

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<sup>24</sup> Yoder, 81.

<sup>25</sup> Yoder, 81-82.

as using a hearing aid as a barrel microphone.<sup>26</sup> However, since the publication of Yoder's dissertation, several options have become available that challenge the argument of sound quality.

### **The Second Wave of Modern Pickup Systems**

Recently, barrel pickups have made a resurgence either through new development or increased exposure via the internet. Taking design cues from the original models of the 1960s, several companies offer ported barrel pickups for clarinet as well as many other instruments. PiezoBarrel is a company located in Australia and run by Steve Francis, who started making barrel pickups in 2014 with the goal of creating an affordable, 'plug and play' package.<sup>27</sup> Through work with Linsey Pollack, a YouTube creator known for creating homemade clarinets, Steve has developed what is currently one of the most affordable barrel pickups at 129.00 AUD, roughly 100.00 USD.

Rumberger Sound Products, based in Germany, also offers two types of pickups, the K1X and the WP-1.<sup>28</sup> The K1X attaches at the barrel, while the WP-1 is meant to be attached via a port in the mouthpiece. Both are significantly more expensive, with the K1X and the WP-1 priced at 389.00 Euro (500.00 USD) and 339.00 Euro (420.00 USD),

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<sup>26</sup> Godfried-Willem Raes, "Contact Microphones For Clarinets," uploaded December 14, 2009, <http://logosfoundation.org/kursus/4523.html>.

<sup>27</sup> Musevibe, "Home Of The PiezoBarrel," accessed March 11, 2018, <http://www.musevibe.com>.

<sup>28</sup> "K1X Pickup for Clarinet and Saxophone," Rumberger Sound Products, accessed March 11, 2018, <https://www.rumberger-soundproducts.de/en/products/pickups-for-woodwind-instruments/k1x/>; "WP-1 Built-in Pickup," Rumberger Sound Products, accessed March 11, 2018, <https://www.rumberger-soundproducts.de/en/products/pickups-for-woodwind-instruments/wp-1/>.

respectively. Nalbantov Electronics based in Bulgaria offers the NCM 8X, priced in the middle at around 300.00 USD.<sup>29</sup>

Of particular note is the Greek company TAP, which produces several different types of pickups ranging from as affordably priced as the PiezoBarrel, to even more expensive than the Rumberger.<sup>30</sup> TAP appears to cater to performers of folk music rather than classical music, since the sound examples provided are of the folk genre, and their list of performing artists includes a great number of folk musicians.<sup>31</sup>

Two of the companies listed above, PiezoBarrel and Nalbantov, are newer examples, only becoming available around 2014-15.<sup>32</sup> Rumberger was started in 1991, though according to online shop thomann.de the K1X has been available since 2012.<sup>33</sup> TAP was started in 1986, making them the oldest company of the group. Thus, with the exception of TAP, these products did not exist at the time of the Yoder dissertation, and so performers would rightfully be unaware of them. Furthermore, as stated above, TAP achieved success through folk musicians rather than the classical performers surveyed by Yoder.

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<sup>29</sup> “Nalbantov NCM 8X Professional Microphone for Clarinet,” Nalbantov Electronics Ltd., accessed March 11, 2018, <https://n-electronics.com/nalbantov-ncm-8x-professional-microphone-for-saxophone/>.

<sup>30</sup> “Products-Clarinet and Saxophone,” TAP Electronics, accessed March 11, 2018, <http://www.tap.com.gr/en/products/clarinet-saxophone.html>.

<sup>31</sup> Ibid.

<sup>32</sup> “Home of the PiezoBarrel,” Musevibe, accessed March 11, 2018, <http://www.musevibe.com/>; “Product Listing-Nalbantov NCM 8X,” Amazon.com, accessed March 11, 2018, [https://www.amazon.com/Clarinet-Microphone-Nalbantov-NCM-set/dp/B00XNF5PR2/ref=sr\\_1\\_4?ie=UTF8&qid=1520817987&sr=8-4&keywords=nalbantov](https://www.amazon.com/Clarinet-Microphone-Nalbantov-NCM-set/dp/B00XNF5PR2/ref=sr_1_4?ie=UTF8&qid=1520817987&sr=8-4&keywords=nalbantov).

<sup>33</sup> “Product Listing-Rumberger K1X,” Thomann GmbH, accessed March 11, 2018, [https://www.thomannmusic.com/rumberger\\_k1x\\_pickup\\_clarinet.htm](https://www.thomannmusic.com/rumberger_k1x_pickup_clarinet.htm).

What remains to be seen is if these new offerings solve the sound quality issues of the past, and if so, will performers utilize this new wave of pickups? The former question is one goal of this paper: to determine how the modern barrel pickup differs in response from air and contact microphones, and from that if the barrel pickup is the optimal choice of current pickup technology. However, as shown above, there is still significant stigma attached to pickups that current designs will have to overcome.

## CHAPTER 3-CLARINET ACOUSTICS

Over the last 60 years, the study of clarinet acoustics has revealed much about how all of the various parts of the instrument interact to create the clarinet's distinctive tone. Starting with the work of Arthur Benade, John Backus, and others in the 1960s to more recent research, notably at the University of New South Wales (UNSW), researchers have created highly detailed models of how the instrument, reed, and player interact to create musical sound. The research conducted into clarinet acoustics is concerned with pure acoustic playing, that is, how the natural sound of the clarinet is produced. Since the main objective of this paper is examining how barrel or contact pickups differ from the pure acoustic sound of the instrument, a basic acoustic model of the clarinet is necessary for determining the validity of pickup methods and potential improvements in current designs. To this end, the discussion that follows is a brief survey of the pertinent acoustic concepts that will inform the analysis of pickup findings, rather than a complete technical model of the acoustic properties of the clarinet.

To begin building a model for this paper, consider first the oft-cited example of a clarinet as a simple cylinder with one end open and the other closed. At the open end, the pressure is atmospheric pressure, or zero acoustic pressure.<sup>34</sup> At the opposing end, when air is introduced into the instrument it creates a maximum pressure variation in the mouthpiece that travels down the effective length of the instrument to where the acoustic pressure is zero and dissipates, which sends a negative pressure back towards the

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<sup>34</sup> "Clarinet Acoustics: An Introduction," University of New South Wales (UNSW) Music Acoustics, accessed March 11, 2018, <http://newt.phys.unsw.edu.au/jw/clarinetacoustics.html>.

mouthpiece and is reflected back down the cylinder.<sup>35</sup> The reed affects the reflection of these pulses during its oscillation because as the negative pulse reaches the mouthpiece, the reed has moved so close to the mouthpiece that it is nearly closed, and thus reflects the negative pressure back towards the open end of the instrument.<sup>36</sup> Another way of understanding this is considering that in creating a sine wave, the distance between the maximum (pressure at the mouthpiece) and zero (atmospheric pressure at the bell/open end) is one-quarter of a full wavelength.<sup>37</sup> This open-closed configuration is what gives the clarinet a more extended low range compared to other members of the woodwind family, since the wavelength is four times the effective length of the cylinder. The open-closed configuration is also the cause for support of only the odd harmonics; since the pressure variation must be a maximum at the closed end and zero at the open end, the even harmonics are not well supported—even wavelengths would start with zero pressure at the closed end, which is impossible for a closed-open cylinder.<sup>38</sup>

In practice, there are several concepts that complicate the simple model of a clarinet as an open-closed cylinder. The spectra produced from any number of studies on the clarinet will show that the even harmonics are present, and their relative strength is frequency dependent; even harmonics become proportionally stronger at higher frequencies compared to the odd harmonics, until there is no functional difference.<sup>39</sup> The

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<sup>35</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 247.

<sup>36</sup> Rossing, et al., 247-248.

<sup>37</sup> UNSW, “Clarinet Acoustics: An Introduction.”

<sup>38</sup> Ibid.

<sup>39</sup> UNSW, “Clarinet Acoustics: An Introduction.”

decreasing difference in even/odd ratios is due to the cutoff frequency determined by the tone-hole lattice, the specific acoustic impedance on a particular note, and the resonances of the reed and vocal tract.

Going back to the simple model of a closed-open cylinder, adding open tone holes to the cylinder will create what was coined by Arthur Benade as a “tone-hole lattice.”<sup>40</sup> At lower frequencies, the sound will begin radiating from the first open tone hole, but as the frequency increases the sound travels further down the bore of the instrument past the beginning of the tone-hole lattice.<sup>41</sup> Due to this filtering effect, a high-pass filter in effect, where low frequencies are reflected and can thus be established while high frequencies continue to travel down the bore, a cutoff frequency can be determined for a particular instrument.<sup>42</sup> The cutoff frequency is the point at which frequencies cannot move the air in the tone-holes fast enough, and therefore travel beyond the first open hole or the entire length of the bore and are radiated by the bell, thereby limiting their presence in the overall spectrum.<sup>43</sup>

Based on Benade’s research, the cutoff frequency for the clarinet is roughly between 1.2 kHz-2.0 kHz, depending on the specific lattice of tone holes created—the fingering of the note.<sup>44</sup> This range allows for three regimes of frequencies, supplied via

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<sup>40</sup> Arthur H. Benade, *Fundamentals of Music Acoustics*, 2<sup>nd</sup> rev. ed. Dover Publications, (New York: Oxford University Press, 1976): 431.

<sup>41</sup> Benade, *Fundamentals*, 431-434.

<sup>42</sup> “Cutoff Frequencies, Crossfingering, and Half-Holing in Woodwinds,” UNSW Music Acoustics, accessed March 11, 2018, <http://newt.phys.unsw.edu.au/jw/cutoff.html>.

<sup>43</sup> Benade, *Fundamentals*, 431-435.

<sup>44</sup> *Ibid.* 489.

UNSW, based on how they behave at the first open tone-hole. The first regime, below the cutoff frequency, radiate from the first open hole—since the effective length of the pipe is equal for all frequencies of this regime, harmonics below the cutoff will be equally spaced.<sup>45</sup> The second regime, at or around the cutoff, extend beyond the first open hole, and therefore do not follow harmonic spacing, meaning that the harmonics of this regime are spaced closer together, resulting in a more complex sound.<sup>46</sup> The third regime, high frequencies above the cutoff, travel the entire length of the bore and become evenly spaced once more.<sup>47</sup>

With a simple model for the clarinet with tone holes, acoustic impedance, which is the ratio of acoustic pressure to acoustic volume flow, can now be discussed.<sup>48</sup>

Acoustic impedance is important to the discussion since it is a measurement of the acoustic potential of the instrument isolated from the player, which can be helpful in comparing ideal response to samples.<sup>49</sup> UNSW has conducted extensive research in this area regarding wind instruments in general, including the clarinet, and features an online resource that includes impedance spectra for the notes E3-C-sharp7.<sup>50</sup>

The impedance spectrum of a given note will show maximum and minimum extrema which can be used to identify resonances and anti-resonances of standing waves

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<sup>45</sup> UNSW, “Cutoff Frequencies.”

<sup>46</sup> UNSW, “Cutoff Frequencies.”

<sup>47</sup> Ibid.

<sup>48</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 243.

<sup>49</sup> “What is Acoustic Impedance and Why is it Important?” UNSW Music Acoustics, accessed March 11, 2018, <http://newt.phys.unsw.edu.au/jw/z.html>.

<sup>50</sup> “Clarinet Acoustics,” UNSW Music Acoustics, accessed March 11, 2018, <http://newt.phys.unsw.edu.au/music/clarinet/>.

in the bore.<sup>51</sup> In the case of the clarinet, consider the simple model proposed above: the reed nearly closes the end, and so the acoustic flow is low, while pressure variation is large.<sup>52</sup> Thus, the ratio of pressure to flow is large, meaning that resonances will fall roughly at the maxima, which correspond to the odd harmonics as shown in ideal cylinder examples provided by UNSW.<sup>53</sup>

However, when considering the cutoff frequency of the tone-hole lattice as well as the effect of the bell, the impedance spectrum of the clarinet becomes much more different from that of the ideal closed-open cylinder. Frequencies at or around the cutoff frequency create an irregular impedance spectrum due to end corrections, and so from roughly 1.4-2.4 kHz the impedance spectrum for the clarinet becomes irregular.<sup>54</sup> Above this range, the frequencies travel the length of the bore and therefore the impedance becomes more regular. However, the bell acts to lengthen the bore, affecting frequency more as it increases, as well as radiate high frequencies, and so the maxima of the impedance spectrum are closer together above the cutoff frequency range.<sup>55</sup>

The reed also plays an important role in determining the spectrum of the instrument. The reed has a resonance frequency of its own, which is around 2000-3000 Hz, much higher than the typical operating boundaries of the clarinet.<sup>56</sup> The reed also

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<sup>51</sup> Paul Dickens, Ryan France, John Smith, and Joe Wolfe, "Clarinet Acoustics: Introducing a Compendium of Impedance and Sound Spectra," *Acoustics Australia* 35, no. 1 (April 2007): 17-24, <http://newt.phys.unsw.edu.au/jw/reprints/AAclarinet.pdf>

<sup>52</sup> *Ibid.*, 19-21.

<sup>53</sup> *Ibid.*, 19-21.

<sup>54</sup> UNSW, "Cutoff Frequencies."

<sup>55</sup> *Ibid.*

<sup>56</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 254.

generates harmonics of its own, both even and odd, though the natural harmonics of the reed are damped by the lower lip, and typically impedance of the bore overpowers that of the reed, further damping certain harmonics.<sup>57</sup> The reed is forced to vibrate at the frequency supported by the bore.<sup>58</sup>

However, if the impedance of the reed or the vocal tract is sufficiently large enough to overpower the impedance of the bore, particularly at higher frequencies, the resonance of either the reed or vocal tract will become the primary resonance. An example of this action with the reed is a squeak, where the higher natural frequency of the reed overtakes that of the bore, causing a squeak. As shown through research by Chen, Smith, and Wolfe, the vocal tract, when tuned to the proper resonance at a suitably high frequency, can overtake the resonance of the bore.<sup>59</sup> This level is located above 600 Hz, roughly corresponding to written E5 on the B-flat clarinet. At this level, the player can tune the resonance of the vocal tract and create a higher impedance than that of the bore, thus overtaking the resonance of the bore. This is especially important in the high reaches of the altissimo, above the natural cutoff frequency of the instrument where resonances are not supported as well in the bore and are determined from the reed or vocal tract.

One final matter of importance to the discussion of pickups is how the body of the instrument interacts with the overall sound. In any sound, most of the total energy is lost

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<sup>57</sup> UNSW, "Clarinet Acoustics: An Introduction."

<sup>58</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 249.

<sup>59</sup> Jer-Ming Chen, John Smith, and Joe Wolfe, "Pitch Bending and *glissandi* on the Clarinet: Roles of the Vocal Tract and Partial Tone Hole Closure" *Journal of the Acoustical Society of America* 126, no. 3 (September 2009): 1511-1520, <http://newt.phys.unsw.edu.au/jw/reprints/ChenetalJASA09.pdf>

through damping of the walls of the instrument.<sup>60</sup> The actual energy represented as audible sound is a small portion of the total energy input by the player, as most energy is lost through friction.<sup>61</sup> A study by John Backus shows that the loss of energy to the walls of the instrument does not affect the tone of the instrument by radiating sound itself or by altering the harmonic structure.<sup>62</sup> Furthermore, the vibrations of the body were found to be mostly caused from the vibrations of the reed striking the mouthpiece rather than expansion from the pressure waves within the bore.<sup>63</sup> However, as shown above, the reed oscillations are typically forced into compliance with the resonance of the bore, and would therefore oscillate with a similar structure to the resonance in the bore, which is defined by the volume and shape of the bore rather than the material itself.

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<sup>60</sup> Benade, *Fundamentals*, 444-447.

<sup>61</sup> Ibid.

<sup>62</sup> John Backus, "Effects of Wall Material on the Steady-State Tone Quality of Woodwind Instruments," *Journal of the Acoustical Society of America* 36, no. 10 (October 1964): 1881-1887, <https://doi.org/10.1121/1.1919286>.

<sup>63</sup> Ibid 1883-4

## CHAPTER 4-PIEZOELECTRICITY

Similar to the previous chapter on clarinet acoustics, a brief discussion regarding piezoelectricity is important to understanding how clarinet pickups work, why piezoelectricity is the chosen means for clarinet pickups, and understanding the results of the following study. Research into piezoelectricity has even more depth than that of clarinet acoustics, and so what follows is not meant to be an in-depth explanation of piezoelectricity, but rather an introduction to the concepts at work to better understand how piezoelectricity is utilized for clarinet pickups.

### **Basics of Piezoelectricity**

Piezoelectricity is a characteristic found in certain materials wherein an electrical charge is produced as a result of mechanical strain. This phenomenon was discovered in 1880 by the brothers Jacques and Pierre Curie while researching certain crystalline minerals that exhibited electric polarization in response to mechanical strain.<sup>64</sup> Not only did polarization occur as a result of mechanical strain, but compression and tension generated voltages of opposing polarity.<sup>65</sup> Conversely, it was found that applying an electric field to the crystals would result in deformation of the crystal; similarly, the crystal would deform according to the polarity and in proportion to the strength of the applied electrical field.<sup>66</sup> These discoveries outline the basic principles of the

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<sup>64</sup> *Piezoelectric Ceramics Principles and Applications*, 2<sup>nd</sup> ed., APC International, Ltd., (Mackeyville: APC International, Ltd., 2011): 8.

<sup>65</sup> Ibid.

<sup>66</sup> Ibid.

piezoelectric effect, voltage generated from applied mechanical strain, and the inverse piezoelectric effect, elastic strain generated from an applied electric field.

Since the initial discovery by the Curie brothers, piezoelectric potential has been observed in many more naturally occurring materials as well as man-made substances including ceramics, piezo-polymers and other composites.<sup>67</sup> Each of these materials exhibits different characteristics in terms of the various piezoelectric constants, which determine how the material exhibits the piezoelectric or inverse piezoelectric effects.<sup>68</sup> The variety of materials exhibiting a wide array of tolerances has contributed to the use of piezoelectric materials in many sectors as sensors, actuators, and transducers.

Three main characteristics determine how a piezoelectric element will function: the composition of the piezoelectric material, the polarization of the element, and the shape of the element. The composition, briefly described above, not only determines the piezoelectric constants of the material, but also how well it will accept polarization and its mechanical strength, which will affect how the element can be shaped. For instance, certain materials, such as lead titanate, are more difficult to polarize, and as a result are not used as often as other materials.<sup>69</sup> Materials with poor mechanical strength would similarly be poorly suited to applications where a very thin element is required, or large amounts of mechanical strain are applied to the element.

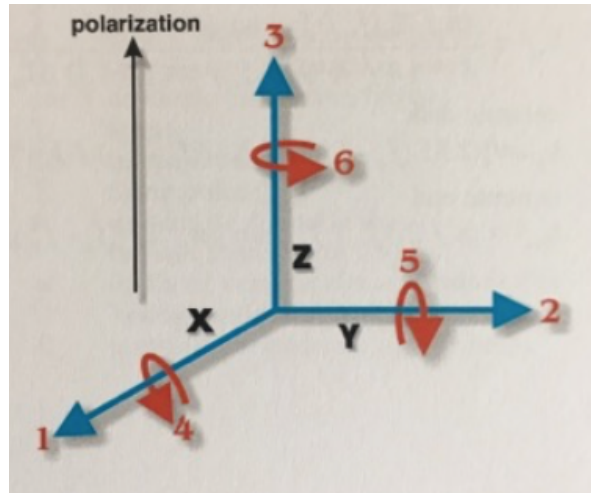
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<sup>67</sup> “Piezoelectric Transducers,” NDT Resource Center, accessed March 11, 2018, <https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/piezotransducers.htm>.

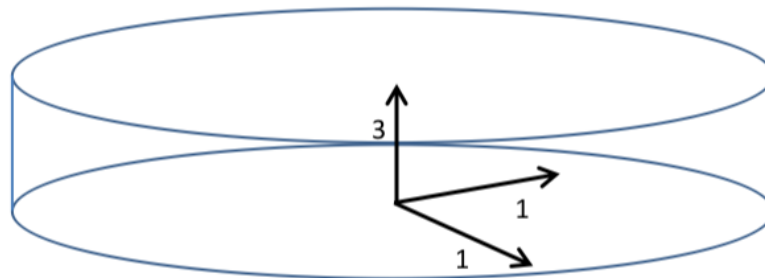
<sup>68</sup> “Intro to Piezoelectric Transducer Crystals,” Boston Piezo Optics Inc., accessed March 11, 2018, <http://www.bostonpiezooptics.com/intro-to-transducer-crystals>.

<sup>69</sup> APC International Ltd., “Piezoelectric Ceramics,” 9.

The polarization of an element makes the element anisotropic, meaning that its properties differ depending on the direction from which they are measured.<sup>70</sup> Polarization results in three axes, as shown in two diagrams below:



**Figure 4.1: Diagram from APC International Ltd. illustrating directions of forces.<sup>71</sup>**



**Figure 4.2: Diagram from Piezo Technologies showing direction of forces in a disc.<sup>72</sup>**

<sup>70</sup> APC International Ltd., "Piezoelectric Ceramics 10.

<sup>71</sup> Ibid., 13.

<sup>72</sup> "Piezo Technologies-Technical Resource Paper," Piezo Technologies, accessed March 11, 2018. <http://www.piezotechnologies.com/knowledge-desk/overview-piezo-materials>.

The direction of polarization is used in calculating several piezoelectric constants that are necessary for understanding how a particular element will function, including the piezoelectric voltage constant, the piezoelectric charge constant, and the electromechanical coupling factor, among others. These constants are used for determining how the element converts mechanical strain into electrical output or the specific mechanical strain that is created when the element is subjected to an electrical field.

The shape of the element is the final characteristic that determines how a specific element will react. The size and thickness of an element determine the bandwidth and resonance frequencies of the element, which correspond to the frequencies that a particular element will operate in either as a receiver or transmitter.<sup>73</sup> Elements can be formed into many shapes, including, plates, discs, rings, cylinders, rods, and many more.<sup>74</sup> Piezoelectric materials are very flexible in terms of size and shape in which they can be constructed, and as a result can cover huge bandwidths, from audible sound (20 Hz-20 kHz) up to the megahertz range.

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<sup>73</sup> “Characteristics of Piezoelectric Transducers,” NDT Resource Center, accessed March 11, 2018, <https://www.nde-ed.org/EducationResources/CommunityCollege/Ultrasonics/EquipmentTrans/characteristicspt.htm>.

<sup>74</sup> APC International Ltd., “Piezoelectric Ceramics,” 34-37.

## Why Piezoelectricity?

In a basic sense, sound is created through changes in pressure, typically through air but also through other mediums.<sup>75</sup> The change in pressure is what is perceived as sound, in this case by microphones or pickups which turn the change in pressure into an electrical signal. Different types of microphones convert the changes in pressure to changes in voltage in distinct ways. Dynamic microphones work under the principal of electromagnetic induction, wherein a diaphragm causes a coil to move in the field of a magnet to generate voltage.<sup>76</sup> Condenser microphones work with a capacitive design, where two metal plates are arranged facing each other and are connected to a voltage.<sup>77</sup> One plate is the movable diaphragm, which changes the distance between the plates when exposed to changes in pressure from sound waves, which will produce a voltage.<sup>78</sup>

Piezoelectric microphones work utilizing the previously discussed piezoelectric effect. The changes in pressure apply mechanical strain to the piezoelectric element, which generates voltage.<sup>79</sup> Though the concept between the three types is essentially the same, the deformation of a diaphragm, the piezoelectric element generates voltage from the deformation in relation to itself, not from the deformation of the diaphragm in relation to a stationary point. Thus, a piezoelectric element can be housed in a much smaller unit

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<sup>75</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 3.

<sup>76</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 451-452.

<sup>77</sup> "Microphone Handbook," PCB Piezotronics, accessed March 11, 2018.  
[http://www.pcb.com/microphonehandbookfiles/microphone\\_handbook\\_lowres.pdf](http://www.pcb.com/microphonehandbookfiles/microphone_handbook_lowres.pdf).

<sup>78</sup> Ibid.

<sup>79</sup> Rossing, et al., *Science of Sound*, 450.

compared to a dynamic or condenser style microphone. In turn, that provides a unit that can attach to the instrument directly as in the case of the barrel pickup.

Since piezoelectric elements produce voltage from applied strain on the element itself, contact microphones that pick up the vibrations of the instrument body are also possible. Building on the previous chapter, the waves that travel along the instrument body do not add significantly to the sound of the instrument.<sup>80</sup> Thus, directly placing an ‘air’ microphone to the body would do nothing; there would be no way for the diaphragm to move and create voltage. However, with a piezoelectric element in direct contact to the body of the instrument, the waves that travel along the body will put mechanical strain on the element and create voltage.

Considering the language used colloquially in music, it is worth noting the difference in meaning for the word ‘pickup’ as it applies to clarinet pickups compared to the pickups found in electric guitar. Guitar pickups work in a similar fashion to dynamic microphones, through electromagnetic induction.<sup>81</sup> The pickup on a guitar is a magnet wrapped with a coil which creates a magnetic field.<sup>82</sup> As the strings of the guitar are plucked within the field, this causes a disturbance which in turn creates the voltage necessary for amplification.<sup>83</sup>

Applying the same concept to clarinet would be much more difficult. The main oscillator of the clarinet is the reed, which poses several problems for using

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<sup>80</sup> Backus, “Effects of Wall Material,” 1887.

<sup>81</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 451.

<sup>82</sup> “Pickups 101,” Seymour Duncan, accessed March 11, 2018, <https://www.seymourduncan.com/support-pickups-101/getting-started>.

<sup>83</sup> Ibid.

electromagnetic induction in a pickup.<sup>84</sup> A reed made of steel, an absurd example, would likely cause much more damage to the tongue and mouth than the steel strings of a guitar would to the fingers. In addition, the placement of the reed inside the oral cavity would make it extremely difficult to, ‘pick up,’ so to speak, when adding the necessary magnet with coil to generate the magnetic field.

Since the reed is suitably difficult to ‘pickup’ using electromagnetic means, that leaves either the bore of the instrument, where the standing waves propagate, or the body of the instrument, where the vibrations of the reed are conducted.<sup>85</sup> In both cases, piezoelectric elements provide the best option for a pickup. Considering the concept of acoustic impedance, where the pressure changes inside the bore are different for each note, and how the clarinet operates at the maxima of pressure changes, the piezoelectric pressure sensor is a suitable option for capturing the sound inside the bore where another microphone would be obtrusive.<sup>86</sup> A piezoelectric transducer on the body of the instrument would also be affected by the waves conducted from the vibrations of the reed that other microphones would be unable to capture.

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<sup>84</sup> Rossing, Moore, and Wheeler, *Science of Sound*, 451.

<sup>85</sup> Backus, “Effects of Wall Material,” 1883-1884.

<sup>86</sup> UNSW, “What is Acoustic Impedance?”

## CHAPTER 5-COMPARATIVE STUDY ON CURRENT PICKUP METHODS

### **Explanation of Study**

The purpose of the following study is first to examine the spectra produced between a reference clarinet sound, the sound captured using a barrel mounted pickup, and the sound captured at various points on the clarinet from a contact microphone. From this data, the next task is to determine which pickup method most accurately represents the spectrum of the reference microphone. Similarity to the reference microphone sample is important due to the established importance of the natural, acoustic clarinet tone quality in the genre of classical music as shown in chapter 2.

The second purpose, after comparing the samples for similarity to the reference sample, is to provide a guide for what sounds can be captured from the various methods. Working under the assumption that each method will produce slightly different results, the purpose is to establish a palette of possibilities for performers and composers to make informed creative decisions when utilizing a clarinet pickup.

The third purpose, working under the further assumption that no clarinet pickup method is ideal, that is, that no method currently available provides the sound quality that classical clarinetists require, is to offer possible improvements to clarinet pickup design. Since the barrel pickup utilized for this study is quite new, the possibility exists that it may solve the problems of past barrel pickups and offer tone quality that is acceptable for classical music. The only comparison for this paper is to the reference sample, though further study into past pickup systems is an area for future study as outlined below.

The discussions on clarinet acoustics and piezoelectricity will be used in each of these steps. First, these discussions help validate and explain the results obtained from

each sample, offering possible causes for each result. Second, these discussions will assist in offering possible improvements to current designs in conjunction with the results obtained.

### **Difficulties with Study**

One of the main difficulties associated with this study is the number of variables associated with reproducing the natural sound of the clarinet, as shown in chapter 3. The variations in temperature, humidity, and reed strength across the recording session contribute to differences in the sound produced, and thus different spectra. Even more important is the human element: controlling the air flow into the instrument, the tuning of the vocal tract, and the force of the embouchure on the reed all have an effect on the resultant spectrum of a sample. Many of these variables were mediated through the process, but some minor variations can occur.

Another difficulty stems from the information available on the piezoelectric elements utilized in the pickups that were tested. Neither of the companies that developed the pickups utilized in this study offer any information regarding the elements other than a frequency range, unlike most microphones that offer a frequency response chart. With no information on what frequencies the pickup can be expected to react to, it is difficult to determine if the placement of the pickup on the instrument (dependent on the instrument) or the pickup itself (dependent on the pickup) is the cause for variations in the spectra.

A final difficulty lies in the niche area that this study falls into. Studies of clarinet acoustics generally associate with the question of what the simple acoustic sound of the

clarinet is or how to optimize it, which while worthwhile to this study, is not the aim. This study focuses on what sound is being produced from the clarinet at a specific point where the pickup is coupled to the instrument, and if that sound properly replicates the full acoustic sound of the clarinet. Furthermore, the use of contact pickups calls in to question how the body of the instrument vibrates in comparison to the resonances supported by the bore, an area of clarinet acoustics, that other than the study by Backus referenced earlier, has not been examined as closely as other aspects of clarinet acoustics.

### **Procedures**

Samples for this test consisted of a recorded E major arpeggio from the lowest written note on the clarinet, E3, to above the expected professional operating range, E7. It should be noted that these are the pitches as written for the B-flat soprano clarinet, which sounds a whole-step lower than written; in concert pitch, the samples would be a D major arpeggio from D3 to D7. For the following, pitches will be referred to as written for the B-flat clarinet. The E major arpeggio was selected since it provided both low and high boundaries for the instrument, provided a reasonable selection of pitches across the registers of the instrument, included cross-fingerings, and pitches that would need significant assistance from the vocal tract. Examining a full chromatic scale would ultimately be ideal but examining the full range of the instrument was sacrificed for examining more pickup methods. Each note was held for approximately 2 seconds, or a half-note at 60 beats per minute, at a mezzo-forte to forte level, and only the ascending arpeggio was played. Each method of pickup was recorded twice in separate files to provide comparison.

Samples were recorded in an isolated booth at Tempest Recording Studios in Tempe, Arizona. All samples were recorded through a Sound Devices USBPre 2 into Praat, an open-source audio analysis application designed primarily for speech research, but quite suitable for other acoustical research.<sup>87</sup> Samples were recorded at 48000 kHz at 16 bits and exported as WAV files for future analysis.

A total of 12 different methods were sampled, including the reference sample. The reference samples were recorded using an Earthworks M30 measurement microphone that features a flat response from 5 Hz-30kHz.<sup>88</sup> The M30 was placed perpendicular to the center tenon of the clarinet, approximately 3 feet from the instrument. This placement offers the best compromise to capture the most complete sound possible compared to close-micing techniques for the clarinet. The barrel pickup sampled was the PiezoBarrel, connected directly to the interface via the mono 3.5 mm jack on the pickup. The PiezoBarrel pickup features a trim-pot volume control, which for the sample was placed at max. The contact pickup used was a Neewer P-007, again connected directly to the interface via 6.3 mm cable. For all samples the clarinet setup was consistent, a Buffet R-13 model, Taplin-Weir barrel, custom Dave McClune SP 1.10 mouthpiece, Ishimori solid silver Woodstone ligature, and a Zonda reed strength 3.5. The only modification to this setup was for the PiezoBarrel pickup, where the Taplin-Weir barrel was substituted for a plastic barrel with a threaded port for the pickup supplied by the manufacturer.

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<sup>87</sup> Paul Boersma and David Weenink, Praat: doing phonetics by computer (Computer program), Version 6.0.39, retrieved March 18, 2018, <http://www.praat.org/>.

<sup>88</sup> "M30," Earthworks Audio, accessed March 11, 2018, <http://earthworksaudio.com/microphones/m-series/m30/>.

The locations for placing the contact pickup on the body of the instrument were selected due to space allowance to couple the pickup to the instrument adequately, minimal disturbance to embouchure or hand position, and coverage on each piece of the instrument. The contact pickup connected to the clarinet via double-sided tape (1 mm thick) attached to a plastic casing around the element. Due to the size and rigidity of the contact pickup, coupling the pickup to the instrument was an issue, since only a small portion of the surface area was in direct contact with the instrument. In addition, in order to determine if the plastic casing had any effect on the response of the contact microphone, one sample was taken with the casing removed with the element affixed directly to the instrument. Samples were taken with the contact microphone in the following positions and methods, shown in figures 5.1-5.11.



**Figure 5.1: Ligature (LIG) placement of contact pickup.**



**Figure 5.2: Ported barrel pickup (BAR Port) by PiezoBarrel.**



**Figure 5.3: Barrel surface (BAR Surf) placement of contact pickup.**



**Figure 5.4: Barrel surface placement of contact pickup with plastic cover removed (BAR NC)**



**Figure 5.5: LefreQue plates spanning the mouthpiece and barrel joint (LF MPB). Pickup was placed directly on the bridge.**



**Figure 5.6: LefreQue plates spanning the barrel and upper joint tenon (LF BUJ). Pickup was placed directly on the bridge.**



**Figure 5.7: Upper joint (UJ) placement of contact pickup.**



**Figure 5.8: Center tenon (CTR) placement of contact pickup.**



**Figure 5.9: Lower joint (LJ) placement of contact pickup.**



**Figure 5.10: Outside of bell (BELL Out) placement of contact pickup.**



**Figure 5.11: End of bell (BELL End) placement of contact pickup. Note placement perpendicular to bore.**

The ligature location offers a contact alternative to the anecdotal pickup between the reed and mouthpiece, as well as a location on the mouthpiece. Similarly, the barrel location can be directly correlated to the barrel pickup. The remaining locations on the upper joint, lower joint, and bell are all representative of each piece of the clarinet body, as well as approximate intervals along the whole instrument.

The LefreQue plates offer an intriguing alternative. Consisting of metal plates coupled to the instrument via an elastic band, LefreQue markets these plates as sound bridges that help facilitate the movement of sound waves across the tenons of the instrument. The company claims these bridges offer “purer overtones, better tuning, easier playing, better slurring, surround projection, [and] extended dynamics.”<sup>89</sup> An indictment of these claims is beyond the focus of this study, though according to research presented elsewhere in this paper the interaction of the bore and reed are the main variables associated with these concepts, with the vibration of the body of the instrument affecting the resultant sound minimally. However, the LefreQue samples were selected due to the manner in which they couple to the body of the instrument and the possibility for producing stronger resultant resonance than the body of the instrument for a contact pickup. Considering the plates span the tenon connections of the mouthpiece and barrel and the barrel and upper joint, they could help counteract the damping associated with tenon connections as suggested by Benade.<sup>90</sup> In addition, the feature of being removable

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<sup>89</sup> LeFreque, “Lefreque,” accessed March 11, 2018, <https://www.lefreque.com>.

<sup>90</sup> A.H. Benade and John K. Cuddeback, “Quasi-Turbulent Damping at Wind Instrument Joints and Tone-Holes,” *Journal of the Acoustical Society of America* 55, no. 2 (February 1974): 457, <https://doi.org/10.1121/1.3437511>.

would offer a significant incentive if equal to or better than the options of a ported barrel or direct coupling to the instrument.

After obtaining these original samples, a Nalbantov barrel pickup was obtained, and a sample was recorded along the same musical parameters and sample rate. However, this sample was subject to three important differences: the barrel utilized was the barrel supplied with the Nalbantov pickup, a Focusrite Saffire 40 pro interface was used instead of the Sound Devices USBPre 2 and the sample could not be recorded in an isolated booth. Due to the nature of the barrel pickups, the sample is isolated enough to provide a reasonable comparison to the PiezoBarrel, though this comparison is meant only to be indicative of the potential differences between the two, and the results from the Nalbantov are included as an appendix.

### **Analysis**

Samples were imported into Audacity, an open-source audio recording and editing program, to utilize the spectrogram and plot spectrum, and waveform dB functions of the program for analysis.<sup>91</sup> The spectrogram view was generated with a window size of 2048 and a Blackman-Harris window. Screenshots of both the full sample (entire arpeggio) and individual pitches were generated for each sample. Plot spectrum was also utilized to generate a spectrum graph for each pitch in a sample, utilizing a Blackman-Harris window but increasing the window size to 4096. In both cases, frequencies from 0 Hz to 10 kHz were included in the widow. Finally, samples were

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<sup>91</sup> Audacity Team (2018), Audacity®: Free Audio Editor and Recorder (Computer program), Version 2.2.2 retrieved February 20, 2018, <https://audacityteam.org>.

imported to Praat, in order to determine the spectral center of gravity.<sup>92</sup> This metric shows the power-weighted mean frequency of each sample and has been associated with the ‘brightness’ of a sound.<sup>93</sup>

The views generated from Audacity were examined for overall level of sound generated for both the fundamental as well as overtones, the frequency cutoff, and the overtone displacement. The overall level of sound is important because it is a direct measurement of reproduction efficiency. While not as important to match the level of the reference, it is still important that the signal is strong enough to be effective in amplification and manipulation, though not overly strong so as to create clipping or distortion.

The frequency cutoff is the highest frequency that is captured by the pickup, either due to the response of the pickup or the frequencies available from the instrument. The frequency cutoff is one measurement that indicates the fullness of the harmonic spectrum of the sound. A higher cutoff frequency indicates that more overtones are present, whereas a lower cutoff would contain less overtones.

The overtone displacement is the measurement of how strong the overtones are in relation to one another and the fundamental. The sound of a clarinet, or any instrument for that matter, is characterized largely through the instrument’s overtone spectrum, and differences in timbre between like instruments can be associated with differences in the

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<sup>92</sup> Boersma and Weenink, Praat (Computer program), <http://www.praat.org/>.

<sup>93</sup> Emery Schubert, Joe Wolfe, “Does Timbral Brightness Scale with Frequency and Spectral Centroid?” *Acta Acustica United with Acustica* 92 (2006): 820-825.

overtone relations. The spectral center was used for this analysis as well as comparing the strengths of individual overtones.

An important point to note is that overtone levels are highly variable based on the reed, air pressure, and vocal tract, despite limiting the variance as described above; however, the variations were mitigated through the procedure.<sup>94</sup> All samples were recorded in the same session to limit ambient humidity and temperature changes, and all samples were recorded by the same performer to limit physiological differences. In addition, the same equipment was used, most importantly the same reed, which did limit the variation between samples.

Two samples were recorded for each method, and for the most part the doubled samples were similar enough to be considered the same. Exceptions do exist in some overtones, though for the most part those can be attributed to minor variances in air pressure, reed strength, voicing, or the coupling of the pickup. In some cases, extra frequencies appeared that were not intended nor expected, given the possible harmonics; in these cases, either the sample without these extra frequencies was used or the unintended frequencies were ignored. These frequencies were determined to be unimportant through comparison between samples through utilizing the harmonic series calculator available through composer Michael Norris' website and consulting the acoustic impedance spectra available via UNSW.<sup>95</sup>

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<sup>94</sup> "How the Clarinet Measurements were Made," UNSW Music Acoustics, accessed March 11, 2018, <http://newt.phys.unsw.edu.au/music/clarinet/methods.html>.

<sup>95</sup> "Harmonic Series Calculator," Michael Norris, accessed March 11, 2018, <http://www.michaelnorris.info/theory/harmonicseriescalculator/>; UNSW, "Clarinet Acoustics," <http://newt.phys.unsw.edu.au/music/clarinet/>.

During analysis, the sample from the contact pickup on the barrel without the cover had to be discarded upon analysis. Compared to the results from the sample with the plastic cover and to the barrel ported pickup, the contact pickup with no cover produced wildly different results. Upon inspecting the element of the pickup, it appeared cracked from curving it to better couple to the barrel. With the crack, the shape had changed and would therefore produce unpredictable results, and so unfortunately the samples from the contact pickup with no cover had to be disregarded due to the unpredictable response from the pickup. However, given the results from other samples utilizing the contact pickup, the concern that the plastic casing would dampen important frequencies was mitigated as explained under “Results.”

### **Results**

For all of the following results, the spectrum graphs, spectrograms, and waveform dB views have been included in appendices. For overtone displacement, graphs generated in Microsoft Excel have been included to offer a side-by-side comparison of the methods tested for each pitch for easy reference, and larger versions of the graphs have been included in Appendix B. Note: these graphs contain the data for the barrel with no cover, labeled as BAR NC, but as stated above these results were not considered due to the faulty element.

## Sample Level in dB

Pitch	M30	LIG	BAR P	BAR S	LF MPB	LF BUJ	UJ	CTR	LJ	BELL Out	BELL End	
E3		-37	-60	-38	-59	-61	-70	-85	-60	-87	-78	-60
G-sharp3		-35	-54	-39	-50	-57	-60	-84	-55	-73	-81	-66
B3		-32	-49	-38	-42	-51	-53	-72	-44	-68	-74	-56
E4		-39	-69	-37	-51	-75	-64	-75	-53	-74	-80	-65
G-sharp4		-40	-60	-37	-54	-62	-70	-66	-50	-80	-79	-78
B4		-40	-43	-36	-42	-44	-61	-70	-42	-60	-65	-49
E5		-28	-44	-35	-45	-44	-56	-76	-57	-66	-66	-56
G-sharp5		-22	-40	-40	-48	-40	-47	-61	-40	-57	-72	-60
B5		-25	-45	-46	-48	-42	-44	-51	-45	-73	-59	-61
E6		-21	-45	-41	-42	-56	-46	-57	-61	-54	-52	-60
G-sharp6		-20	-50	-30	-51	-66	-58	-44	-56	-37	-50	-49
B6		-36	-46	-27	-58	-64	-68	-55	-67	-54	-67	-54
E7		-36	-74	-34	-66	-70	-71	-69	-73	-81	-59	-55

**Figure 5.12: Strength of fundamental in decibels for each pitch per pickup method.**

The first measurement compared is the decibel level of the fundamental pitch. The only pickup method to come close to the reference sample is the ported barrel pickup. With all thirteen notes of the sample compared, the reference sample produces a maximum of -20 dB, compared to a maximum of -27 dB for the ported barrel pickup. The next highest maximum is found in the lower joint pickup at -37 dB, but beyond that outlier no location for the contact pickup produces above -40 dB. The reference sample also produces a minimum fundamental level of -40 dB, compared to -46 dB in the ported barrel pickup, and compared to the next highest minimum of -59 dB. Not only are the maximum and minimum the closest, but the range between is comparable between the ported barrel pickup and the reference.

While the level of the barrel surface pickup is much lower than that of the reference or ported barrel sample, the range is consistent, with a maximum of -42 dB and a minimum of -59 dB. In addition, the sample from the end of the bell produces a range consistent with the above methods, with a maximum of -49 dB and a minimum of -66 dB; there is an outlier of -78 dB for the note G-sharp4, which based on the fingering

utilizes a very short section of the pipe, offering a possible explanation of why this note specifically is much weaker than the others.

The remaining methods fall into two groups. The first contains the ligature, both LefreQue locations, and the center tenon. These locations all produce a consistent range, with 25-30 dB between the maximum and minimum, and all reach a maximum of approximately -40 dB. The second group includes the upper joint, lower joint, and the outside of the bell. These locations all have the widest range, 30 dB or above, as well as the lowest maximum.

Examining the level of the fundamentals one layer further reveals some key differences. Comparing the ported barrel pickup to the reference, the reference shows a strong band between E5 and G-sharp6, a similar band to where the ported barrel pickup dips in strength, from G-sharp5 to E6. Another important difference is in the chalumeau register, where the ported barrel pickup is extremely consistent compared to the reference. From E3-G-sharp4 the ported pickup only has a difference of 2 dB between pitches, whereas the reference has a difference of 8 dB. Finally, in the high altissimo from G-sharp6-E7 the ported pickup actually reaches its maximum level, while the reference drops significantly between G-sharp6 and B6, from its max of -20 dB to -36 dB respectively.

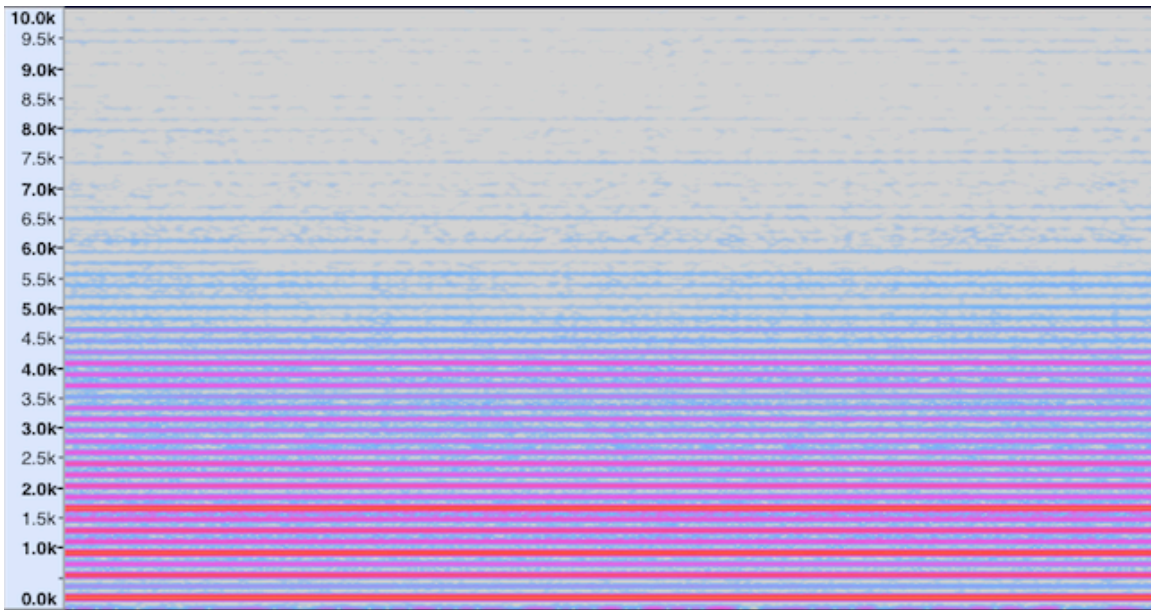
All other methods show the trend of being weaker in the chalumeau, stronger in the clarion register, and produce mixed results in the altissimo. The altissimo is the source of some of the more interesting results in the upper joint, center tenon, lower joint, and outside of bell, where the altissimo is consistently stronger than in other methods. The more mixed results of the altissimo overall could be related to the greater range of

flexibility for this range on the part of the performer—minute changes in air production, vocal tract manipulation, and embouchure force result in greater changes in this register. The ligature, barrel surface, and end of the bell produces the most consistent measurements below the ported barrel pickup, with some outliers over the task. The LefreQue plates are not as consistent, and remaining locations along the body produce similarly inconsistent results.

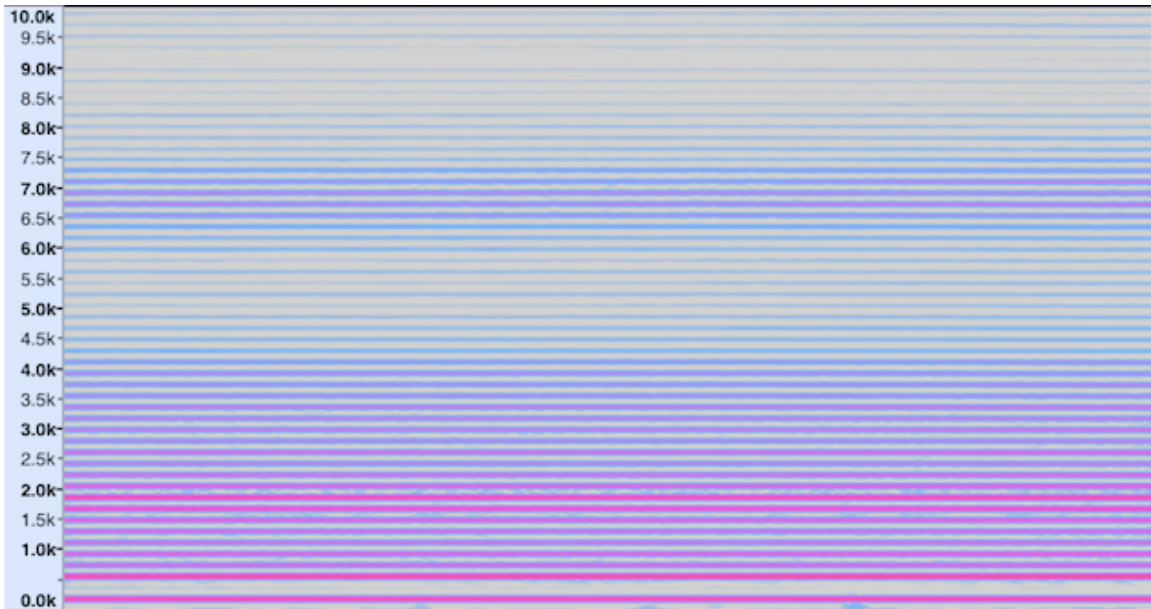
Another consideration to examine for sound level is the significance of the key noise. Using the waveform dB view, key noise appears as a spike at the beginning of each new pitch, assuming it is stronger than the sound of the note. As expected, the contact pickups uniformly show some key related spike at the beginning of each new note, and it can be generally stated that the level of noise directly correlates to the proximity of the pickup to specific keys. For instance, the two strongest key noise transients in the upper joint sample are located between prior to G-sharp4 and B5, where the keys moving would be limited to the upper joint, while the strongest transients for the outside of the bell are located after E3 and around B4, where the E/B key would be utilized. Due to this, the ligature and barrel surface samples show the least amount of key noise transients, with the rest of the samples closer to the keywork showing much higher levels compared to the level of the note.

## Frequency Cutoff

The reference sample spectrogram shows an effective cutoff frequency of around 6.5 kHz, with the exception of the altissimo notes, which show overtones up to around 9.5 kHz. The only sample to meet or exceed this frequency is from the ligature, which shows overtones up to 10 kHz, the top of the range. Figures below show representative examples of the cutoff frequencies associated with the reference and ligature.



**Figure 5.13: Spectrogram of reference G-sharp3.**

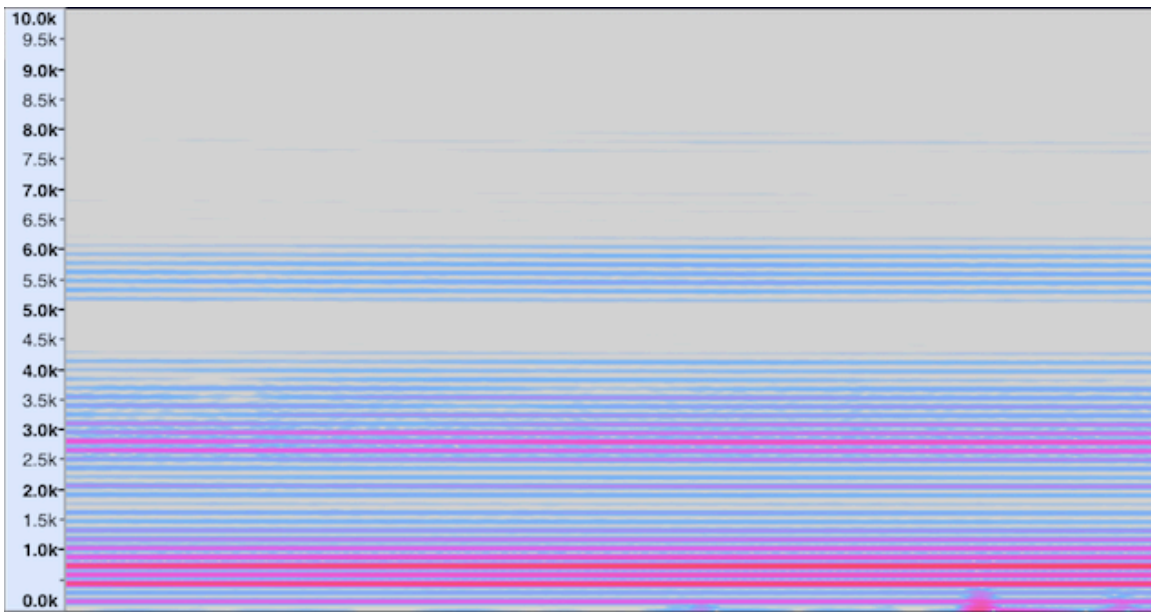


**Figure 5.14: Spectrogram of ligature (LIG) G-sharp3.**

Due to this sample, it is clearly evident that the contact pickup is responsive over the range that is being tested, which acts as confirmation that the plastic casing does not affect frequency cutoff response negatively. However, it is highly likely that the cause of the higher frequencies present in the ligature sample is the proximity to the reed. Frequencies above that of the reference are not found in any other sample, and accounting for the natural frequency and overtones of the reed helps explain the higher frequencies found in the ligature sample. In addition, between roughly 4.25-6.25 kHz, the ligature sample shows a weaker band, similar to where other contact pickup samples also show weaker response.

The LefreQue samples show a unique response completely unlike any of the other samples. The sample spanning the mouthpiece and barrel show a similar cutoff around 4.25 kHz, though it then shows a band between 5.25 and 6.25 kHz. Furthermore, the band from 1.5 to 2.5 kHz is much weaker than any other method located near the top of the

clarinet. The sample spanning the barrel and upper joint shows a significant cutoff around 3.75 kHz, though with inconsistent overtones up to around 6 kHz. Similarly, the strength drops between 1.5 and 2.5 kHz, though with less of an increase around 2.5 kHz as the mouthpiece-barrel sample. The cause for the difference in these samples is likely related to the cause for the ligature sample. In the same way the reed likely affected the ligature sample, the resonance of the plates themselves could be affecting the LefreQue samples. The band in which both samples exhibit a slight increase in strength, roughly 2.5-3 kHz, is analogous to a study on their website that shows significant results with the plates.<sup>96</sup> An example of the LefreQue spectrogram is given below.



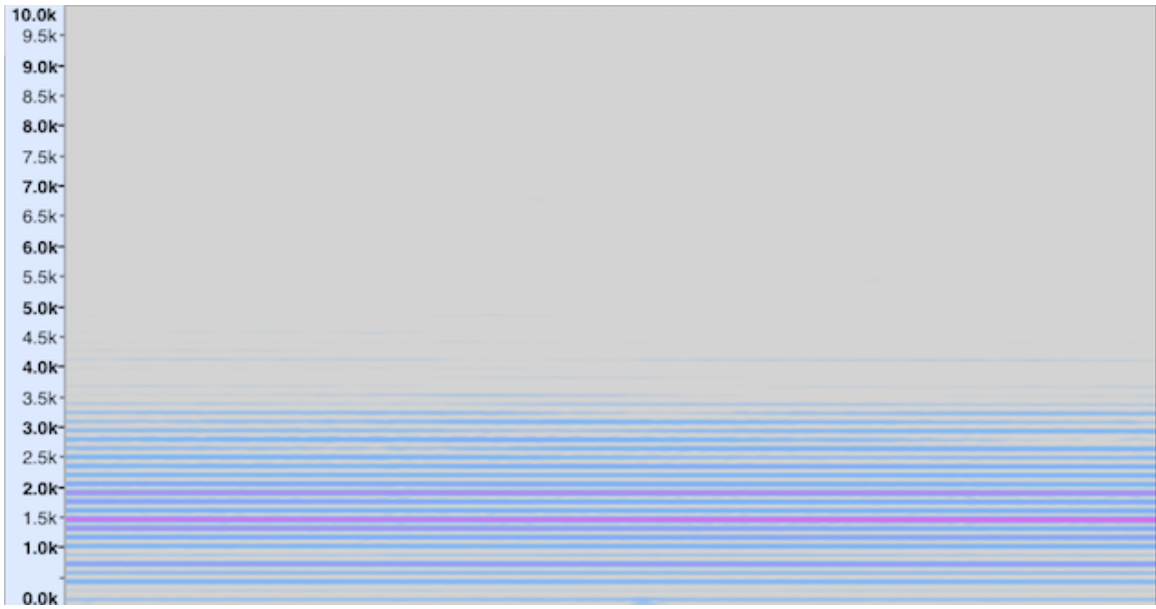
**Figure 5.15: Spectrogram of LefreQue at mouthpiece-barrel (LF MPB) E3.**

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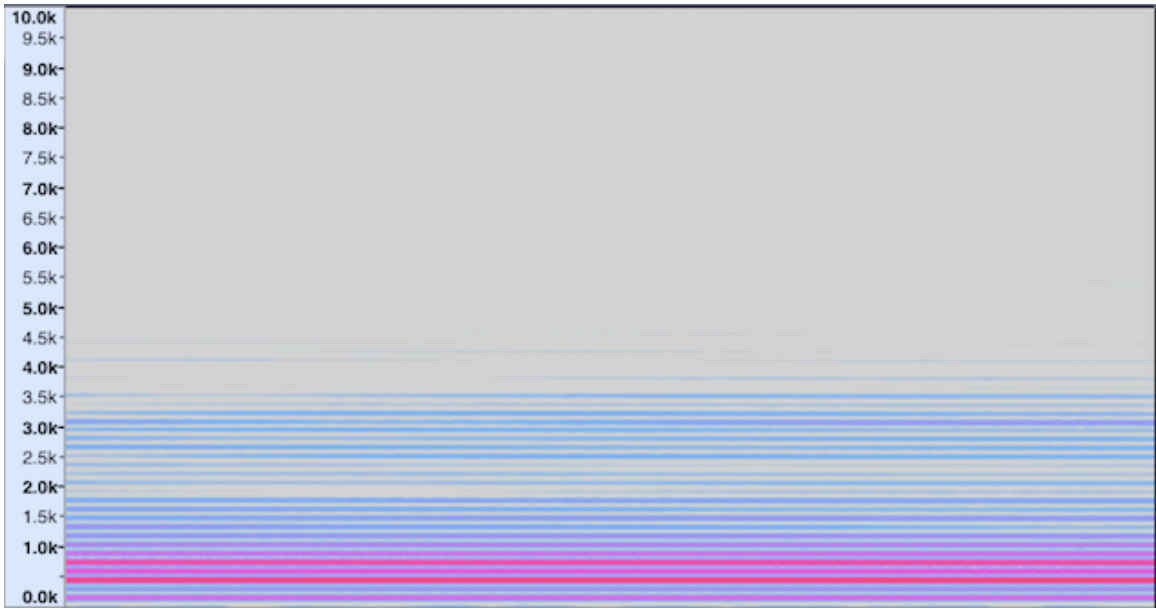
<sup>96</sup> “How to Use-Spectral Analysis,” LefreQue, accessed March 11, 2018. <https://www.lefreque.com/how-to-use/spectral-analysis>.

The ported barrel pickup shows the highest frequency cutoff of the remaining samples, cutting off around 5.5 kHz, with much less strength in the upper overtones of the altissimo pitches. In comparison, the barrel surface pickup has a cutoff around 4.25 kHz, though it shows similar response to the ported pickup in the upper altissimo overtones. Overall, both barrel methods exhibit similar response to the reference, though with lower respective cutoffs.

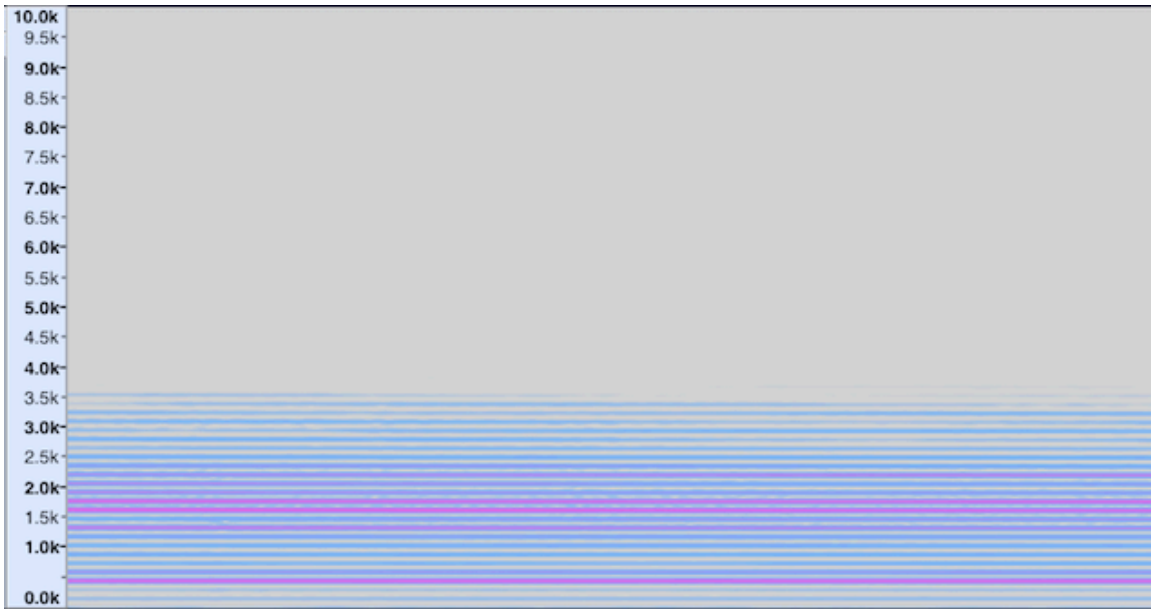
The pickups placed at the upper joint, center tenon, lower joint, and outside of the bell all produce nearly identical cutoff frequencies at approximately 3.5 kHz. The difference between each of these methods is a strong band found in each except the outside of the bell; the outside of the bell is consistently weak, showing no significantly strong bands. The center tenon is strongest below 1.0 kHz, producing strong fundamentals and lower overtones up through B5, becoming noticeably weaker in the altissimo range, which has fundamentals above 1.0 kHz. The upper joint shows a strong band from 1.0 kHz to approx. 1.75 kHz, much stronger in the altissimo than the center tenon but weaker below 1.0 kHz. The lower joint shows a strong band between 1.3 and 2.3 kHz, overlapping somewhat with the upper joint but wider towards higher frequencies. Examples of each are shown below.



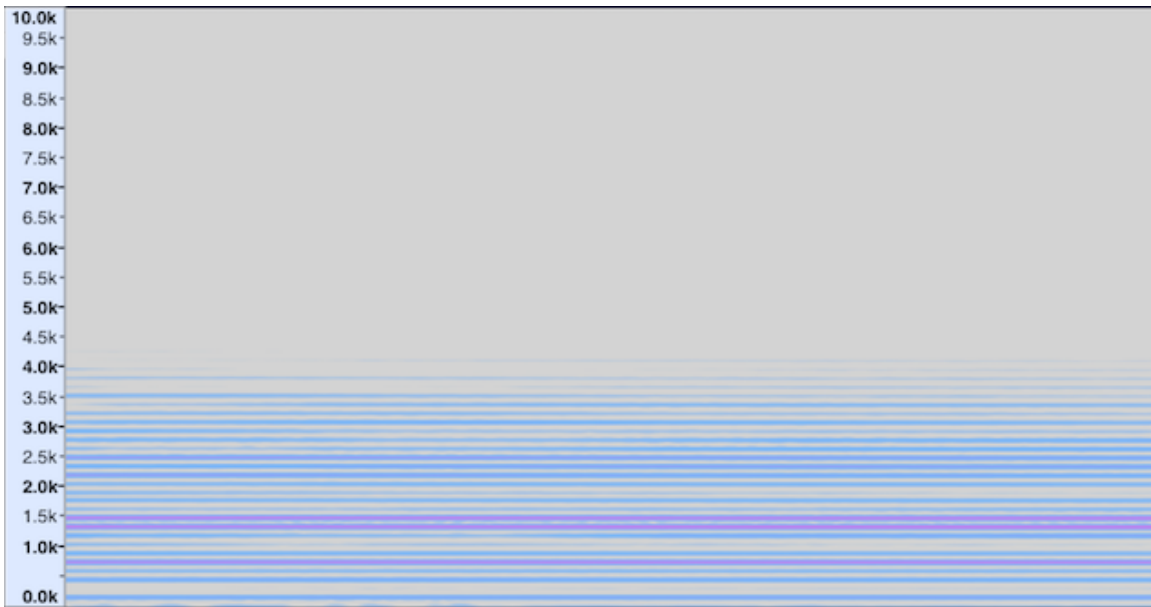
**Figure 5.16: Spectrogram of upper joint (UJ) E3.**



**Figure 5.17: Spectrogram of center tenon (CTR) E3.**



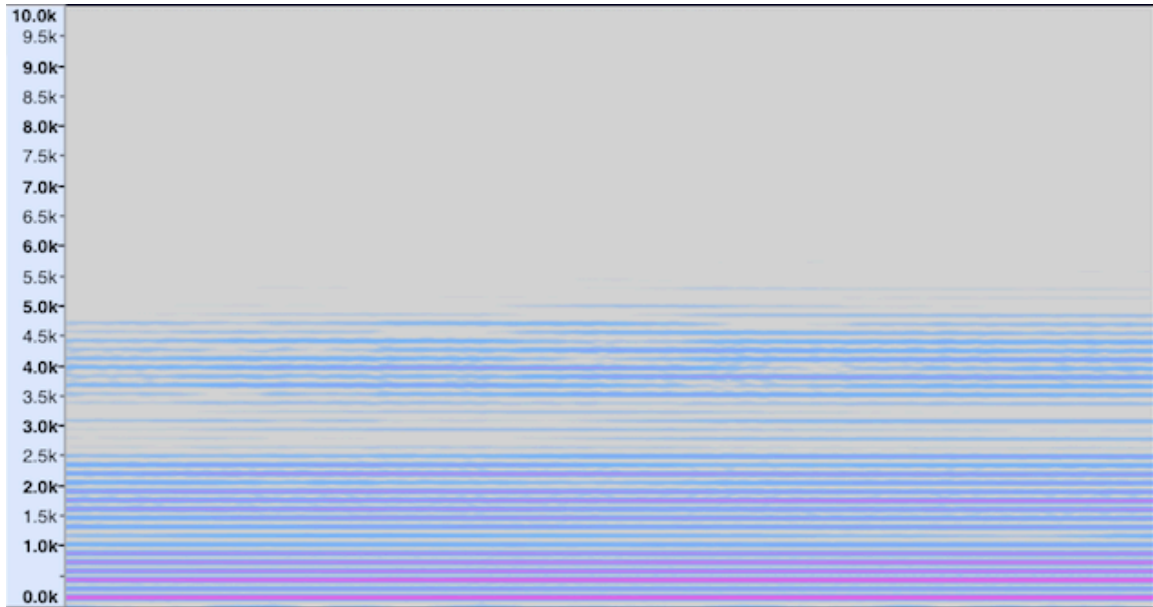
**Figure 5.18: Spectrogram of lower joint (LJ) E3.**



**Figure 5.19: Spectrogram of outside of bell (BELL Out) E3.**

The end of the bell pickup provides interesting, yet not unexpected results. With a cutoff frequency around 5 kHz, the end of the bell pickup was much higher than any other method than the ported barrel and ligature. In addition, where other locations provide a band of strong frequencies, the end of the bell pickup was stronger for higher

notes than for lower notes. An unexpected result comes from the band between 2.75 and 3.5 kHz that is significantly weaker than the rest of the spectrum. An example of the end of the bell is given below.



**Figure 5.20: Spectrogram of end of bell (BELL End) E3.**

### **Overtone Displacement**

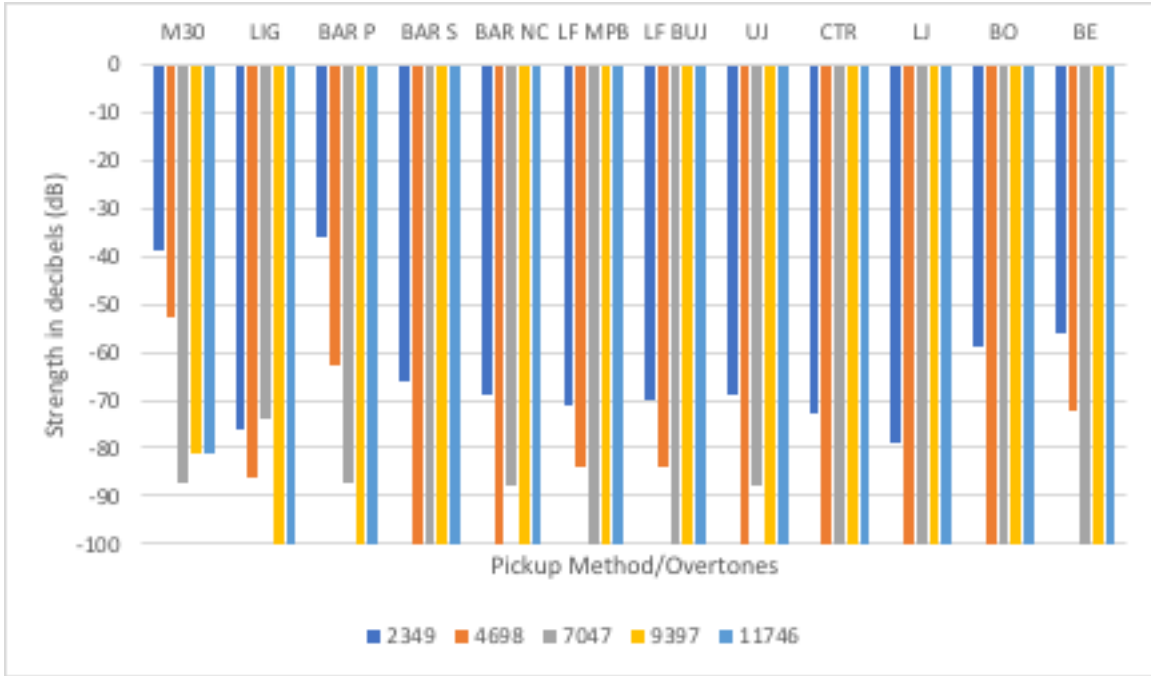
As stated above, due to the number of factors that can influence the spectrum of the clarinet, especially when using a human player, it is highly unlikely that an exact spectra can be replicated. However, considering the similarity between repeated samples of this study, large disparities in overtone displacement can be correlated to the pickup method rather than the variables associated with performance.<sup>97</sup> This section will be divided into results for each pitch due to the specificity of harmonic spectra. Larger graphs are also provided in Appendix B.

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<sup>97</sup> See ‘Analysis’ for how performance variables were mitigated.

## E7

The reference E7 exhibits an evening out from the third harmonic after steep drop off from the fundamental to the second, and from the second to the third. No pickup method matches the harmonic content of the reference, with all cutting off significantly after the third harmonic, whereas the reference has significant harmonics up to the fourth (and fifth, but the fifth harmonic was found at 11746 Hz, above the range for comparison). The ported barrel pickup most closely matches the displacement of the reference, though with a much weaker second harmonic despite having a nearly equal fundamental and third harmonic. The ligature pickup also shows response up to the third harmonic, though the fundamental, second, and third harmonic are much closer in strength than the reference or the ported barrel pickup. All other methods show low fundamental strength coupled with cutoff after the second harmonic, if the second harmonic is even present. While it shows steep cutoff after the second harmonic, the end of the bell pickup has the strongest fundamental and second harmonic after the reference and barrel pickup. The spectral center of gravity was consistent for most methods, close to the reference of 2371 Hz, which indicates weak harmonics above the approximate frequency of 2350 Hz for E7. The methods that showed significantly higher centroids are the ligature, which is recorded at 6659 Hz, showing much greater strength in the higher harmonics coupled with weakness in the fundamental. Other methods to show a higher centroid include the LefreQue plates, particularly at the mouthpiece-barrel joint, and the end of the bell.

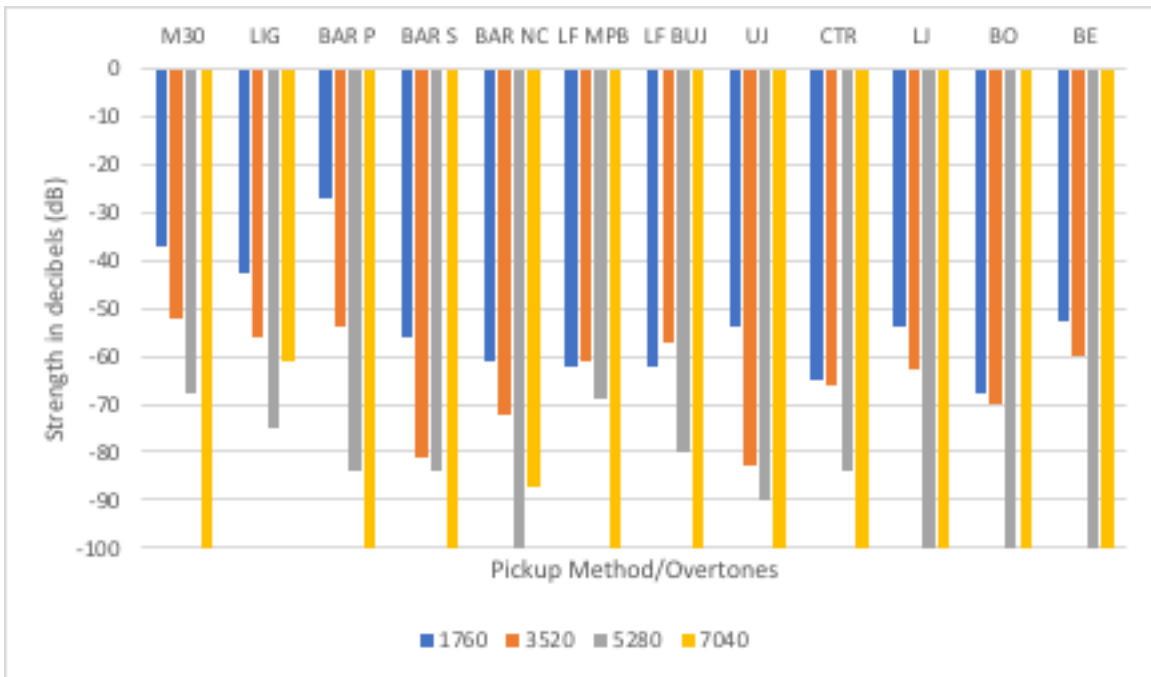


**Figure 5.21: Frequency response for E7.**

B6

The reference B6 exhibits consistent decreases in strength between the fundamental and second harmonic, and the second and third harmonic, with the fourth harmonic cutoff. Most pickup methods are similarly aligned, though with one of the relations much larger than the other. The ligature produces the most similar displacement, with consistent decreases to the third harmonic, but with the fourth harmonic present and nearly as strong as the second. The ported barrel pickup also produces consistent decreases in strength, though over a much wider range, nearly double that of the reference. The barrel surface and the upper joint pickups results have very close second and third harmonics, while the center tenon, lower joint, and both bell pickups show very close fundamental to second harmonic relations. The LefreQue plates produce a second

harmonic that is slightly stronger than the fundamental, and in the case of the mouthpiece-barrel span a third harmonic that is nearly equal. The spectral center for the B6 reference is 2460 Hz, which is consistent with most the contact pickup methods. The ligature and both LefreQue locations are much higher, around 3500 Hz, whereas both the ported barrel and barrel surface methods are significantly lower, near the fundamental frequency of 1760 Hz.

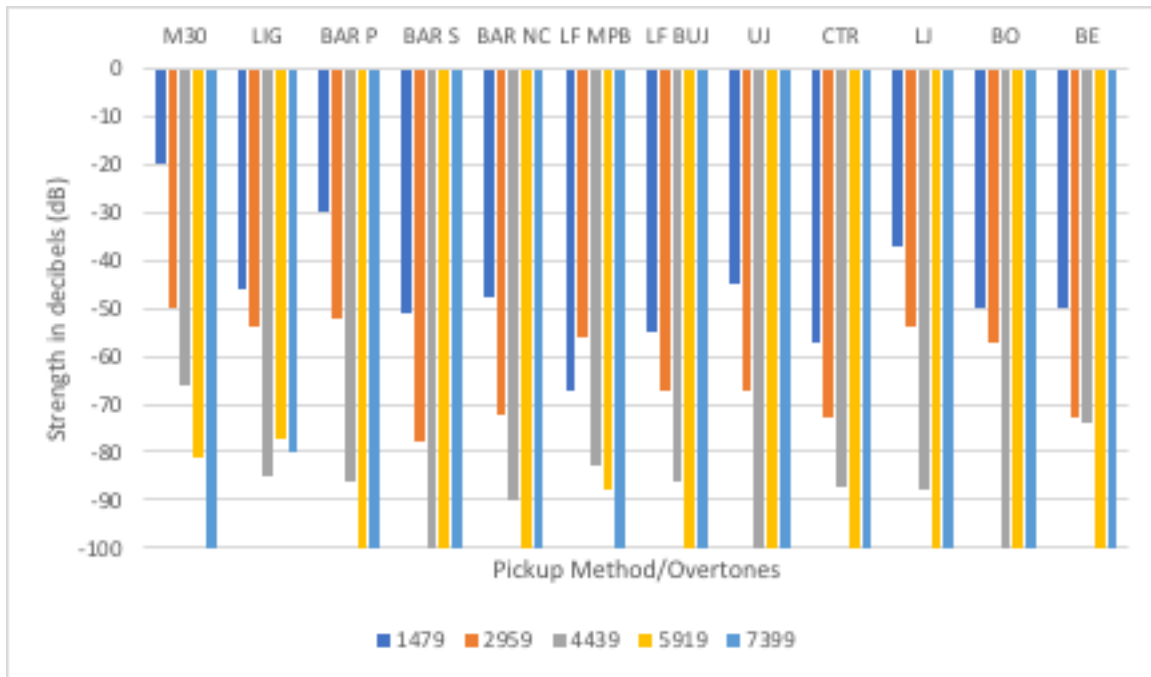


**Figure 5.22 Frequency response for B6.**

### G-sharp6

The reference G-sharp6 shows a steep drop from the fundamental to the second harmonic, with consistent decreases up to the fifth harmonic. No other method shows the same consistency coupled with frequency response. The ported pickup is the most similar, showing a regular decrease in strength, though with the second harmonic

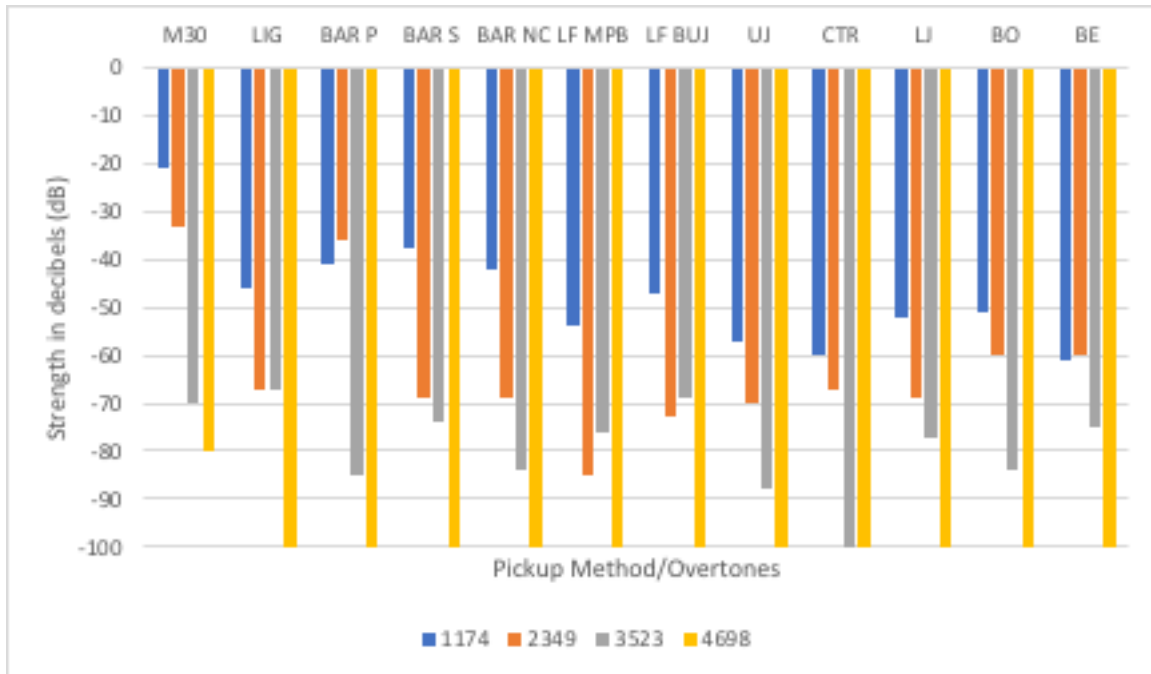
proportionally stronger to the fundamental. The center tenon location also shows consistent decrease, though only to the third harmonic and with much smaller decreases. The ligature, though it has the highest frequency response, has a very strong second harmonic with the third, fourth, and fifth harmonics all comparatively equal. Similarly, the LefreQue mouthpiece-barrel pickup shows response up to the fourth harmonic, though the second harmonic is again stronger than the first, and the third and fourth about equal. The remaining methods show inconsistent decreases in strength coupled with low cutoffs. The spectral center shows similar results, with the ported barrel pickup at 1505 Hz compared to the reference of 1526 Hz. The barrel surface and upper joint are also very close to the reference, though this is due to lower cutoffs. All other methods show much higher readings, highlighting the weaker fundamentals in relation to the overtones.



**Figure 5.23: Frequency response for G-sharp6.**

## E6

The reference E6 shows four strong harmonics, with the fundamental and second harmonic much stronger than the third and fourth harmonic. No other method shows strength in the fourth harmonic, and most methods show a steep drop between the fundamental and the second harmonic. The upper joint, center tenon and the outside of the bell exhibit relations closest to the reference, though at much lower strengths. The ligature, barrel surface, and both LefreQue positions show second and third harmonics that are close in strength, with the LefreQue samples having a stronger third harmonic than second. Both the ported barrel and the end of the bell show second harmonics that are stronger than the first, with the third harmonic of the bell end much stronger proportionally than either the ported barrel or the reference. The spectral center for E6 is quite consistent with the reference of 1380 Hz, with only two methods deviating significantly: the ported barrel, which was much higher at 2193 Hz, and the end of the bell which was even higher at 2238 Hz.

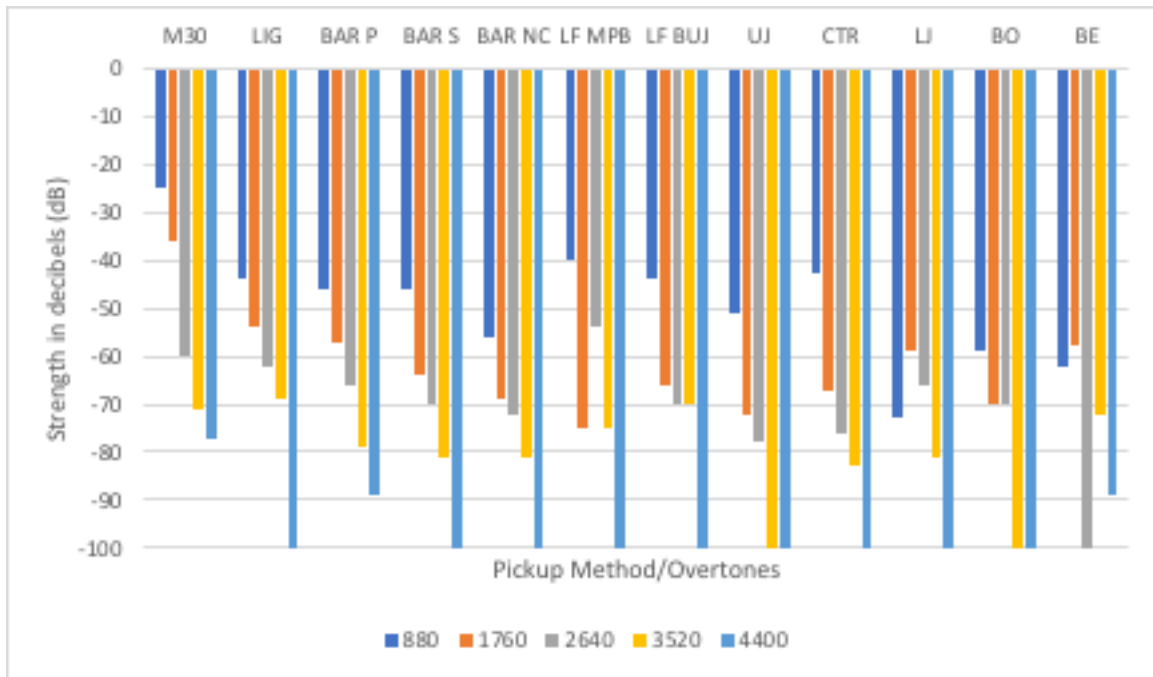


**Figure 5.24: Frequency response for E6.**

### B5

The reference B5 shows five strong harmonics, decreasing in strength as frequency increased, with a sharp decrease between the second and third harmonics. The ligature, ported barrel, and barrel surface show a similar pattern, though with much tighter decreases as well as greater proportional strength, closest with the ligature and widest with the barrel surface. The LefreQue barrel-upper joint, upper joint, center tenon, and outside of the bell exhibit similar shapes but with different relations: the LefreQue had tightly bunched second, third, and fourth harmonics, similar to the outside of the bell and upper joint but missing the fourth, and the center has a regular decrease over the second, third, and fourth but after a sharp decline from the fundamental. The LefreQue at the mouthpiece-barrel show strange relations, with the third harmonic much stronger than

the second or fourth, almost the inverse of the end of the bell which has a very weak third harmonic but stronger second and fourth harmonics. The lower joint has second and third harmonics that are stronger than the fundamental. The spectral center shows most methods measuring only slightly brighter than the reference of 968 Hz, with the exceptions of the lower joint and both the outside of the bell and the end of the bell locations much higher at 2009 Hz, 1840 Hz, and 1691 Hz respectively.

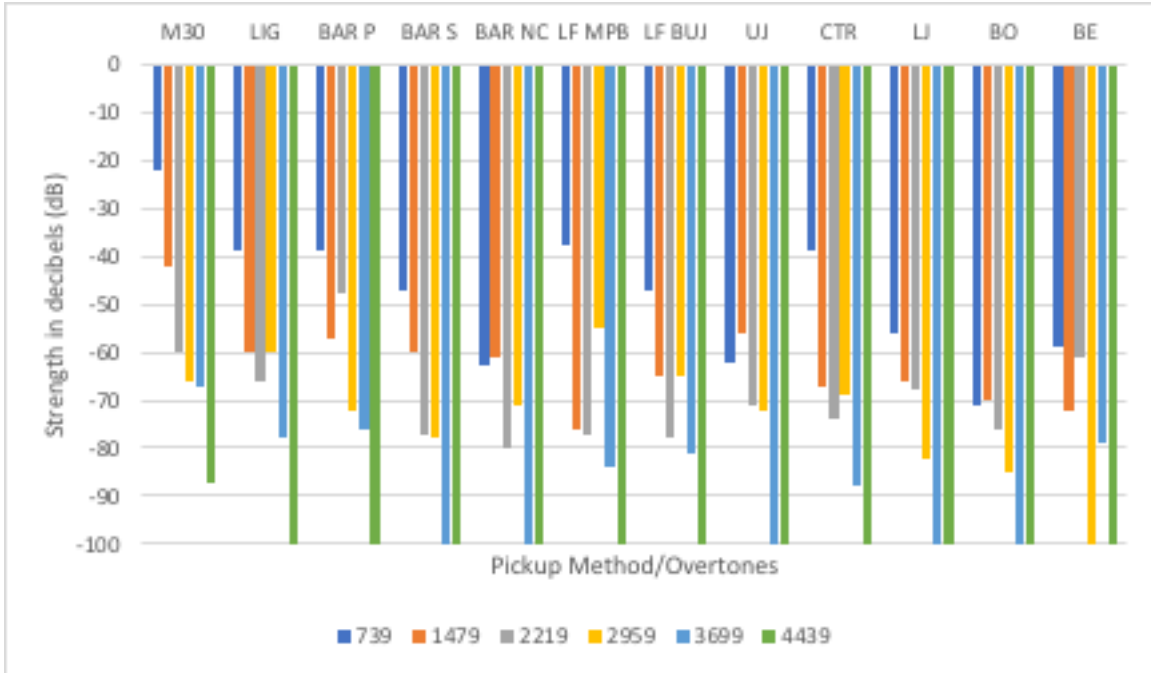


**Figure 5.25: Frequency response for B5.**

## G-sharp5

The reference G-sharp5 shows six harmonics, with regular decrease from the fundamental to the second and third, with the third, fourth, and fifth tightly bunched before a larger decline to the sixth. The results of the different pickup methods are greatly varied. The barrel surface produces the most similar result, with regular decline to the third harmonic, a close fourth, but with much lower cutoff. The ligature and the center tenon produce similar results to each other with tightly bunched second, third, and fourth harmonics and a weaker fifth, with the center tenon producing slightly weaker harmonics overall compared to the fundamental. The ported barrel and end of the bell also produce similar results, with a comparatively strong third harmonic, and weaker fourth and fifth harmonics (the end of the bell did not show a fourth harmonic). The upper joint and outside of the bell also match, with a very strong second harmonic and decrease to the third and fourth, with the results of the outside of the bell in a tighter grouping. The lower joint shows the second and third harmonics as bunched and only slightly weaker than the fundamental. The LefreQue plates produce a very strong fourth harmonic compared to the weaker second and third harmonics.

The spectral center for G-sharp5 is similarly varied, with most methods higher than the reference of 762 Hz. The ligature, barrel surface, both LefreQue methods and the center tenon locations are only slightly higher than the reference, within 100 Hz, while the ported barrel, upper joint, lower joint and both bell locations are significantly higher, from 1185 Hz at the lower joint to 1880 Hz from the end of the bell.

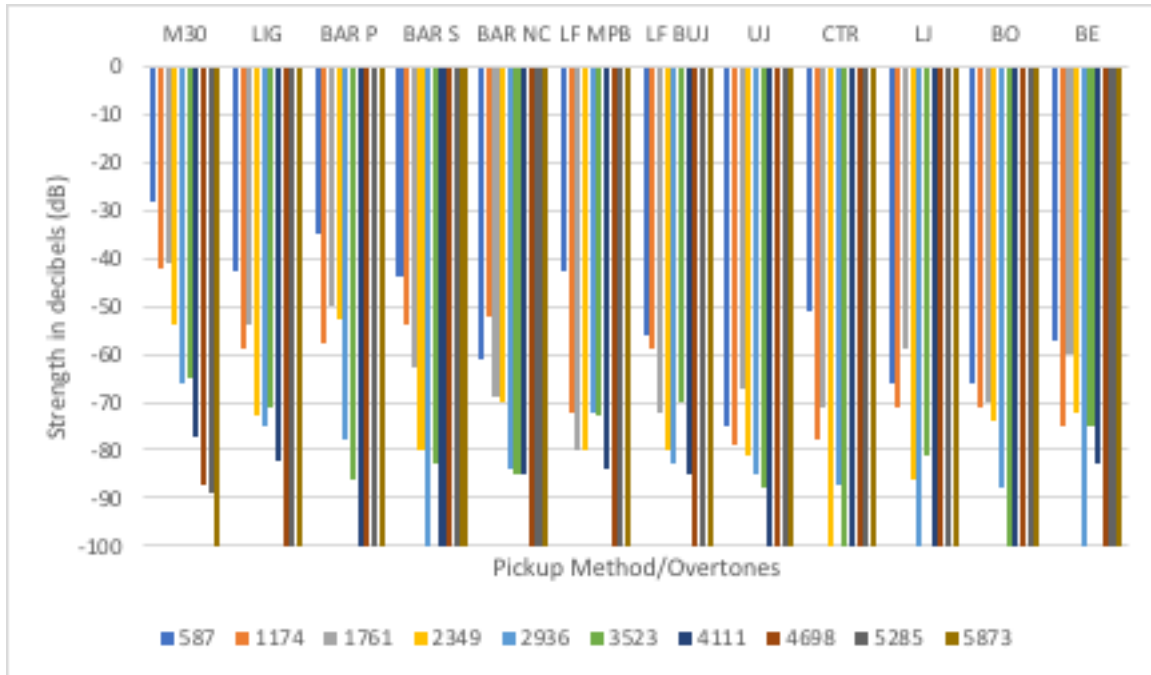


**Figure 5.26: Frequency response for G-sharp5.**

E5

The reference E5 shows close pairings of the second and third, fifth and sixth, and eighth and ninth harmonics. The fourth and seventh harmonics lie halfway between their respective pairs. The ligature shows a similar result, though over a much smaller range, and with the fourth through the seventh harmonics more even than the reference. The ported barrel shows the second through fourth harmonics bunched, with sharp decline to the fifth and sixth before the cutoff. The barrel surface, comparatively, shows regular decline for each harmonic. All other methods show a comparatively tighter range before a much lower cutoff, showing varied strong harmonics. The spectral center supports this, with the ligature, ported barrel, and barrel surface methods measuring at 905 Hz, 762 Hz, and 703 Hz respectively, compared to the reference of 750 Hz. Similarly, most other

methods measure significantly higher, except for the LefreQue at the mouthpiece and barrel and the center tenon—this can be explained by stronger fundamentals for both of these methods.



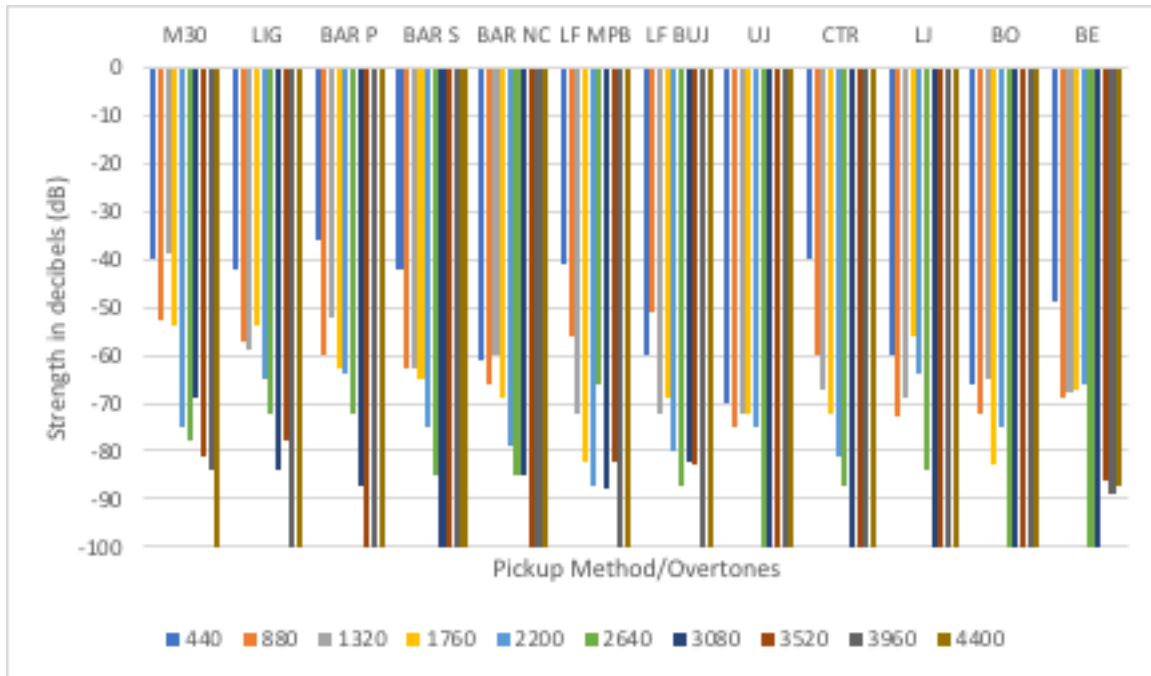
**Figure 5.27: Frequency response for E5.**

#### B4

B4 is the lowest note of the clarion register, where the even harmonics start to lose their systematic weakness compared to the chalumeau register; since the analysis started at the highest pitch and moves downward, this is where the even harmonics will become characteristically weaker. Such is the case with the reference sample, where the second and fourth harmonics are weaker than the fundamental and third. The remaining harmonics drop off significantly, with a slight bump in the seventh. Despite the beginning of the even harmonics' weakness, the only method to show this is the ported

barrel. However, the third harmonic of the ported barrel is proportionally much weaker than that of the reference, compared to a smaller decrease in strength of the second and fourth. The ligature and barrel surface produce similar results, where the second, third, and fourth harmonics are more tightly bunched, before a consistent drop to the cutoff. The center tenon and LefreQue mouthpiece-barrel show similarities from the fundamental through the fifth harmonic, with the center continuing a regular decrease while the LefreQue evened out at the fifth with a spike in the sixth harmonic. The upper joint and end of the bell produce similar results as well, with almost even strength to the fifth, with the exception of the strong fundamental in the bell as well as response in the upper eighth, ninth, and tenth harmonics. The LefreQue barrel-upper joint, lower joint, and outside of the bell produce inconsistent results, with strong even harmonics.

Many methods recorded a much lower spectral center than the reference, which was found at 1128 Hz. The only methods to come close to this were the upper joint at 1406 Hz, the lower joint at 1531 Hz, and the outside of the bell at 1151 Hz. All other methods are much lower, including the ligature pickup that typically exceeds the reference; the measurement for the ligature location is only 665 Hz.



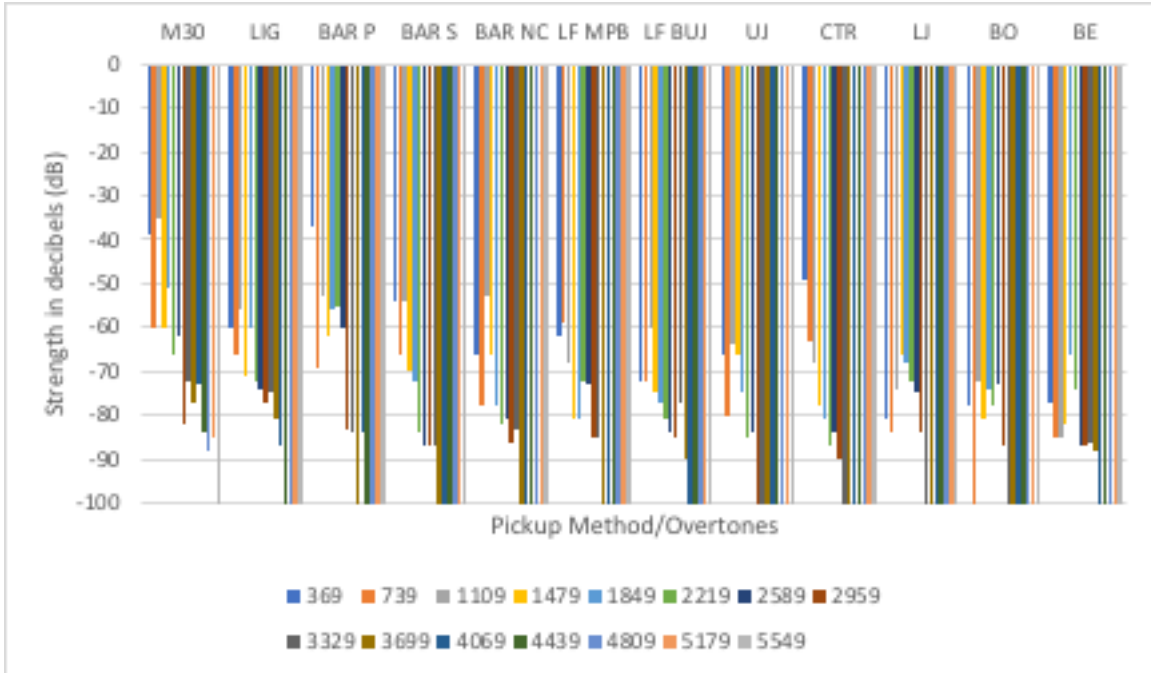
**Figure 5.28: Frequency response for B4.**

### G-sharp4

The reference G-sharp4 shows the characteristic weaker second and fourth harmonics, with the difference between even and odd gradually smoothing out starting at the sixth harmonic. The odd harmonics gradually decrease in strength, with the third slightly stronger than the fundamental. The most similar spectra can be found with the ligature, ported barrel and barrel surface methods. The ligature produces the most similar relationships, though over a much smaller range; the fundamental is much weaker, by approximately 20 dB, though the upper harmonics starting at the ninth are in the same dB range as the reference. The ported barrel has proportionally stronger even harmonics compared to the strength of the odd harmonics above the fundamental, but the range of the second to the seventh and the eighth to the eleventh harmonics are roughly the same

as the reference. The barrel surface provides a compromise between the two, but at the lowest level overall of the three. Both LefreQue locations provide very strong even overtones, with the second harmonic equal to and stronger than the fundamental. The center tenon provides a consistent decrease along to odd harmonics, though at the expense of slightly stronger even harmonics, particularly the second and fourth, compared to the reference. The upper joint, lower joint, and both bell methods provide inconsistent results, with flatter response over all harmonics and lower cutoffs.

Though the spectra appear similar for the ligature, ported barrel and barrel surface methods, the spectral center shows the ligature as much brighter, measuring 1558 Hz compared to the 1002 Hz of the reference. The ported barrel and barrel surface are both lower, measuring 568 Hz and 867 Hz respectively. The lower joint and both bell locations give a characteristically much higher reading, and the two LefreQue methods and the upper joint also read higher than the reference. The center tenon provides the lowest measurement at 415 Hz.



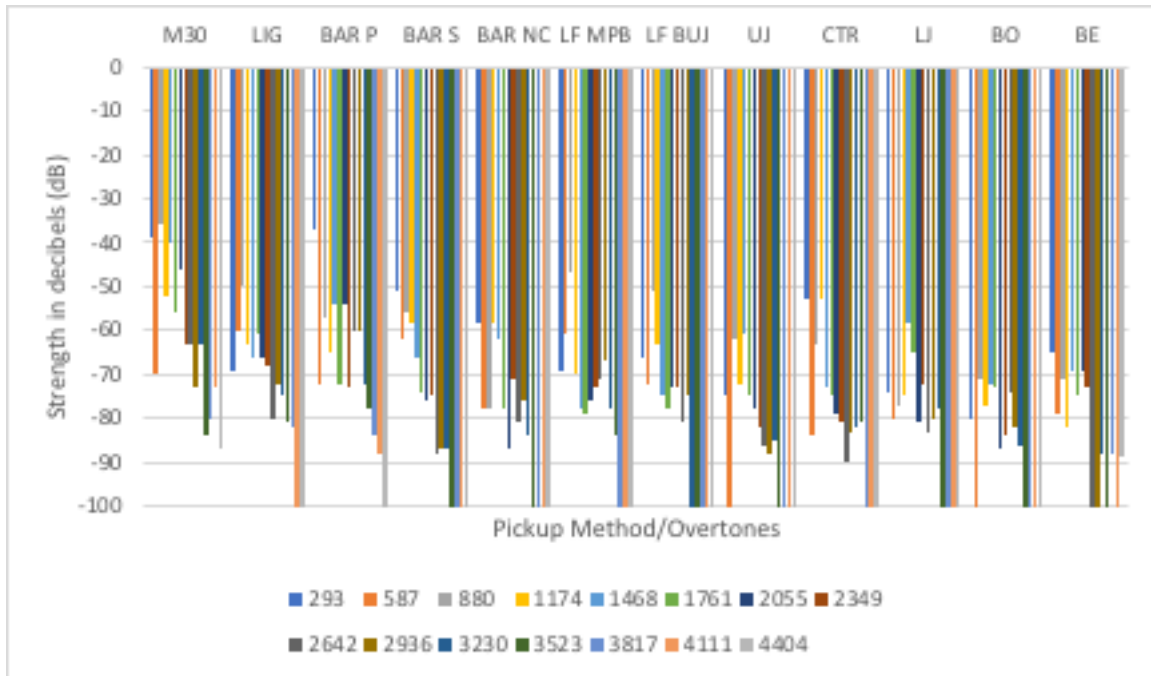
**Figure 5.29: Frequency response for G-sharp4.**

#### E4

The reference E4 sample shows the characteristic weakness of the even harmonics especially the second, fourth, and sixth, evening out from the eighth to the eleventh, and dropping lower for the twelfth and higher. The ported barrel shows the most similarity to the reference, with the weaker even harmonics, though with much weaker third, fifth, and seventh harmonics compared to the reference; these lower odd harmonics are in fact equal in strength to the ninth and tenth harmonics, which in the reference were much lower. The ligature and barrel surface exhibit similar displacement, though with a much stronger fundamental in the barrel surface. In both the harmonics up to the eighth are much tighter in relation, showing little difference between even and odd after the fourth. The LefreQue samples are even flatter in their response, with the exception of a very

strong third harmonic. Above the sixth harmonic the upper joint, center tenon, and lower joint are nearly identical. The upper joint shows a weak fundamental with strong third and fifth harmonics, while the lower joint is weak in the fundamental and third harmonic with a strong fifth. The center tenon actually shows an uncharacteristically strong fourth harmonic. The outside of the bell shows inconsistent results, while the end of the bell shows strong odd harmonics up to the 15<sup>th</sup> harmonic, with an exception of the 11<sup>th</sup> harmonic. That being said, harmonics of the bell end are very tightly bunched.

The spectral center supports these findings, with the measurement for the ported barrel at 435 Hz much lower than the reference at 1036 Hz. The barrel surface is similarly much lower at 628 Hz than the ligature at 1265 Hz, illustrating the stronger fundamental frequency in the barrel surface pickup. The LefreQue methods lie close to the reference, at 1158 Hz for the mouthpiece-barrel joint and 975 Hz at the barrel-upper joint despite their different spectra. The upper joint, lower joint, outside of the bell, and end of the bell all produce the characteristic higher centroid.



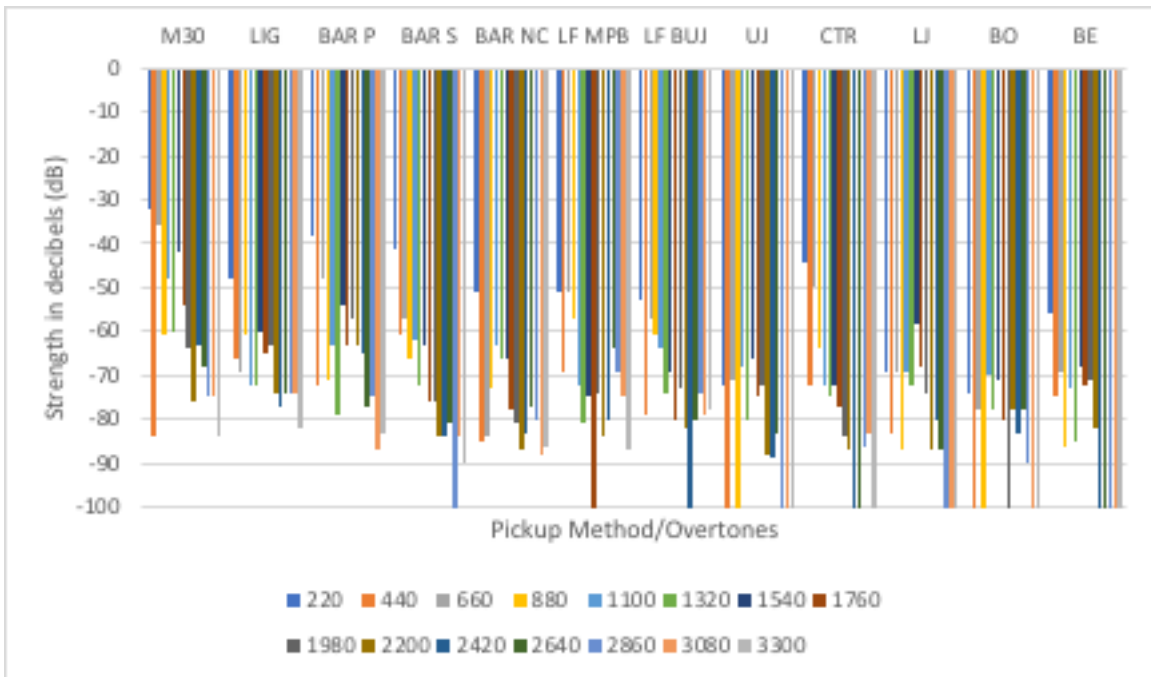
**Figure 5.30: Frequency response for E4.**

### B3

The reference B3 shows even more weakness in the even harmonics, with stronger third and seventh harmonics compared to the fifth and ninth harmonics. The ported barrel is most similar to this, though with proportionally weaker harmonics in general, and slightly more strength in the ninth. The ligature exhibits proportionally weaker lower harmonics despite the upper harmonics from the ninth and above being equal to those of the reference. The upper joint, center tenon, lower joint, outside of bell and bell end all show similarities in response to the ligature, though with different cutoffs. The barrel surface maintained the stronger odd harmonics and exhibits a decrease in strength as frequency increased, though over a small range after an initial steep decline

from the fundamental. Both LefreQue methods exhibit the even/odd relations, though with a much weaker fundamental and overall smaller range.

The spectral center supports these measurements, with the ported barrel pickup measuring at 422 Hz most closely matching the reference mark of 513 Hz. The ligature measures higher at 760 Hz, showing the proportional strength of the upper harmonics. The barrel surface and center tenon locations, exhibiting much stronger fundamental frequencies than the remaining locations, consequently have lower centroids at 273 Hz and 350 Hz respectively. The remaining methods, both LefreQue locations, the upper and lower joints, and both bell locations show higher spectral centers due to weak fundamental frequencies.

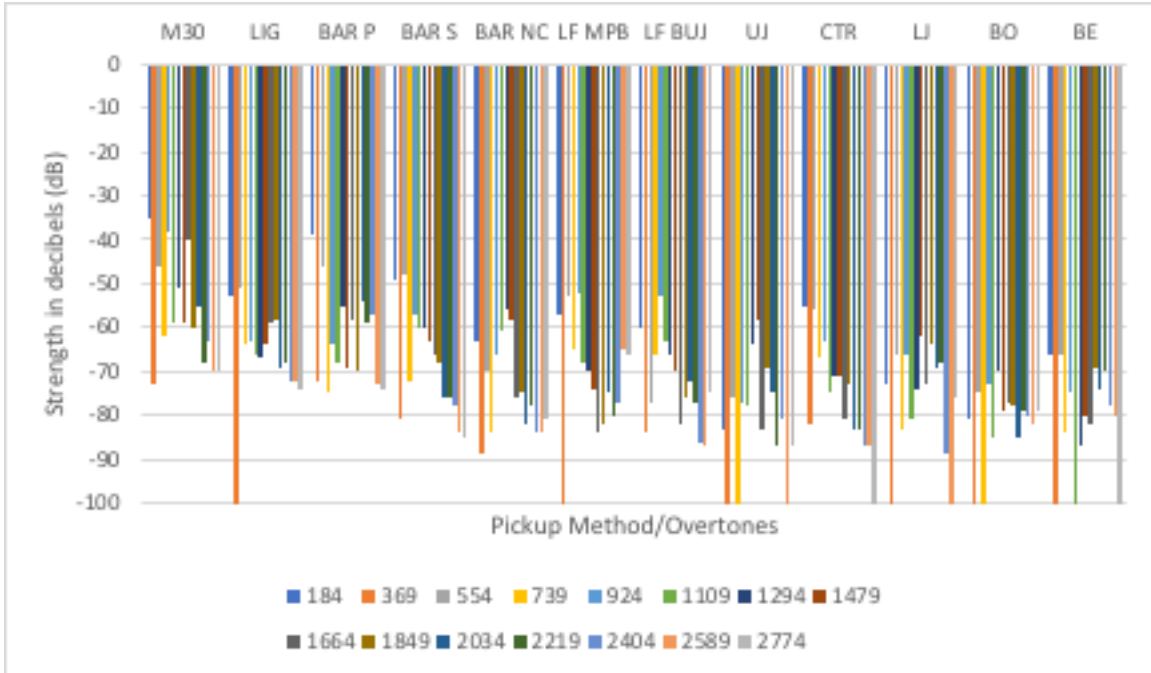


**Figure 5.31: Frequency response for B3.**

### G-sharp3

The reference G-sharp3 also shows strong even/odd relations, though with stronger fifth and ninth harmonics than third and seventh. After the ninth, the even/odd relations smooth out somewhat, though not completely. The ported barrel exhibits the most similar even/odd relations, though the emphasis was on the third and seventh harmonics rather than the fifth and ninth. In addition, there is much less evening out toward the higher frequencies. The ligature evens out the most above the third harmonic, with proportionally much stronger harmonics compared to the fundamental than the reference. The lower joint, bell outside, and bell end show very weak fundamentals compared to the harmonics, with the fundamental equal to or weaker than the third and fifth harmonics. The barrel surface and center tenon provide similar profiles with a third harmonic close in strength to the fundamental and a gradual decrease as frequency increased. Both LefreQue locations yield inconsistent results.

The spectral center of the reference measures at 930 Hz, and though the ported barrel pickup measures much lower at 537 Hz, this can be attributed to the different harmonic strength noted above. The ligature measures much higher at 1250 Hz due to the weak fundamental. Similar to other results from the chalumeau register, the barrel surface and center tenon locations measure lower than the reference at 640 Hz and 555 Hz respectively, while all other methods measure higher.



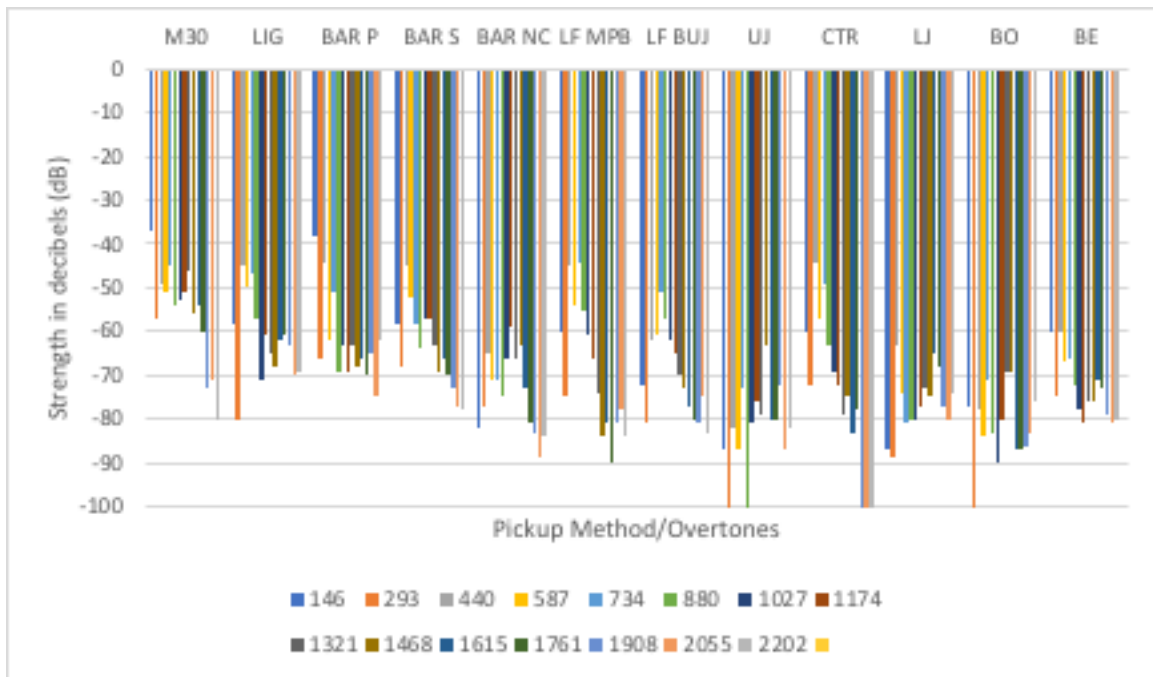
**Figure 5.32: Frequency response for G-sharp3.**

### E3

The reference sample shows stronger third and fifth harmonics, with a stronger fifth, even out of sixth, seventh, and eighth, a stronger ninth, and then decrease from tenth and above. The only other sample to show a fundamental that is stronger than the third and fifth harmonics is the ported barrel, where the third is stronger than the fifth. The ported barrel also exhibits the evening out from the sixth and above, though with more difference in the even/odd relations. The ligature and barrel surface provide samples very similar to the ported barrel, though with much weaker fundamentals. The center tenon sample also shows similar characteristics to the ligature and barrel surface, though over a much greater range and lower overall. Both LefreQue samples show a weaker fundamental, with stronger third through seventh harmonics, and weak harmonics from

the eighth and above. The upper joint, lower joint, and bell outside show flat responses by comparison, and were the weakest overall. The bell end, however, shows similarity to the ported barrel sample, though over a much smaller range and much weaker overall.

The spectral center for the reference is 494 Hz, compared to 274 Hz for the ported barrel pickup, likely due to the weaker even harmonics in the ported barrel sample. The ligature and barrel surface measure higher at 789 Hz and 605 Hz respectively, illustrating the comparative weakness of the fundamental; the center tenon measures similarly at 530 Hz. The other methods all measure much higher than the reference.



**Figure 5.33: Frequency response for E3.**

## Discussion

Based on the results of the study, the two pickup methods that most accurately reproduce the results of the reference recording are the ported barrel pickup and the ligature location for the contact microphone. These two locations are the most consistent with the reference in response, frequency cutoff, and overtone displacement of all the locations tested. However, despite being the closest of the methods tested, there are still significant differences.

The ligature location has the highest cutoff frequency of the methods tested, and therefore most closely resembles the higher cutoff of the reference. As stated above, this is likely due to the proximity to the reed, allowing the higher harmonics produced by the reed that are not as well supported in the bore to be captured by the pickup. In addition, the placement on the ligature situates the pickup far enough away from the key work to limit the amount of extra noise added via key noise transients. In contrast, the overall level of the ligature pickup is weaker than that of the reference and ported barrel pickup, though this is of slightly less concern than other considerations since level can be adjusted with a simple preamplifier. What is of more concern to the validity of the ligature pickup is the overtone displacement, which when compared to the reference or the ported barrel pickup shows much stronger overtones as frequency increases. In other words, the higher harmonics are stronger in comparison to the fundamental and lower harmonics on the ligature than on other methods. The spectral center of gravity measurements support this, as the measurements recorded for the ligature samples all exceed that of the reference, highlighting the comparative proportional strength of the harmonics in the ligature pickup.

The ported barrel pickup offers the opposite of what the ligature offers, with a lower cutoff, resulting in a slightly less full harmonic spectrum, but with much stronger signal and better overtone displacement. Whereas the effective cutoff of the reference is around 6.5 kHz for all but the altissimo notes, the ported barrel pickup cutoff is around 5.5 kHz. In addition, the reference does show some presence of harmonics above 6.5 kHz as shown on the spectrogram, while the ported barrel does not. The overtone displacement for the ported barrel pickup resembles that of the reference much more than the ligature though, with the strength of higher harmonics weaker in proportion to the lower harmonics than shown in the ligature. However, though the spectral center is typically close to the reference, the throat tones (E4 and G-sharp4) and upper clarion register (G-sharp5 and B5) are two areas of concern, producing much lower or much higher centroids respectively.

One point worth noting, although small, is the greater change of intensity in the even/odd relations found in the ported barrel pickup compared to the reference. In the chalumeau register the ported barrel has weaker low even harmonics (second, fourth, sixth) in comparison to its fundamental than the reference has to its low even harmonics. This is due to weak bore support for even harmonics; the ported barrel pickup only captures what is in the bore, whereas the reference captures more of the even harmonics as they are radiated out from the instrument. The spectral center highlights this, with lower measurements for the ported barrel pickup than the reference due to the greater difference in intensity between the even and odd harmonics in the chalumeau.

Three other methods provide compelling, if not as exact results. These methods include the surface of the barrel, the center tenon, and the end of the bell. The surface of

the barrel shows results similar to the ported barrel pickup, though less defined overall. The overall signal of the barrel surface is typically weaker than the ported barrel, and the cutoff frequency is much lower at around 4.25 kHz compared to the 5.5 kHz of the ported barrel pickup. The overtone displacement for the barrel surface is also much more gradual from low to high, with closer even/odd relations than the ligature or ported barrel. The spectral center measurements for the barrel surface pickup follow those for the reference more closely than those of the ported barrel pickup due to the more gradual attenuation across the harmonic spectrum. The center tenon exhibits these same qualities though to a larger degree, with a lower level, lower cutoff frequency (around 3.75 kHz); the spectral center supports this, with measurements slightly lower than those of the barrel surface.

The probable explanation for the results of the surface mounted pickup locations is the source of the vibrations on the body of the instrument: the reed. According to Backus, the vibrations on the body are caused by the oscillation of the reed.<sup>98</sup> The barrel and center tenon are likely located at wave anti-nodes along the surface, creating mechanical strain on the pickup and thus voltage. Since the vibration is caused by the reed, that would explain the more prominent even harmonics, since the reed produces both even and odd harmonics; it is the bore that does not support the even harmonics.

The end of the bell shows results that are similar to the ligature, though to a lesser degree. The end of the bell produces the highest cutoff frequency of any of the contact pickup methods next to the ligature at slightly over 5.0 kHz, and similar to the ligature the overtone displacement was flatter, with proportionally stronger high harmonics

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<sup>98</sup> Backus, "Effects of Wall Material," 1883-1884.

compared to other methods. The overall level is quite weak in comparison to the methods described above. The spectral center is consequently much higher for the end of the bell location.

Several factors may explain the improved frequency response of the end of the bell. First, this is the only pickup to be placed perpendicular to the propagation of the wave; all other pickups were positioned parallel to the longitudinal wave produced in the bore. Second, the cutoff frequency of the clarinet would allow higher frequencies above the cutoff to travel the length of the bore and radiate from the bell, meaning that the pickup is ideally situated to capture these higher frequencies.<sup>99</sup> Third, the bell acts as a means to radiate unsupported frequencies out of the bore, again making the pickup ideally situated.<sup>100</sup>

The remaining contact pickups placed on the body of the instrument, at the upper joint, lower joint, and outside of the bell do not accurately reproduce or represent the acoustic clarinet tone. This seems to be caused by being placed in less than ideal locations for waves caused by the vibration of the reed to be captured. Compared to the pickup placed on the center tenon, these three locations exhibit a similar cutoff frequency, though the overtone displacement is much flatter, with certain bands stronger than others depending on location. Thus, these locations are less than ideal for using a pickup on the clarinet.

The LefreQue plates similarly are not ideal for using a pickup. These two locations, as noted above, give much different results from the other pickup methods. The

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<sup>99</sup> Benade, *Fundamentals*, 435

<sup>100</sup> UNSW, "Clarinet Acoustics: An Introduction."

LefreQue plates seem to attenuate the middle frequencies, especially on the mouthpiece-barrel joint sample. In addition, the plates have a higher cutoff frequency compared to similar locations, especially with the barrel-upper joint sample. The likely cause for both of these is the resonance of the plates, which vibrate sympathetically with the vibration of the instrument, but add their own resonances as well.

### **Empirical Listening**

In order to characterize the results above, a brief account of listening to the samples is provided. As expected, the methods that sound the most clarinet-like follow the results outlined above. The barrel pickup does sound the most similar, though the ligature pickup borders on the artificial due to the extended range of harmonics. The barrel surface, in a sense, sounds more clarinet-like than the ligature, though much stuffier rather than bright and artificial due to the comparative lack of overtones. The center tenon and end of the bell also sound rather clarinet-like, as shown through the results, though the level of each sample is noticeably less than the methods previously described in this section.

The other pickups methods all sound somewhat artificial due to their respective filtering effects. The LefreQue plates give a buzzier, more metallic sound, especially the barrel-upper joint location. The sound can be likened to adding a moderate amount of harmonic distortion. In contrast, the upper joint and lower joint locations give a very filtered sound, as if a bandpass filter were applied to the middle range of the acoustic clarinet tone. Using that analogy, the upper joint sounds as if the filter is much narrower, whereas the lower joint sounds wider.

While the main purpose of this paper was to examine what pickup methods most accurately reproduce natural, acoustic clarinet tone, a secondary objective was to provide a reference for the resultant sounds of each method. While some of these other pickup methods may not sound like a natural clarinet, they could still find use in certain applications.

### **Possible Improvements**

The results of this study show compelling evidence that current pickup methods have progressed to a point where it is possible to accurately represent the acoustic tone of the clarinet with either a ported barrel pickup or a contact transducer placed near or on the reed. However, despite evidence, a discerning performer may or may not perceive key differences. Performer perception, as well as comparisons to different microphones and pickups remains an area of study beyond the scope of this paper.

Based on the research presented here, there are some possible improvements to clarinet pickup design that could assist current designs in better replicating the acoustic clarinet sound. The first suggested improvement is in adding a transducer to the end of the bell to work in conjunction with a ported barrel pickup. As shown above, the ported barrel pickup has two notable differences from the reference: lower cutoff frequency and larger even/odd harmonic relations. Both of these characteristics can make the ported barrel pickup sound thinner than the reference due to the lack of or weaker harmonics.

Placing a transducer at the end of the bell could potentially compensate for the harmonics that have less support in the bore, and therefore are not as strong on the ported barrel pickup. The bell helps radiate the higher frequencies that travel the length of the

bore as well as those frequencies unsupported by the bore, and as shown in the sample could assist in compensating for the weaker harmonics of the ported barrel pickup, bringing the spectral center up for lower notes of the chalumeau to more closely resemble the reference.

Another improvement is in the design of a barrel pickup. The current designs use a small port to tap into the bore and expose the piezoelectric element to the pressure changes inside the bore. The barrel or mouthpiece is an ideal place to position this port due to the maximum change in pressure at the closed end of the instrument. However, as shown in the ported barrel sample, due to the changing acoustic impedance of each different pitch the port may not be located in an ideal location to allow for consistent volume throughout the range of the instrument. Furthermore, several performers have anecdotal evidence of certain ‘dud’ notes with their personal pickup systems, which would offer some evidence to suggest that this is an issue.

A possible improvement from the small port to an external device is to utilize a piezoelectric film throughout the bore component of the barrel in a similar manner to a surface acoustic wave (SAW) sensor.<sup>101</sup> SAW sensors, typically used to detect specific particles in a stream of gas, can be made thin and small enough to line the inside of a barrel, thus making the length of the barrel into a pickup rather than just a single point. Assuming the pickup was crafted in such a way that the mechanical displacement of the element did not cause significant changes in the shape of the bore so as to appreciably disrupt the response of the instrument, this style of pickup would be less prone to uneven notes due to changing pressure nodes.

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<sup>101</sup> APC International Ltd., *Piezoelectric Ceramics*, 57.

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APPENDIX A

NCM 8X COMPARISON AND DATA

The comparison that follows utilizes the PiezoBarrel data found in appendices B-Q. After the initial recording session to capture the samples used above, a Nalbantov NCM 8X barrel pickup was obtained for comparison to the PiezoBarrel. Due to the isolated nature of barrel pickups, it was deemed possible to provide a comparison between the two ported barrel pickups, though the differences in the performer, reed, instrument, recording space, and equipment disqualified the Nalbantov from comparison with the other methods. As shown in the figure below, the Nalbantov pickup is similar in nature to the PiezoBarrel, connecting via a threaded port in the barrel. The Nalbantov was recorded via direct connection to a Focusrite Saffire Pro 40 into Ableton Live. The sample rates of 48000 kHz at 16 bits were maintained, as was the WAV file format.

The Nalbantov pickup also arrived with a pre-ported barrel that was used for this supplemental test. The threaded section of the port was the same size as the PiezoBarrel, and the two pickups could be used on either barrel, but the port into the bore was of significantly different size between the PiezoBarrel barrel and the Nalbantov barrel. The PiezoBarrel barrel shows a much smaller hole drilled into the bore, and according to the website it is recommended to use a 2.5mm or 0.125 inch hole.<sup>102</sup> The Nalbantov barrel appears to have a much larger port, approximately the size of the threaded plug which is 8mm.

The Nalbantov provides a good amount of gain, similar to the PiezoBarrel. The Nalbantov is not as consistent throughout the range, with greater loss from G-sharp5-E7. The PiezoBarrel only shows one note that has significant loss, B5, whereas the Nalbantov is consistently weaker in the upper clarion and altissimo range, with the exception of B6.

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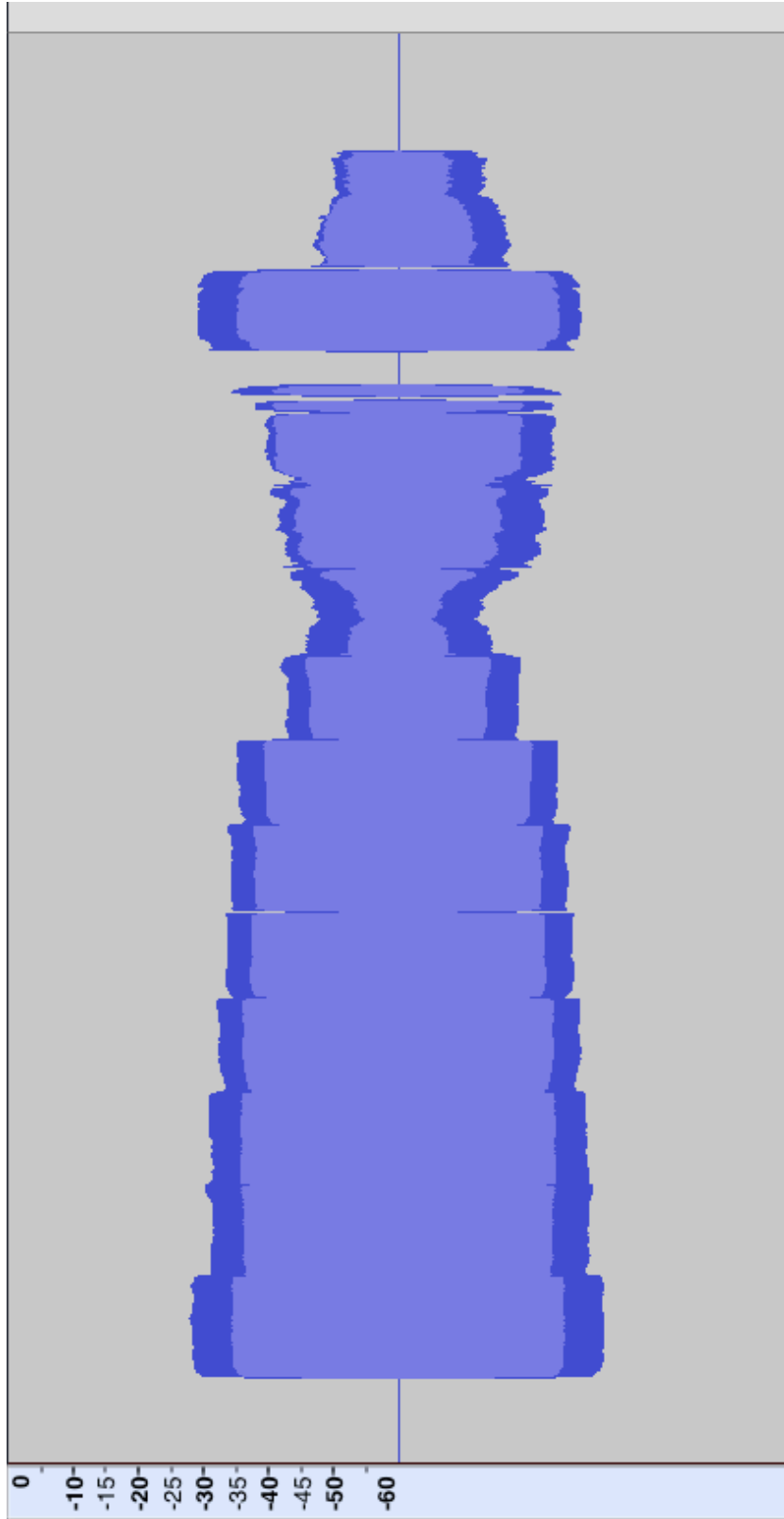
<sup>102</sup> "Instructions," PiezoBarrel, accessed March 11, 2018, <http://www.piezobarrel.com/instructions.htm>.

The Nalbantov has a much higher cutoff frequency, around 6.75 kHz compared to the 5.5 kHz of the PiezoBarrel, though the harmonics of the Nalbantov are nearly all much weaker than those of the PiezoBarrel, even when the level of the Nalbantov fundamental is stronger than that of the PiezoBarrel. In addition, the Nalbantov appears to lose signal in the overtones between 2000-3000 Hz, with the range of 3500-4000 Hz stronger.

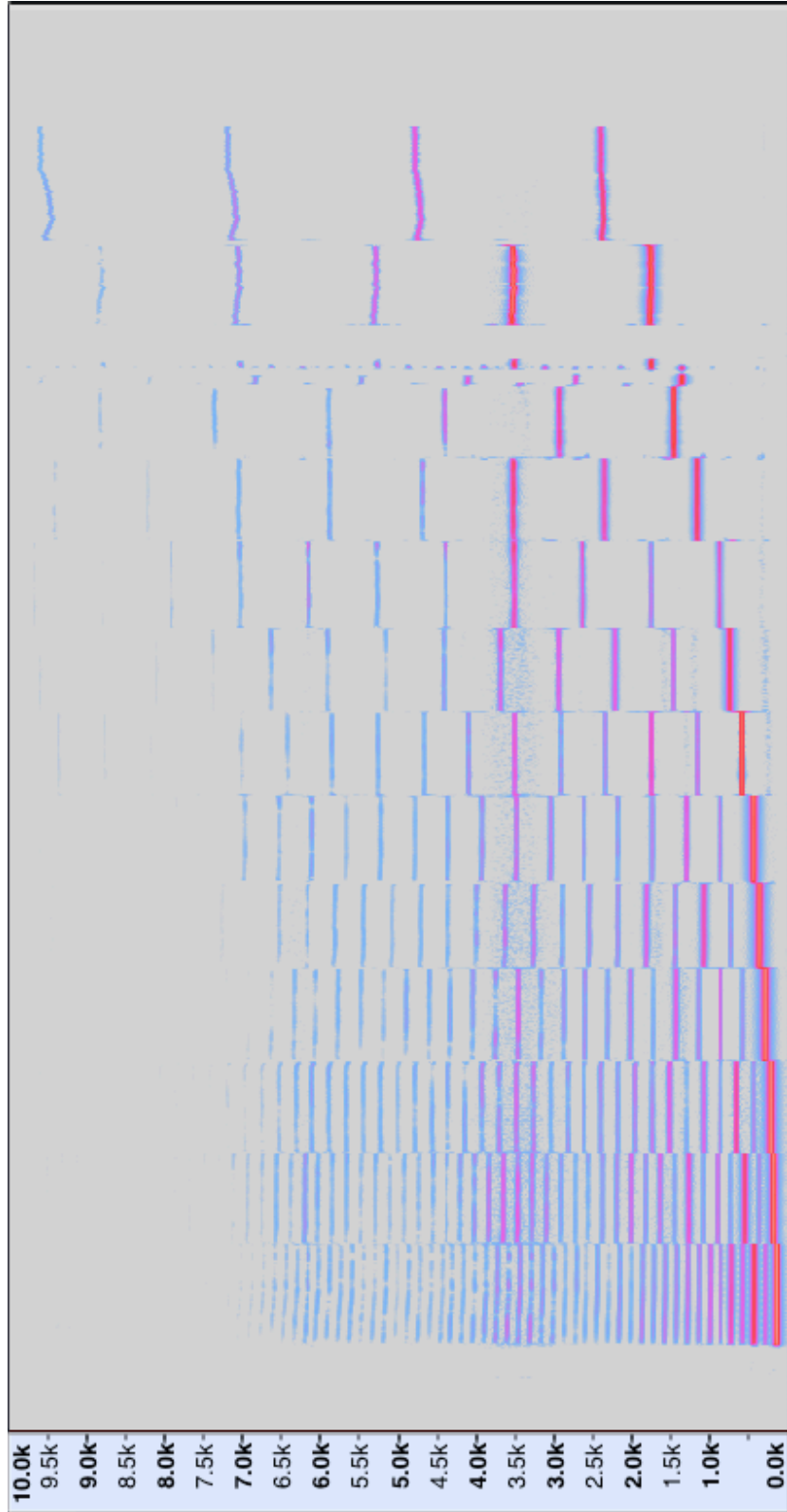
In an empirical listening test, these differences are apparent. The Nalbantov does sound slightly fuller than the PiezoBarrel, but not as ‘warm,’ with a slight emphasis on higher harmonics. The PiezoBarrel is slightly fuzzier, and the stronger lower harmonics are apparent.



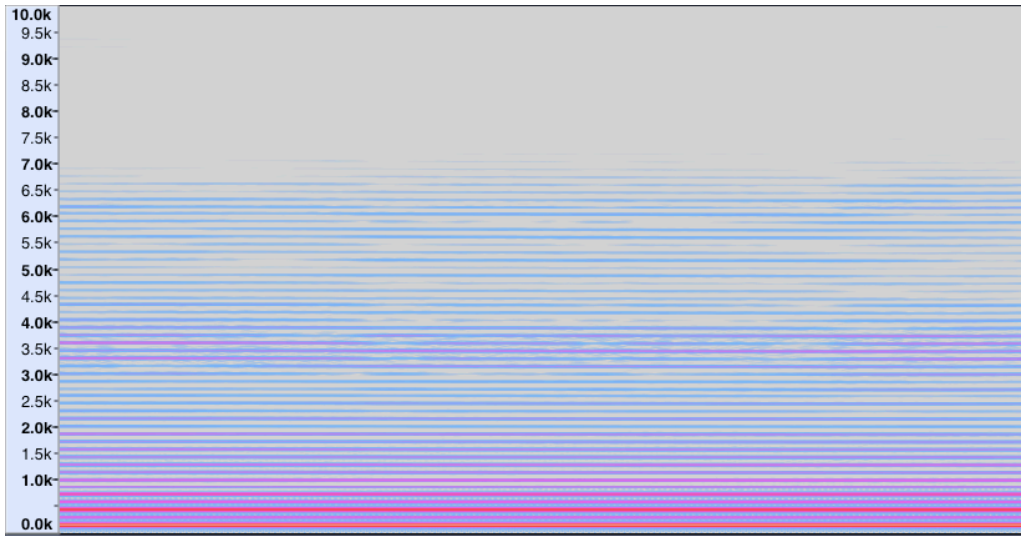
**Figure A.1: Nalbantov NCM 8X barrel pickup with included barrel.**



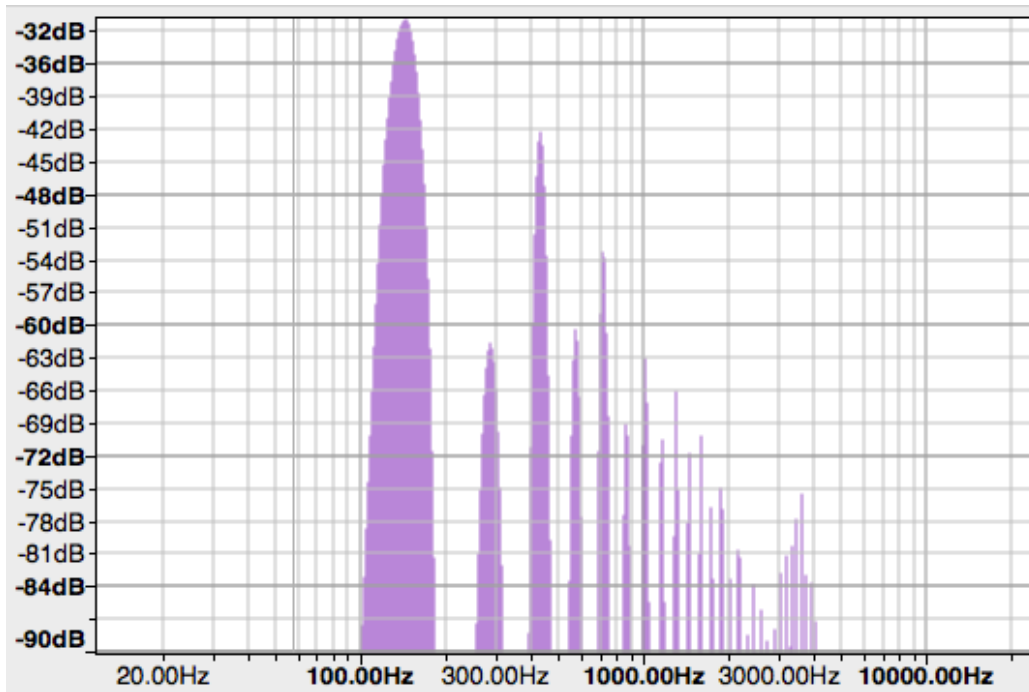
Nalbantov Full dB Waveform



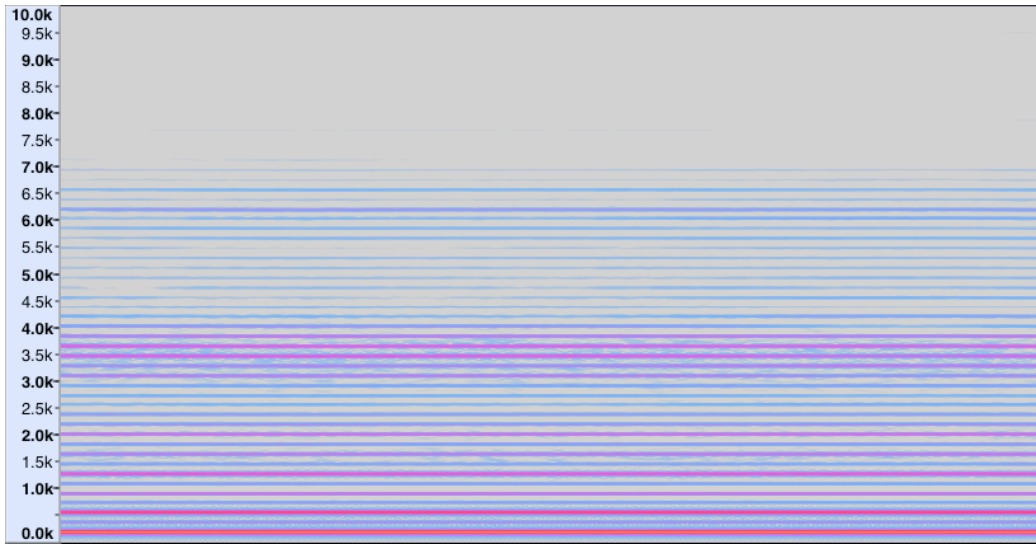
Nalbantov Full Spectrogram



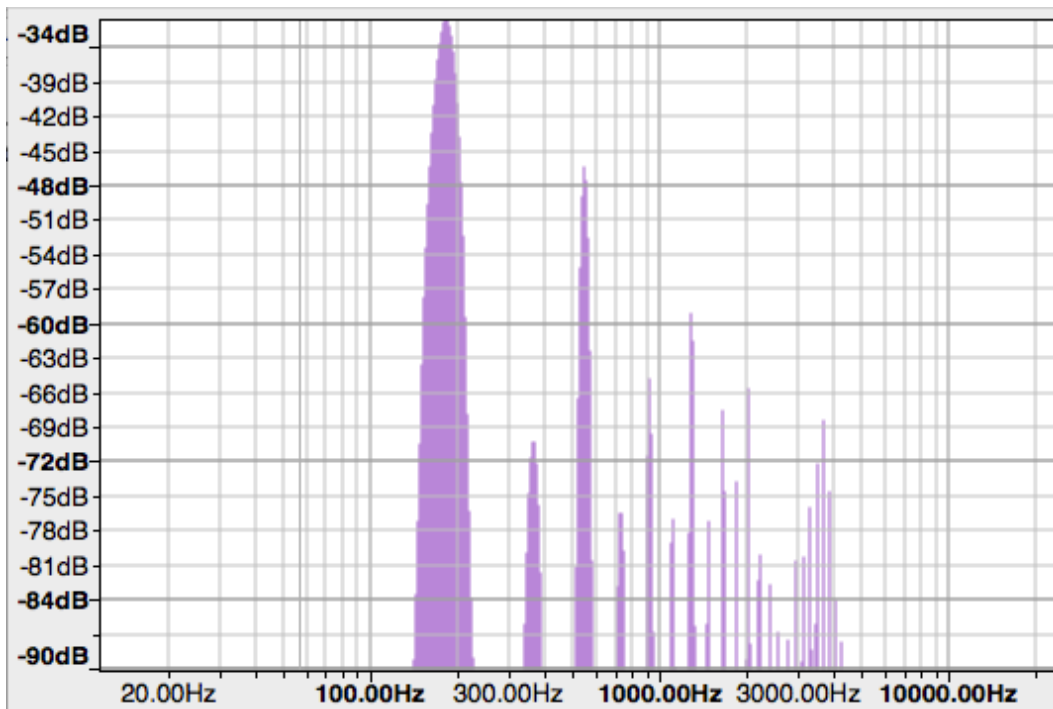
Nalbantov E3



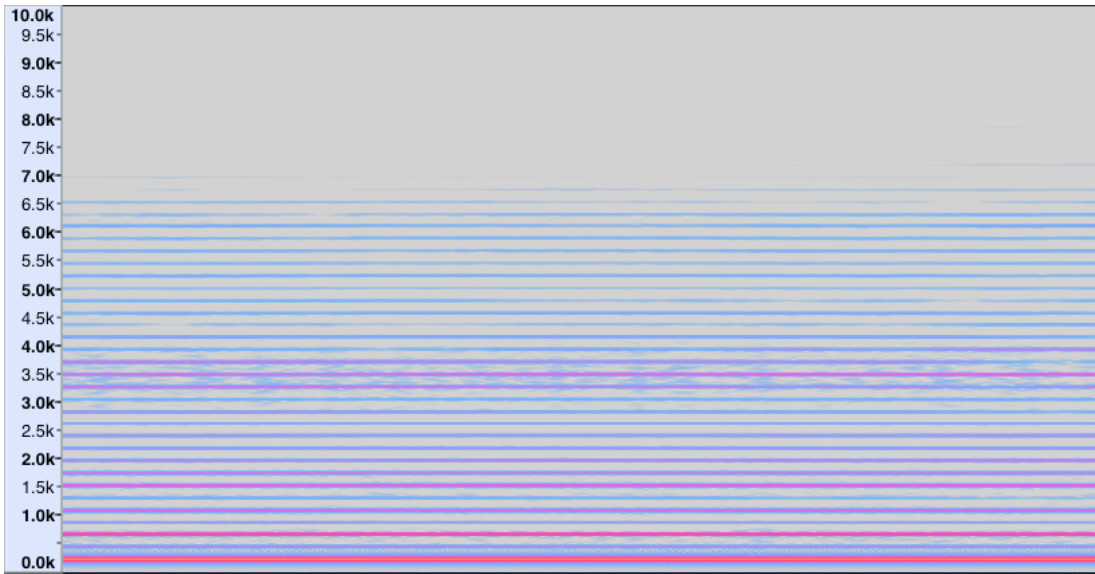
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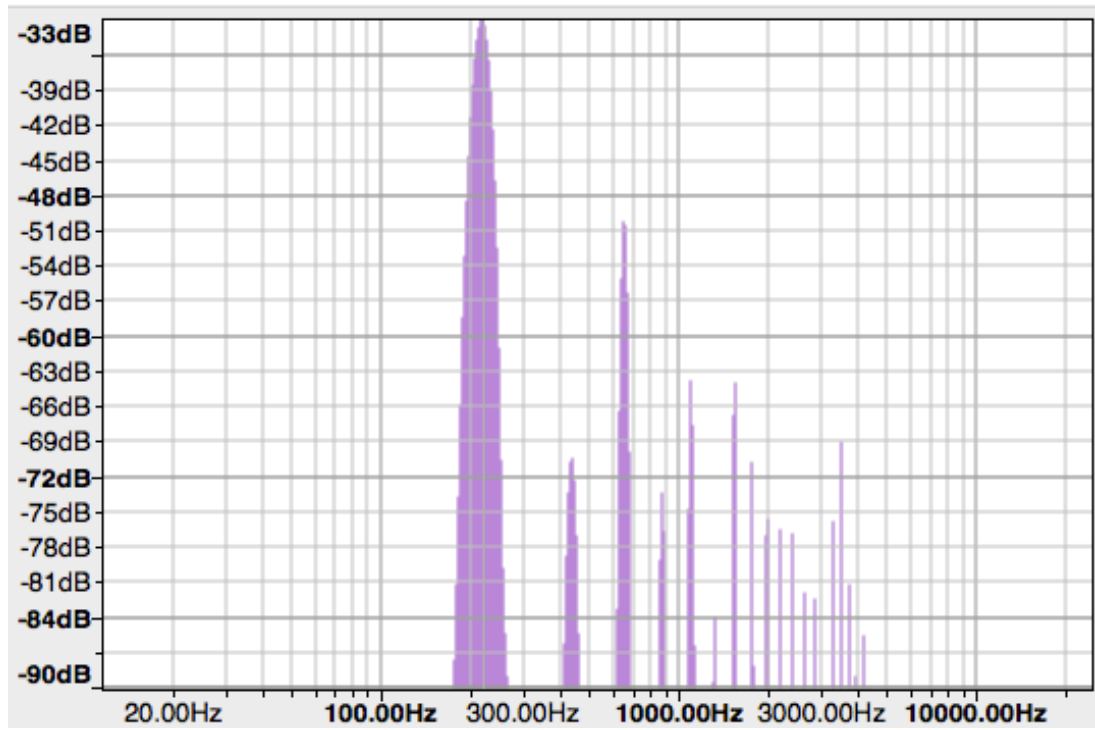
Nalbantov G-sharp3



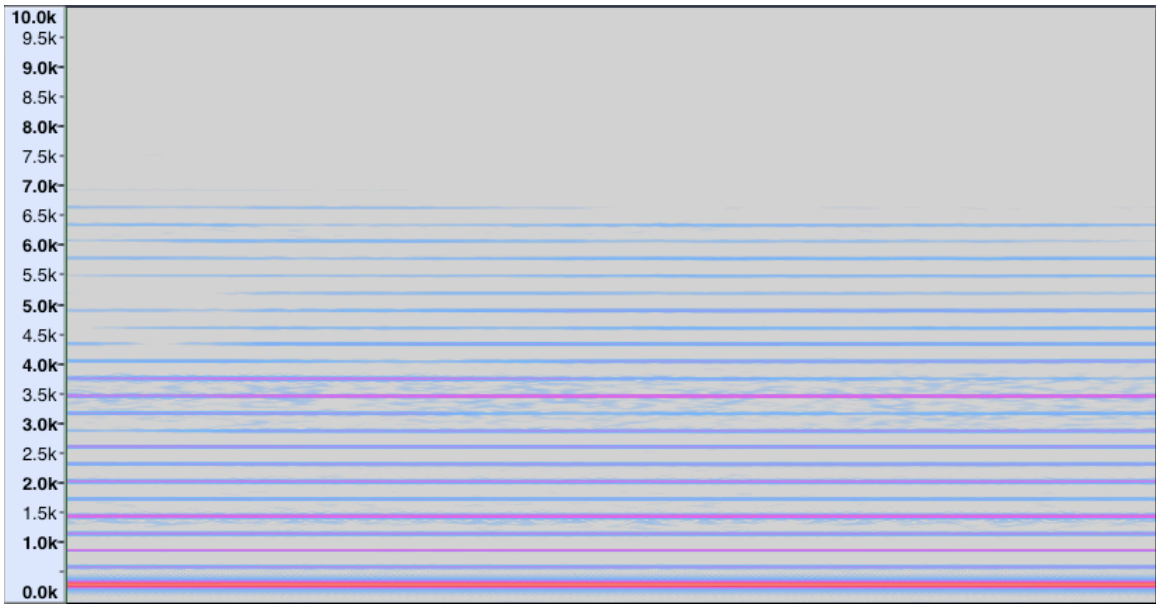
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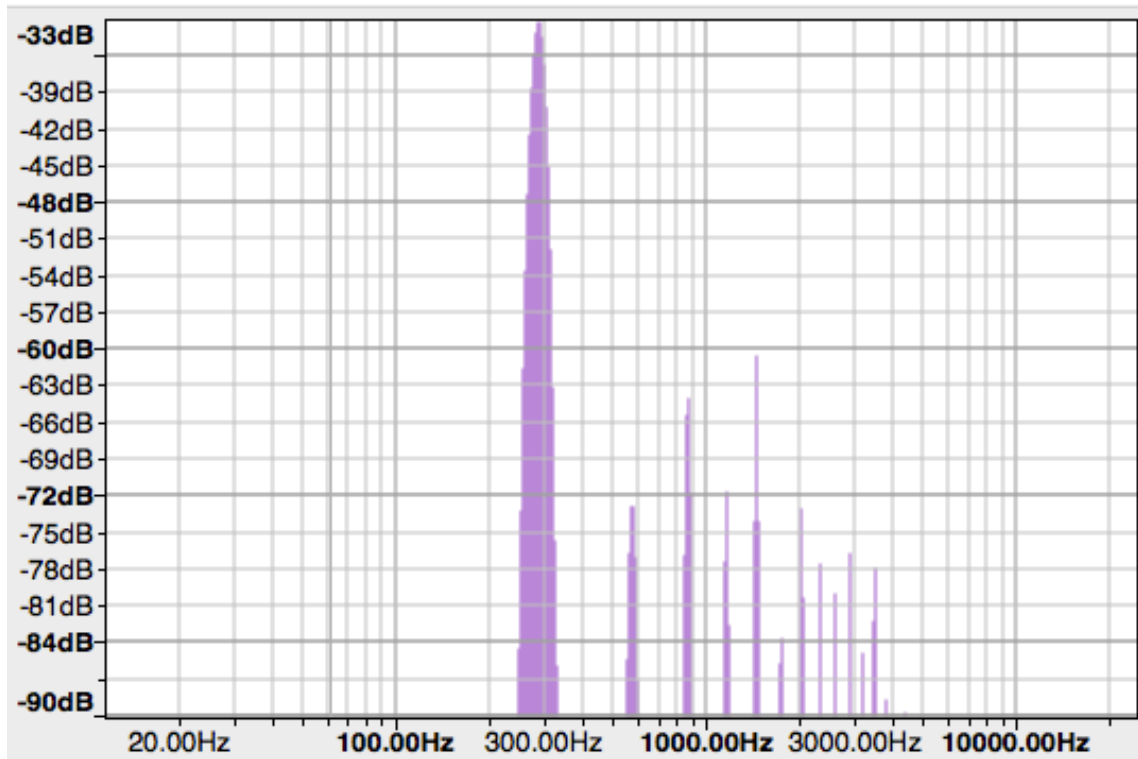
Nalbantov B3



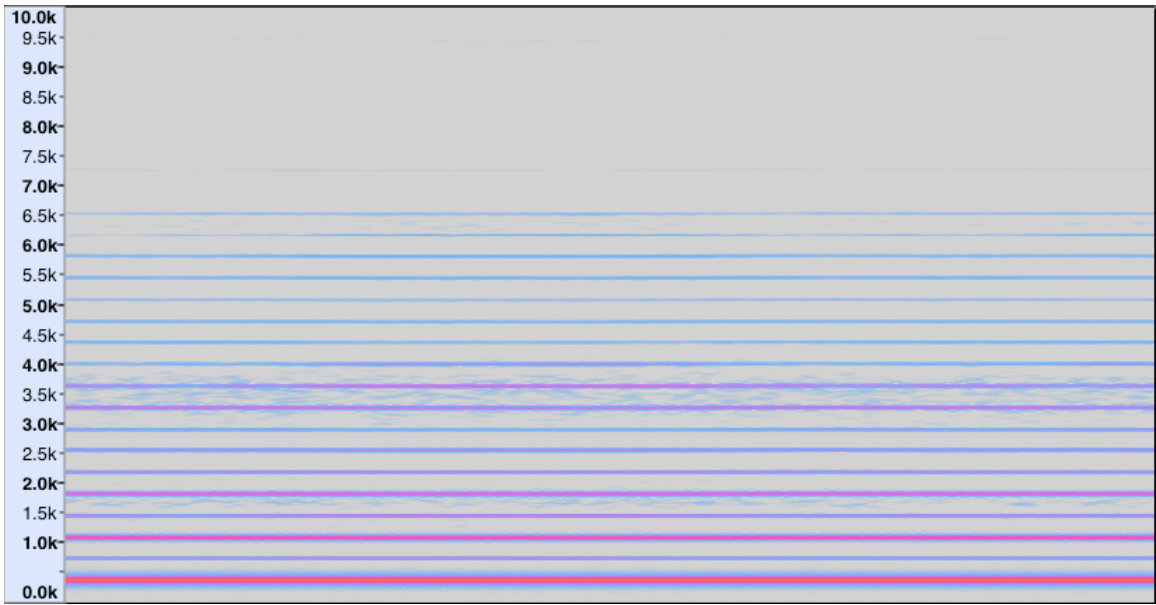
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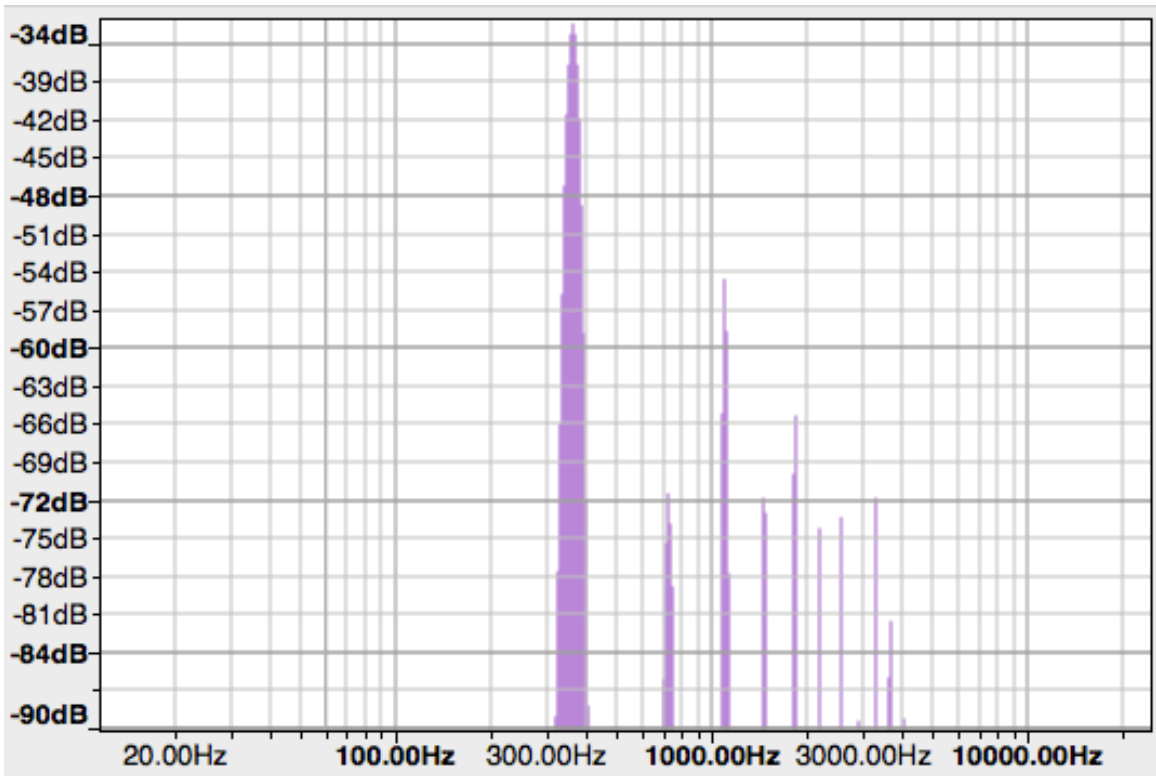
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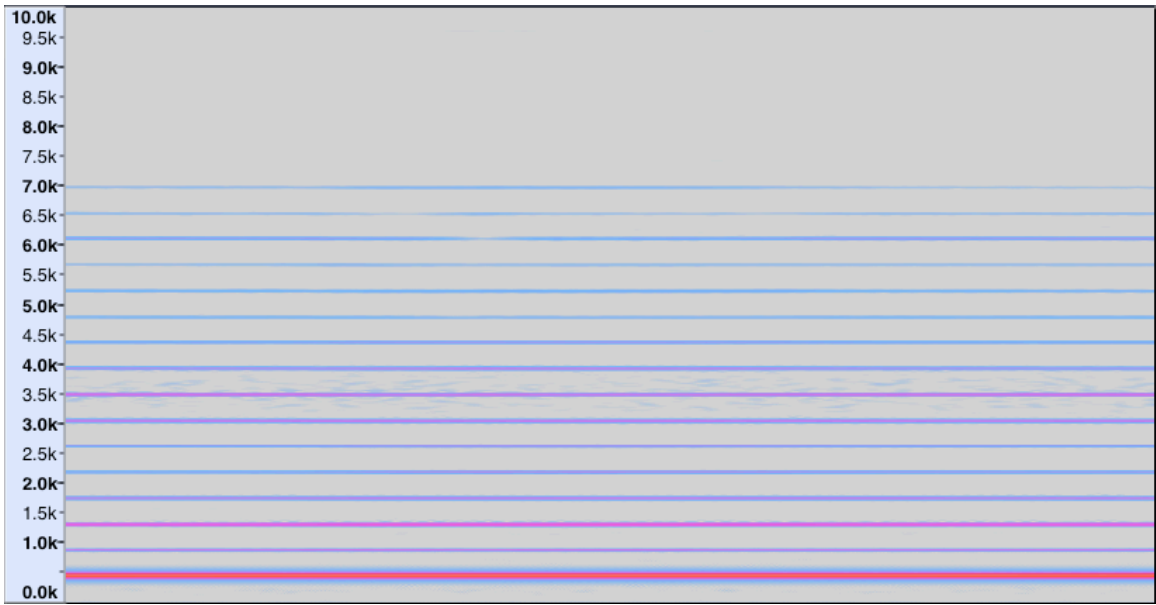
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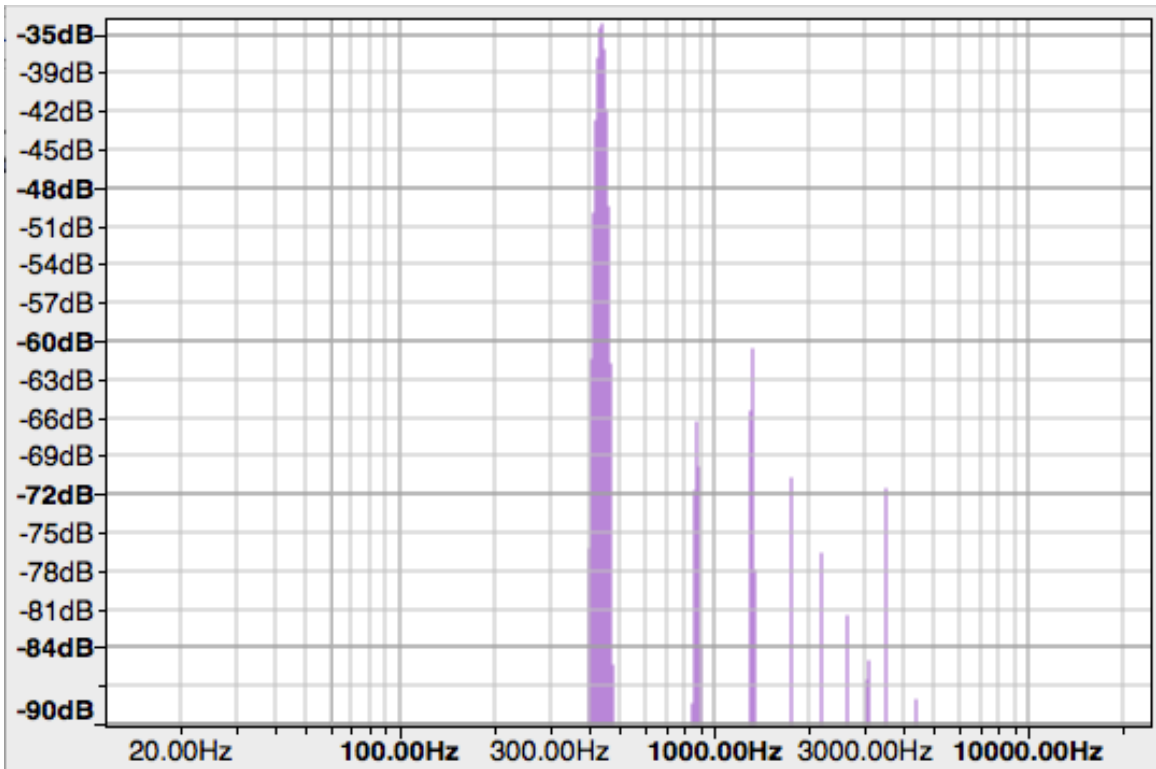
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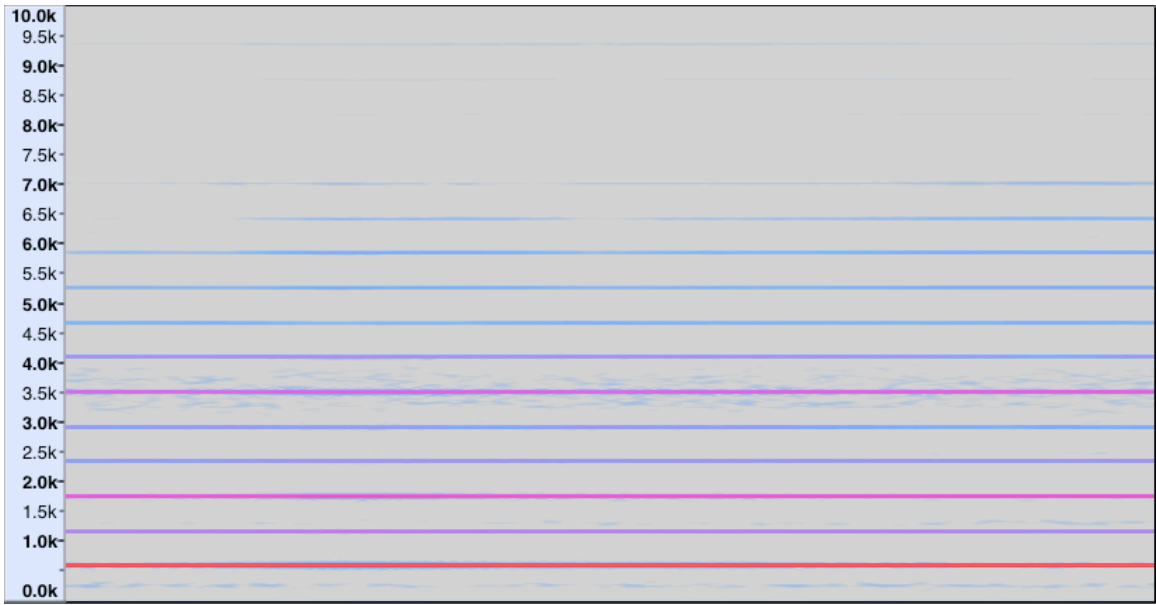
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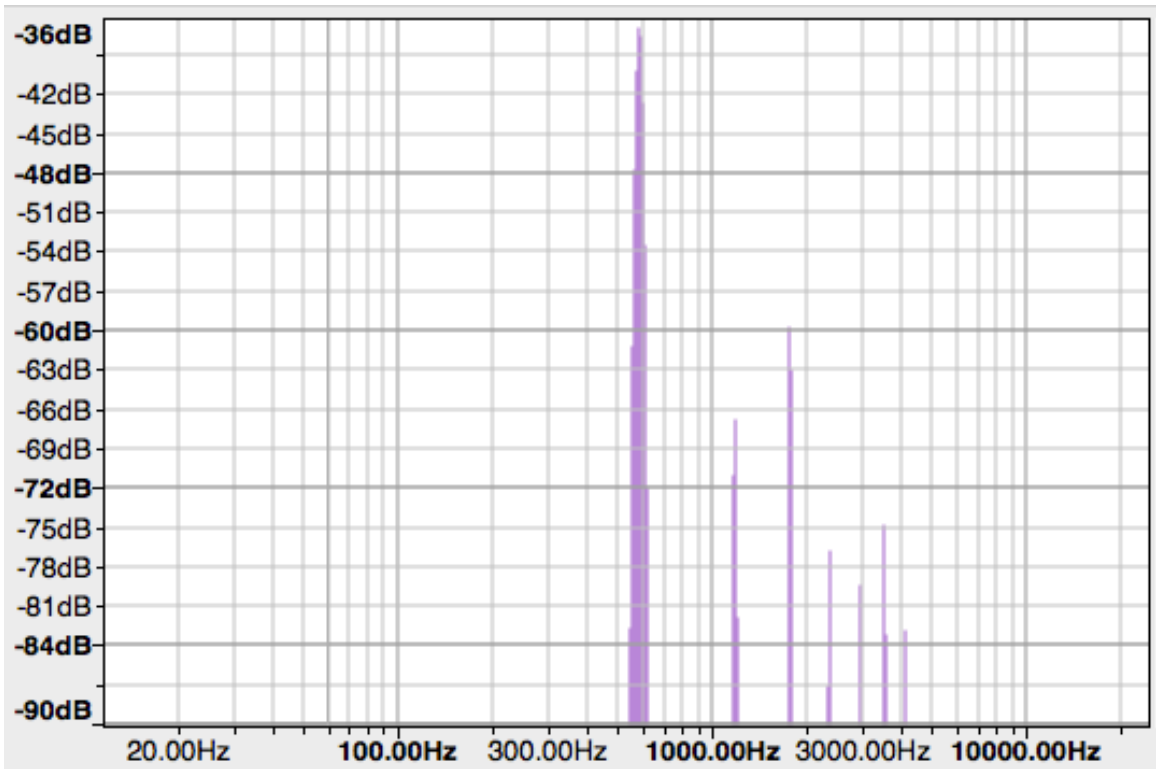
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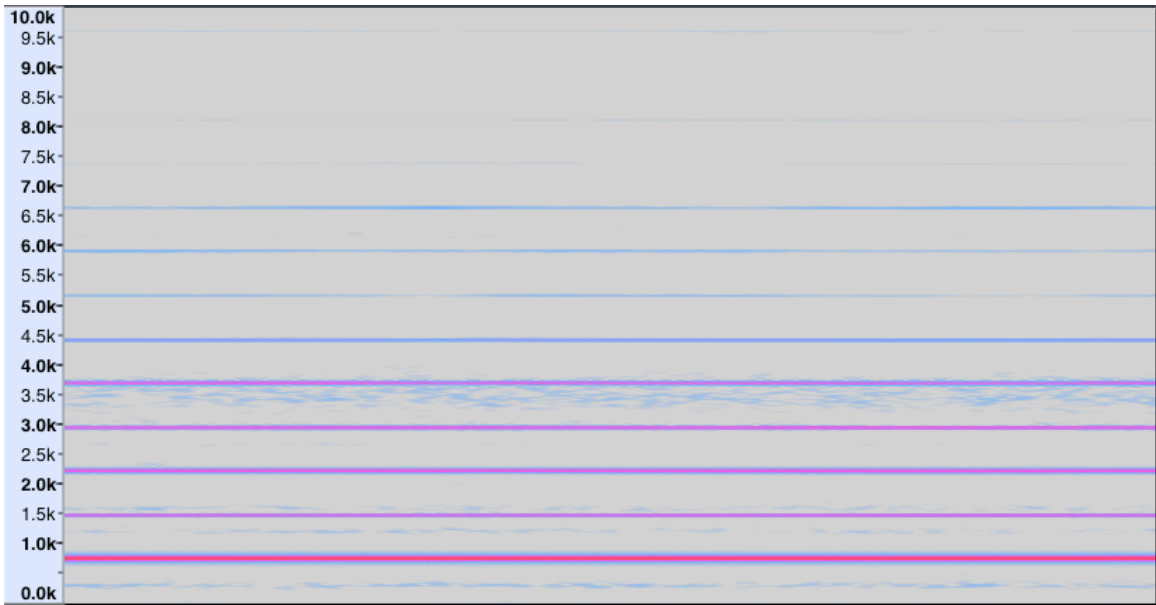
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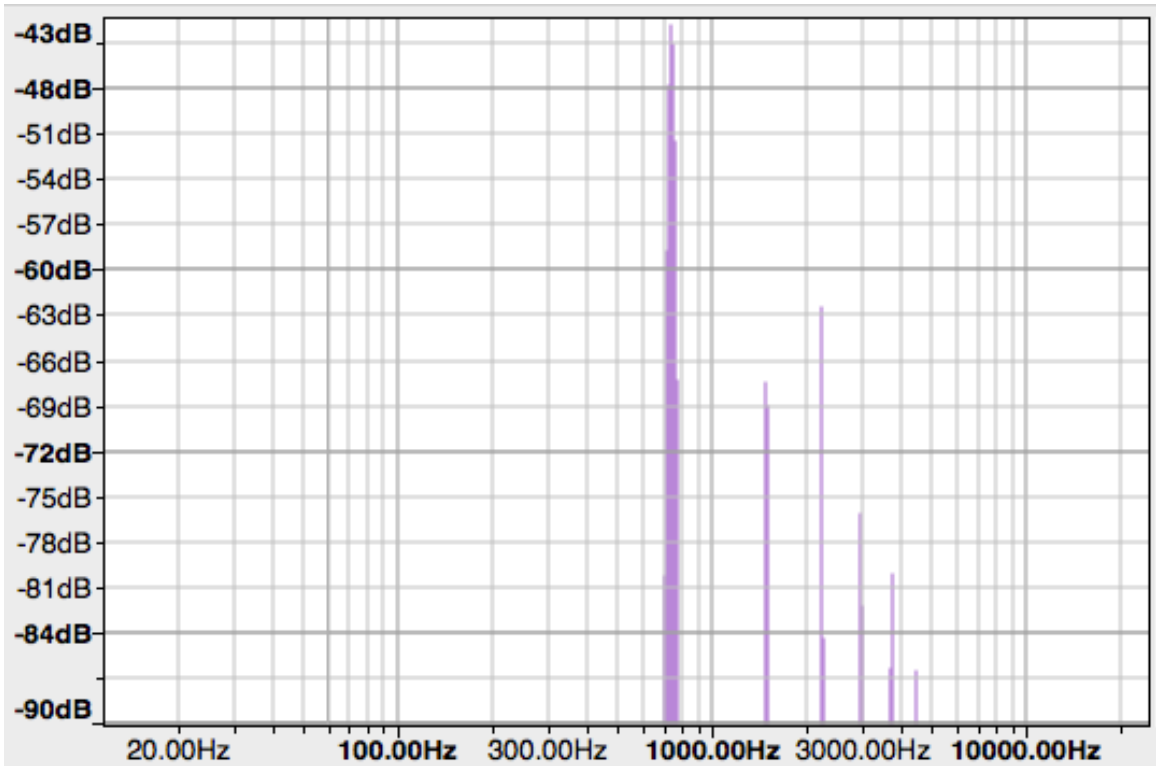
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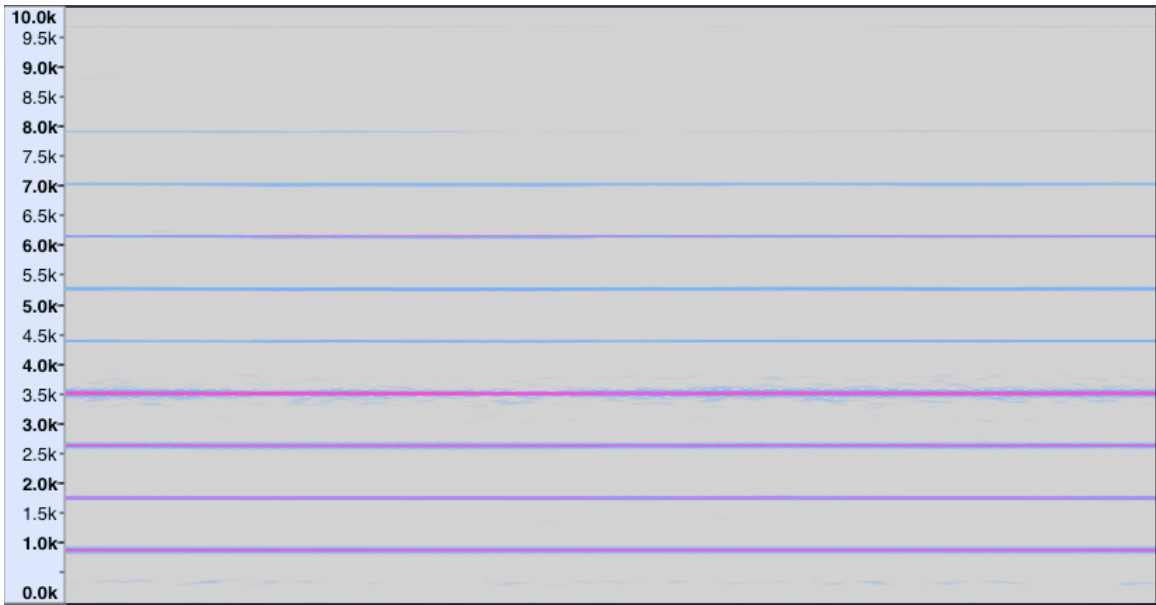
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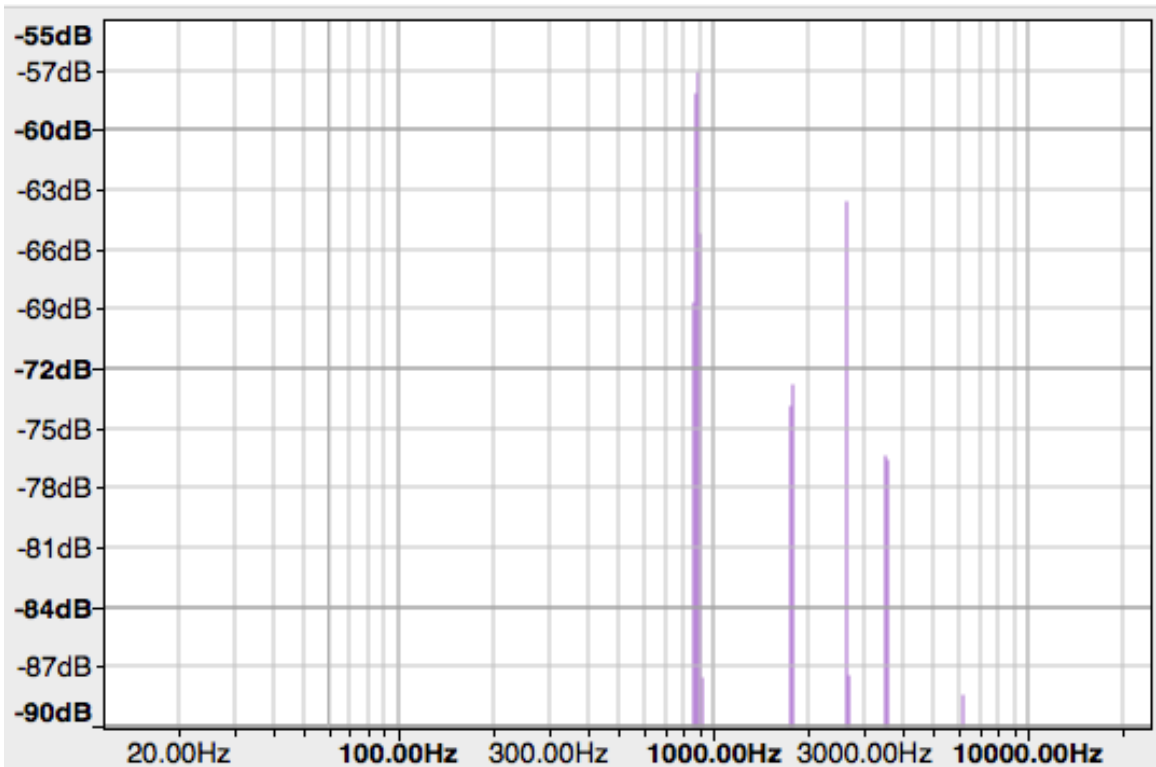
Nalbantov G-sharp5



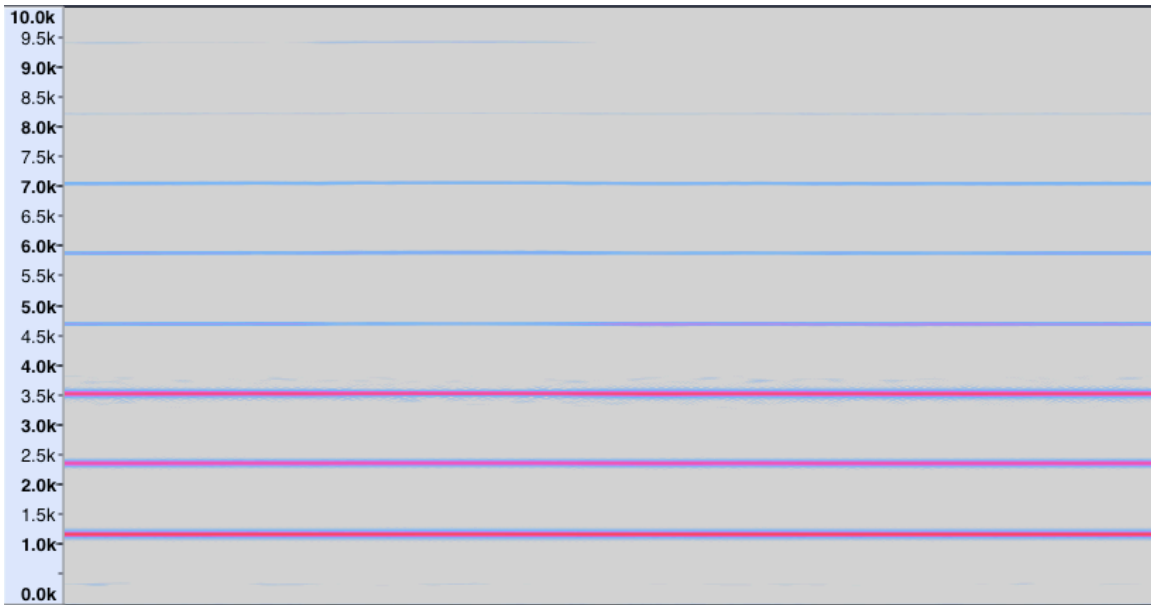
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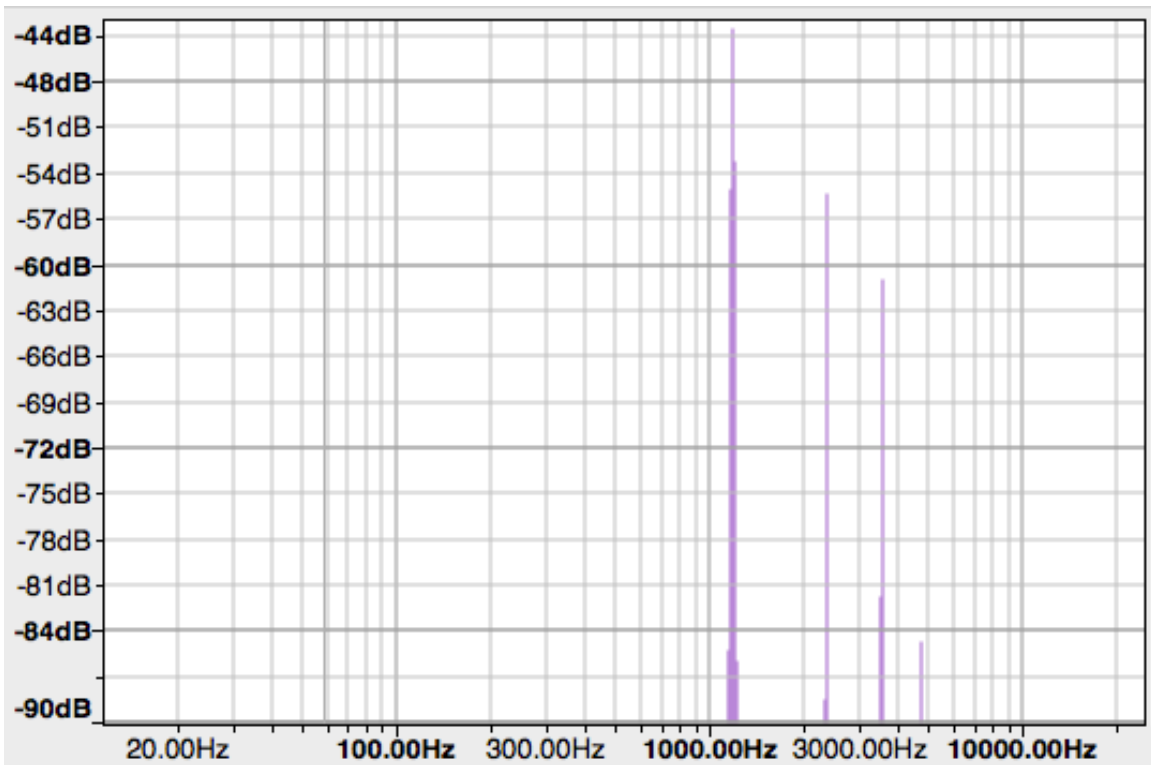
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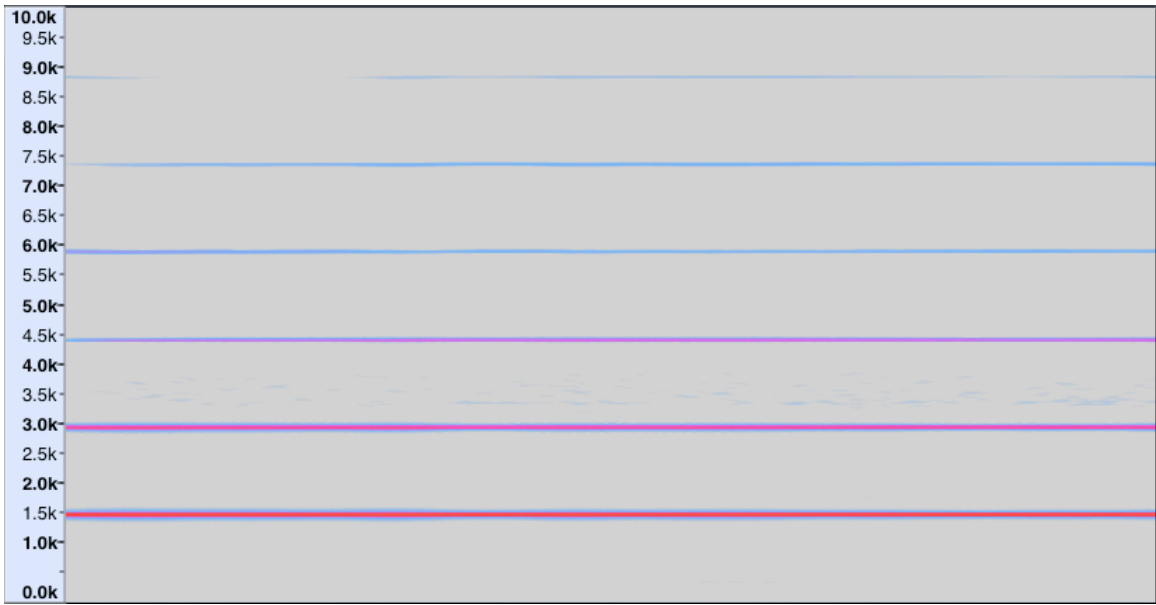
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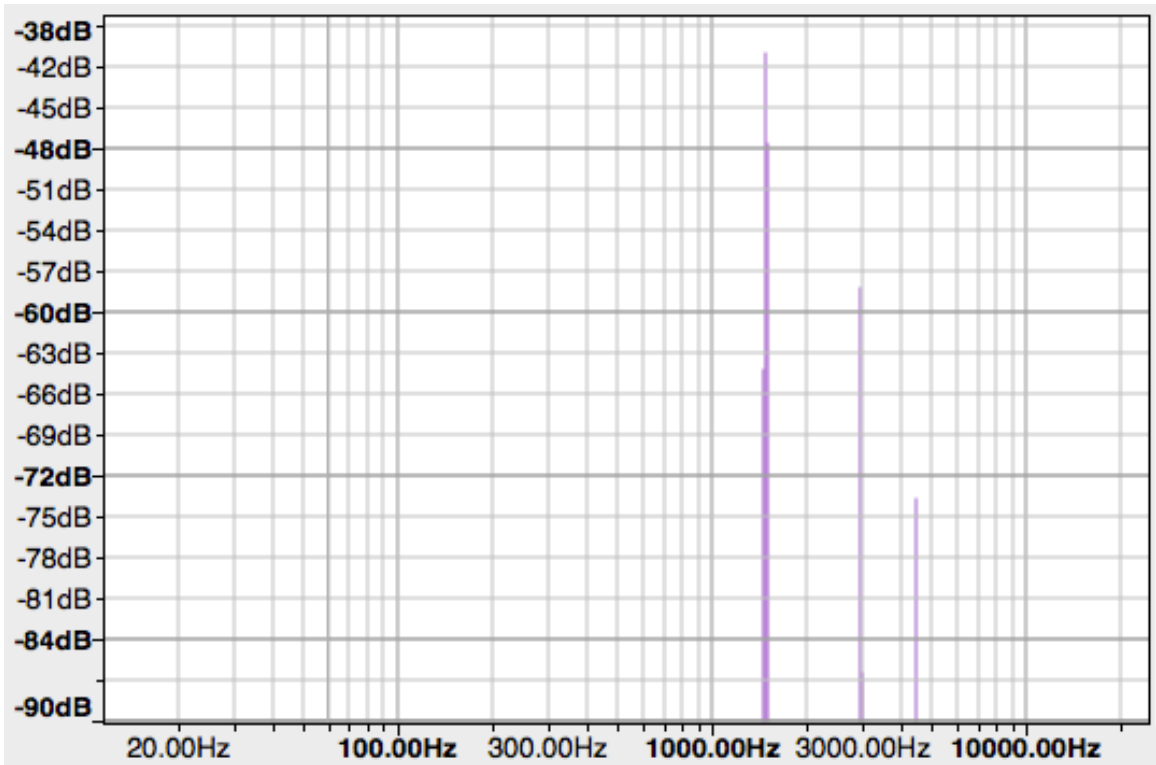
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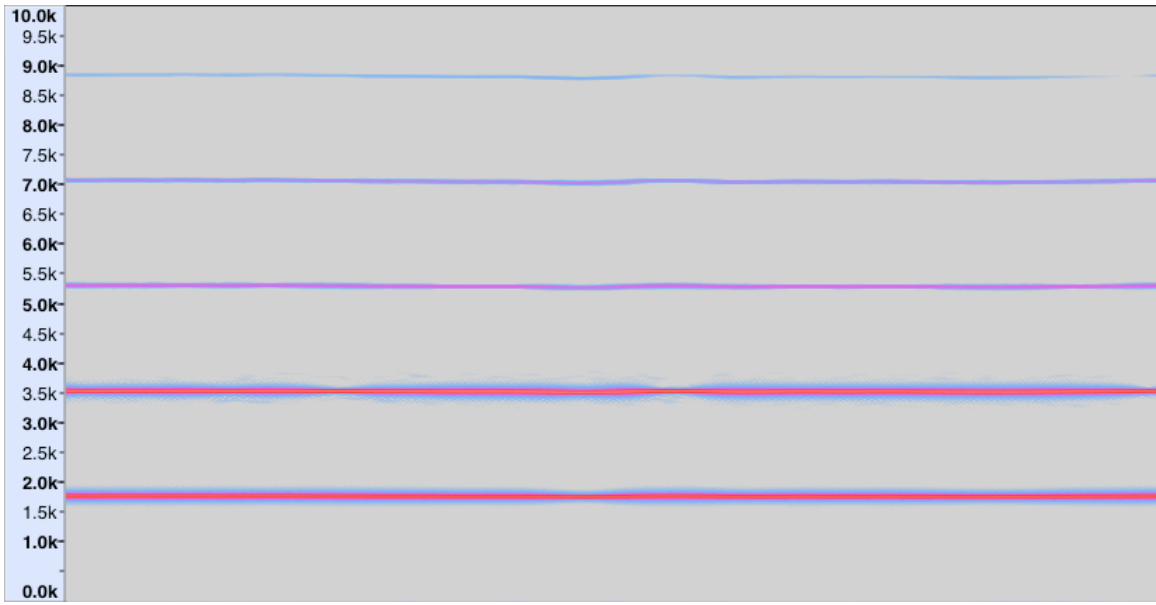
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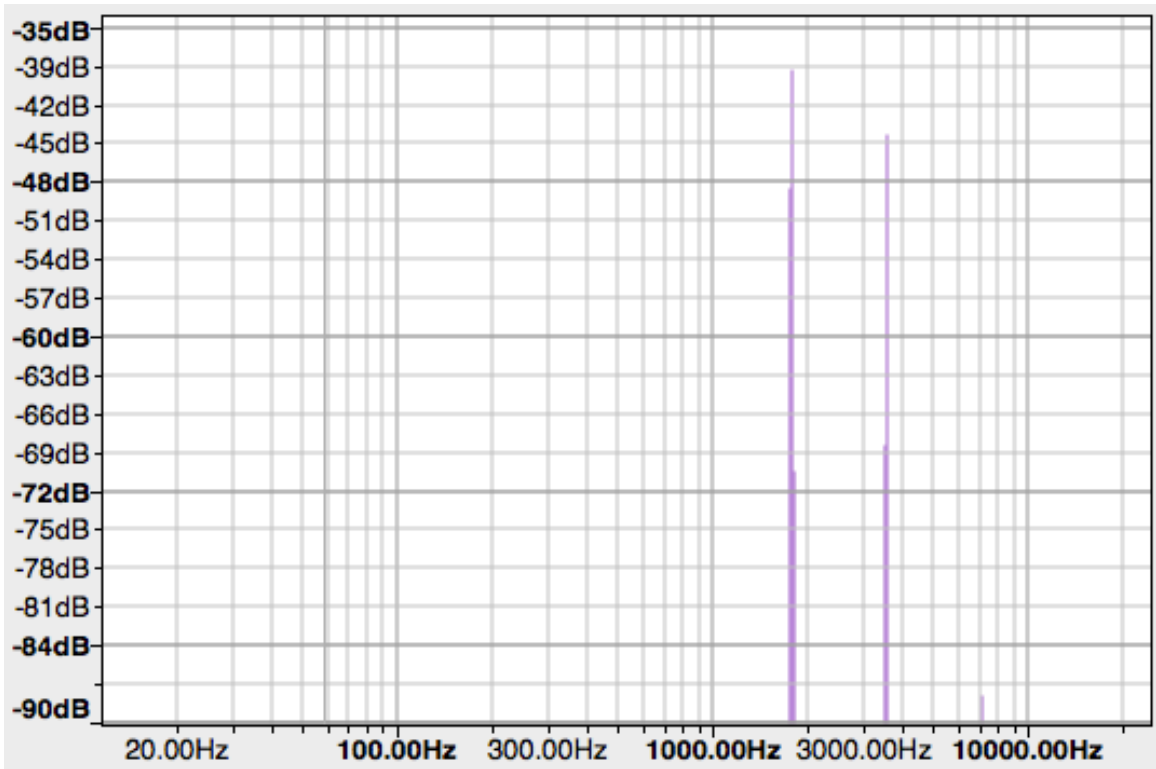
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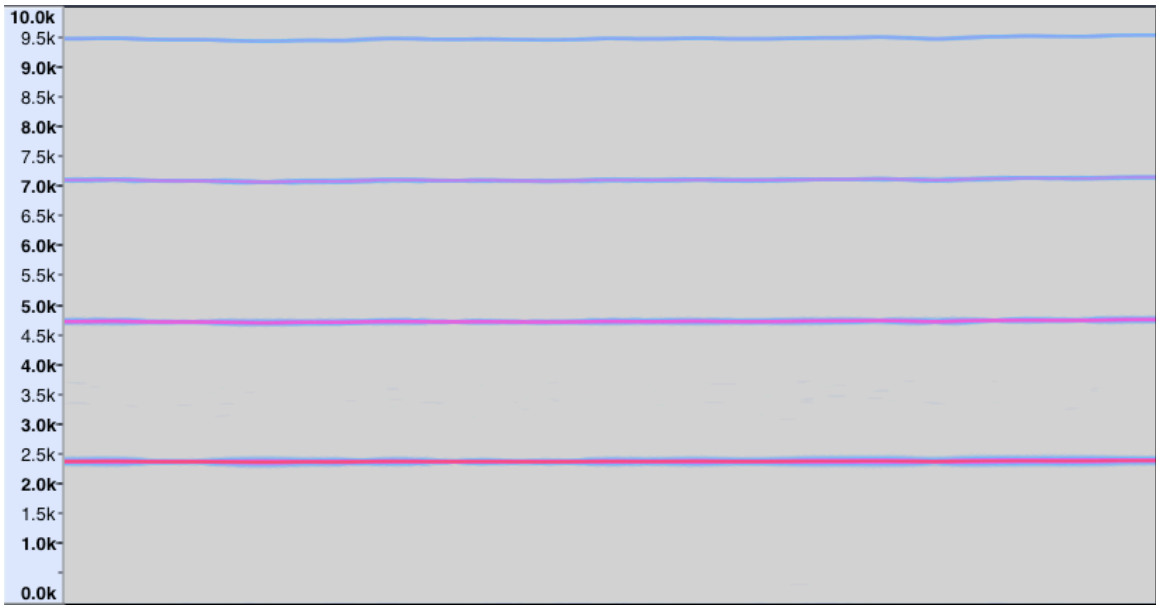
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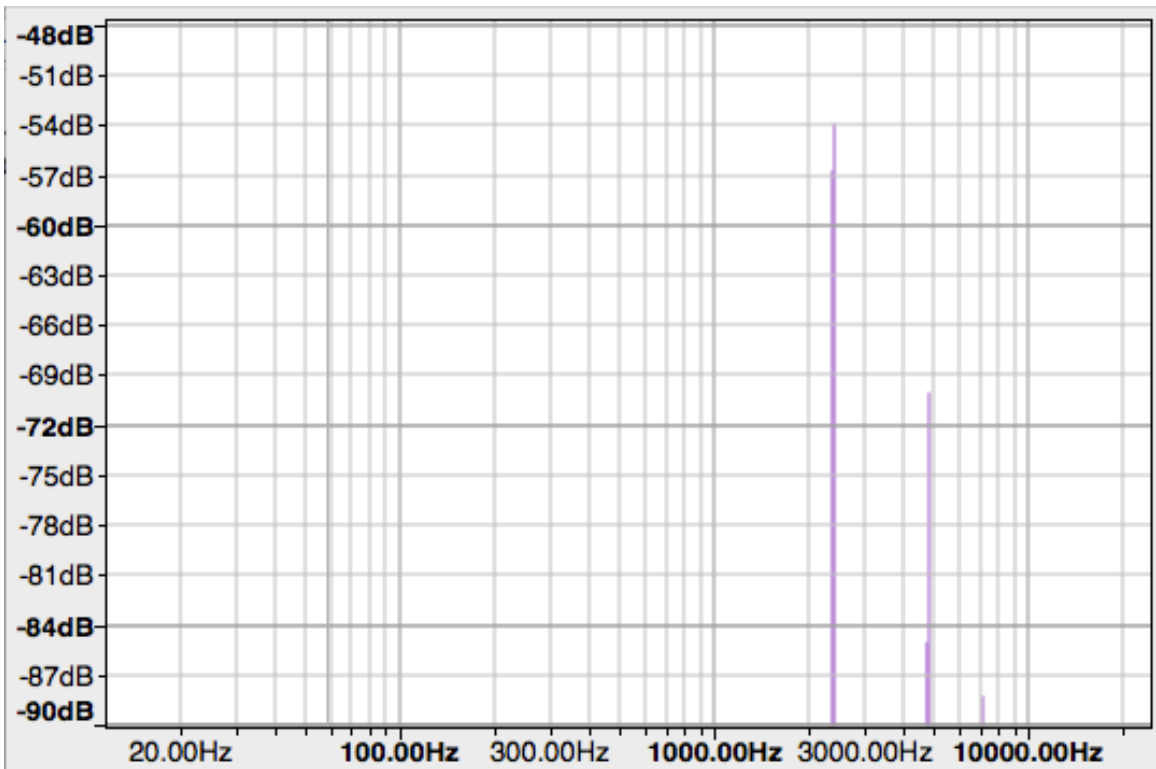
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Nalbantov B6



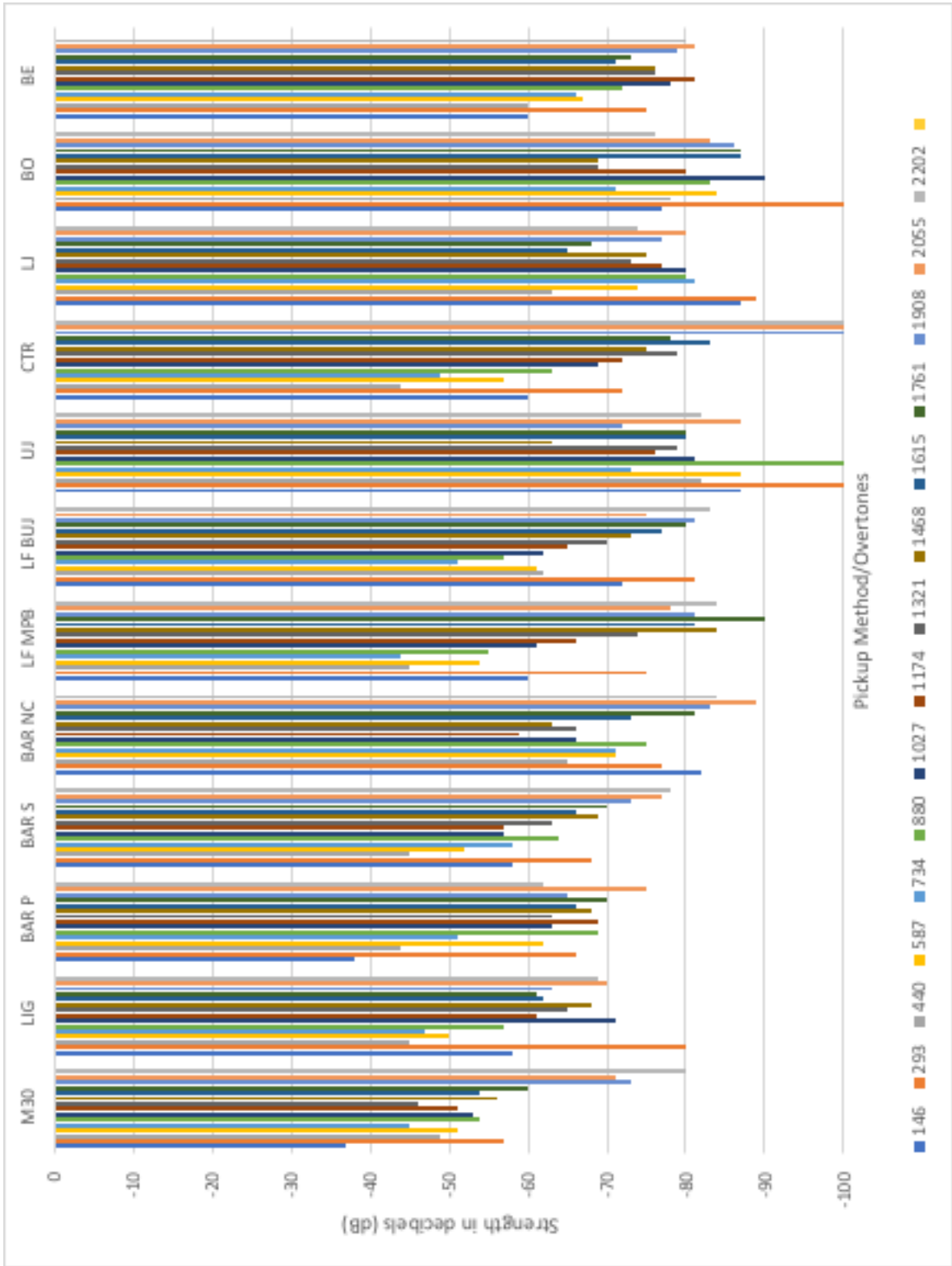
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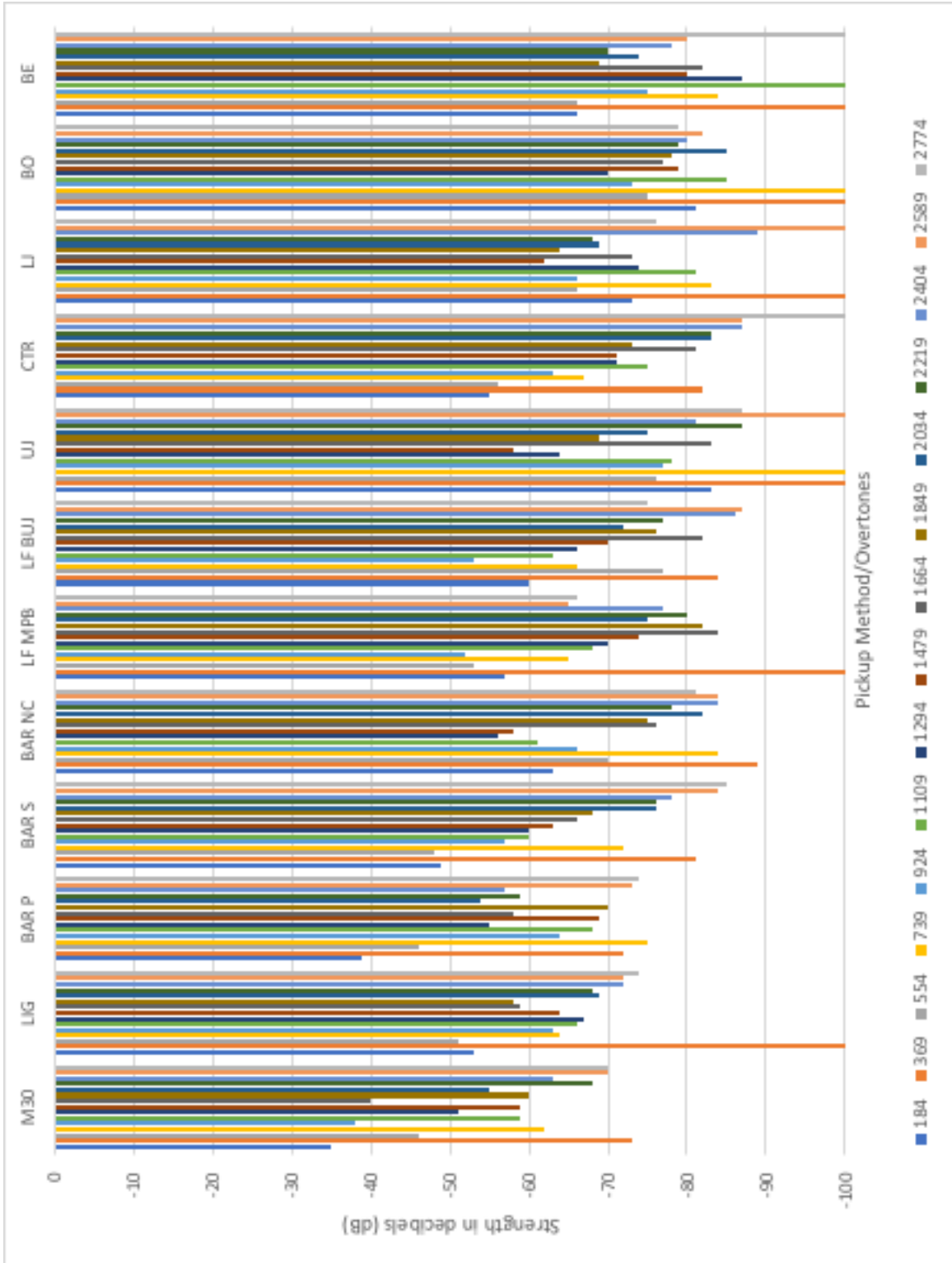
Nalbantov E7

APPENDIX B

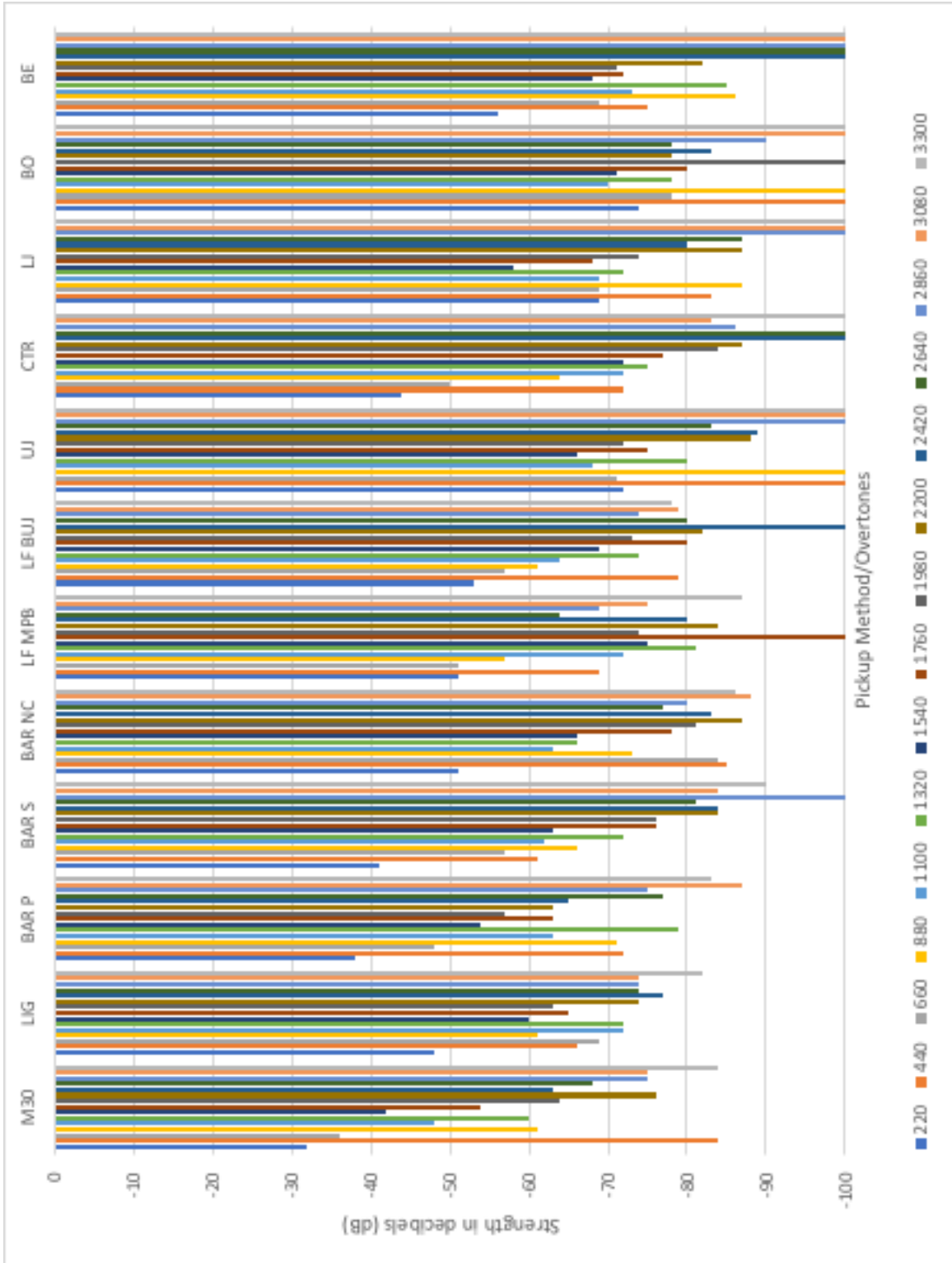
LARGER GRAPHS FROM “OVERTONE DISPLACEMENT”



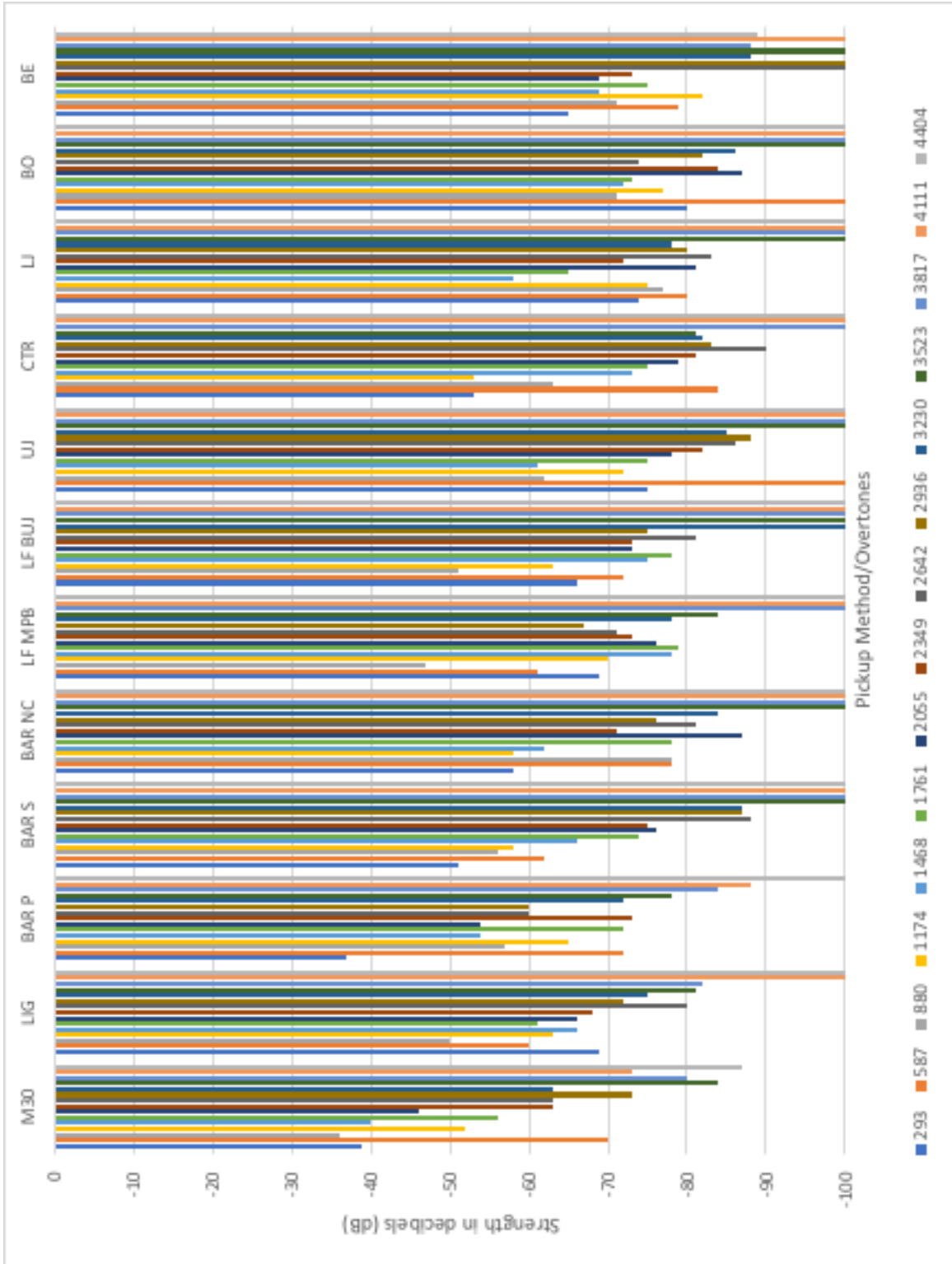
Graph for E3



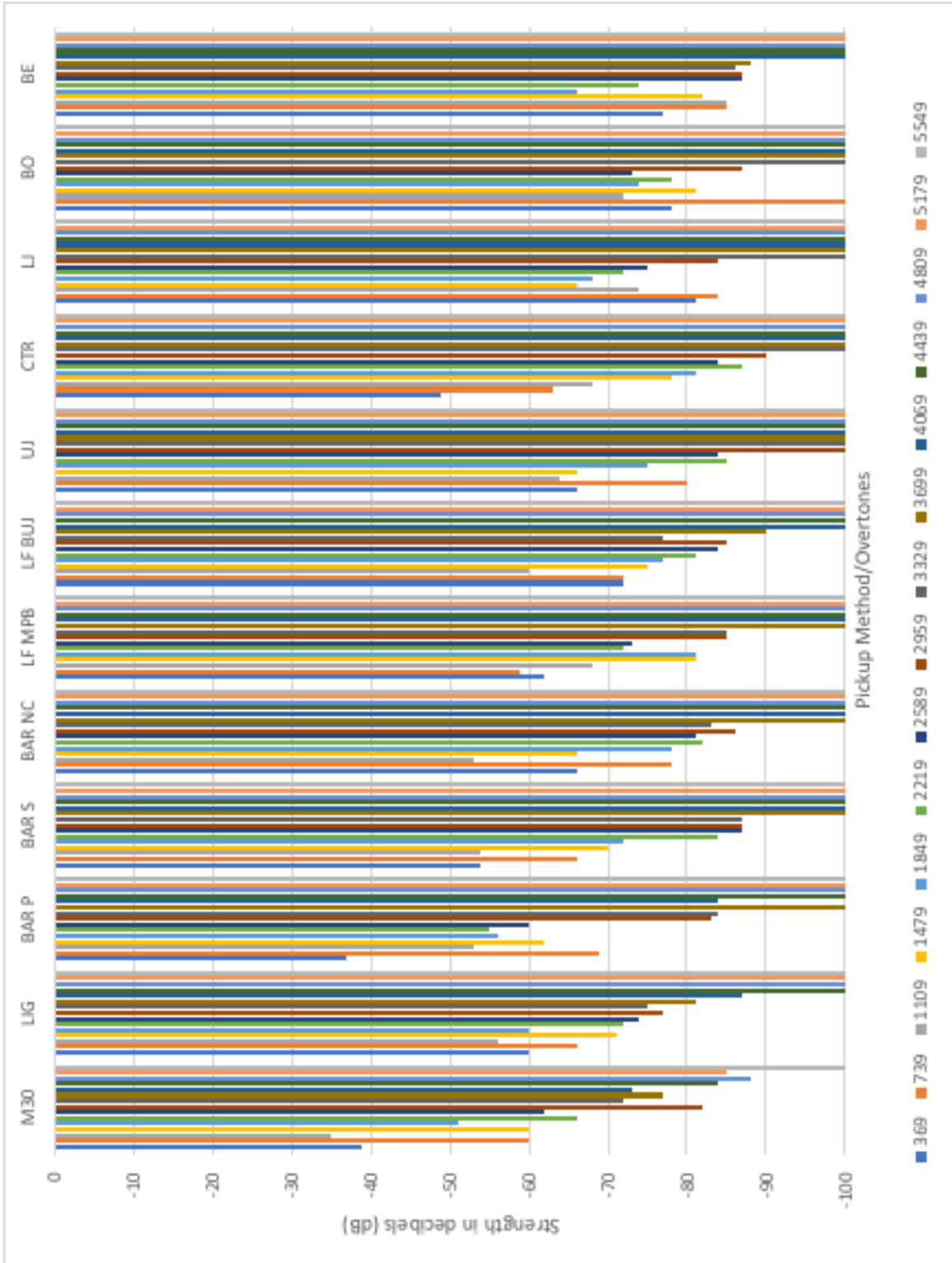
Graph for G-sharp3



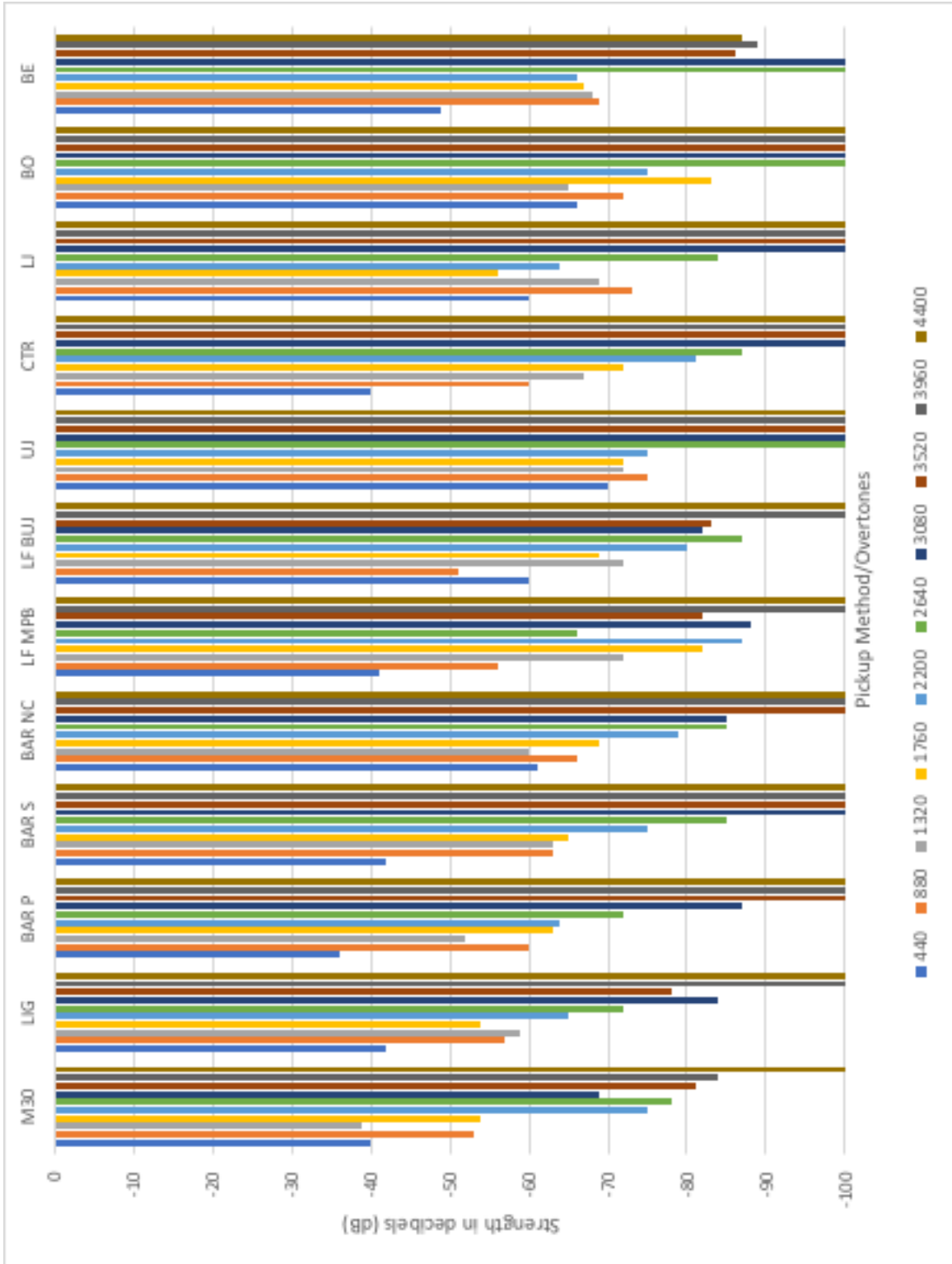
Graph for B3



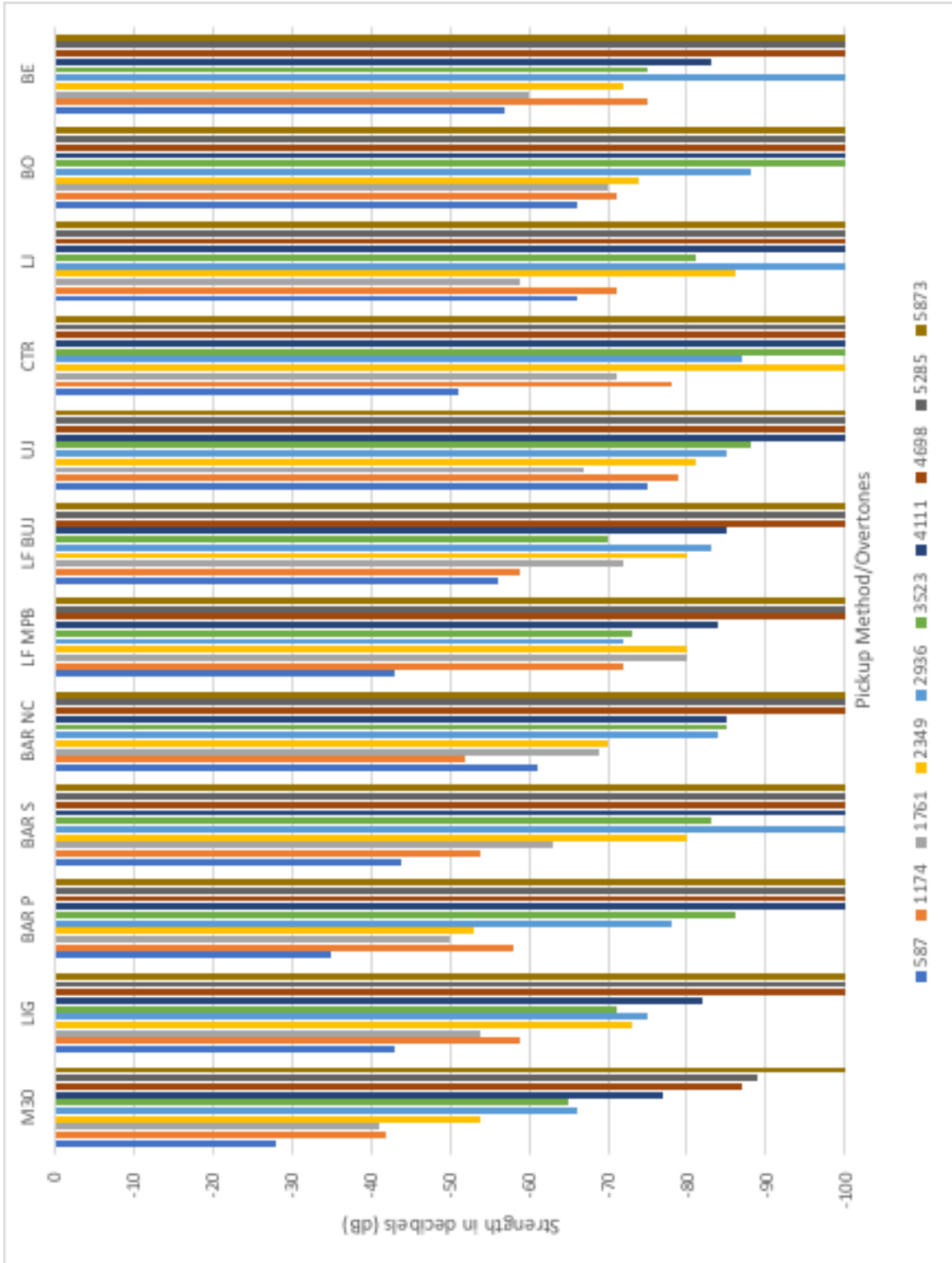
Graph for E4



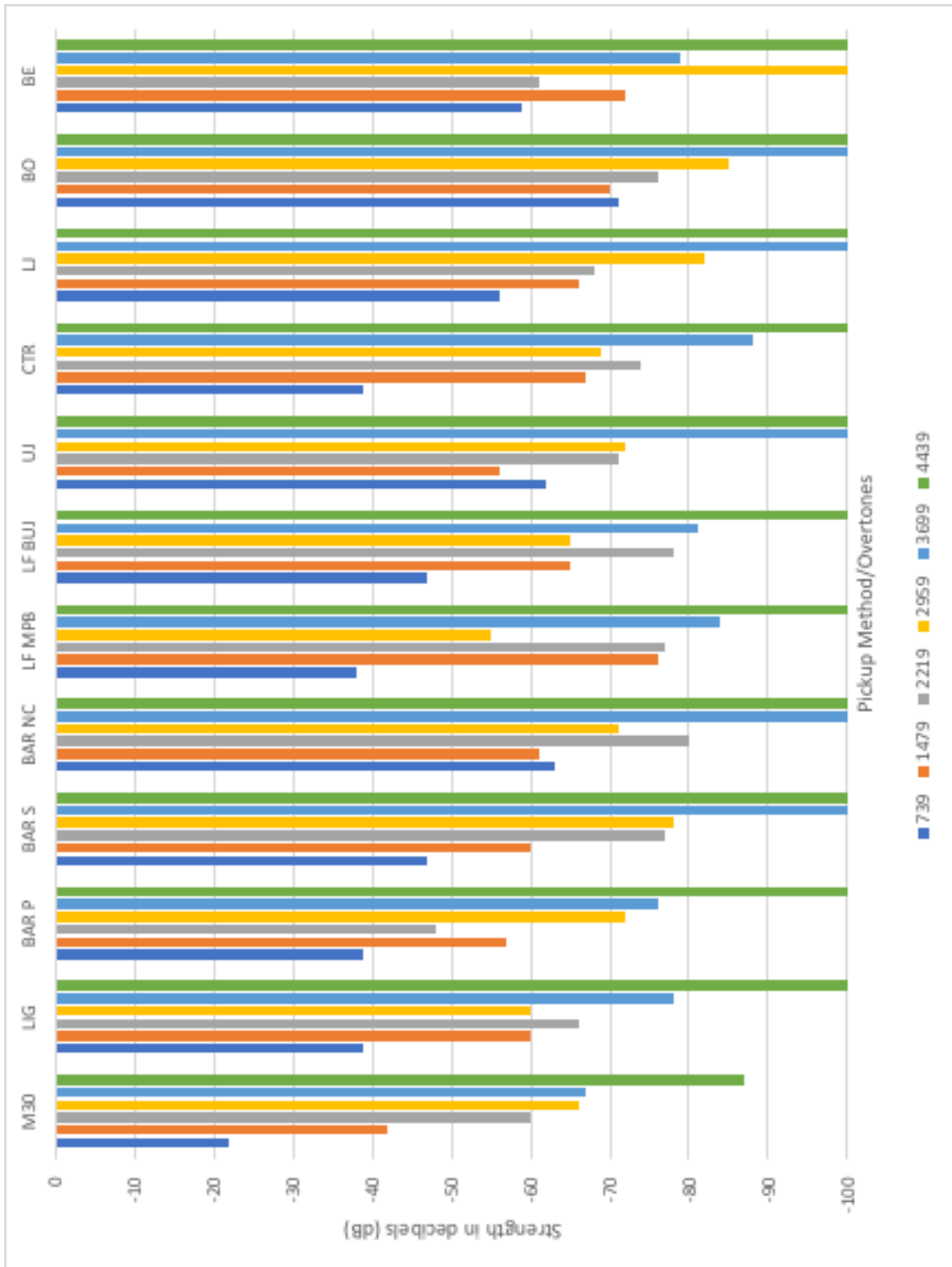
Graph for G-sharp4



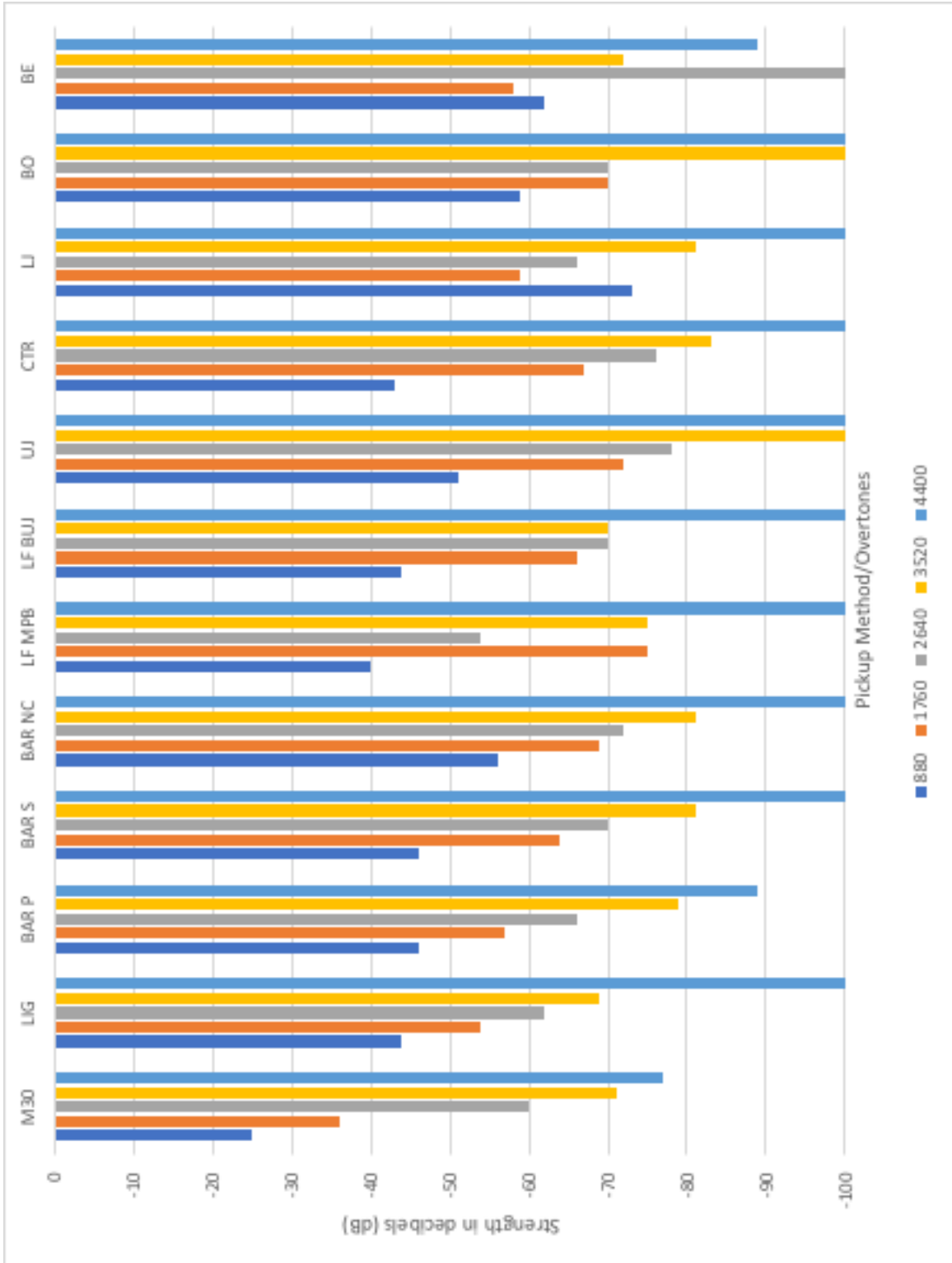
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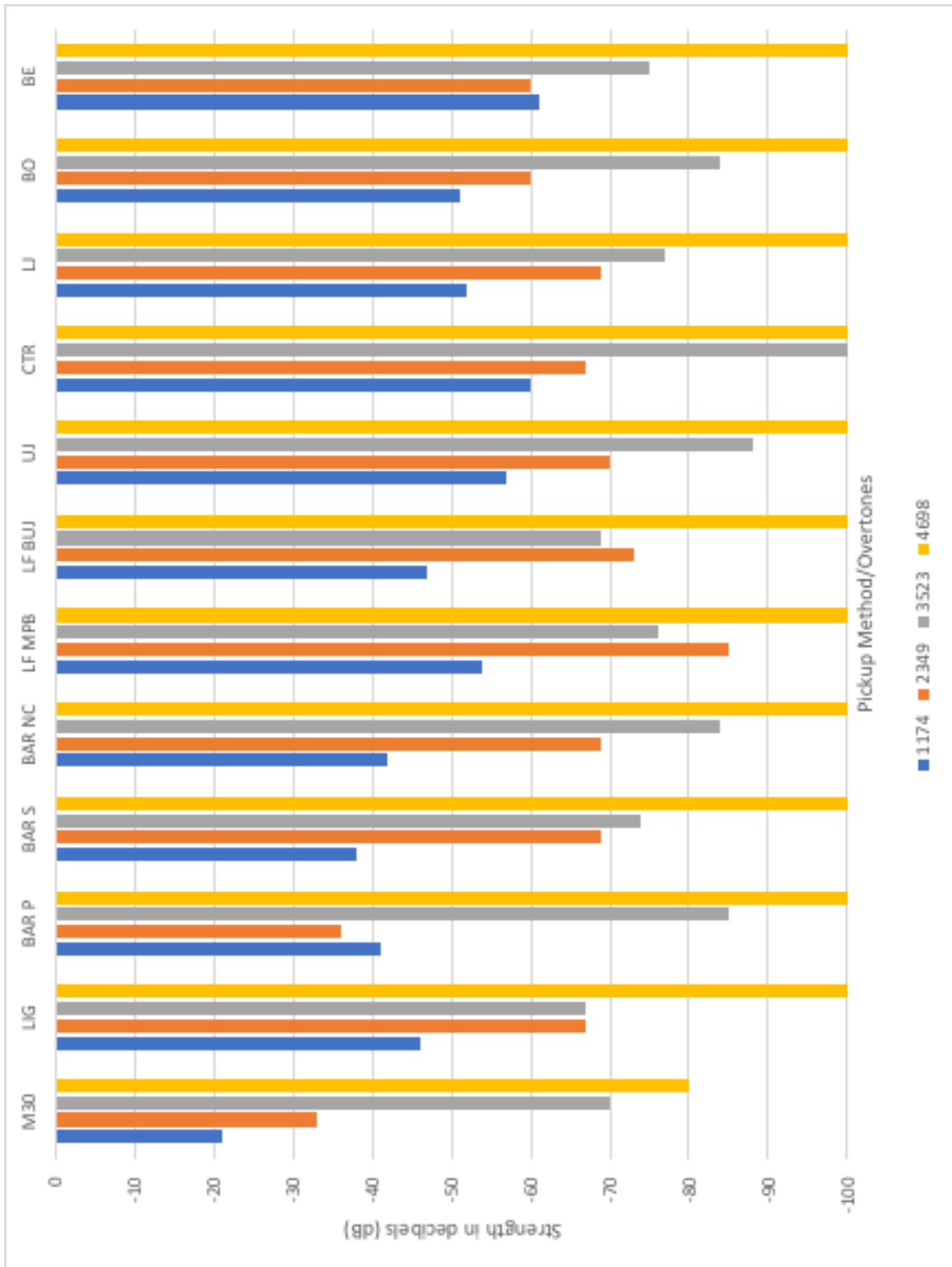
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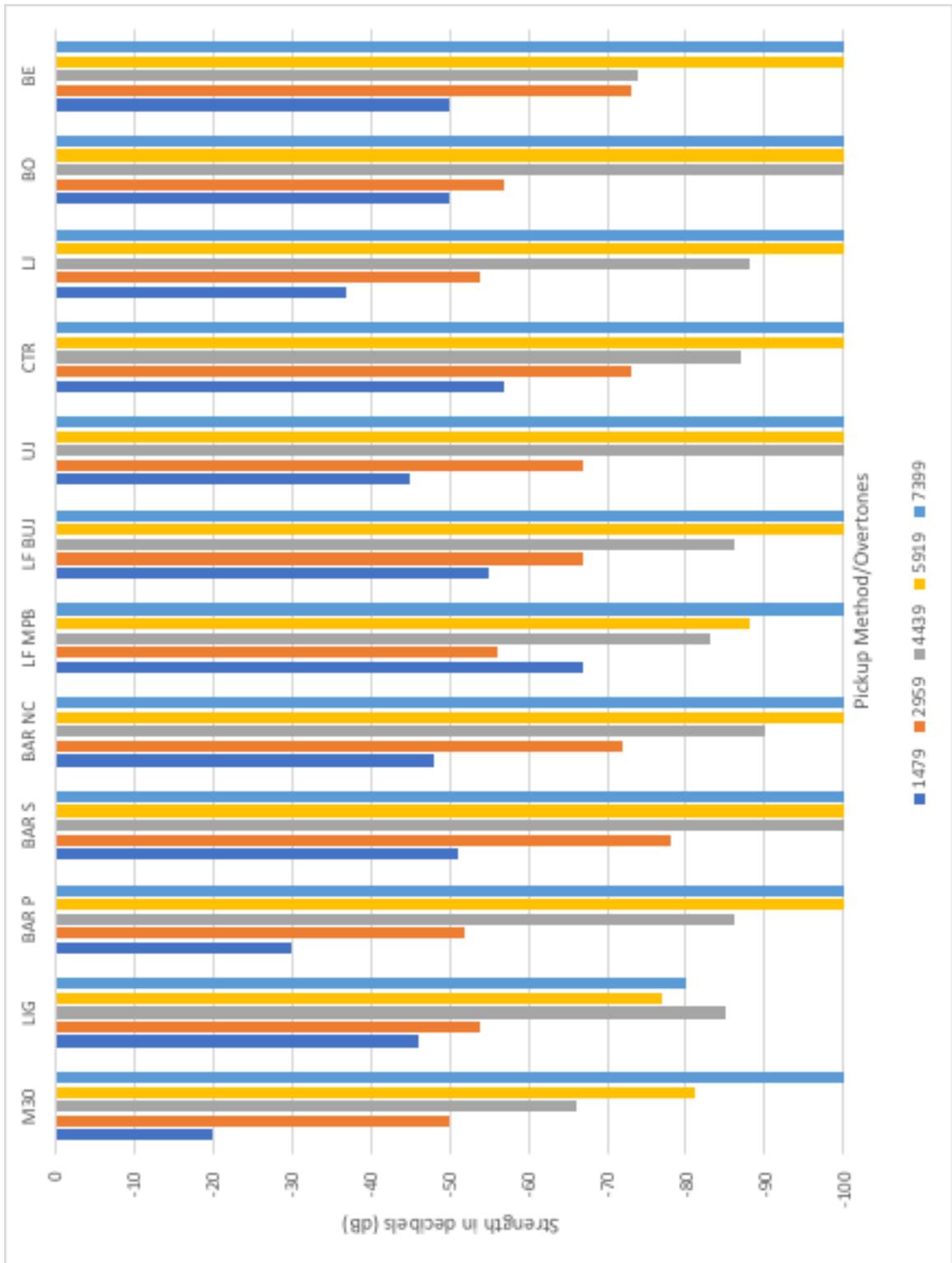
Graph for G-sharp5



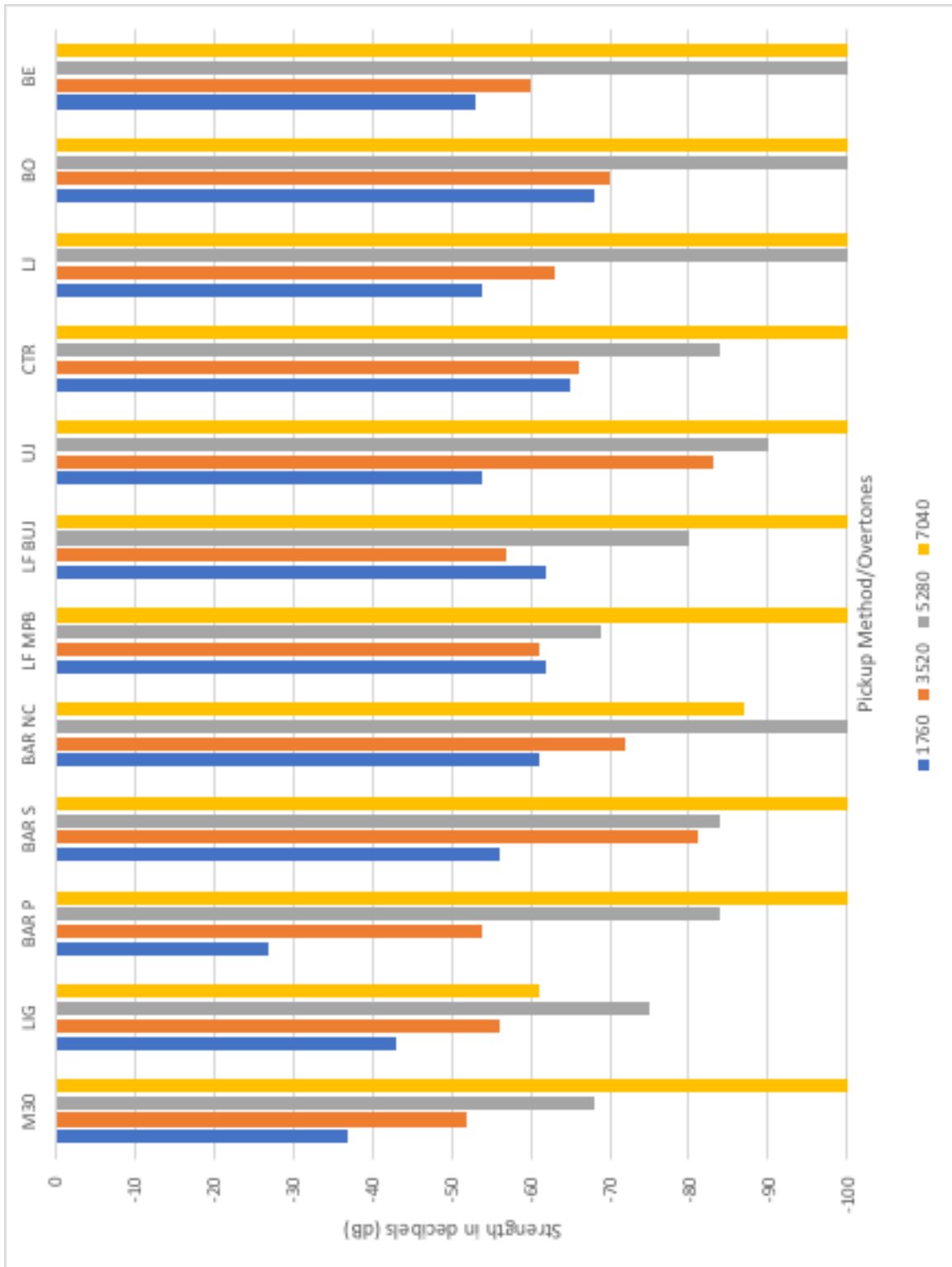
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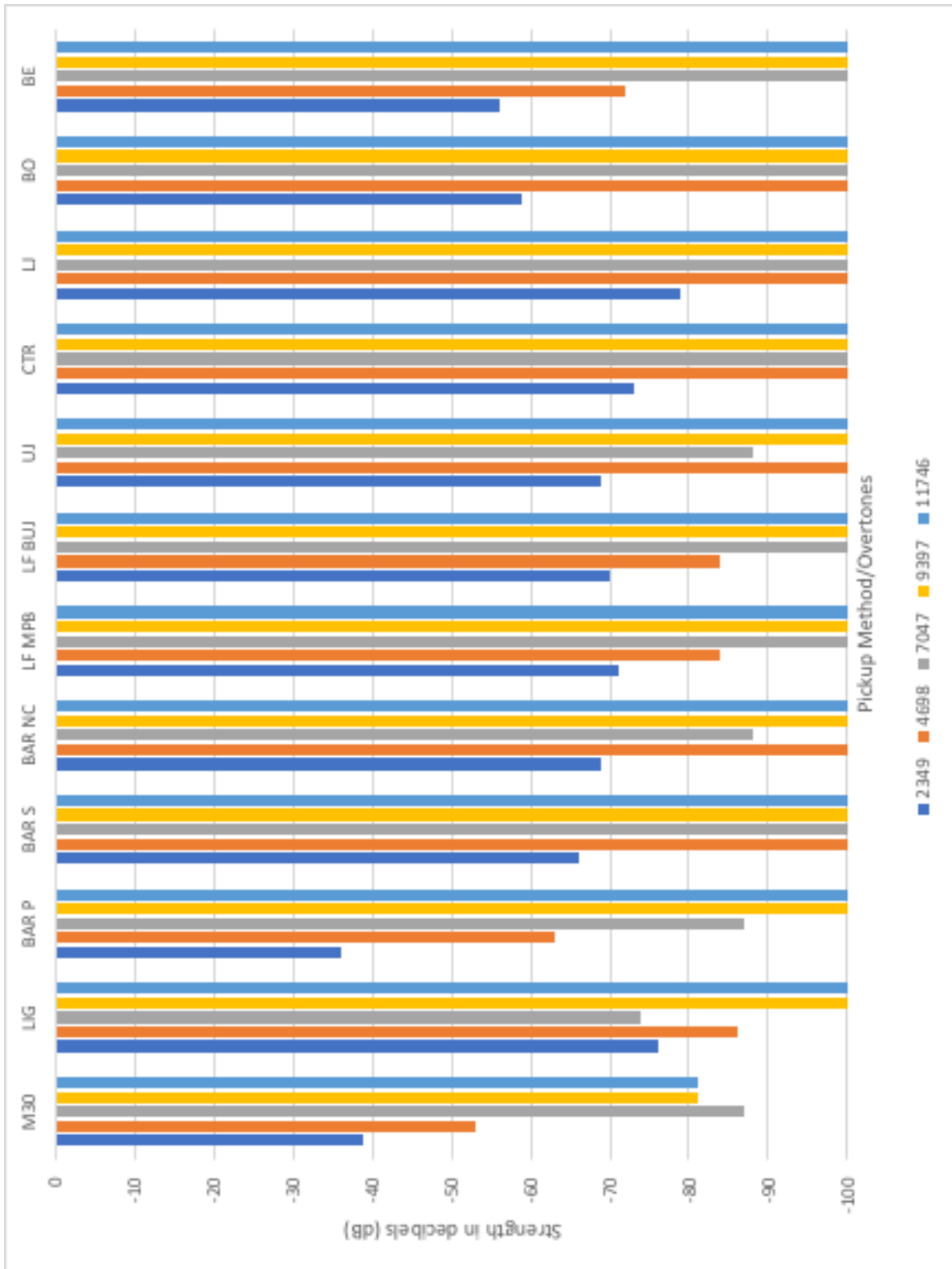
Graph for E6



Graph for G-sharp6



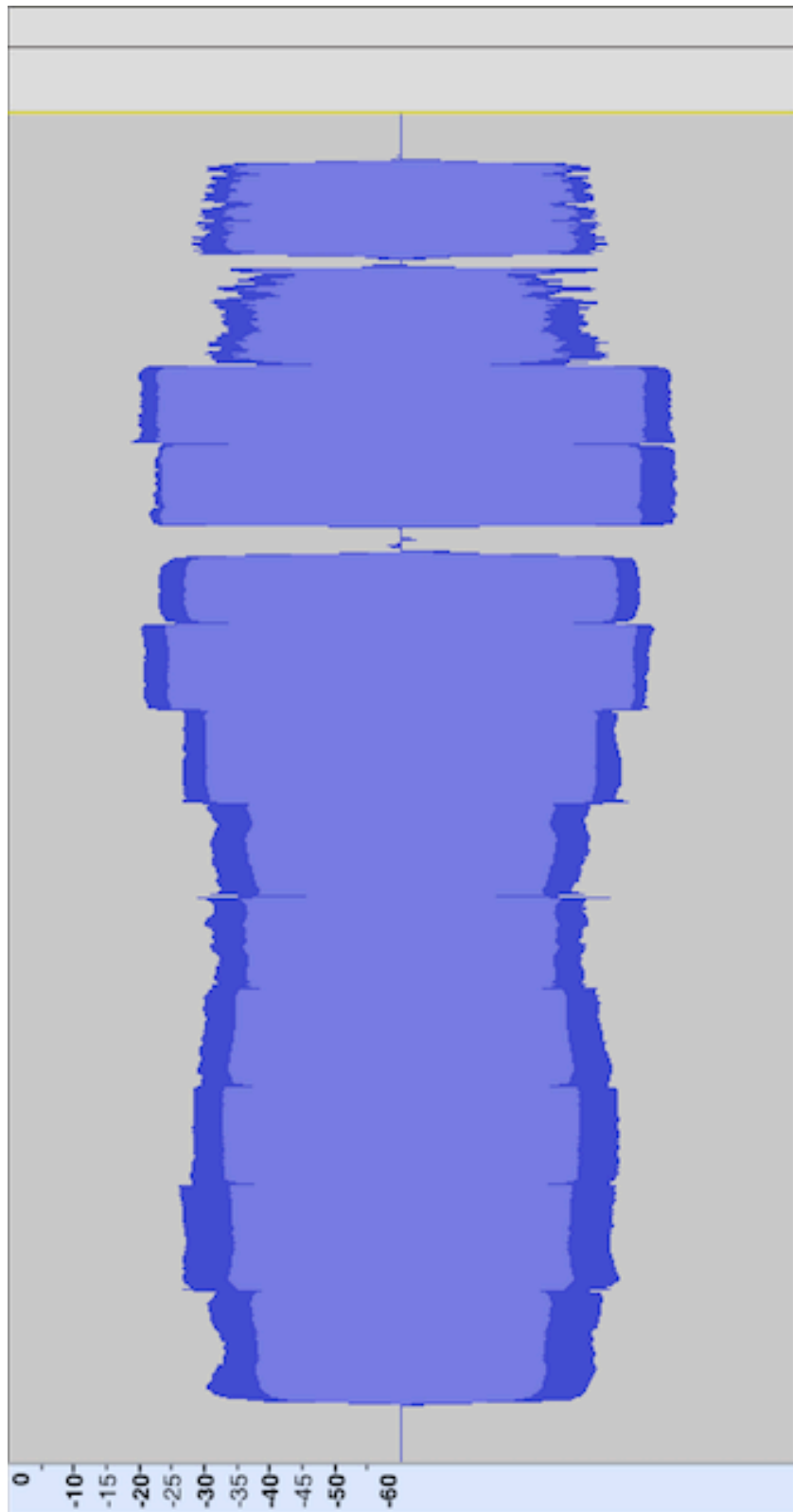
Graph for B6



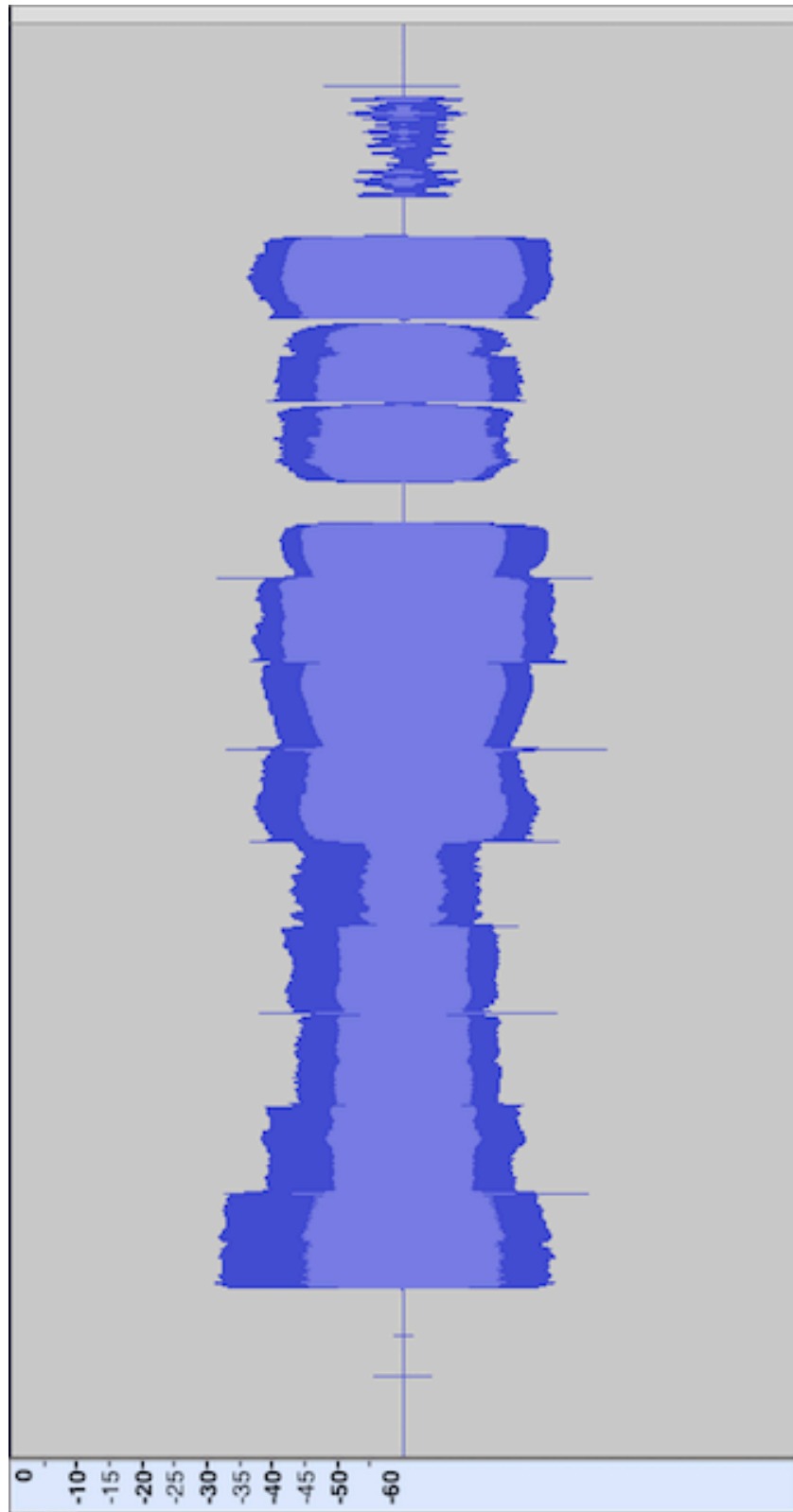
Graph for E7

APPENDIX C

SAMPLE DATA WAVEFORM dB

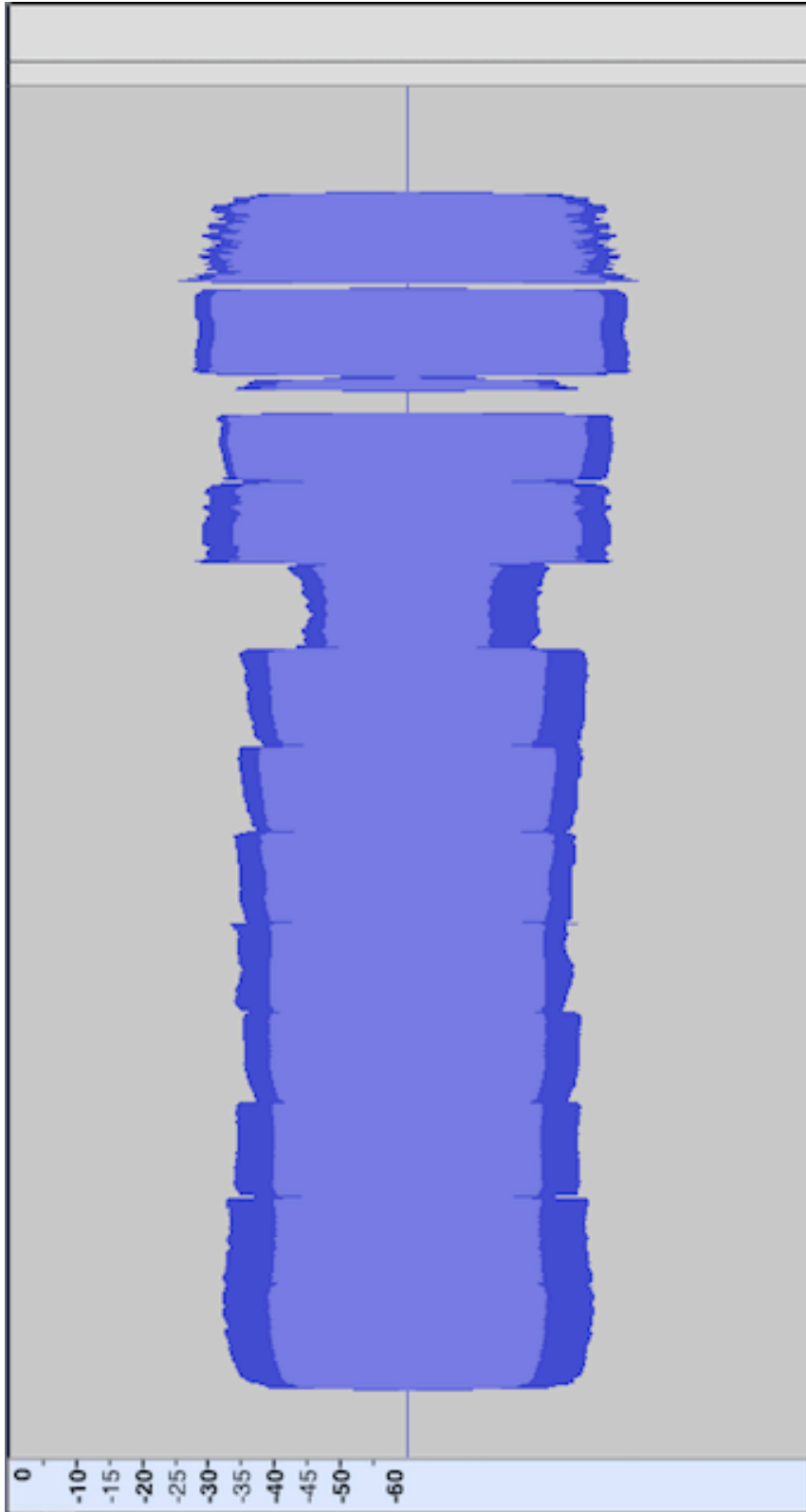


M30 (Reference)

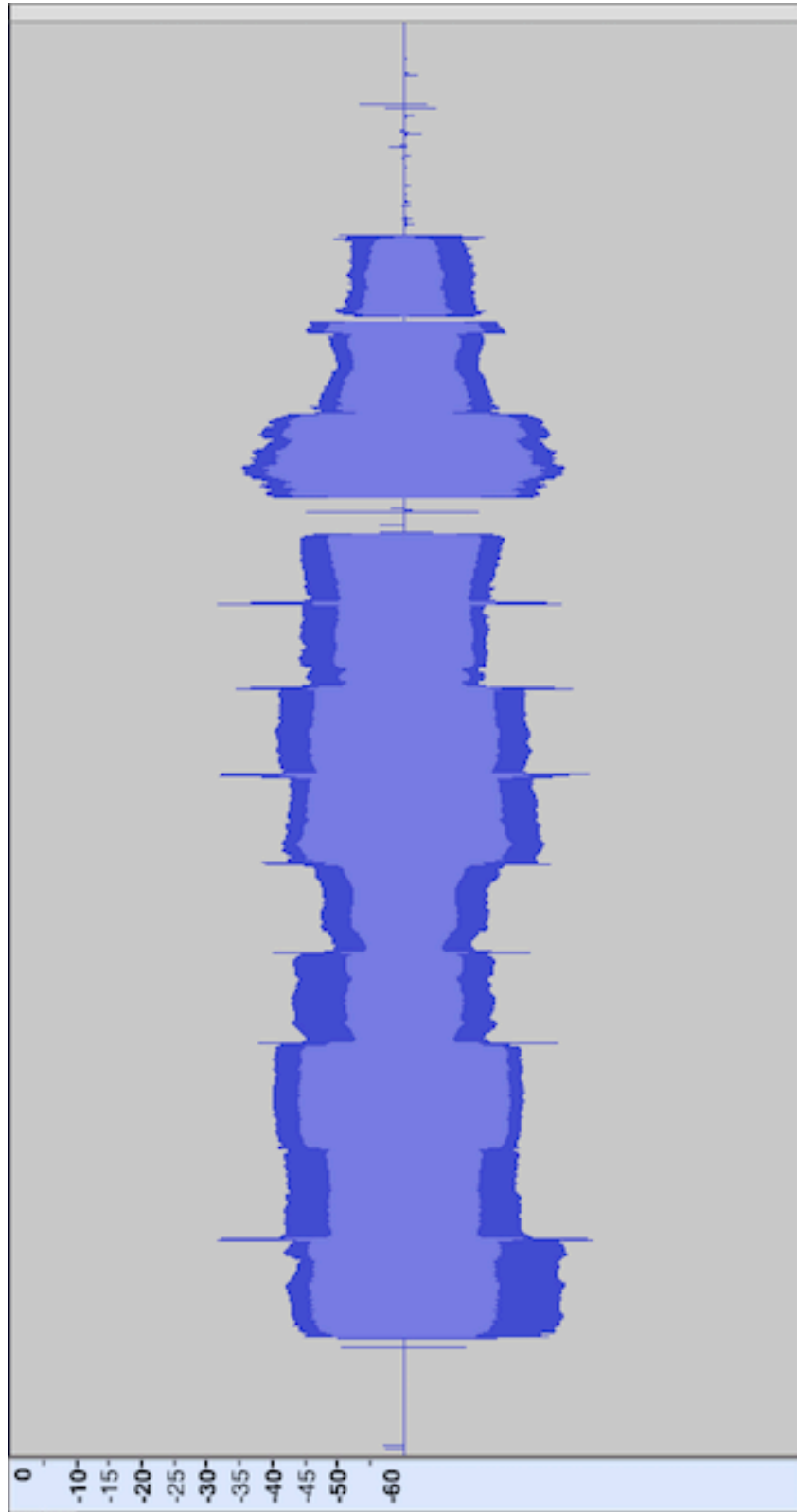


LIG

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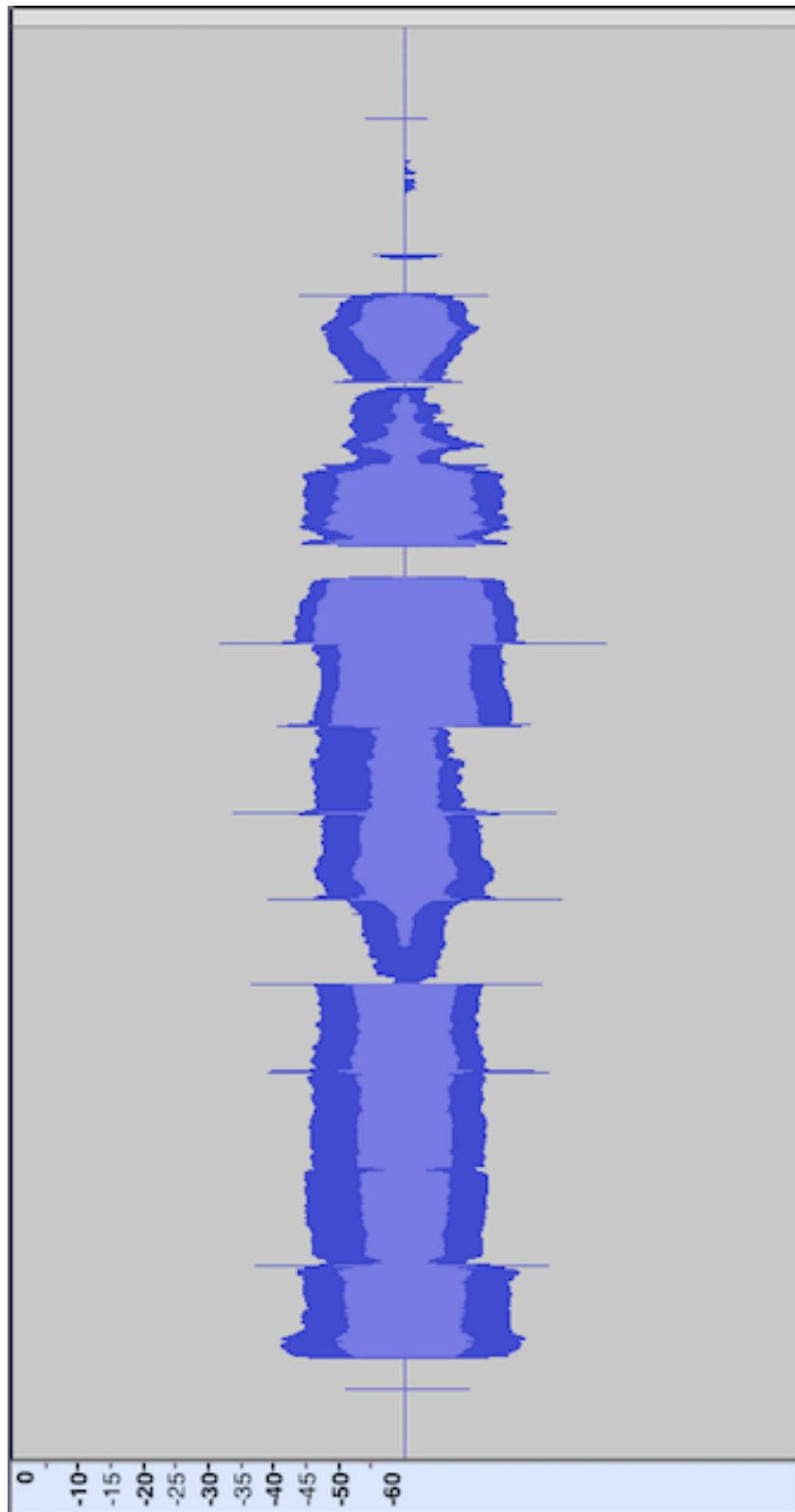


BAR Port

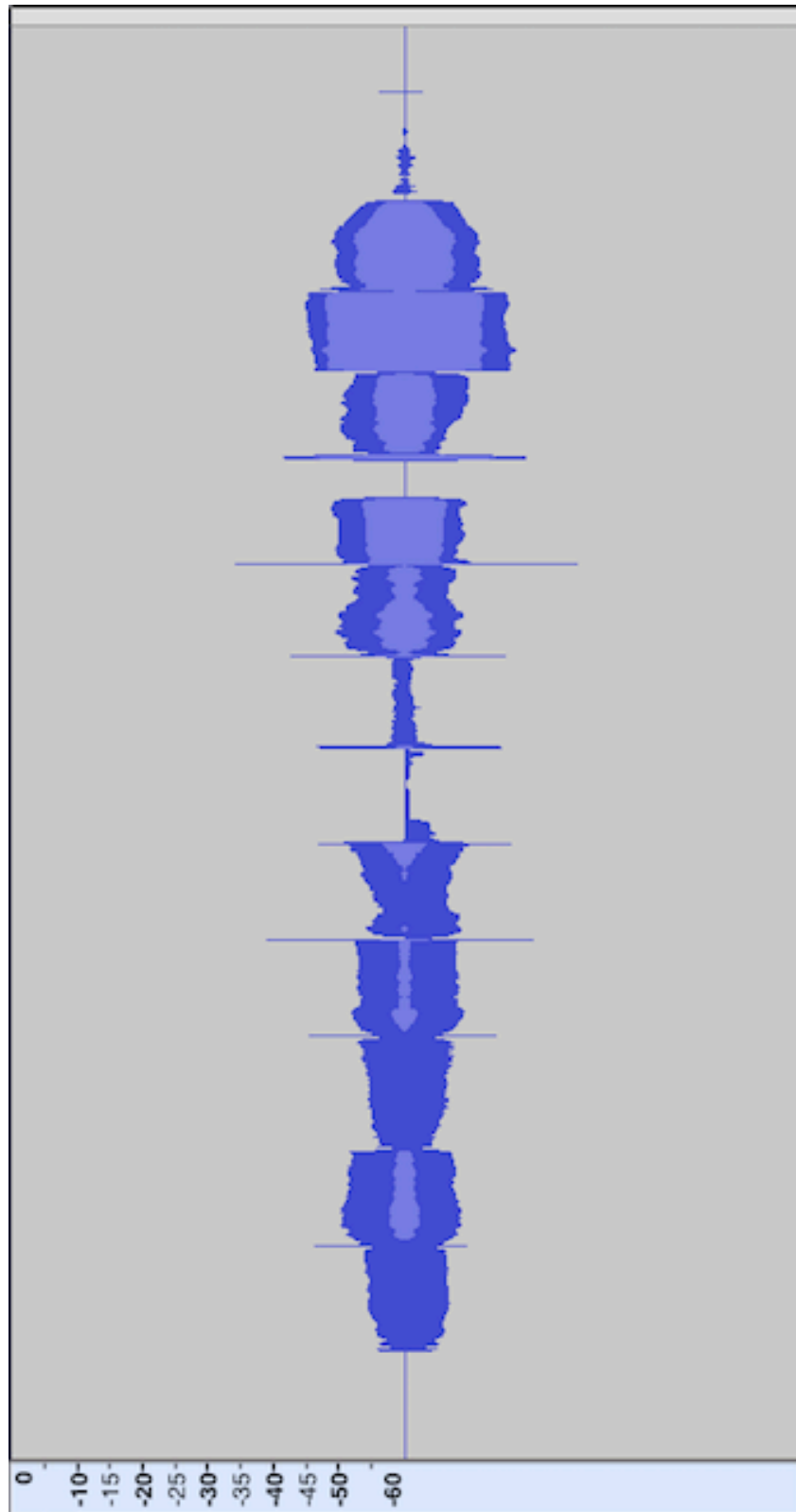


BAR Surf





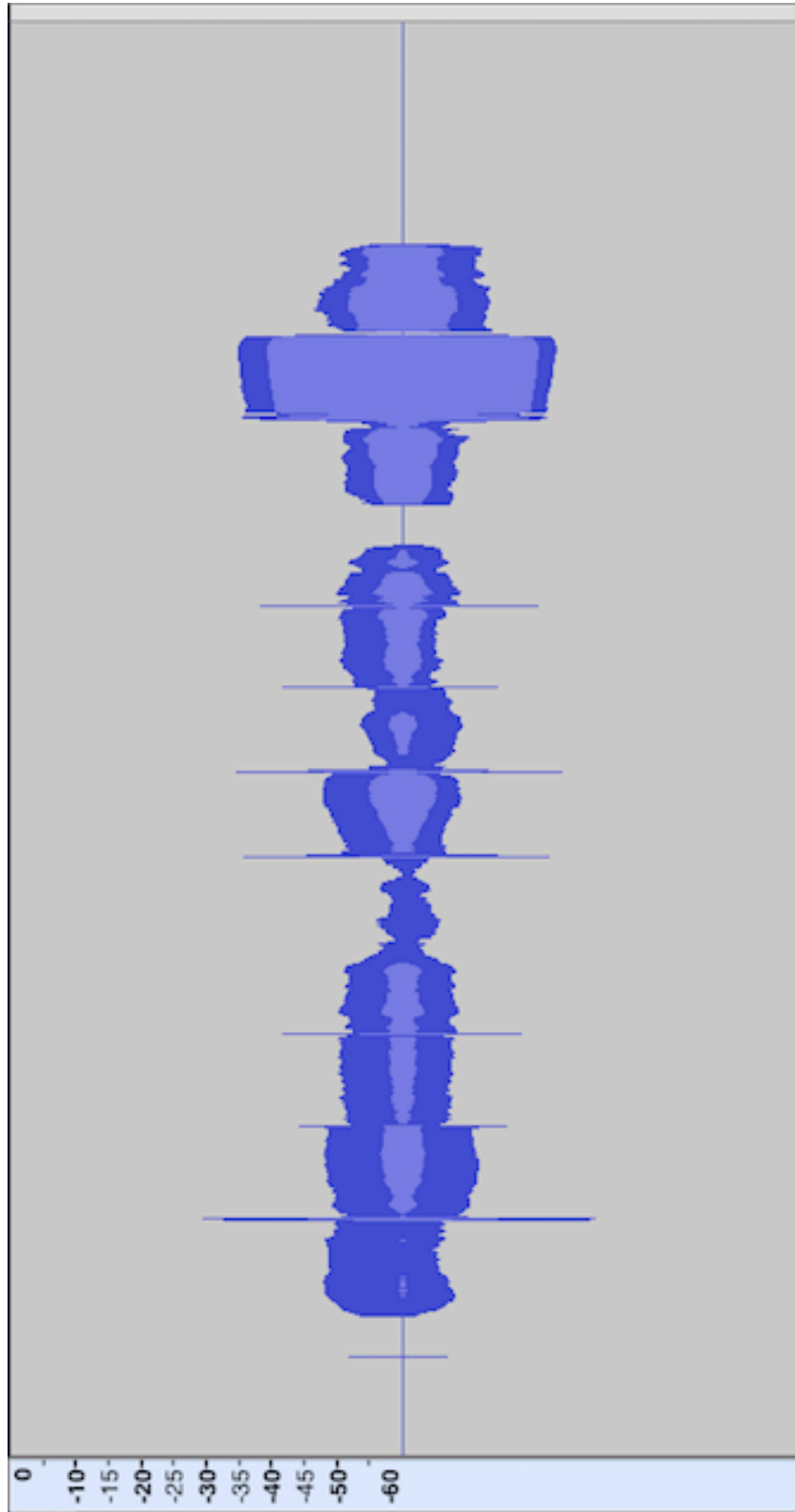
LF BUJ



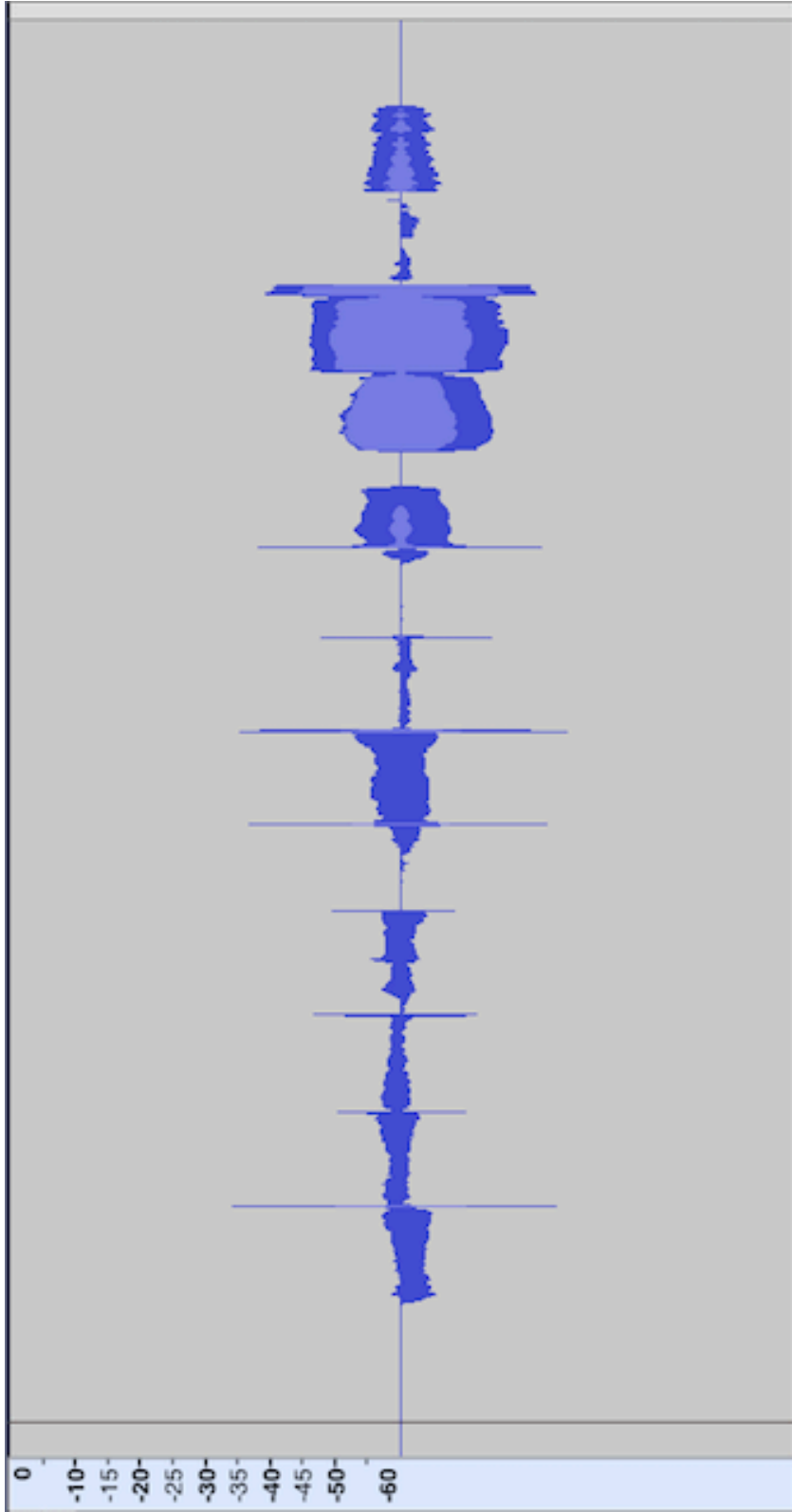
UJ

125

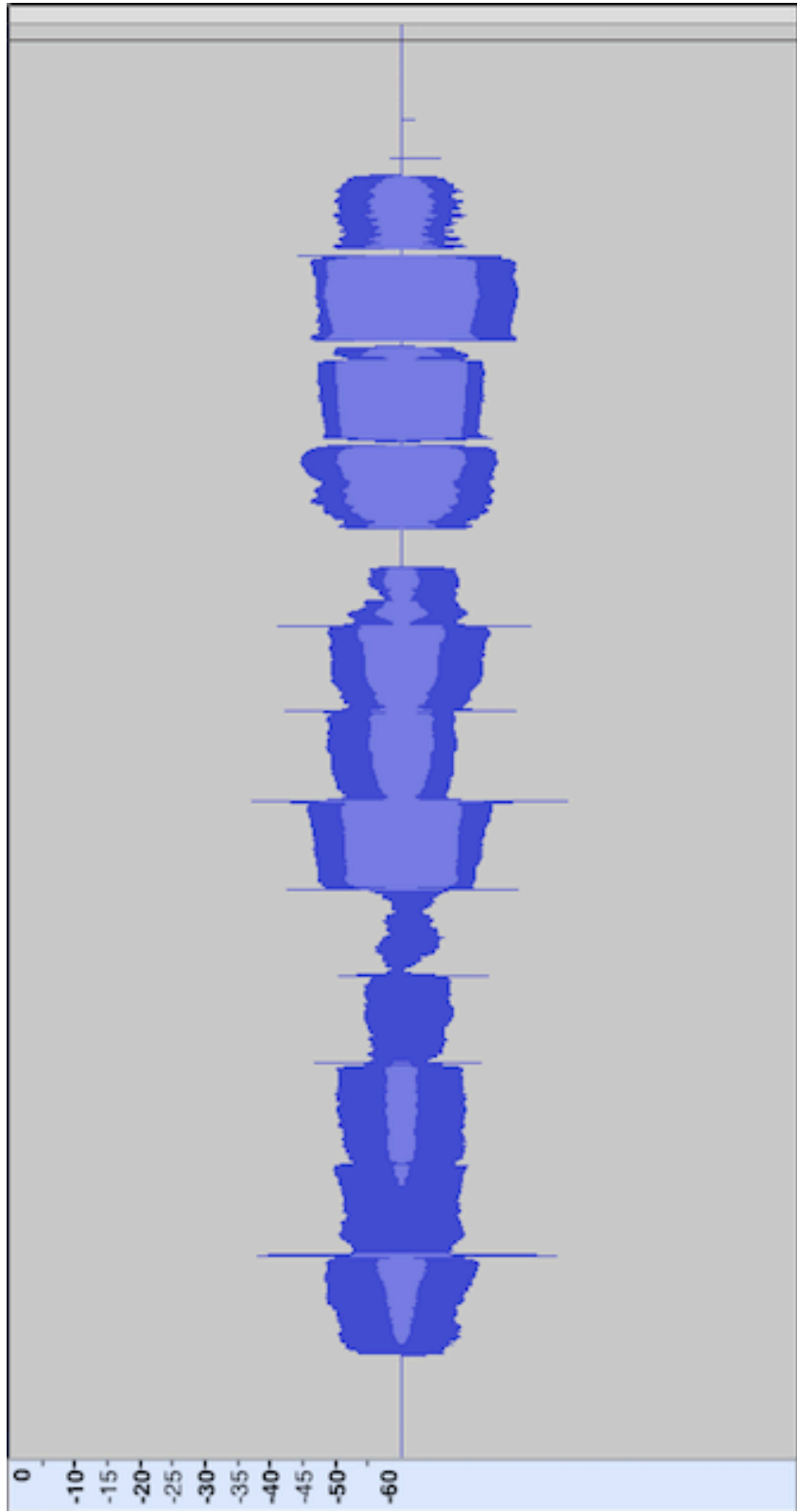




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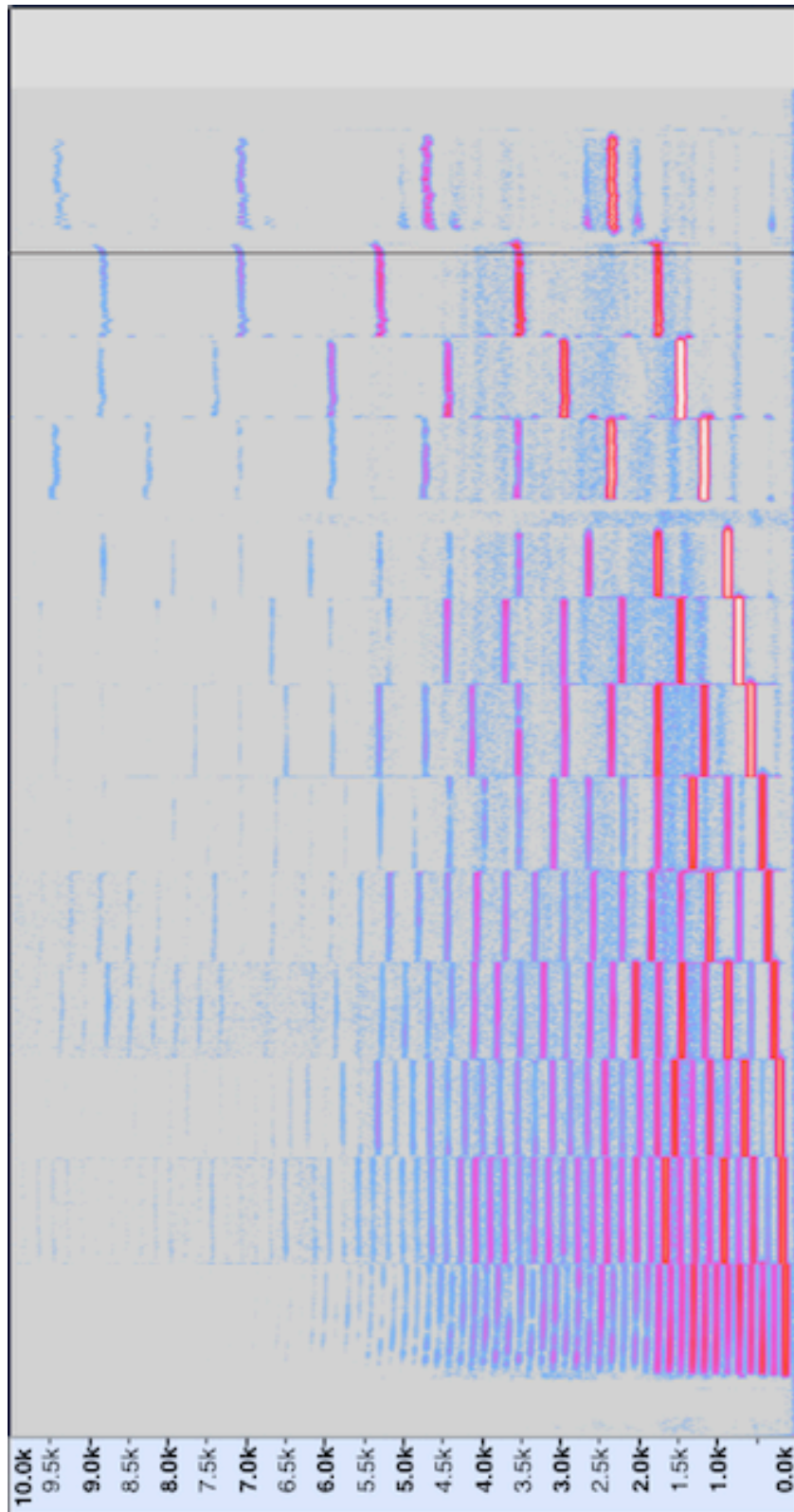


BELL Out

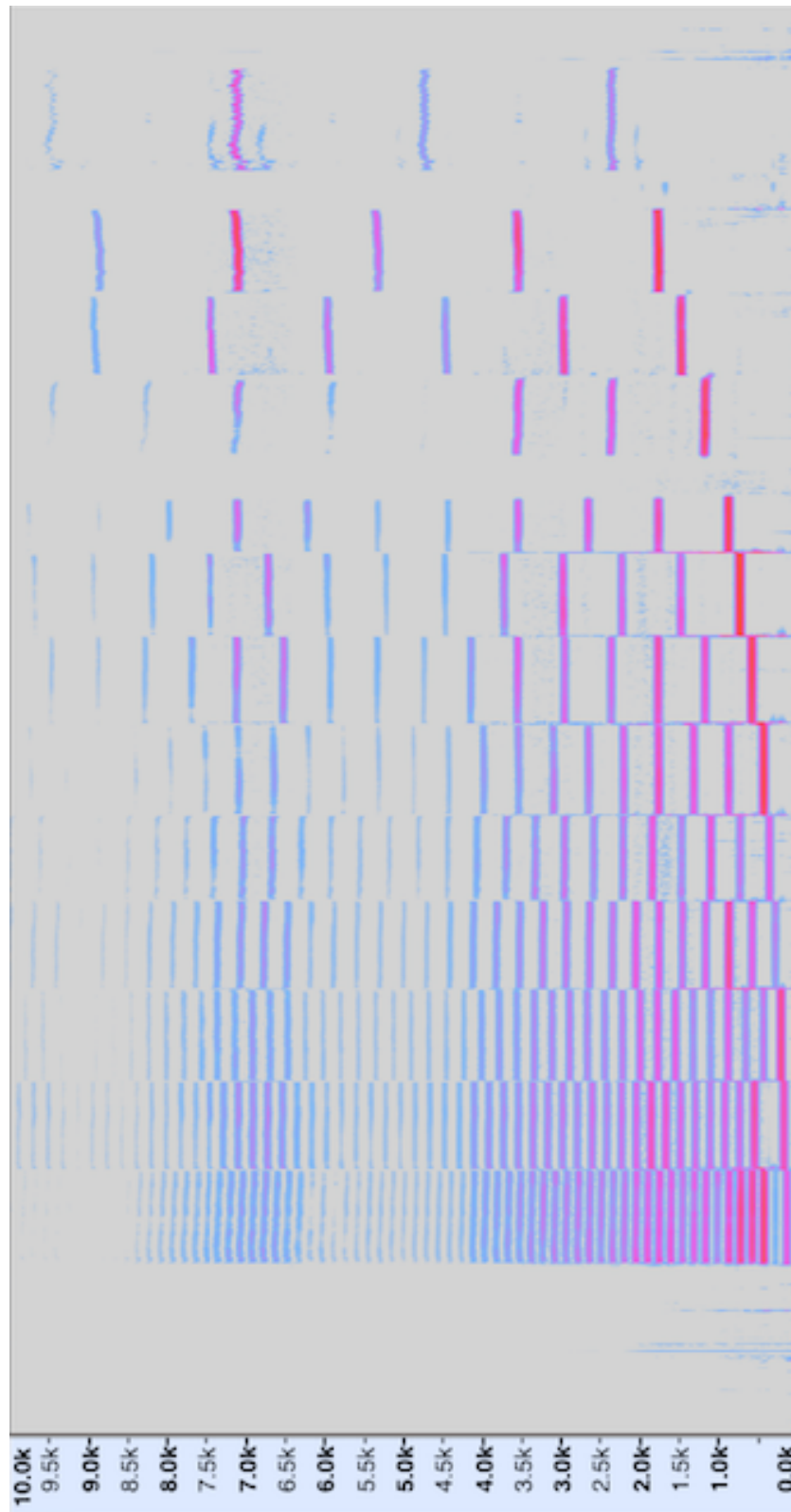


BELL End

APPENDIX D  
SAMPLE DATA FULL SPECTROGRAM

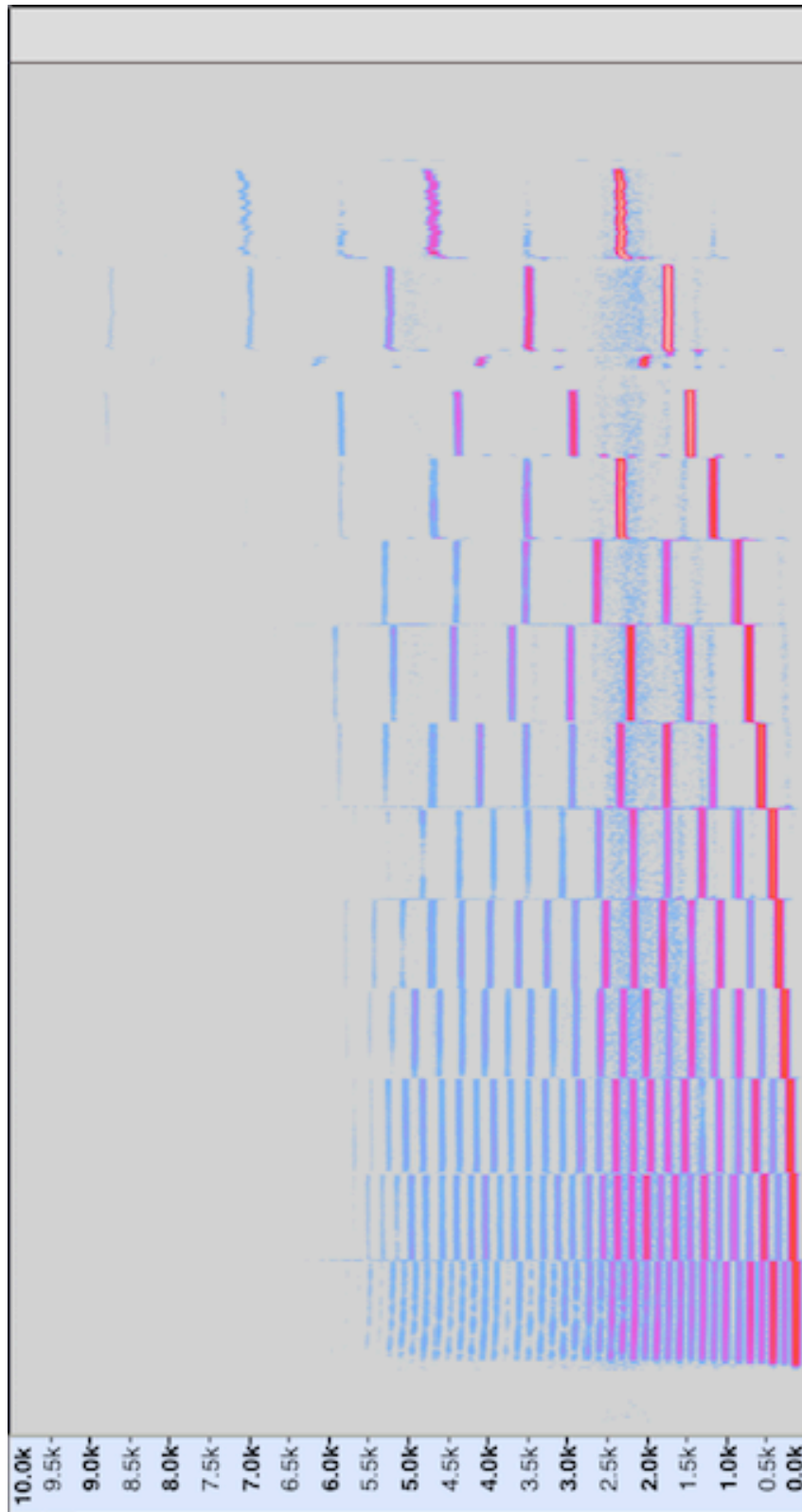


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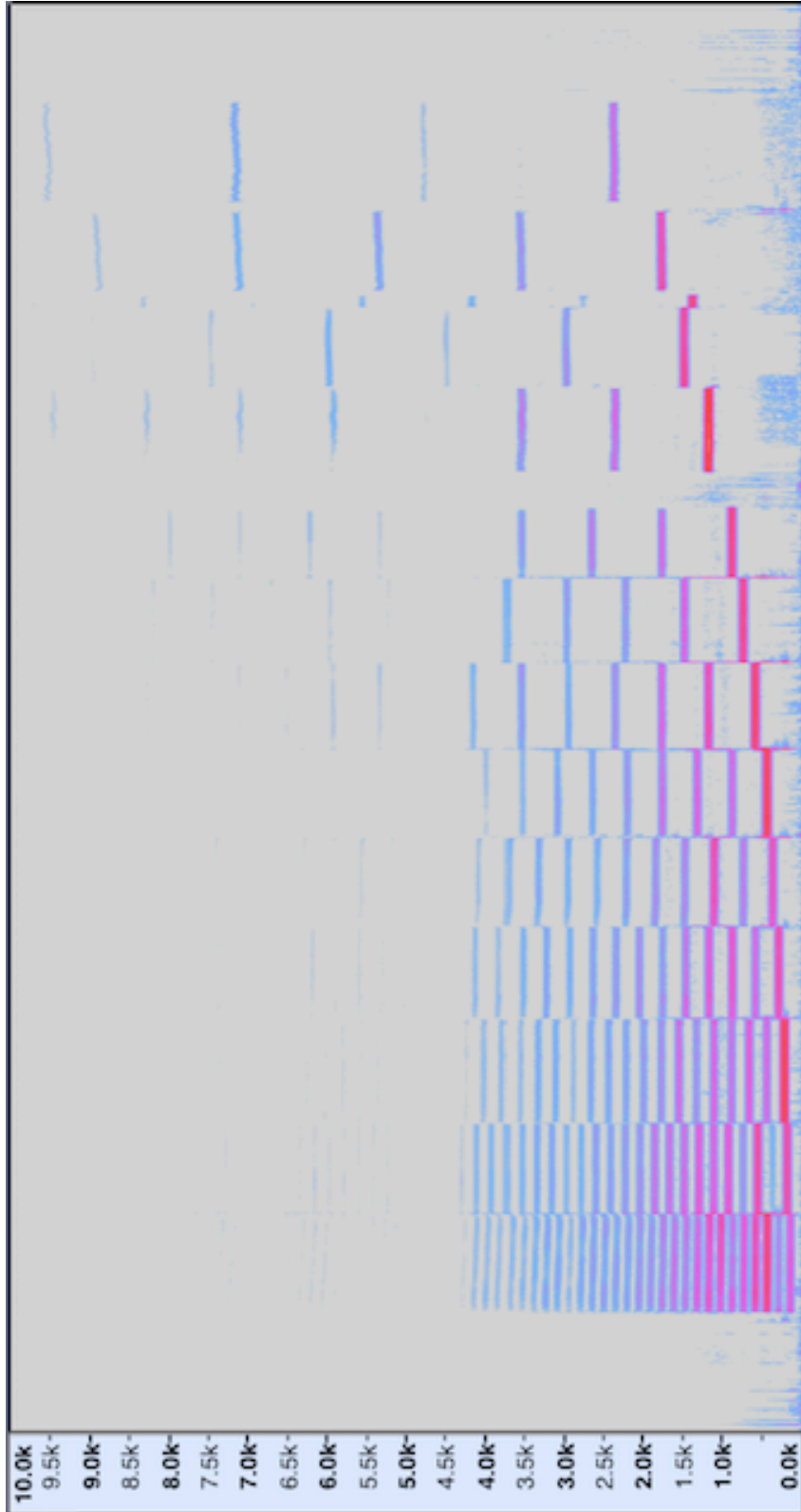


LIG

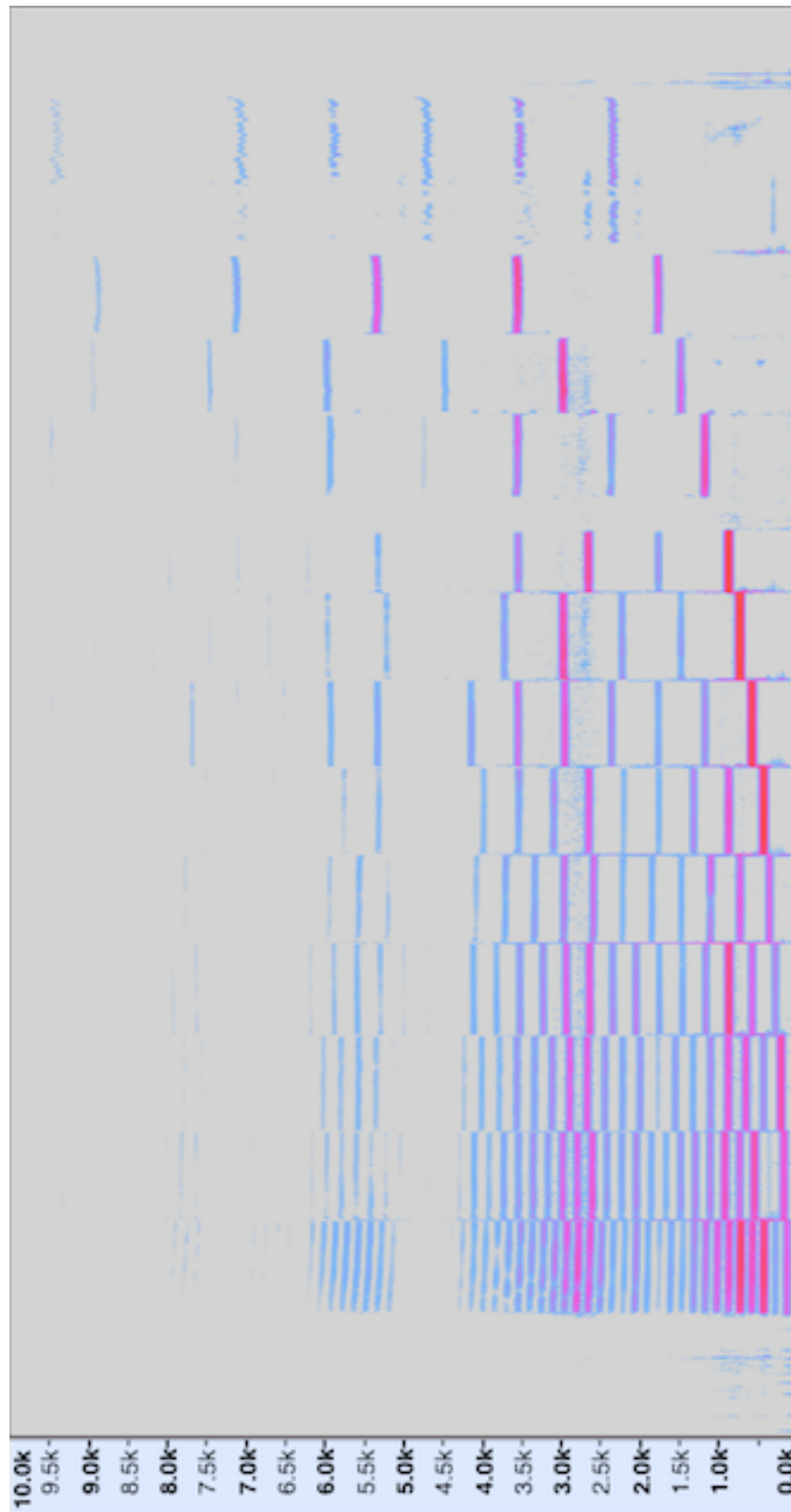
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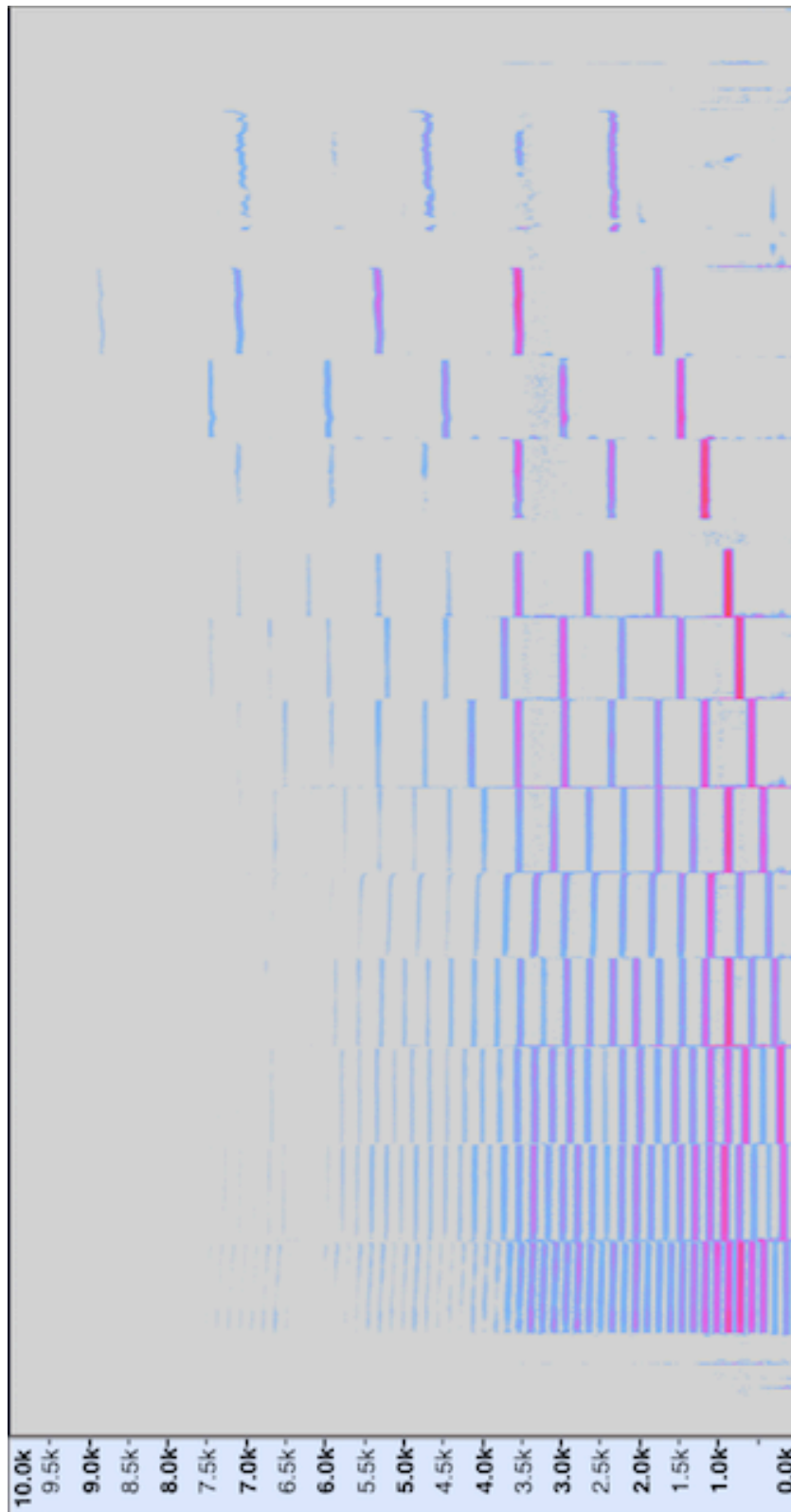
BAR Port



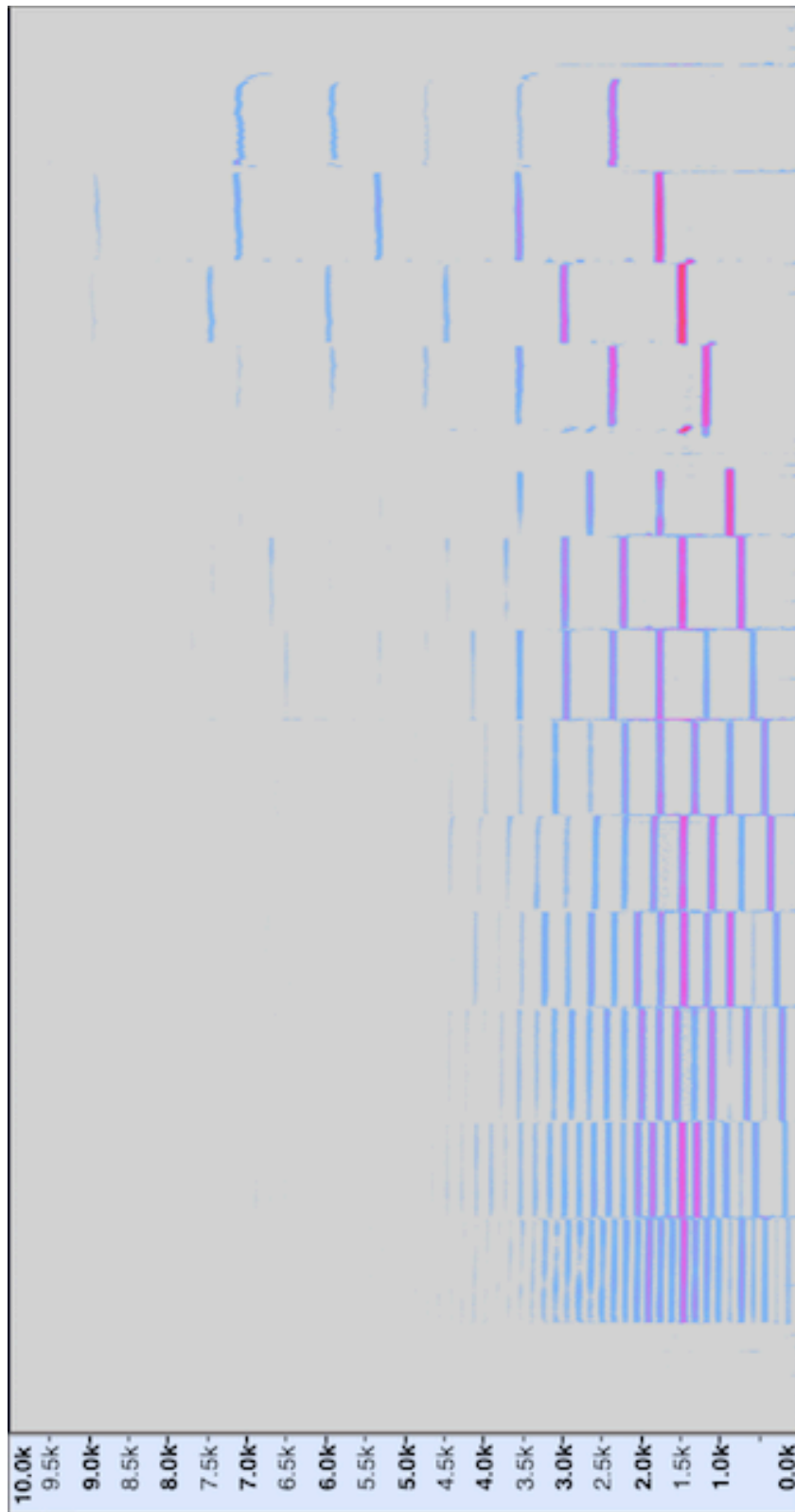
BAR Surf



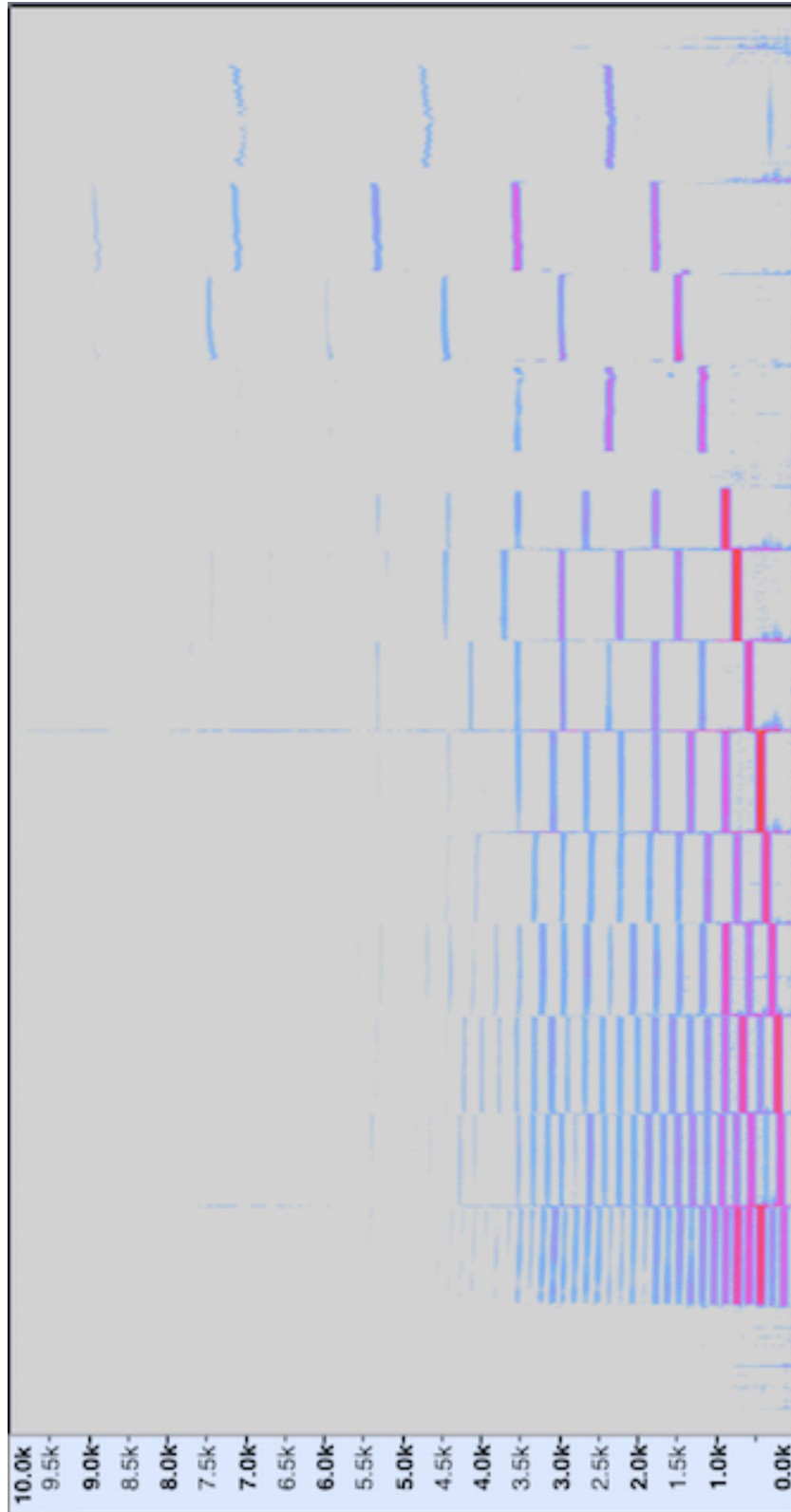
LF MPB



LF BUJ

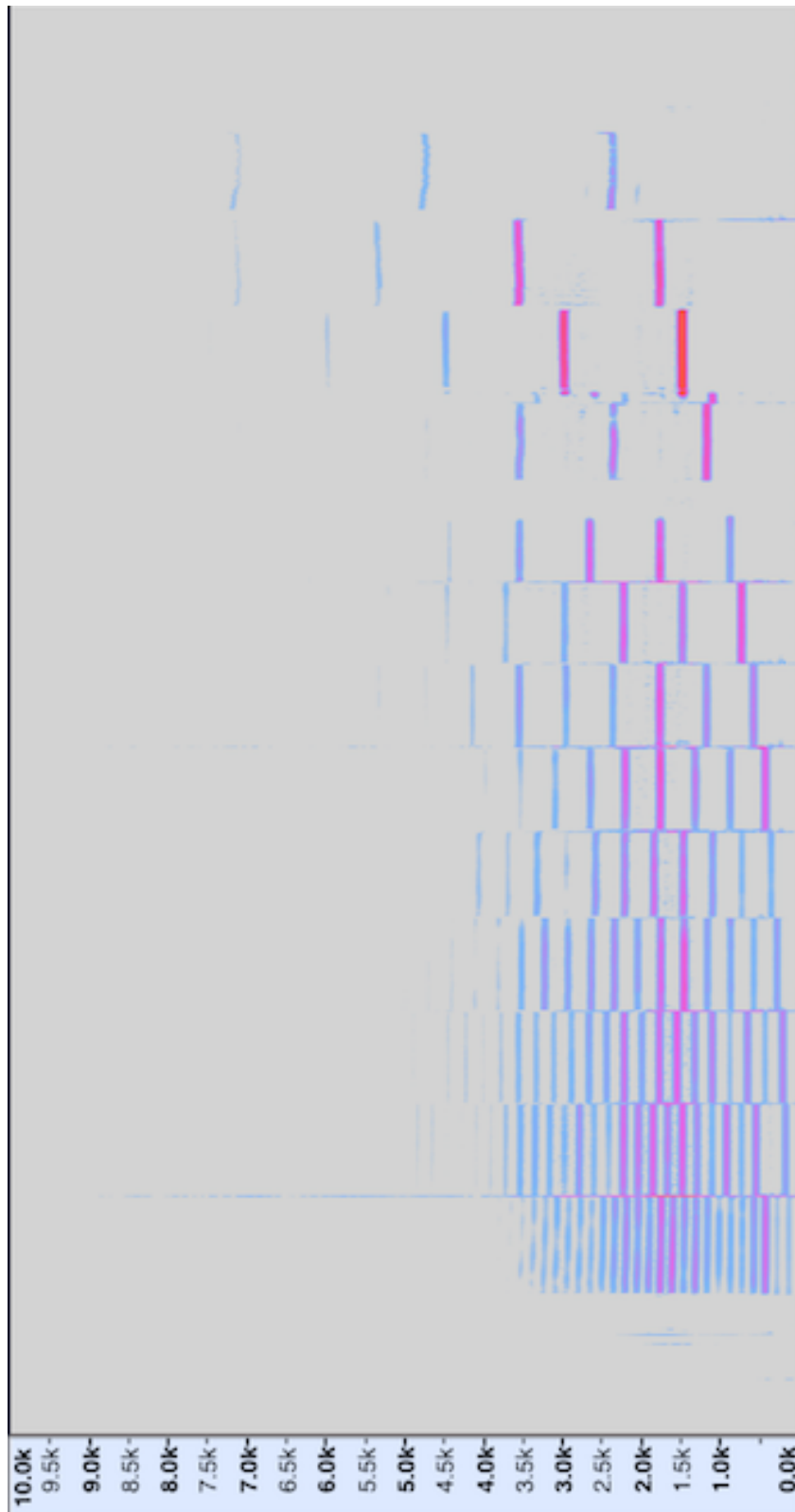


UJ

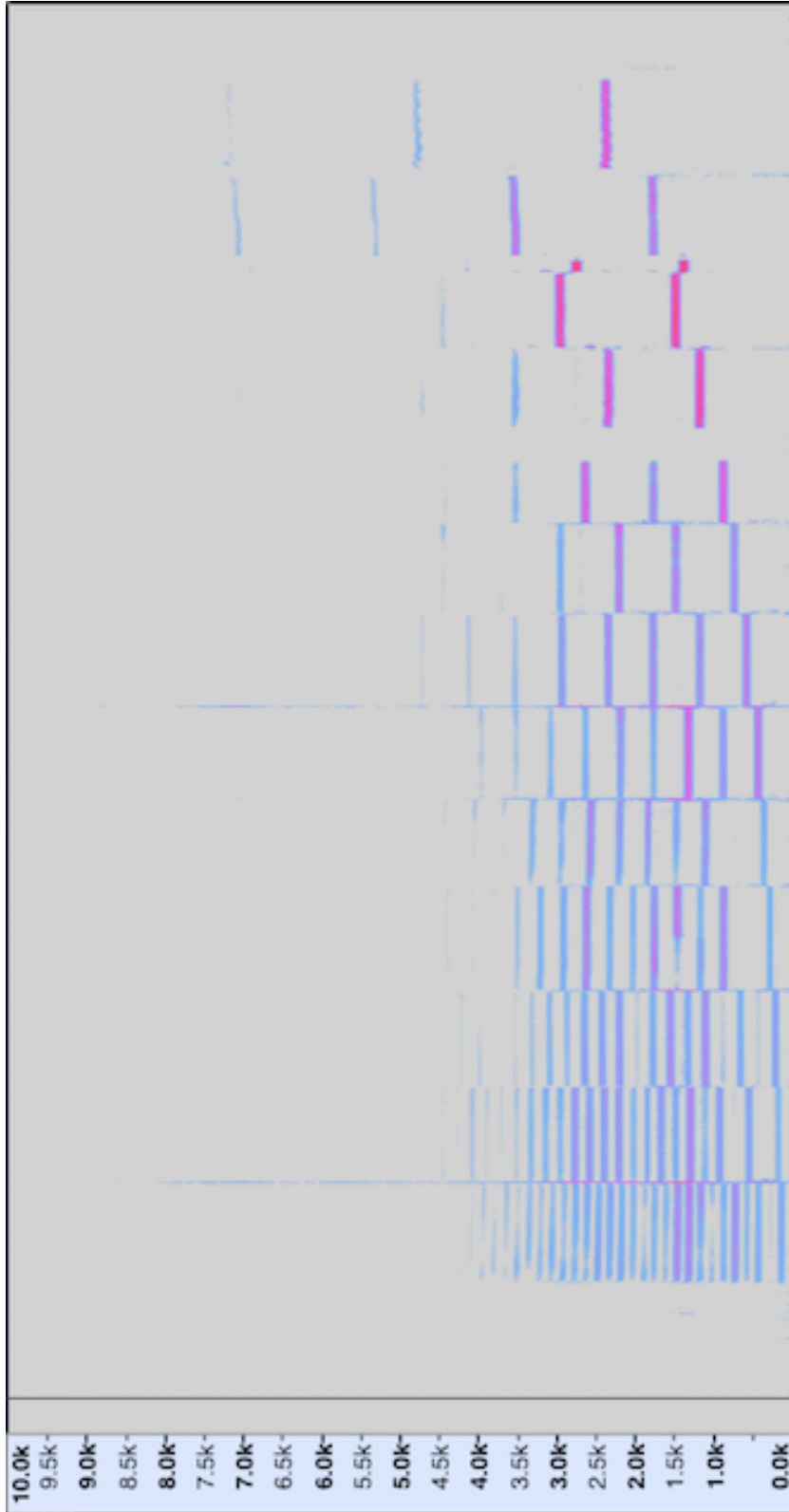


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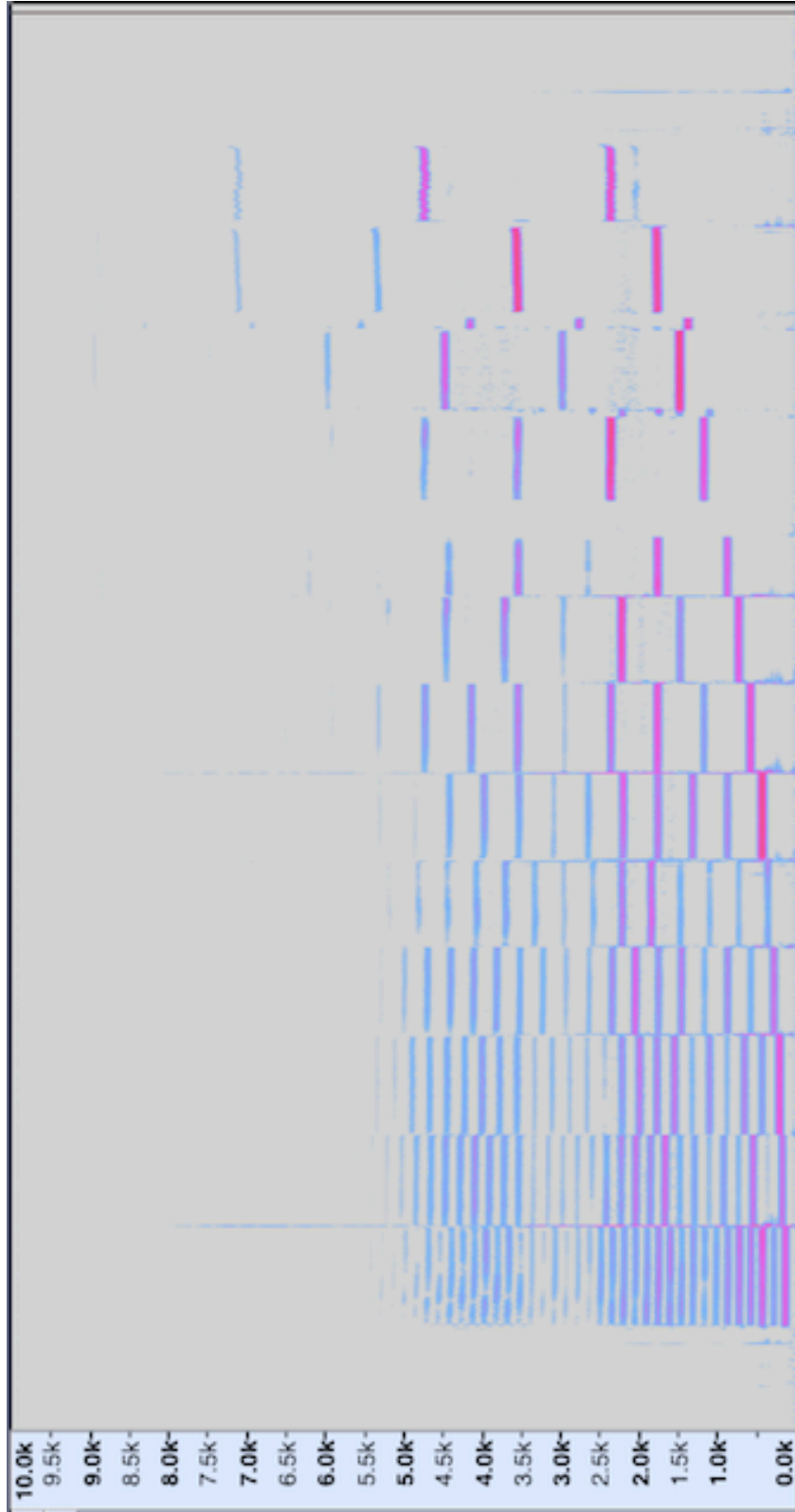
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LJ

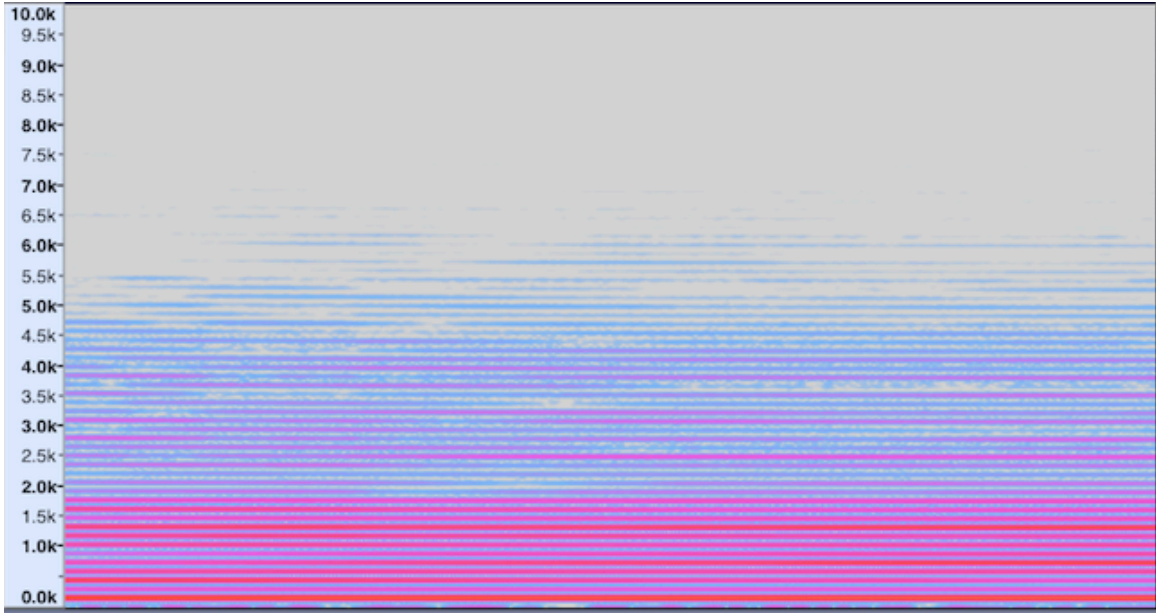


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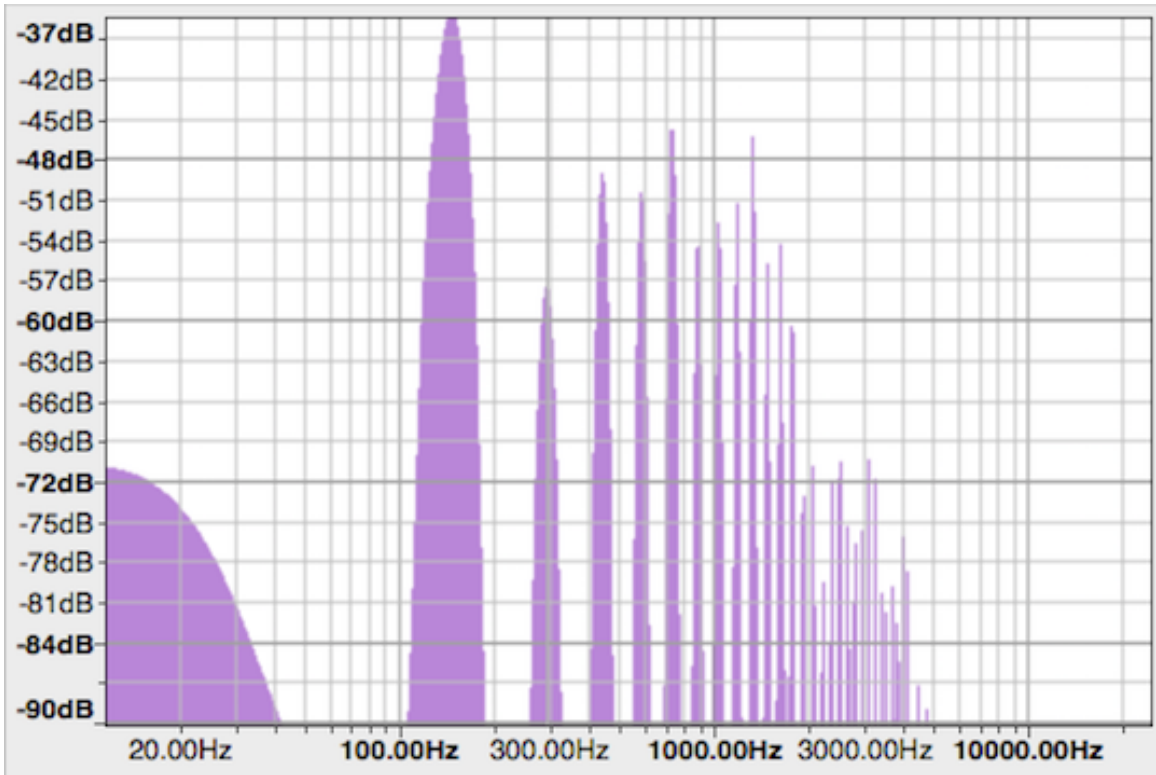


BELL End

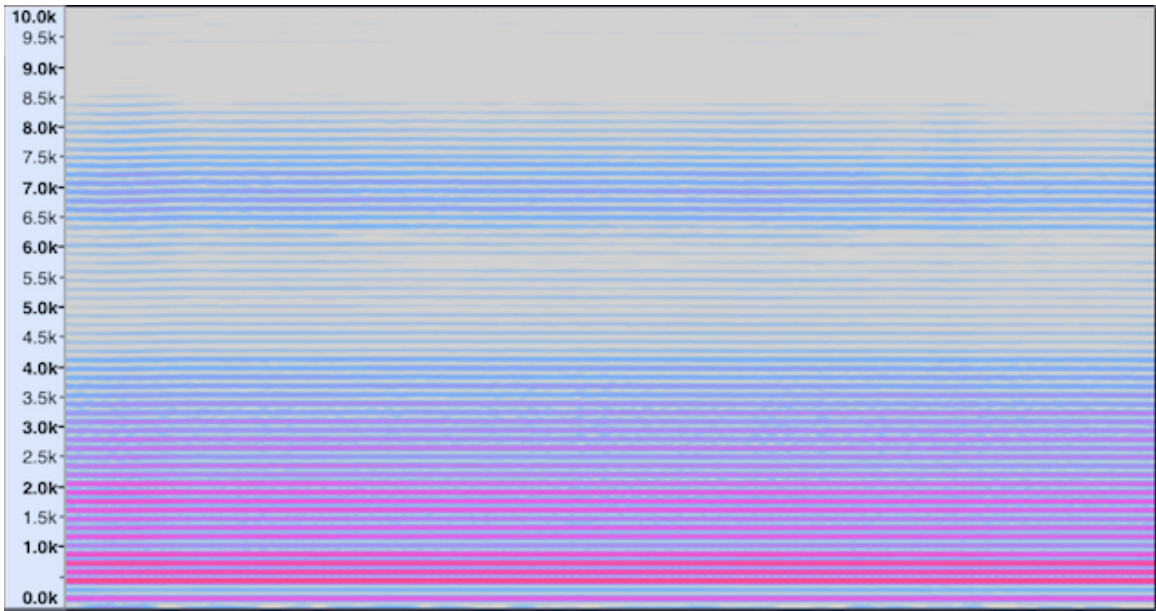
APPENDIX E  
SAMPLE DATA E3



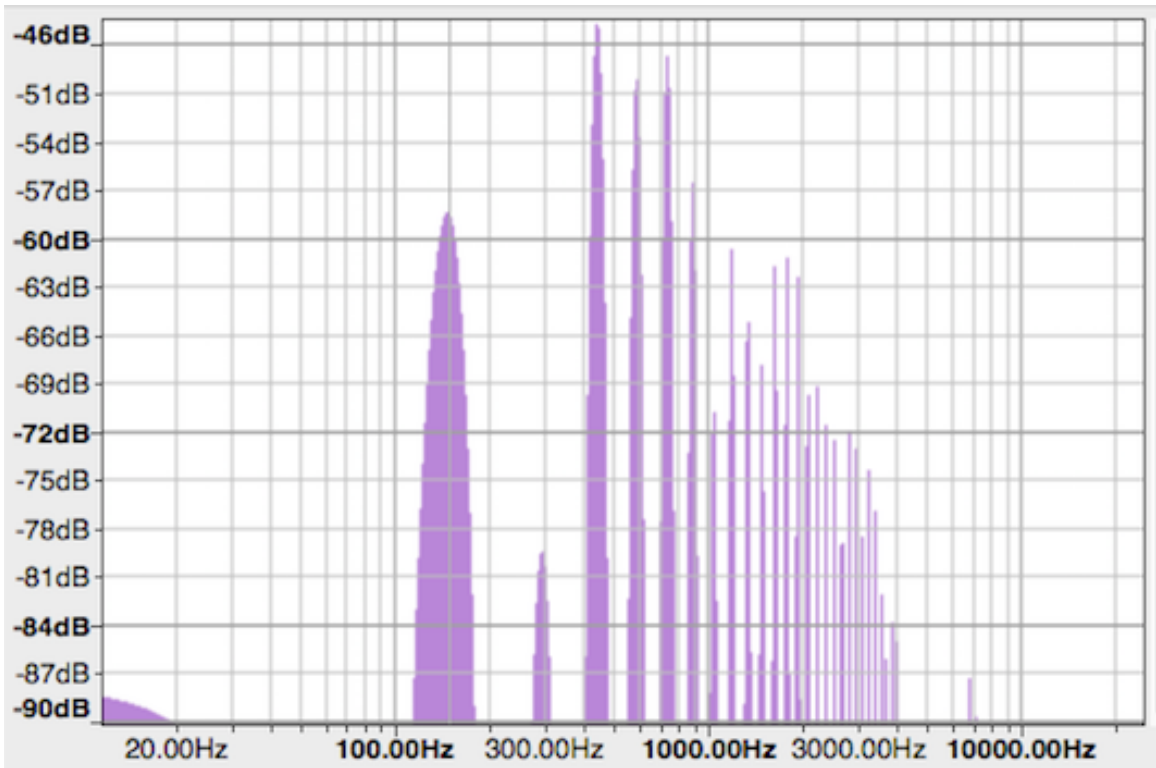
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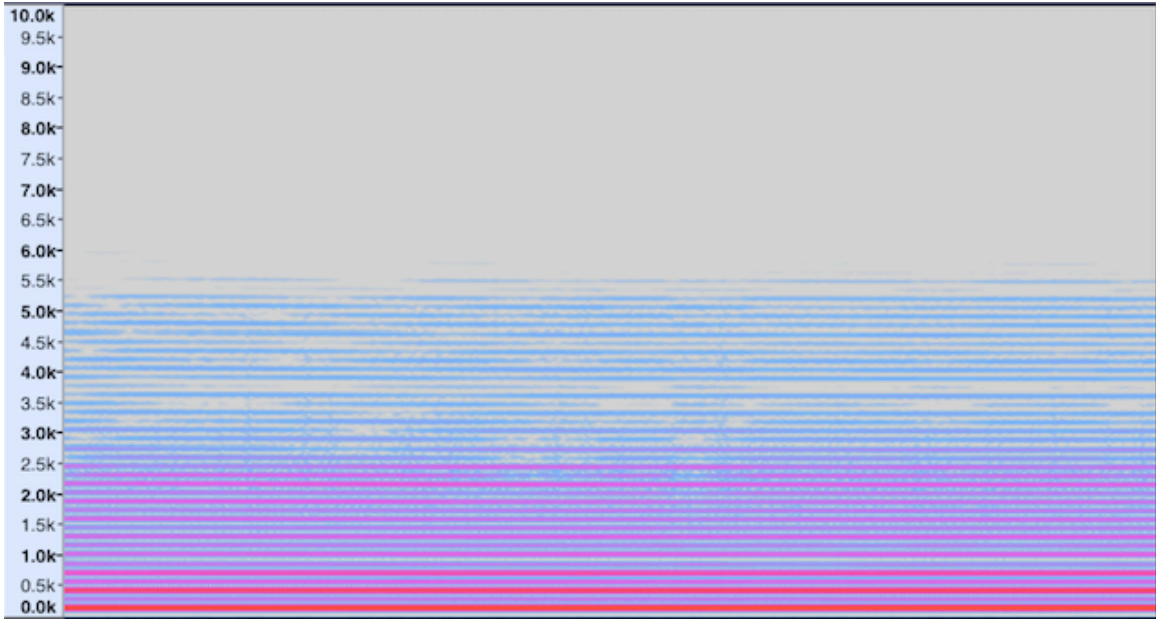
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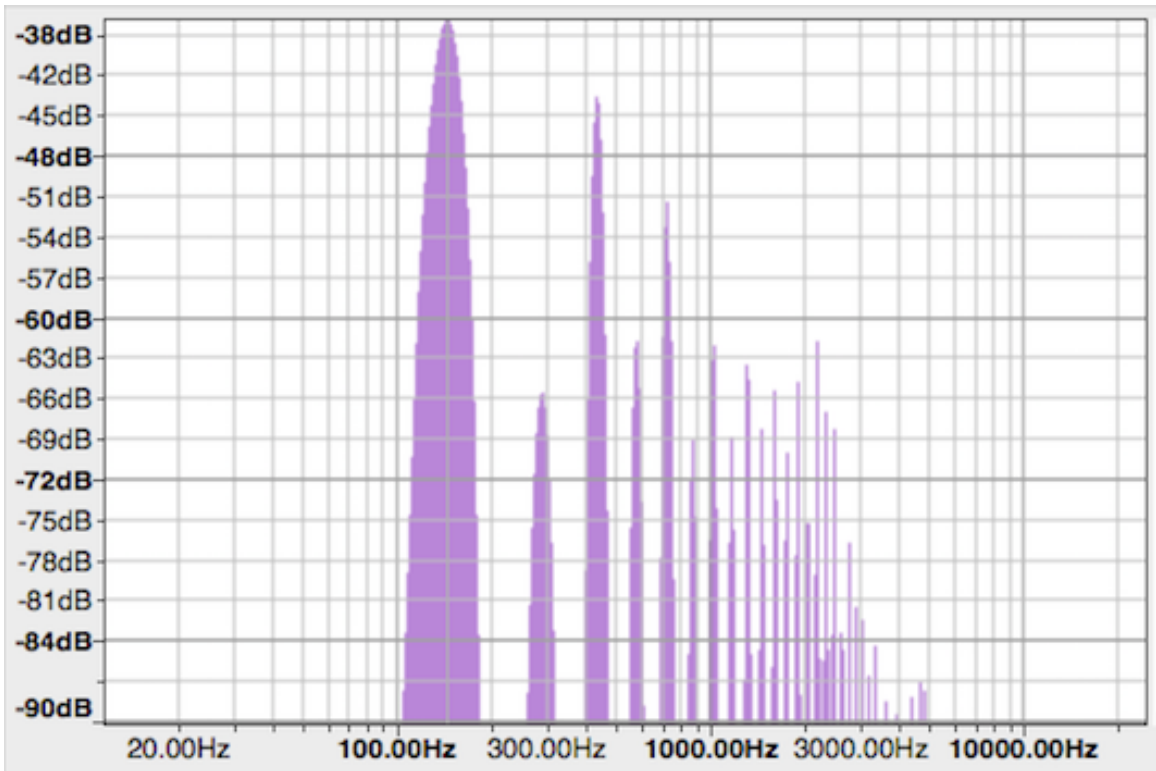
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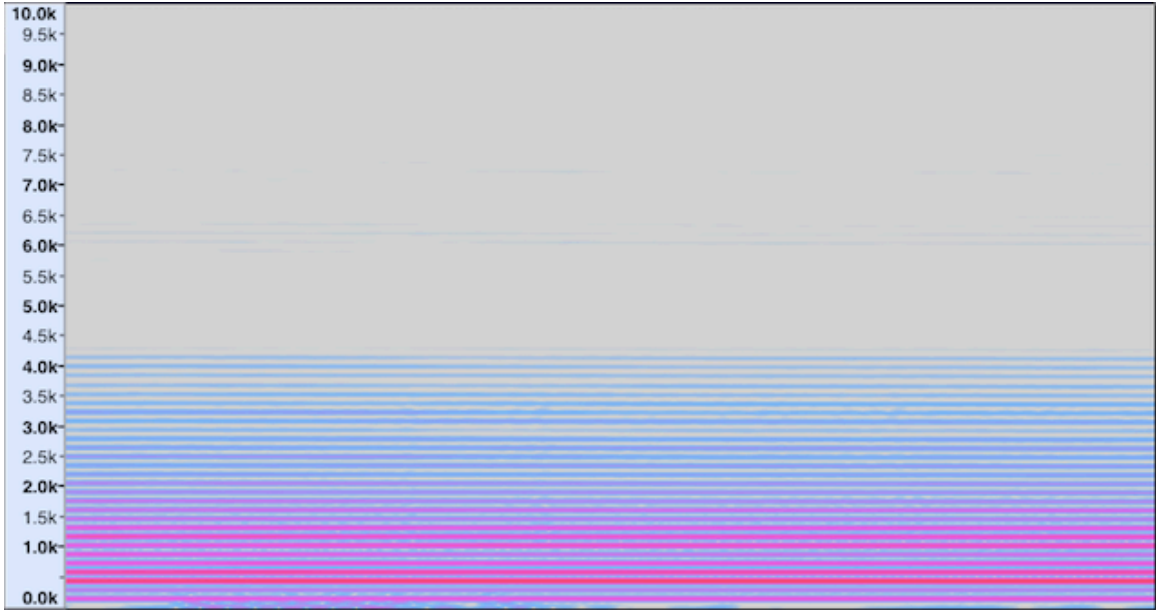
LIG



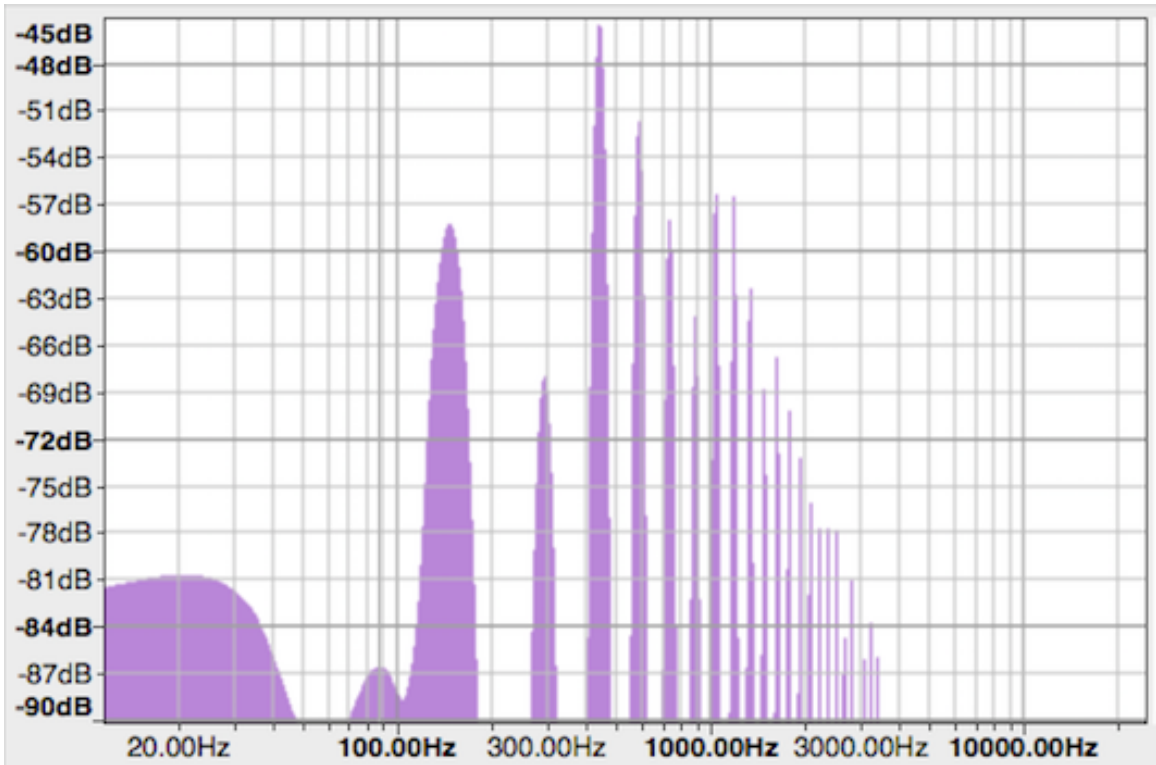
BAR Port



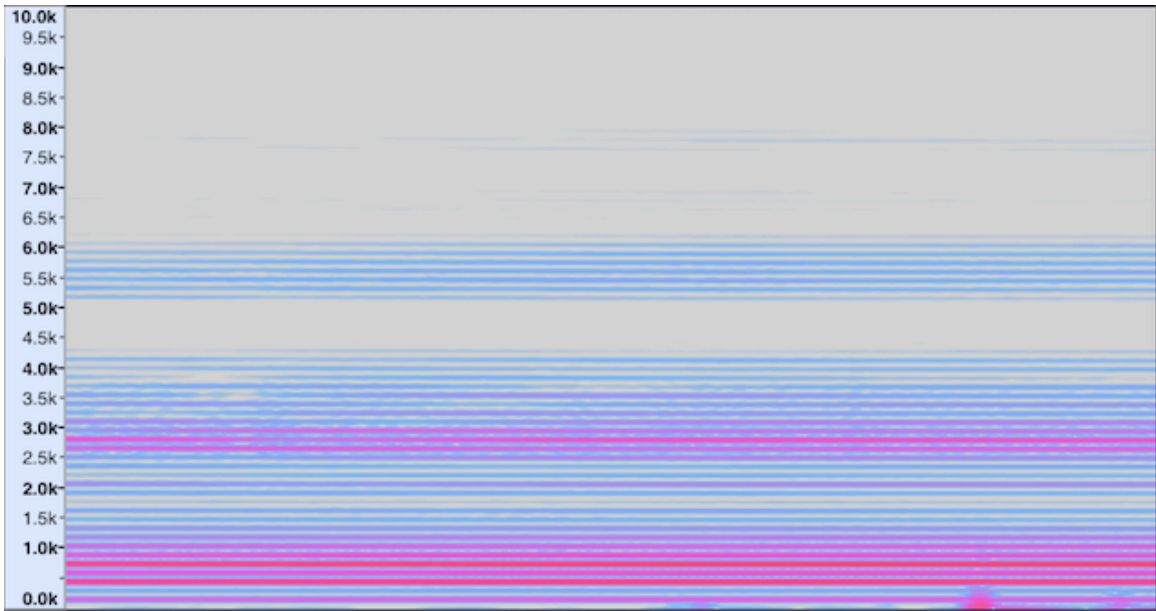
BAR Port



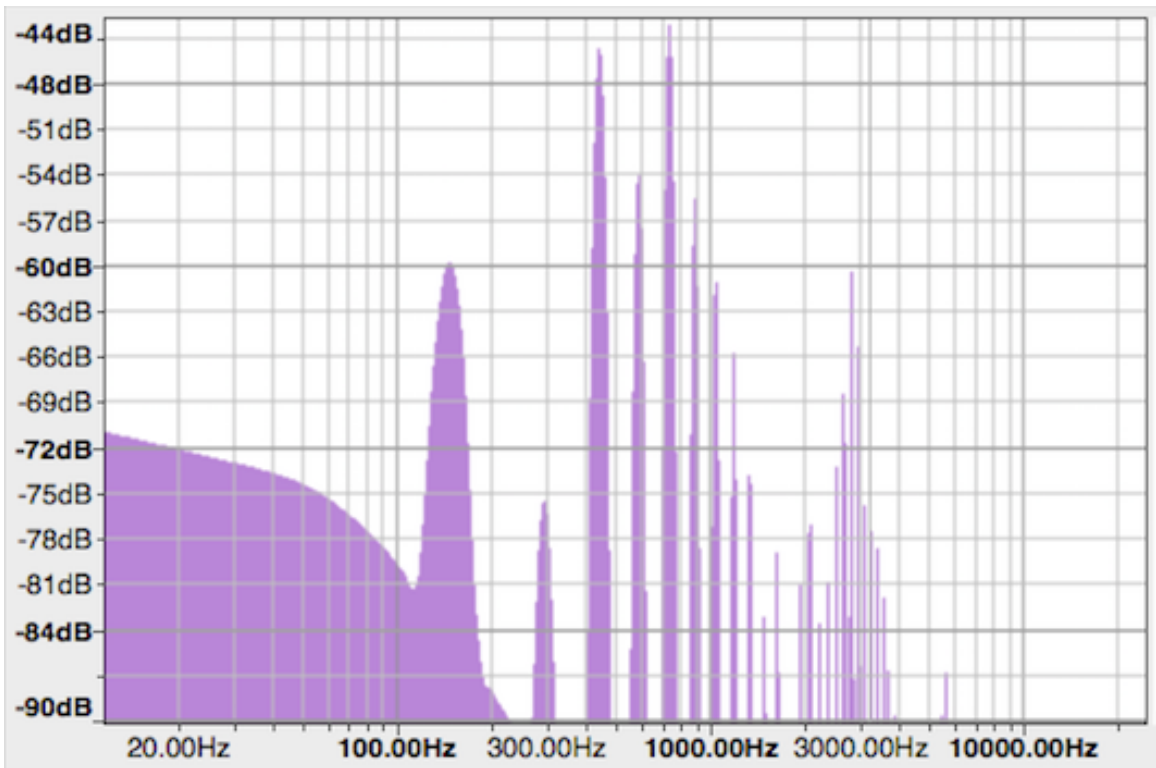
BAR Surf



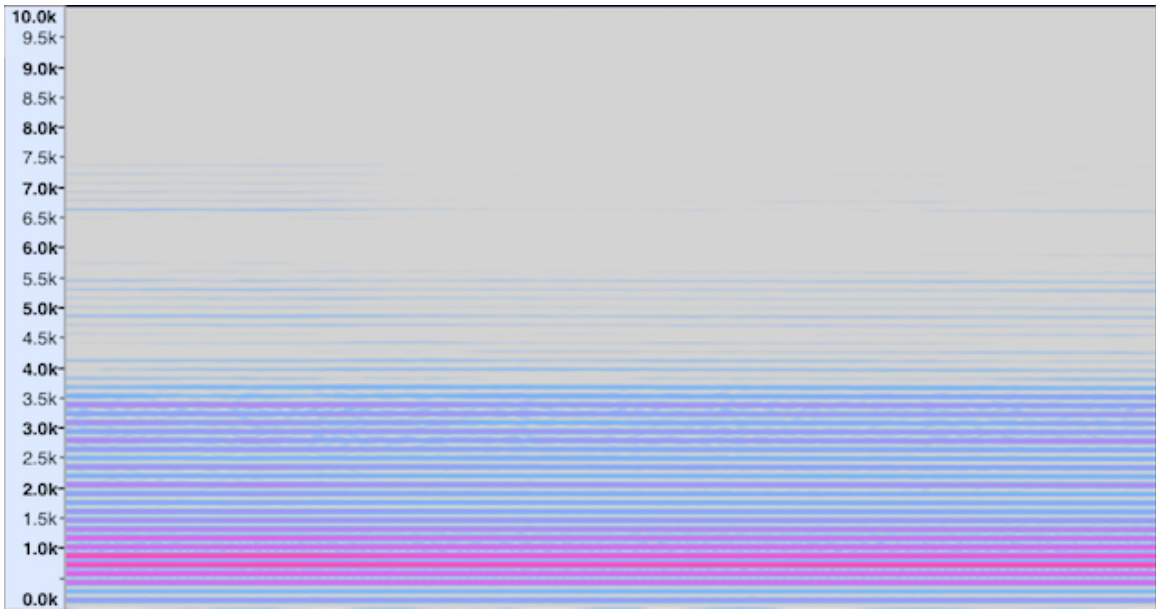
BAR Surf



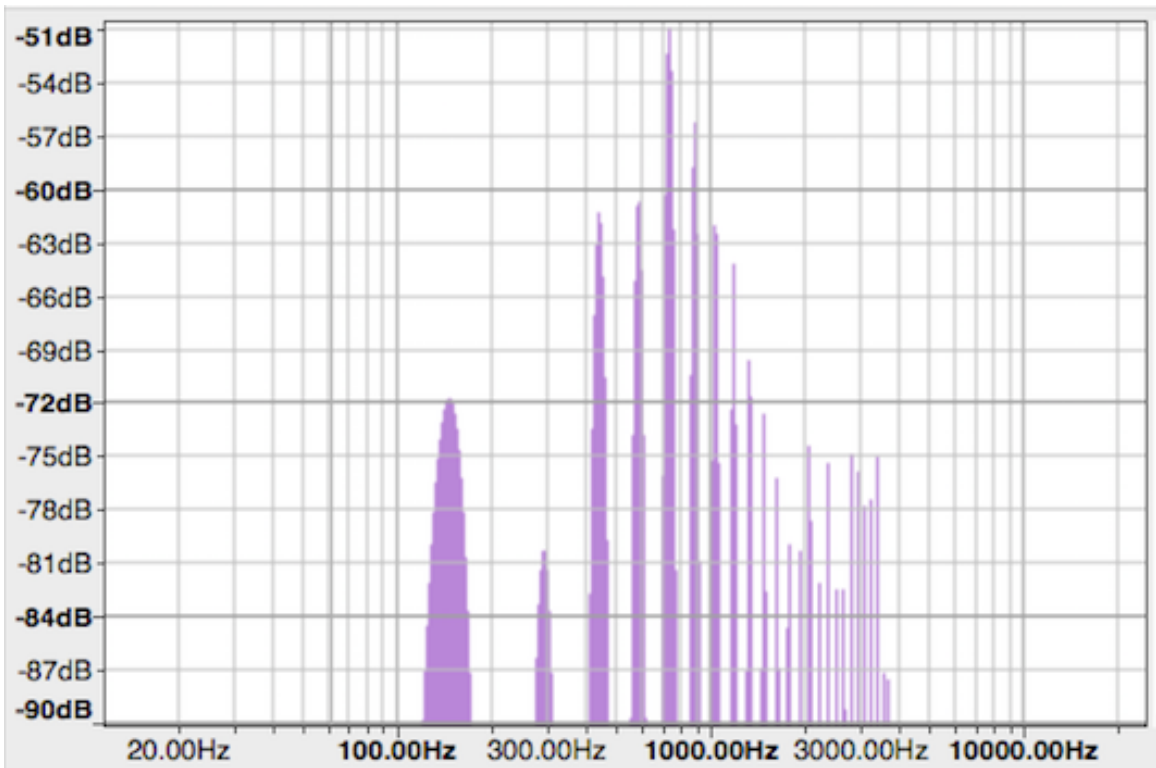
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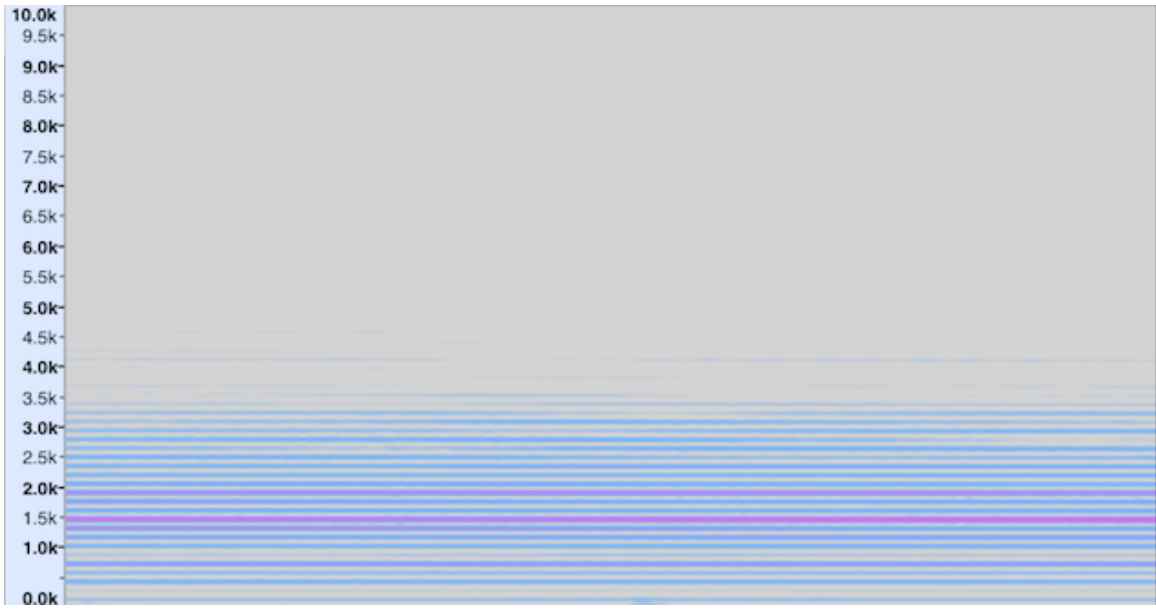
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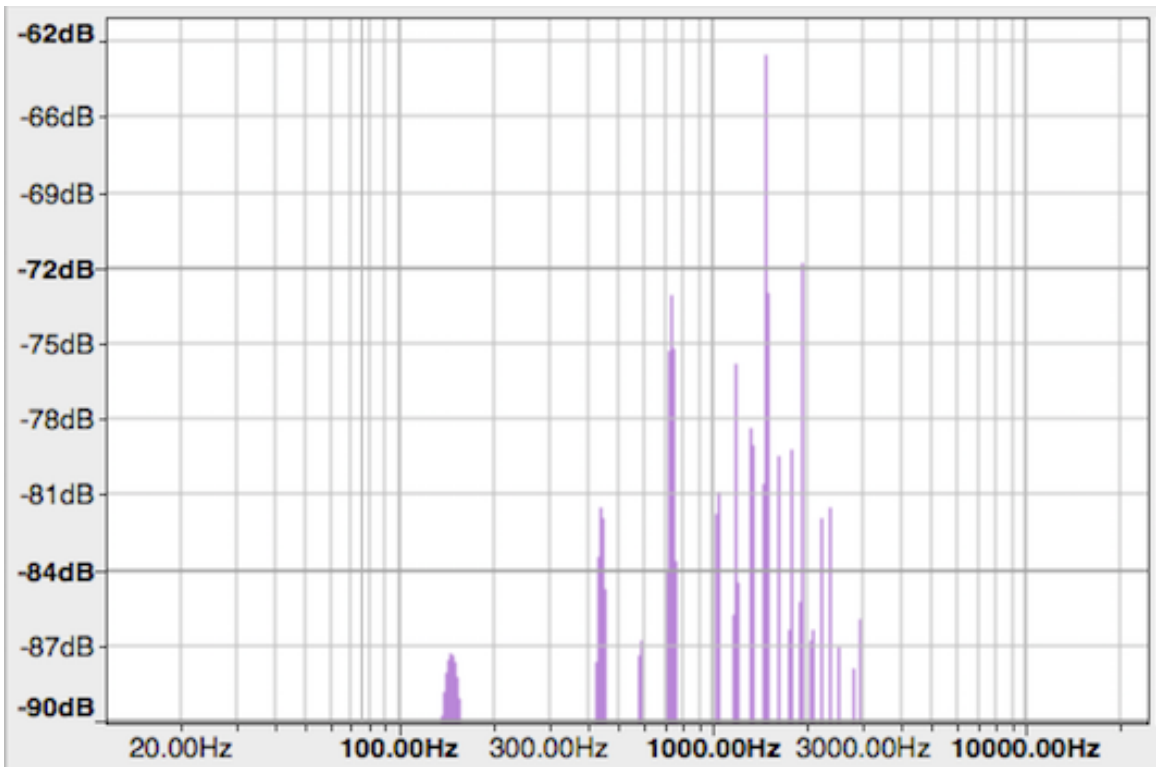
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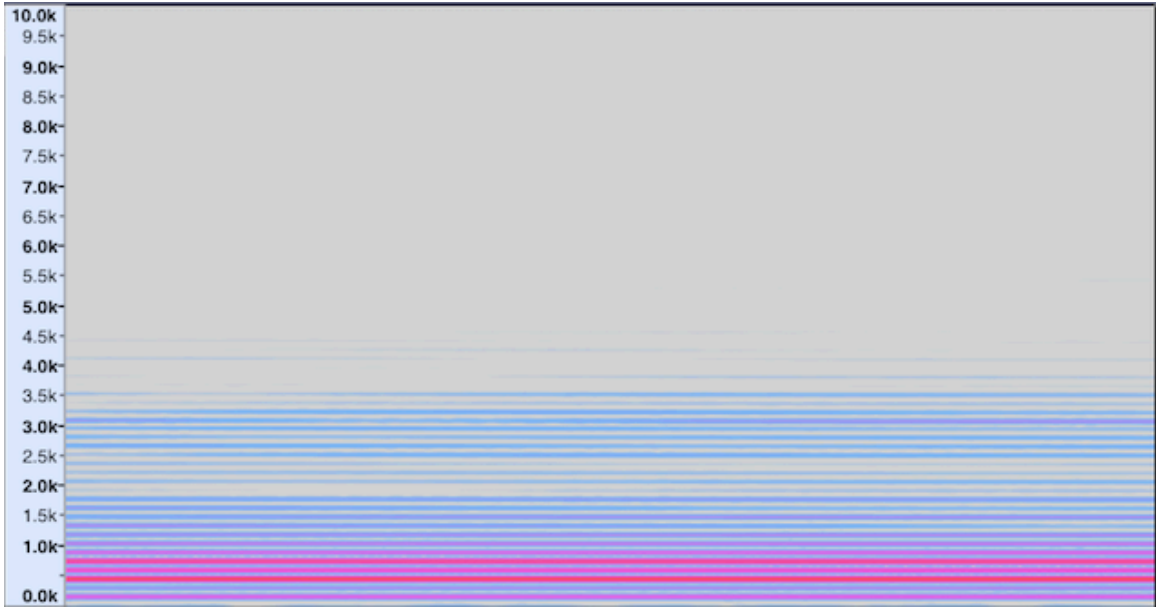
LF BUJ



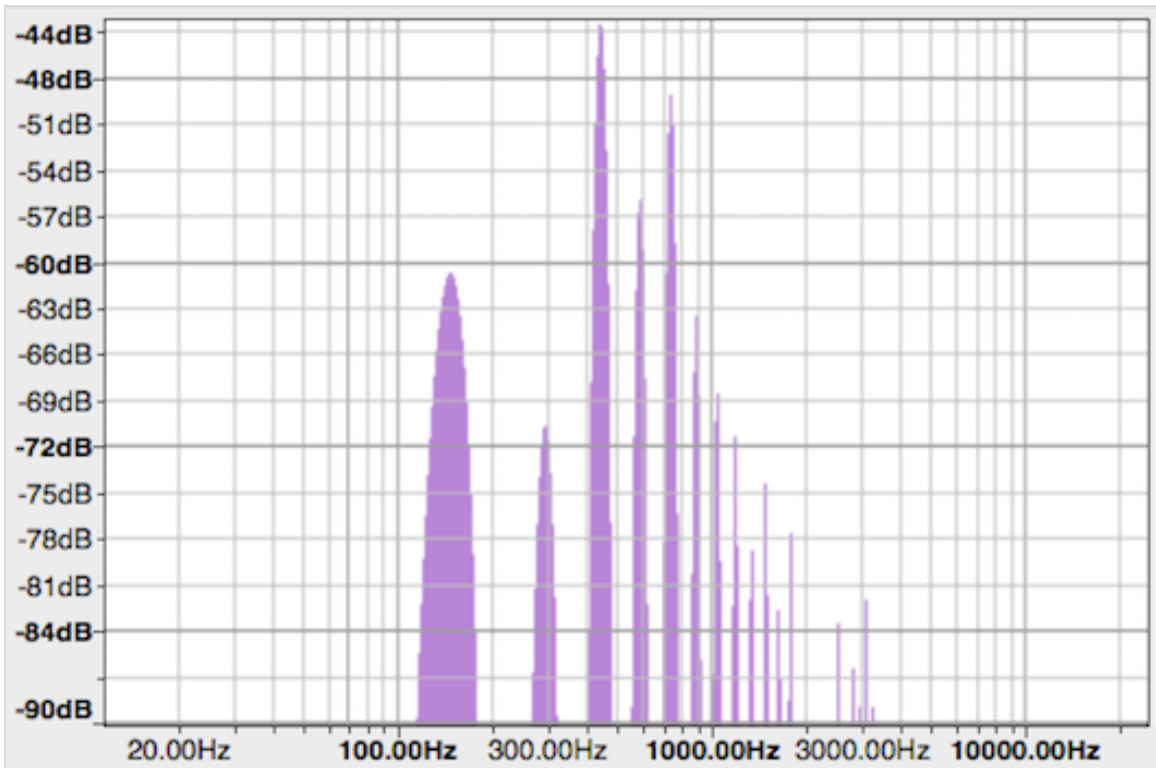
UJ



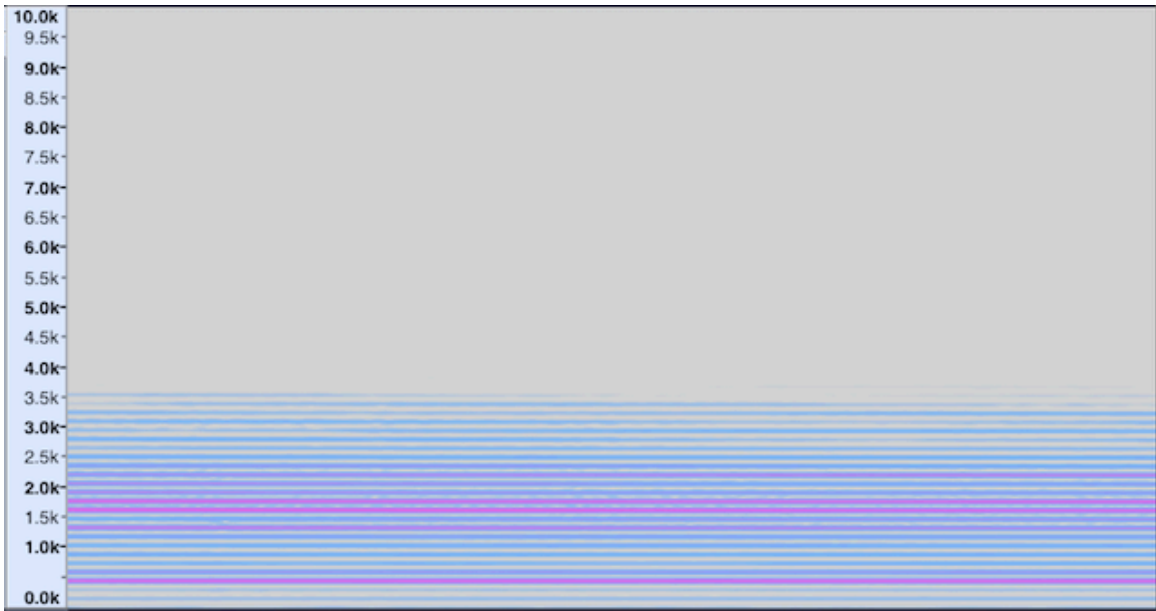
UJ



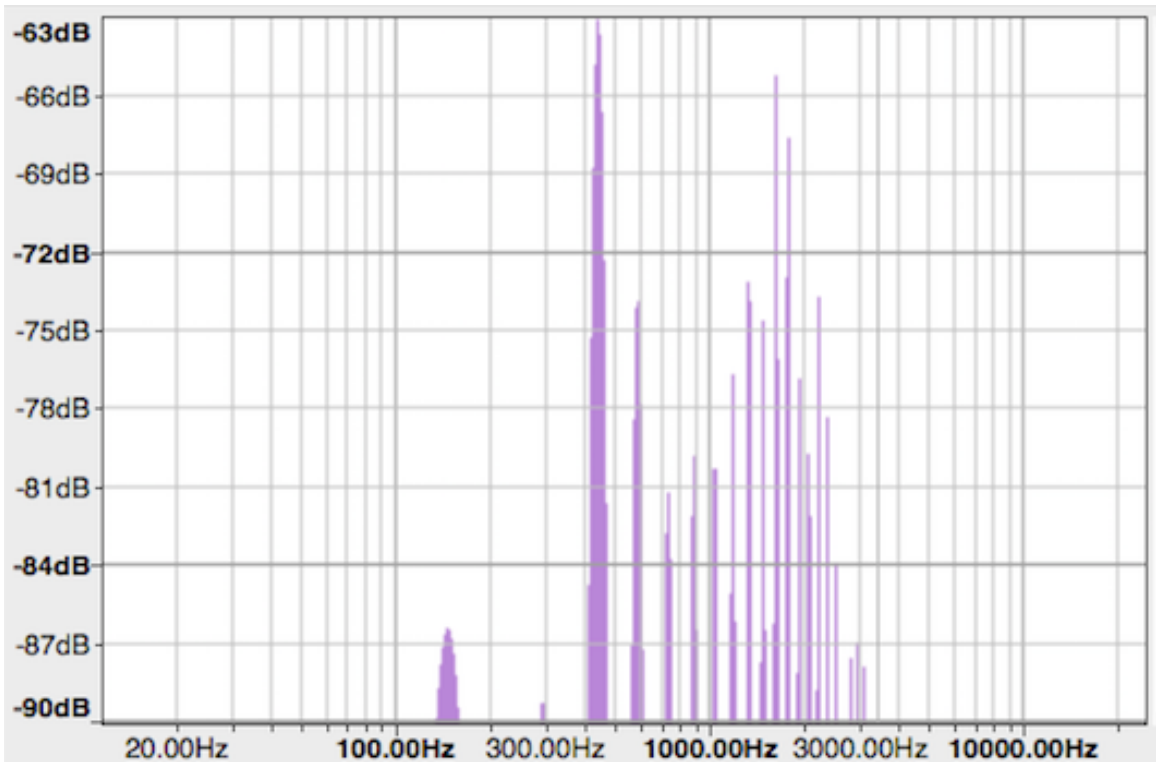
CTR



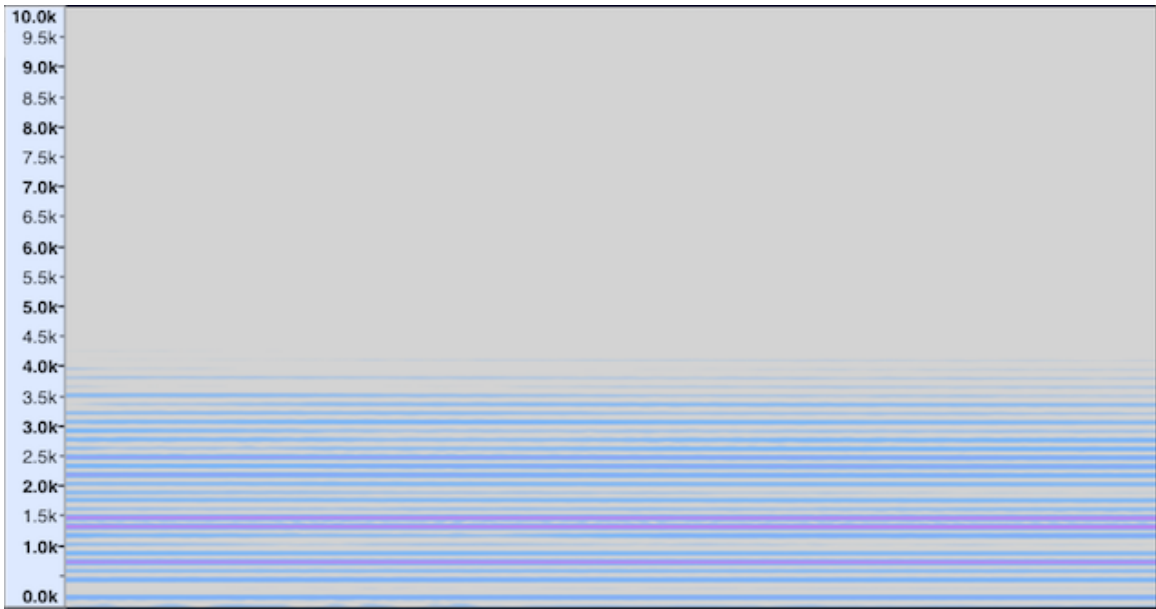
CTR



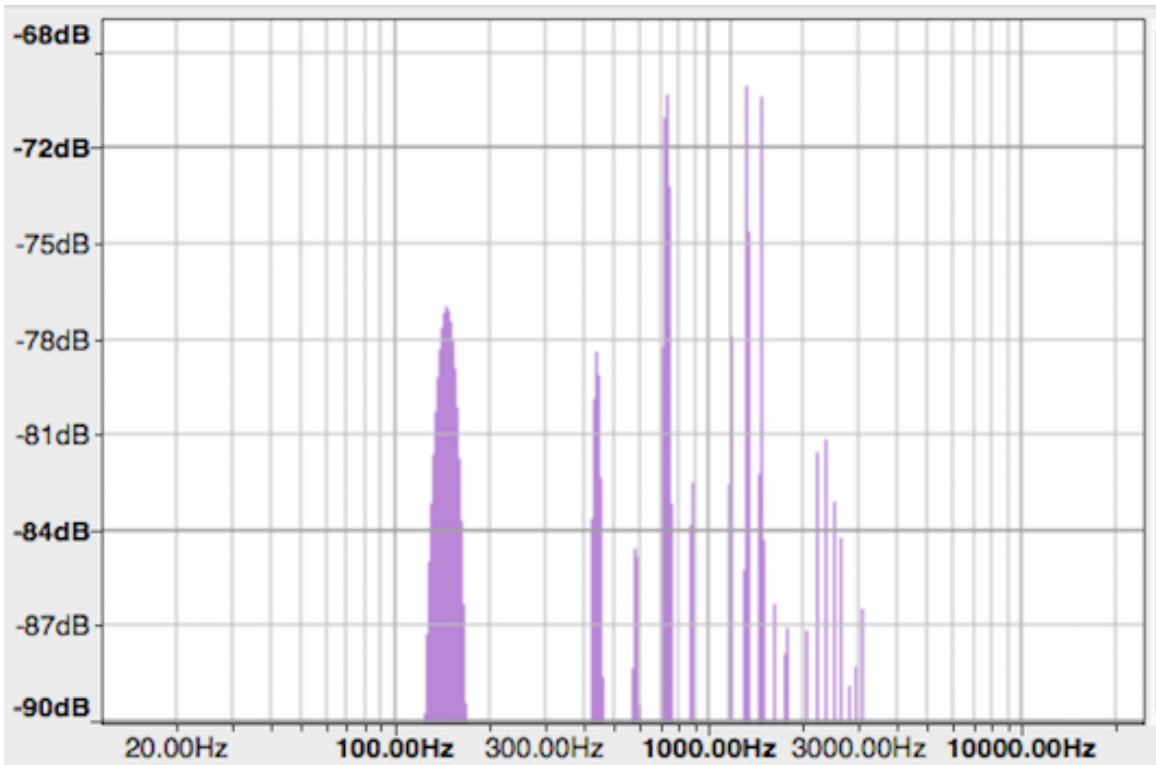
LJ



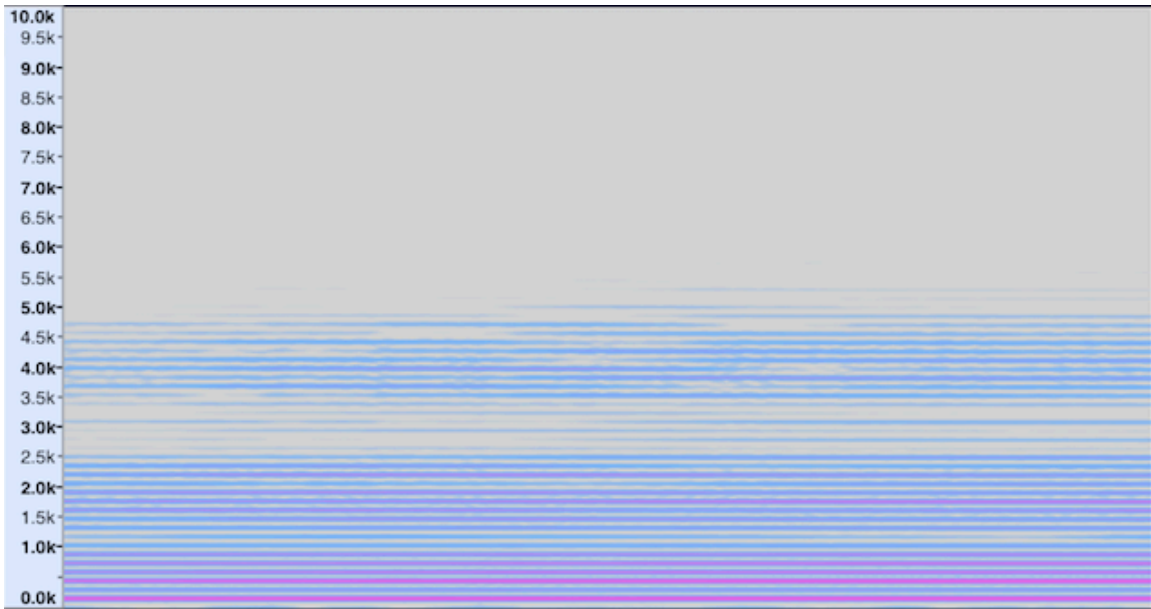
LJ



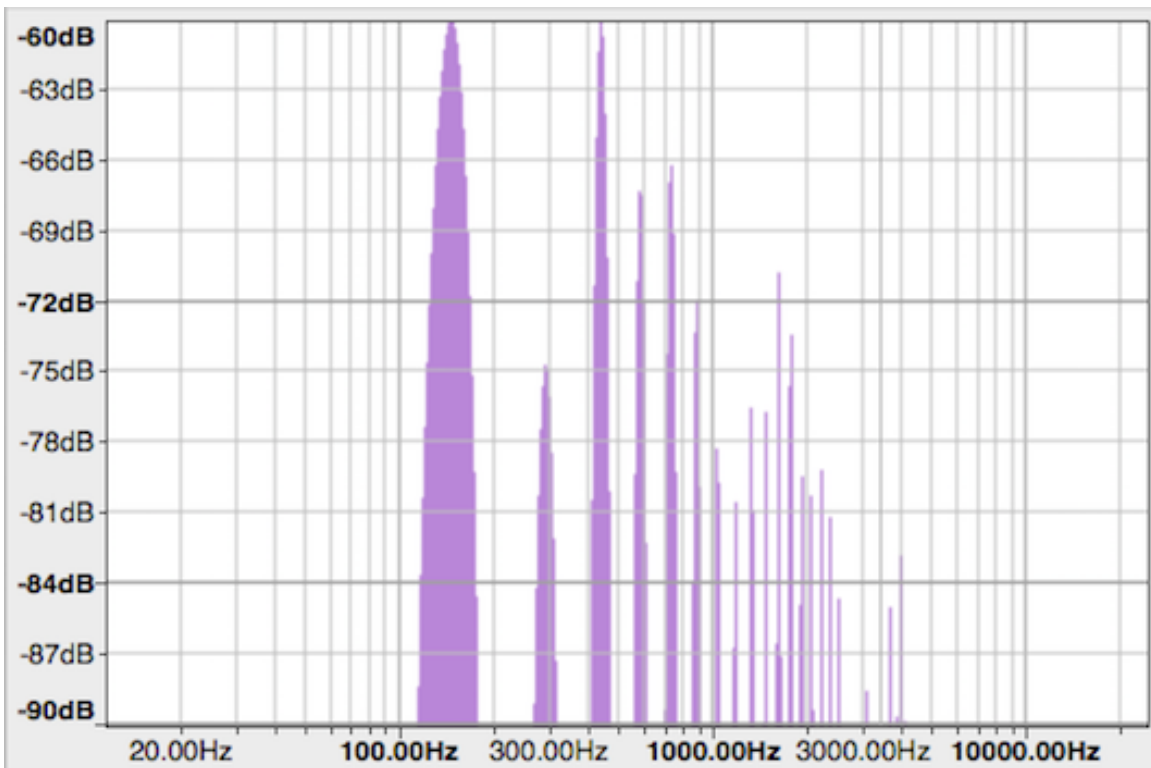
BELL Out



BELL Out

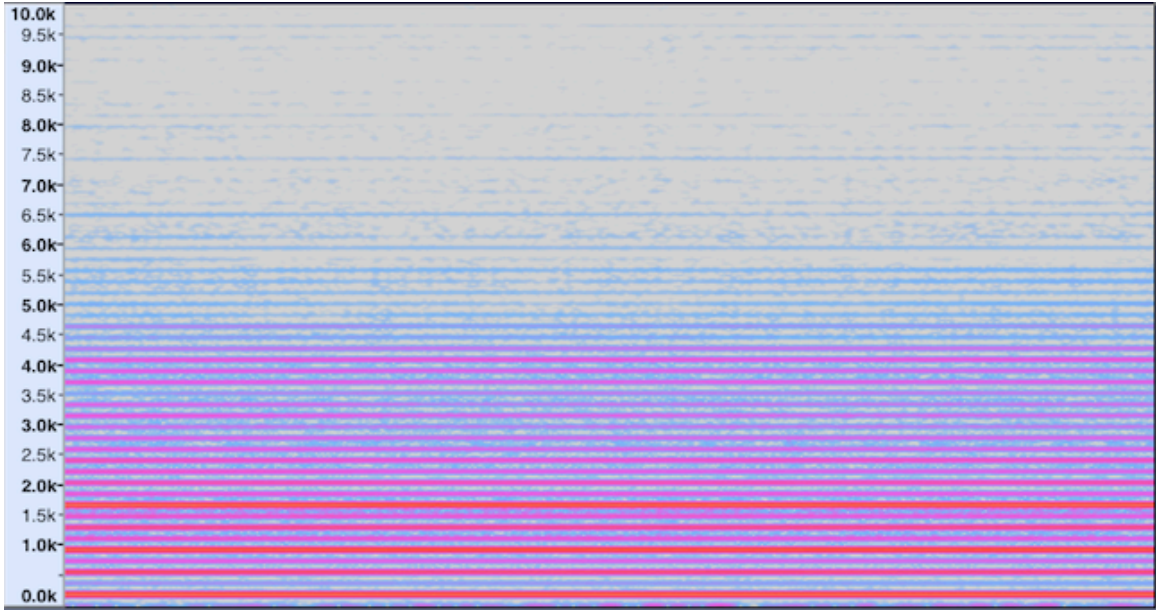


BELL End

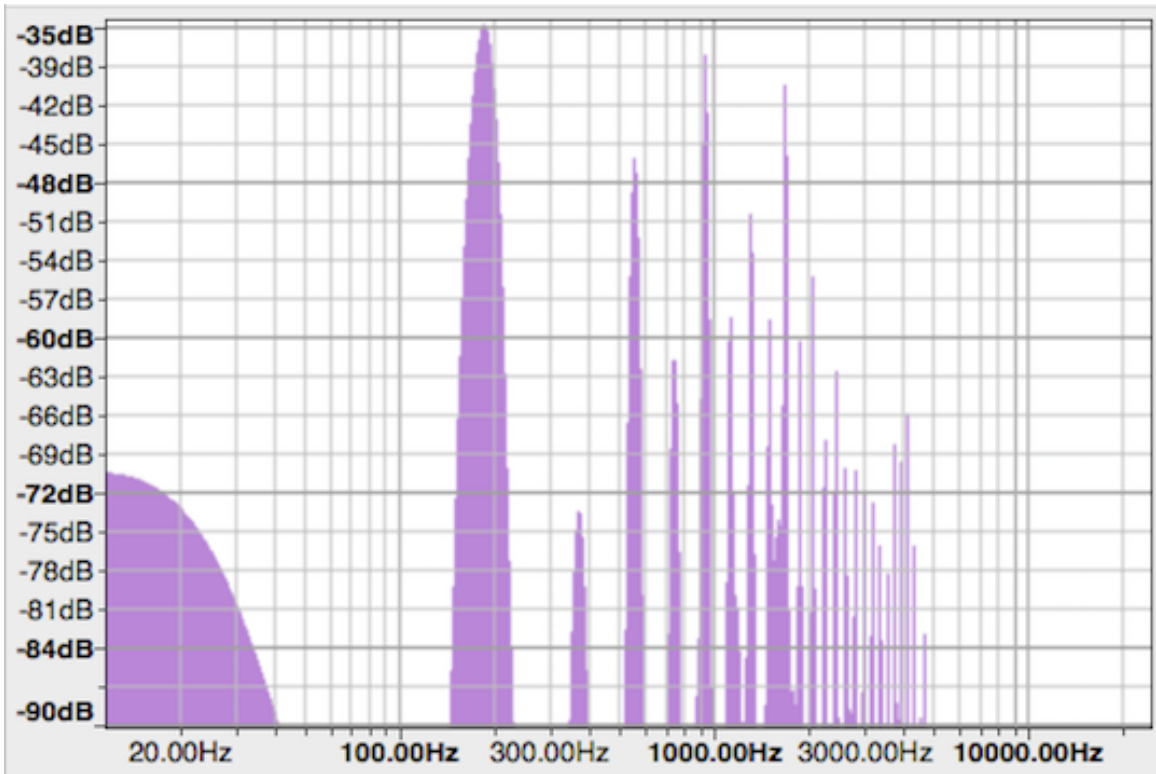


BELL End

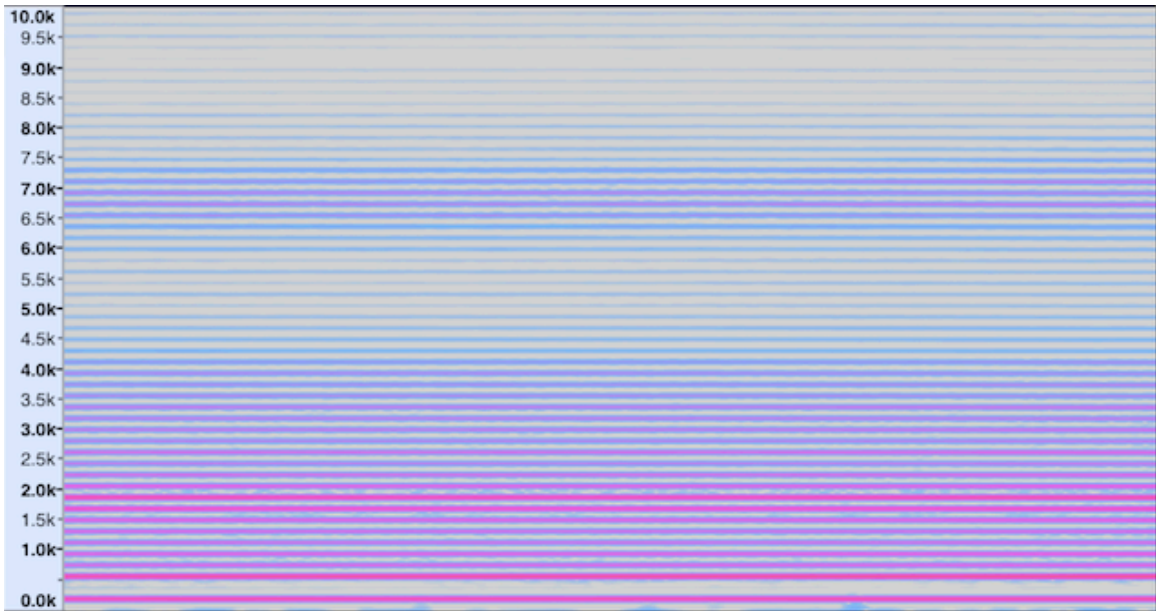
APPENDIX F  
SAMPLE DATA G-SHARP3



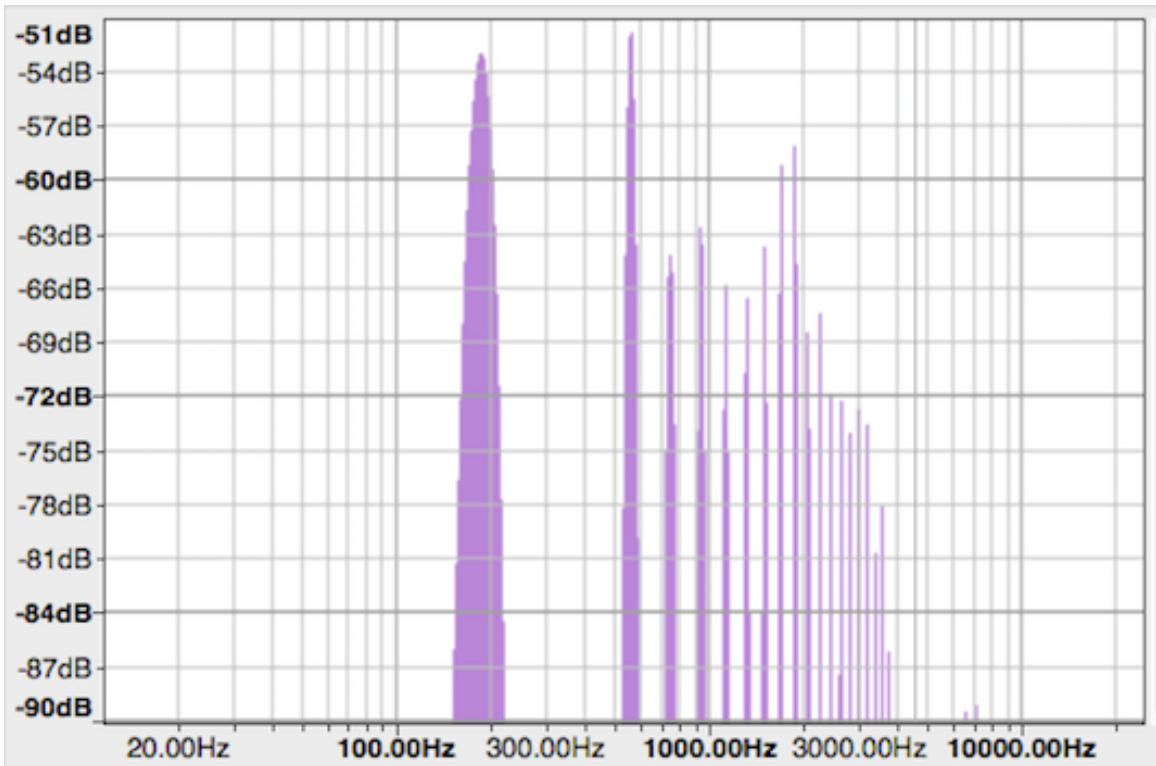
M30 (Reference)



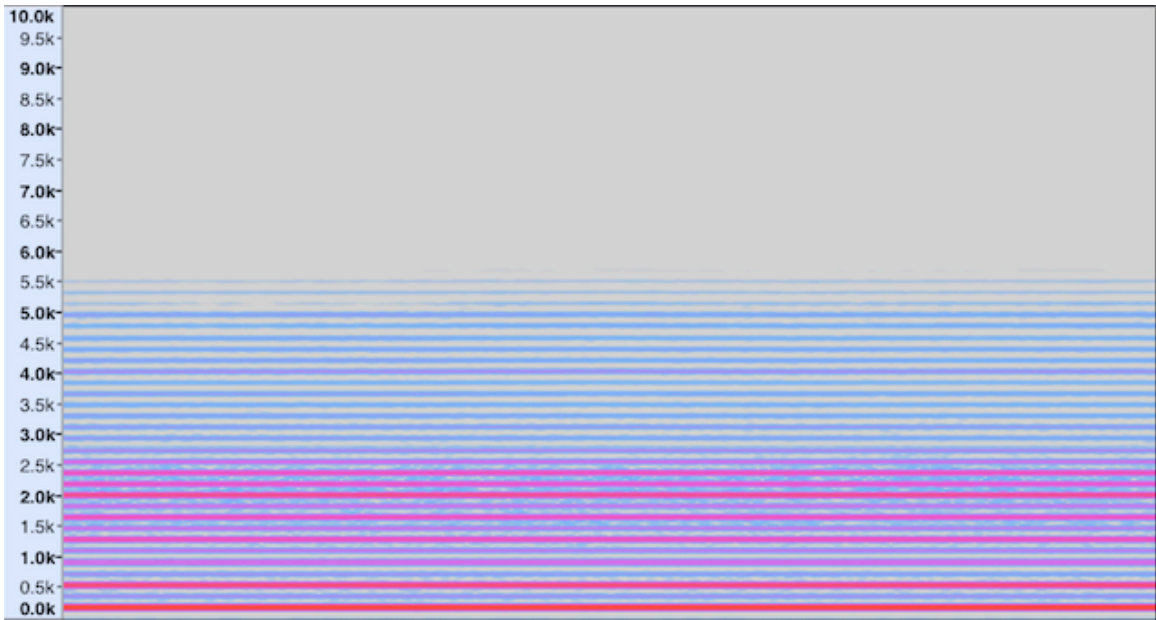
M30 (Reference)



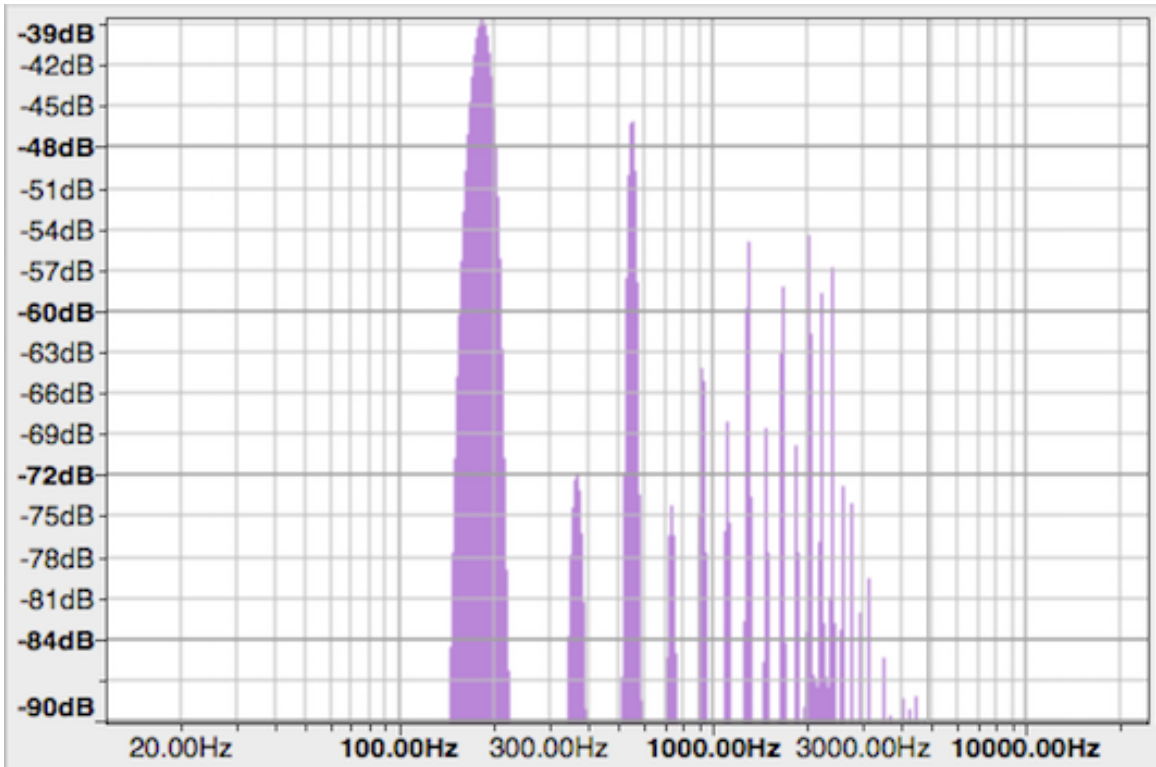
LIG



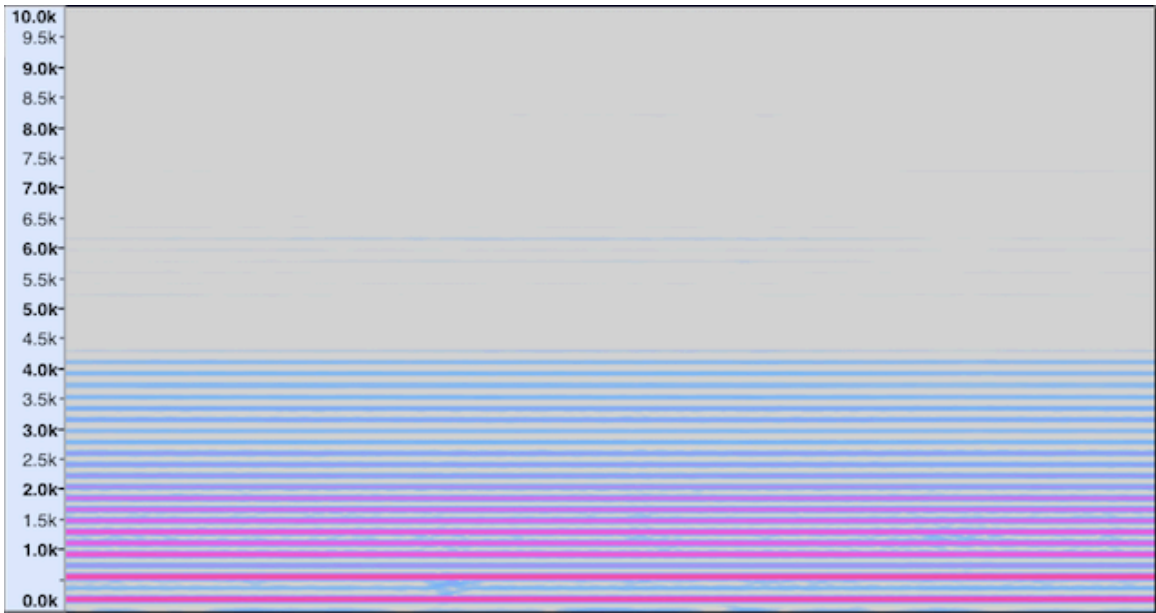
LIG



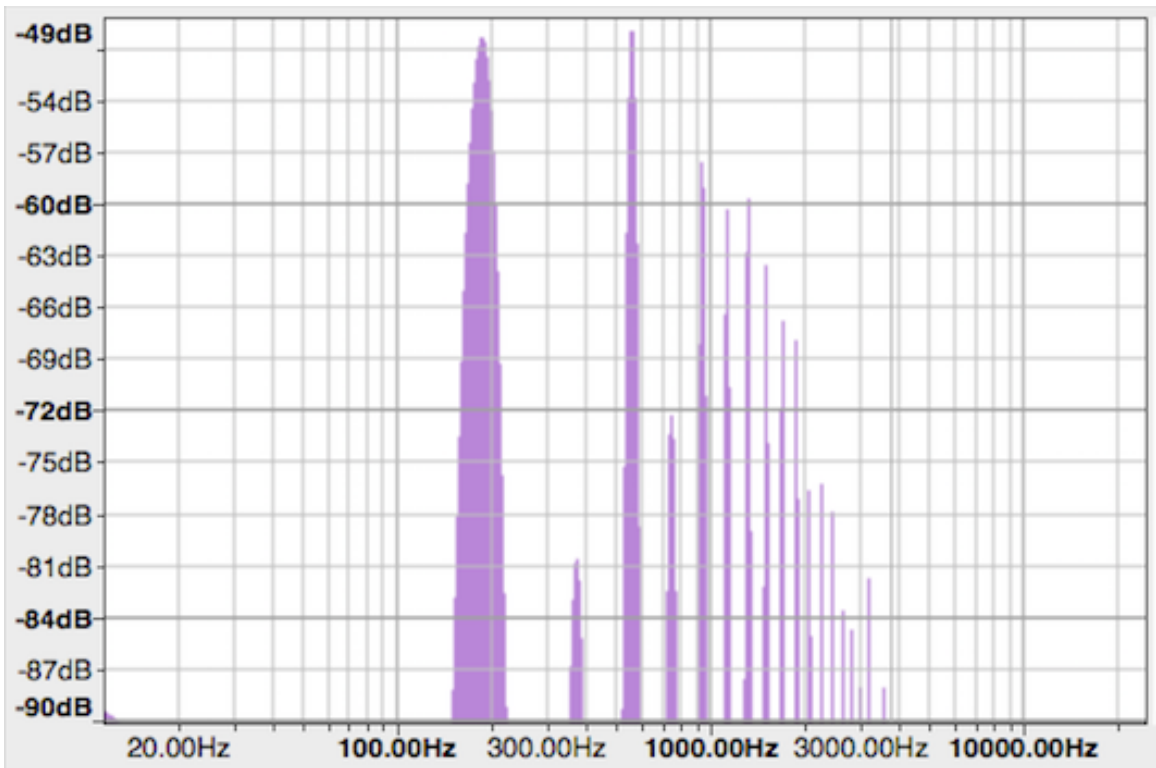
BAR Port



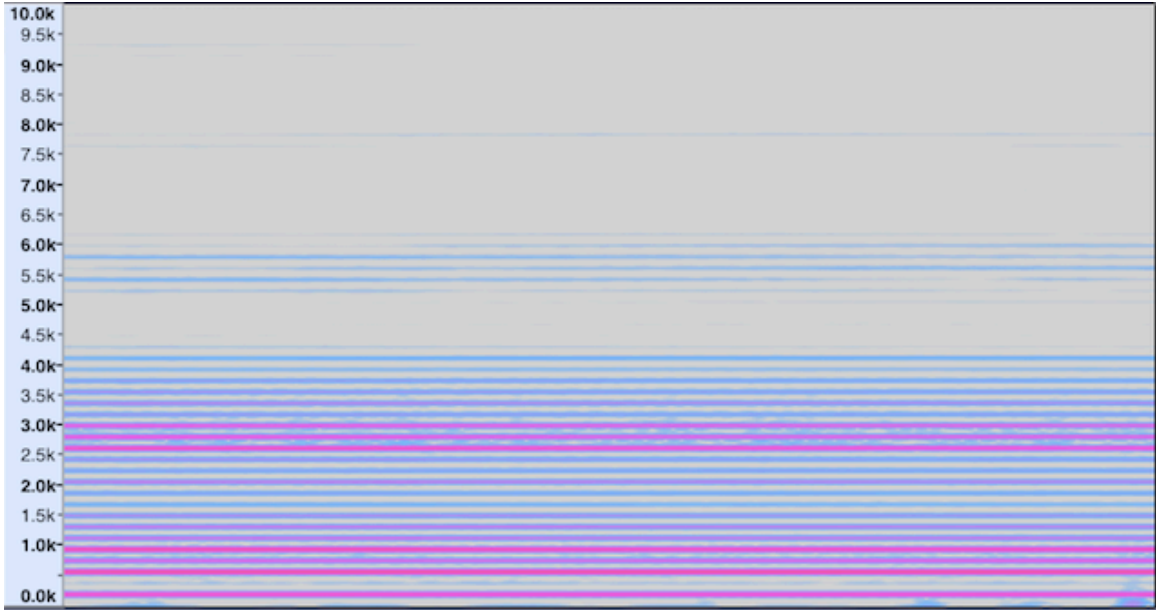
BAR Port



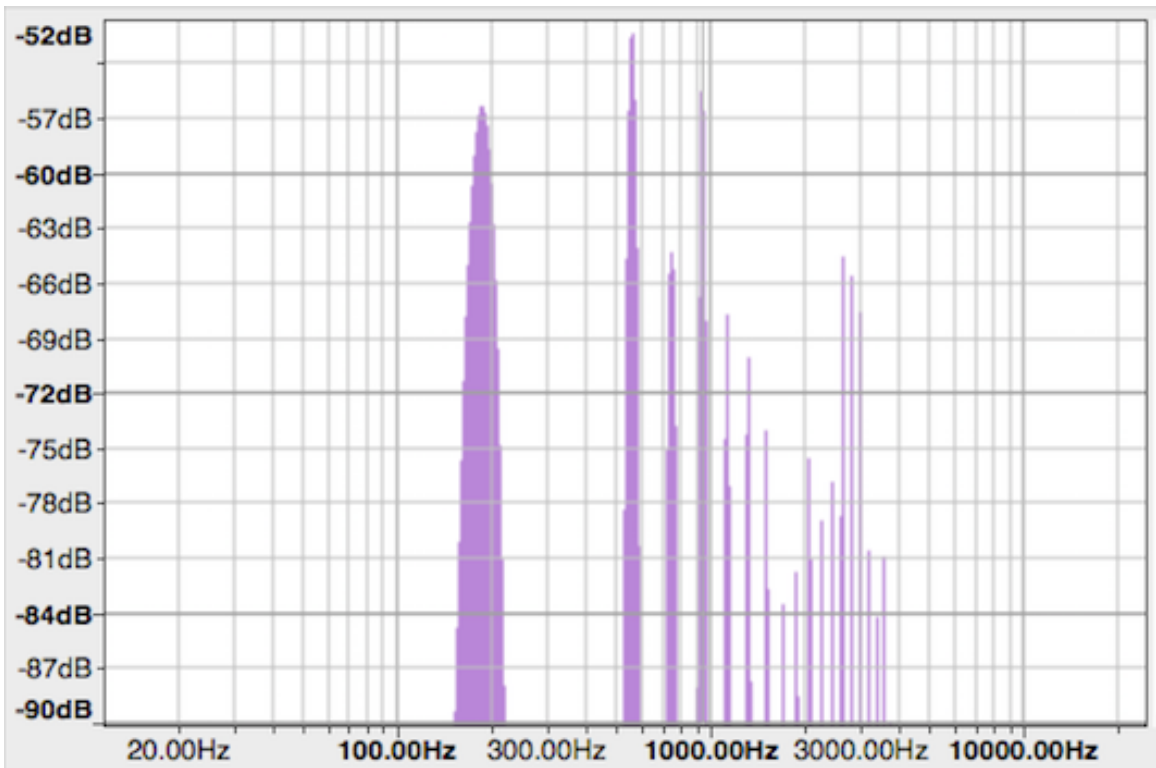
BAR Surf



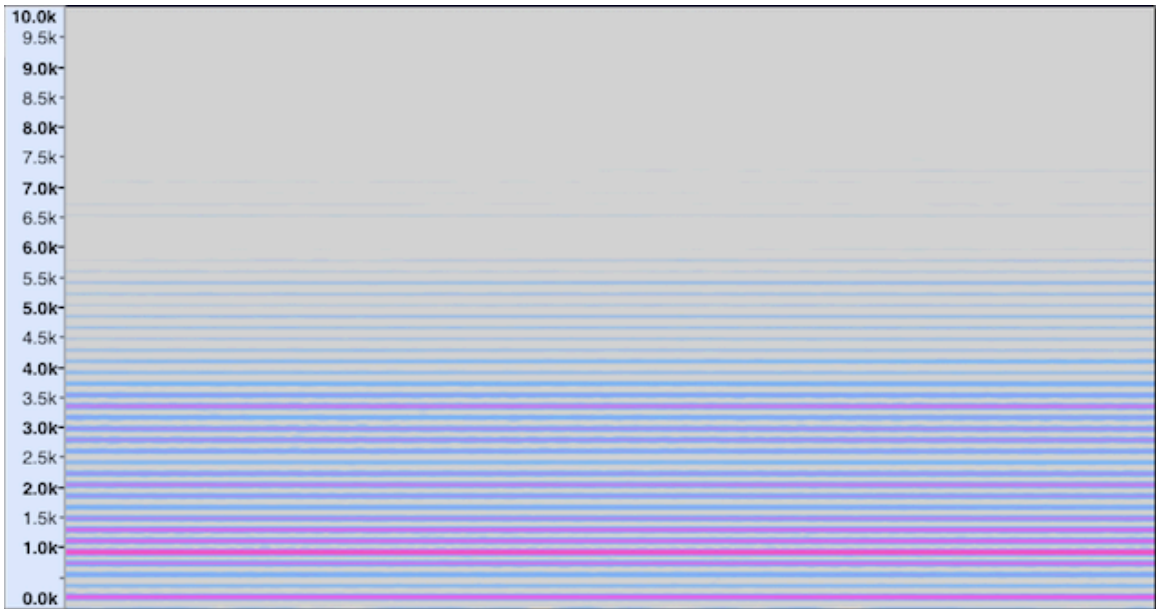
BAR Surf



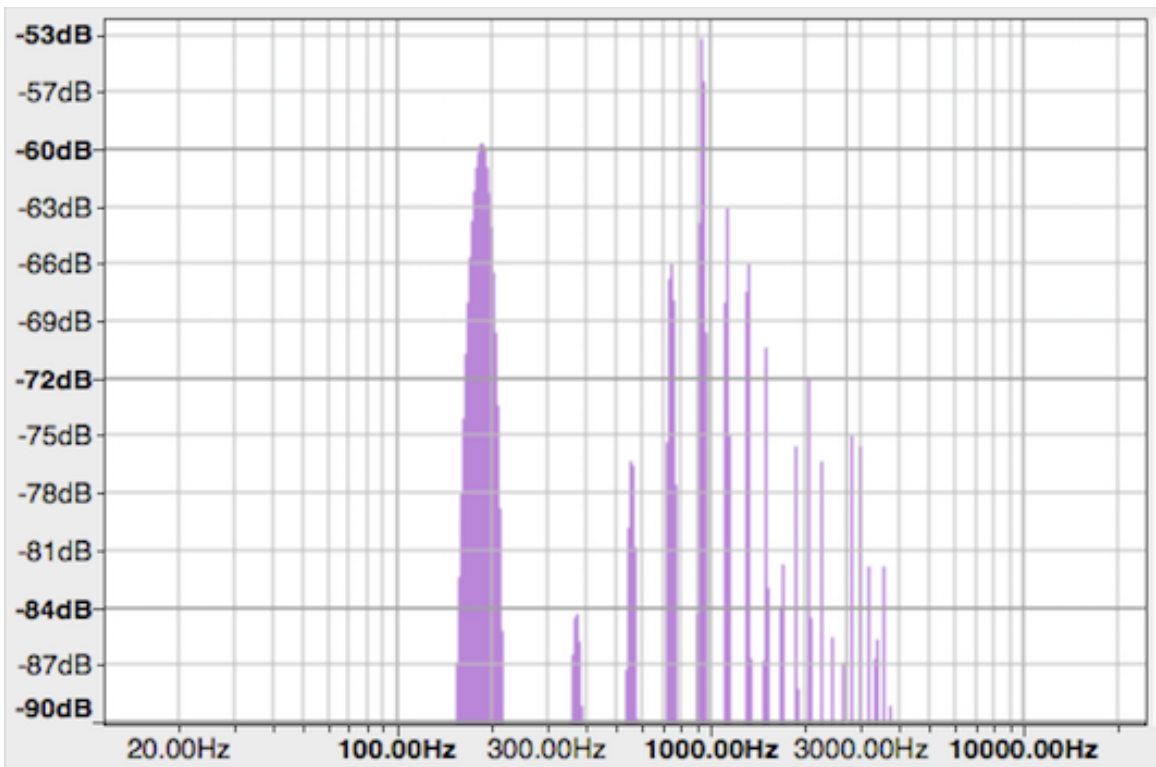
LF MPB



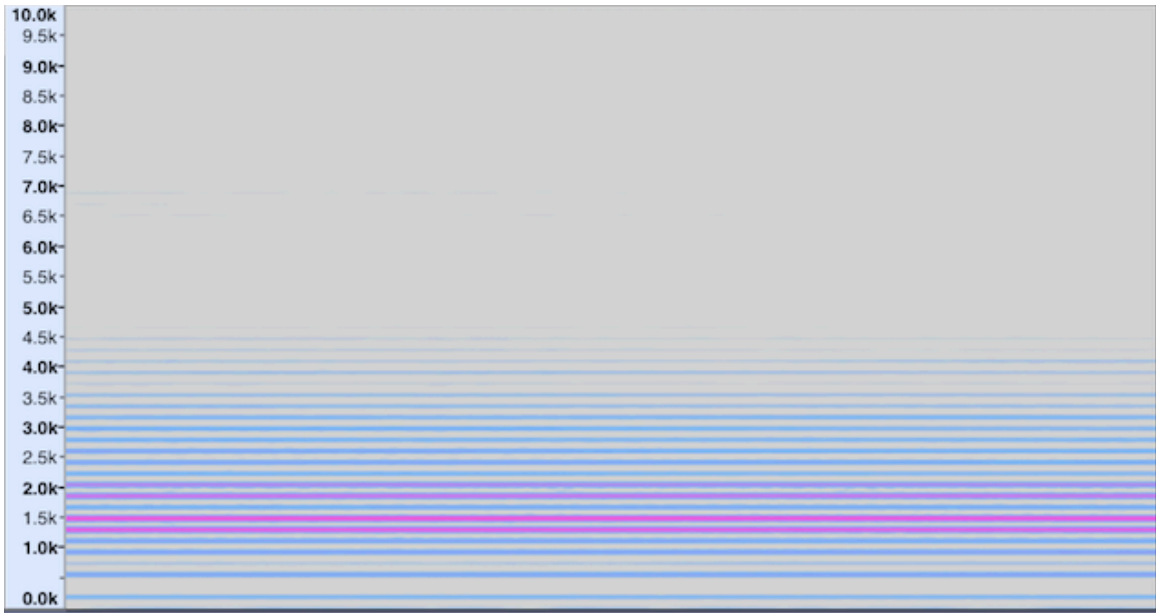
LF MPB



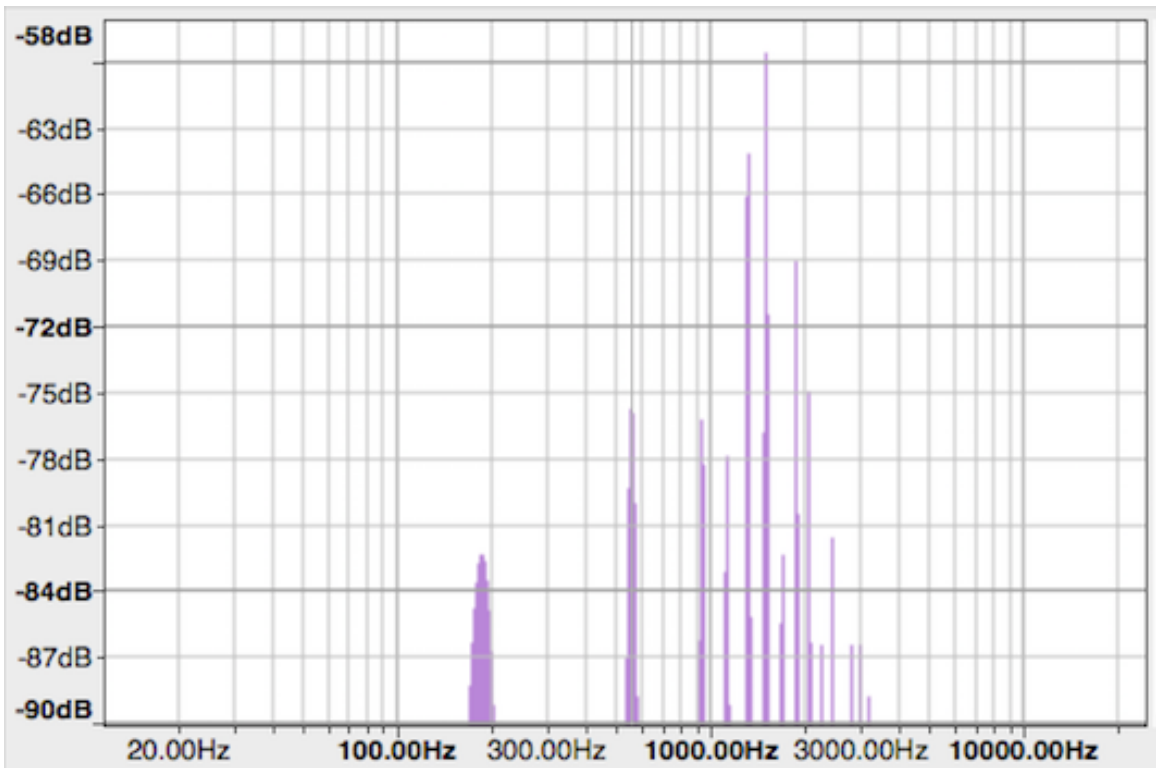
LF BUJ



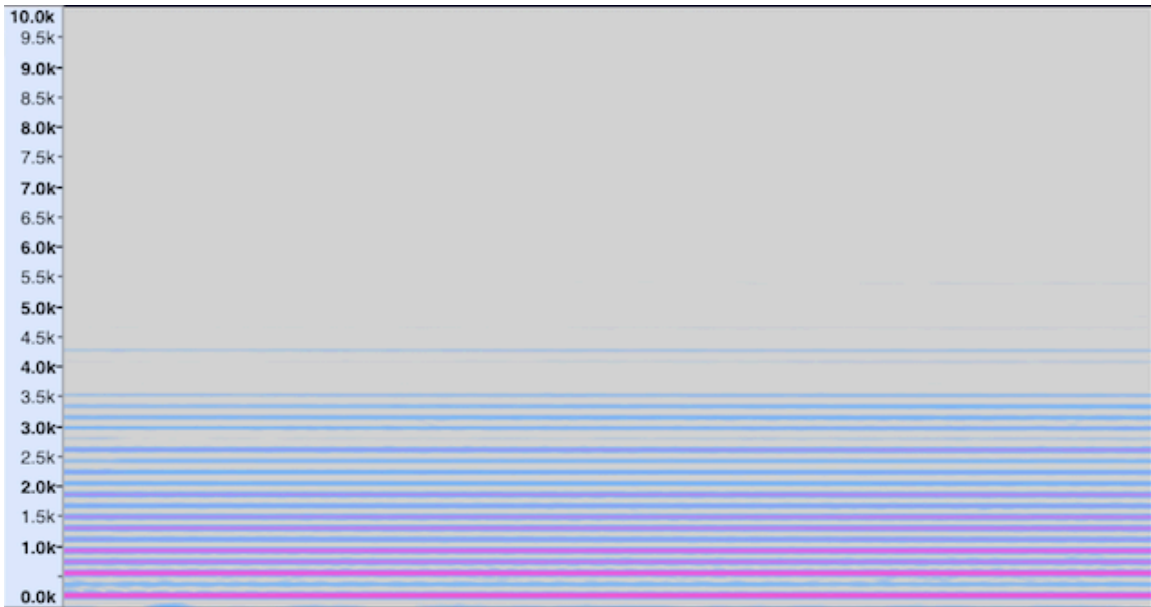
LF BUJ



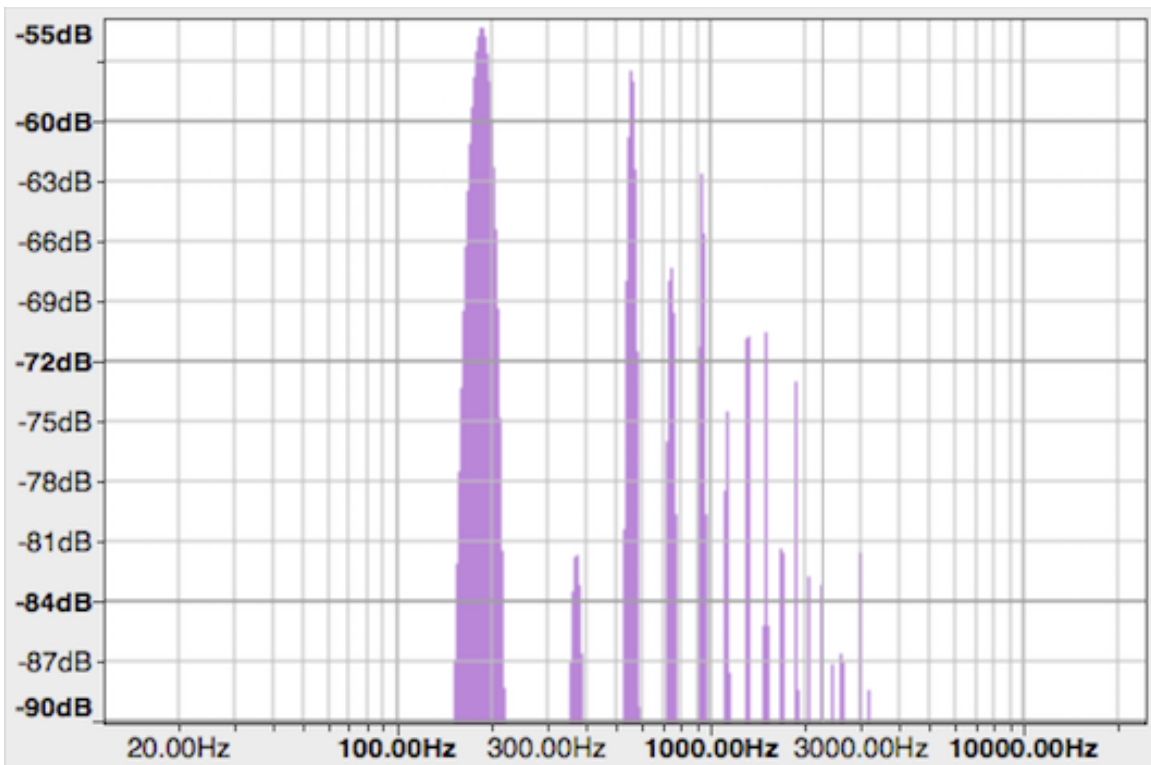
UJ



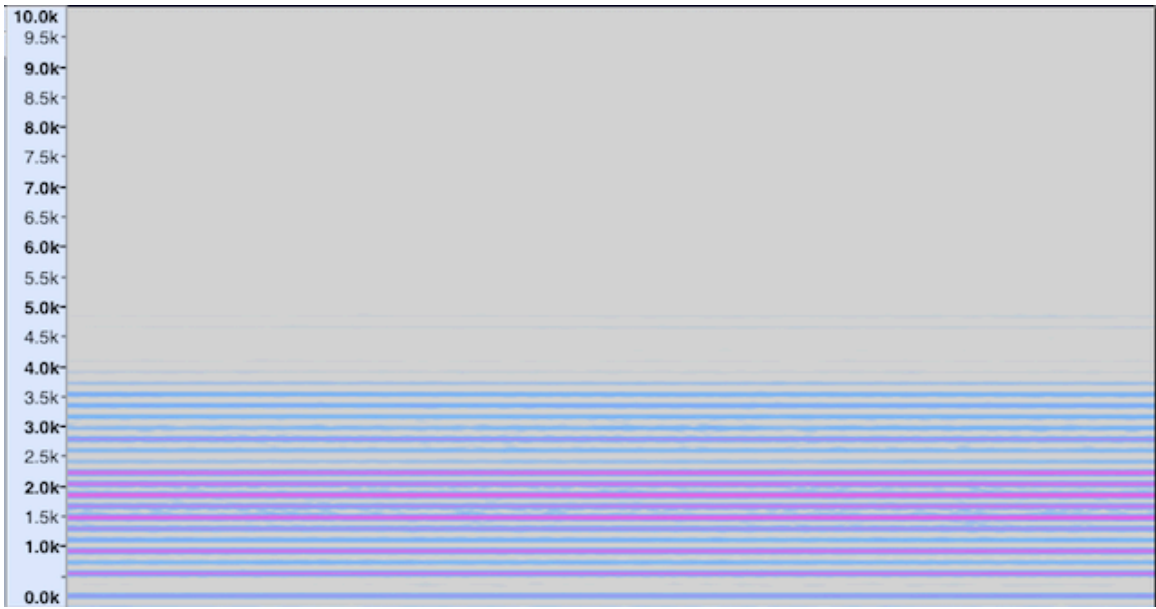
UJ



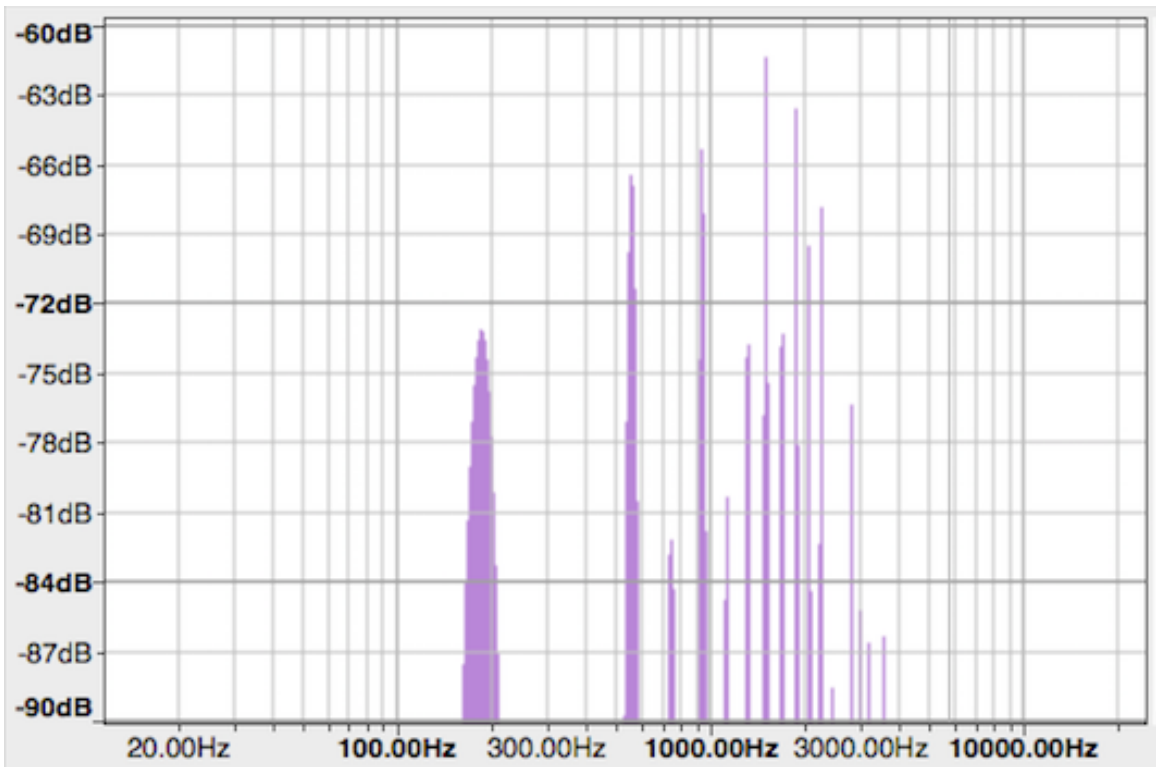
CTR



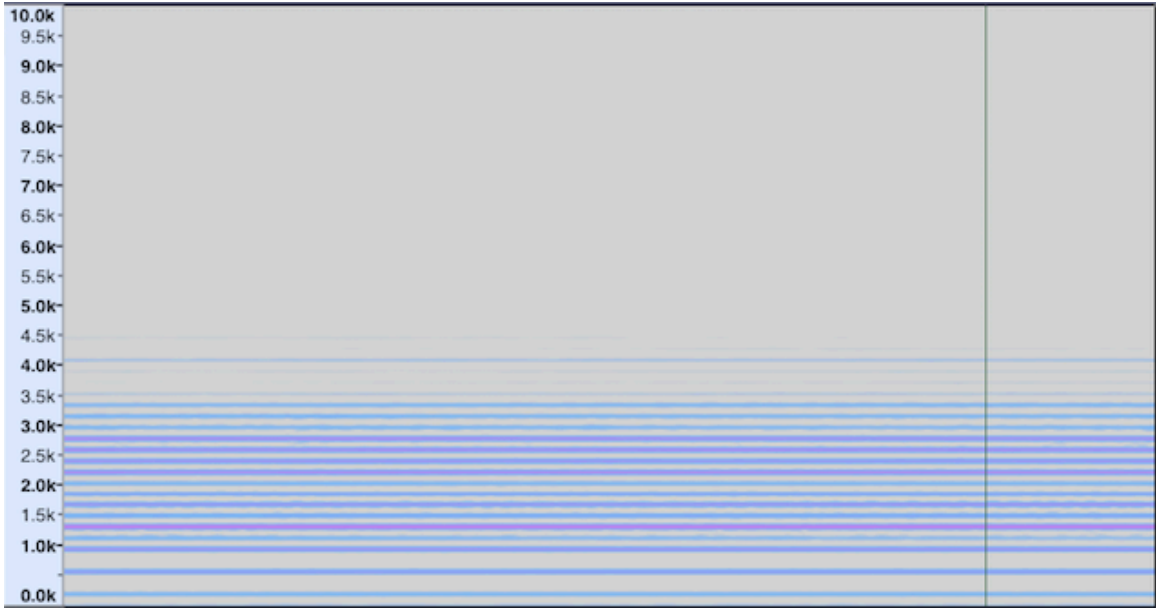
CTR



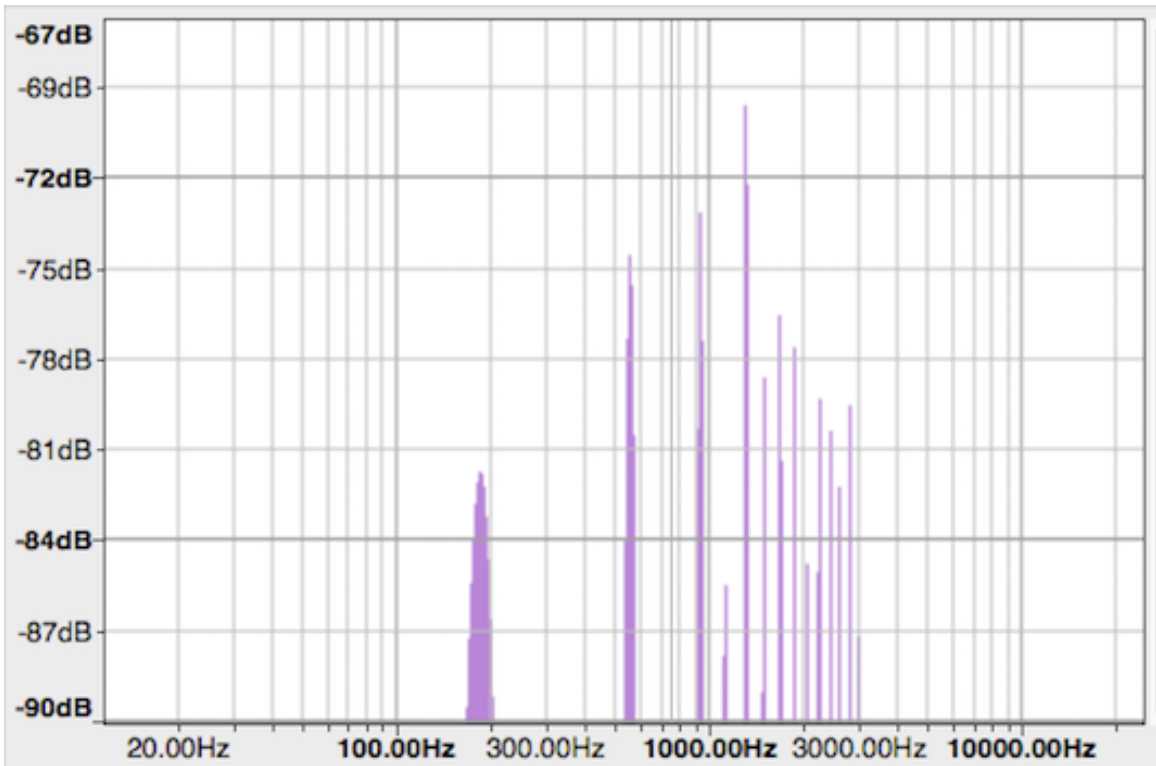
LJ



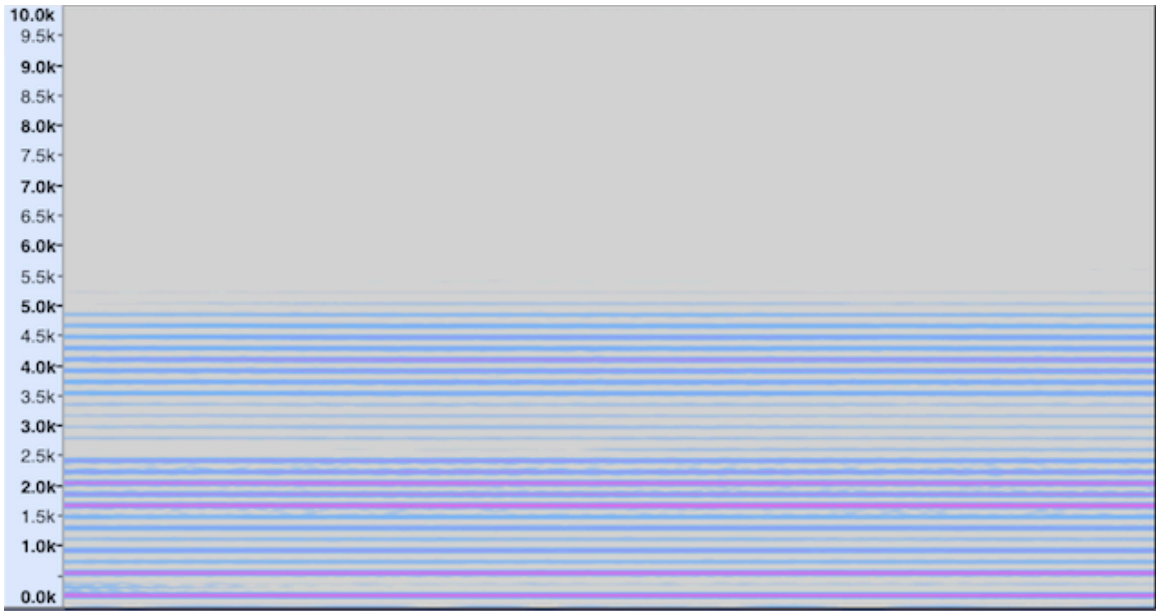
LJ



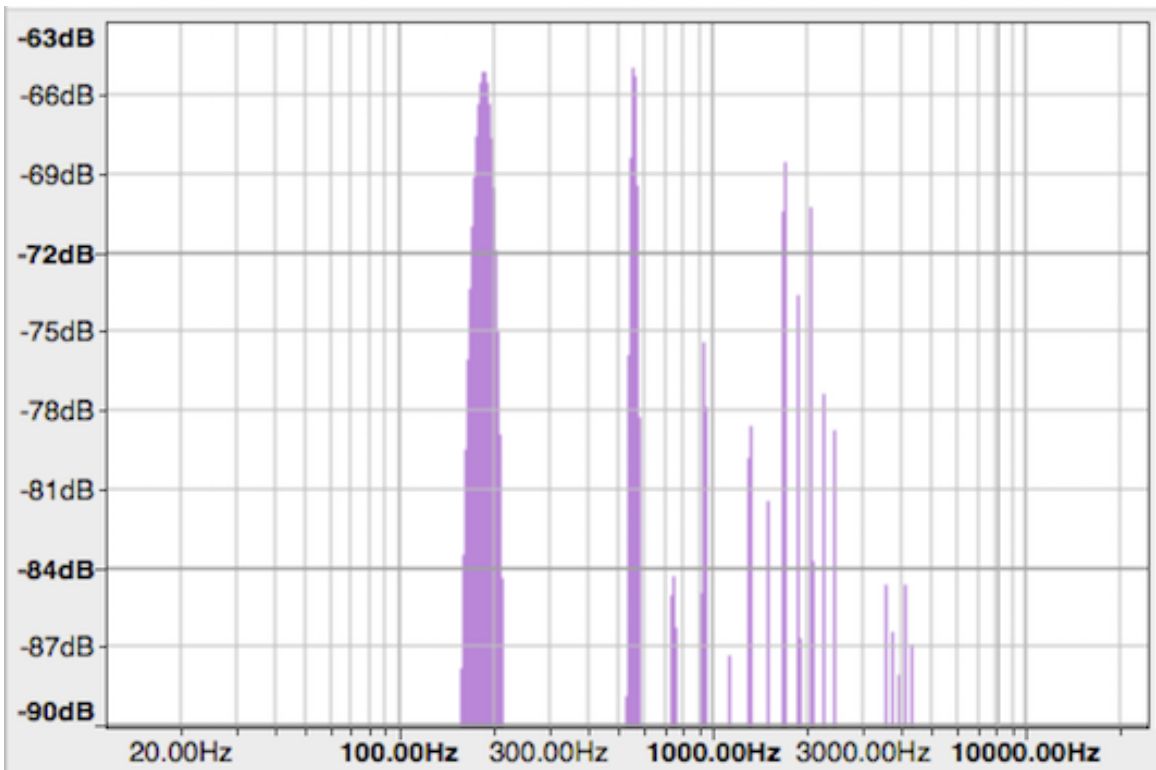
BELL Out



BELL Out

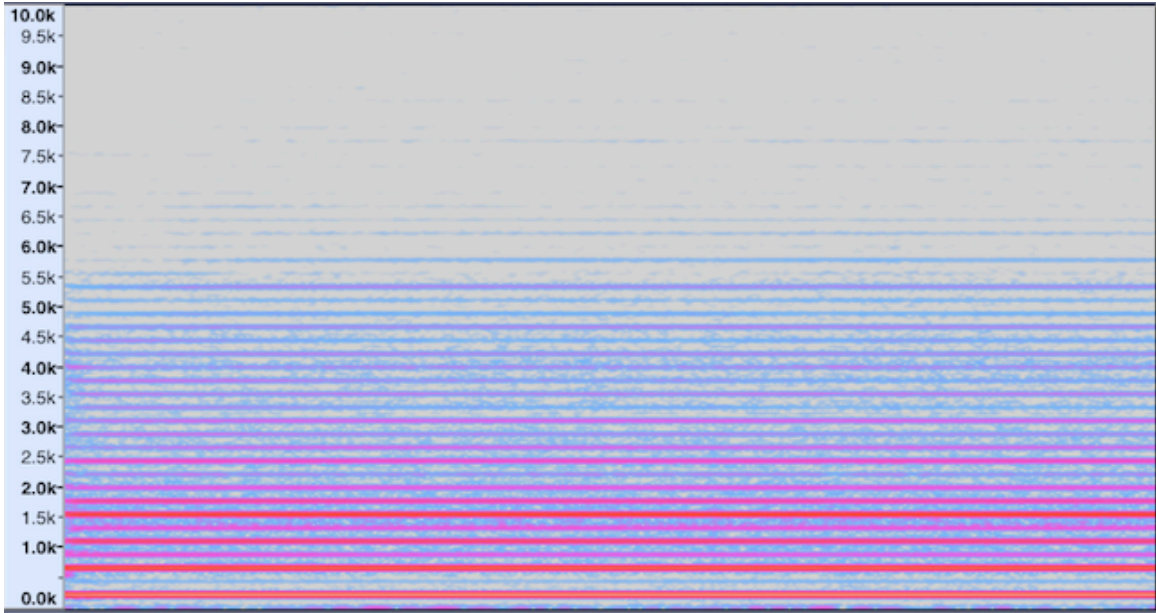


BELL End

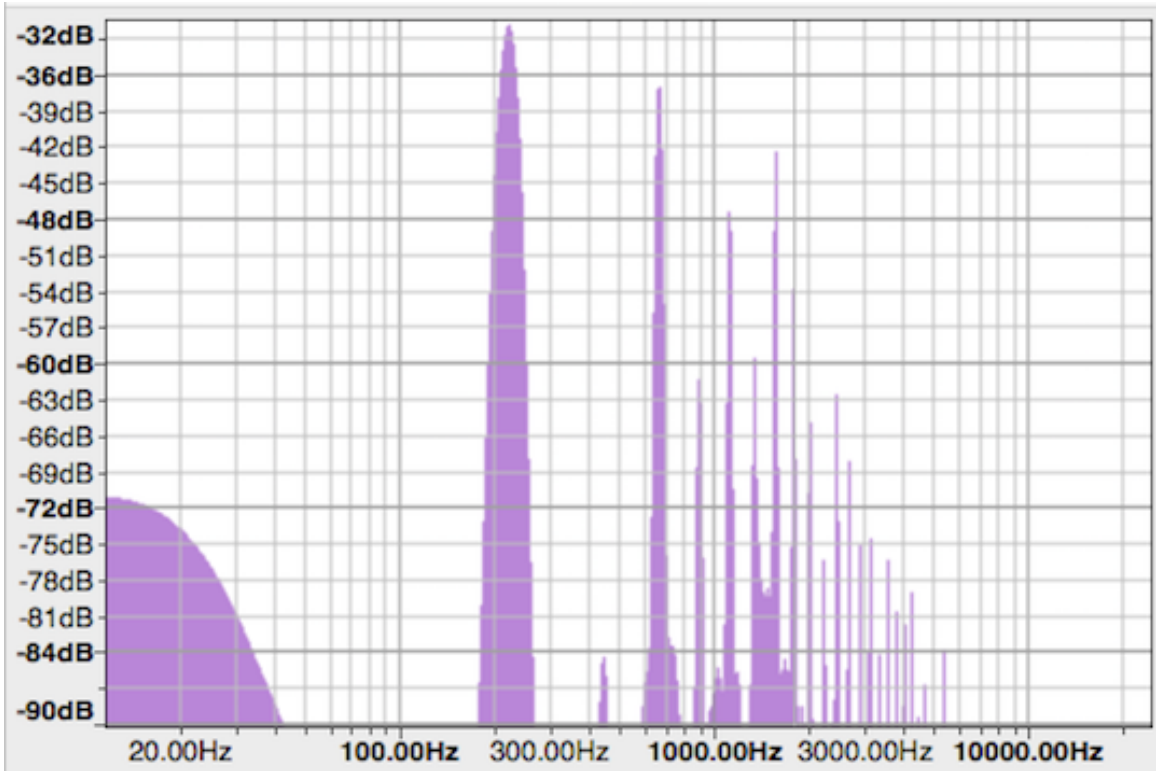


BELL End

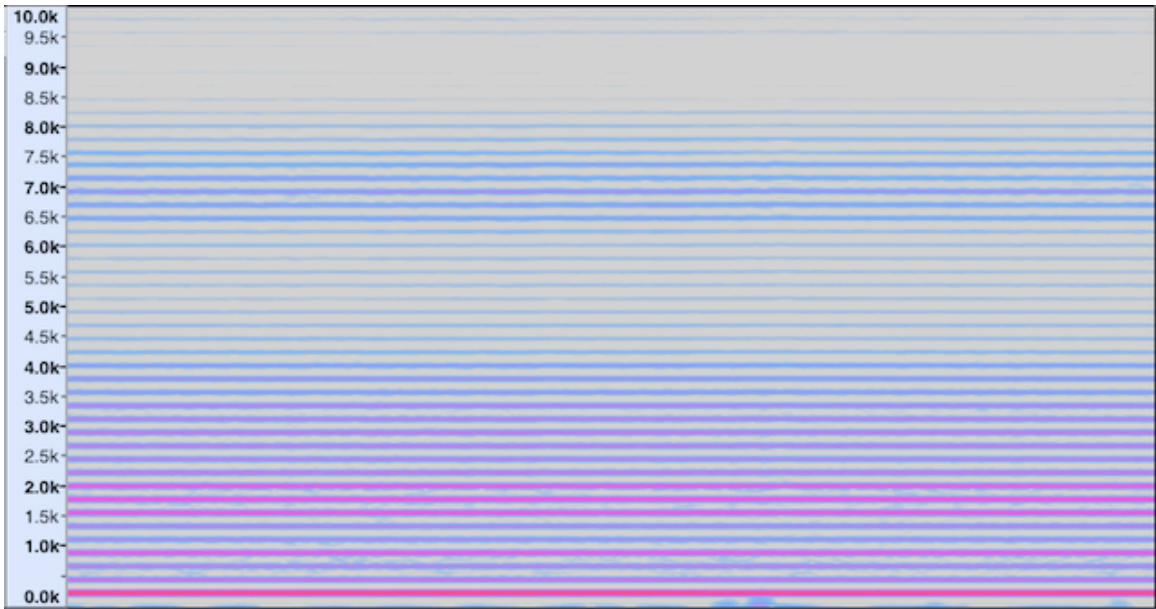
APPENDIX G  
SAMPLE DATA B3



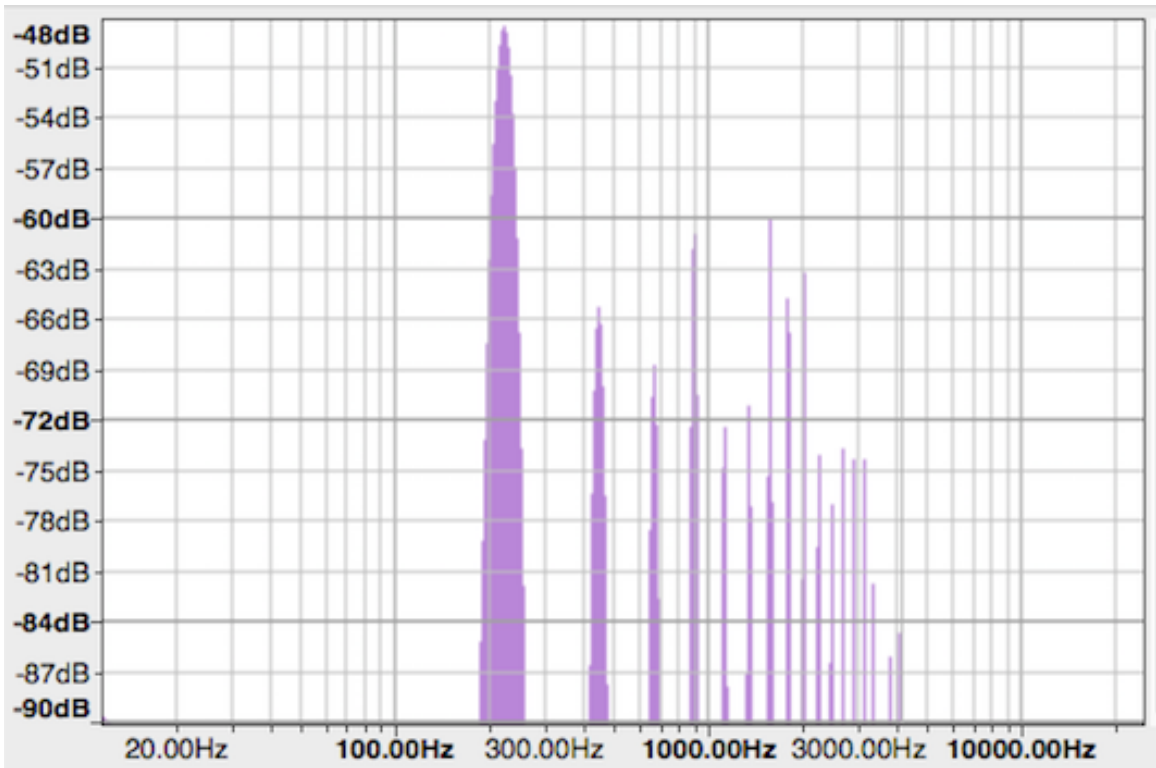
M30 (Reference)



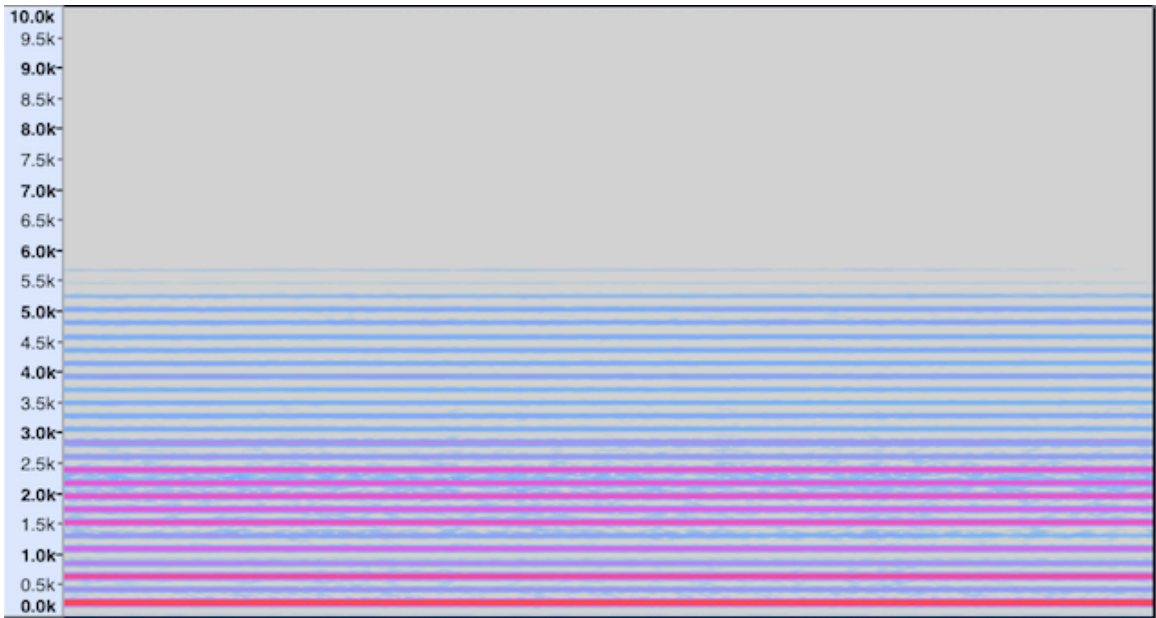
M30 (Reference)



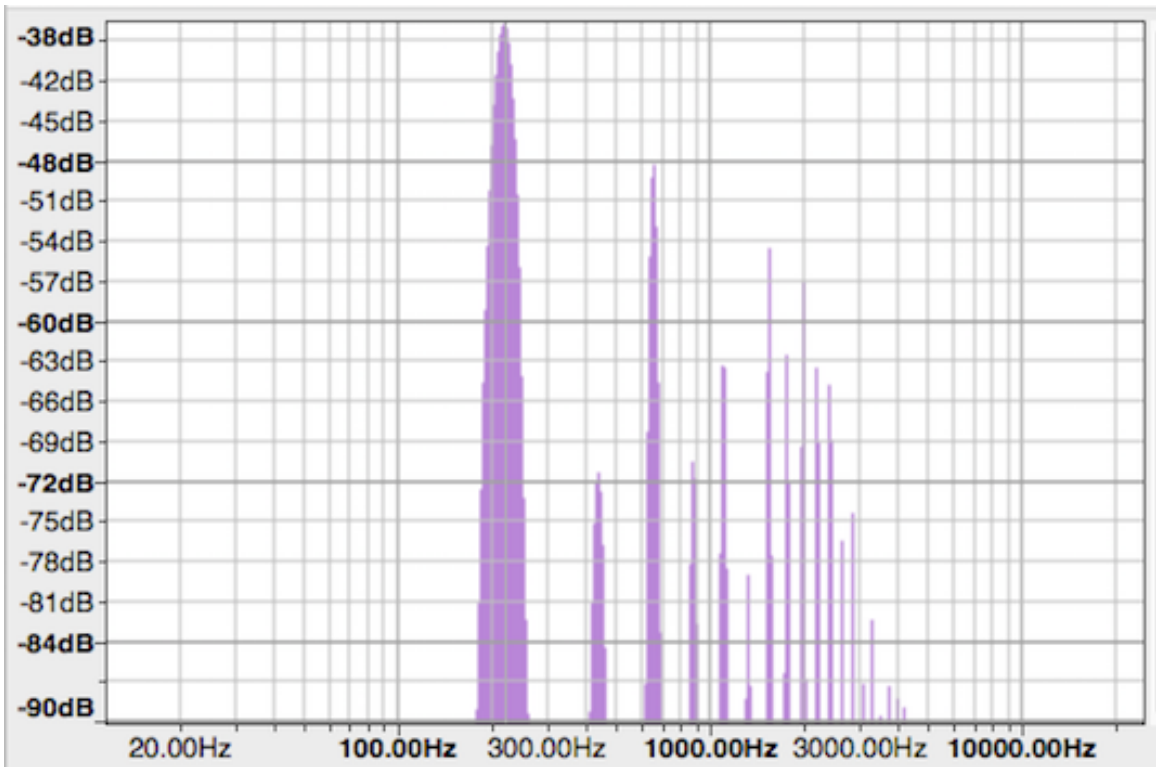
LIG



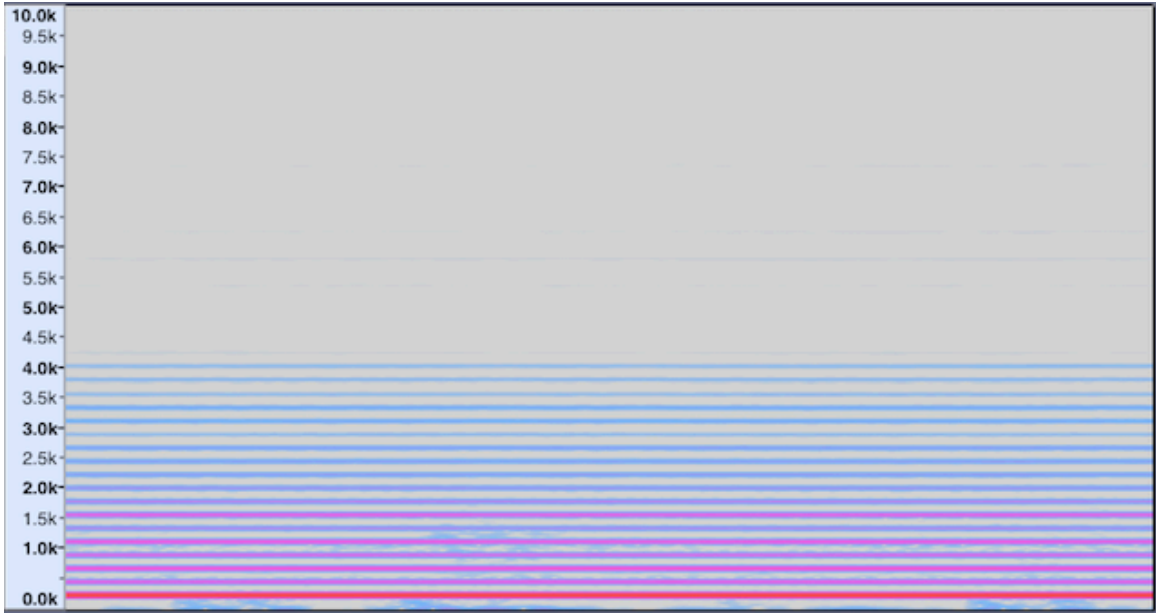
LIG



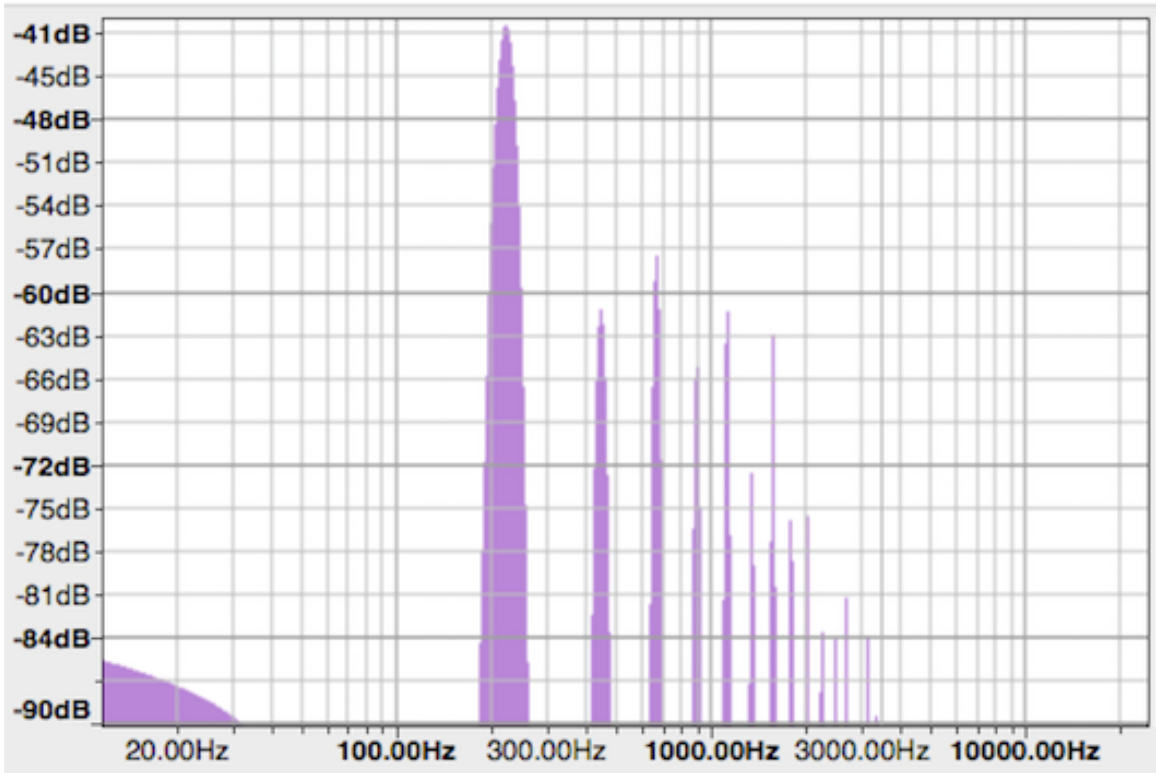
BAR Port



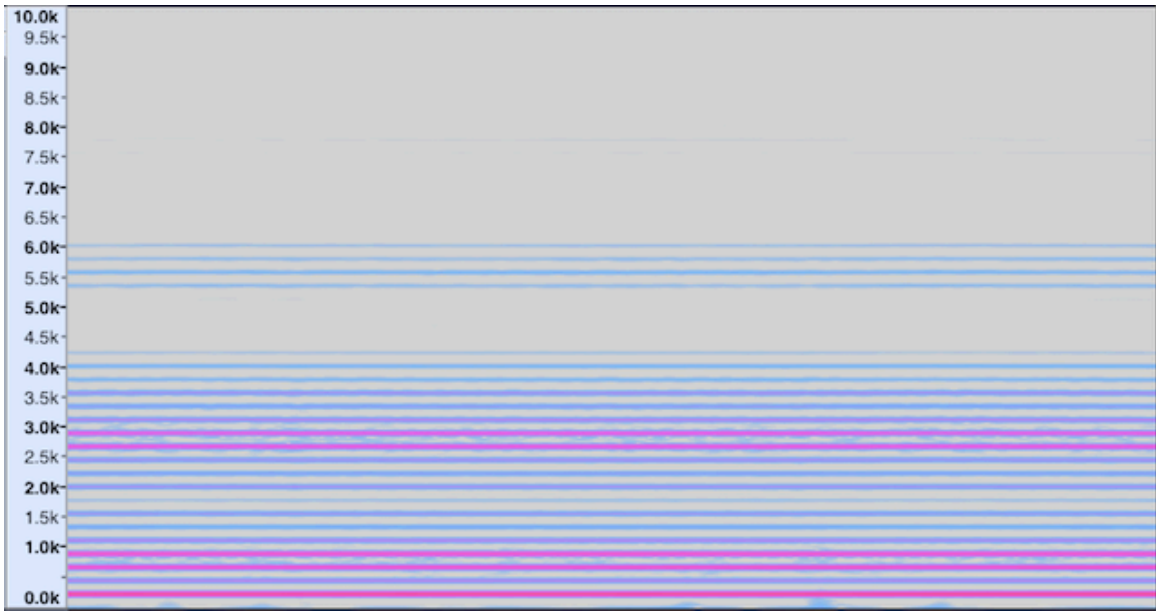
BAR Port



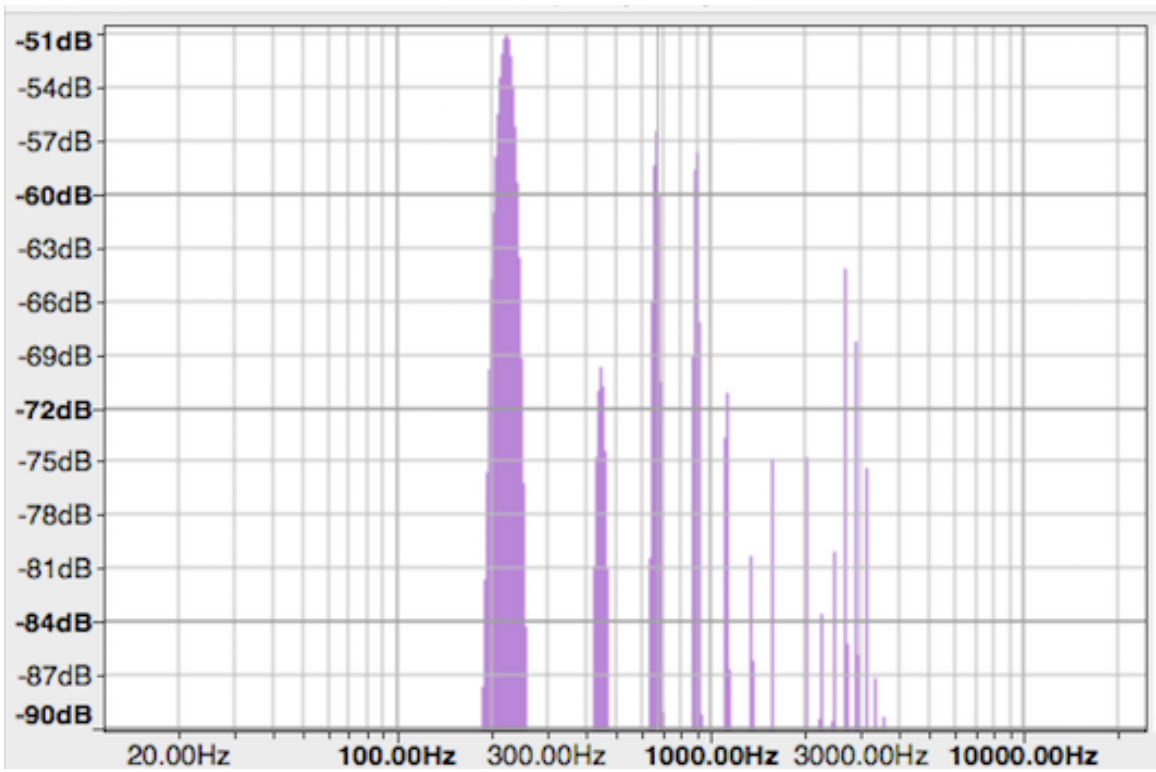
BAR Surf



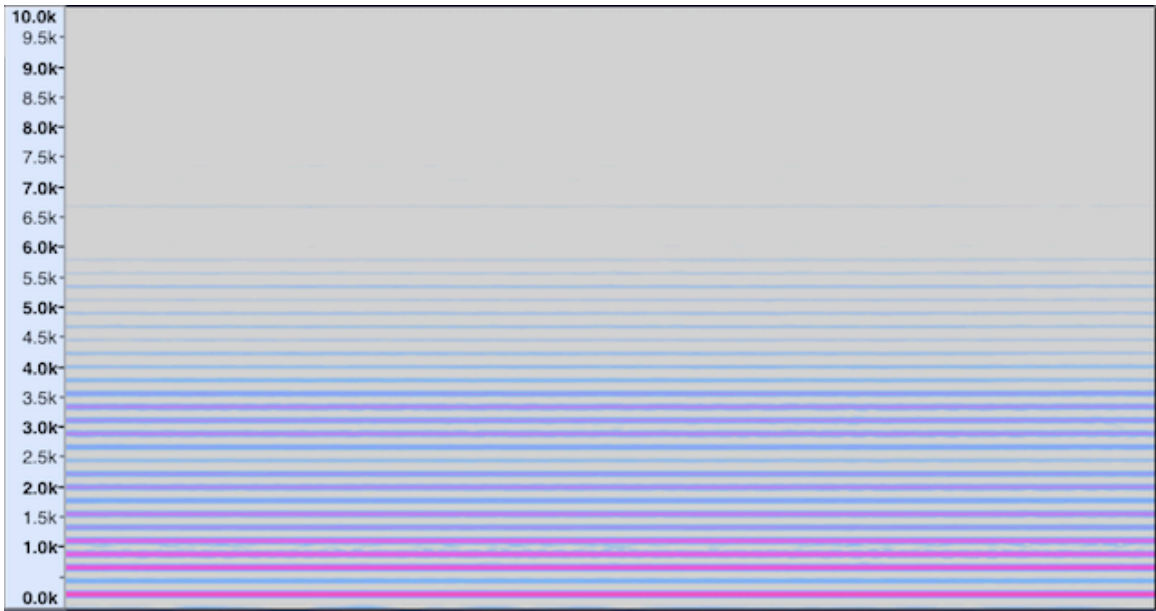
BAR Surf



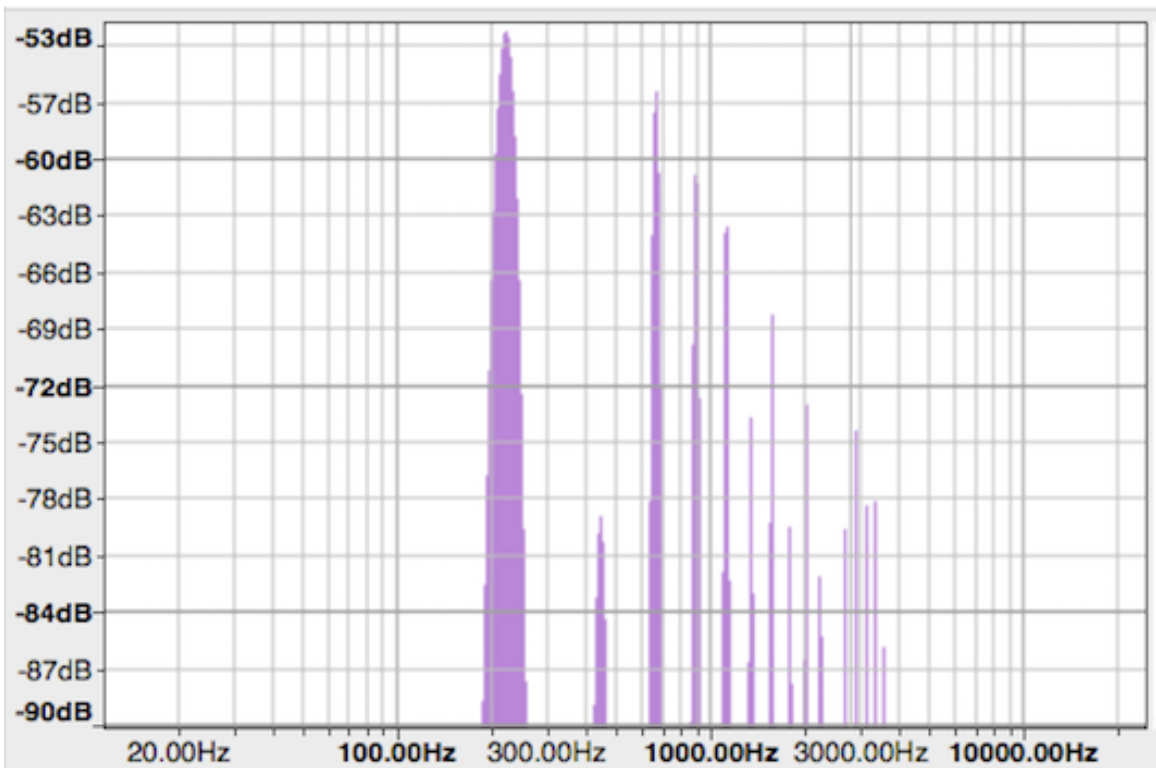
LF MPB



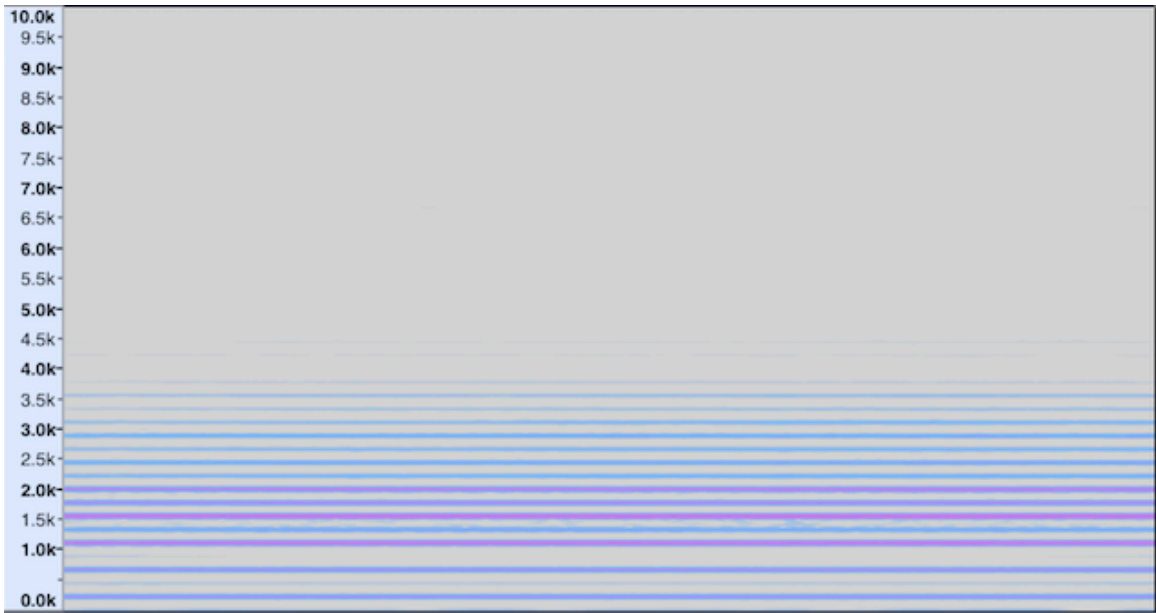
LF MPB



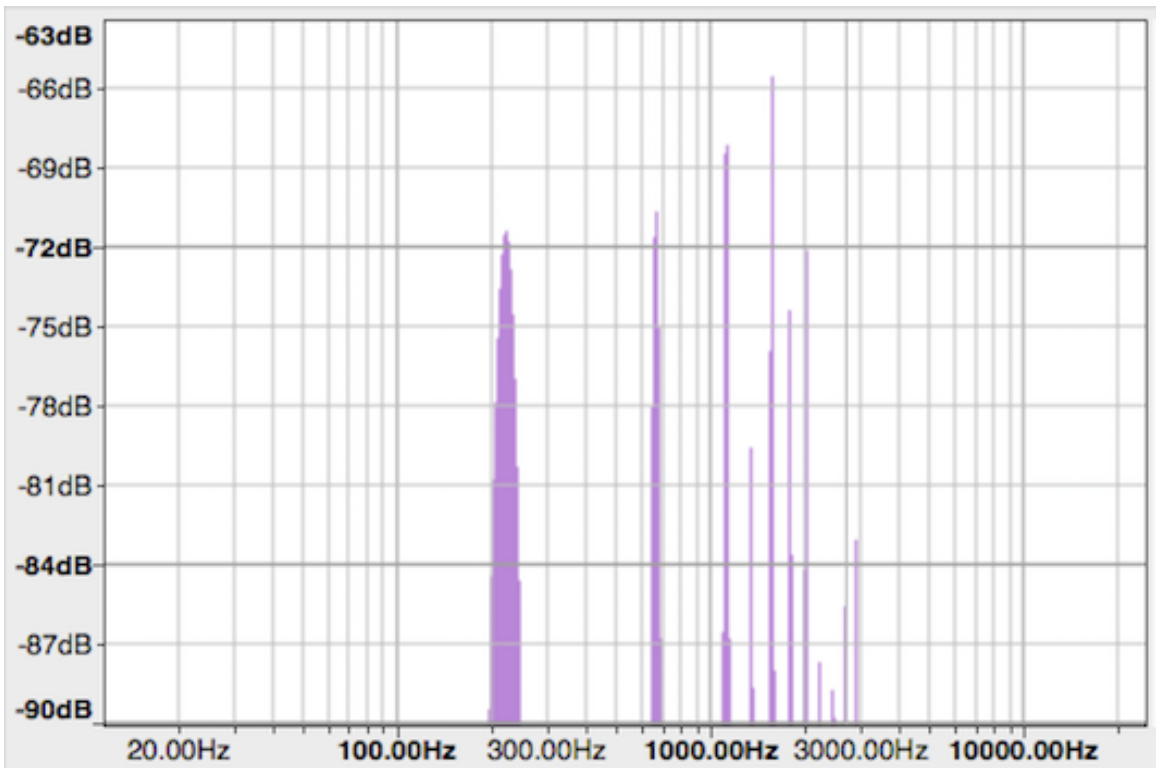
LF BUJ



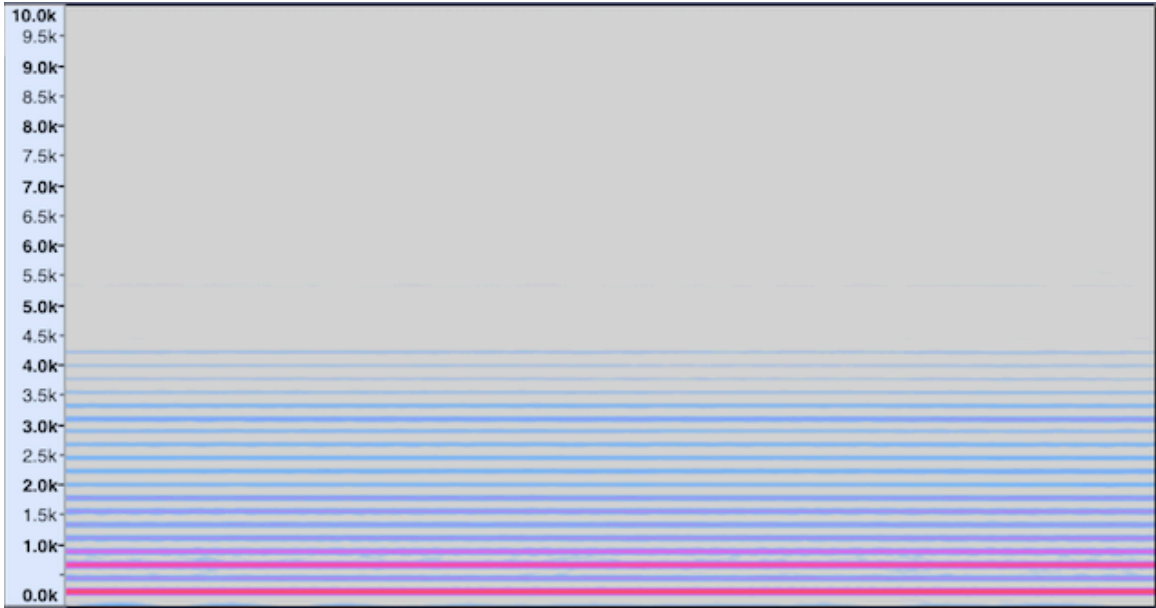
LF BUJ



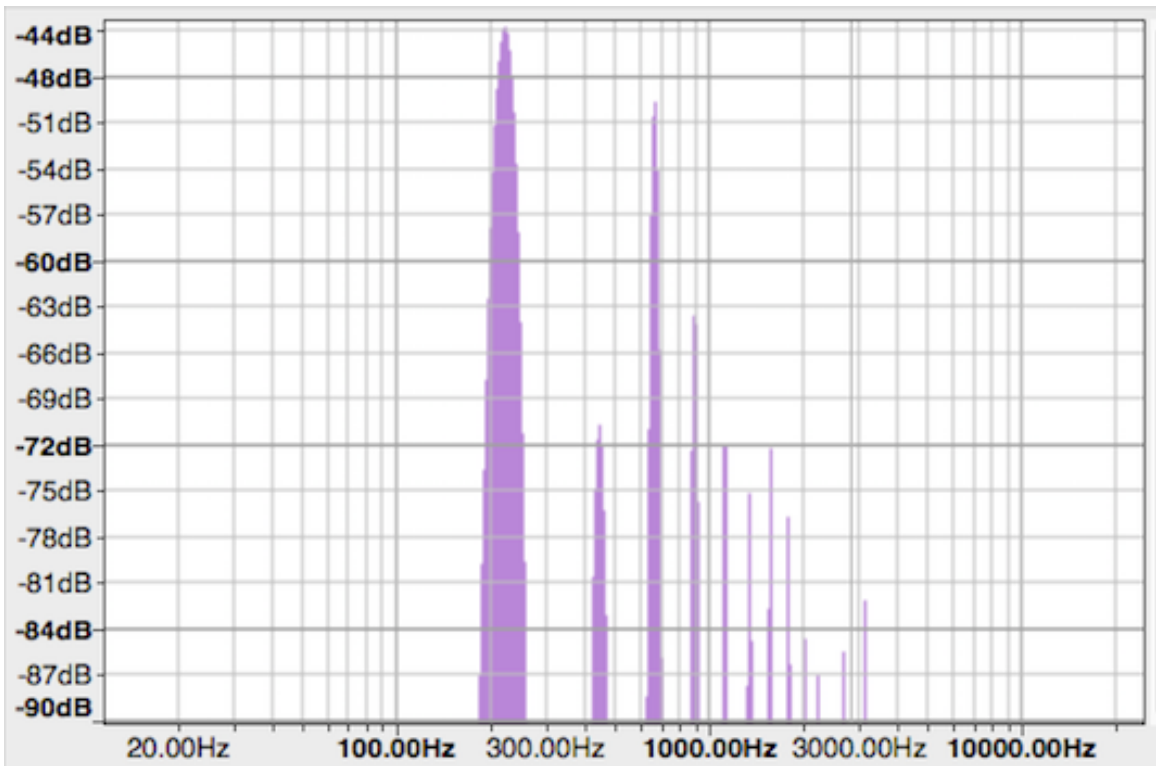
UJ



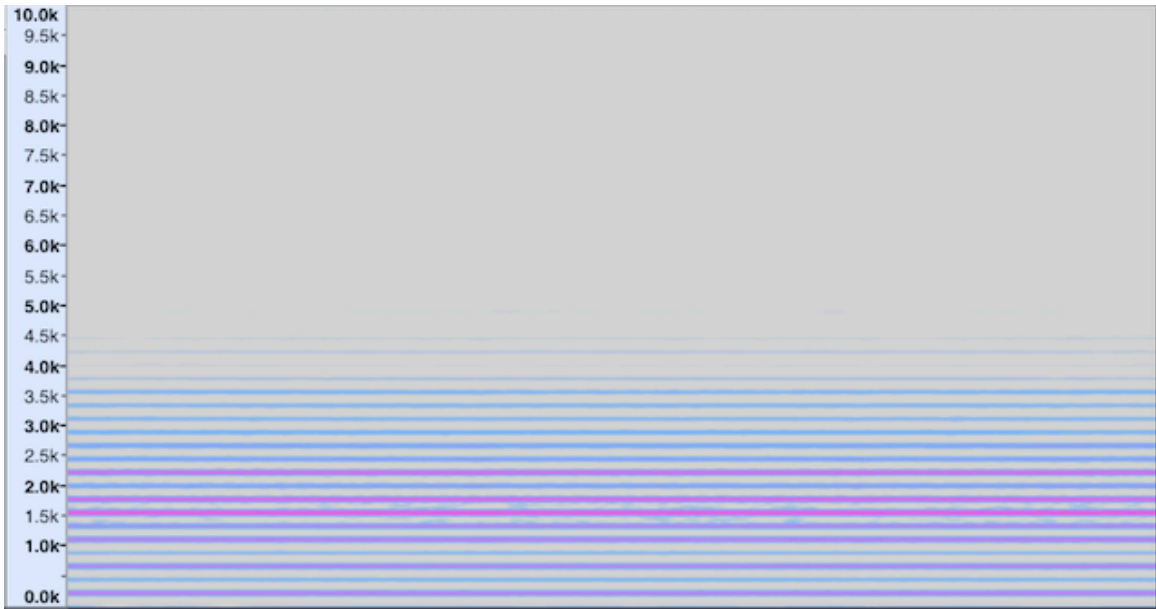
UJ



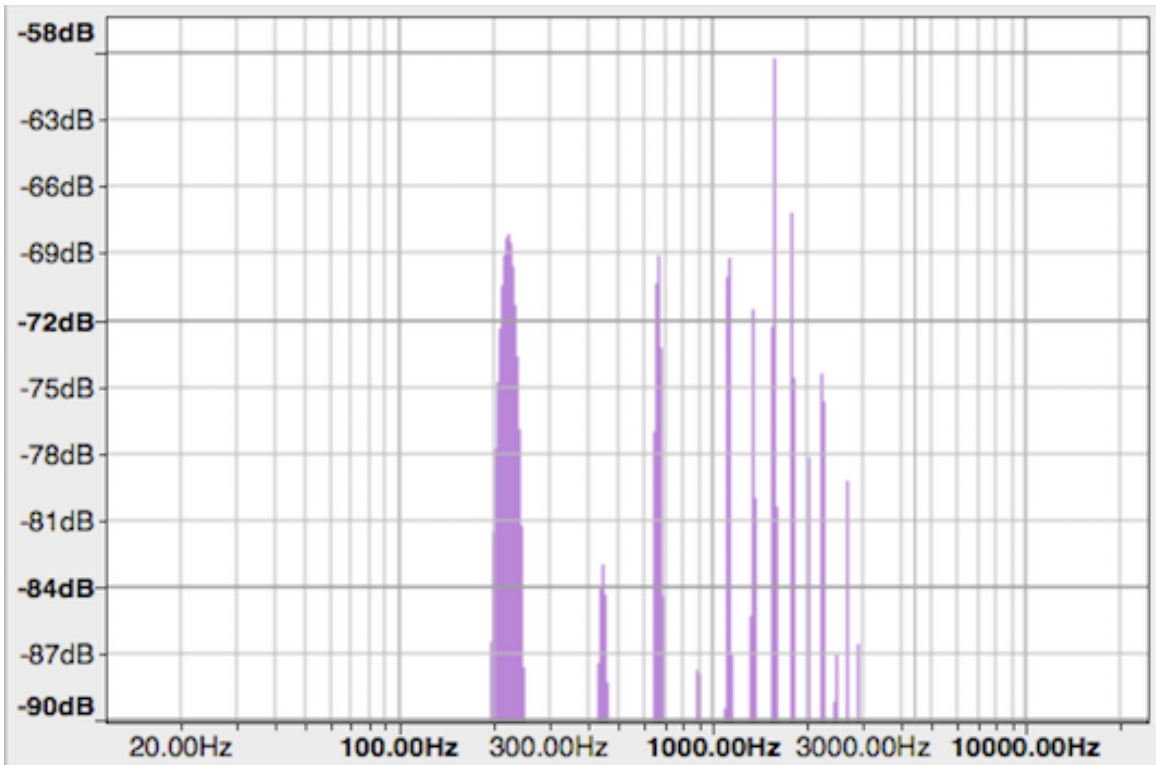
CTR



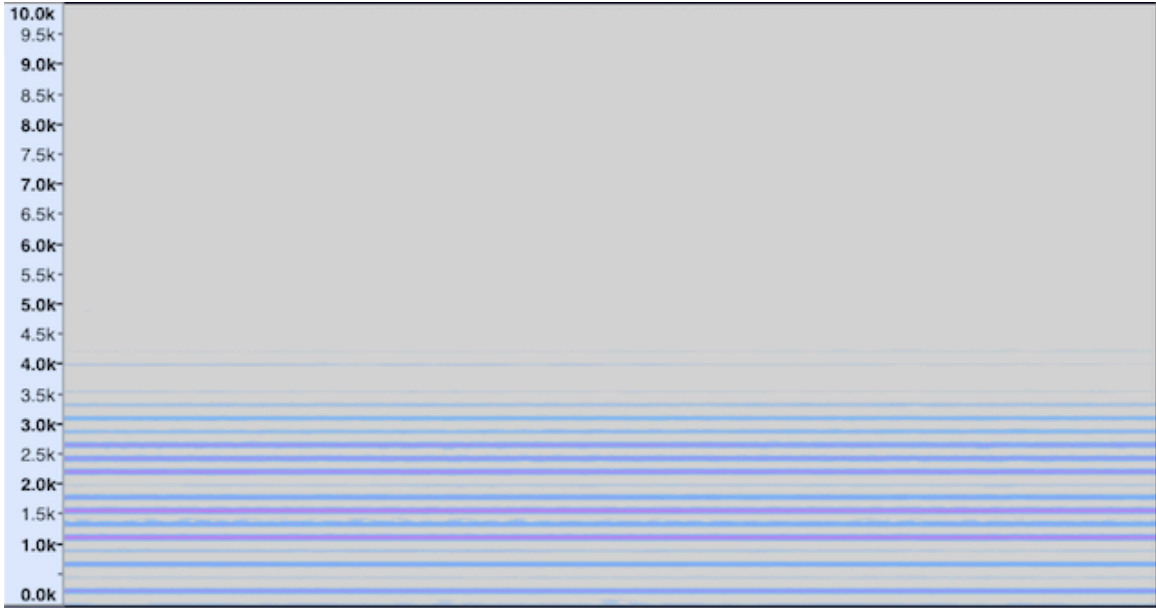
CTR



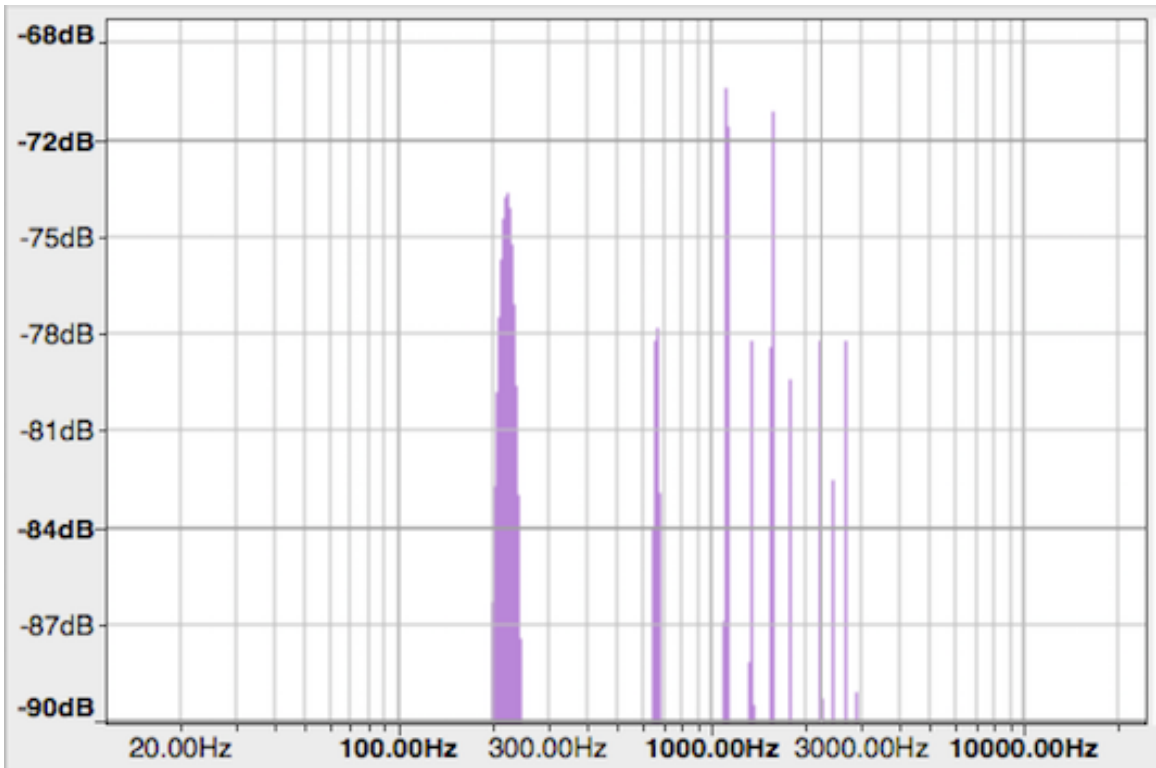
LJ



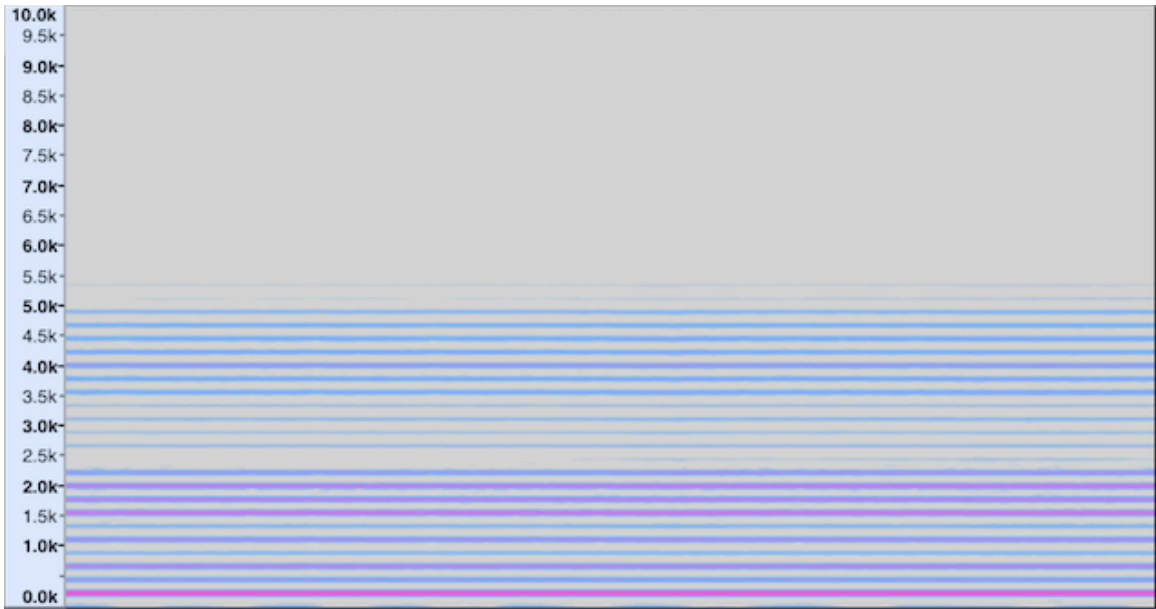
LJ



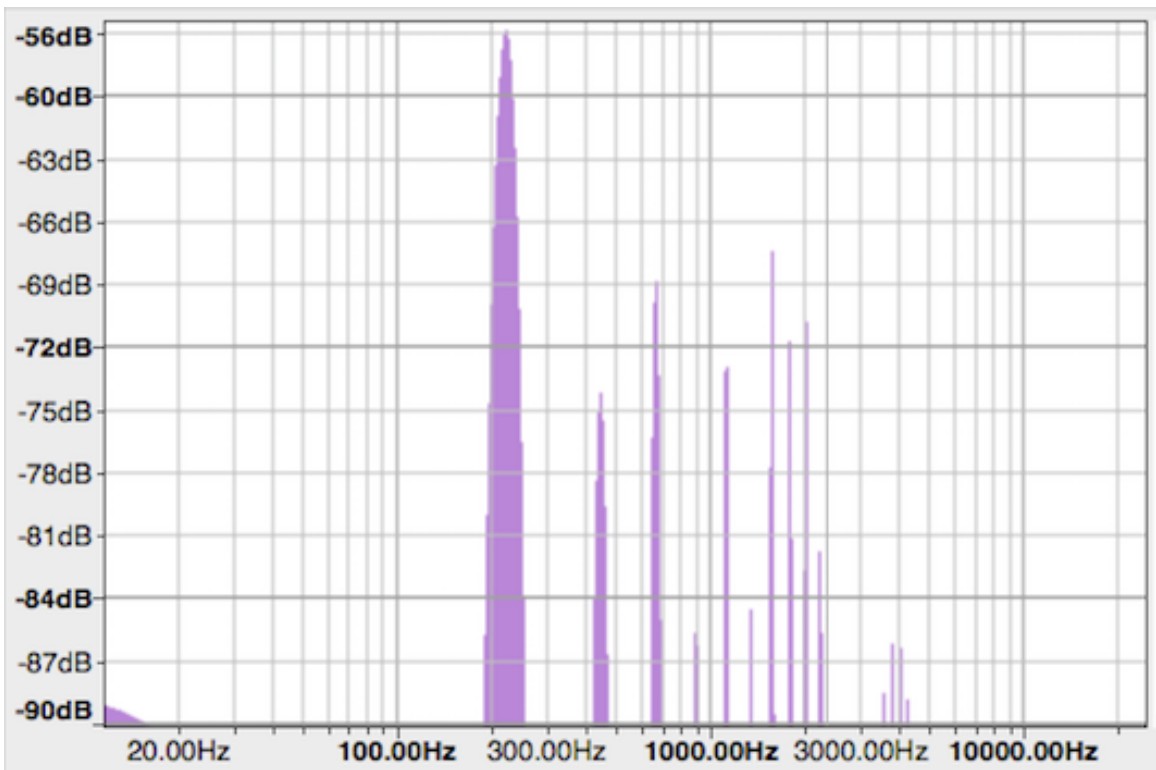
BELL Out



BELL Out

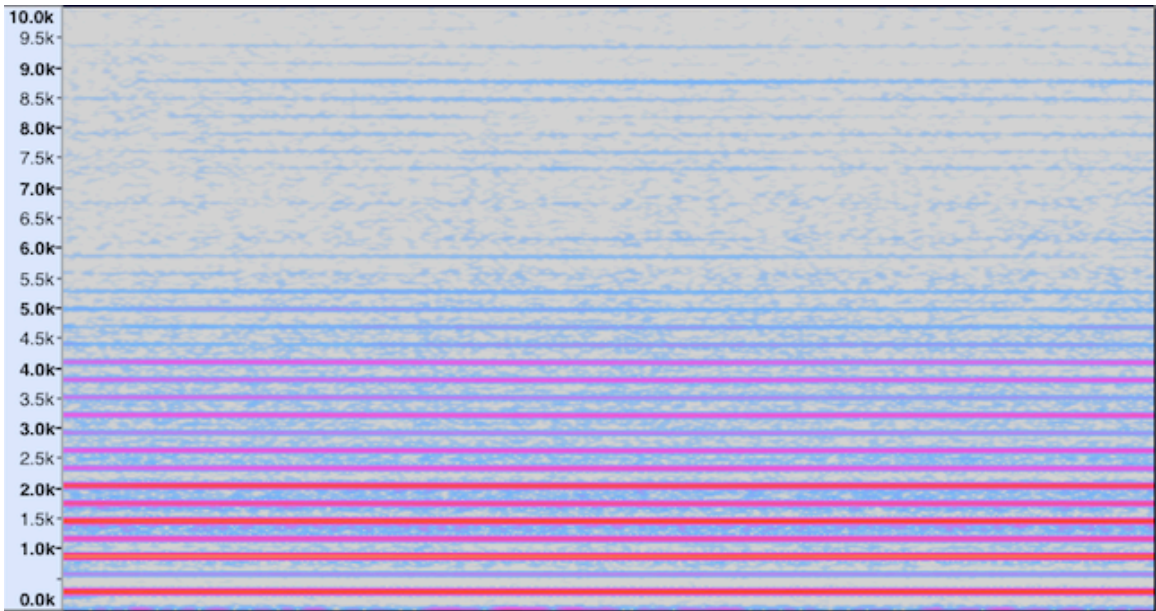


BELL End

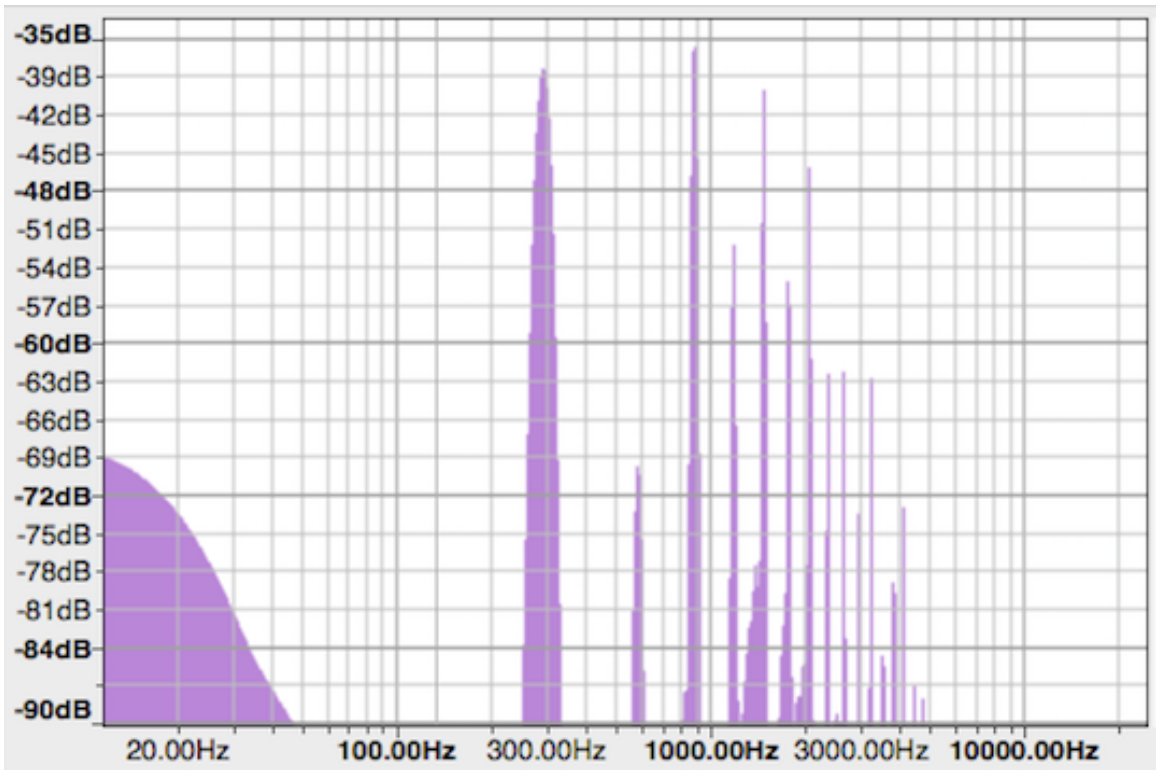


BELL End

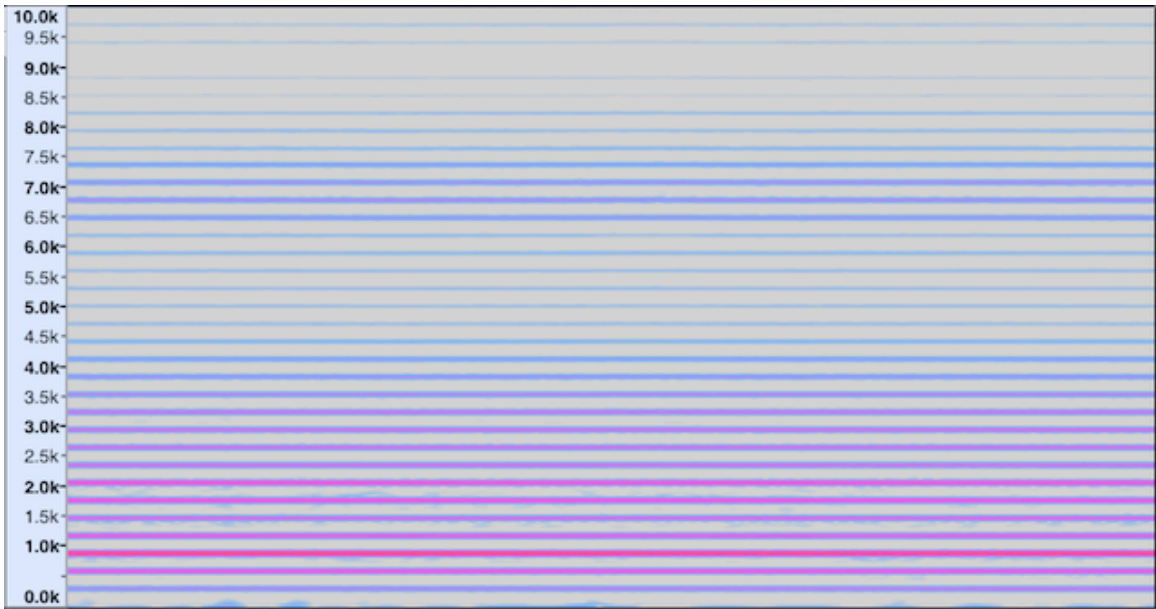
APPENDIX H  
SAMPLE DATA E4



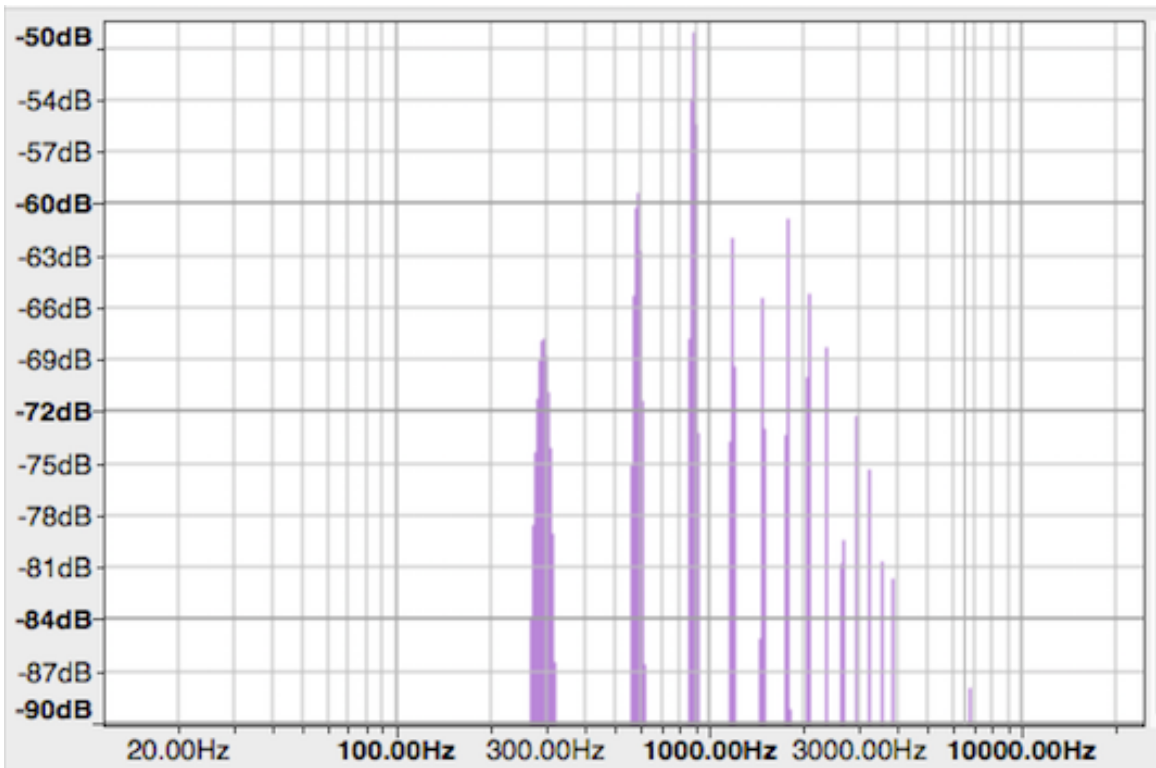
M30 (Reference)



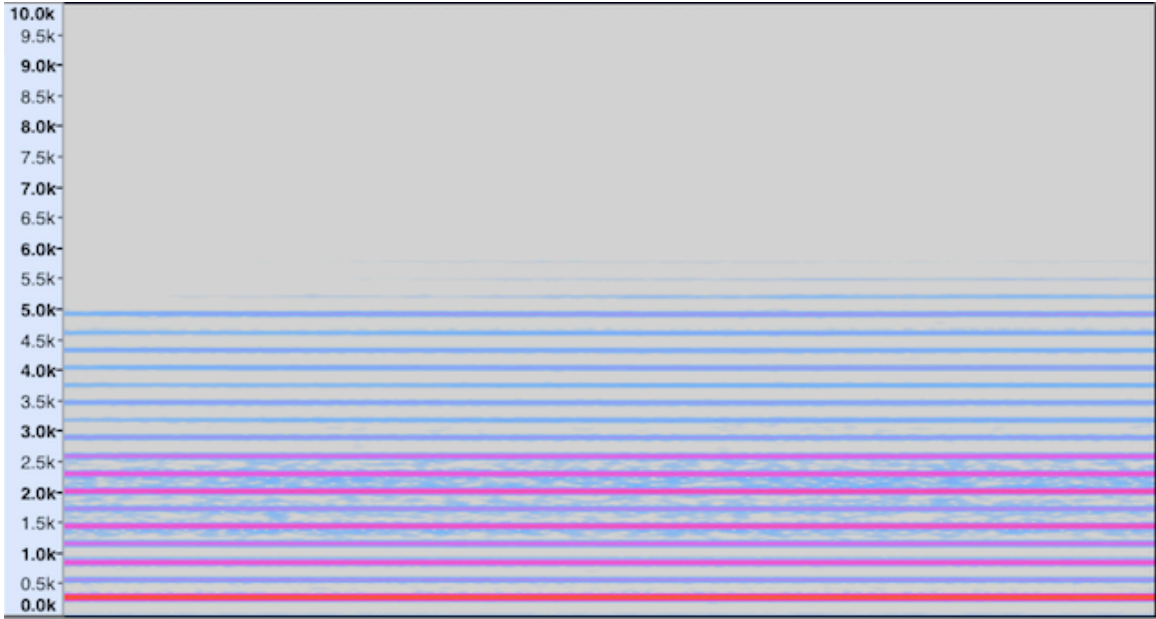
M30 (Reference)



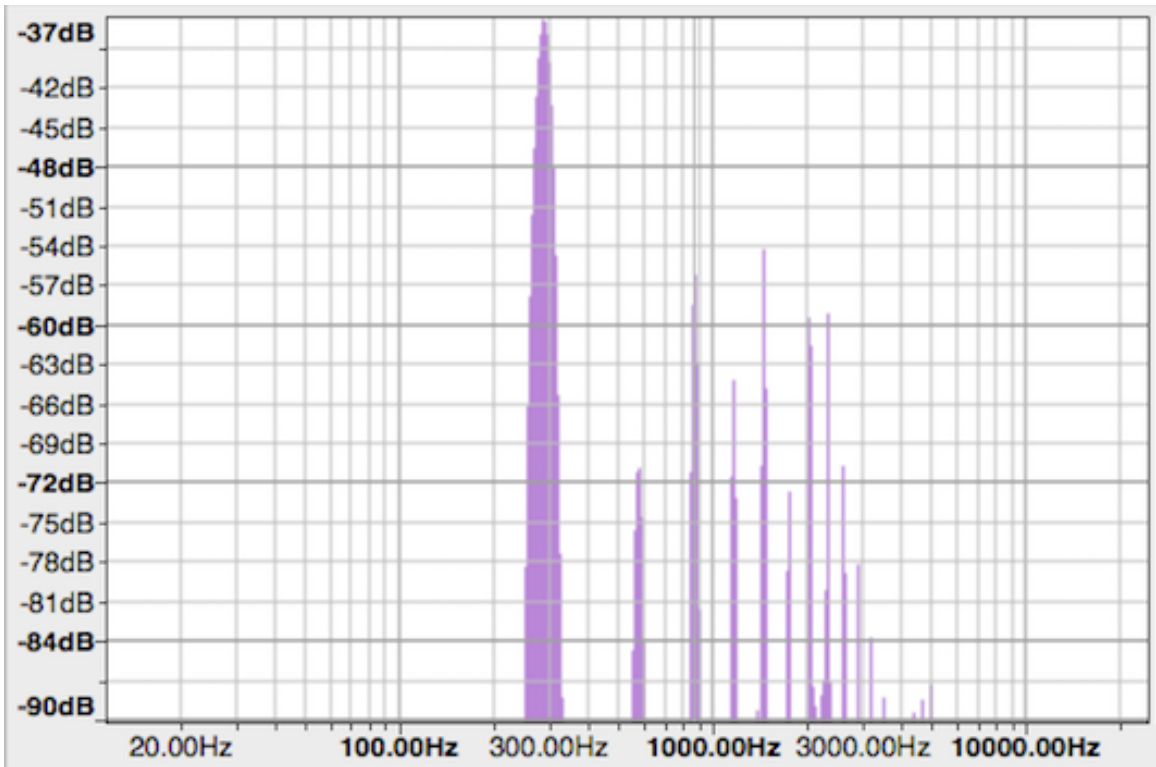
LIG



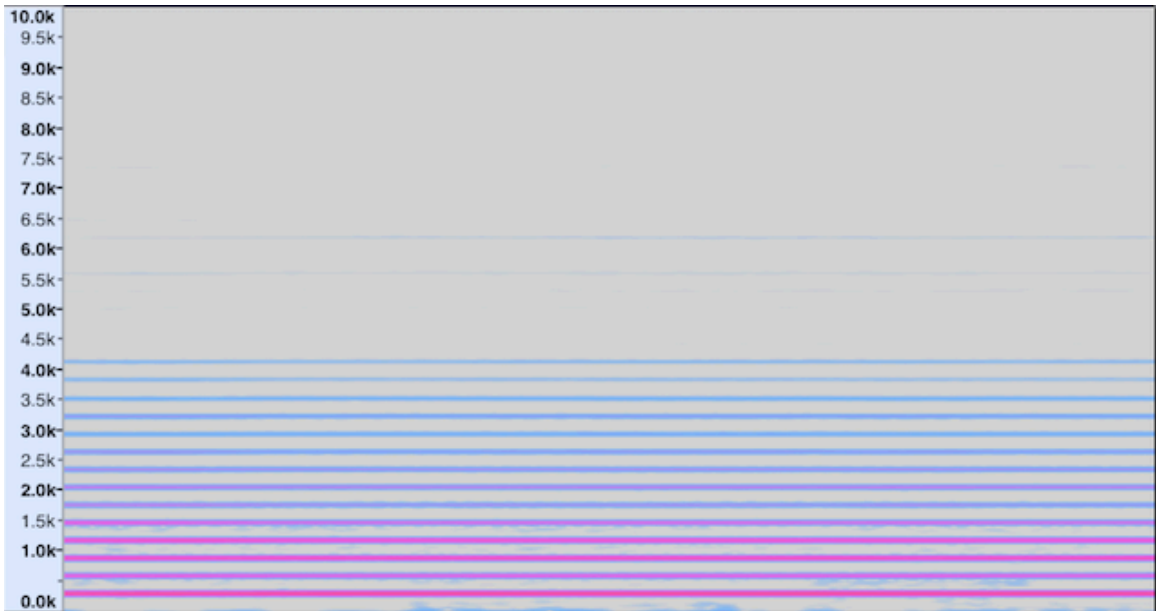
LIG



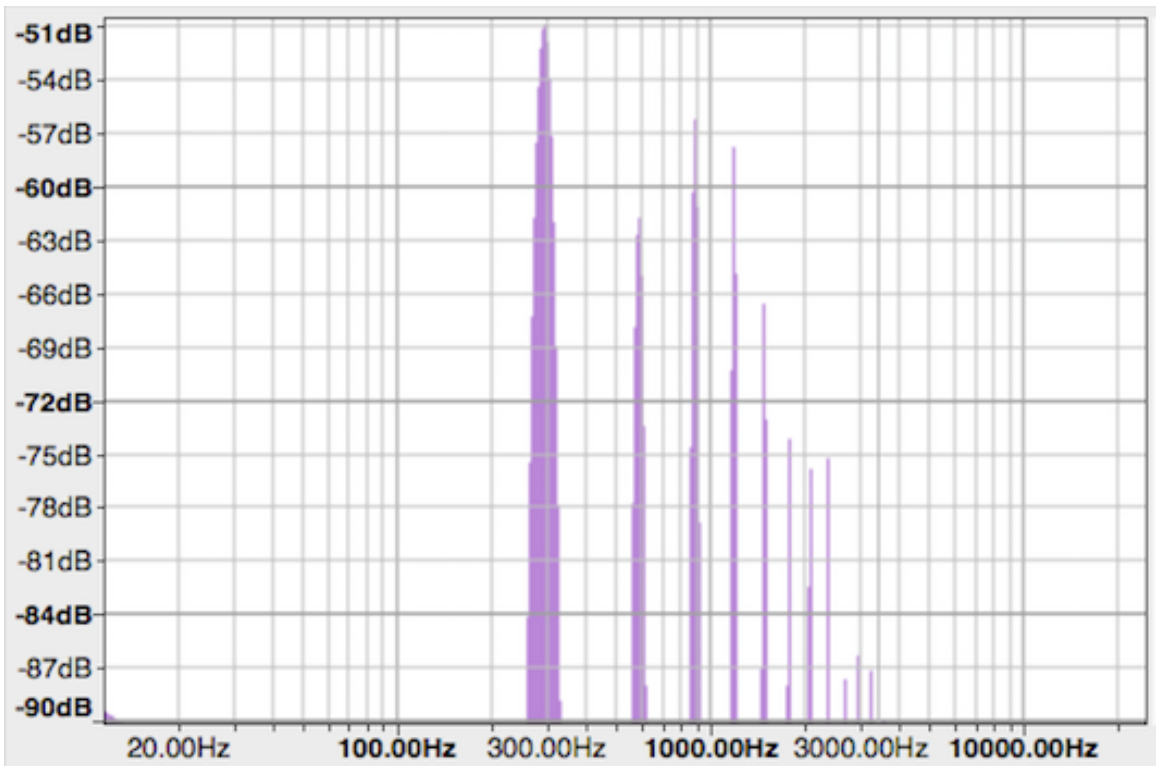
BAR Port



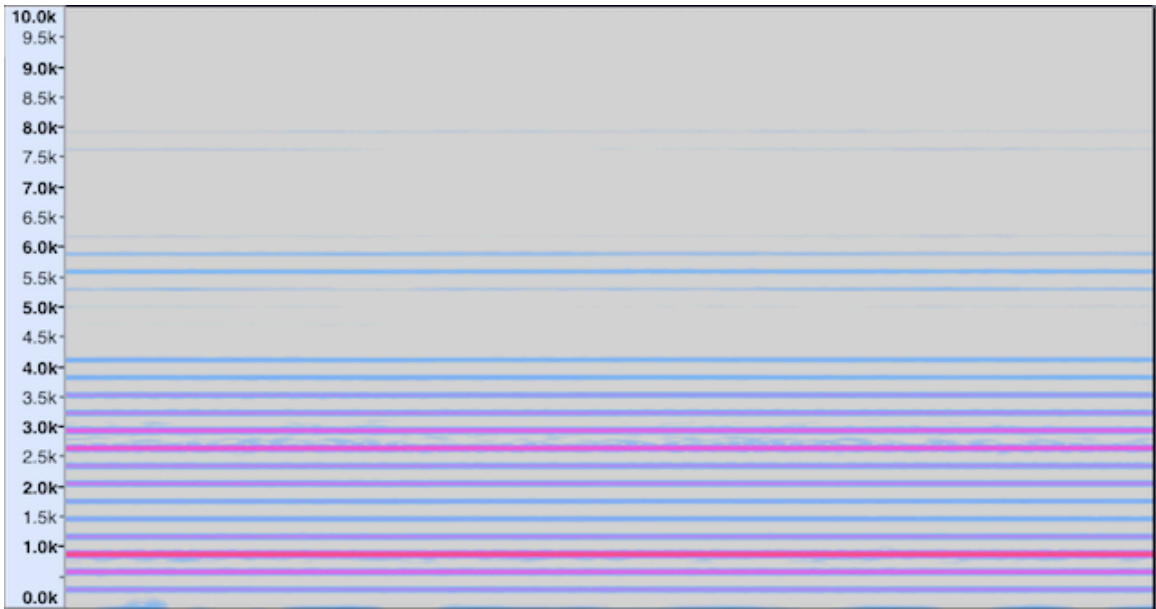
BAR Port



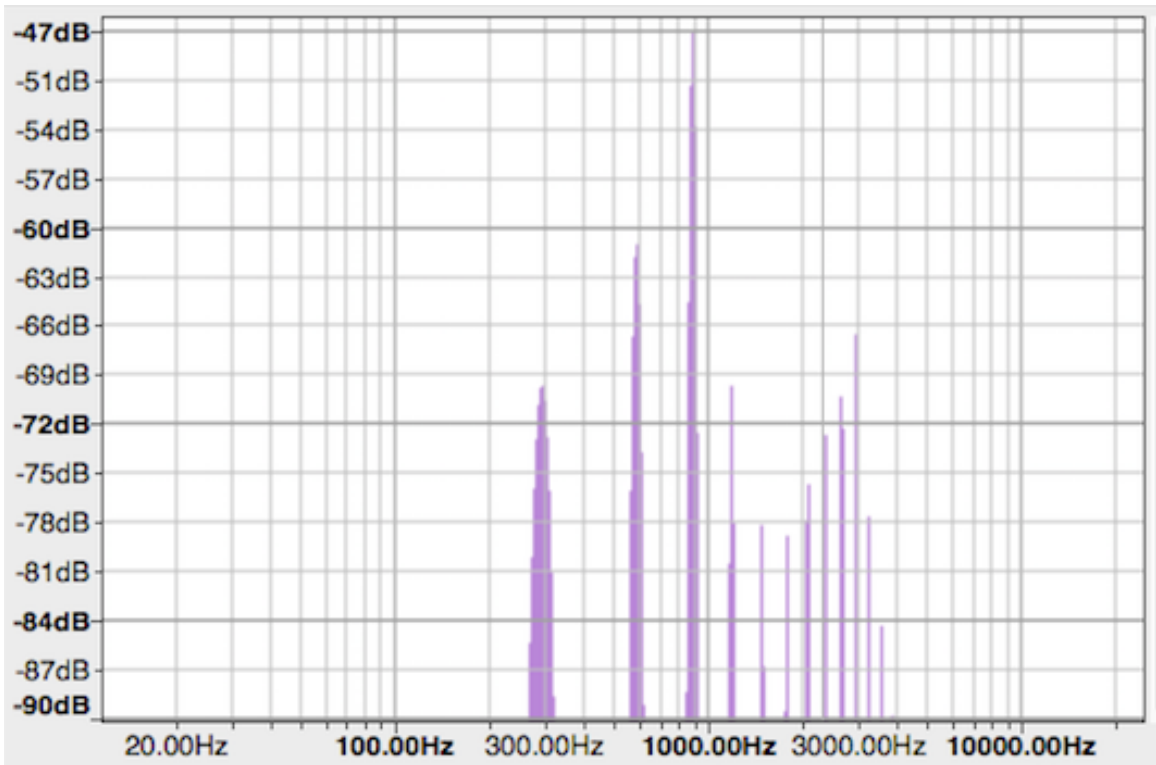
BAR Surf



BAR Surf



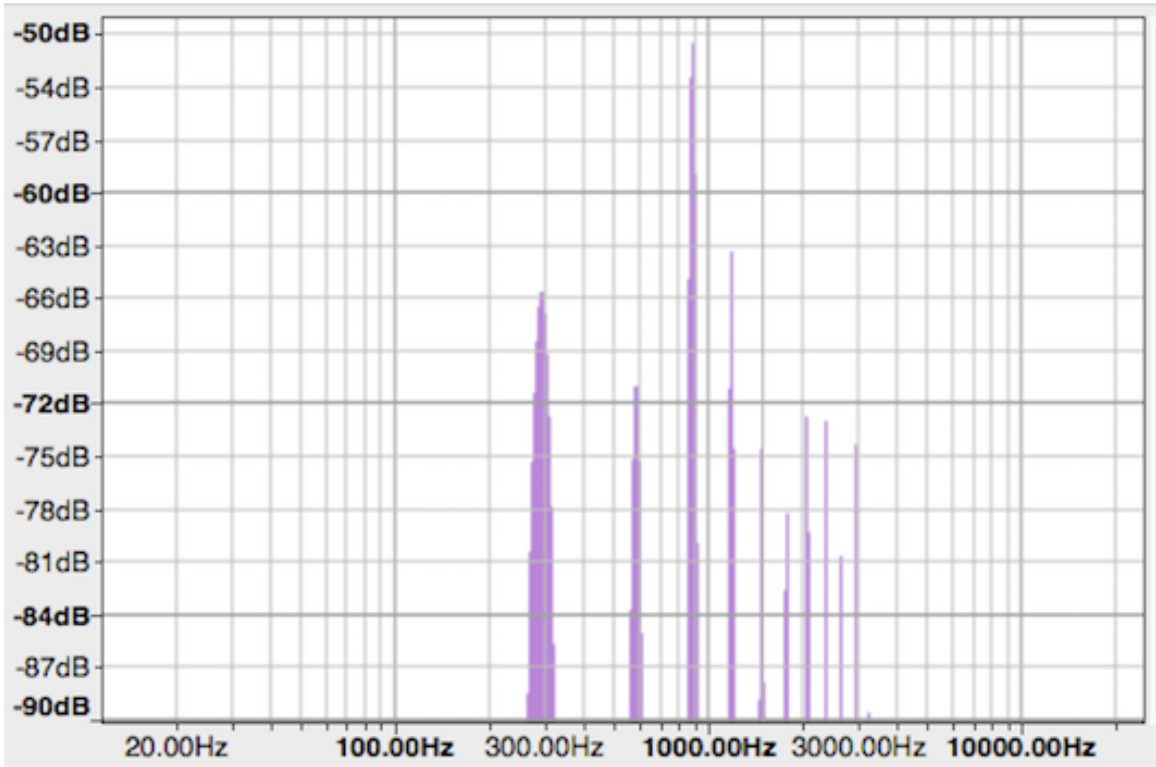
LF MPB



LF MPB



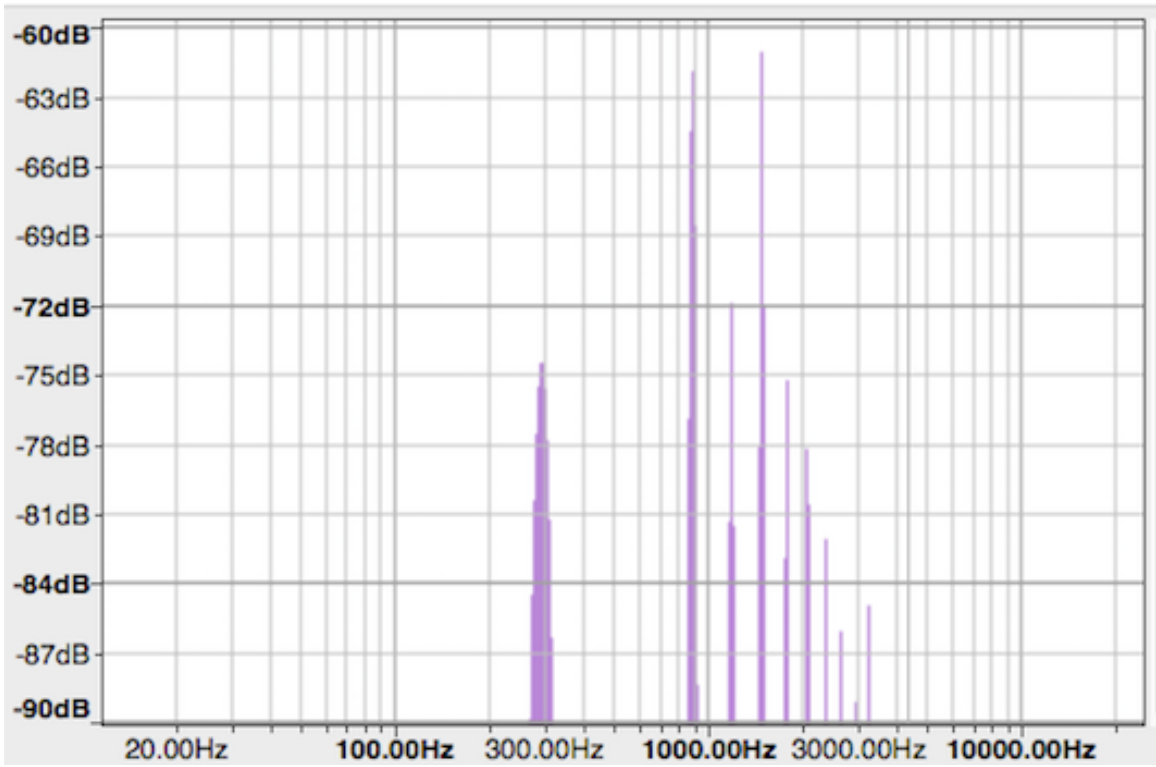
LF BUJ



LF BUJ



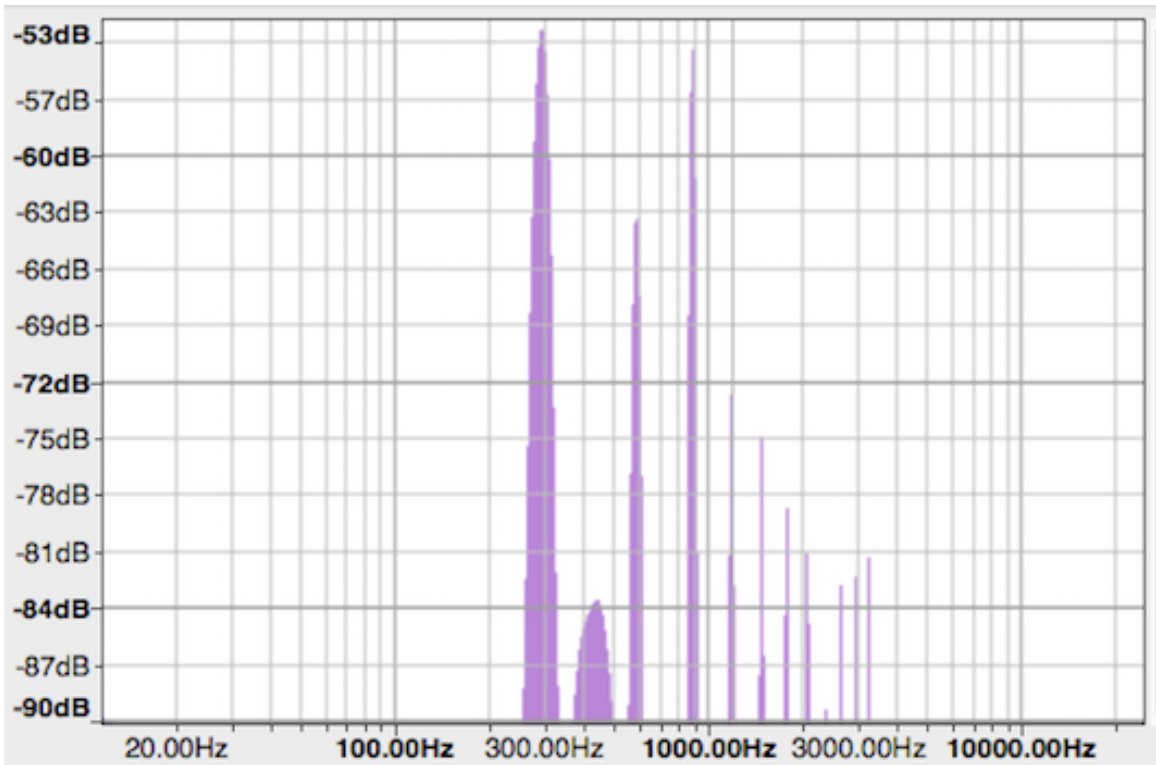
UJ



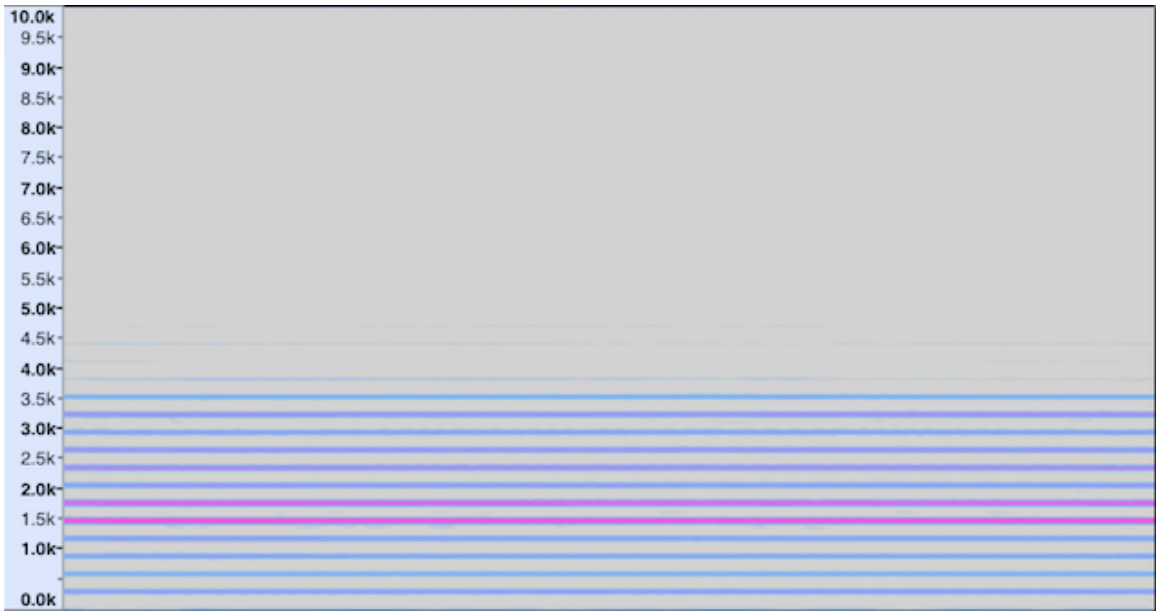
UJ



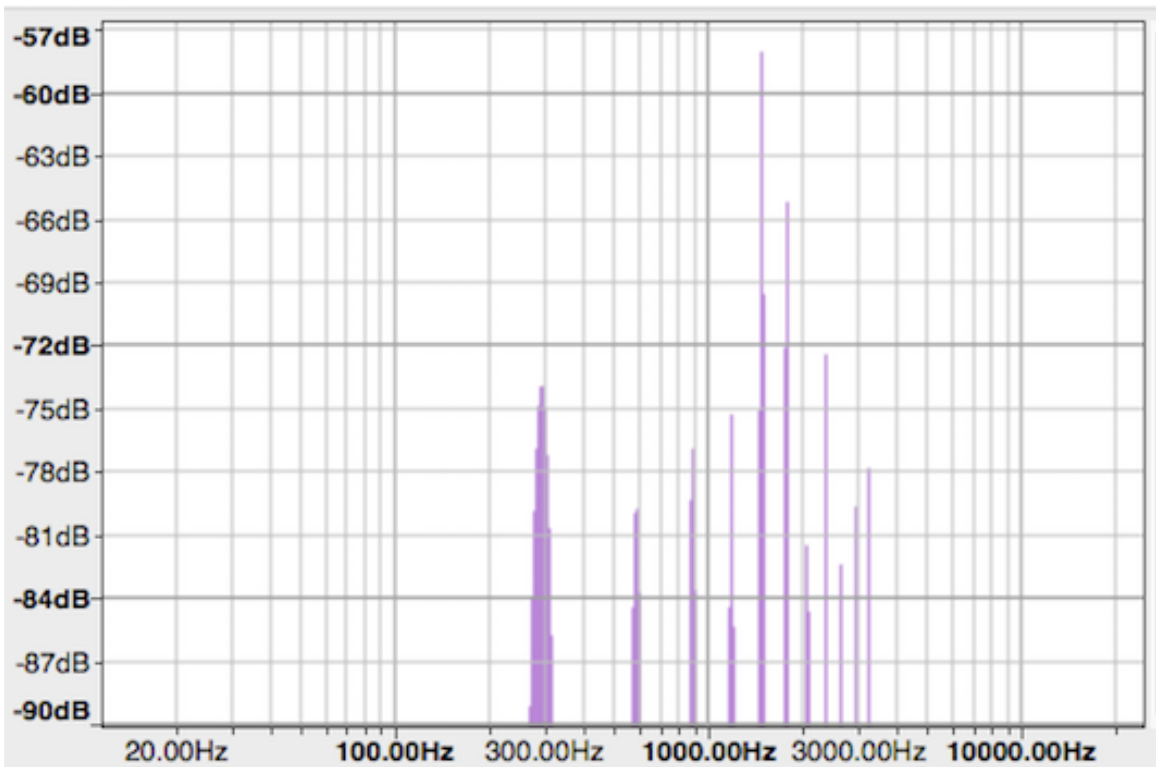
CTR



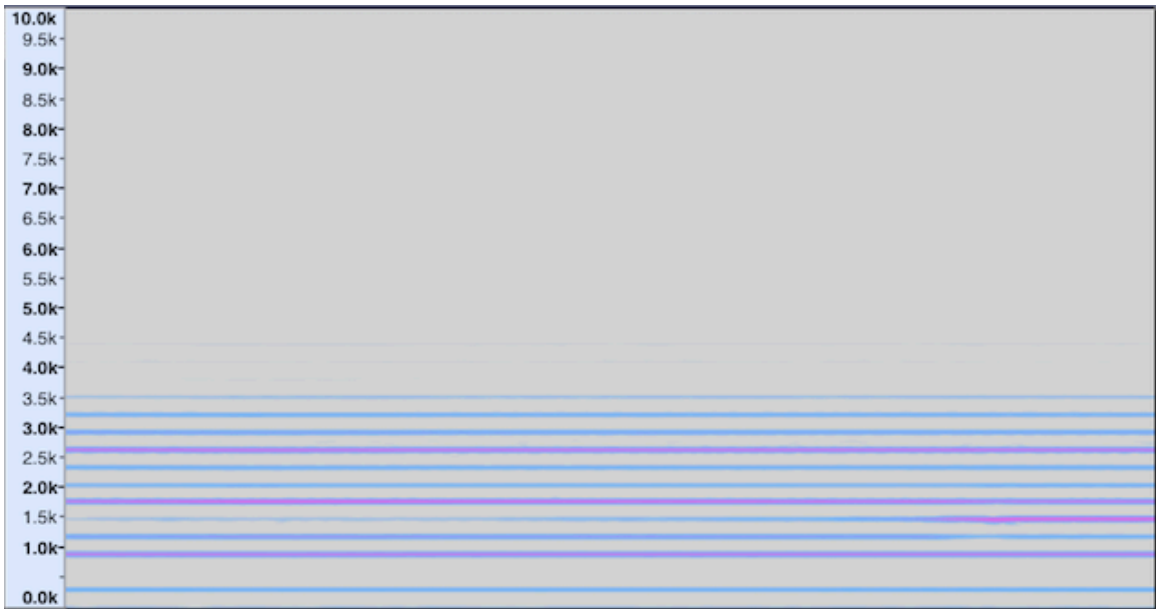
CTR



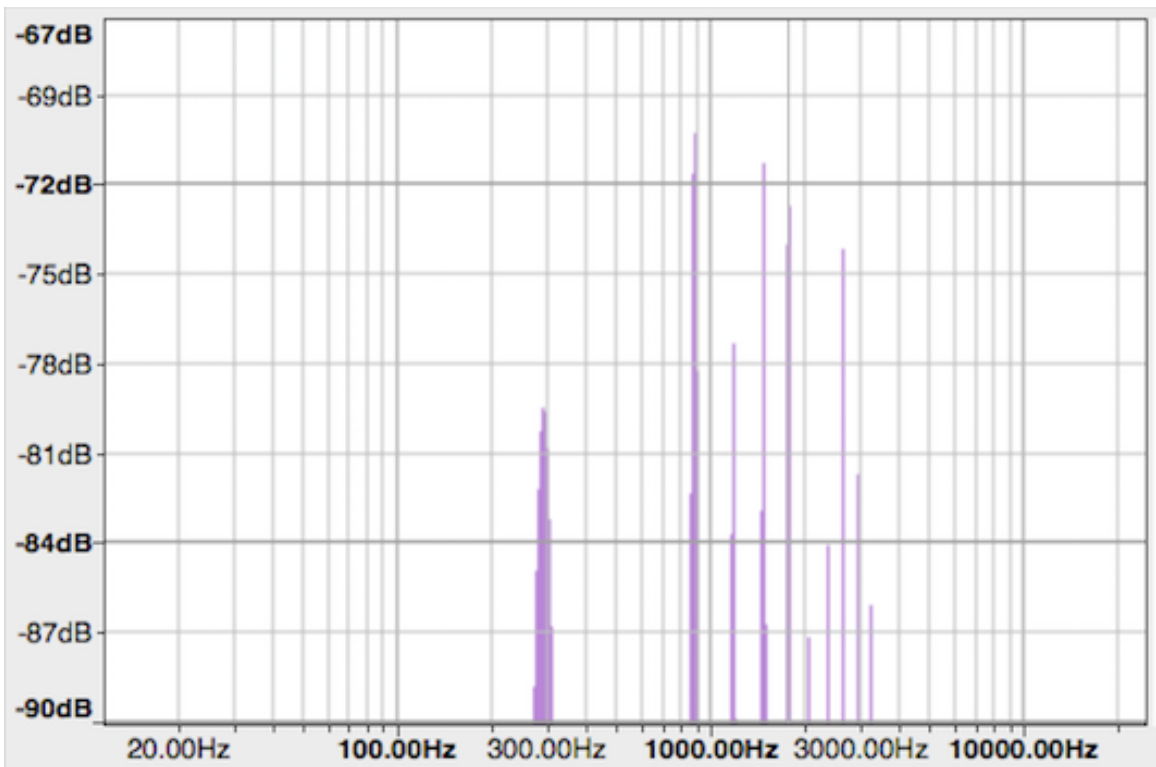
LJ



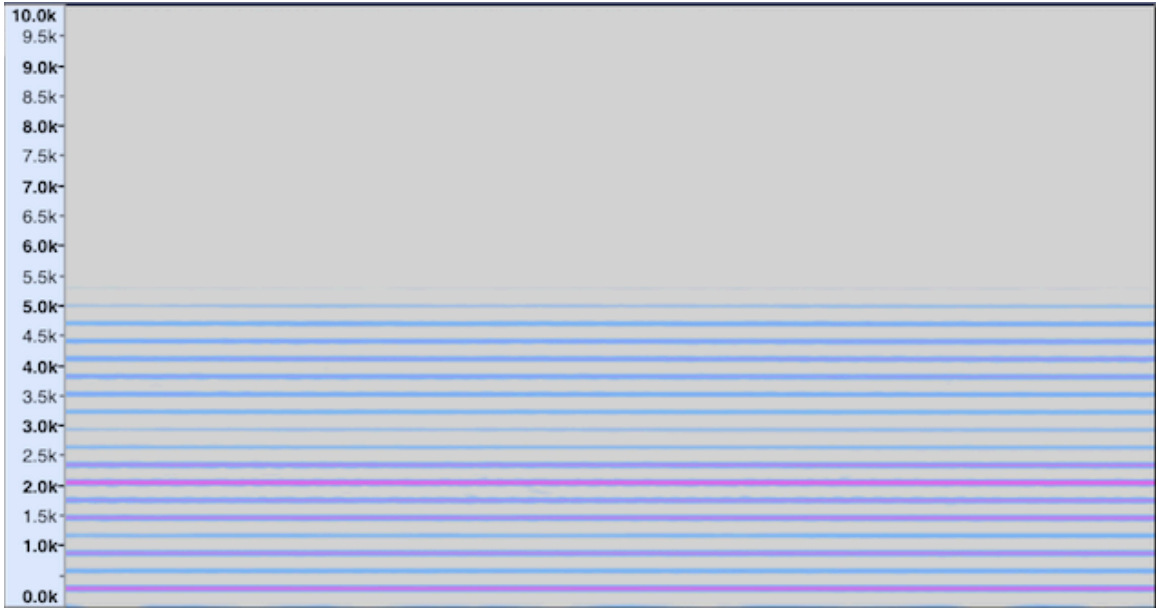
LJ



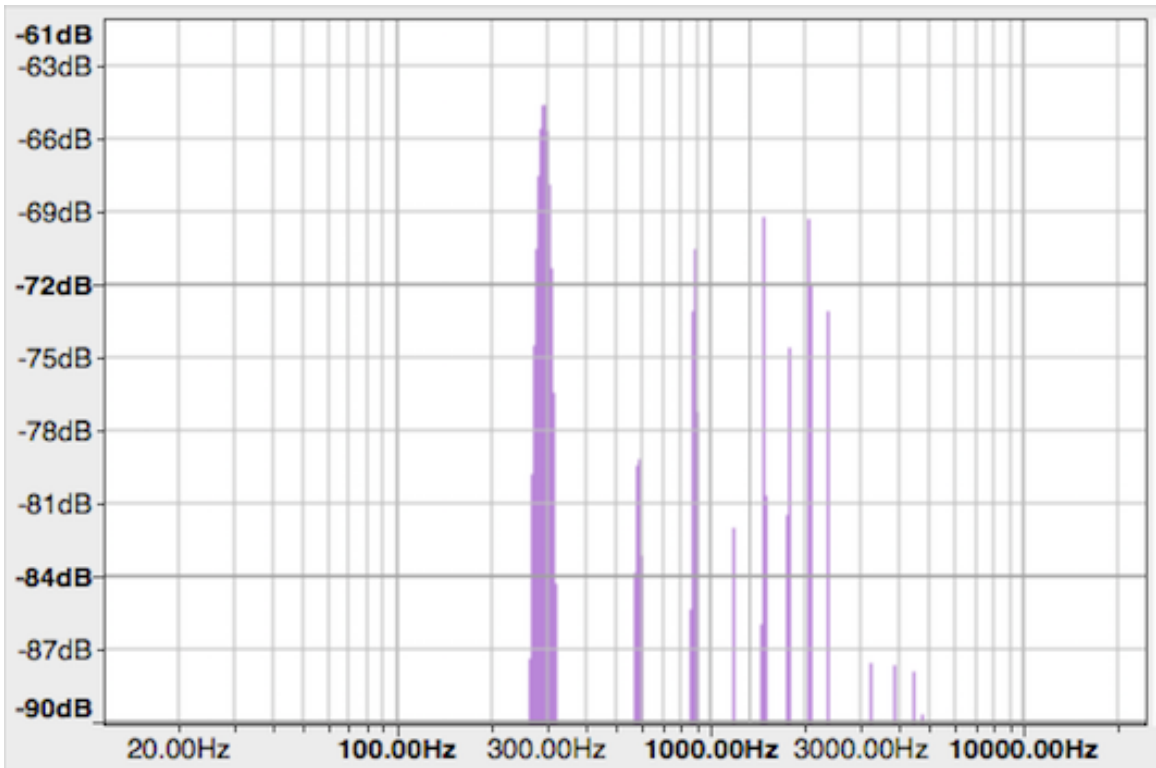
BELL Out



BELL Out

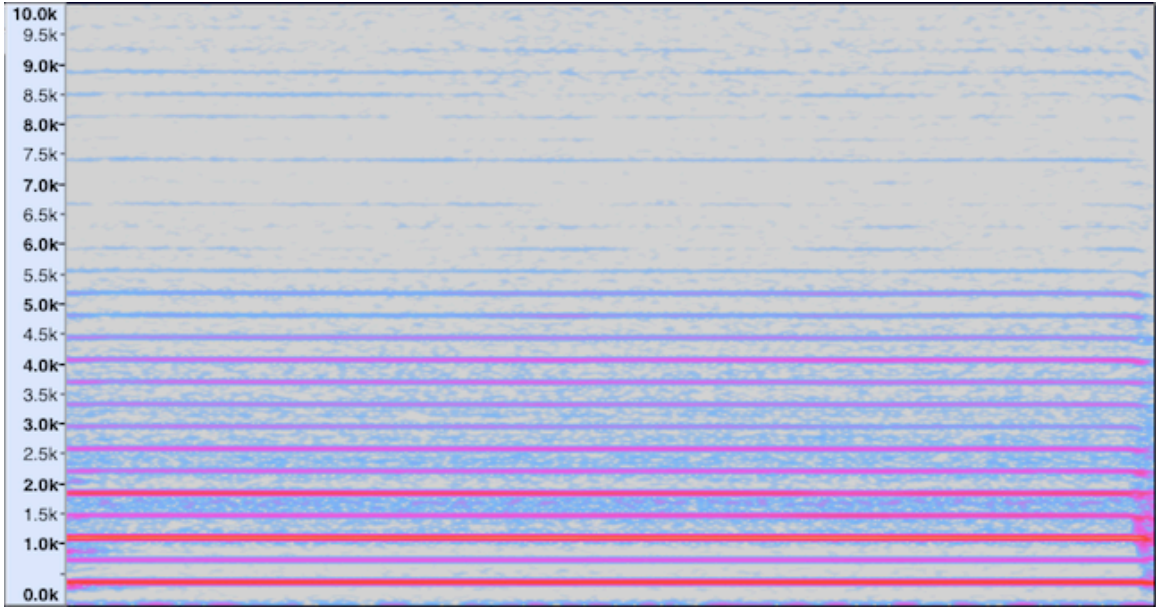


BELL End

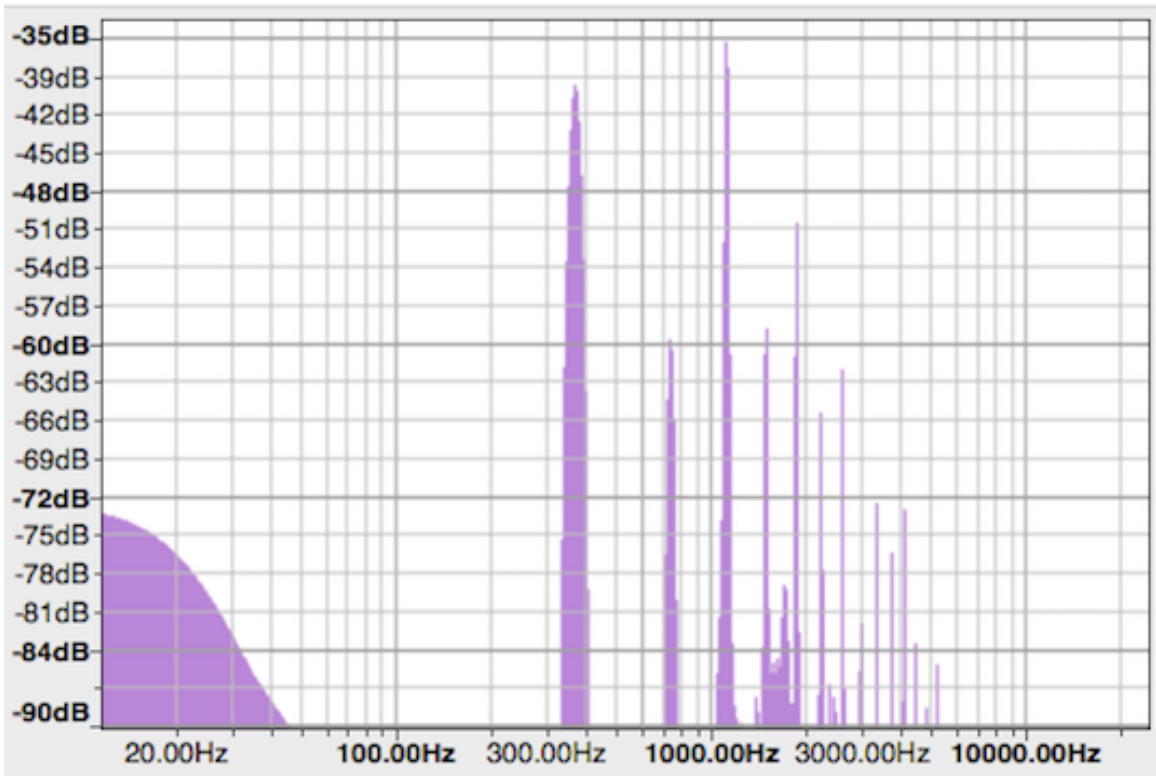


BELL End

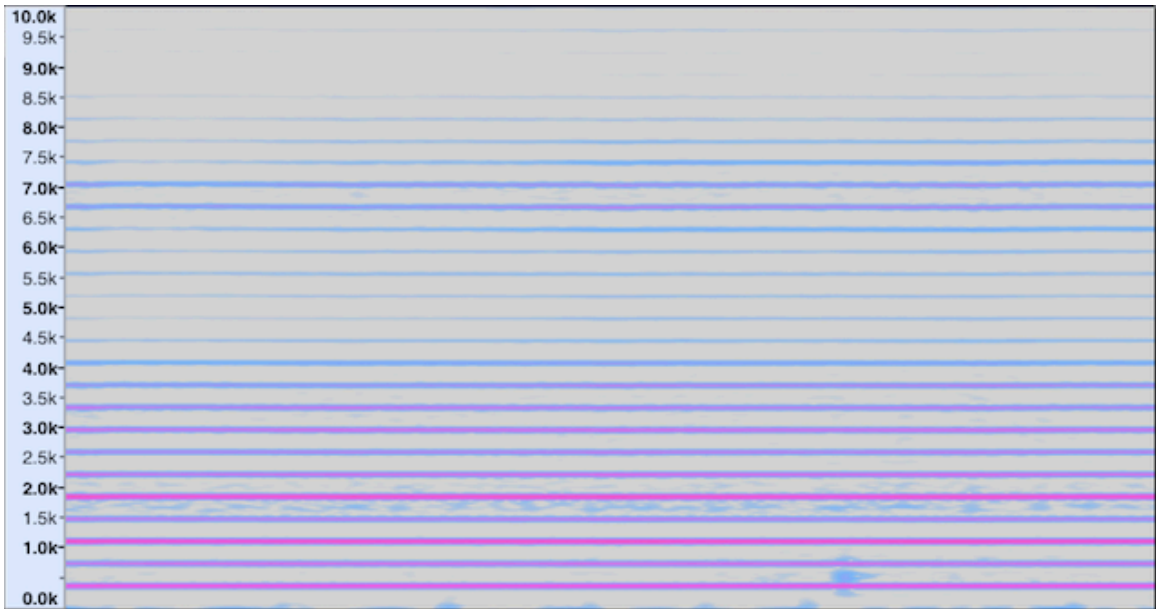
APPENDIX I  
SAMPLE DATA G-SHARP4



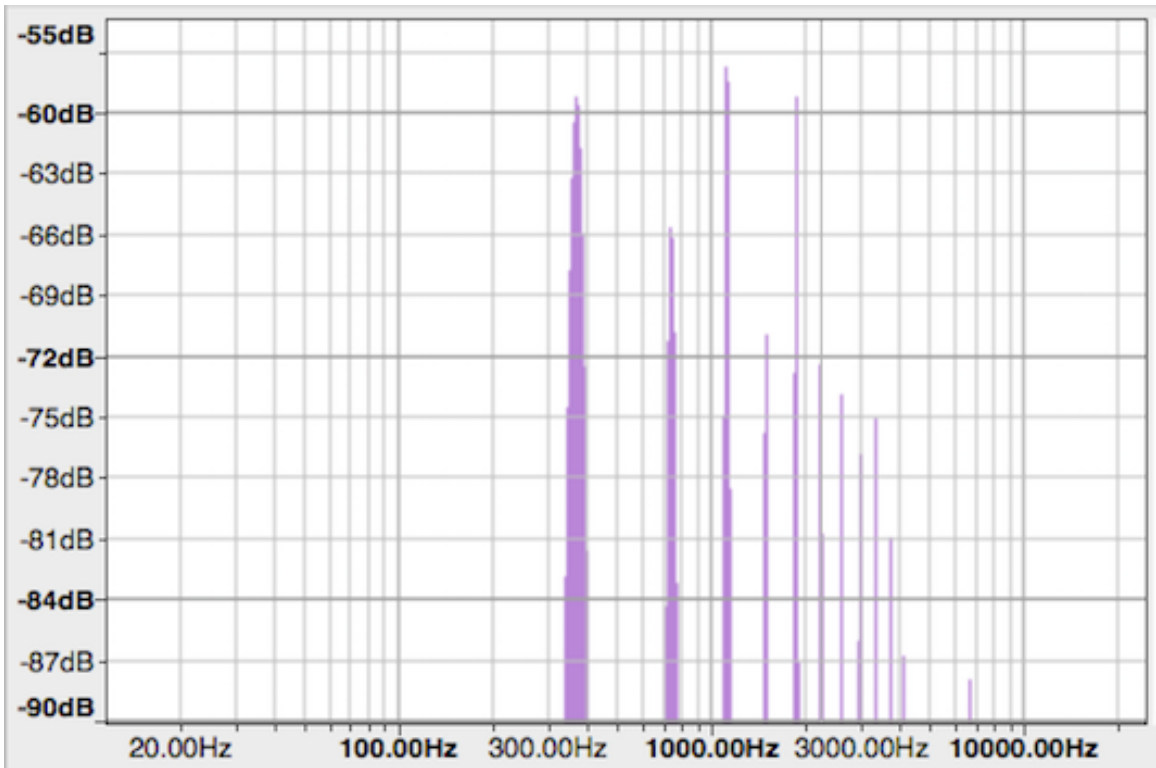
M30 (Reference)



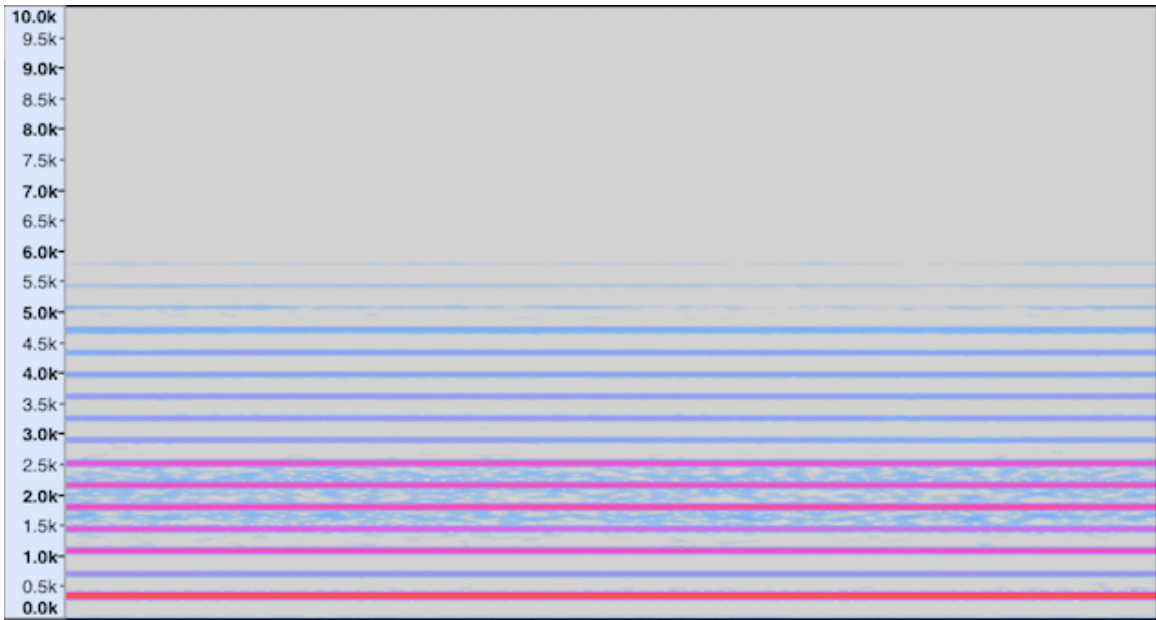
M30 (Reference)



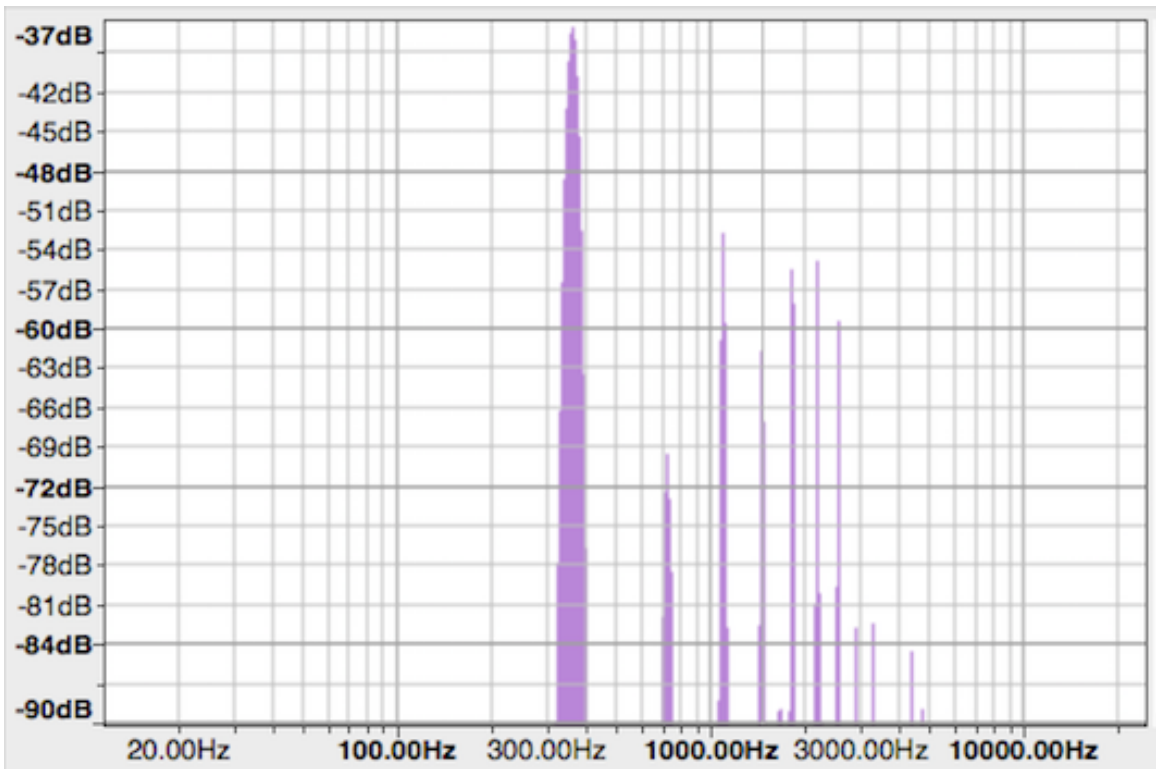
LIG



LIG



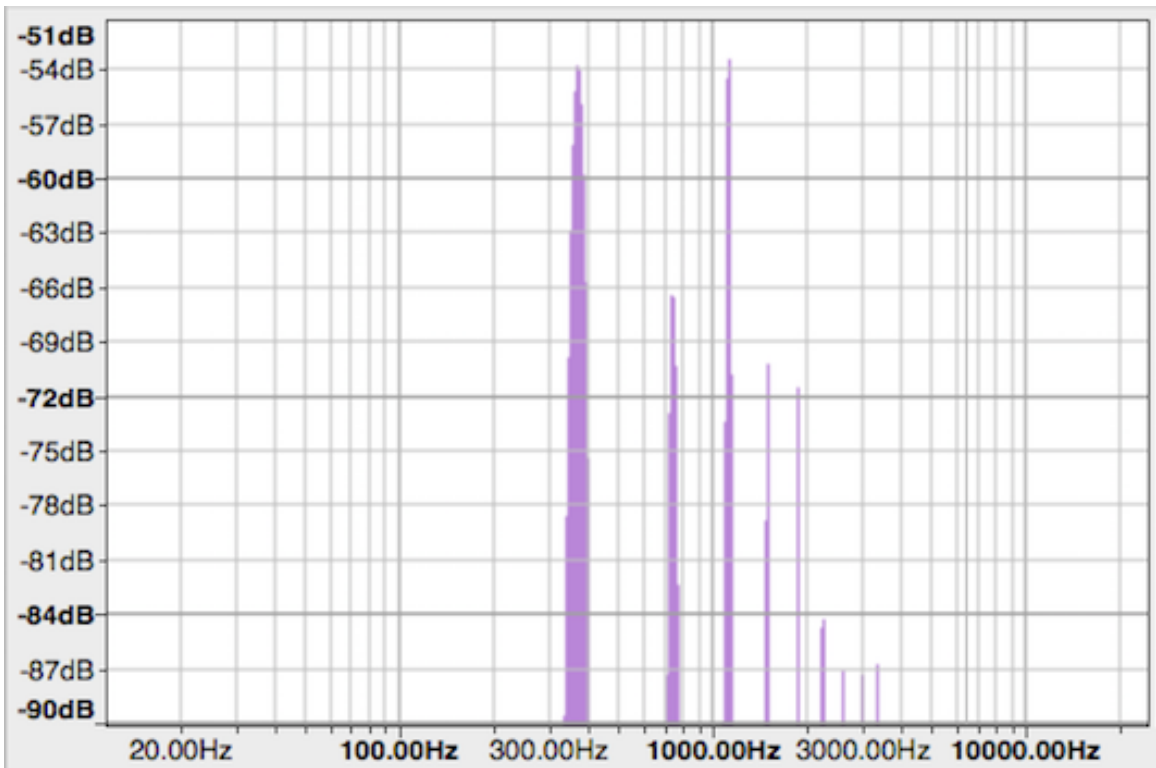
BAR Port



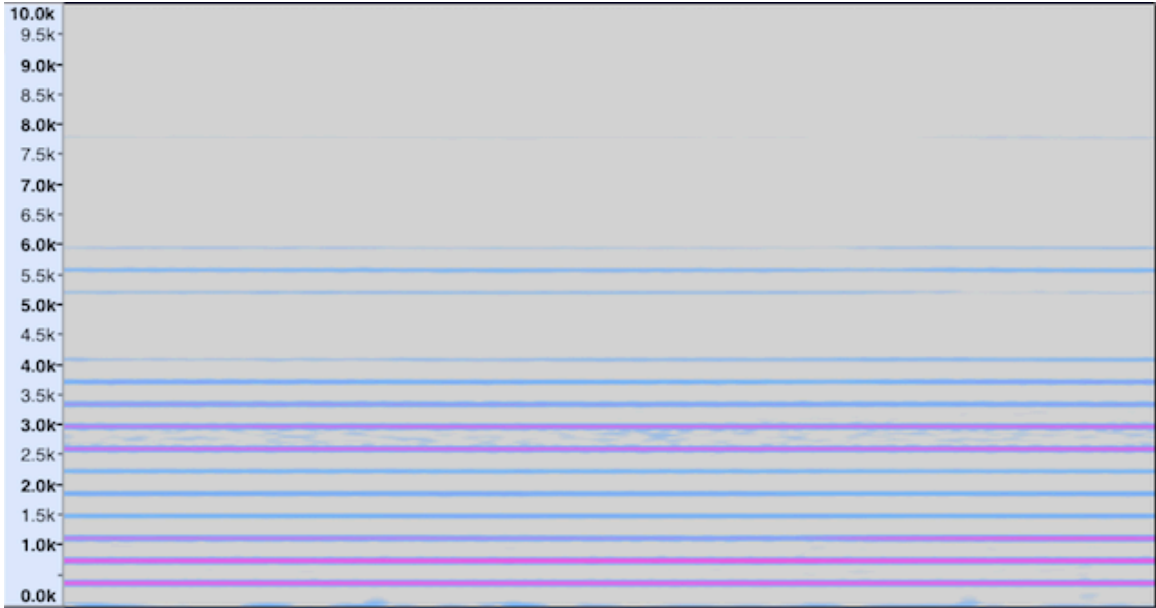
BAR Port



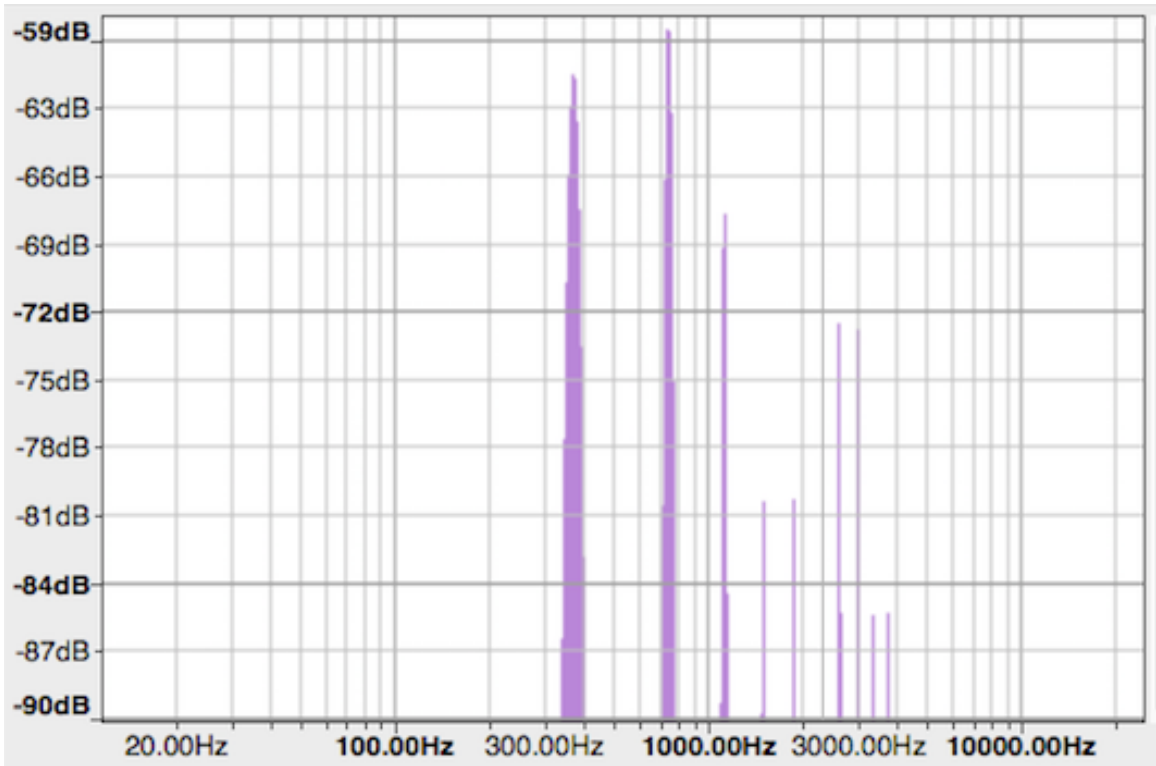
BAR Surf



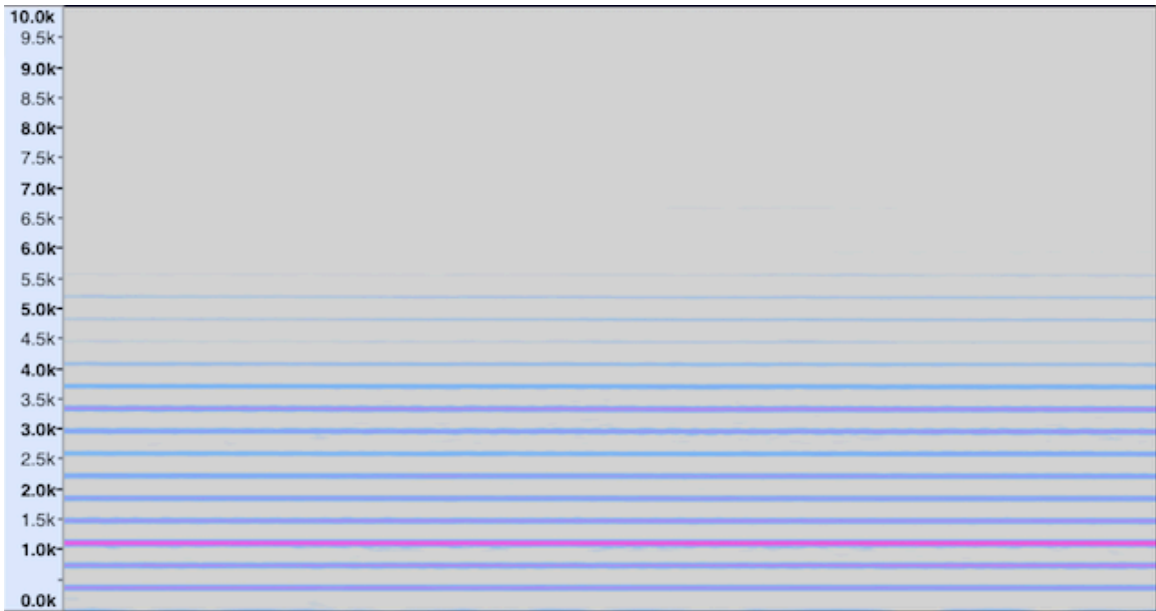
BAR Surf



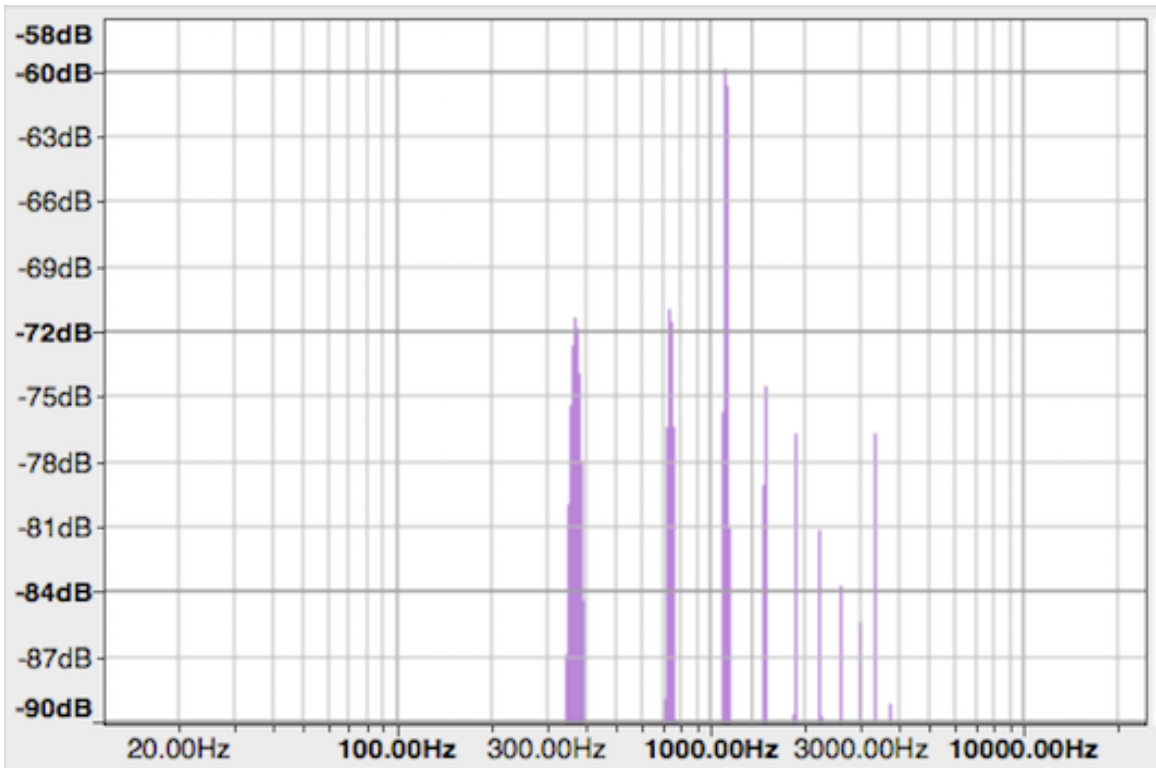
LF MPB



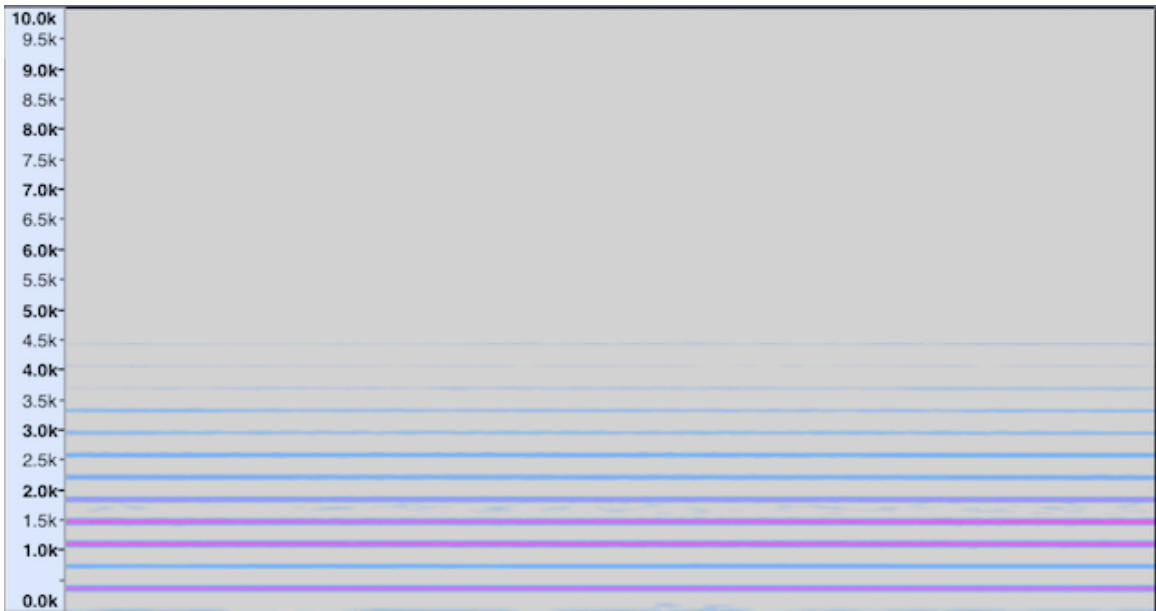
LF MPB



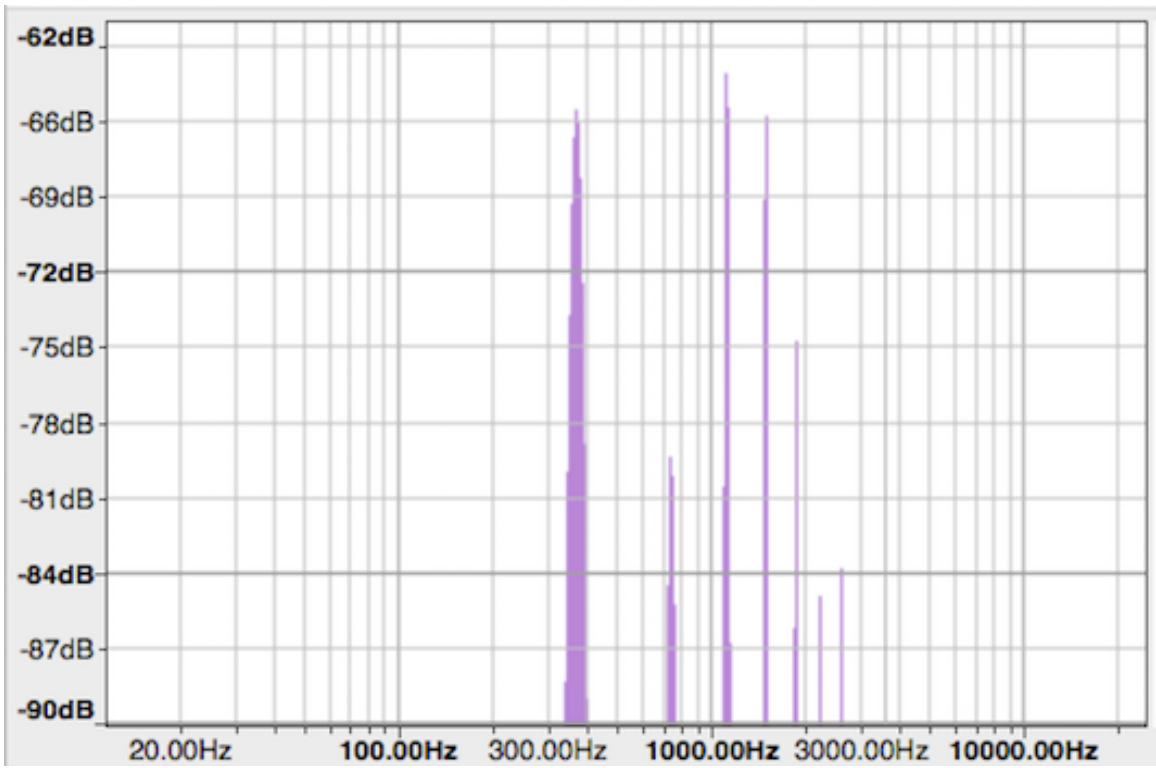
LF BUJ



LF BUJ



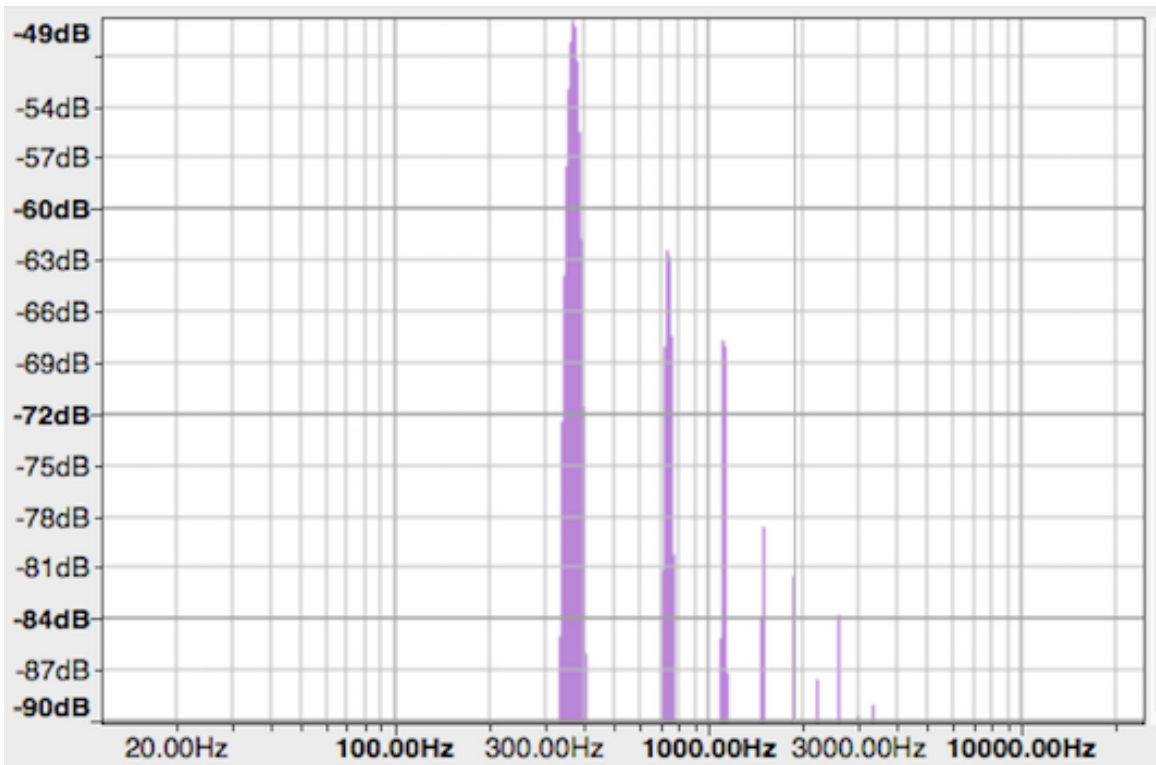
UJ



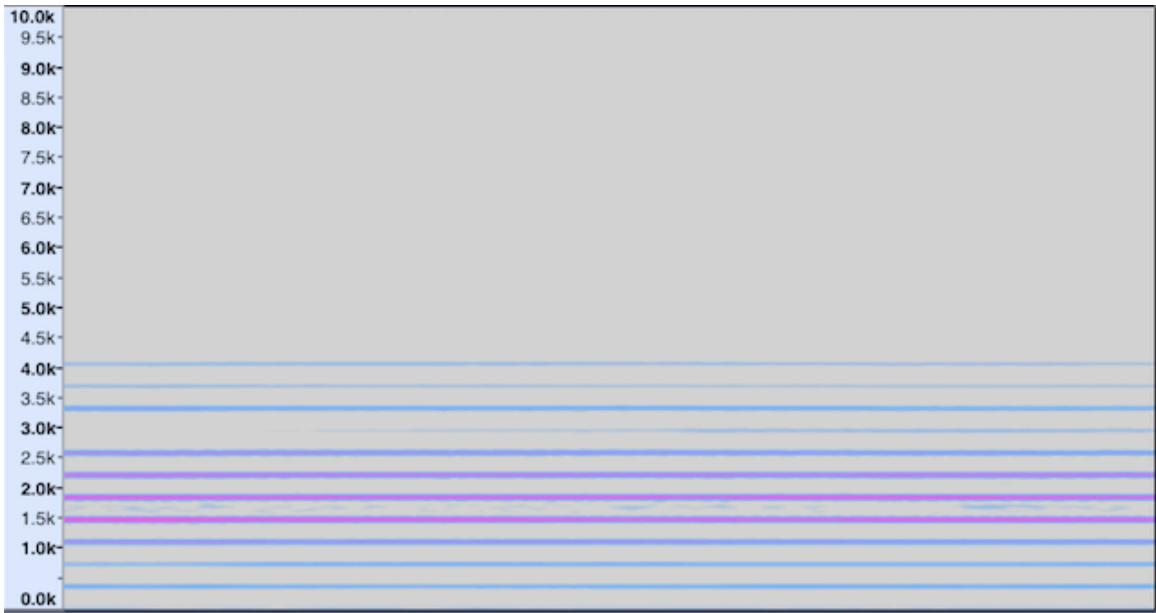
UJ



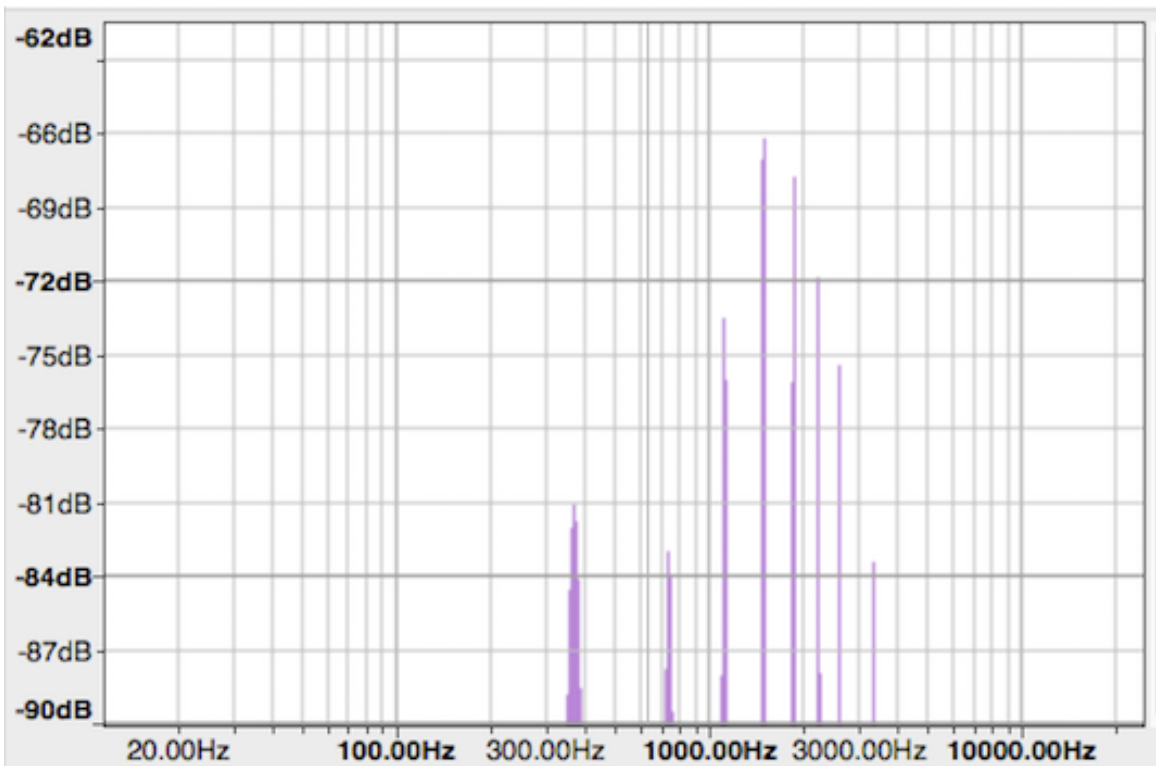
CTR



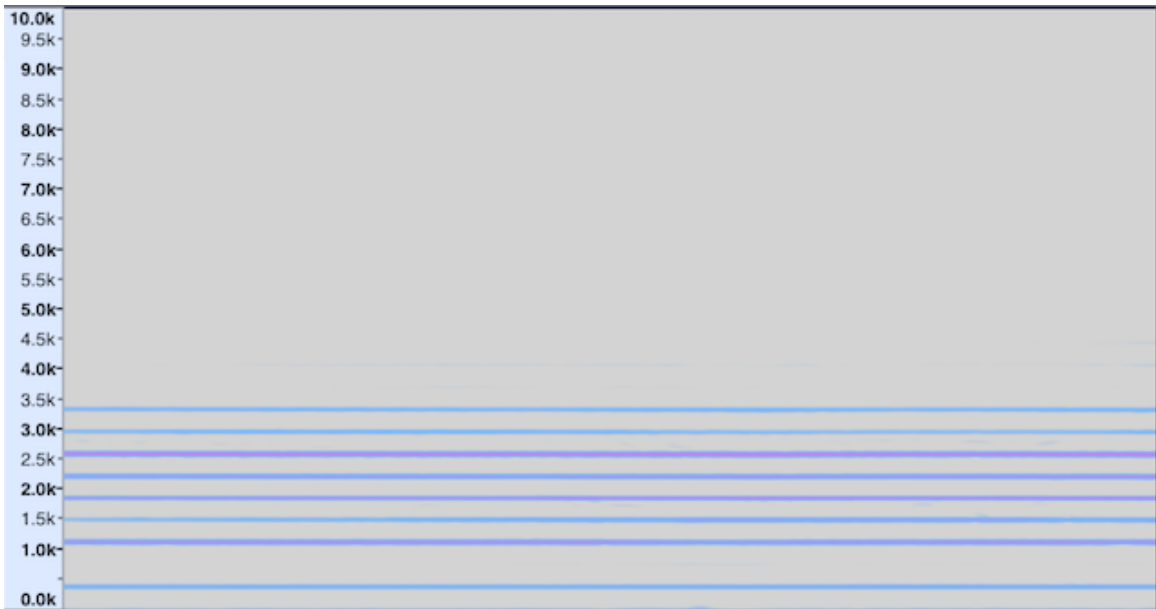
CTR



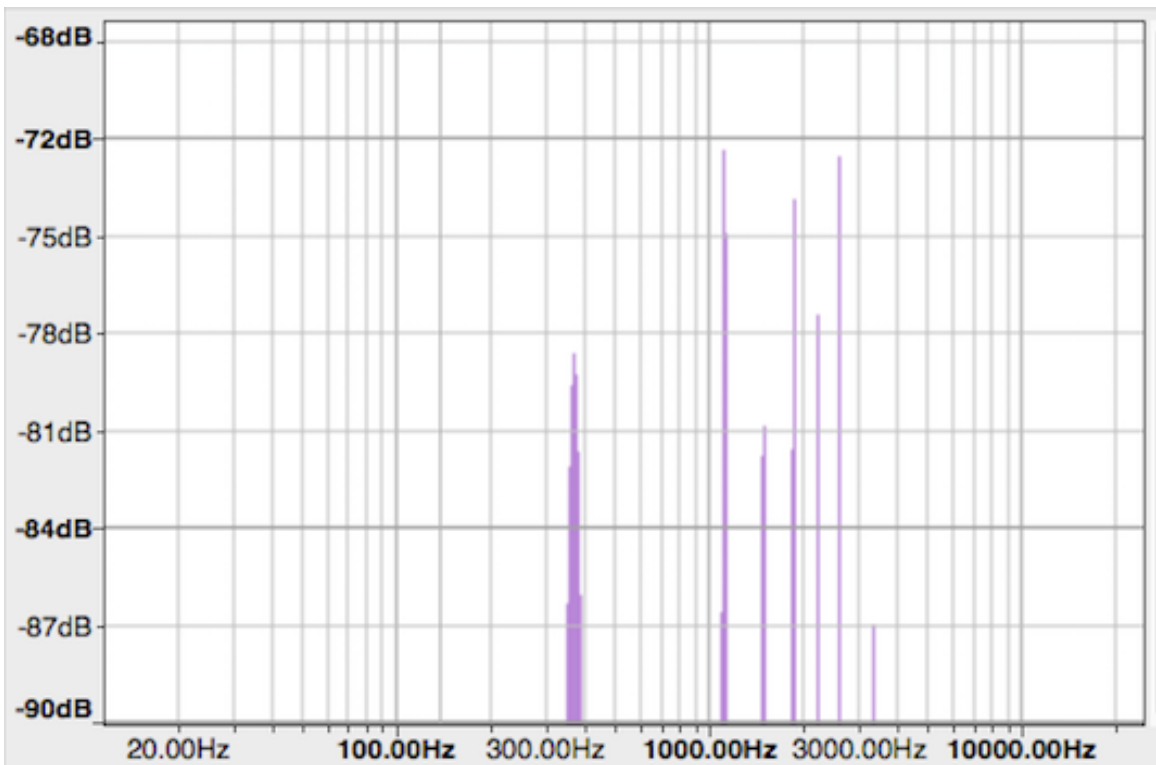
LJ



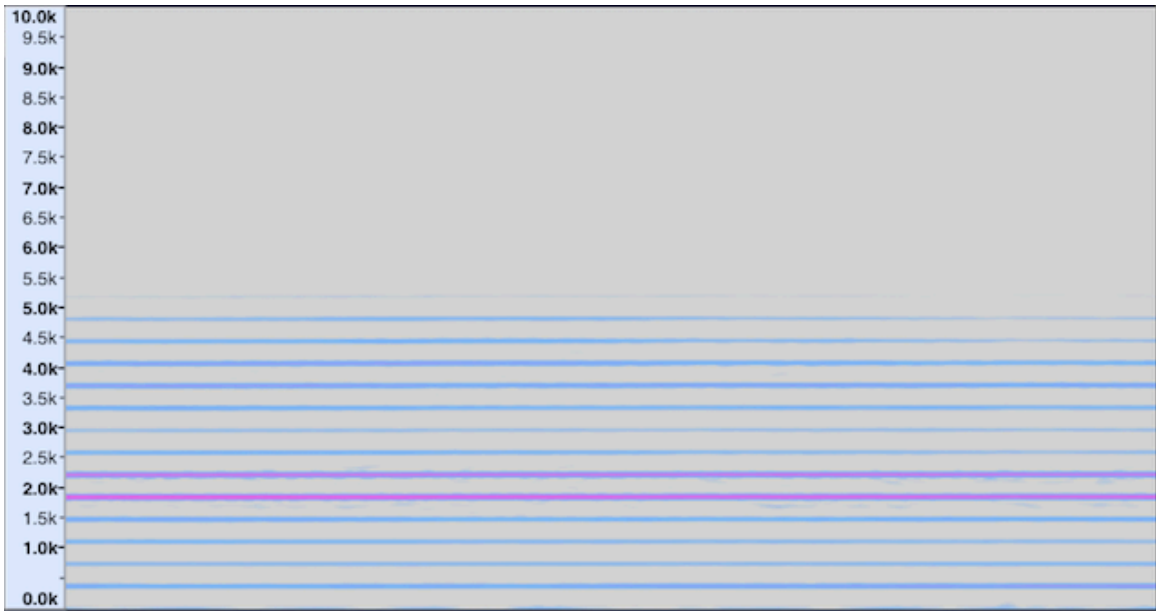
LJ



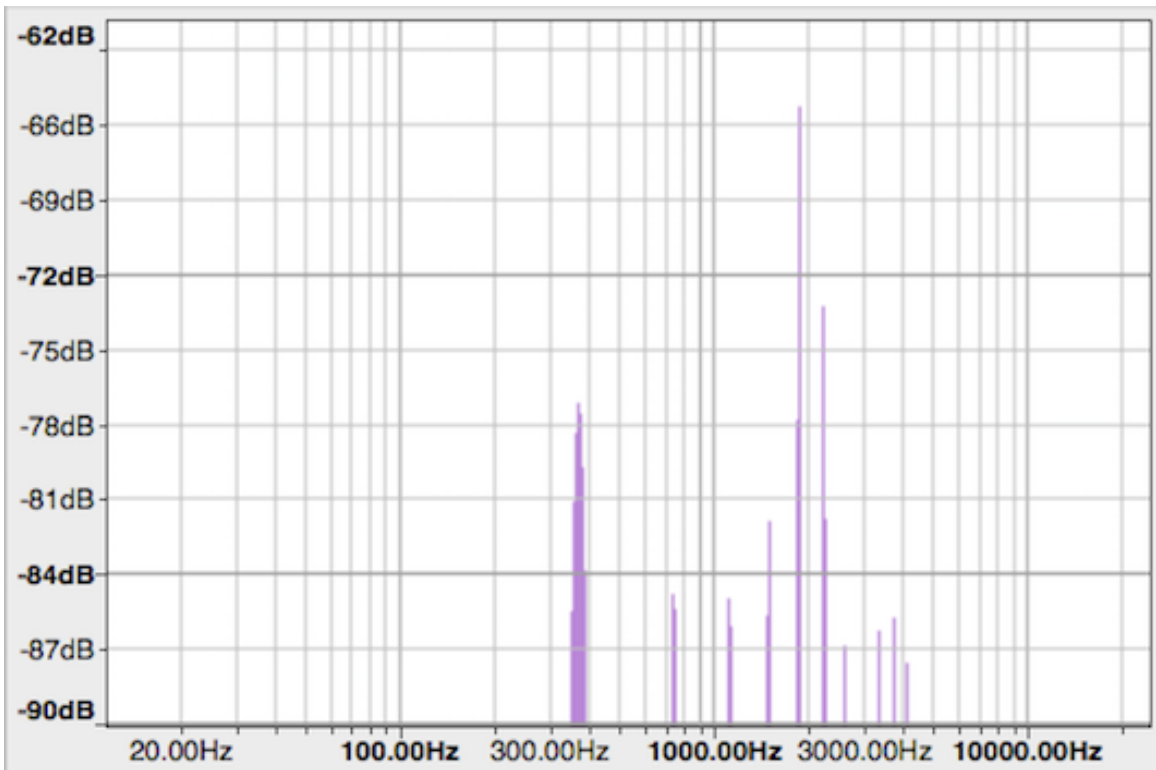
BELL Out



BELL Out

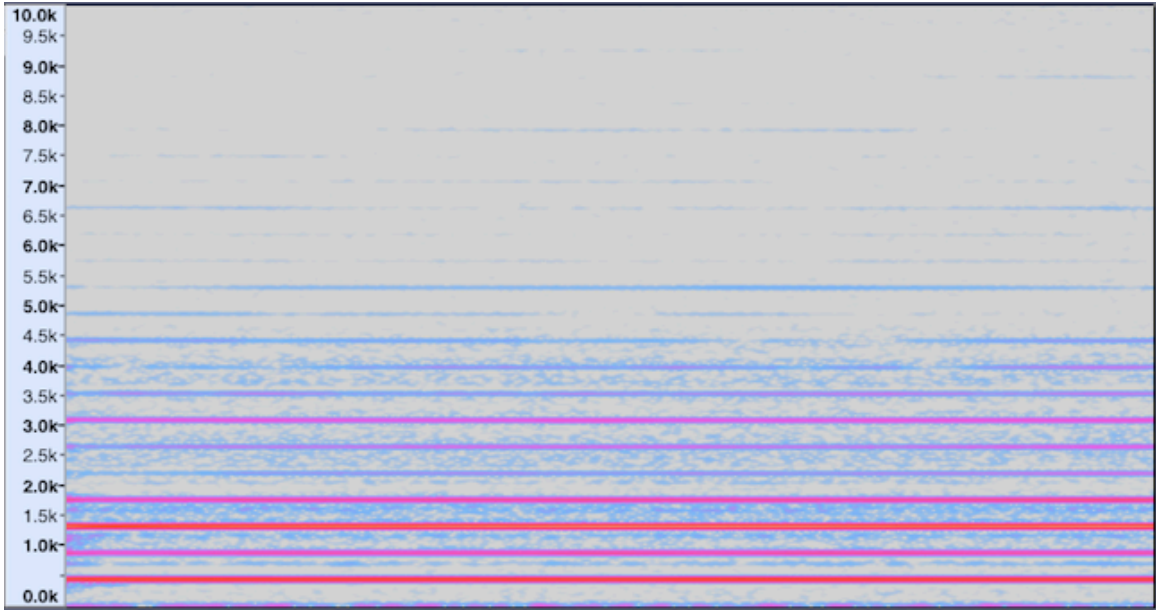


BELL End

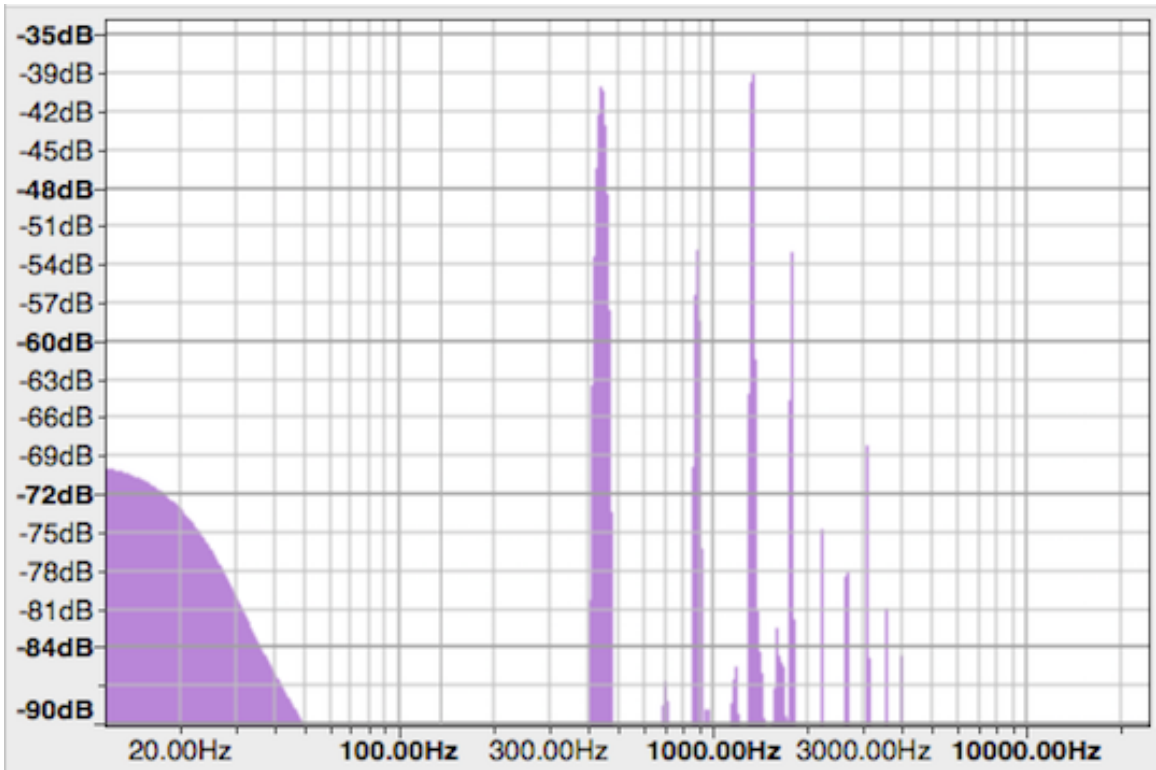


BELL End

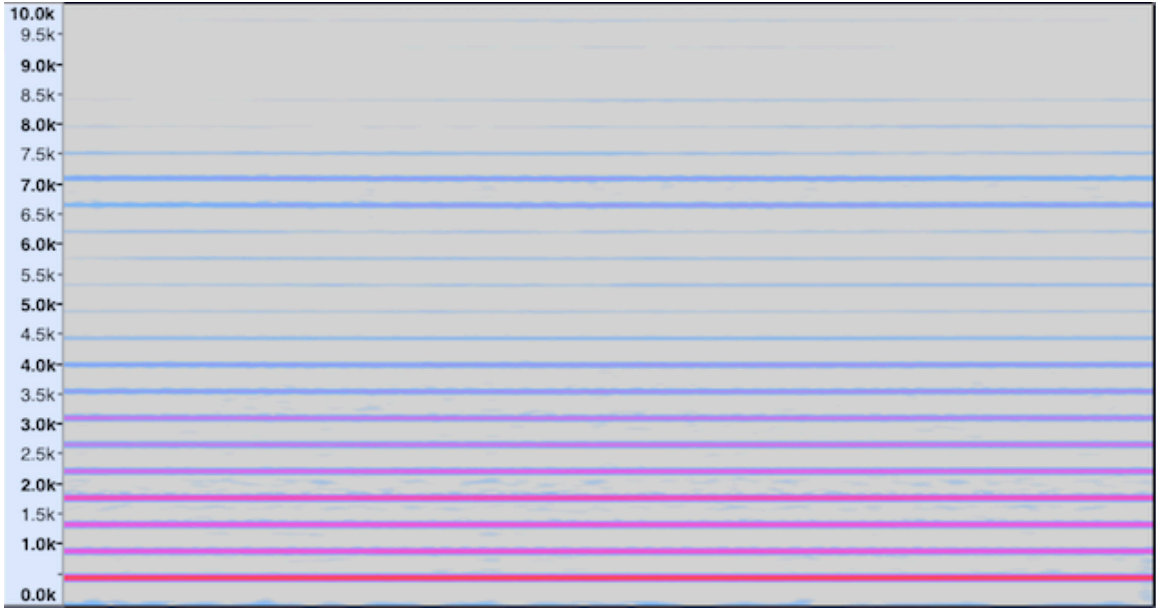
APPENDIX J  
SAMPLE DATA B4



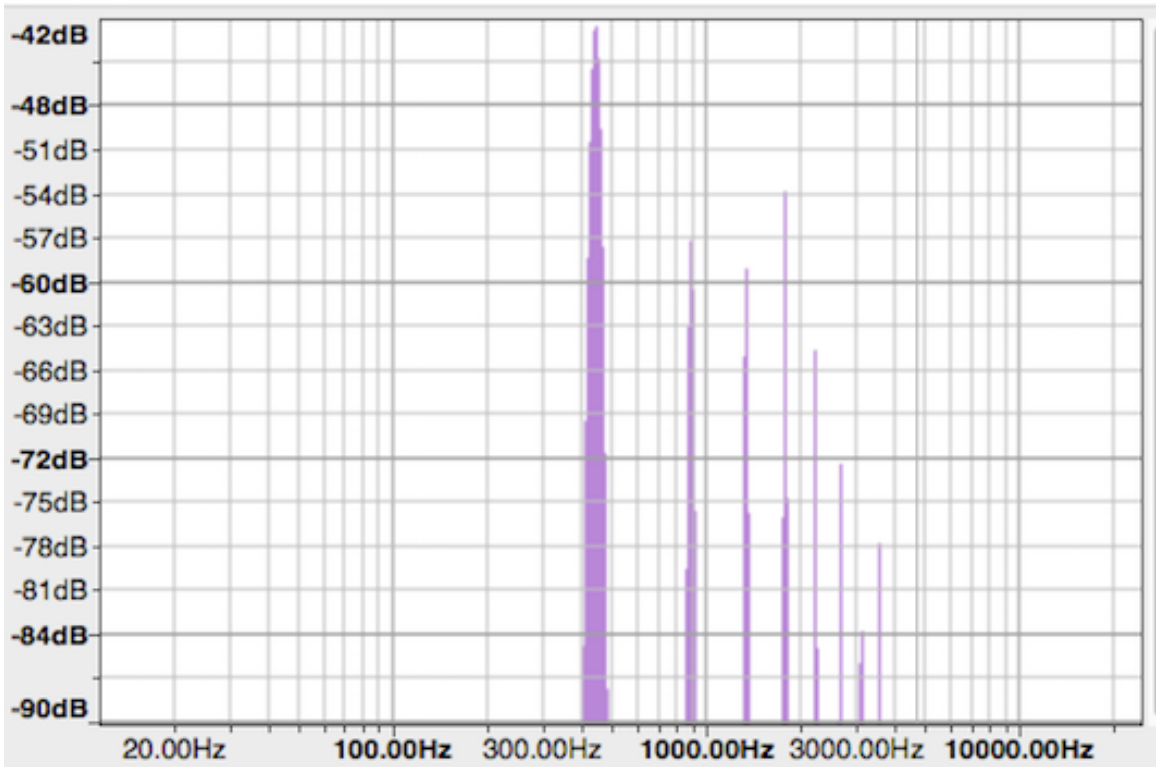
M30 (Reference)



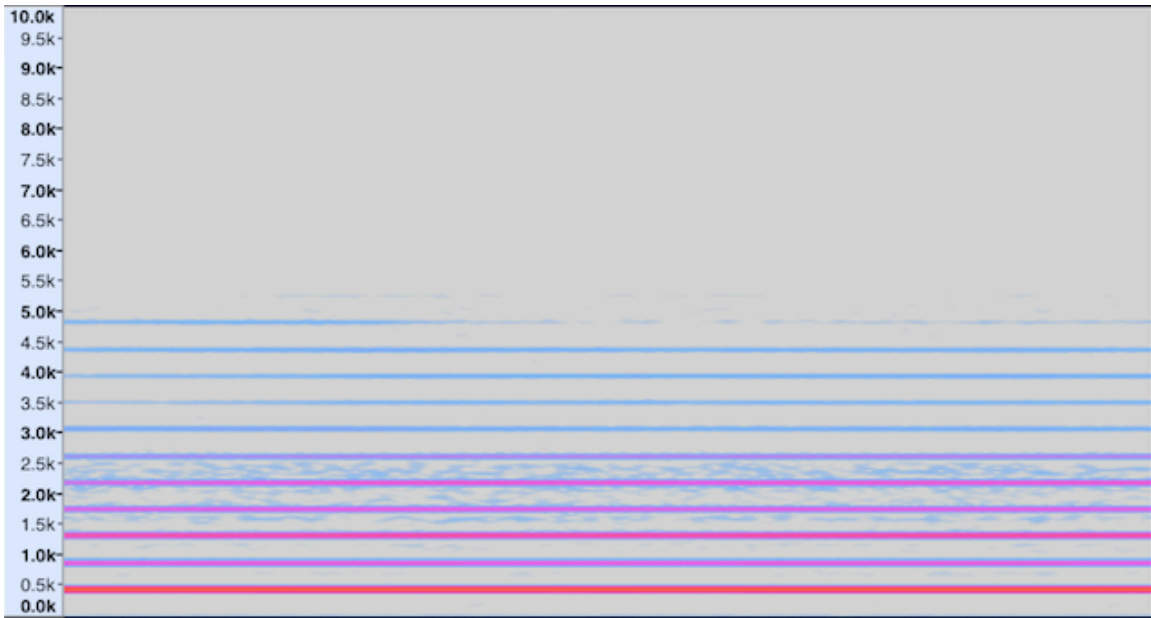
M30 (Reference)



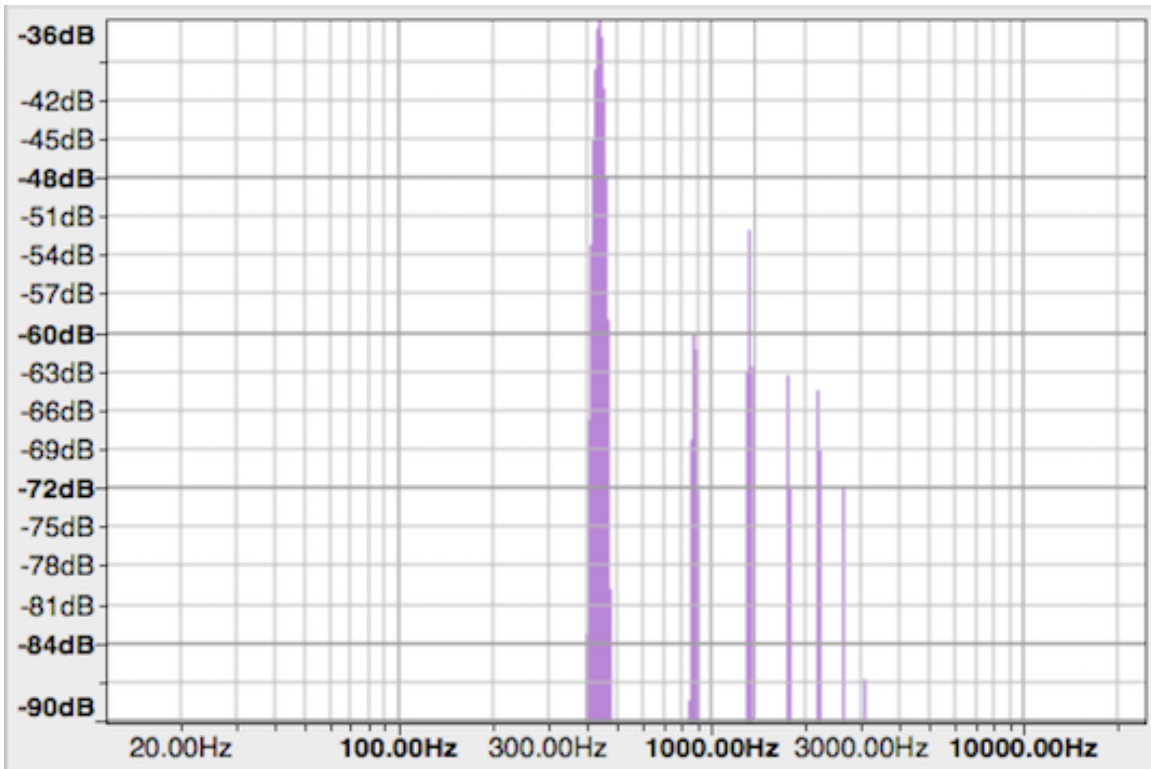
LIG



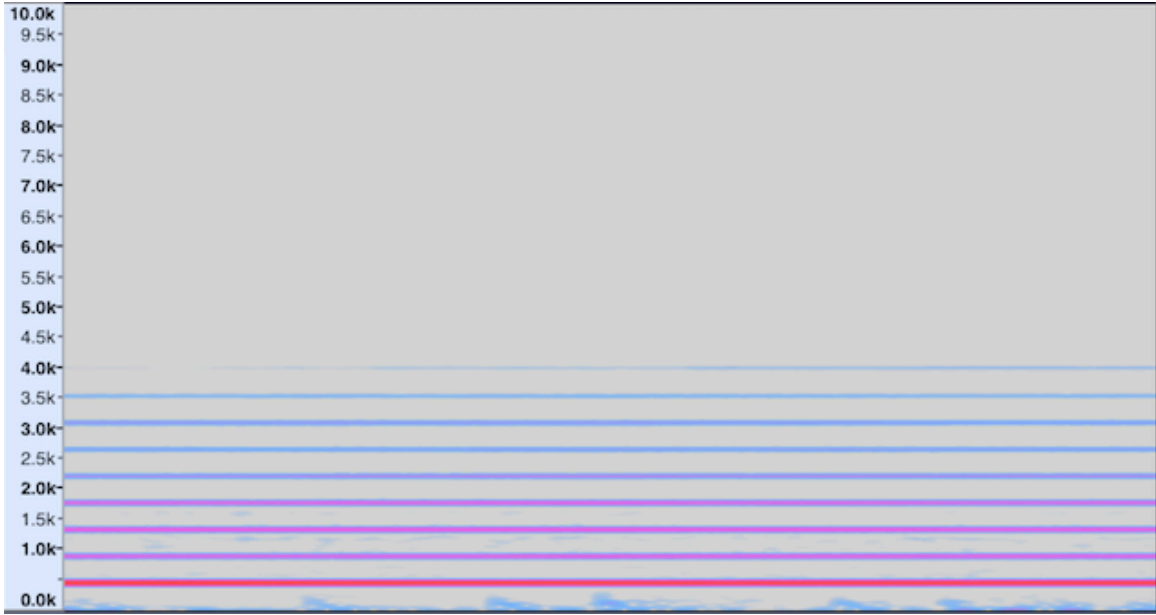
LIG



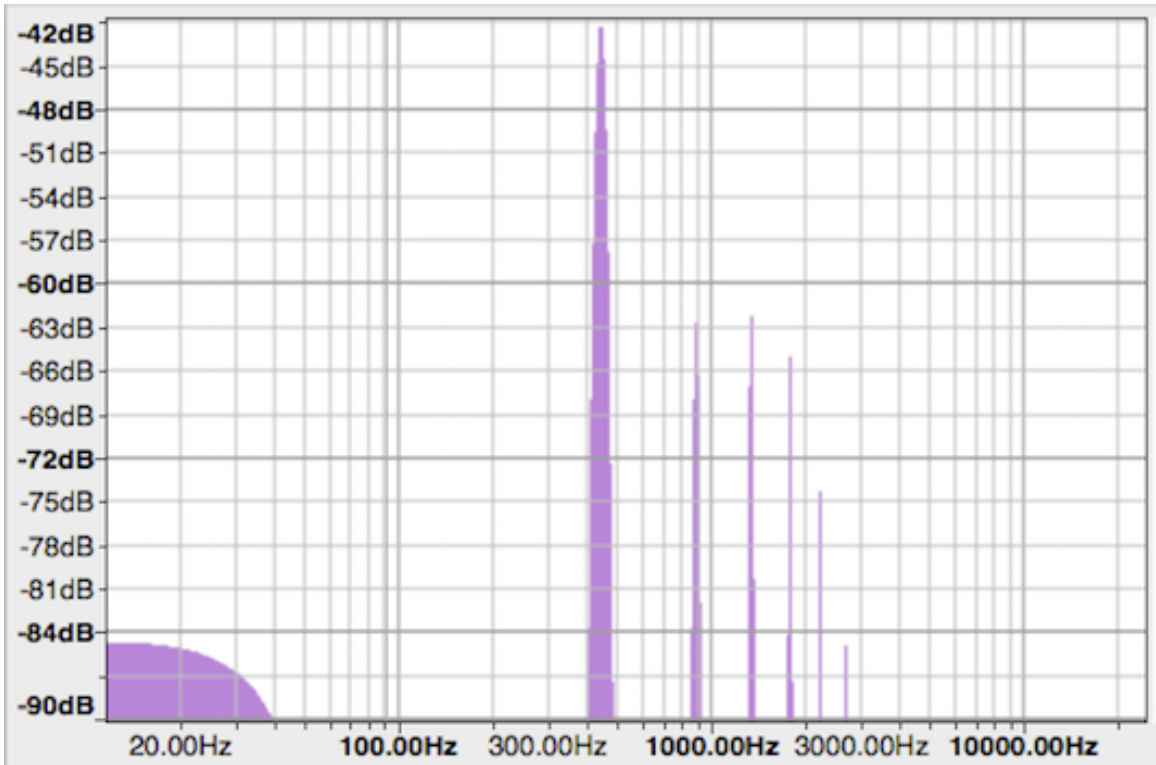
BAR Port



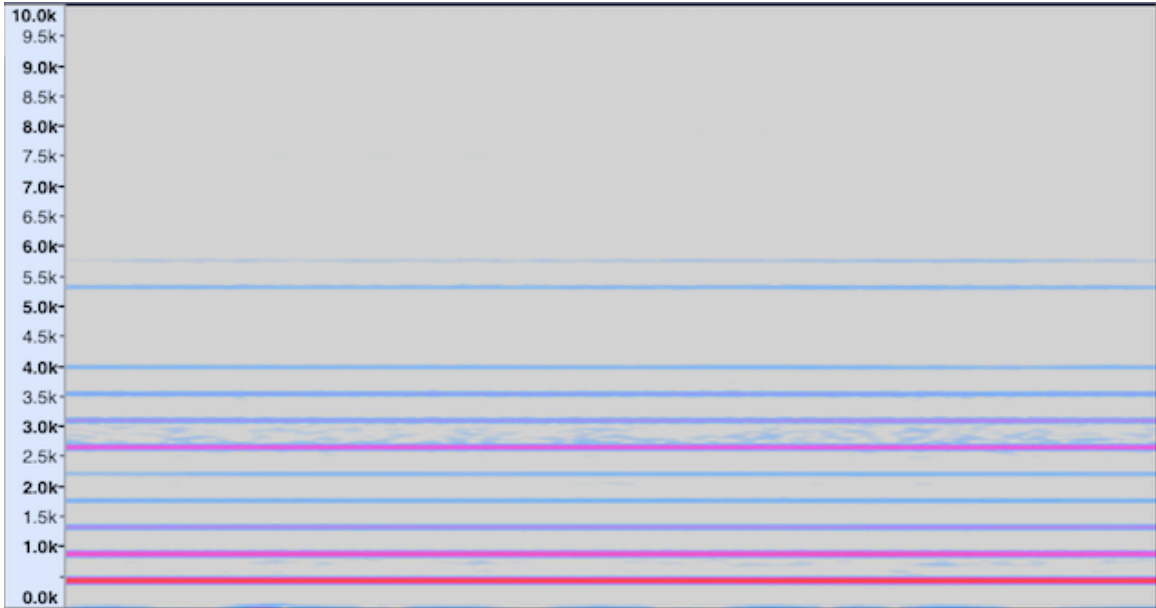
BAR Port



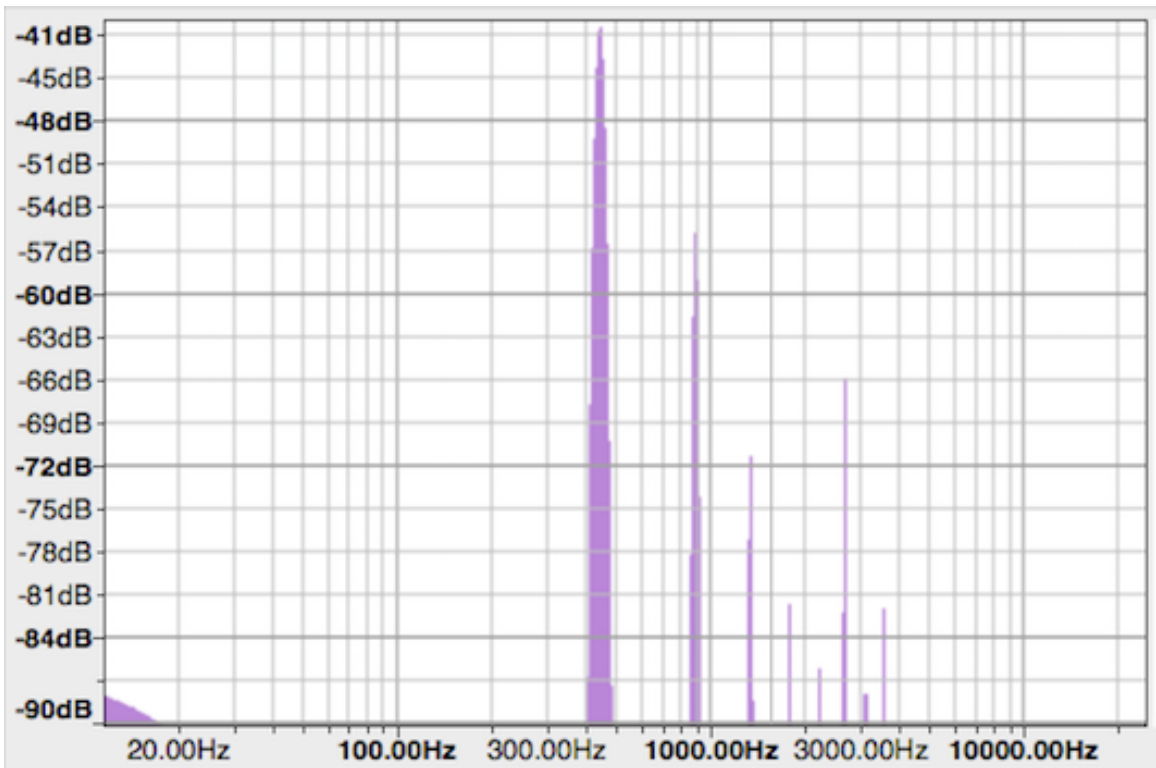
BAR Surf



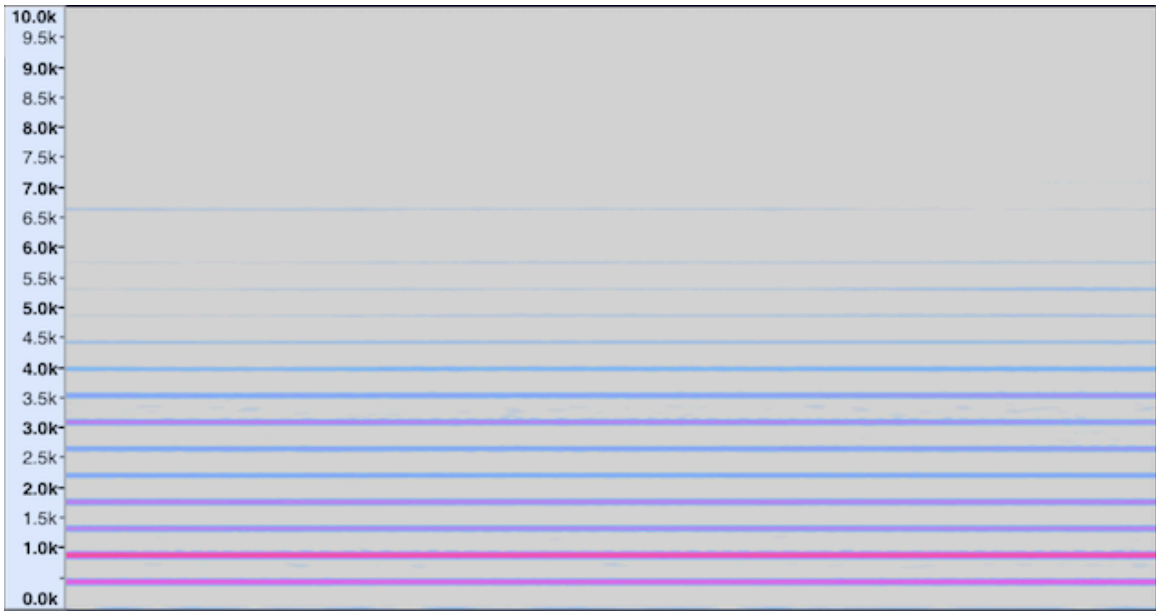
BAR Surf



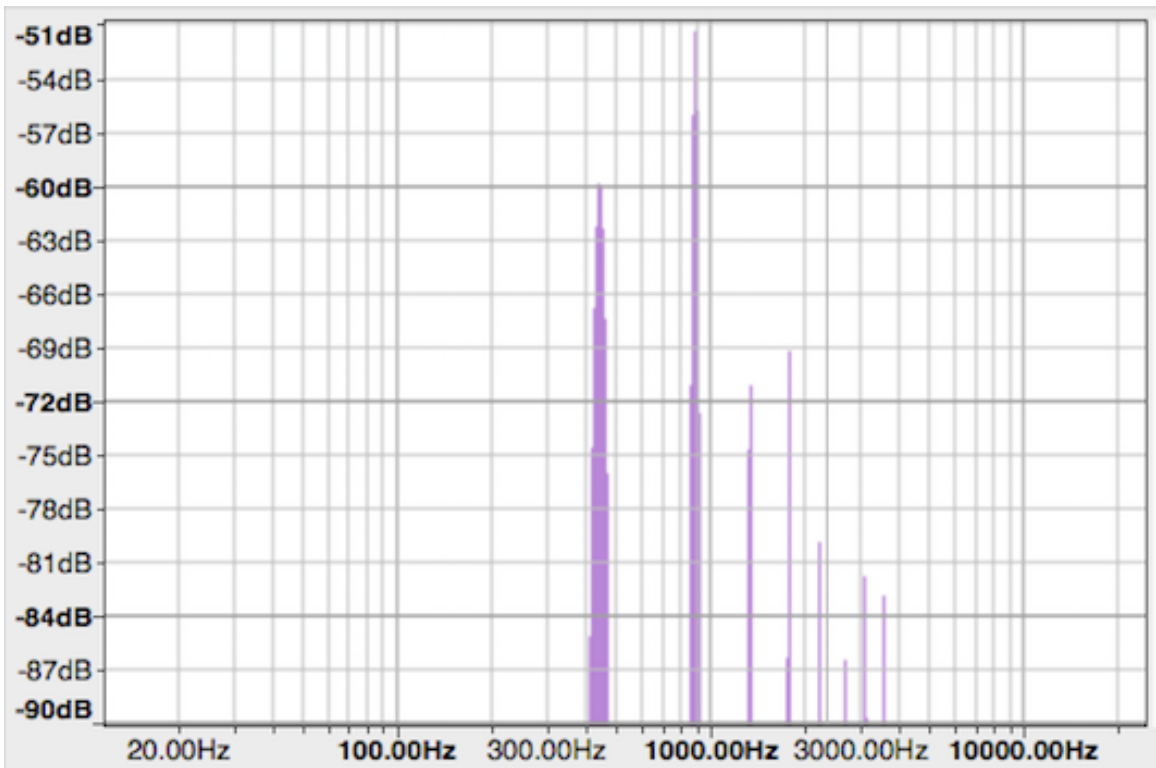
LF MPB



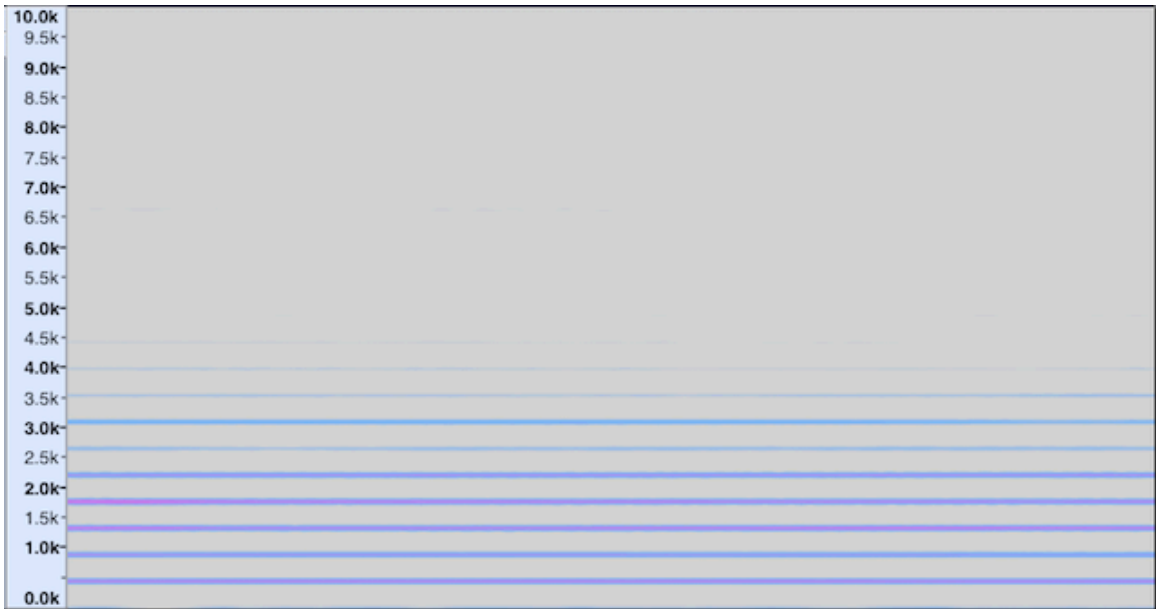
LF MPB



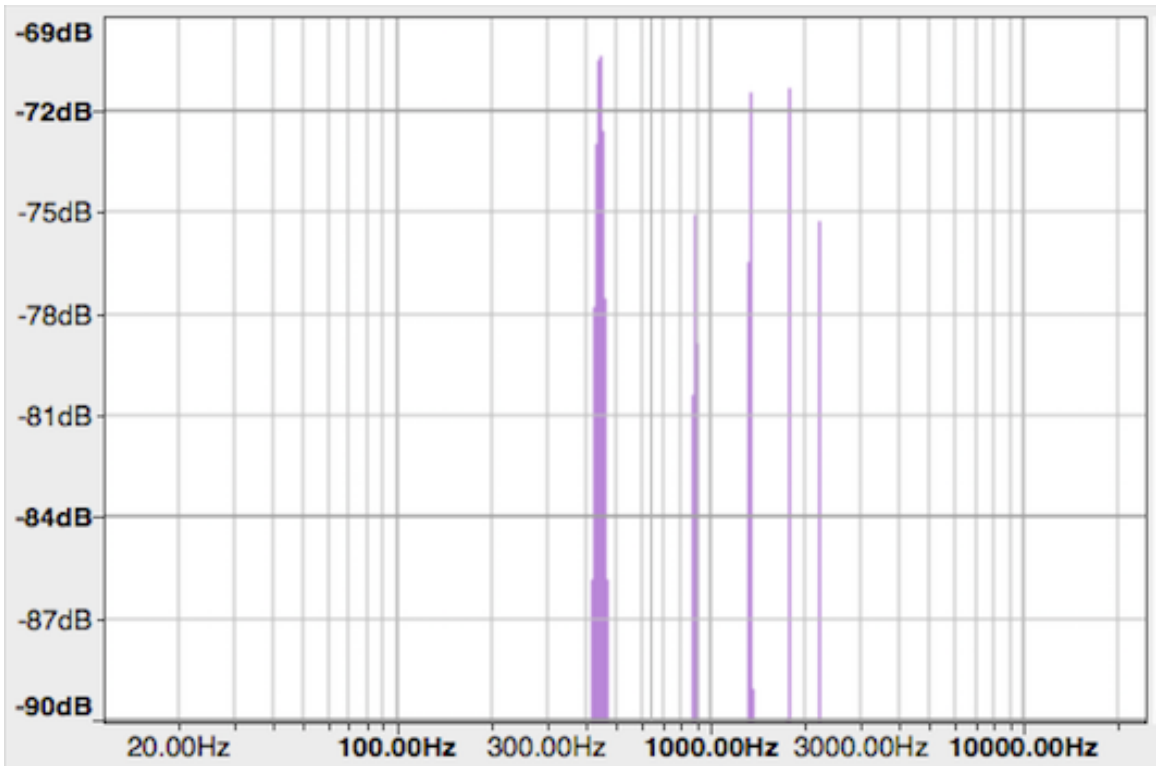
LF BUJ



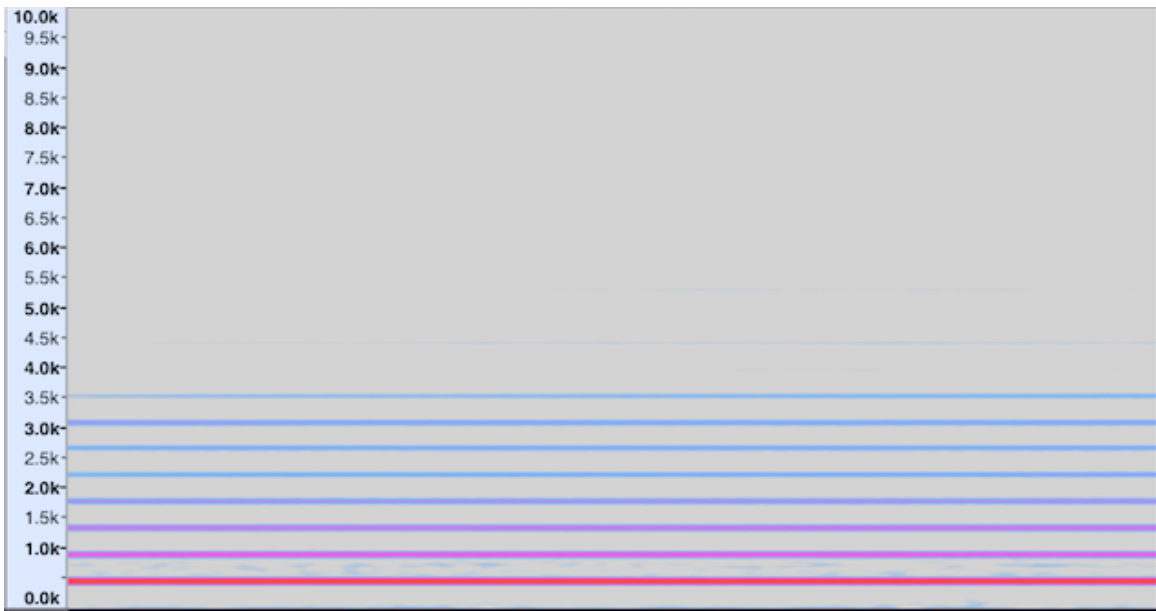
LF BUJ



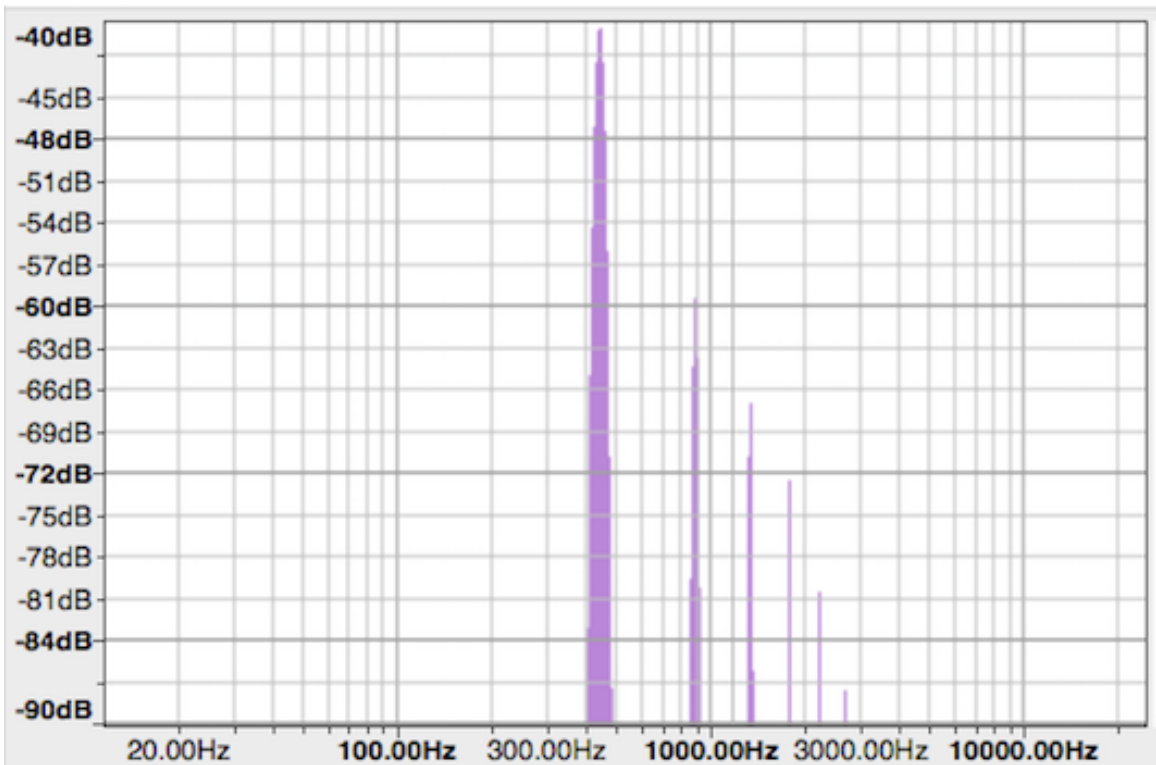
UJ



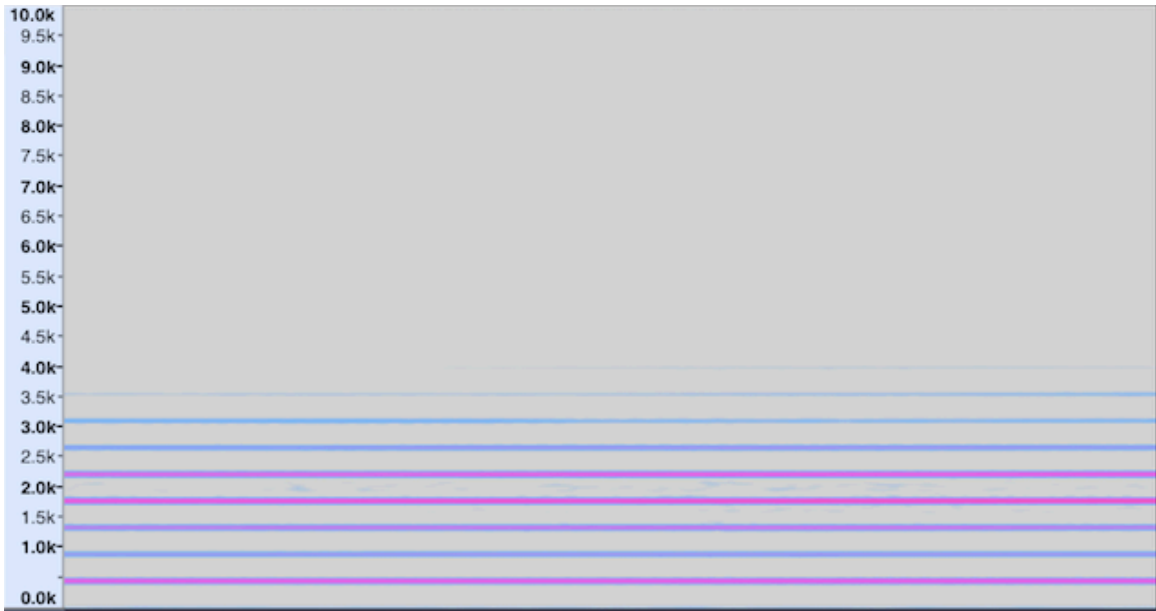
UJ



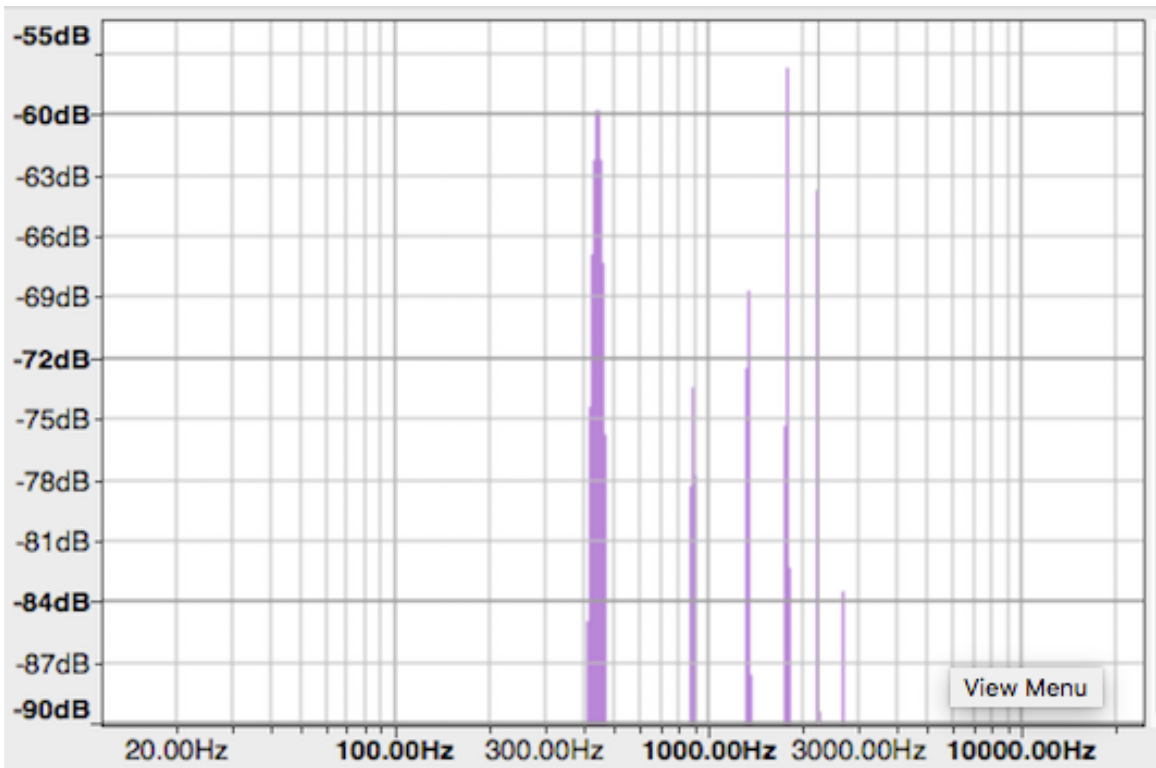
CTR



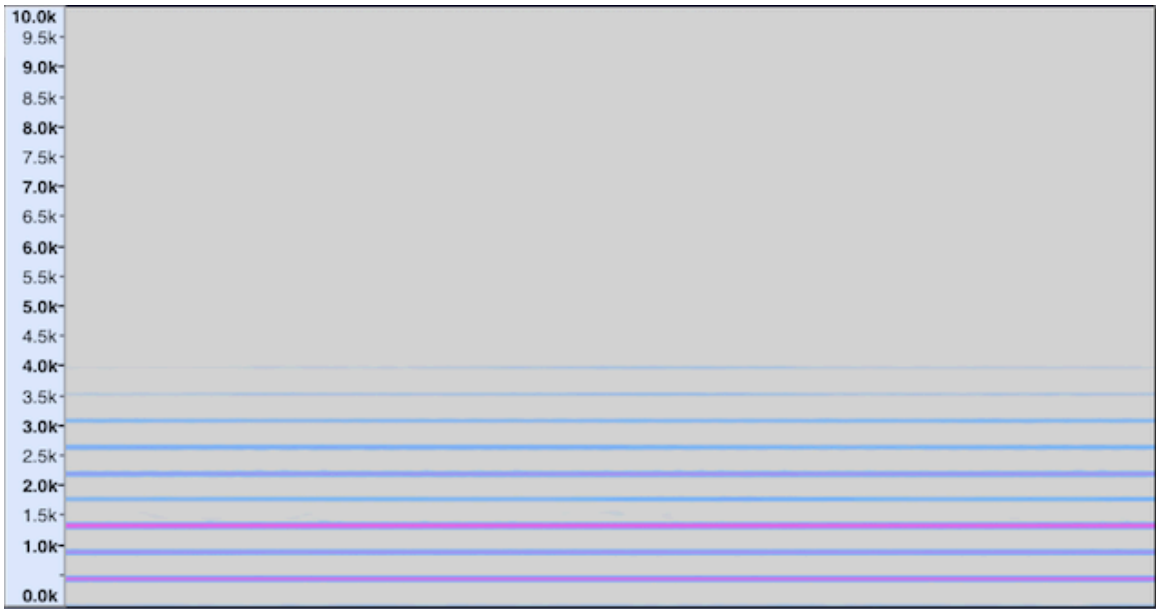
CTR



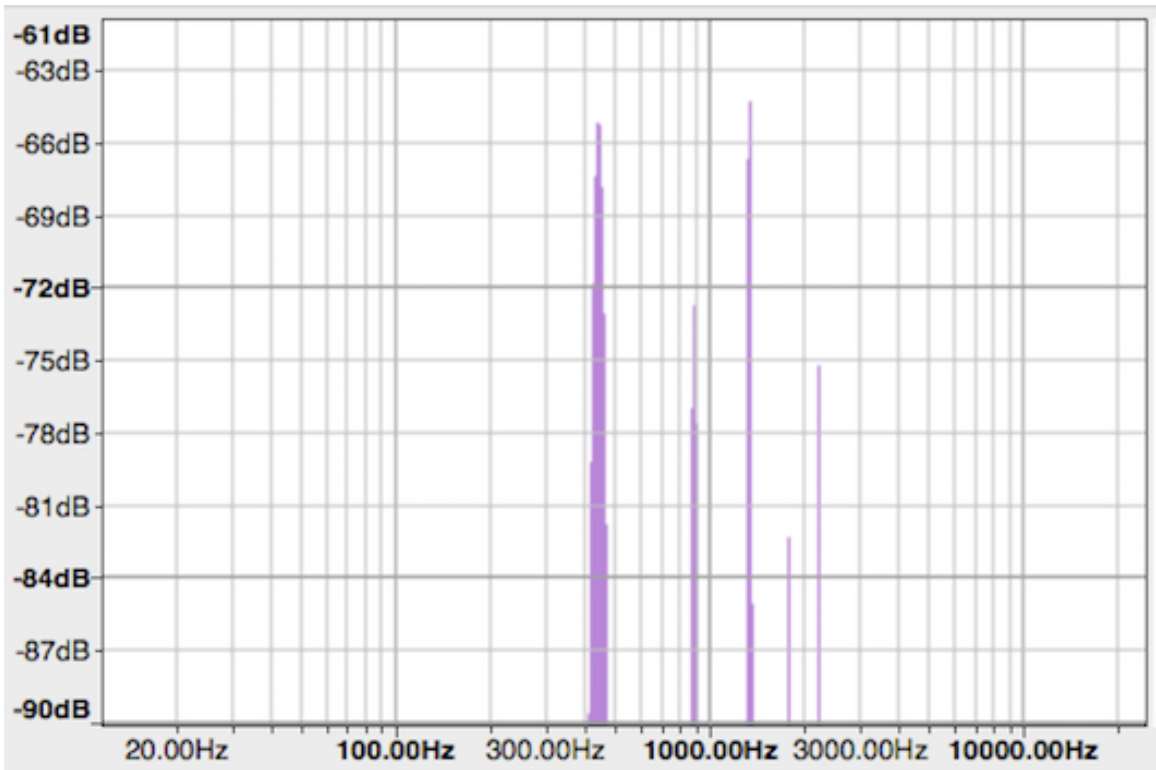
LJ



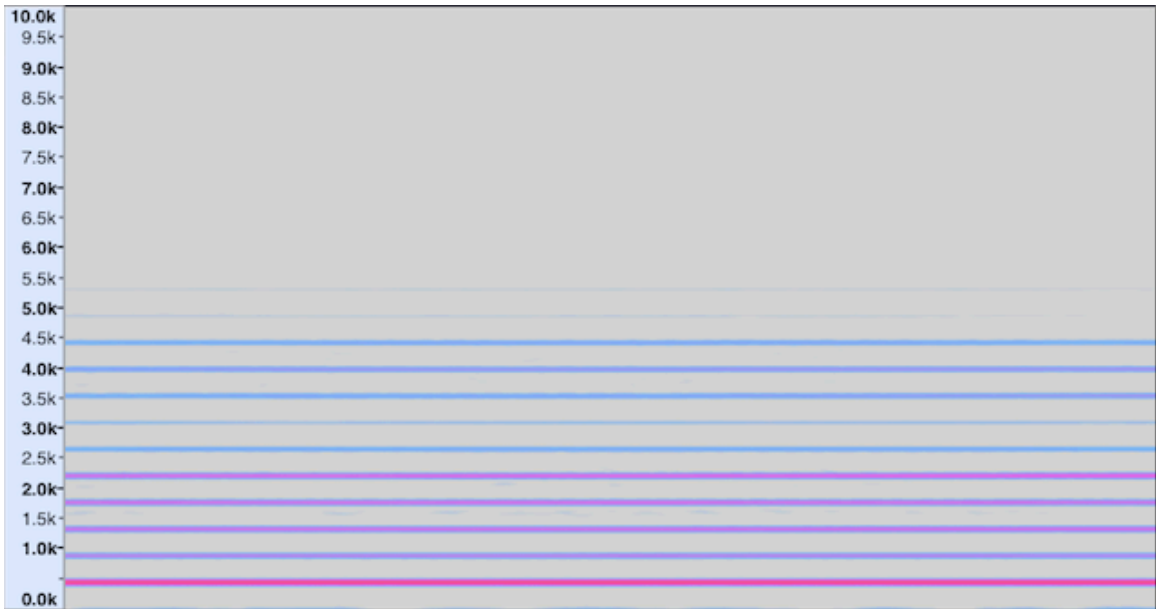
LJ



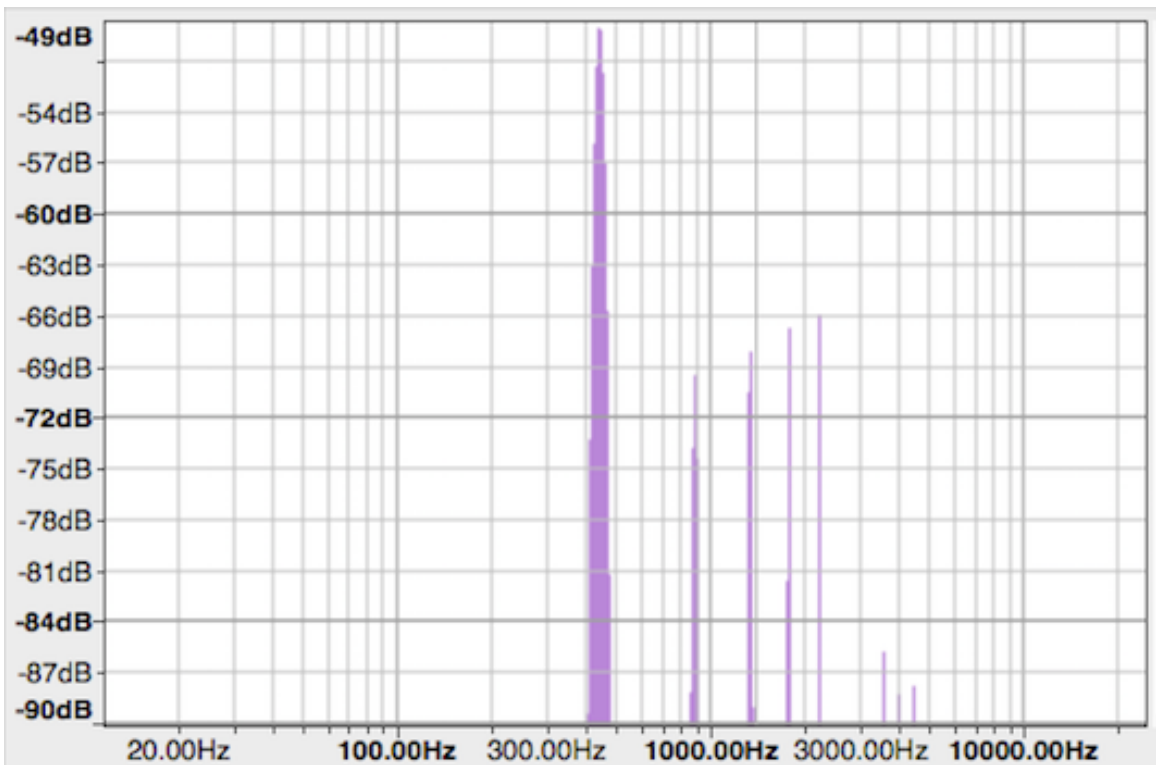
BELL Out



BELL Out

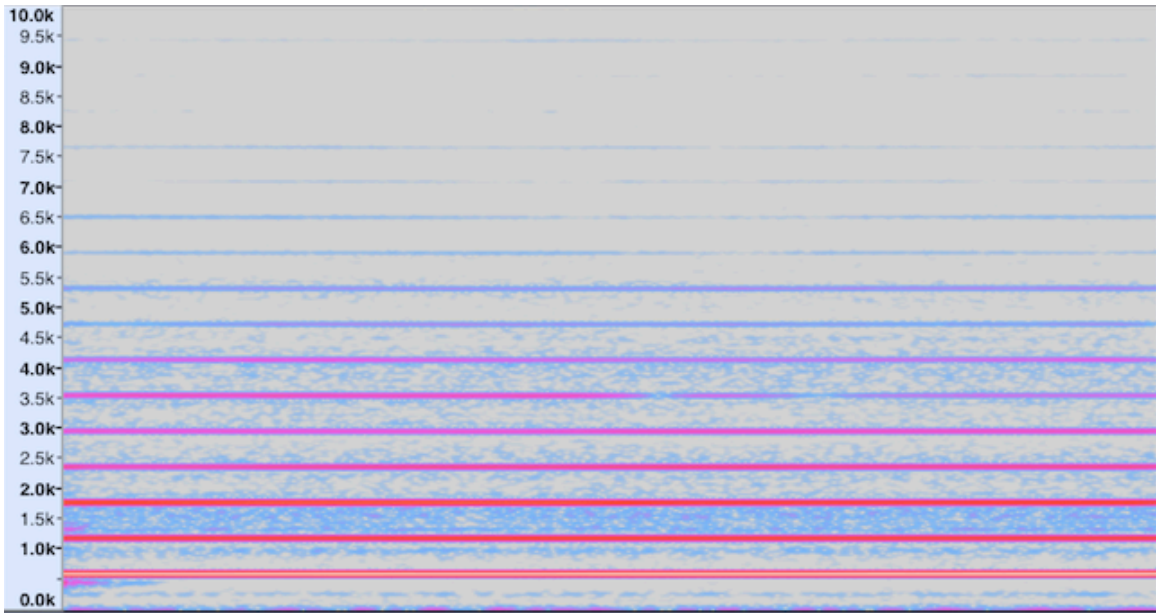


BELL End

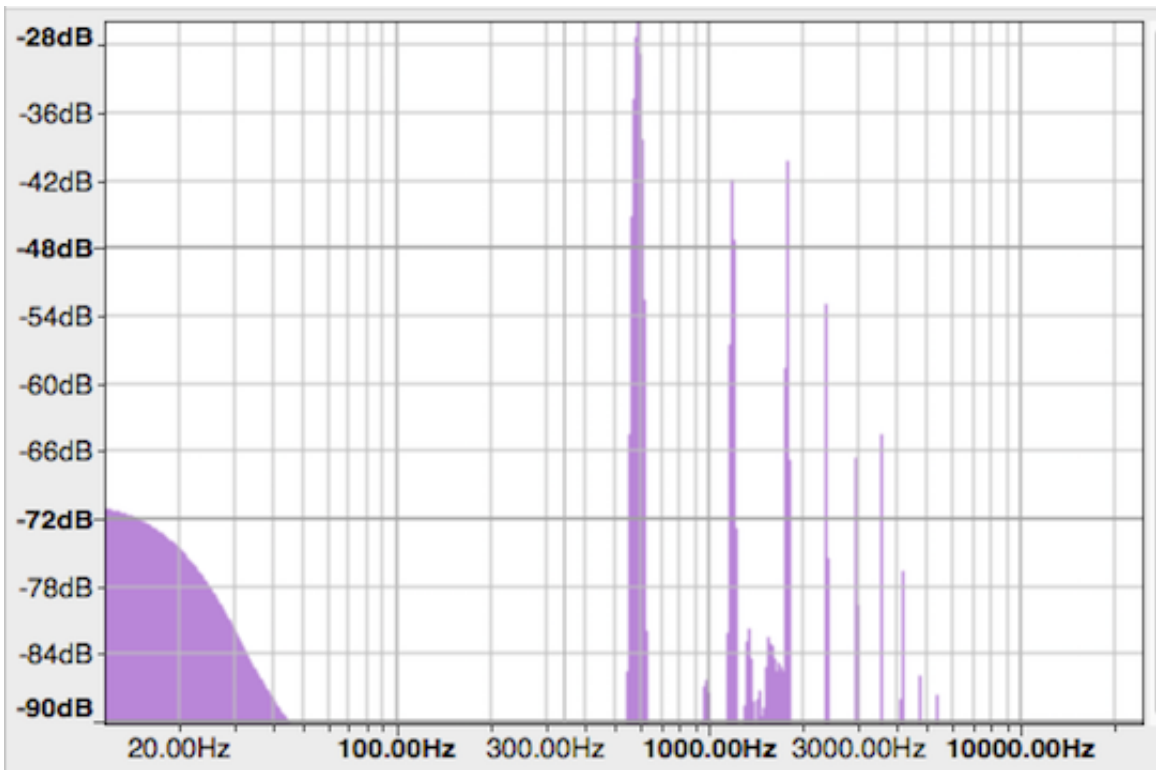


BELL End

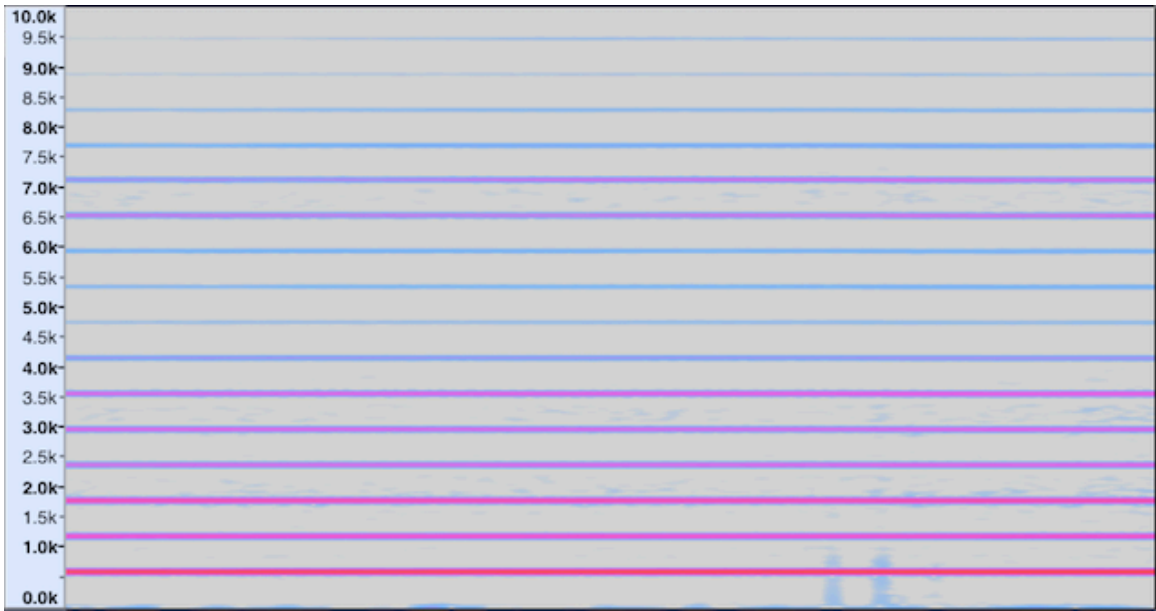
APPENDIX K  
SAMPLE DATA E5



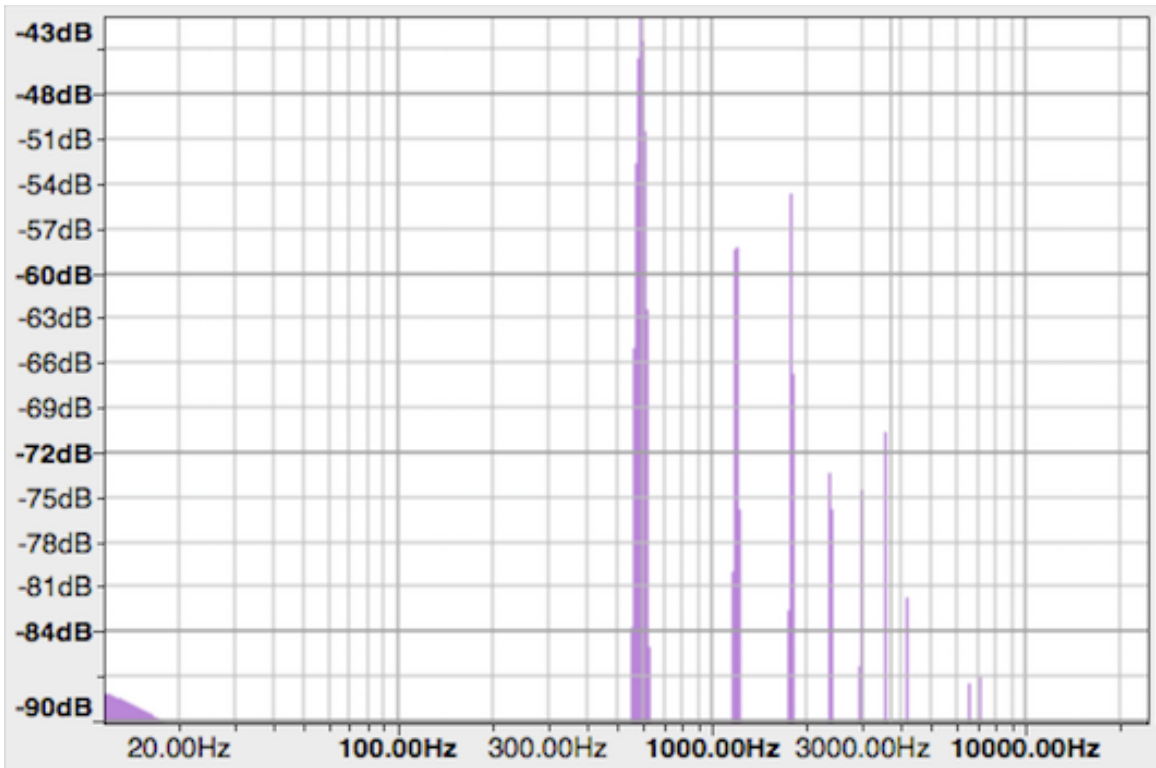
M30 (Reference)



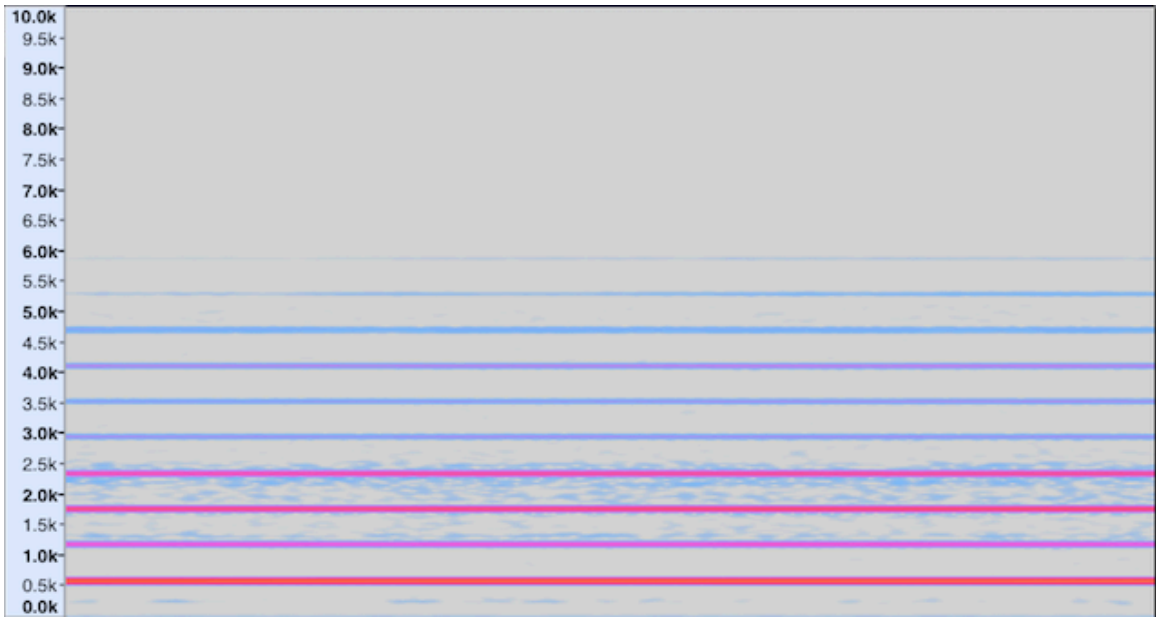
M30 (Reference)



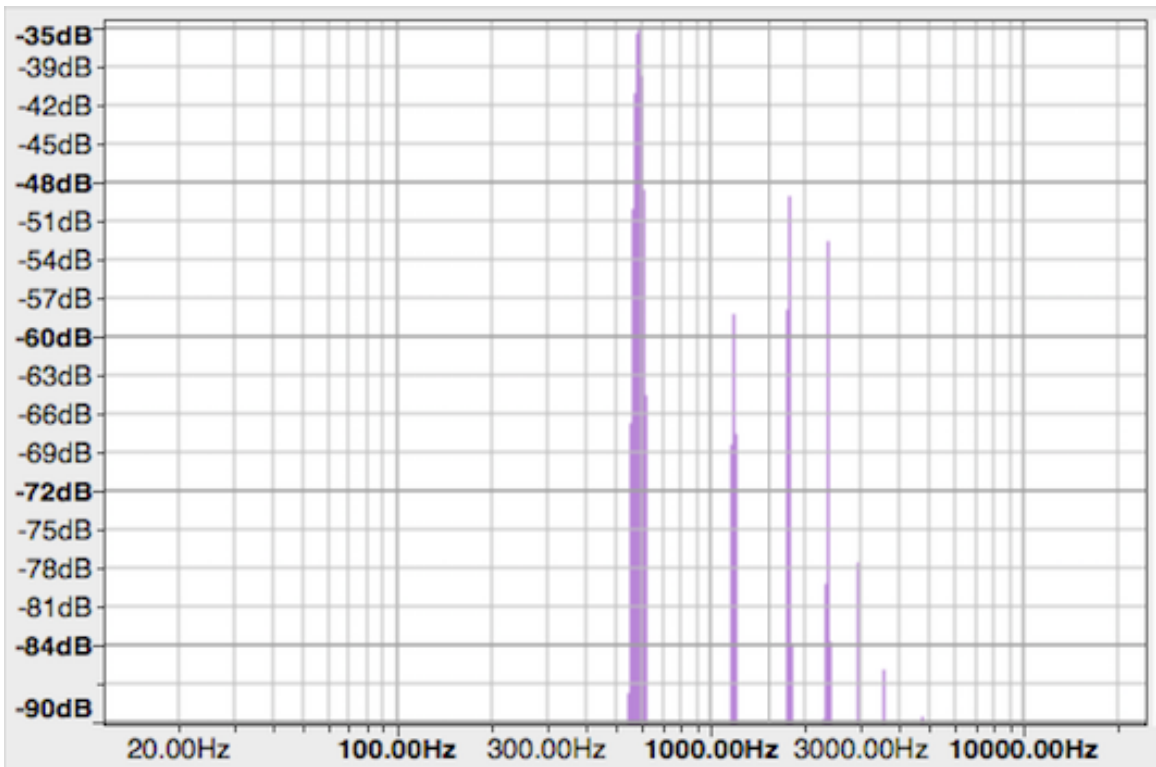
LIG



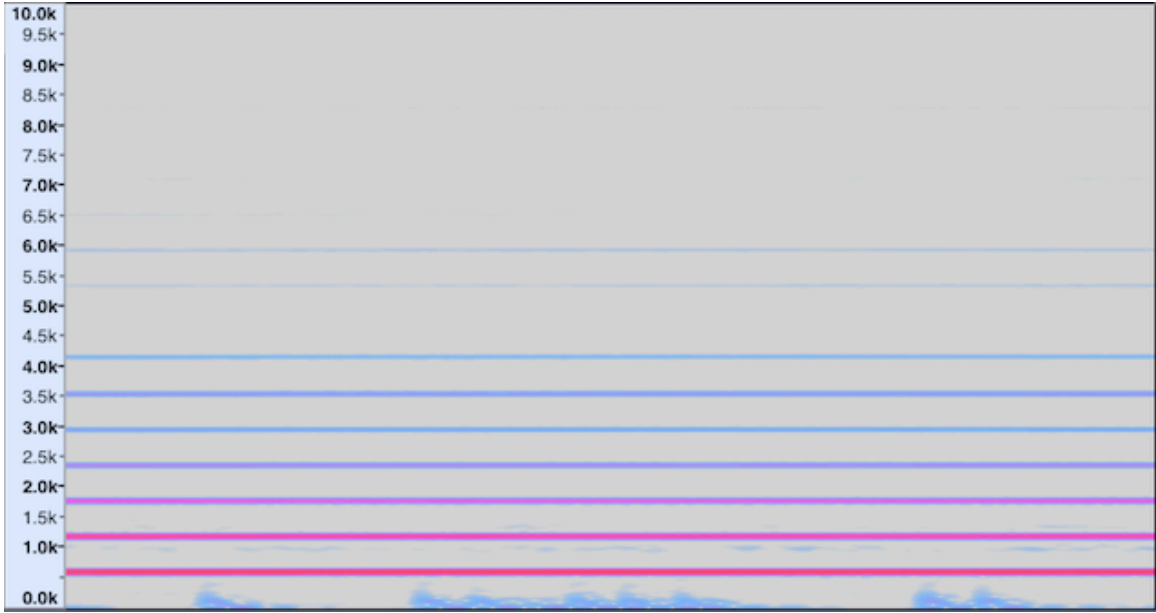
LIG



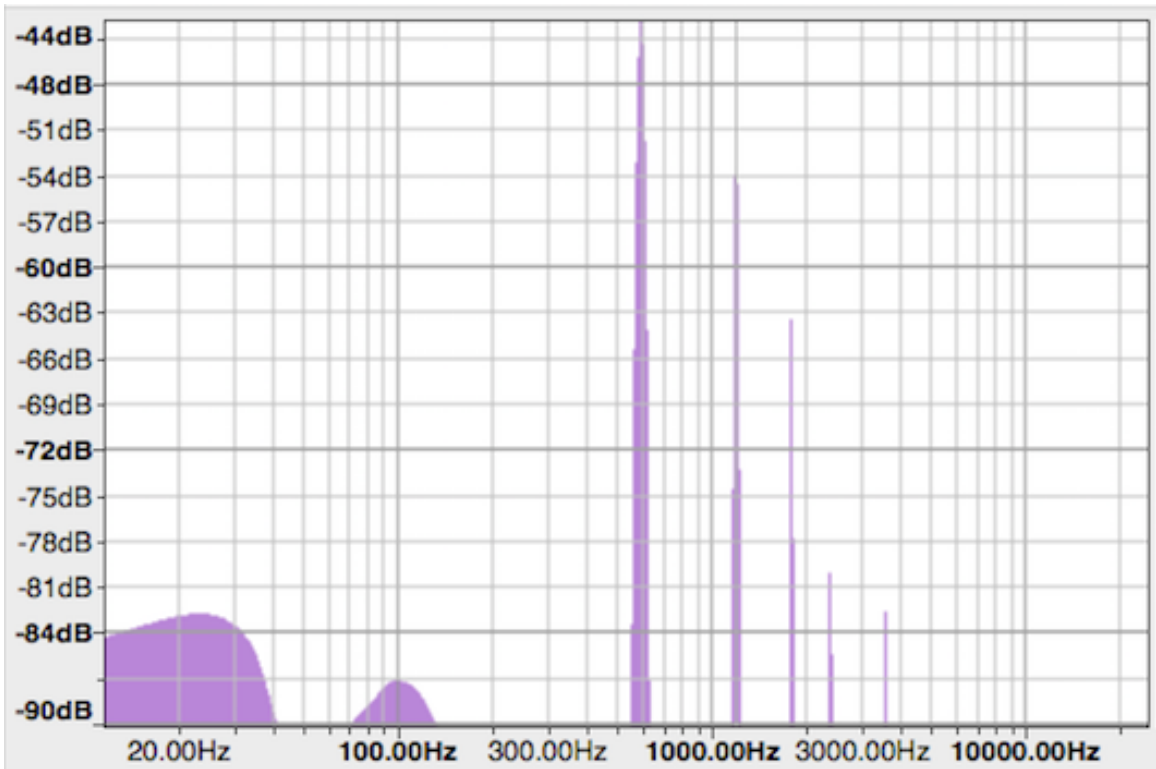
BAR Port



BAR Port



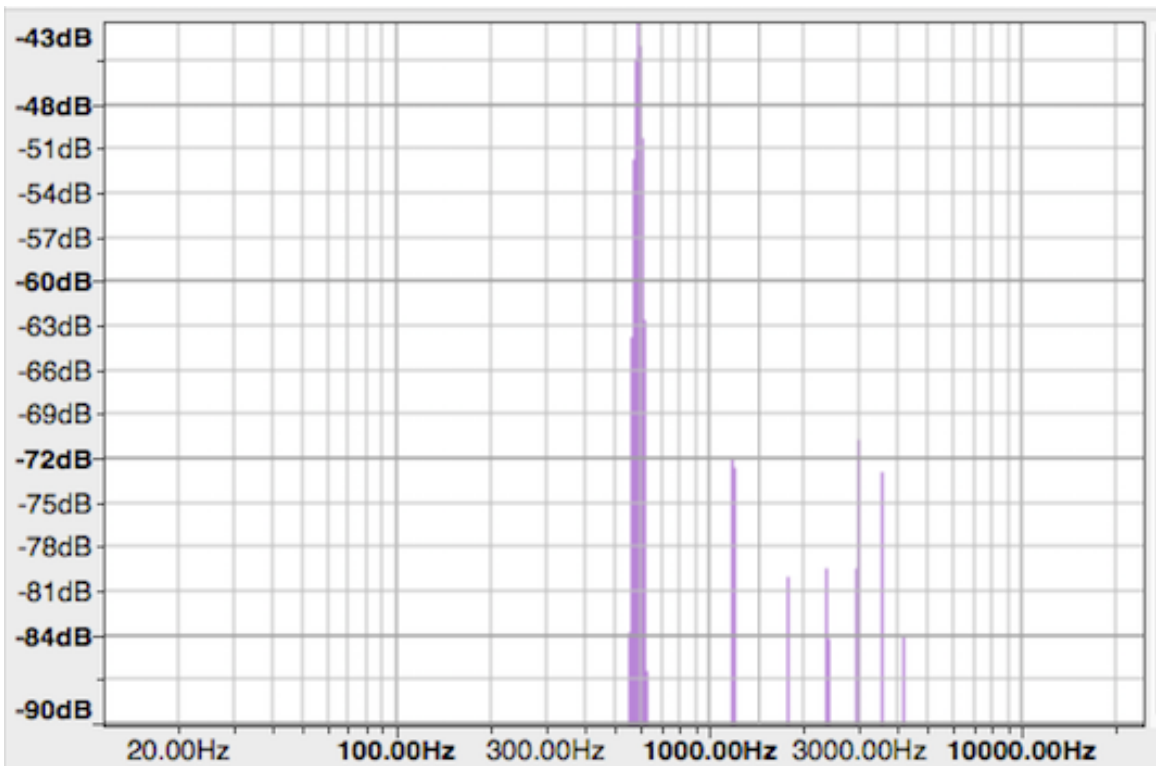
BAR Surf



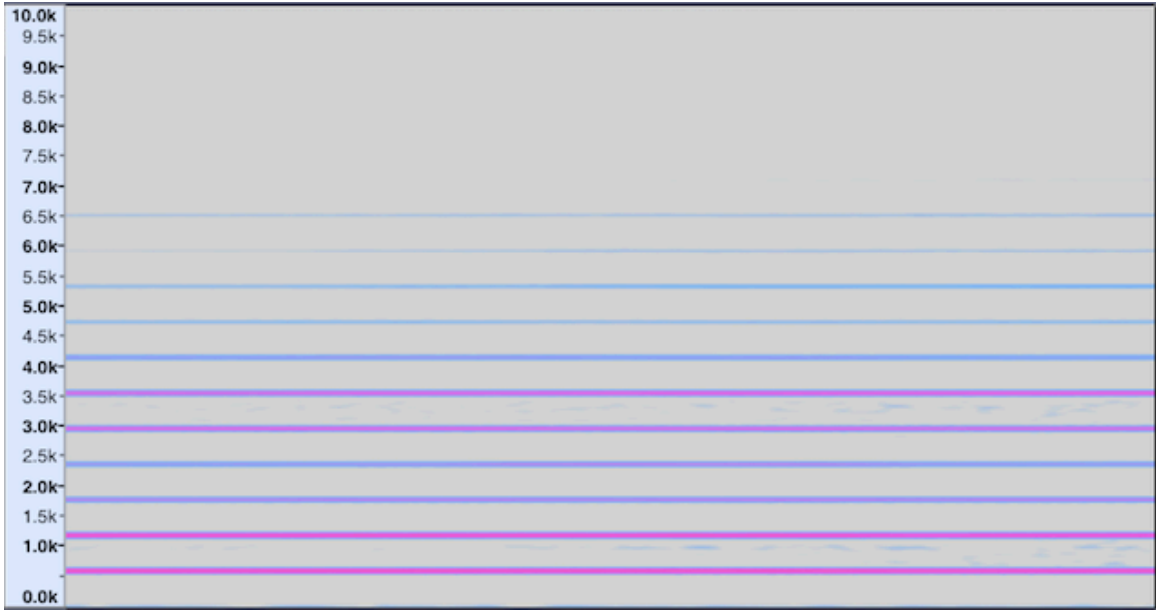
BAR Surf



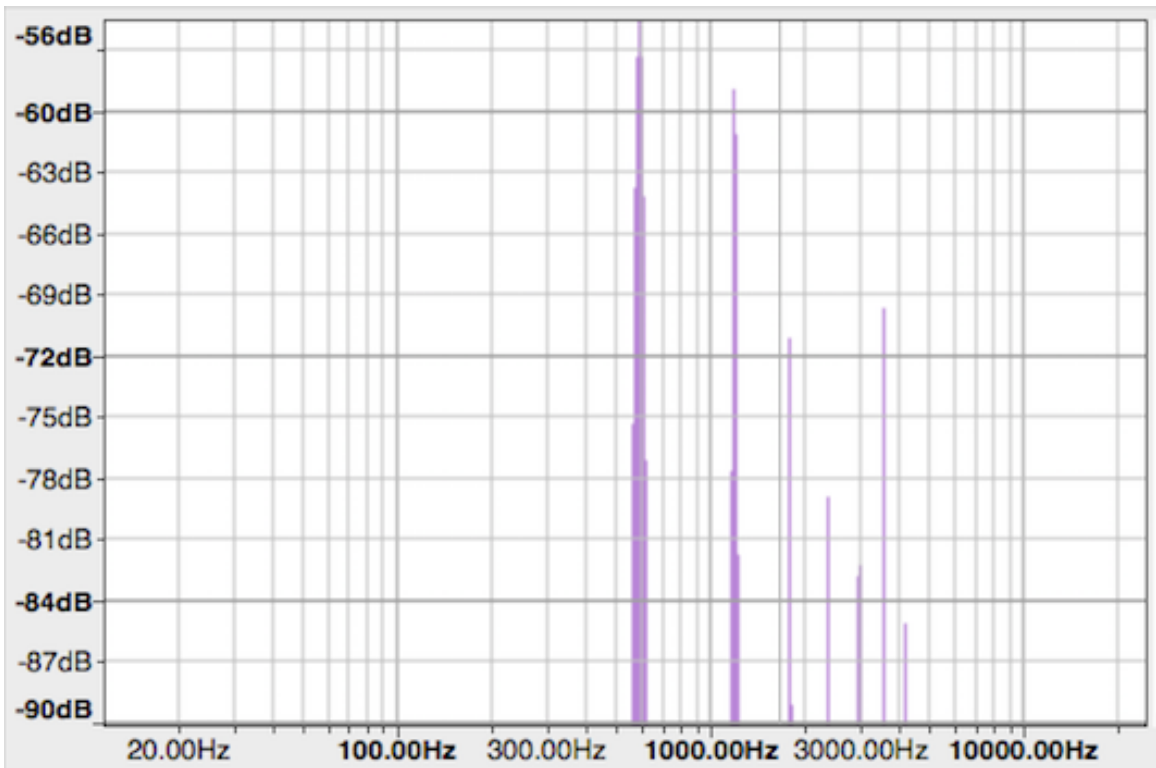
LF MPB



LF MPB



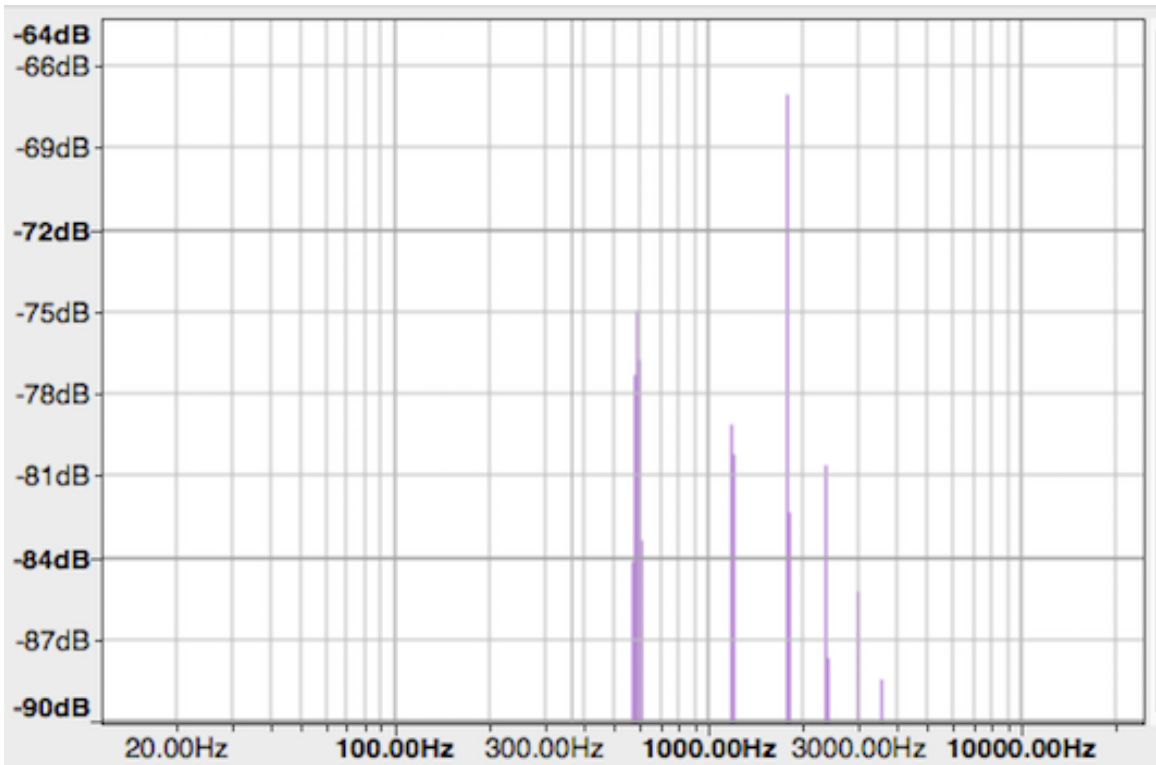
LF BUJ



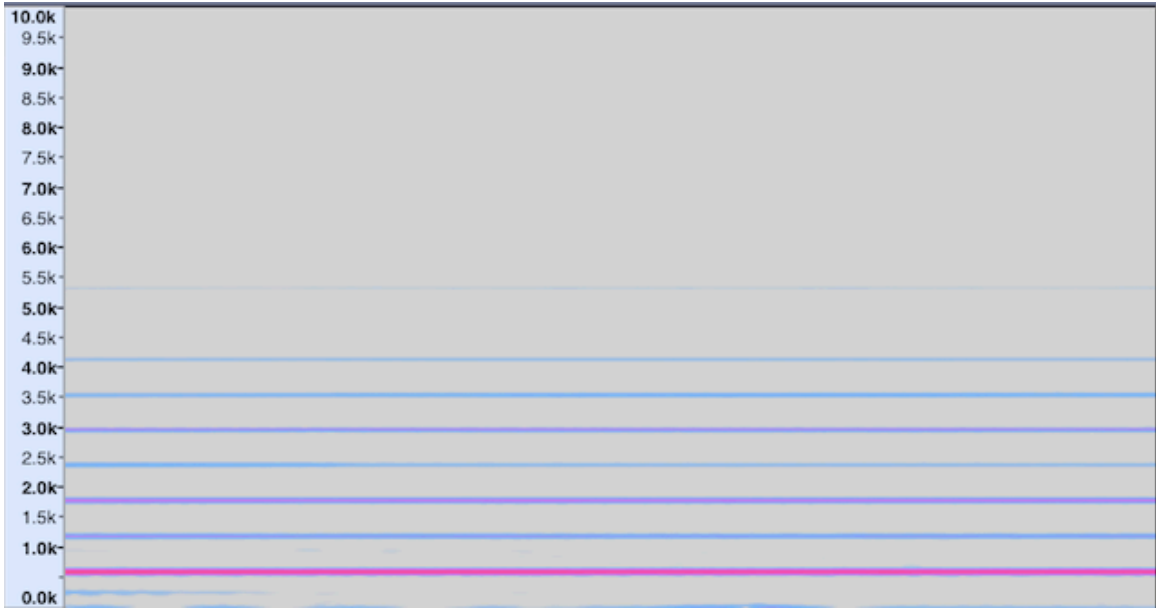
LF BUJ



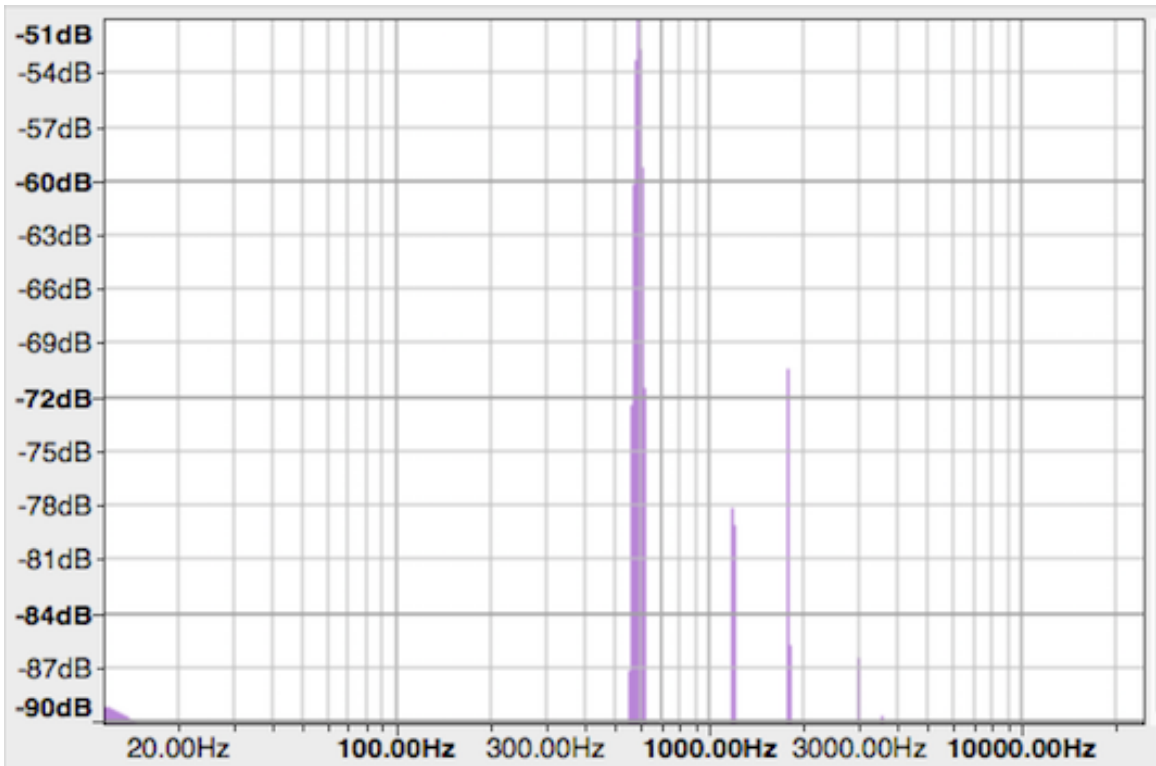
UJ



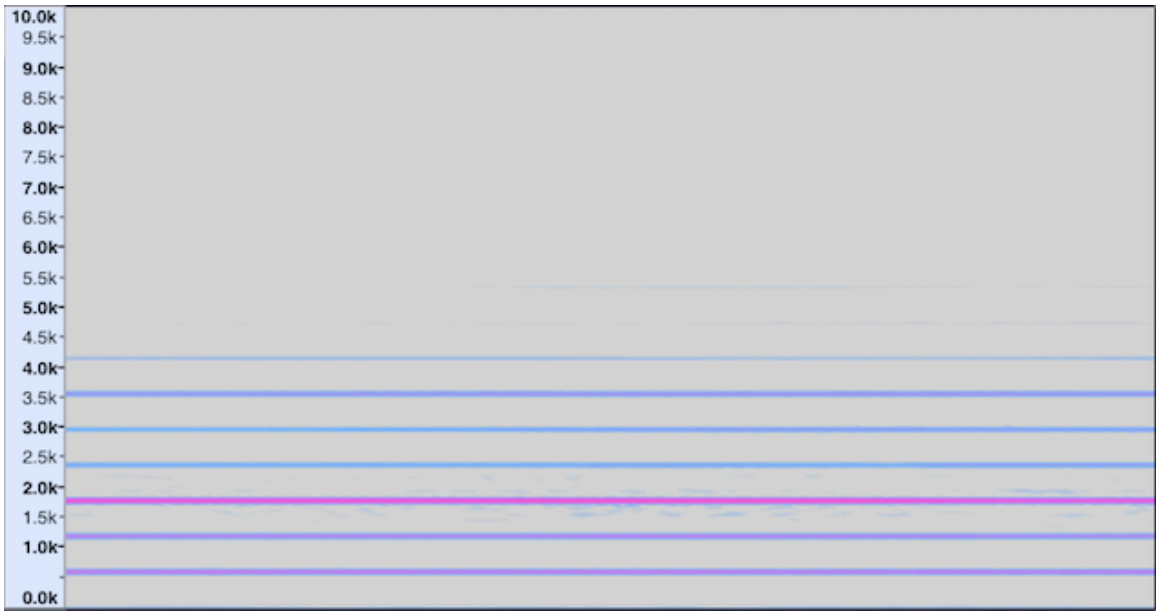
UJ



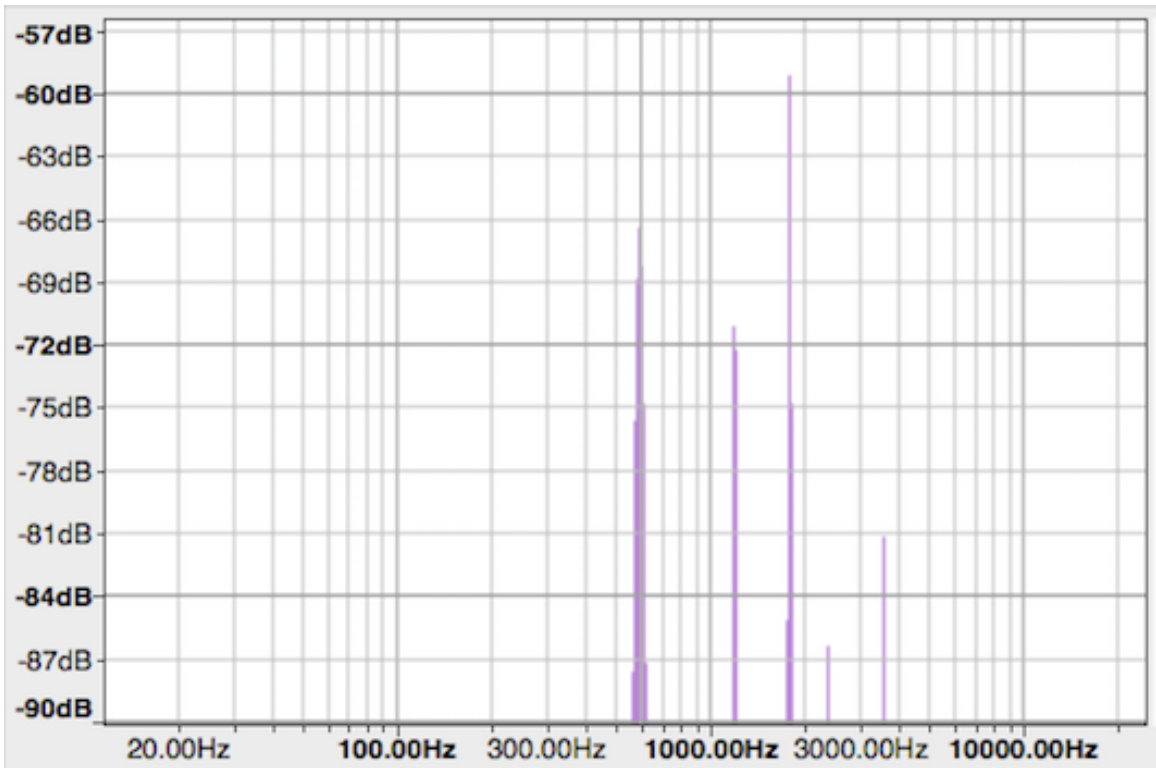
CTR



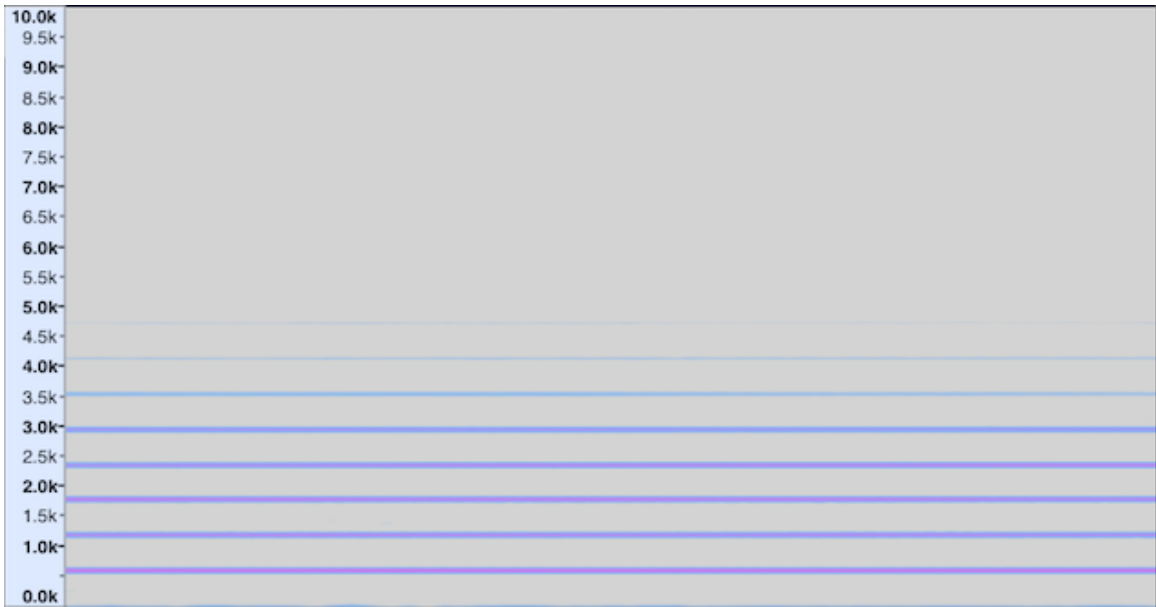
CTR



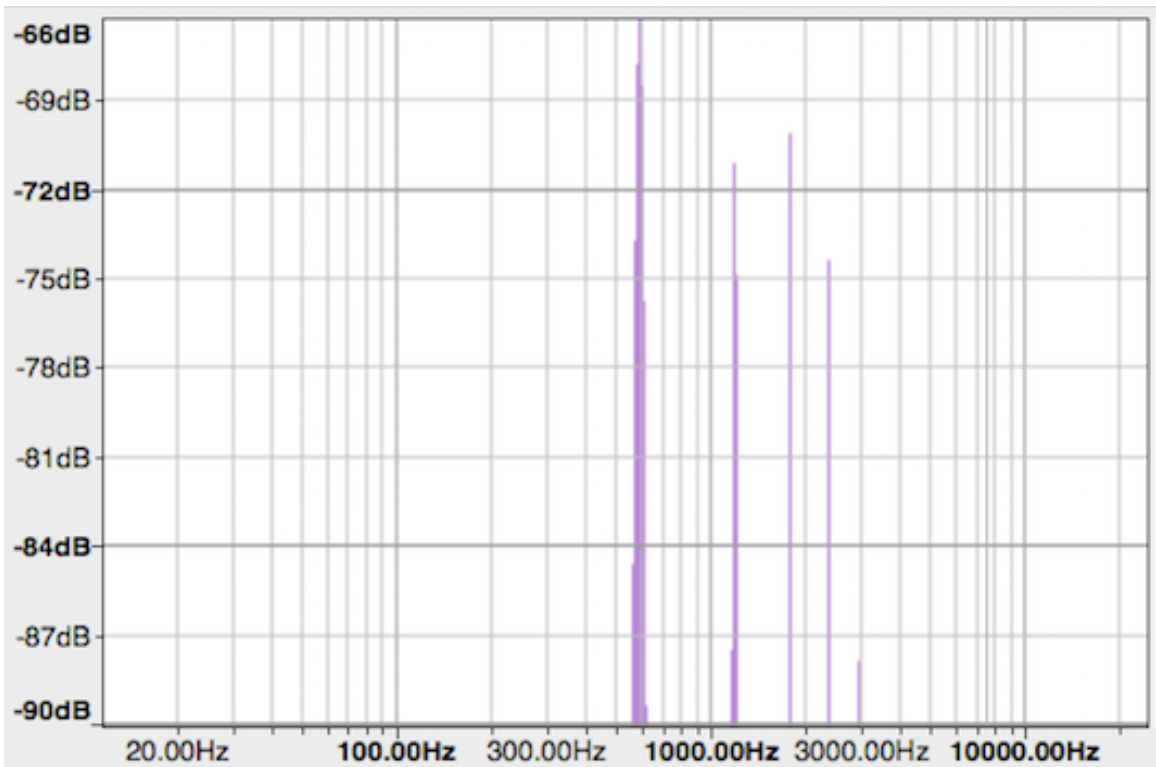
LJ



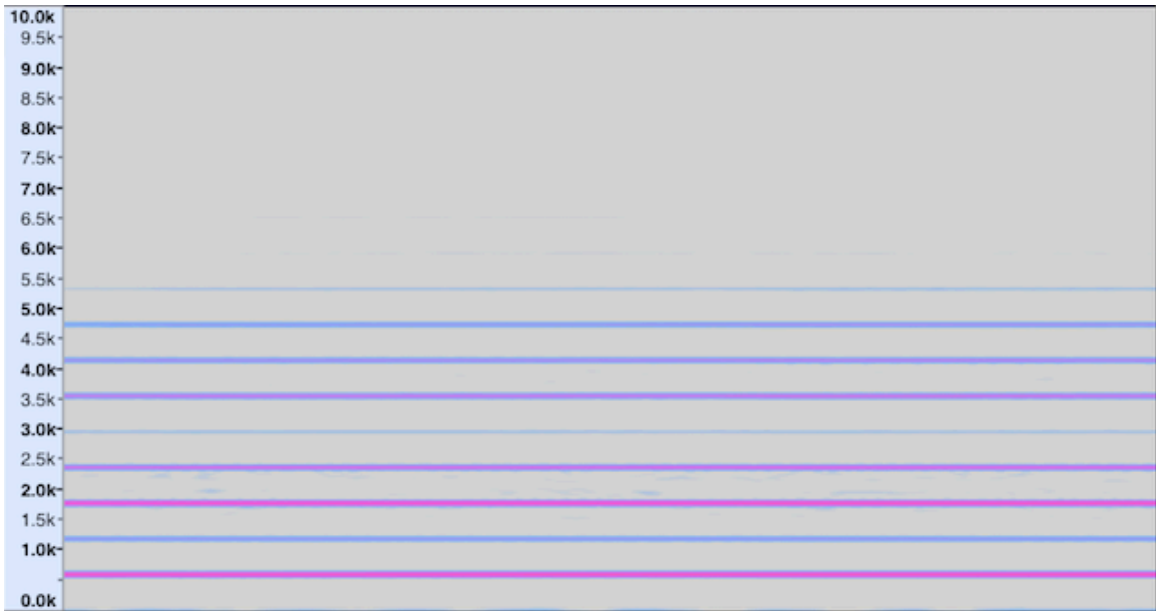
LJ



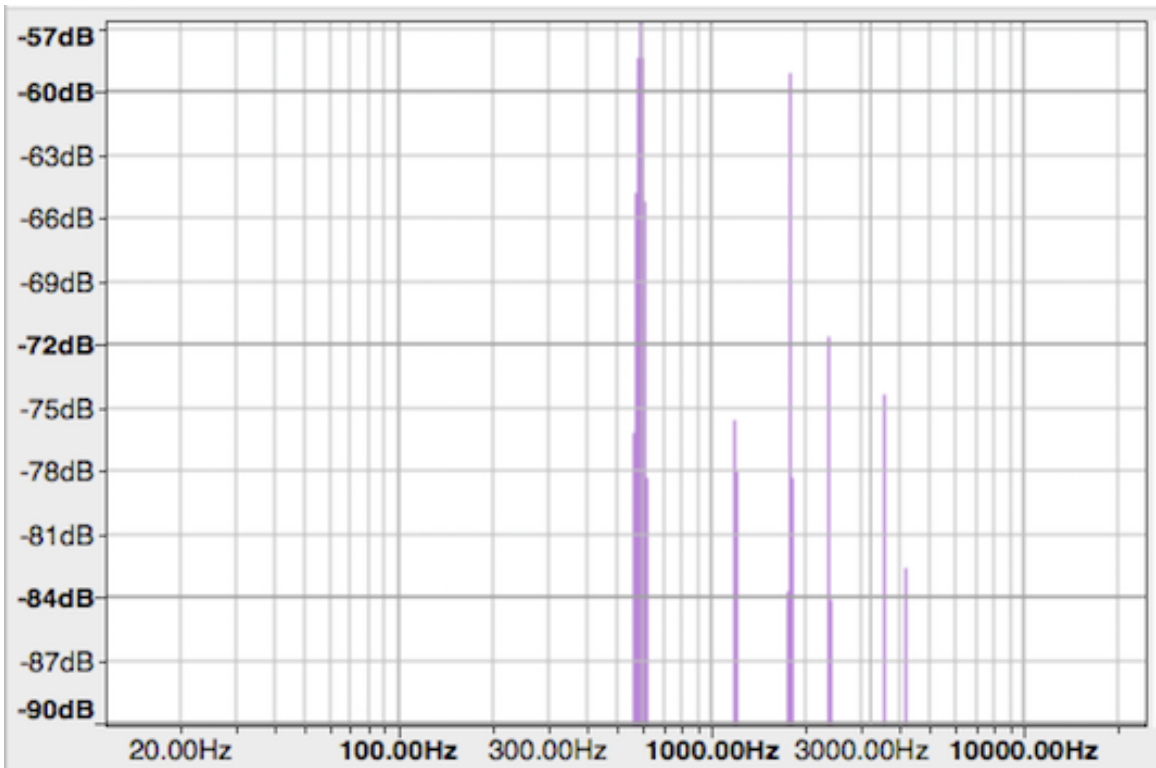
BELL Out



BELL Out

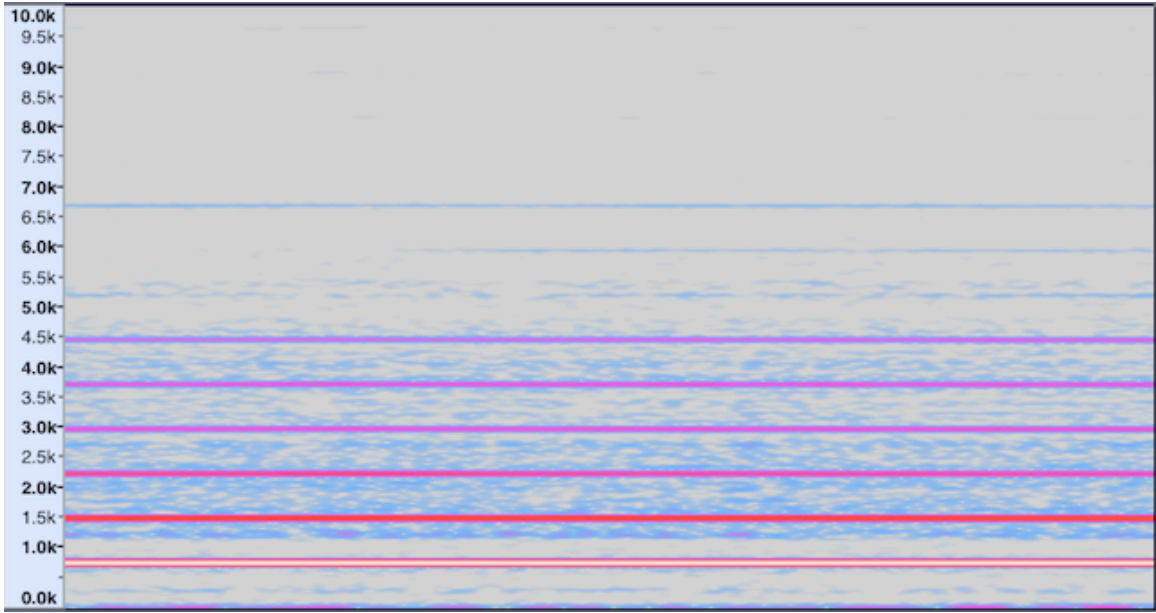


BELL End

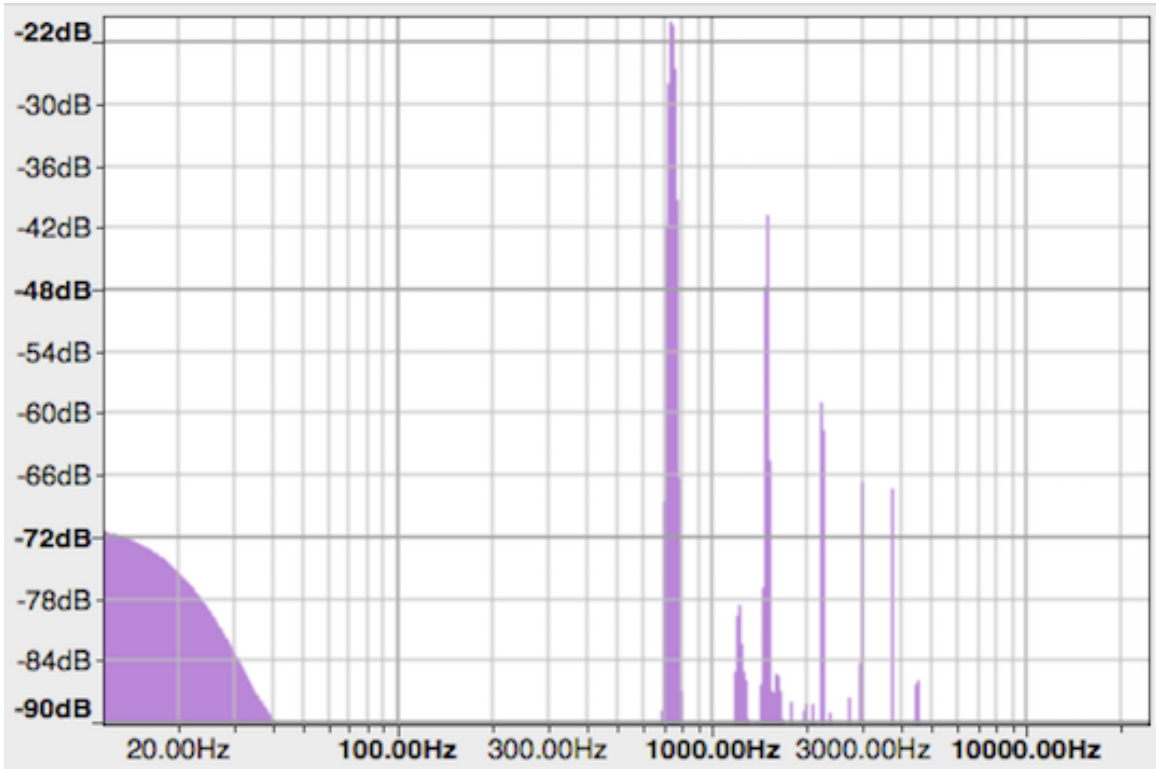


BELL End

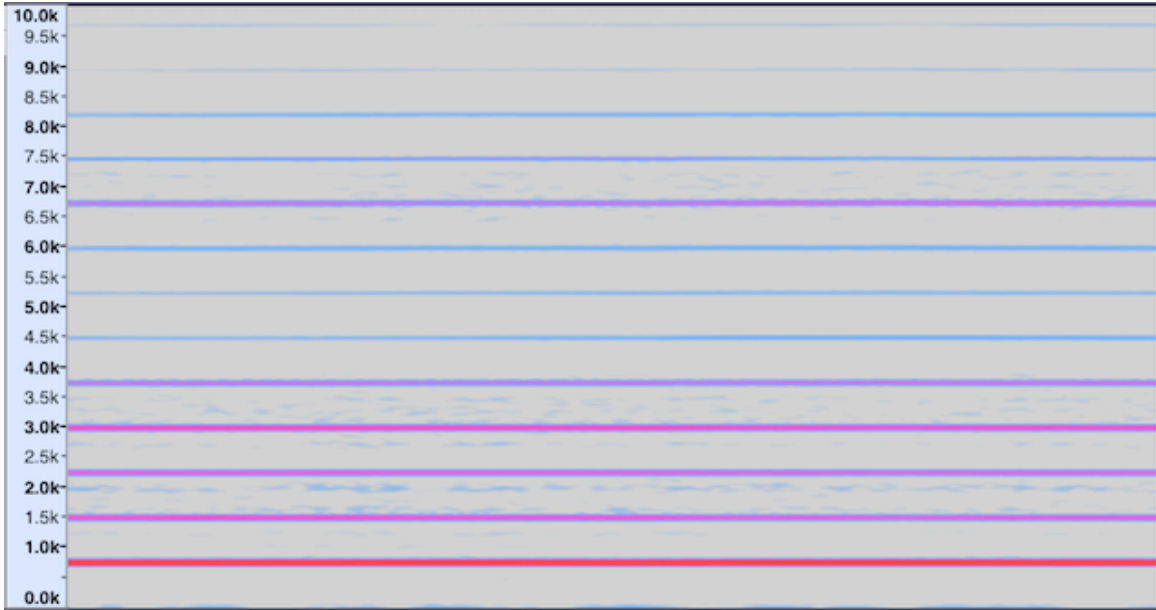
APPENDIX L  
SAMPLE DATA G-SHARP5



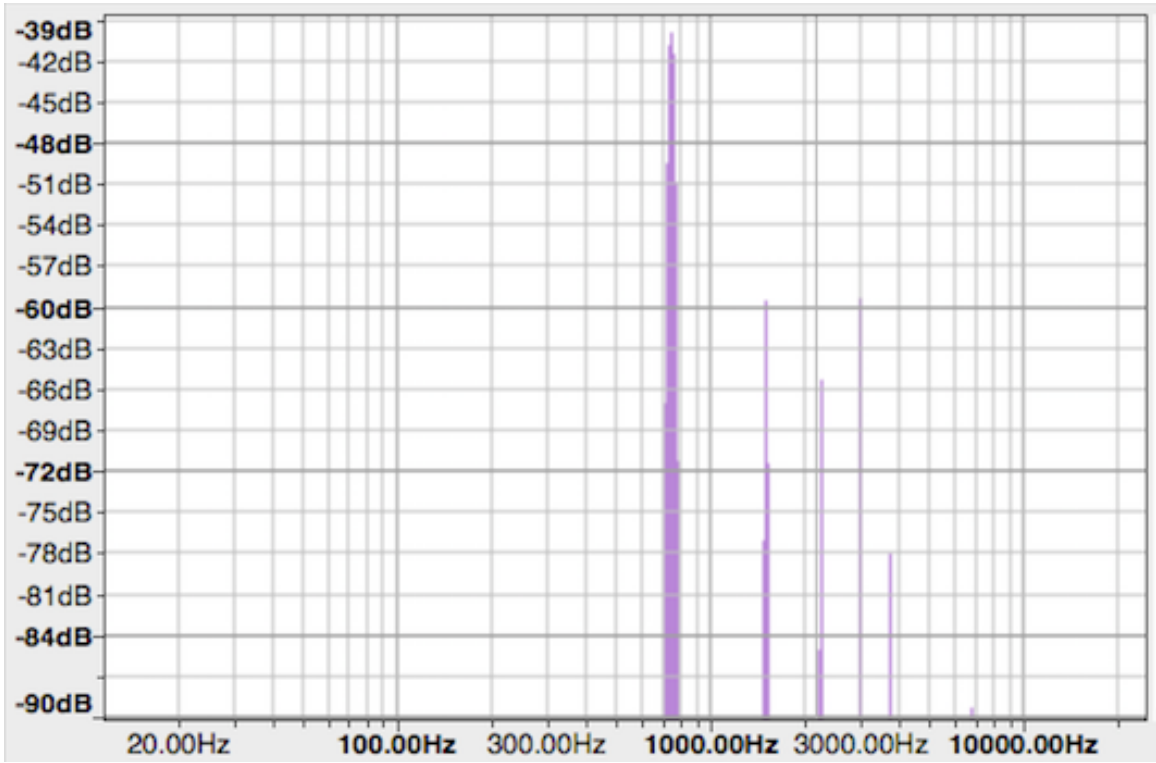
M30 (Reference)



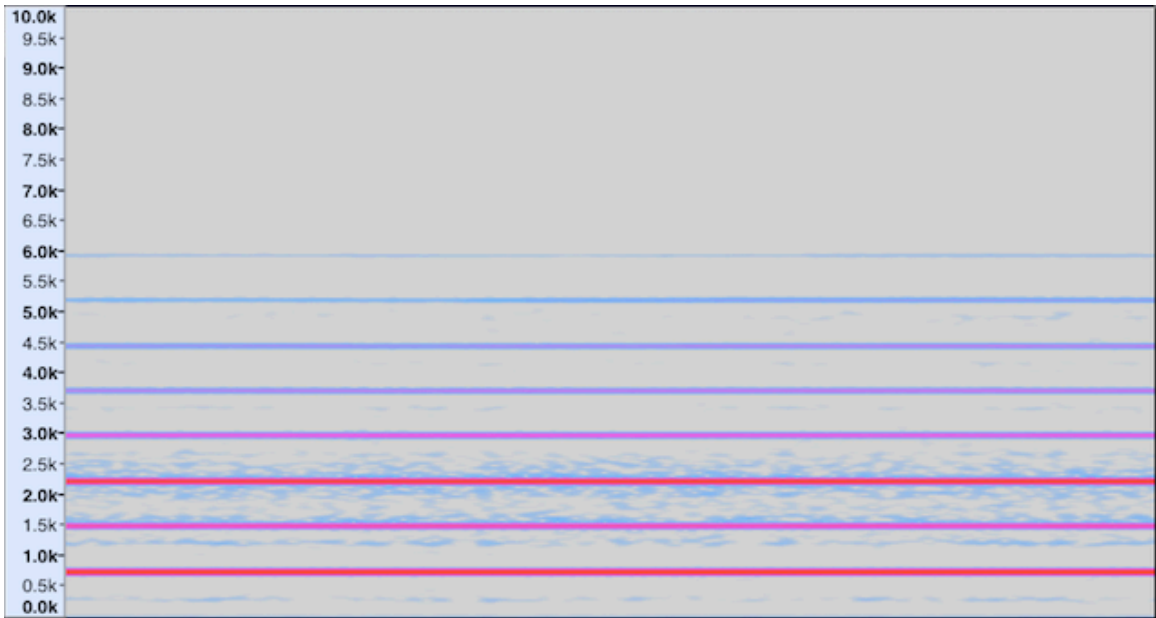
M30 (Reference)



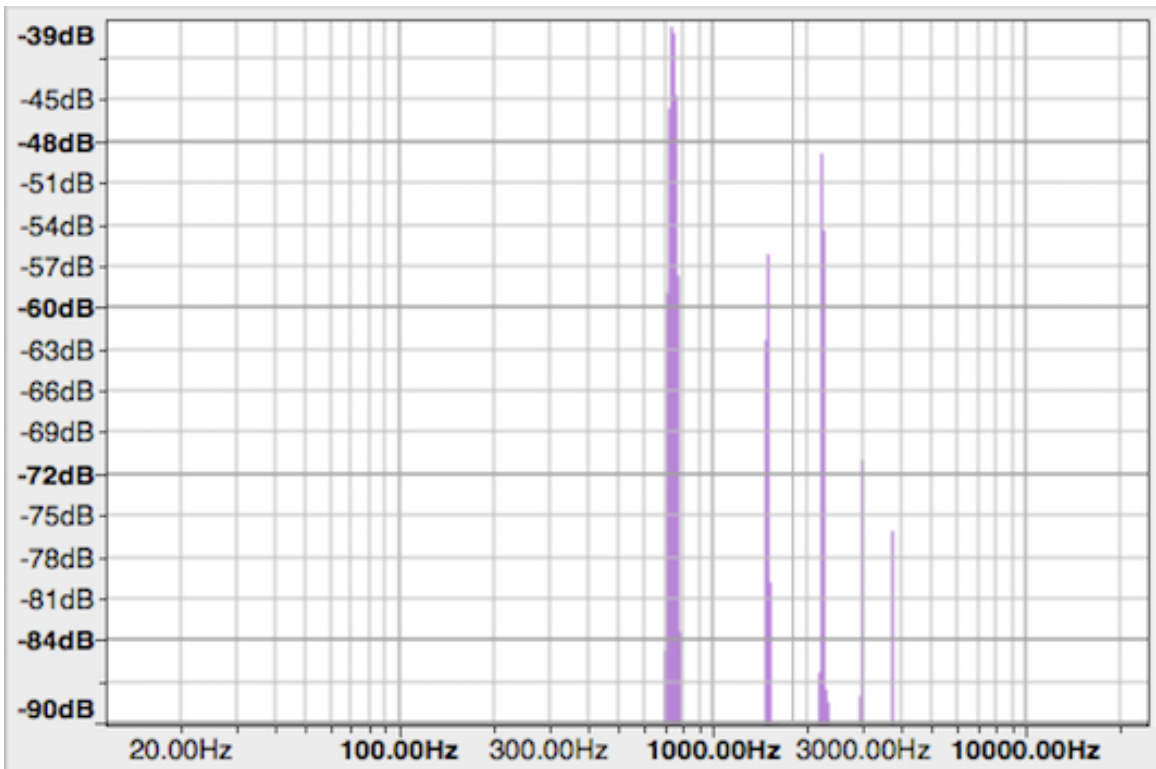
LIG



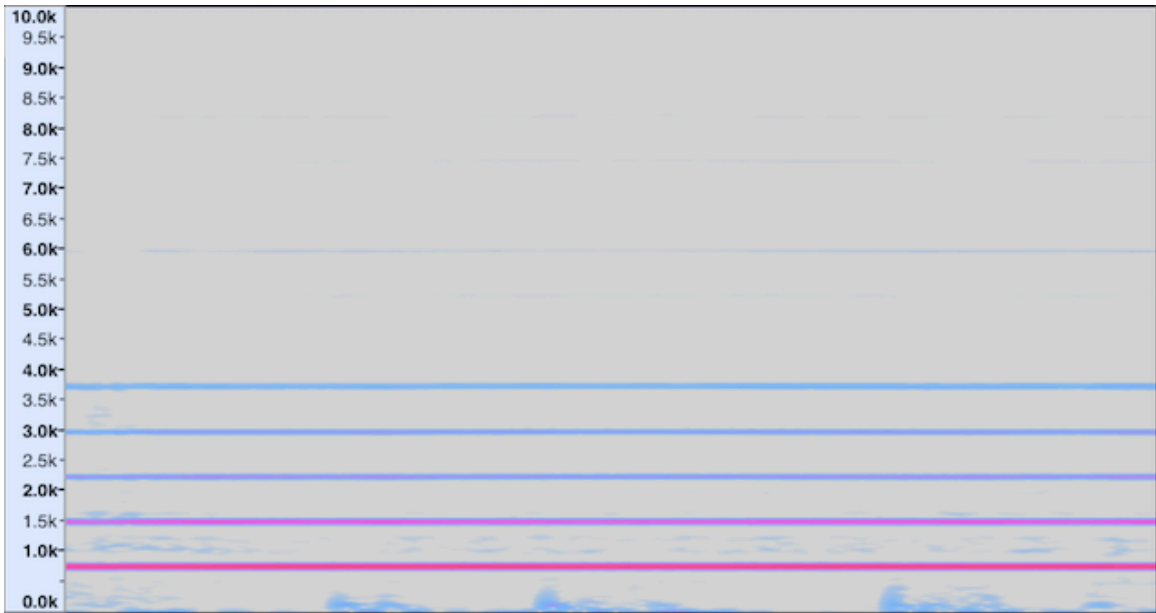
LIG



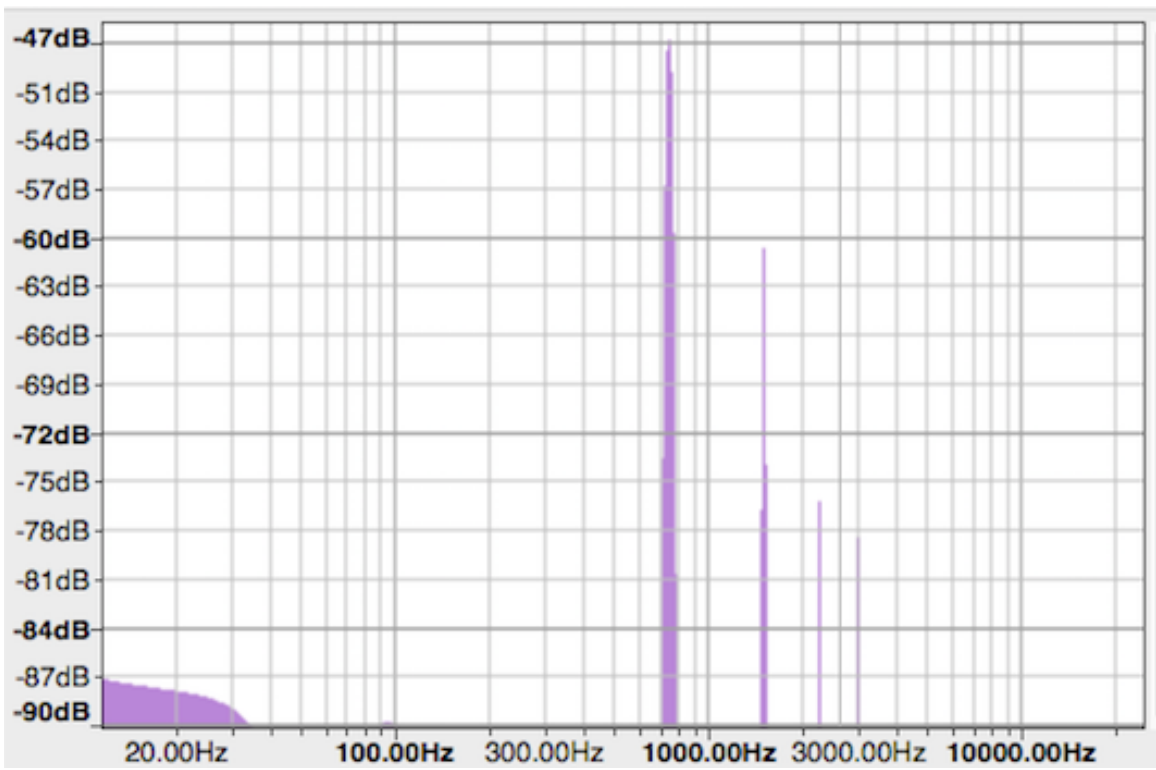
BAR Port



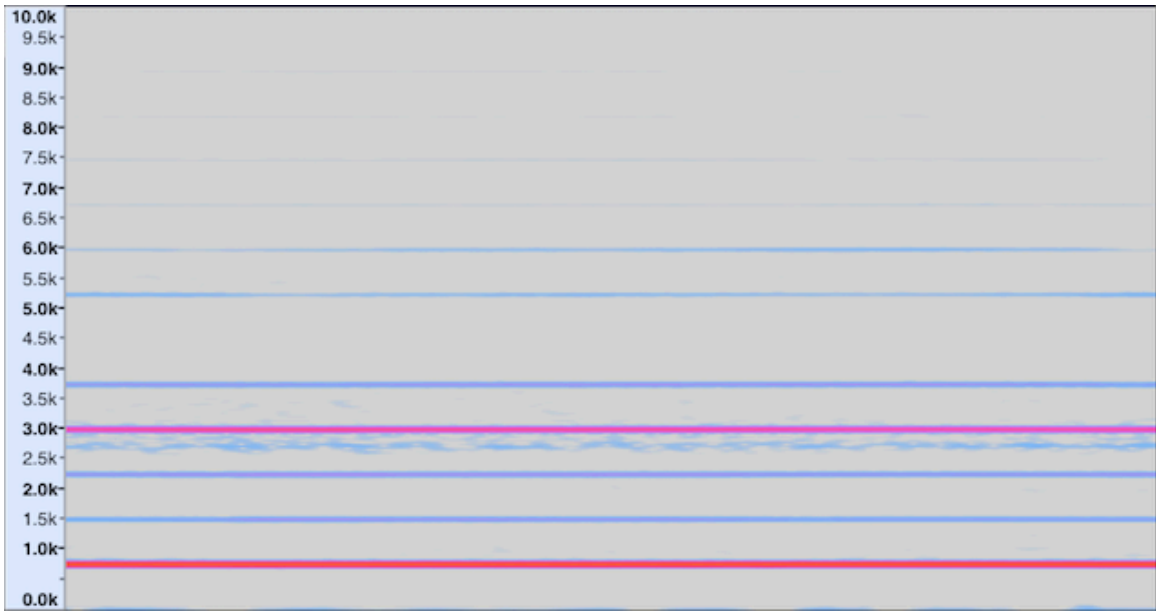
BAR Port



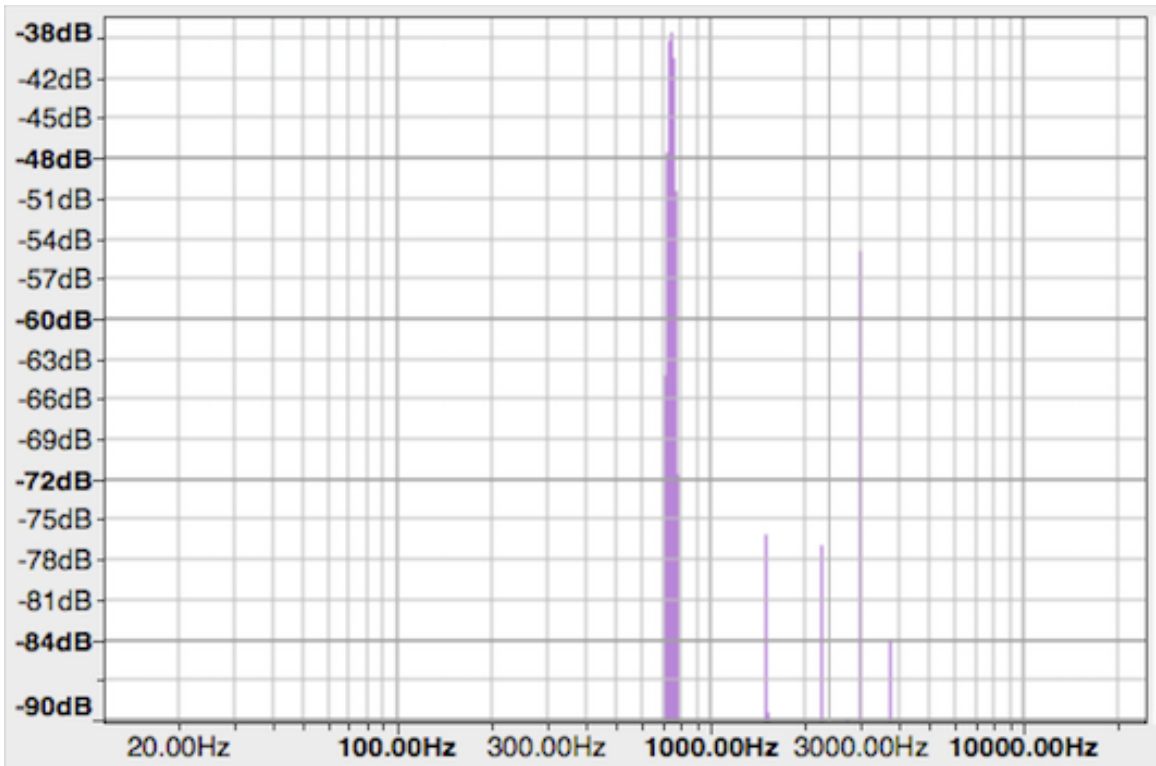
BAR Surf



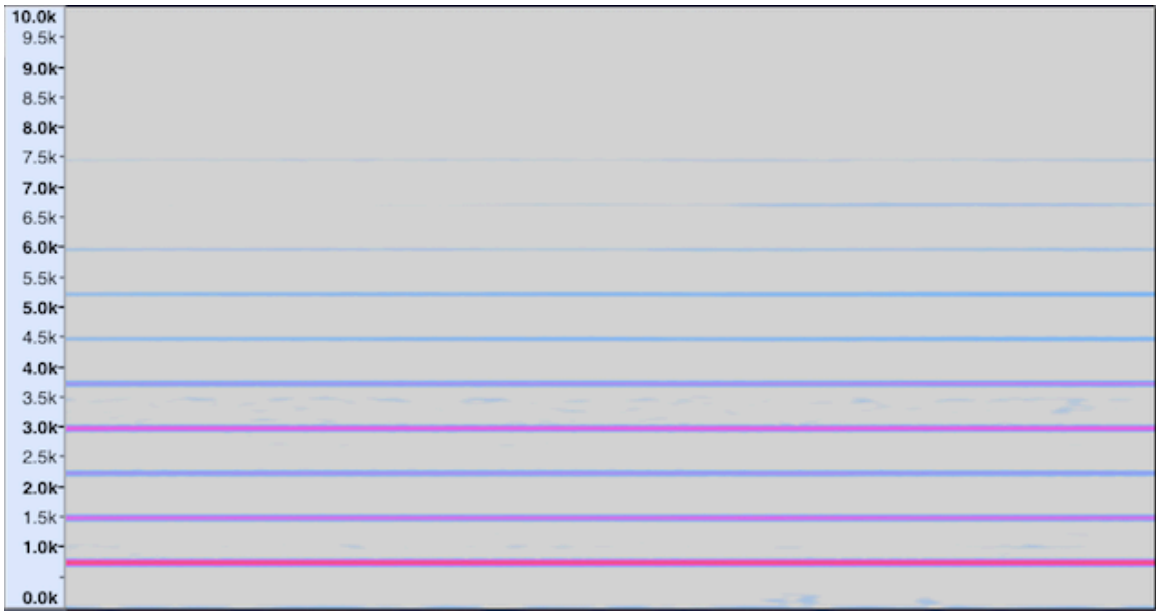
BAR Surf



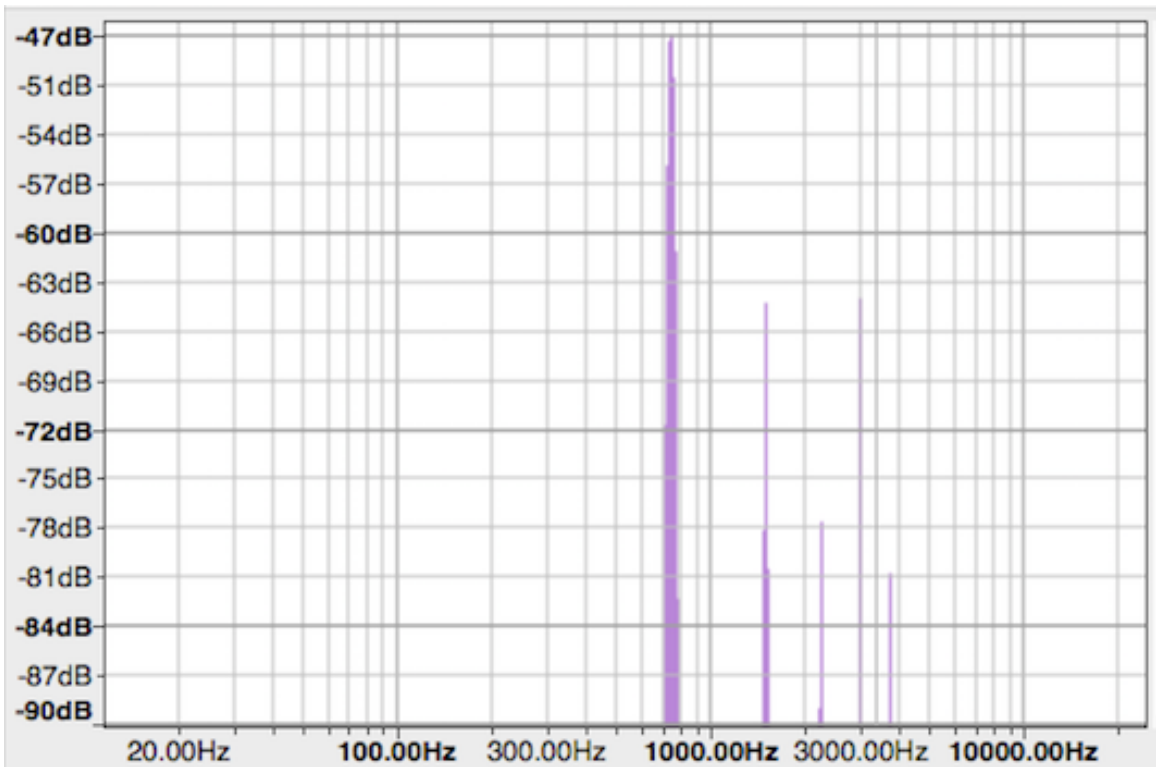
LF MPB



LF MPB



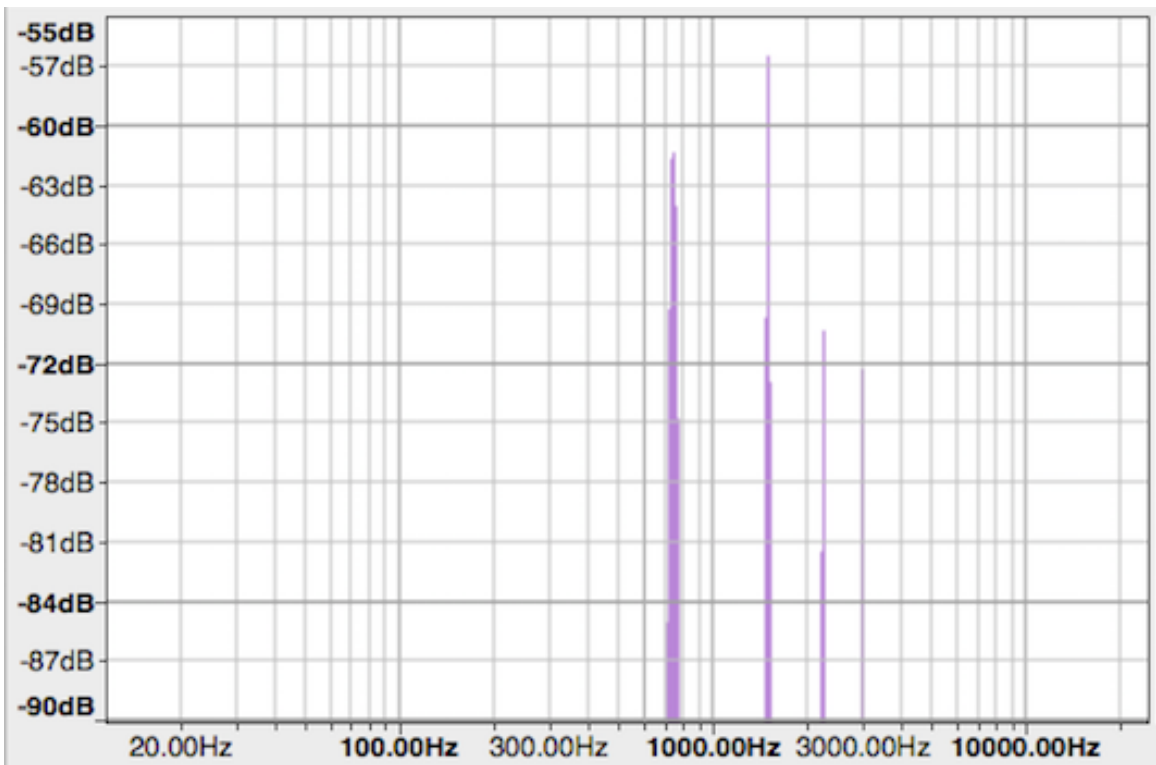
LF BUJ



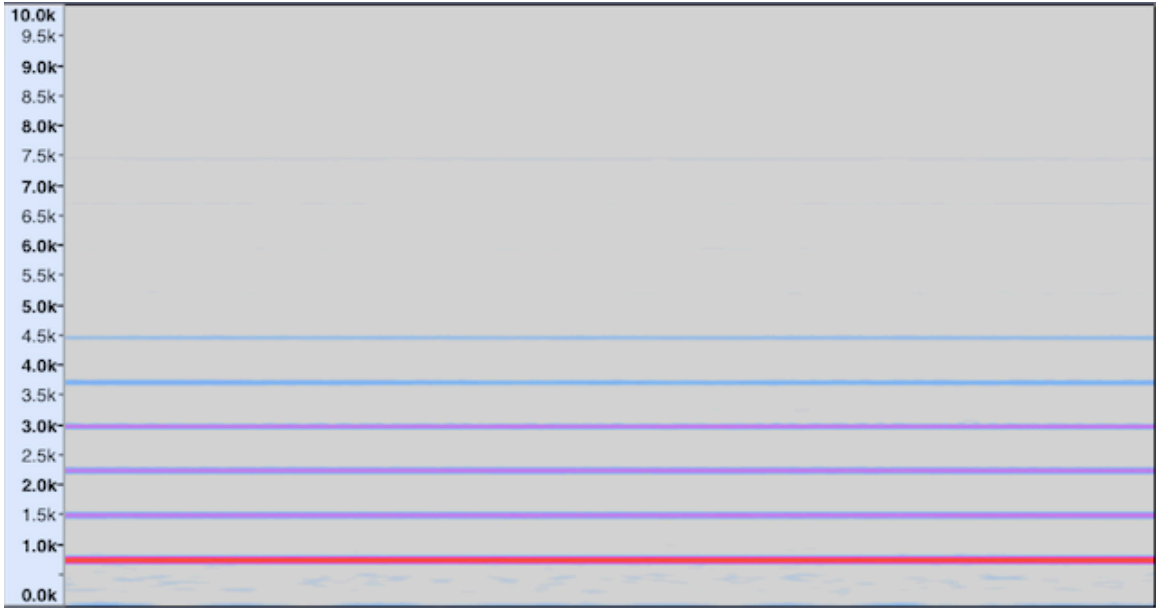
LF BUJ



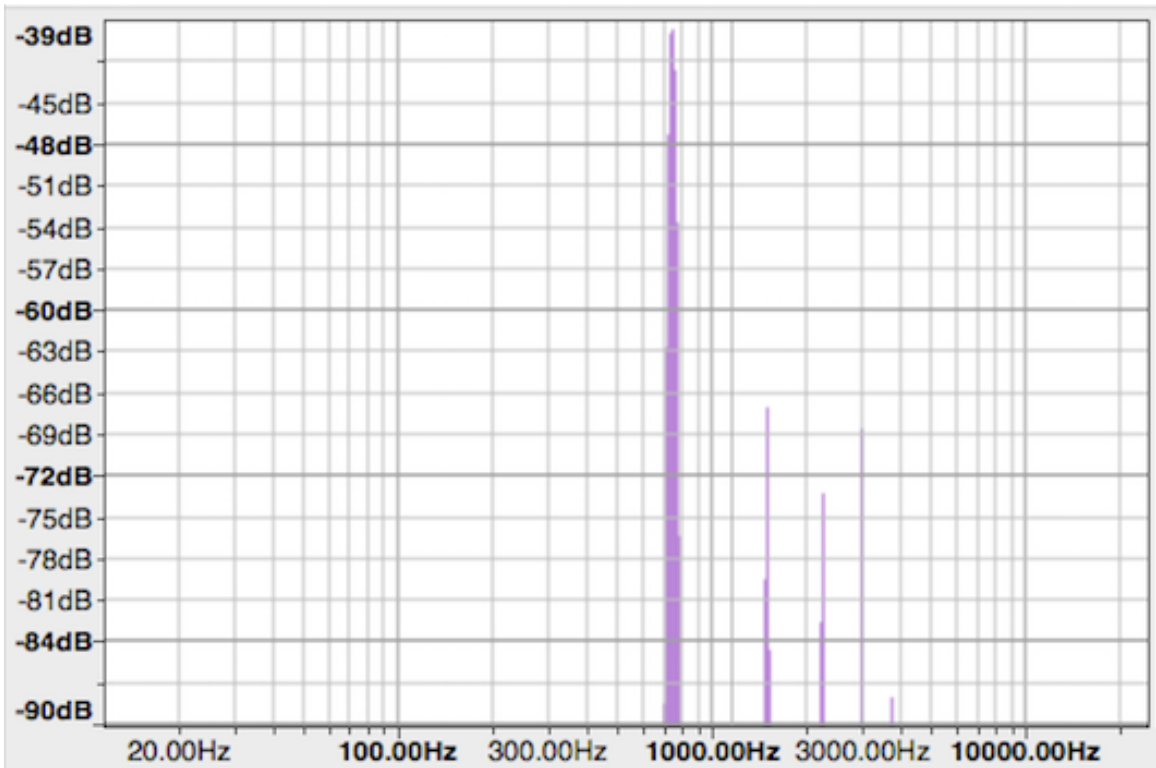
UJ



UJ



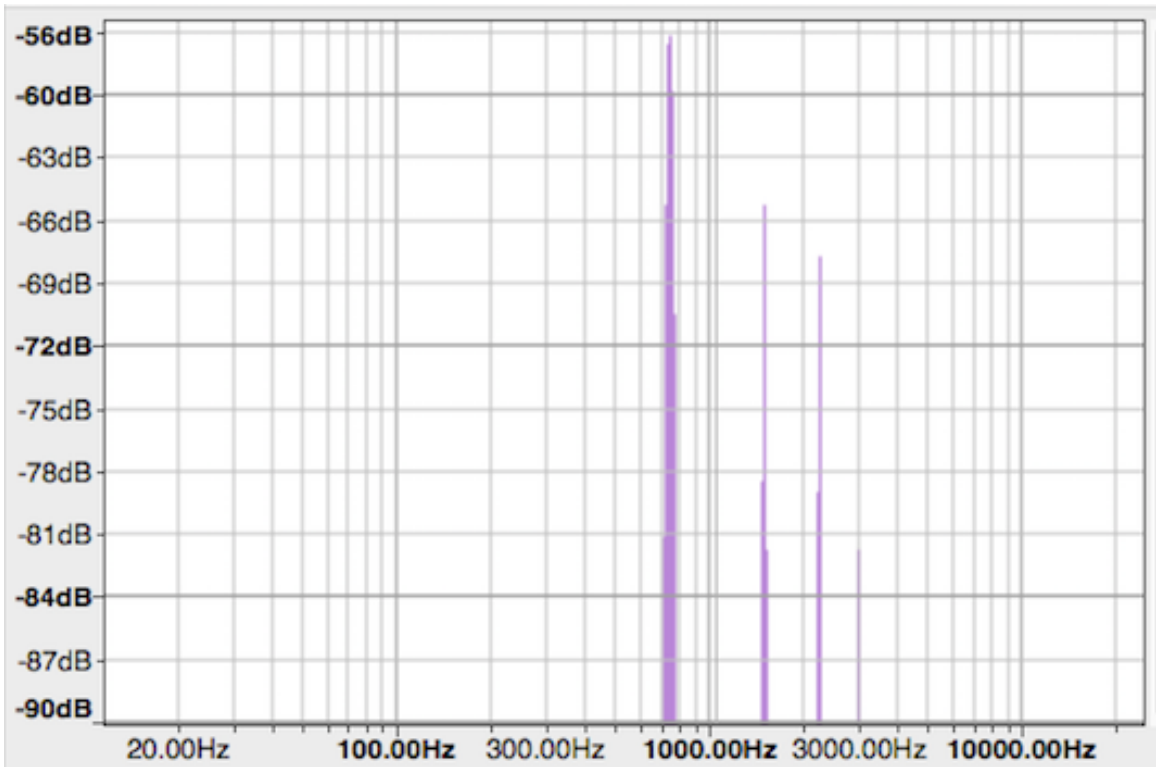
CTR



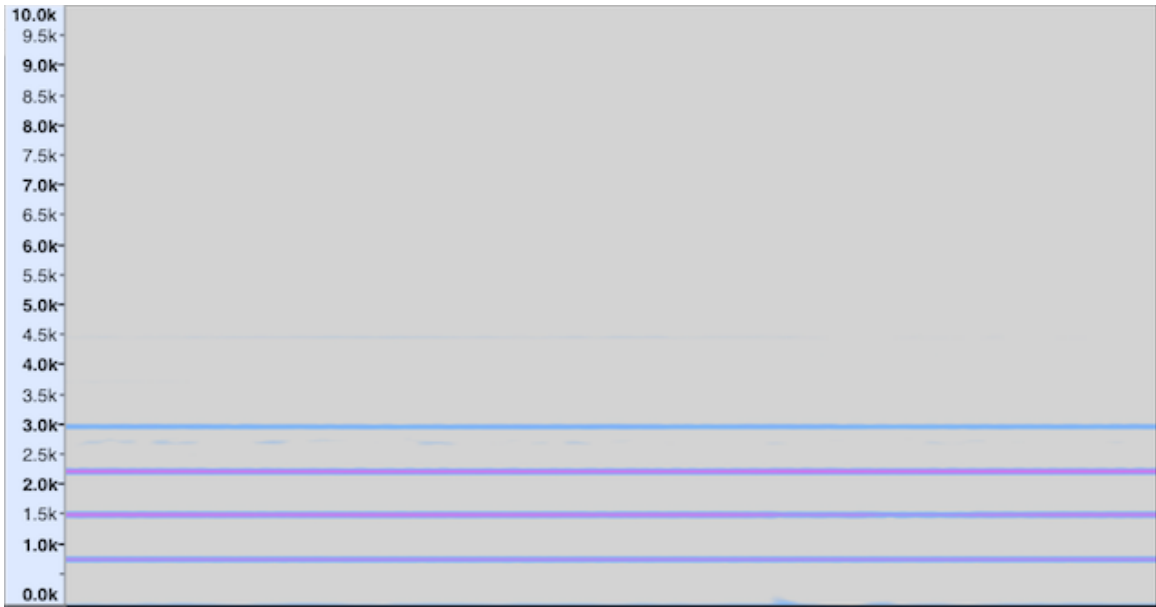
CTR



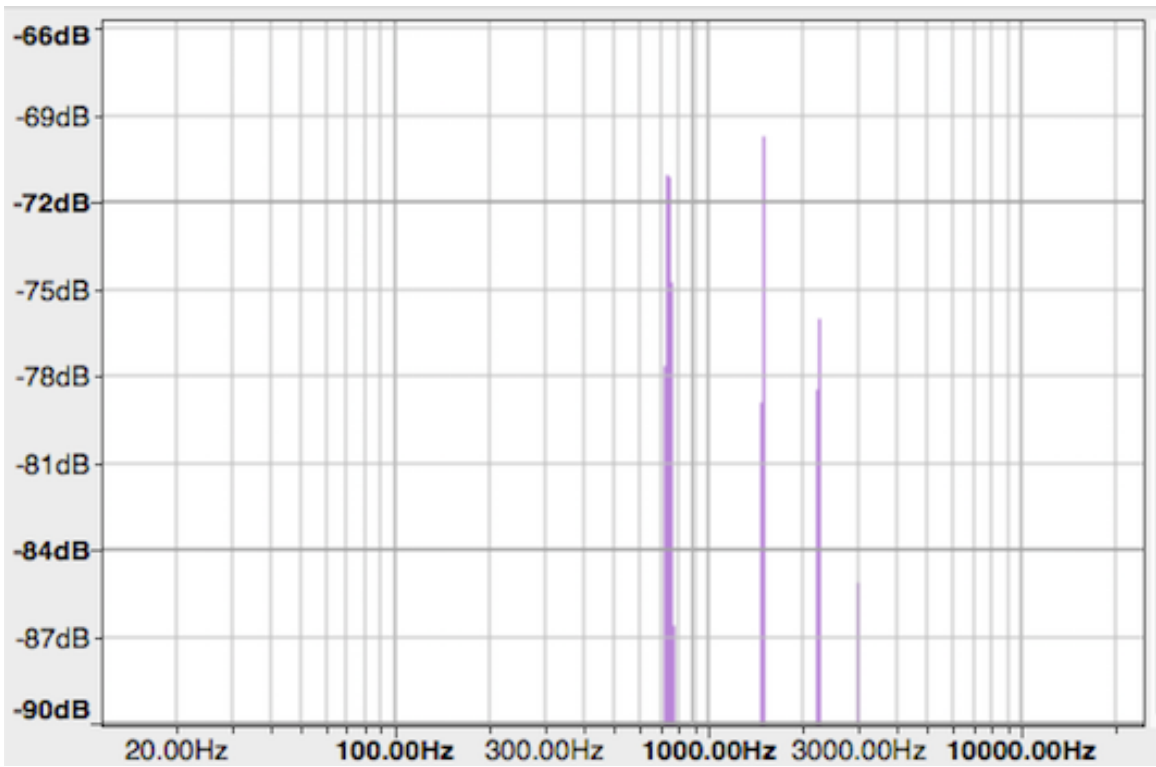
LJ



LJ



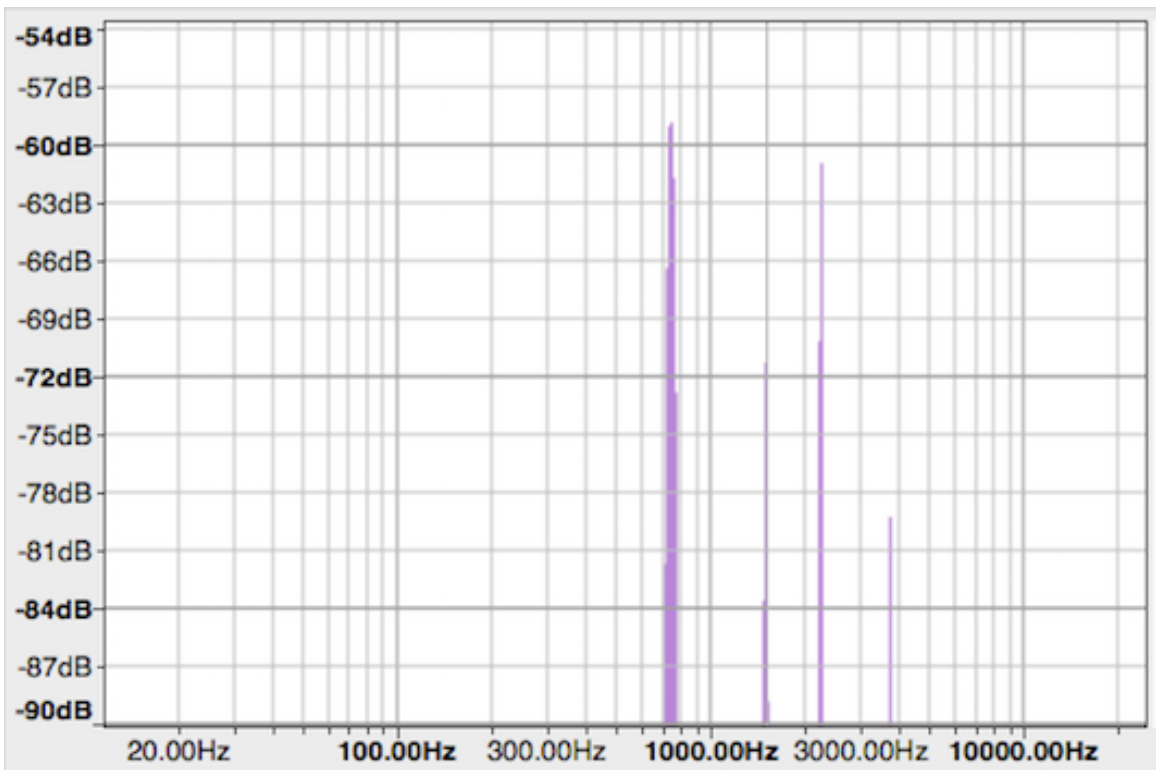
BELL Out



BELL Out

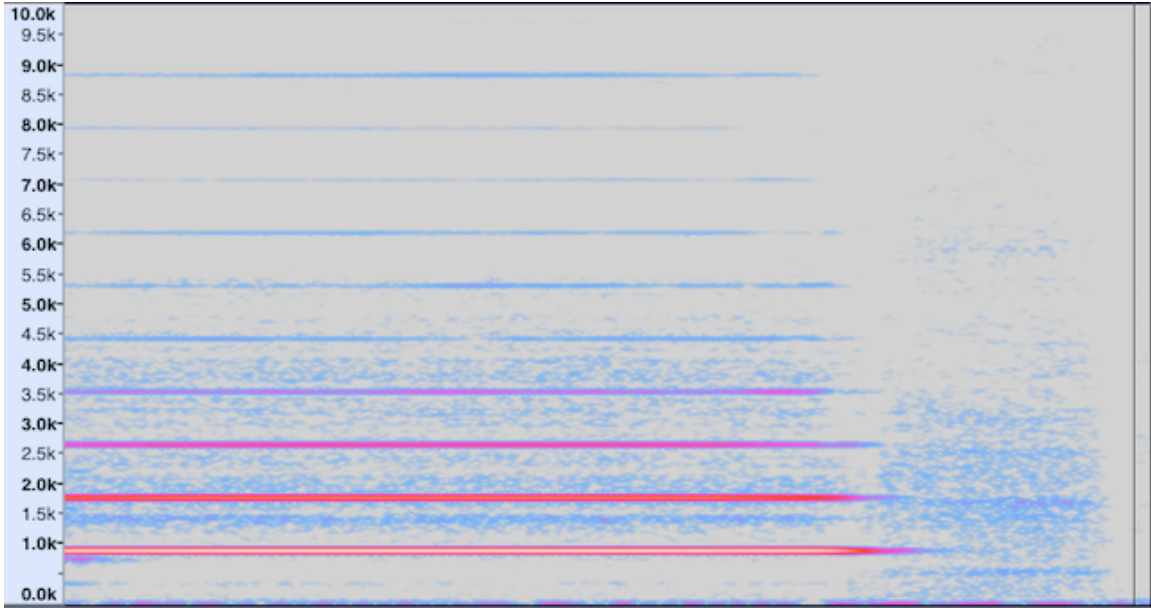


BELL End

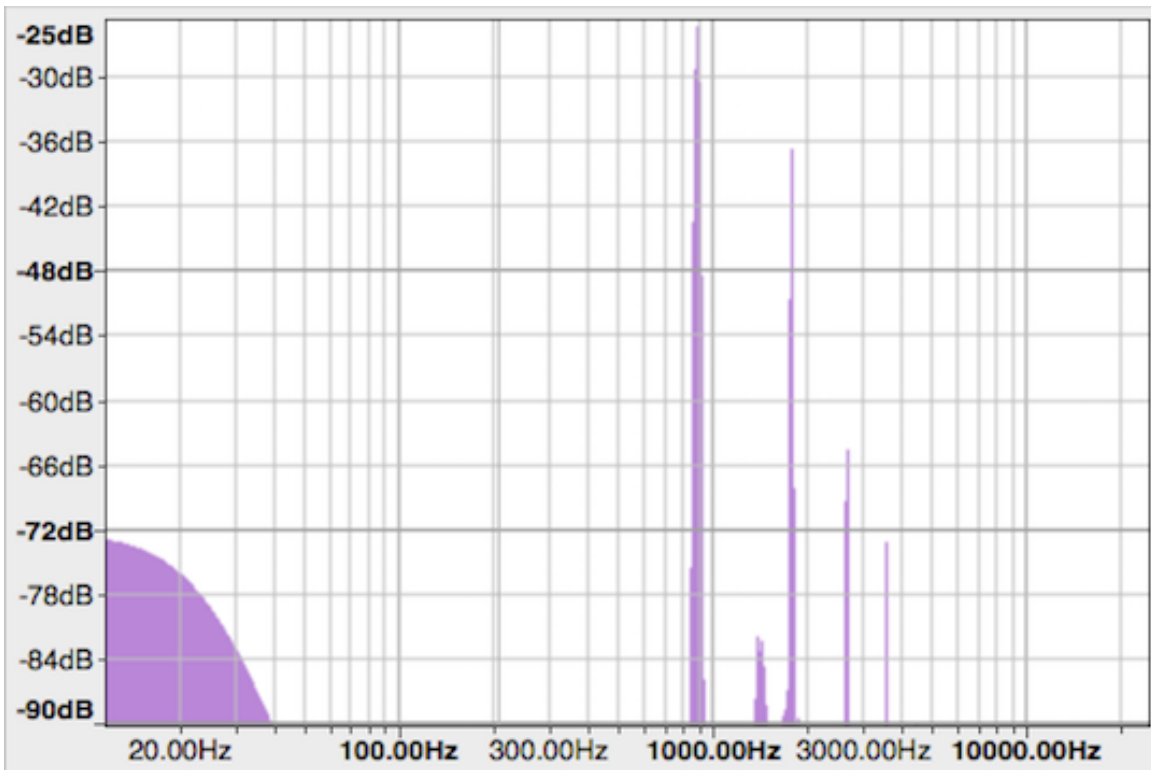


BELL End

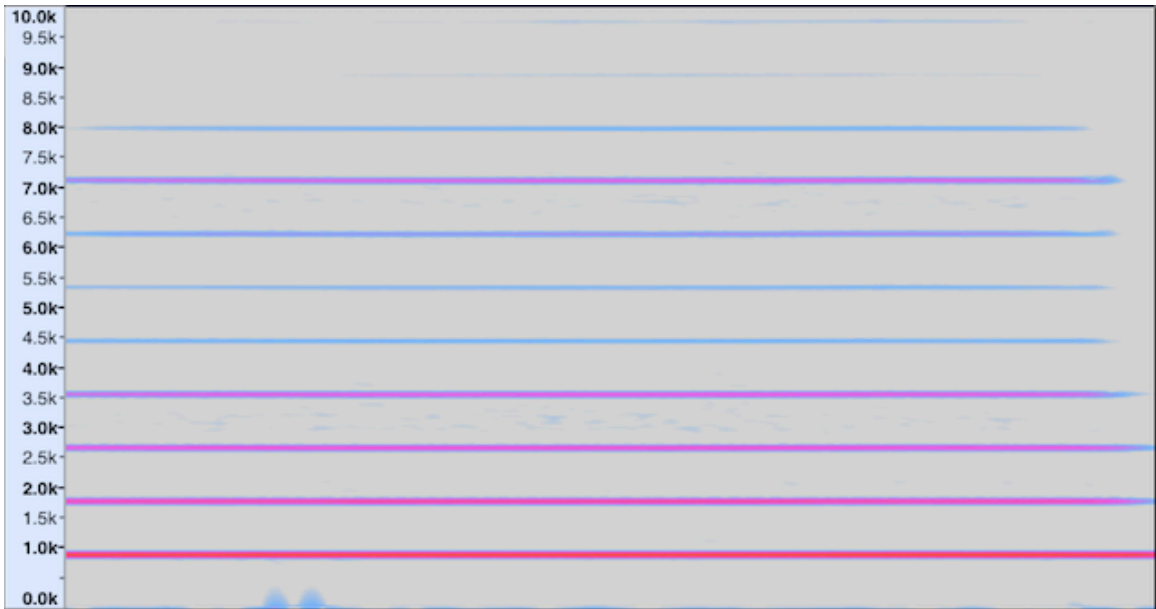
APPENDIX M  
SAMPLE DATA B5



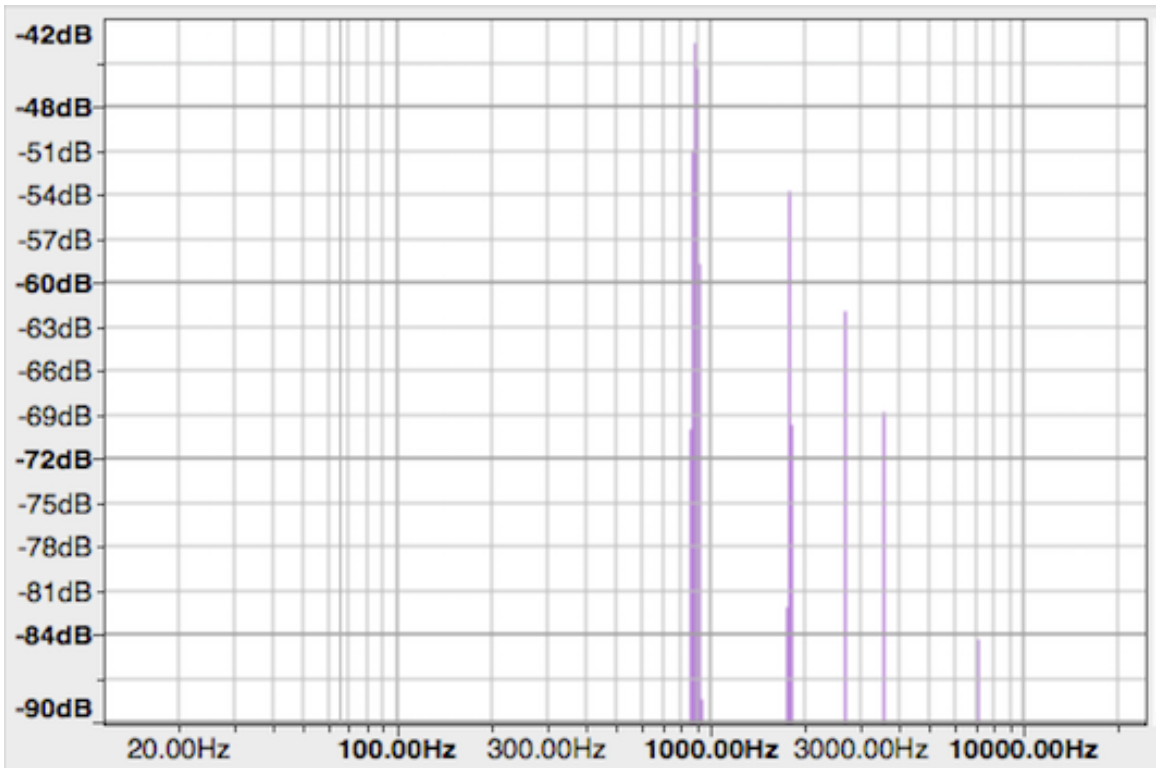
M30 (Reference)



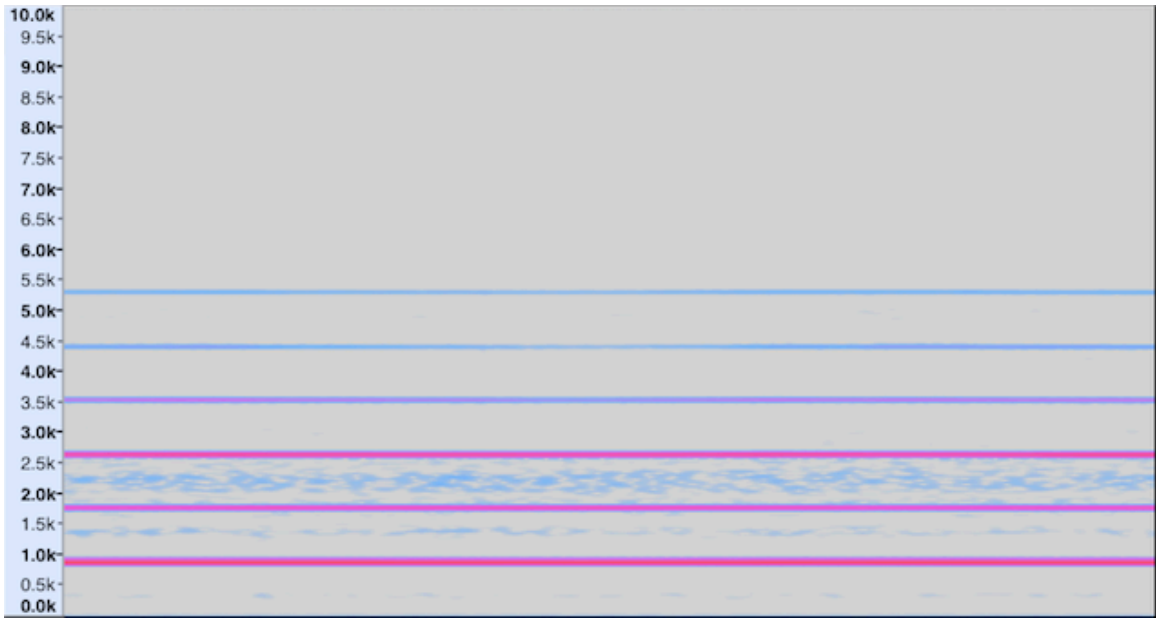
M30 (Reference)



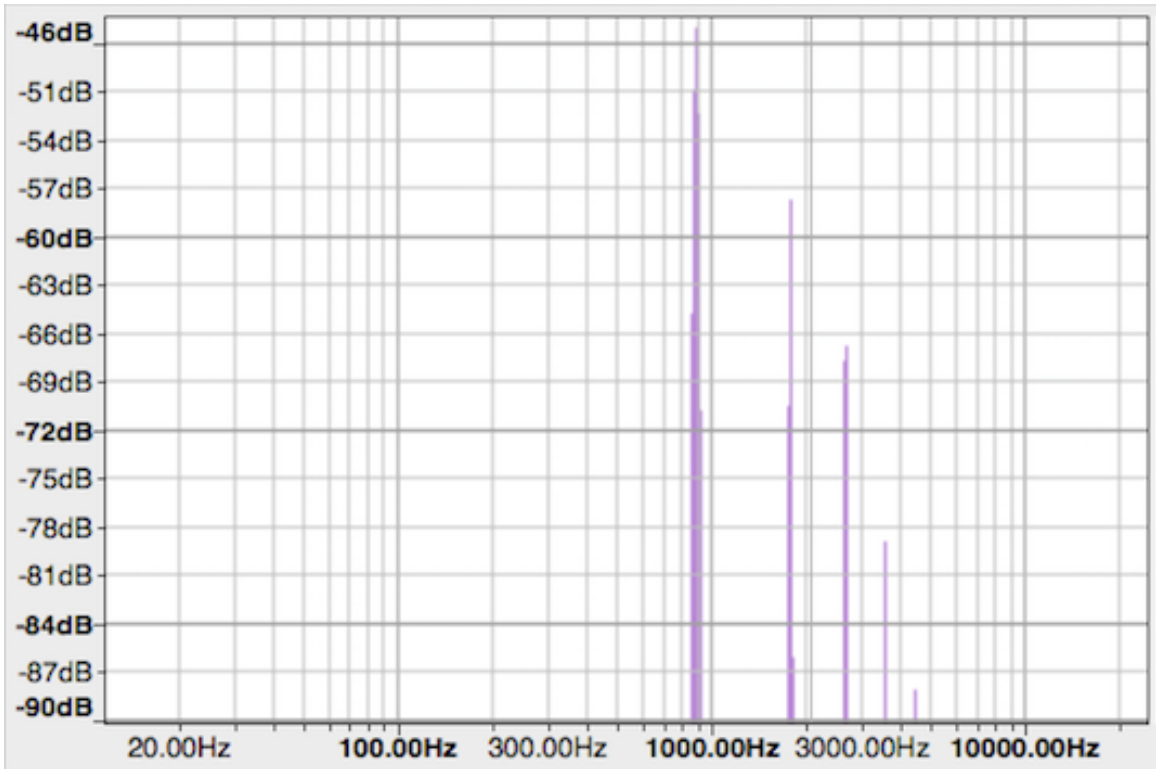
LIG



LIG



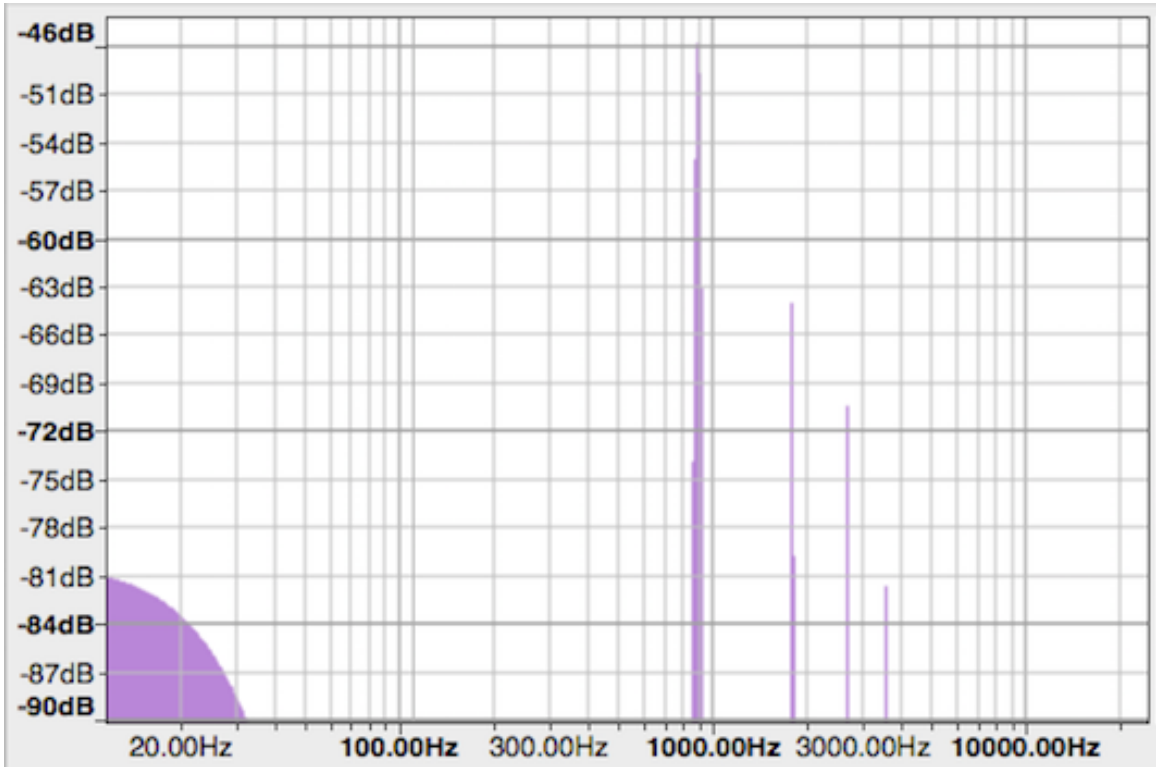
BAR Port



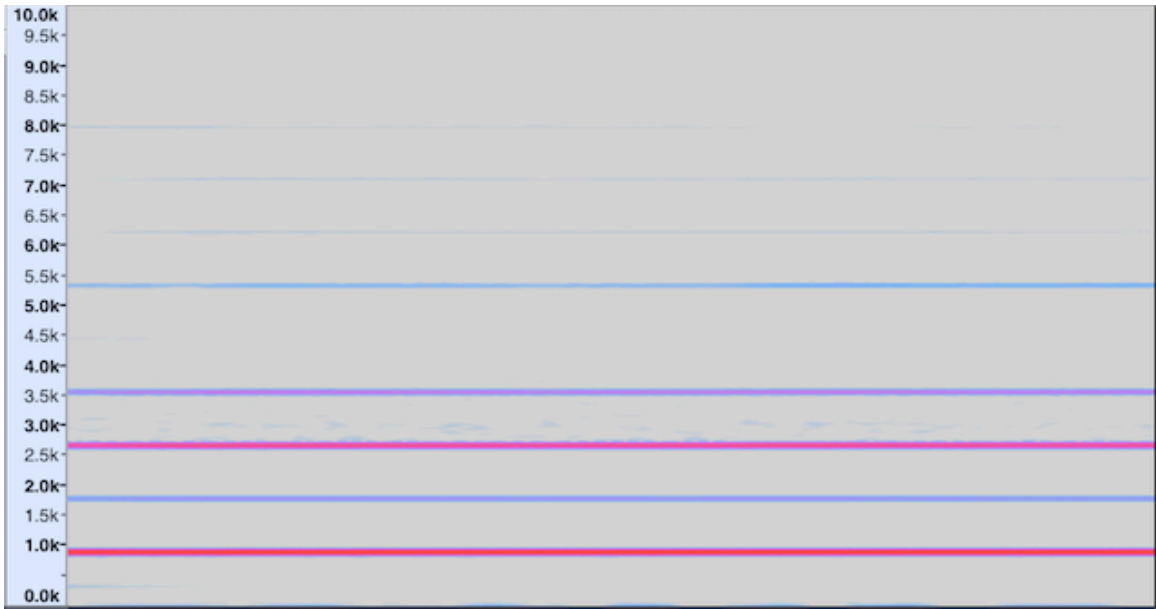
BAR Port



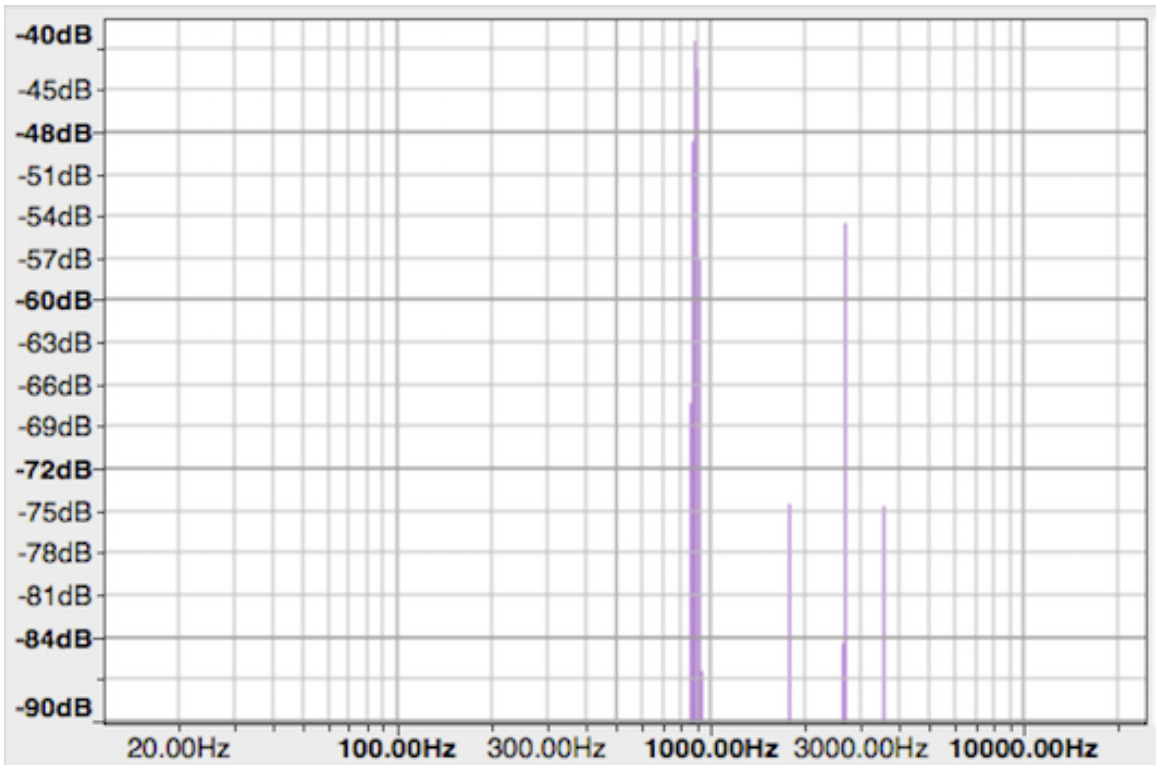
BAR Surf



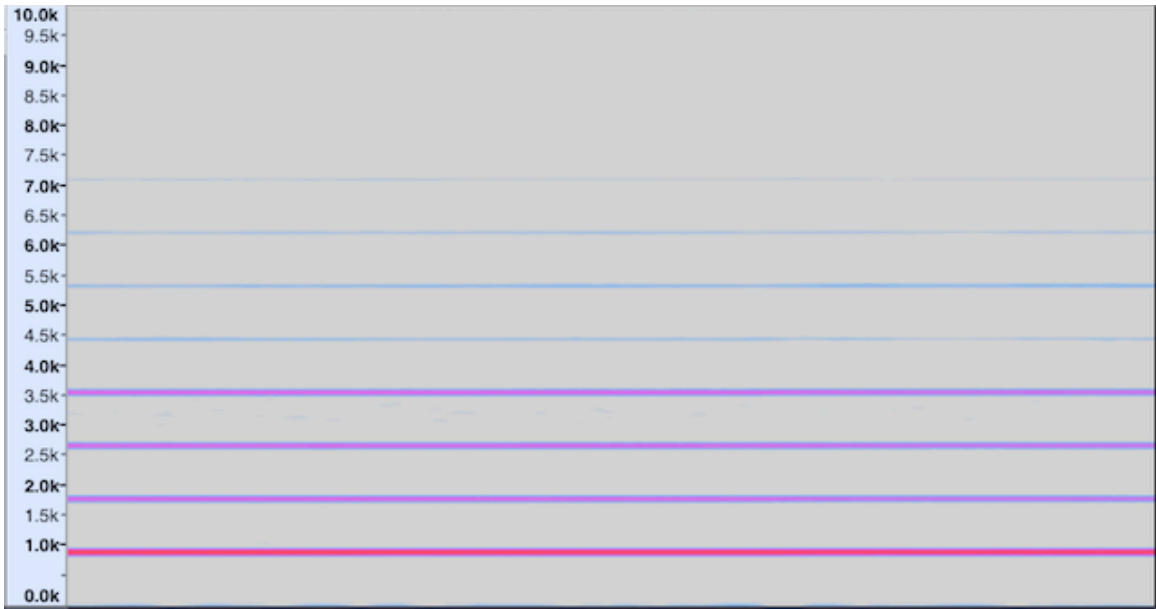
BAR Surf



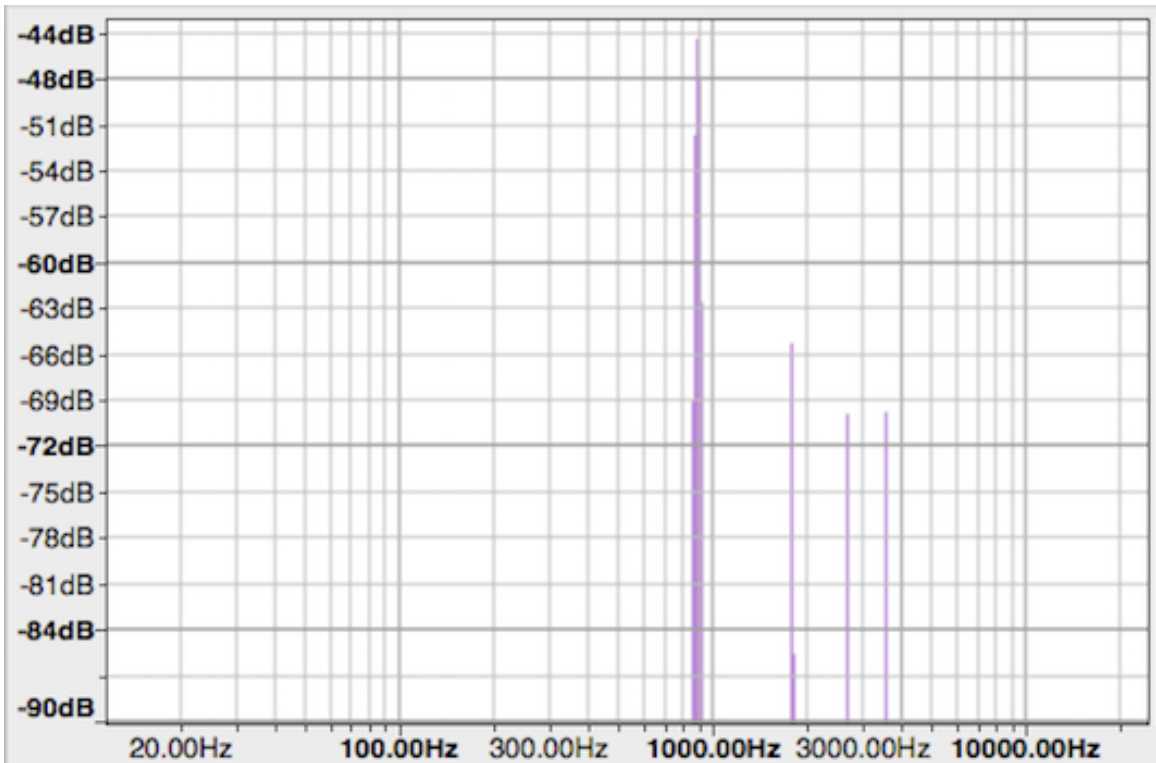
LF MPB



LF MPB



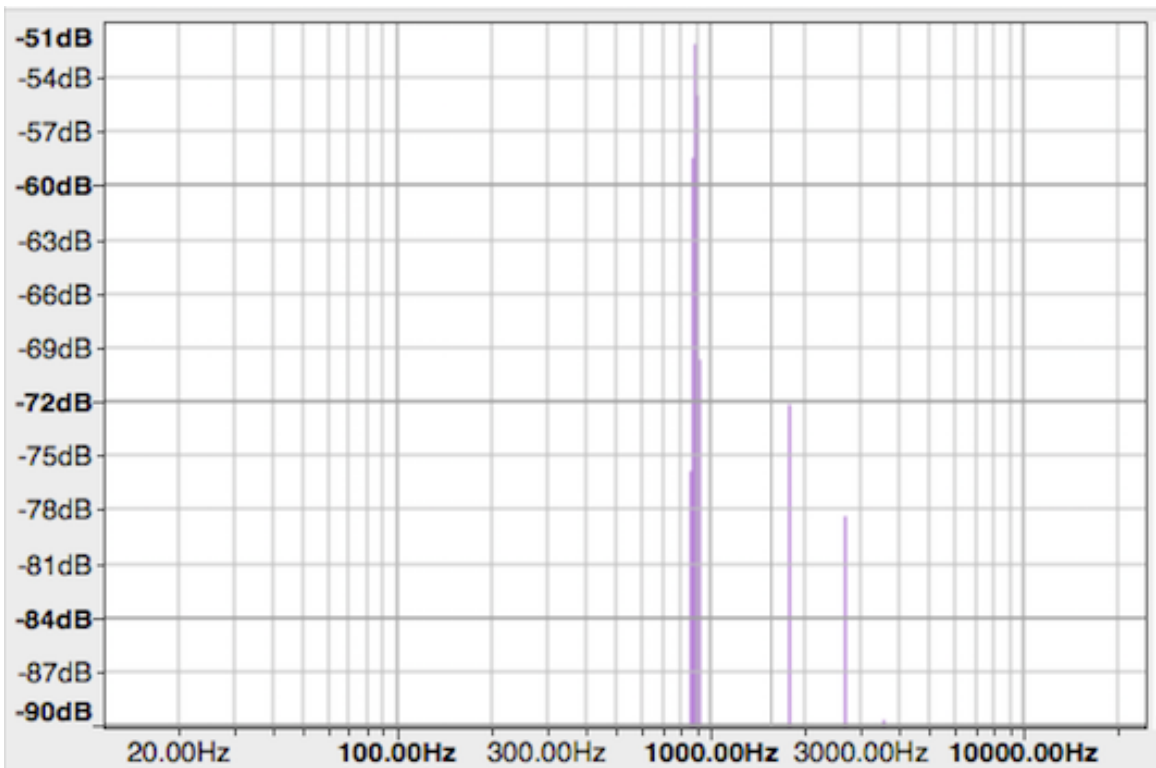
LF BUJ



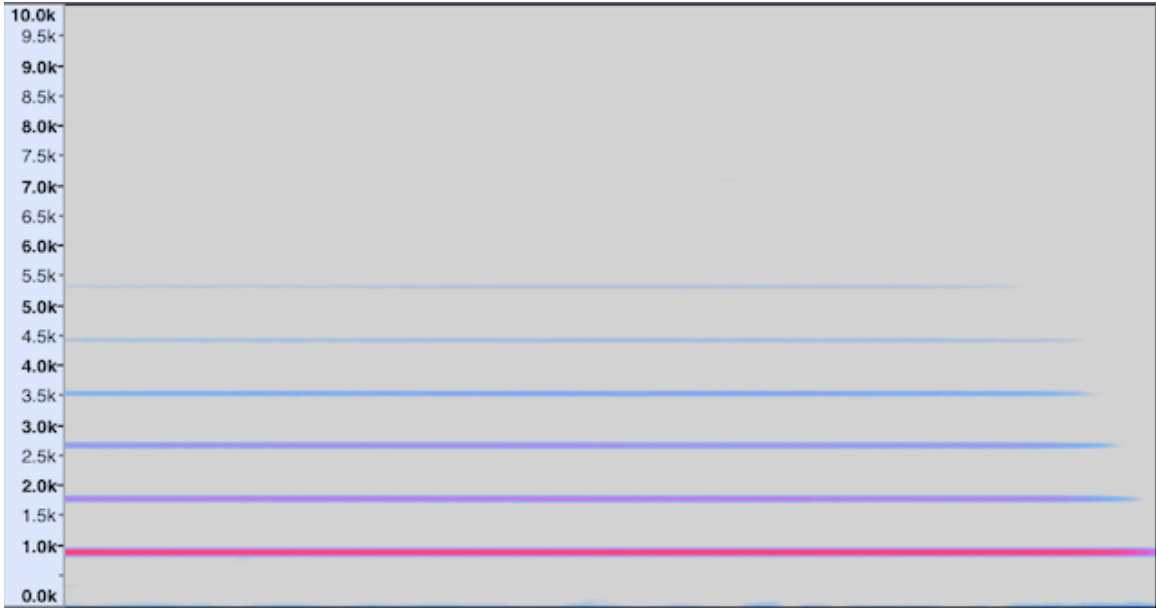
LF BUJ



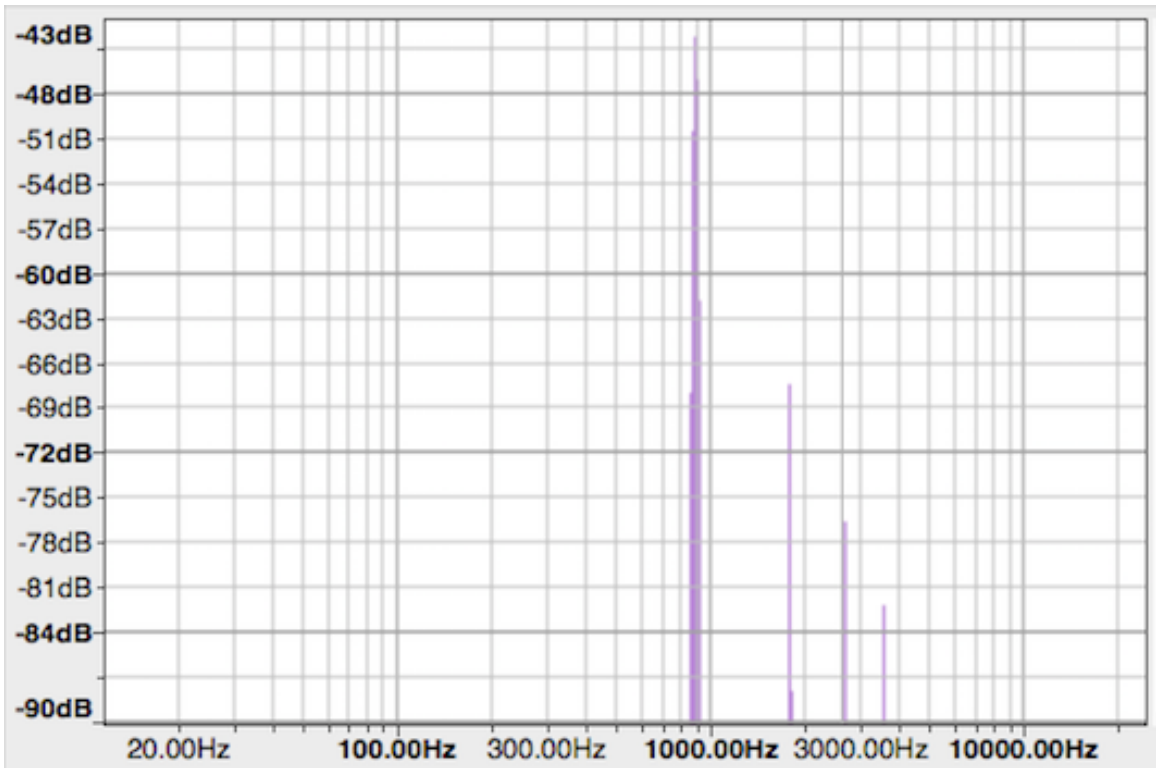
UJ



UJ



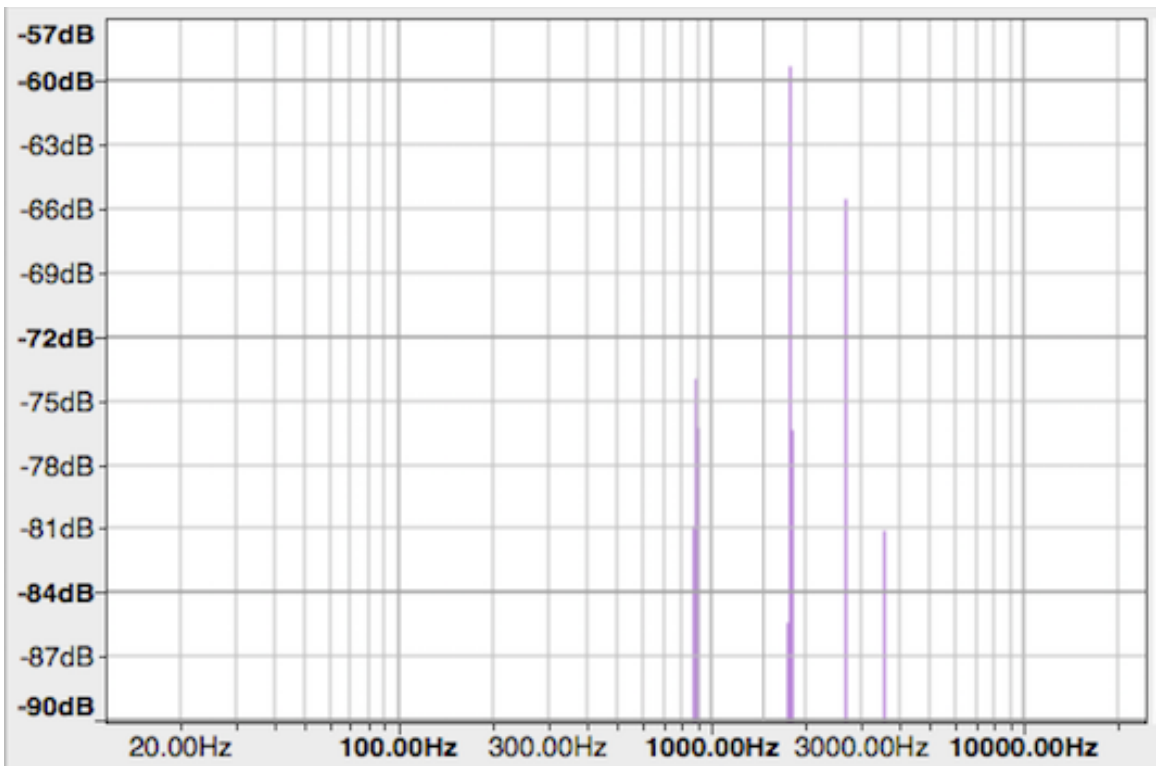
CTR



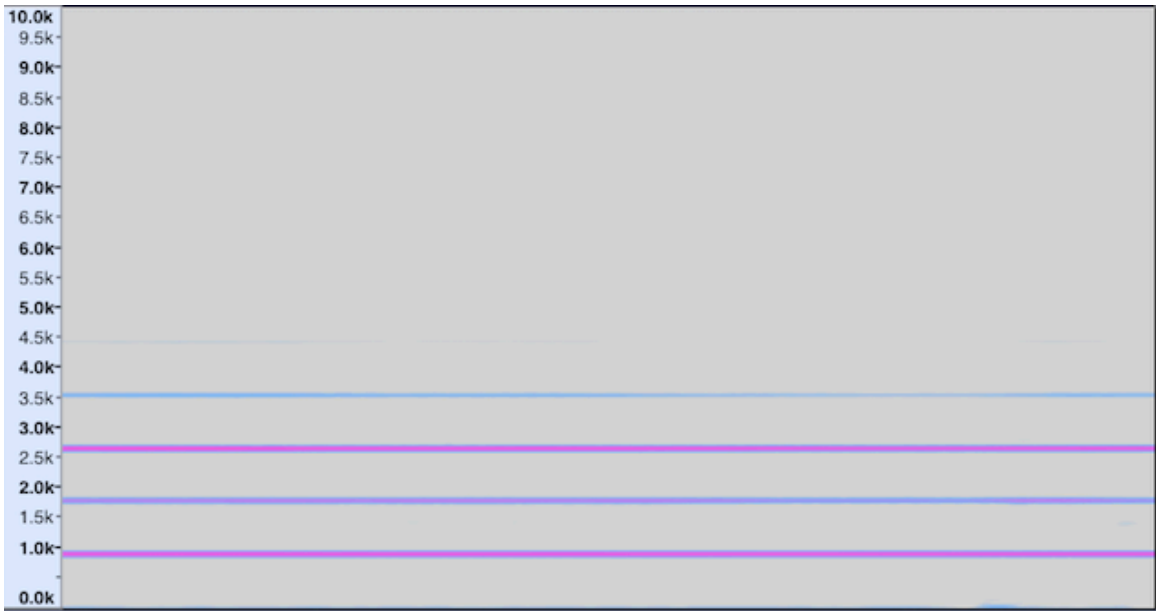
CTR



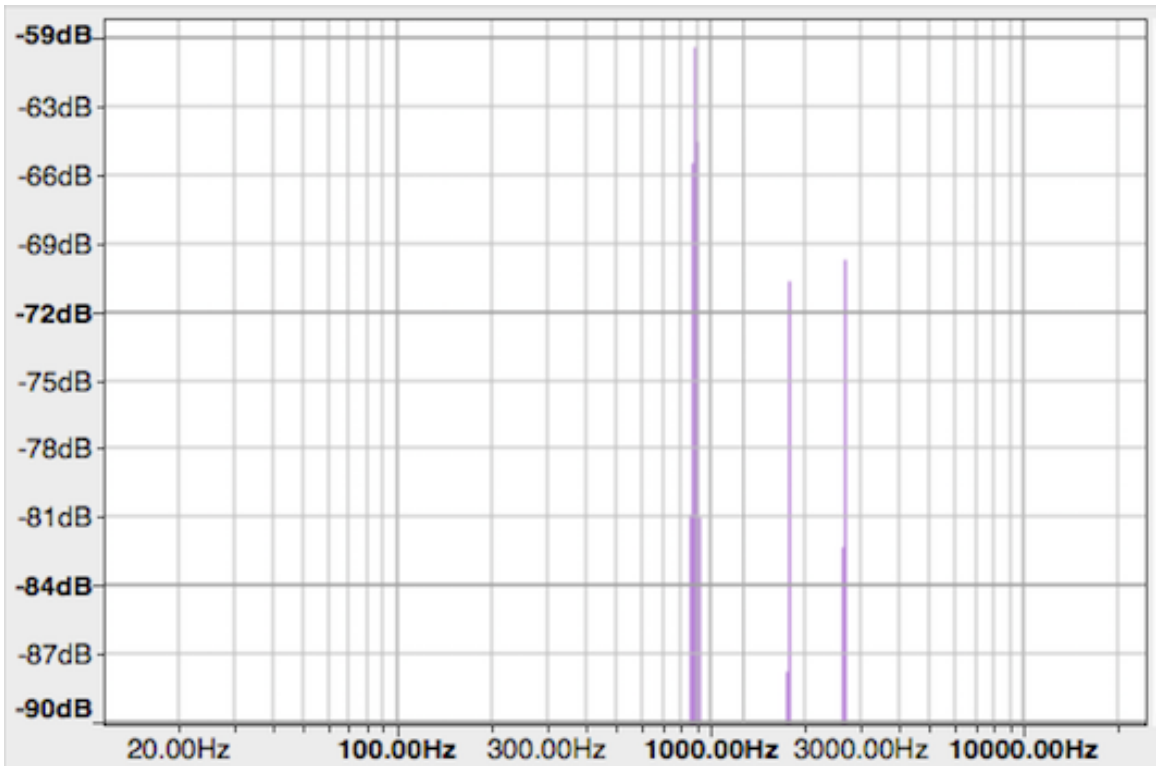
LJ



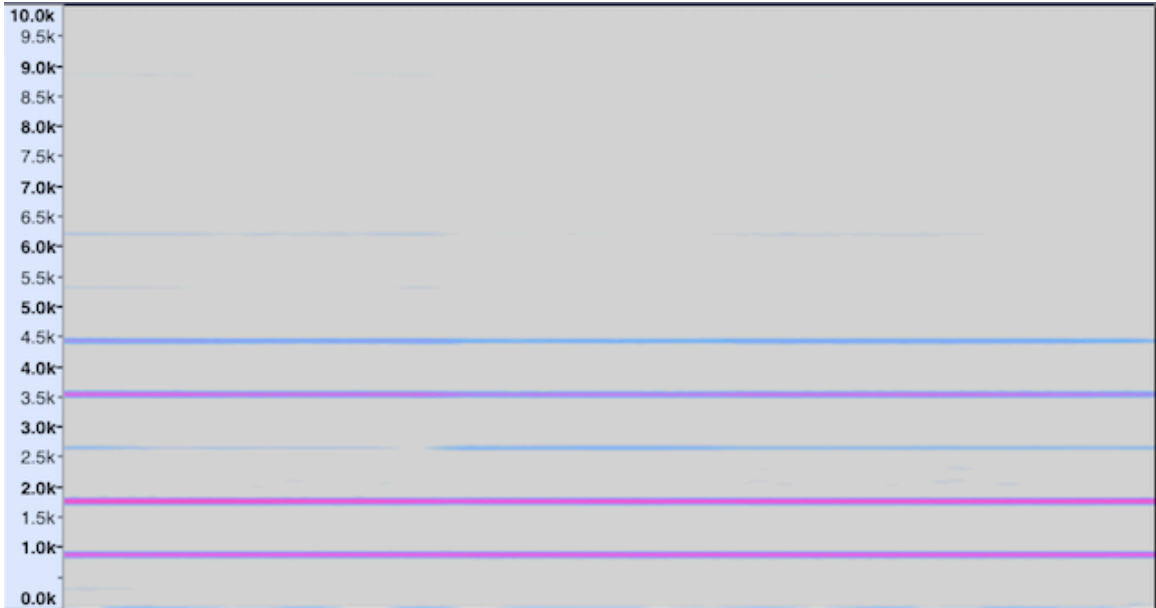
LJ



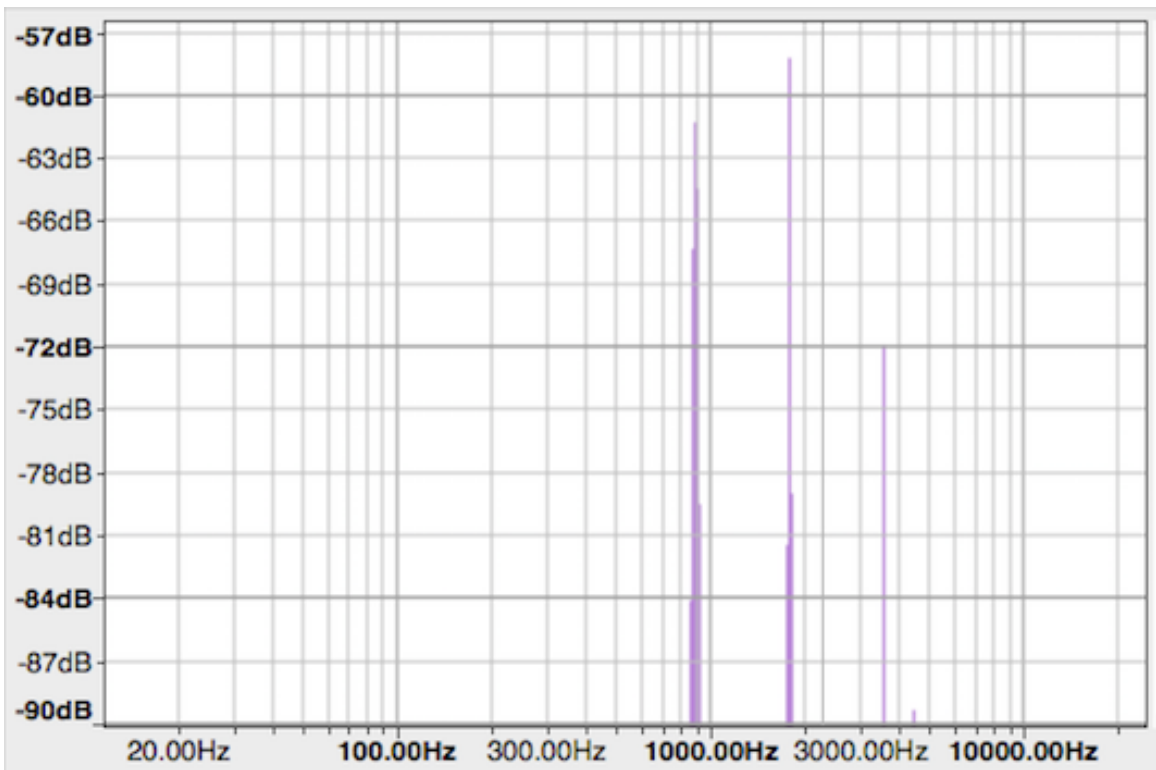
BELL Out



BELL Out

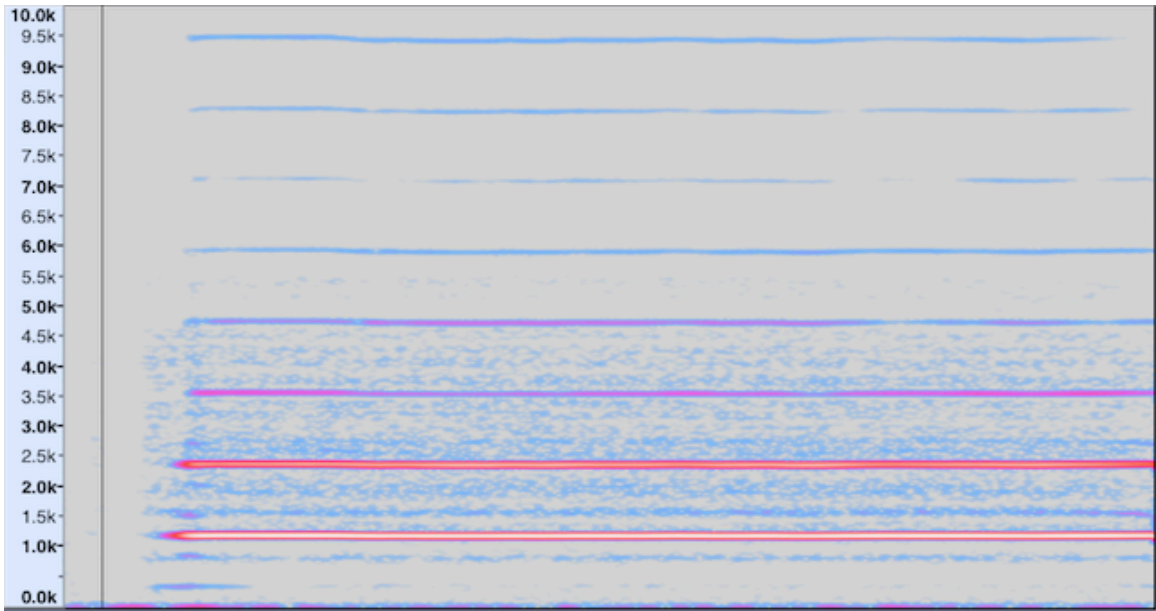


BELL End

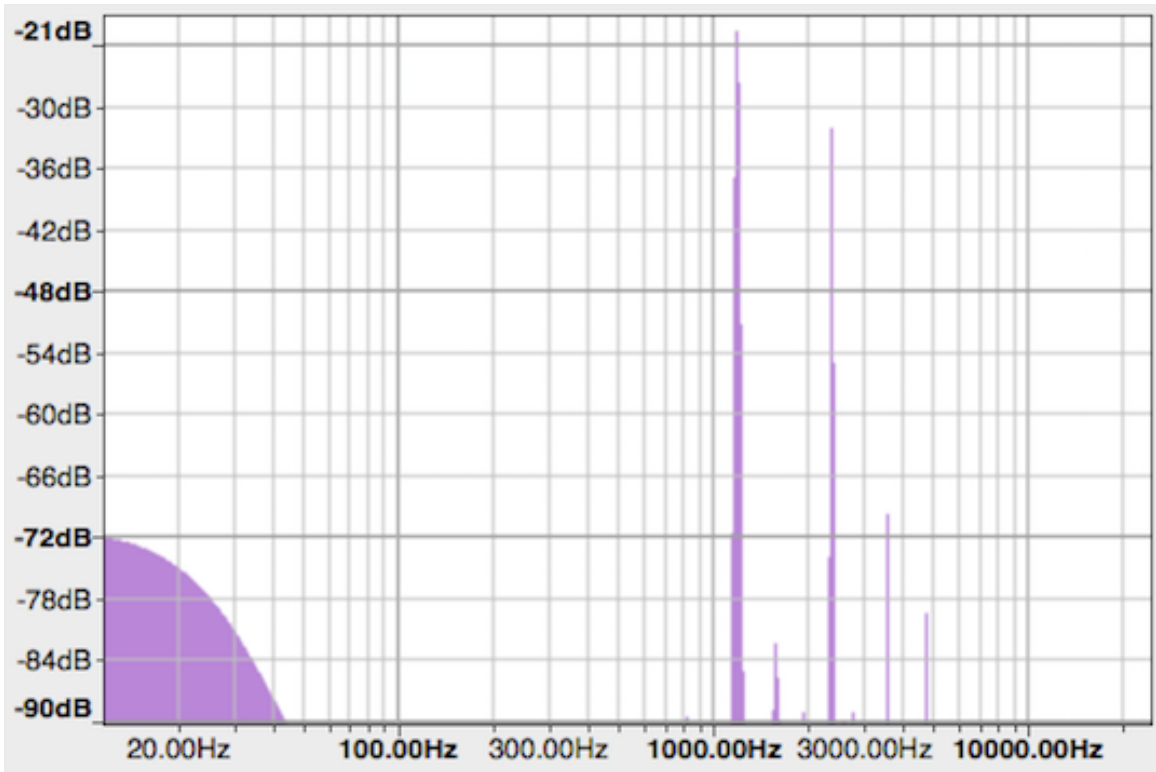


BELL End

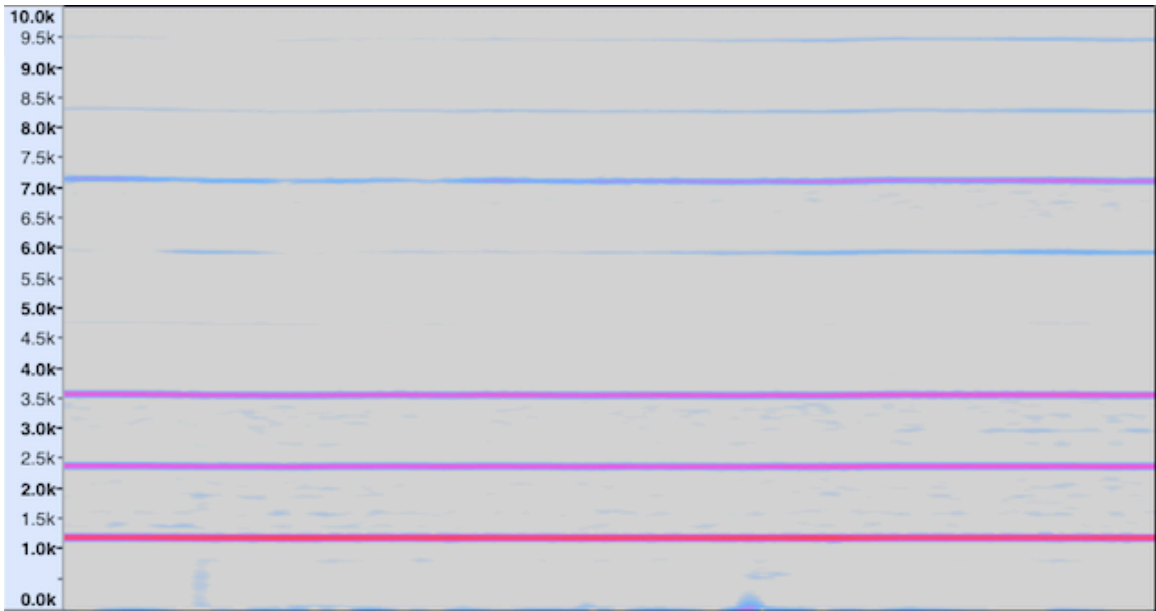
APPENDIX N  
SAMPLE DATA E6



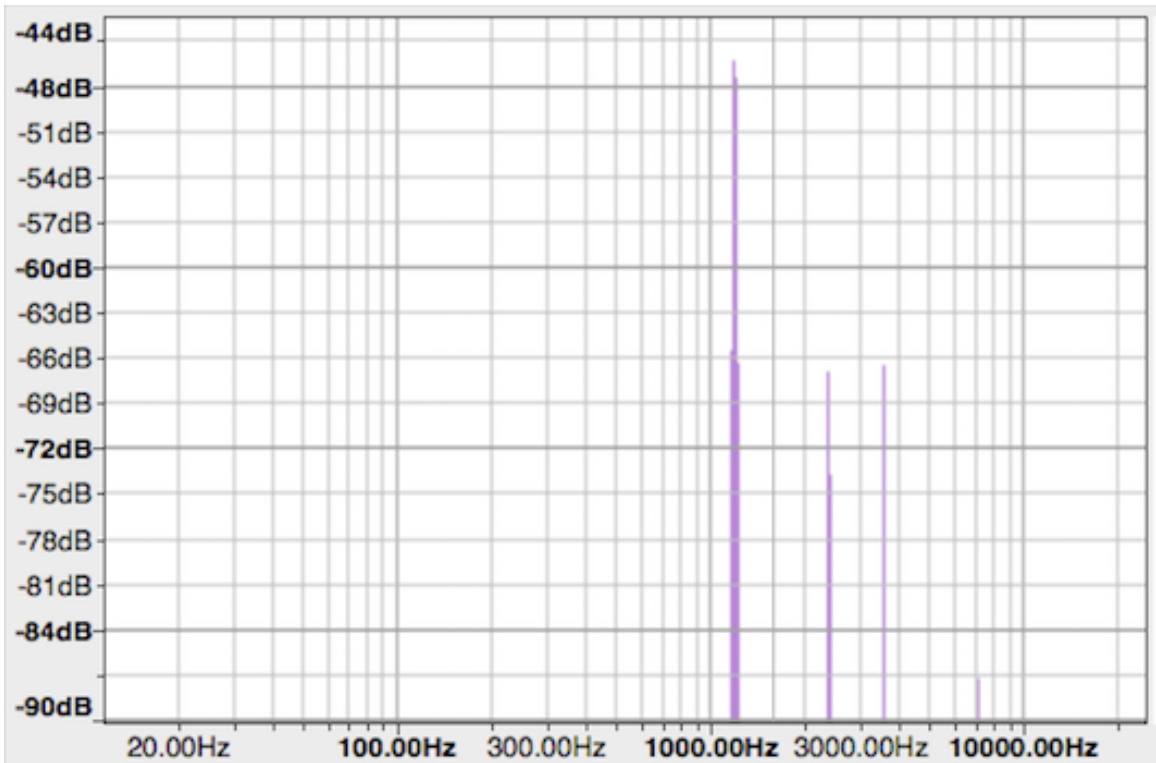
M30 (Reference)



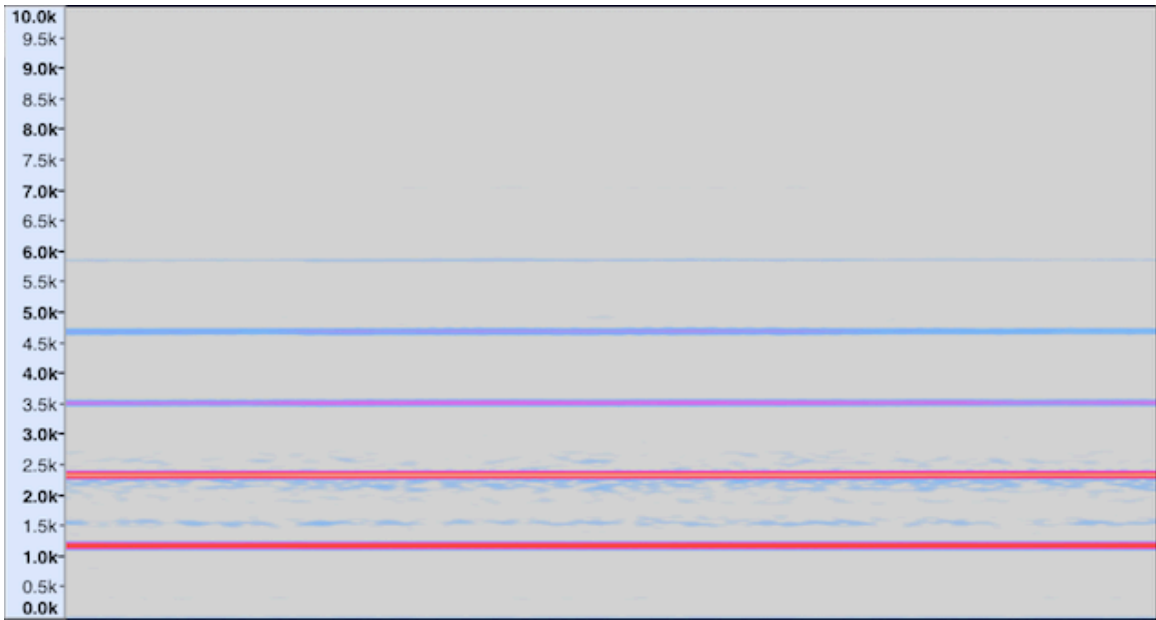
M30 (Reference)



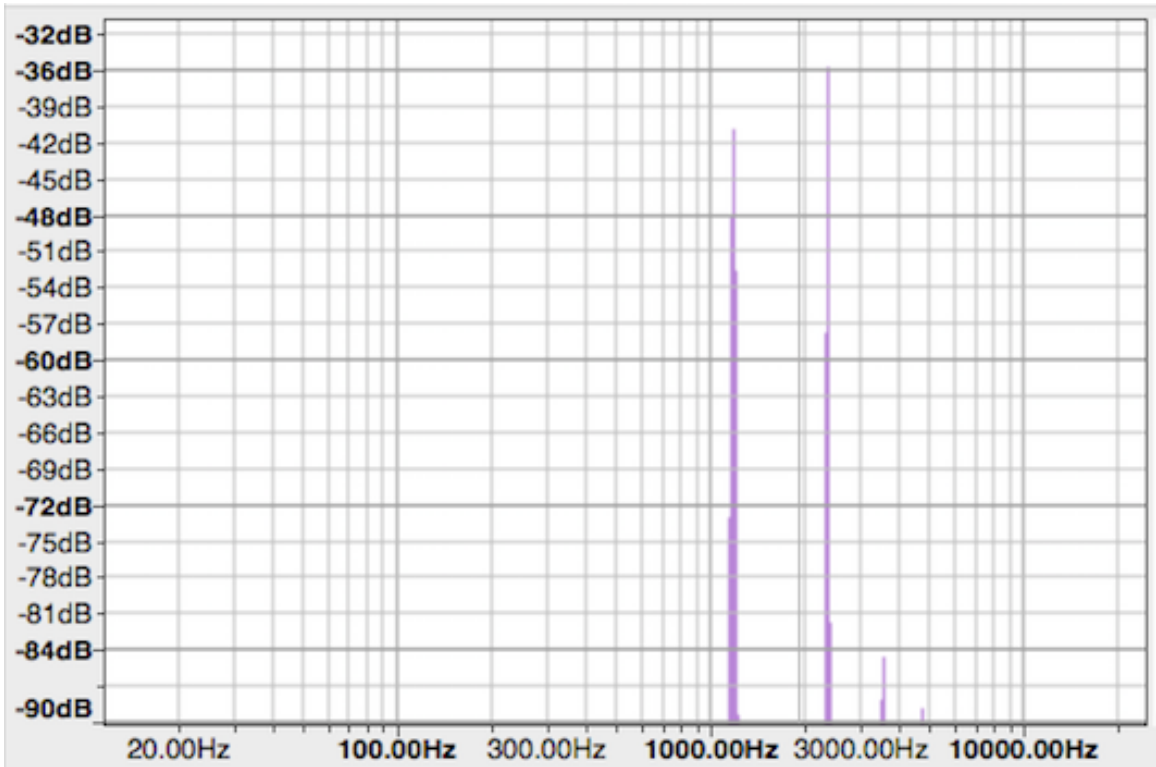
LIG



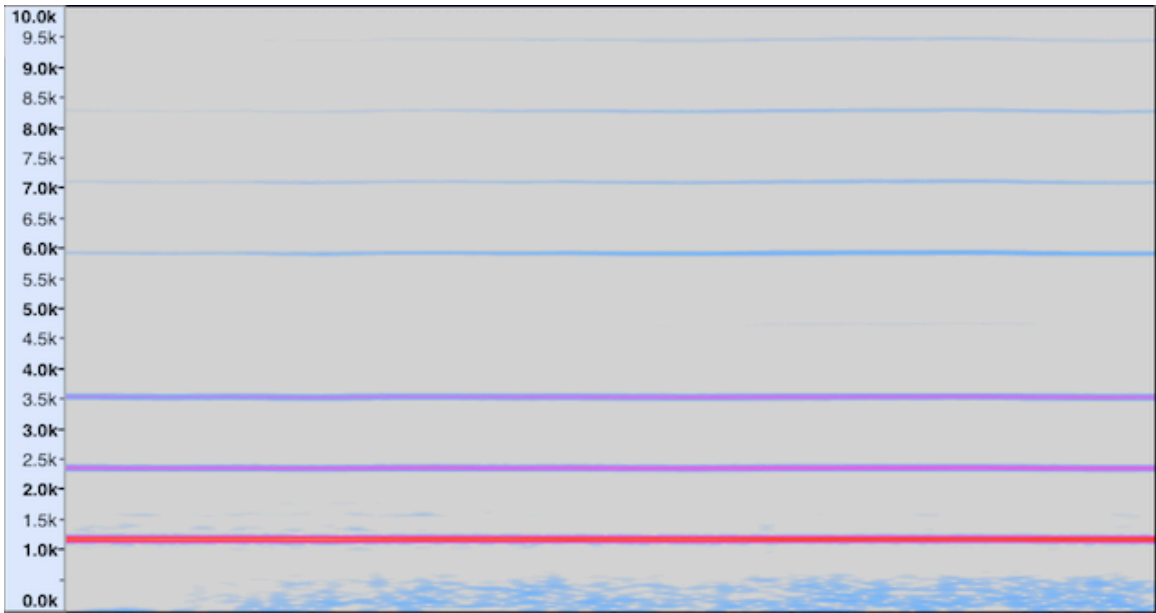
LIG



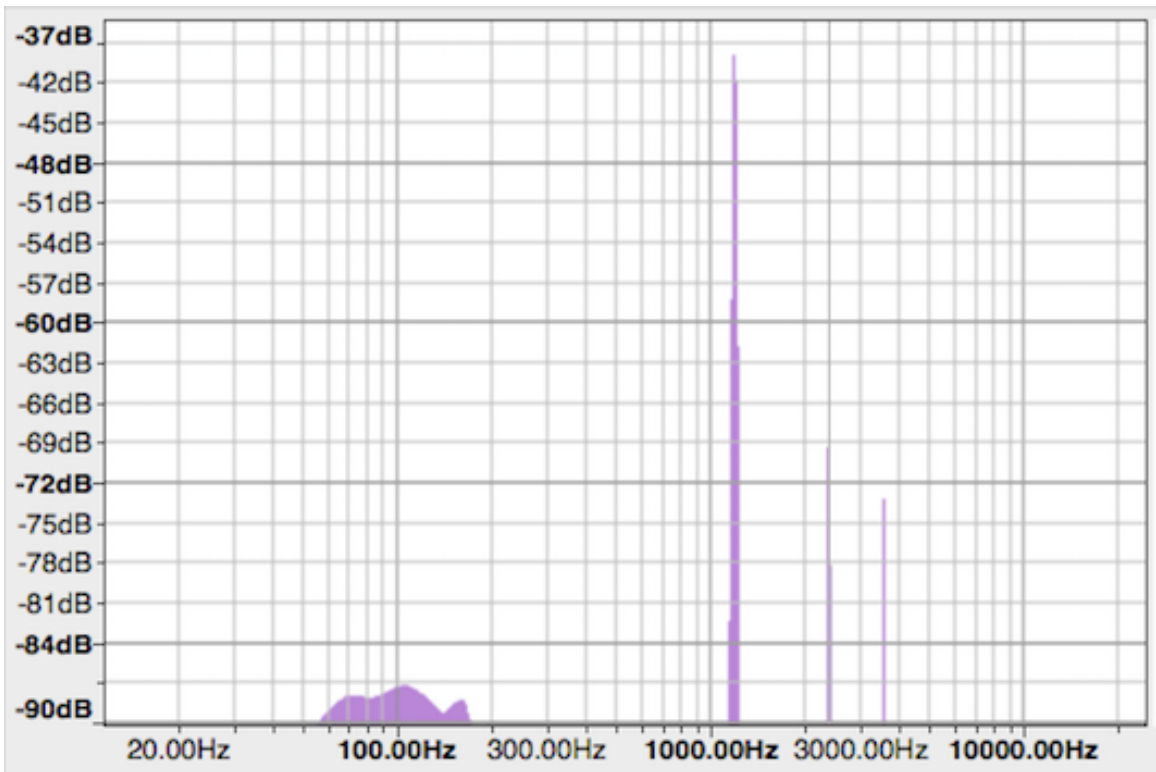
BAR Port



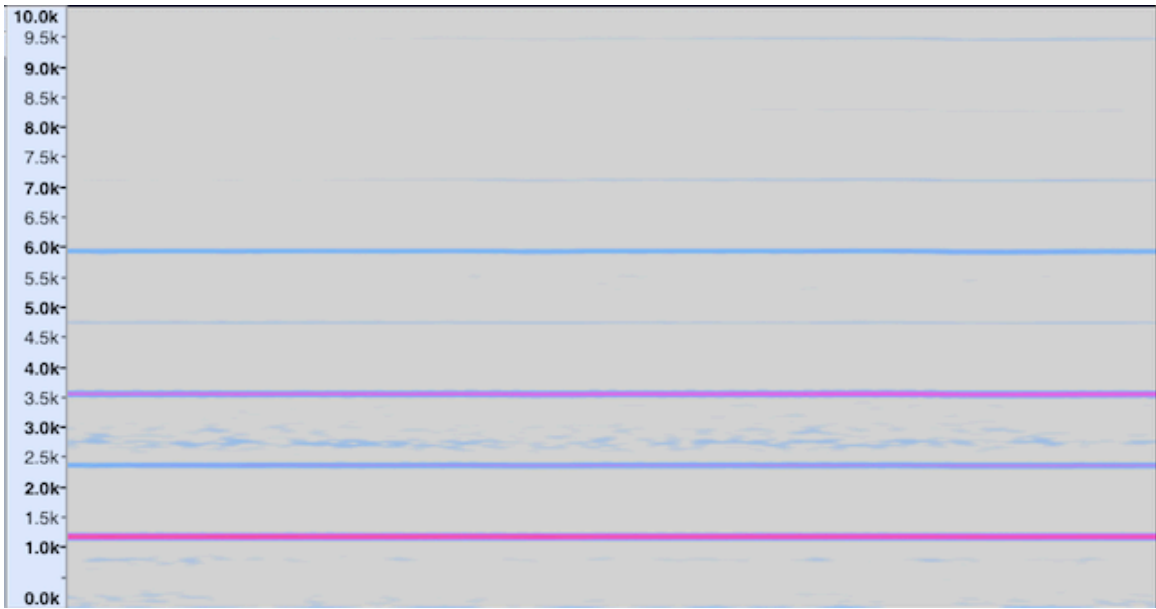
BAR Port



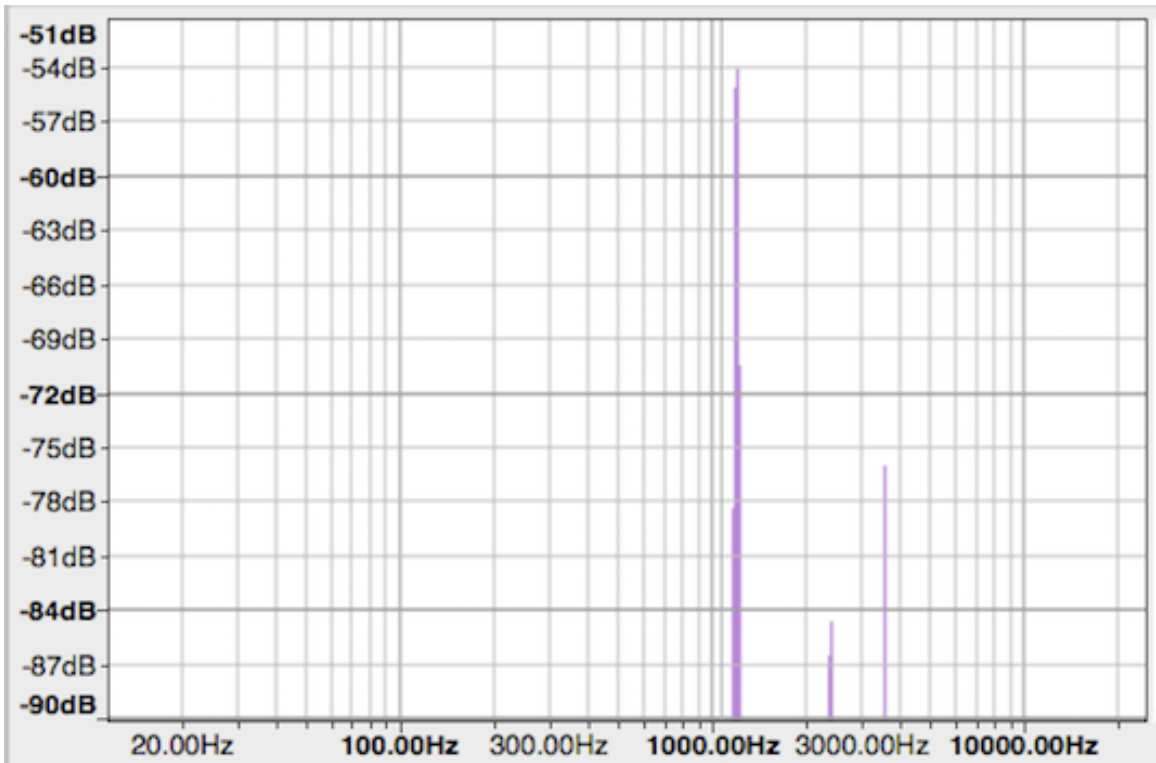
BAR Surf



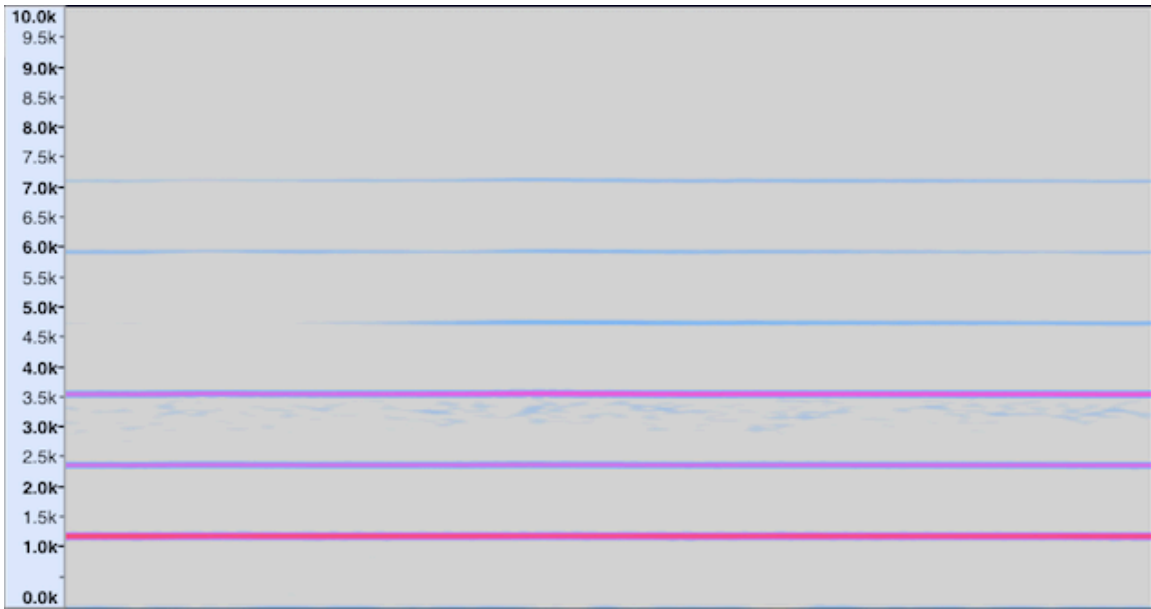
BAR Surf



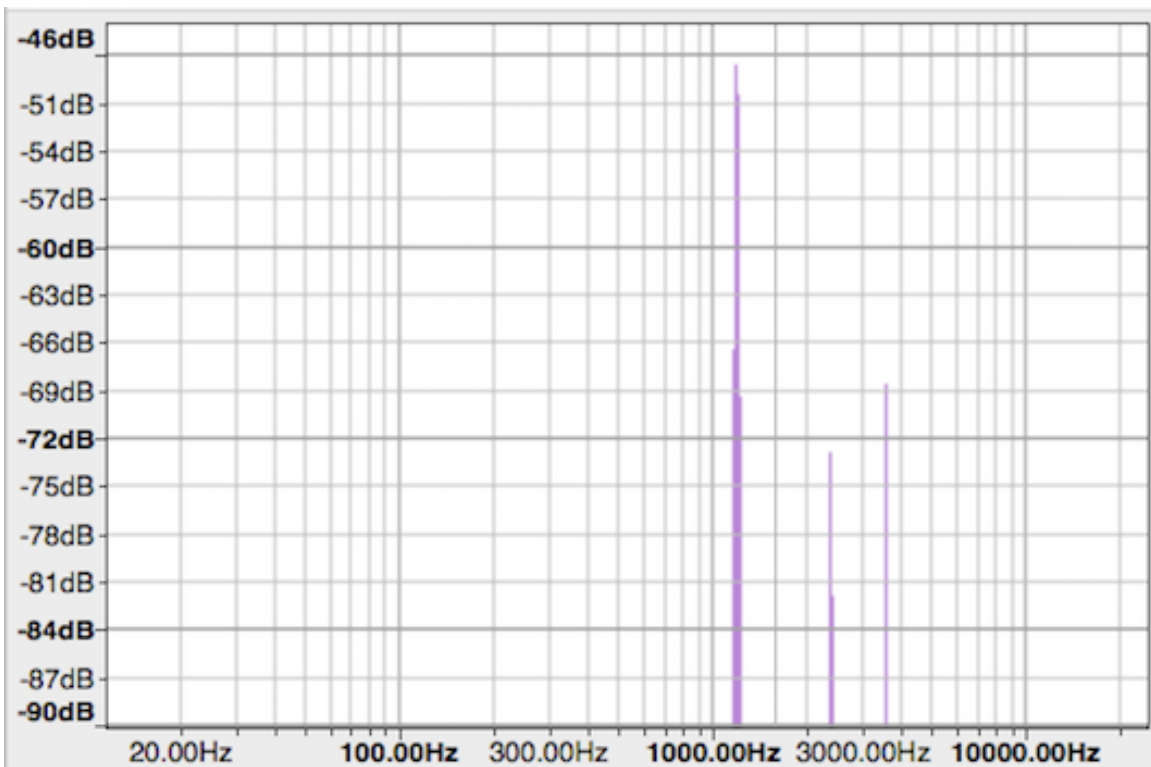
LF MPB



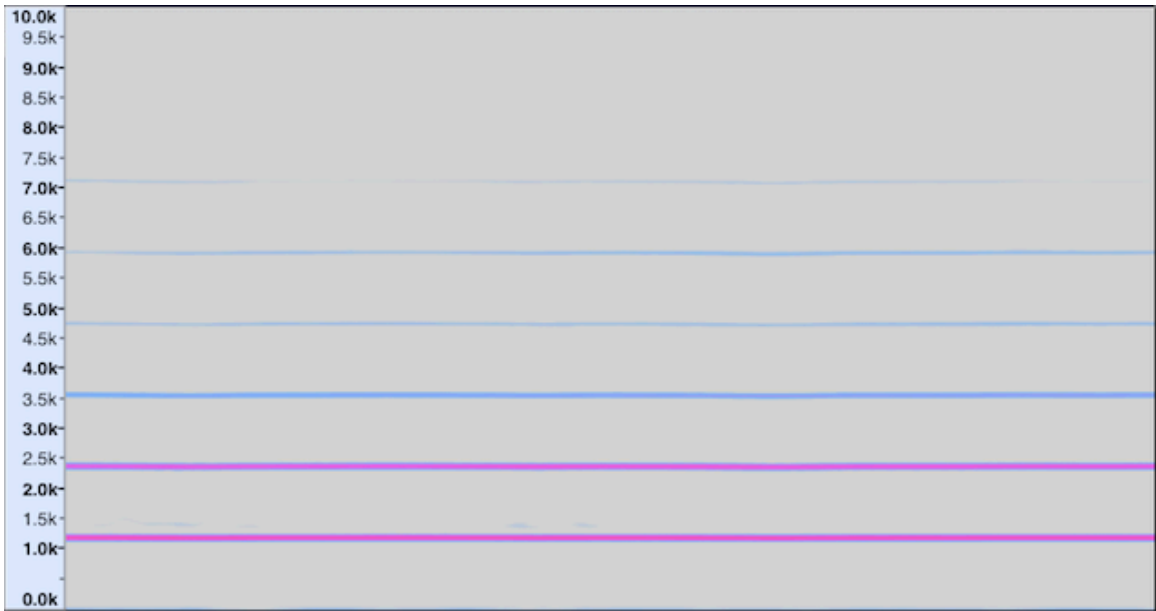
LF MPB



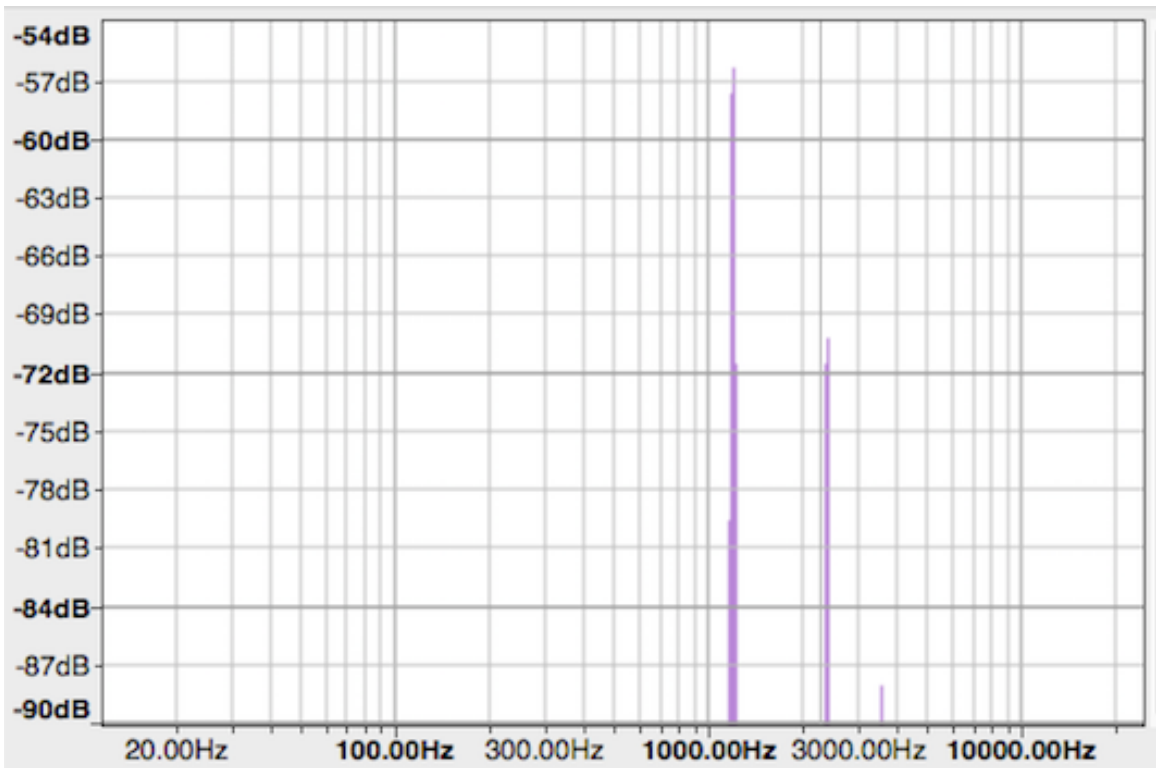
LF BUJ



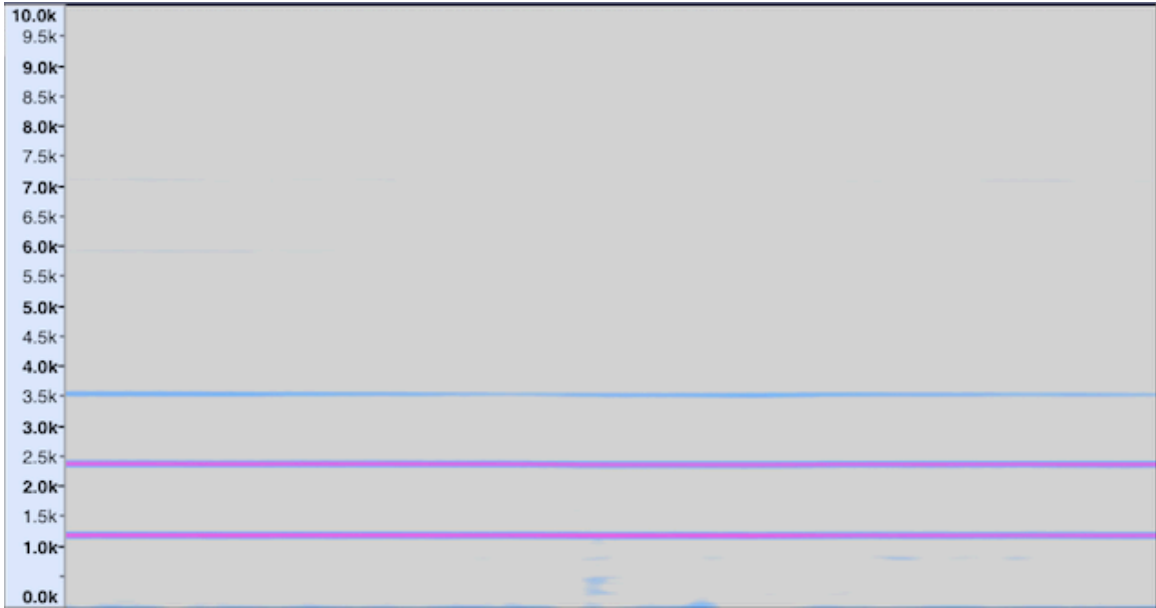
LF BUJ



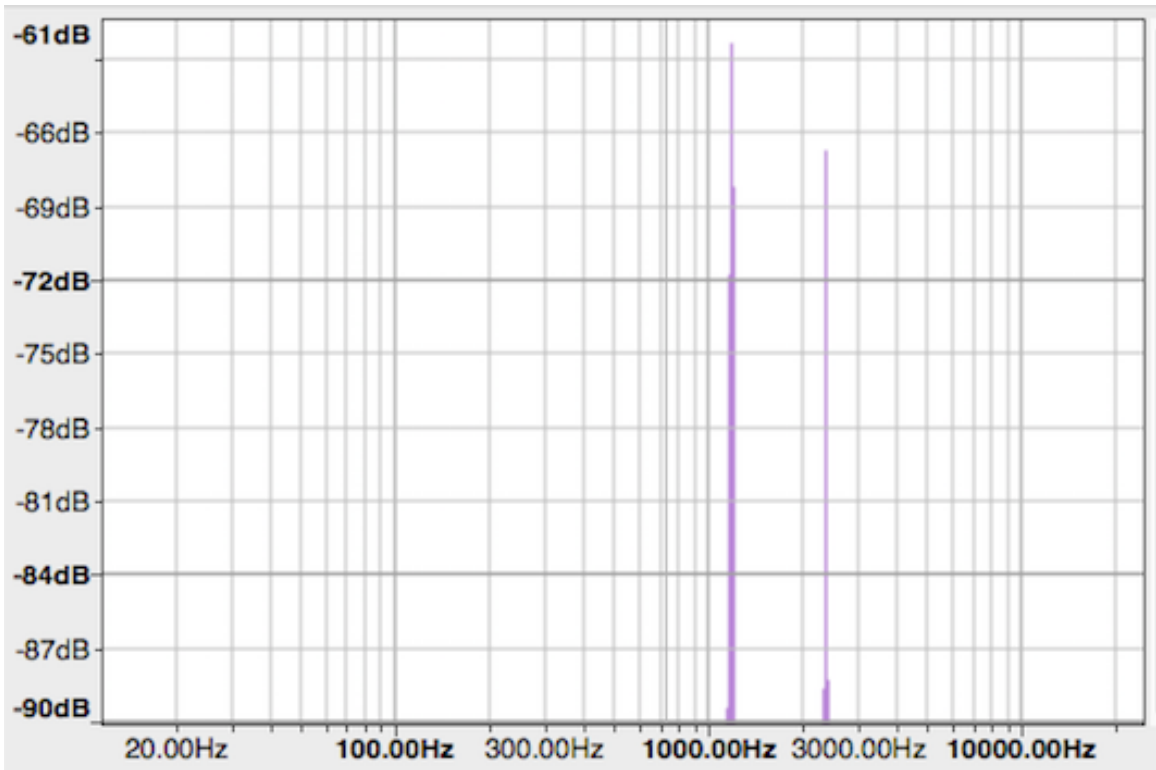
UJ



UJ



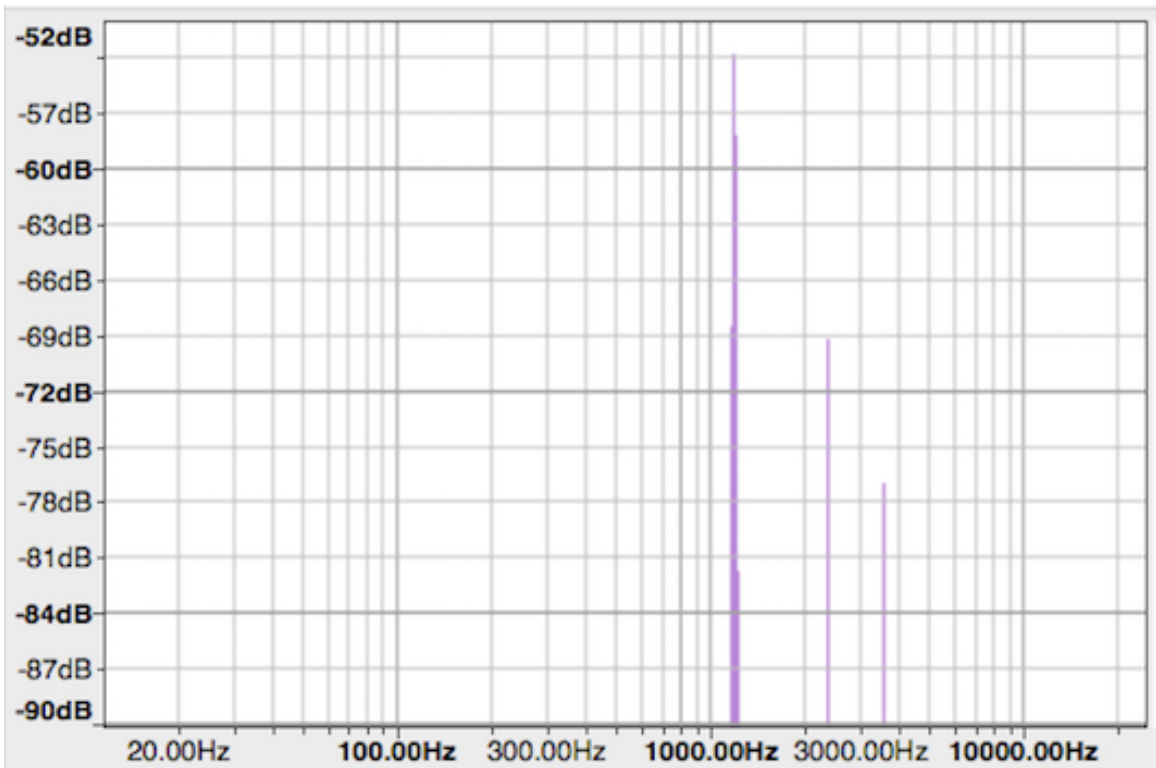
CTR



CTR



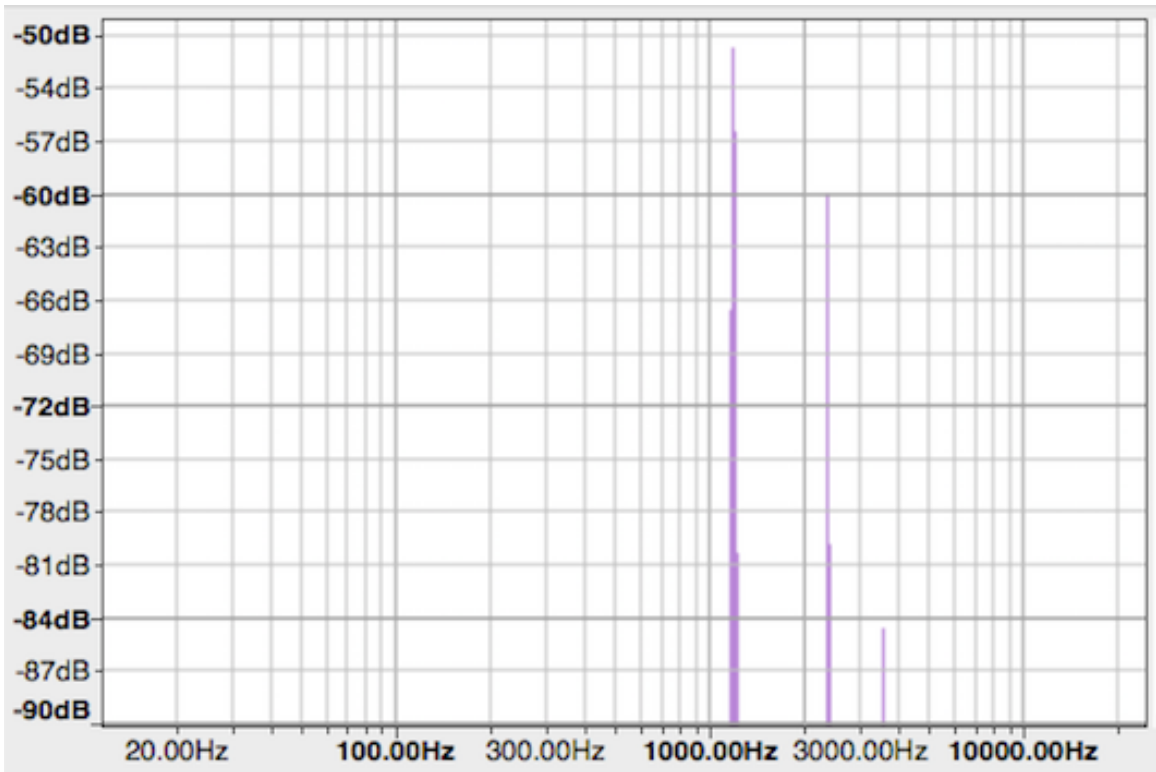
LJ



LJ



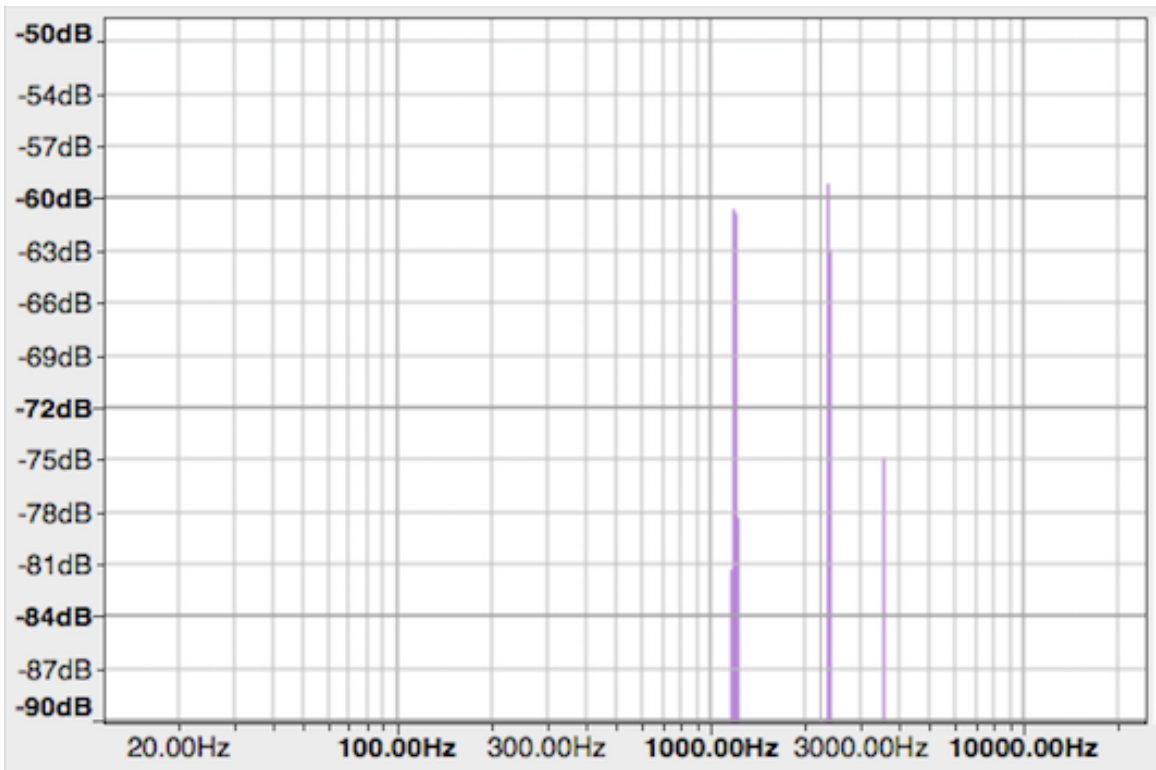
BELL Out



BELL Out

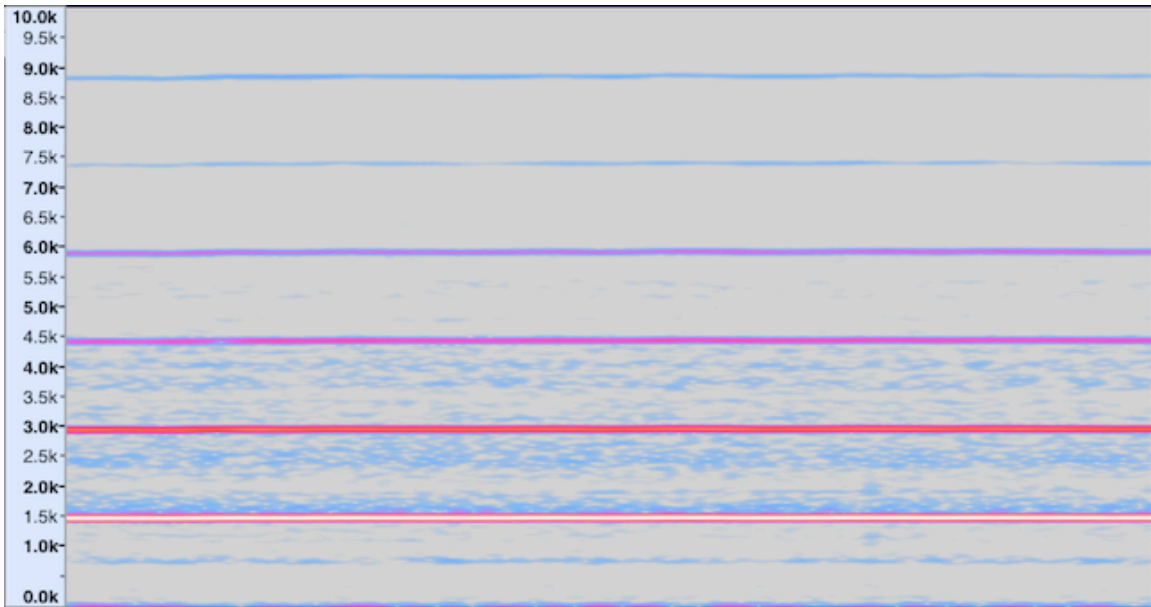


BELL End

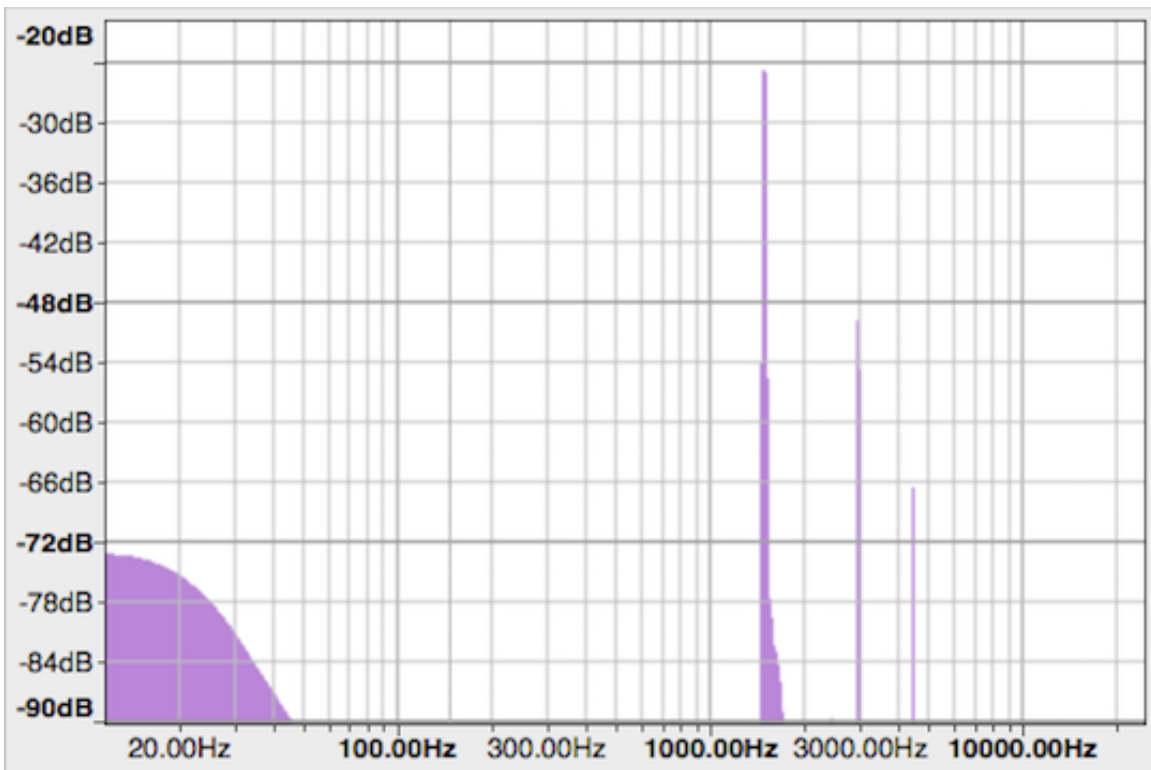


BELL End

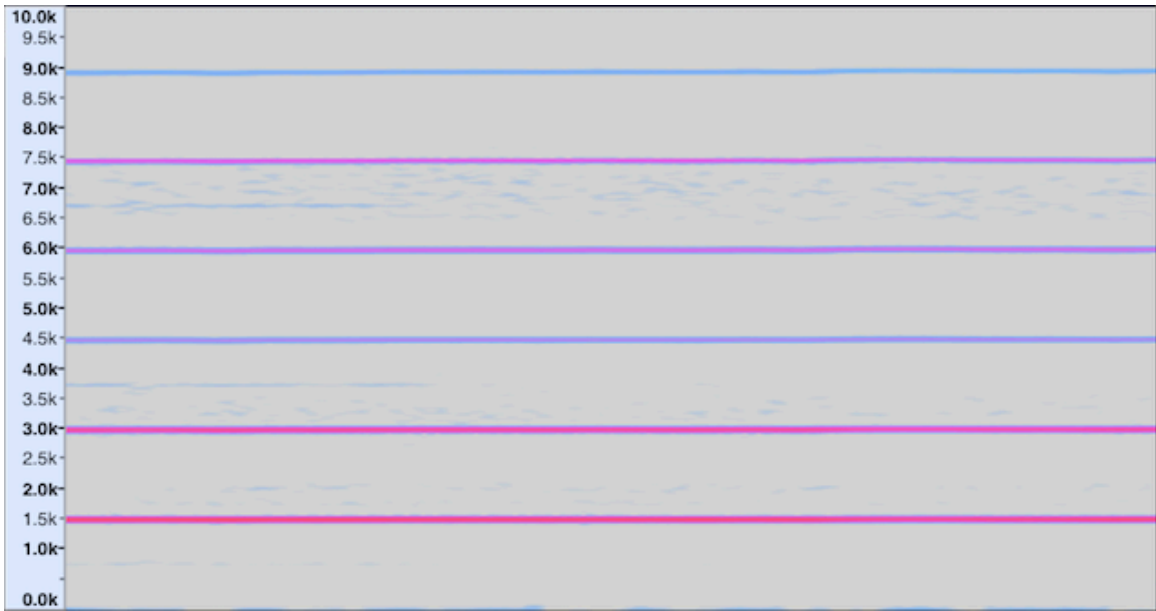
APPENDIX O  
SAMPLE DATA G-SHARP6



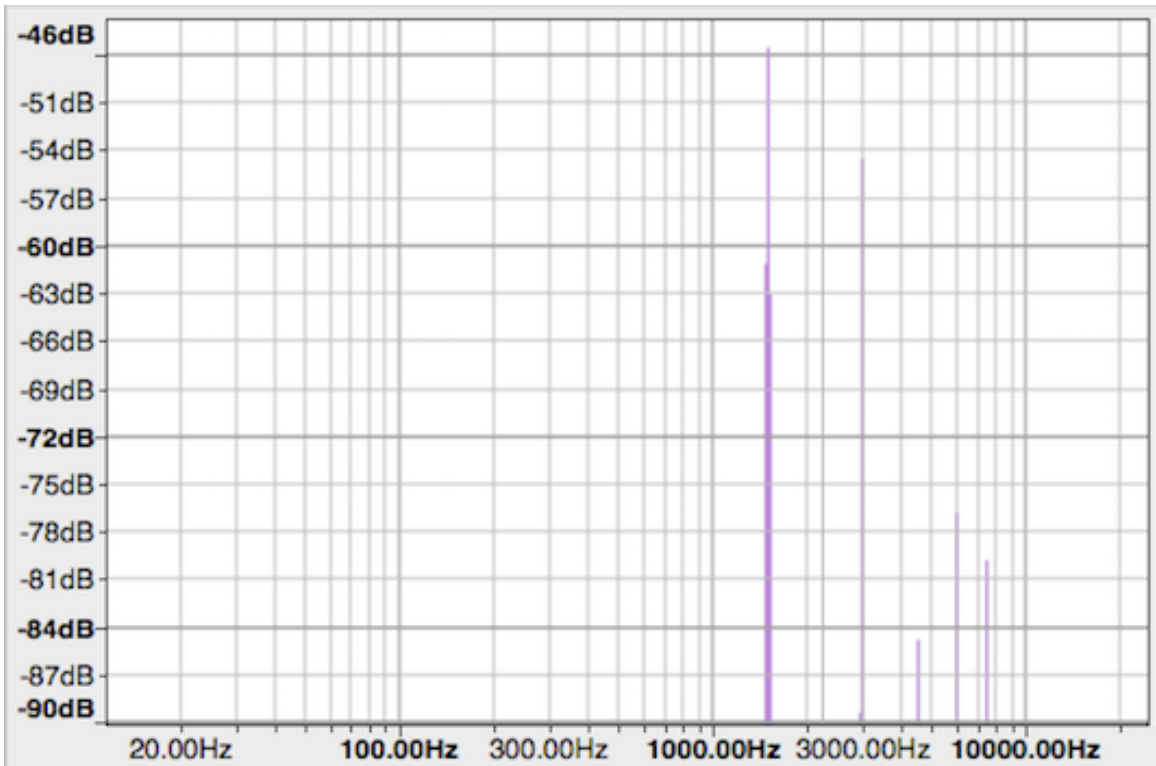
M30 (Reference)



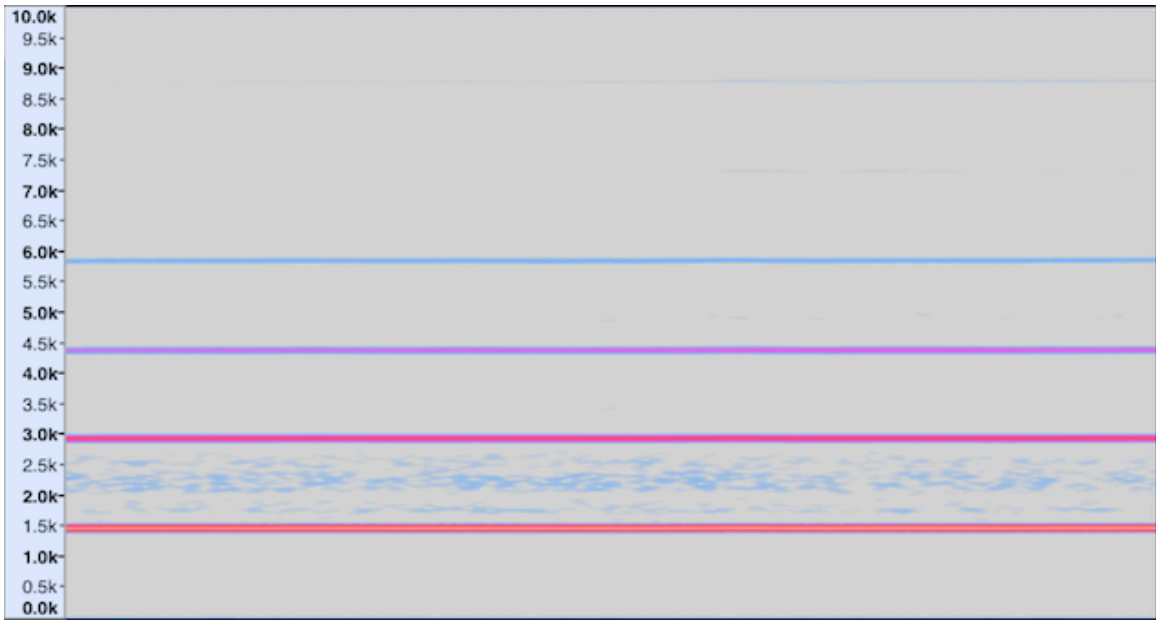
M30 (Reference)



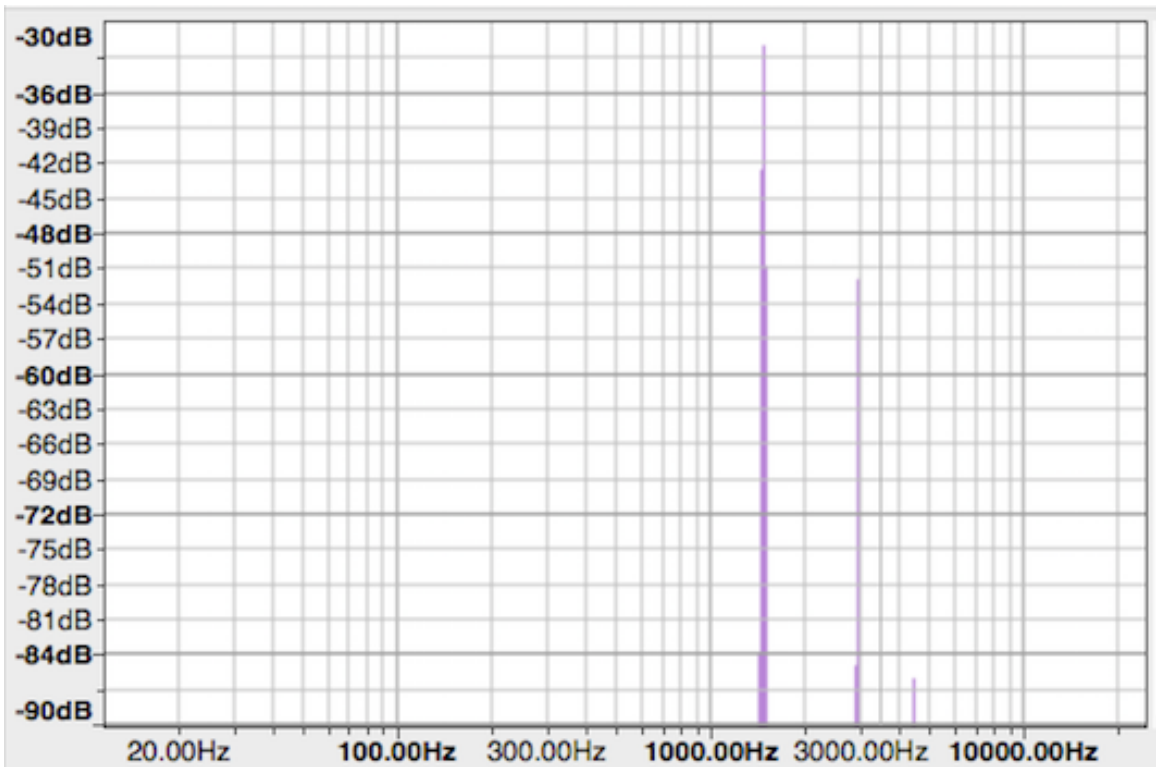
LIG



LIG



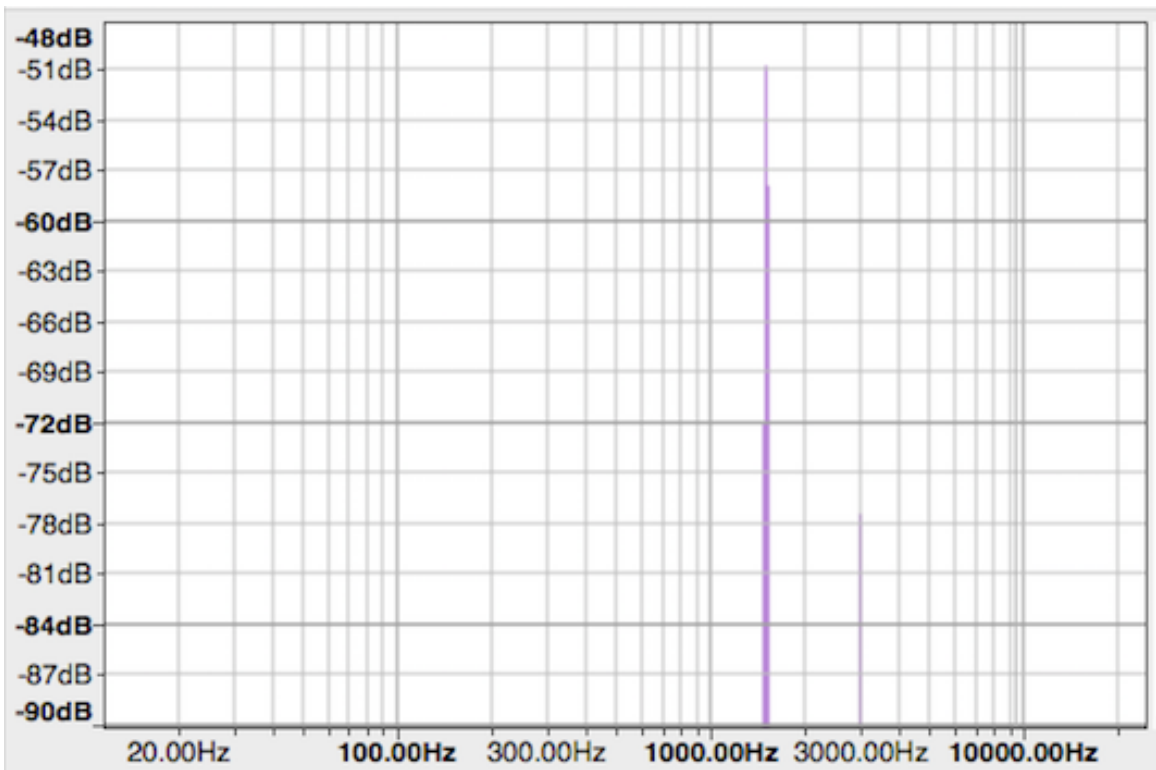
BAR Port



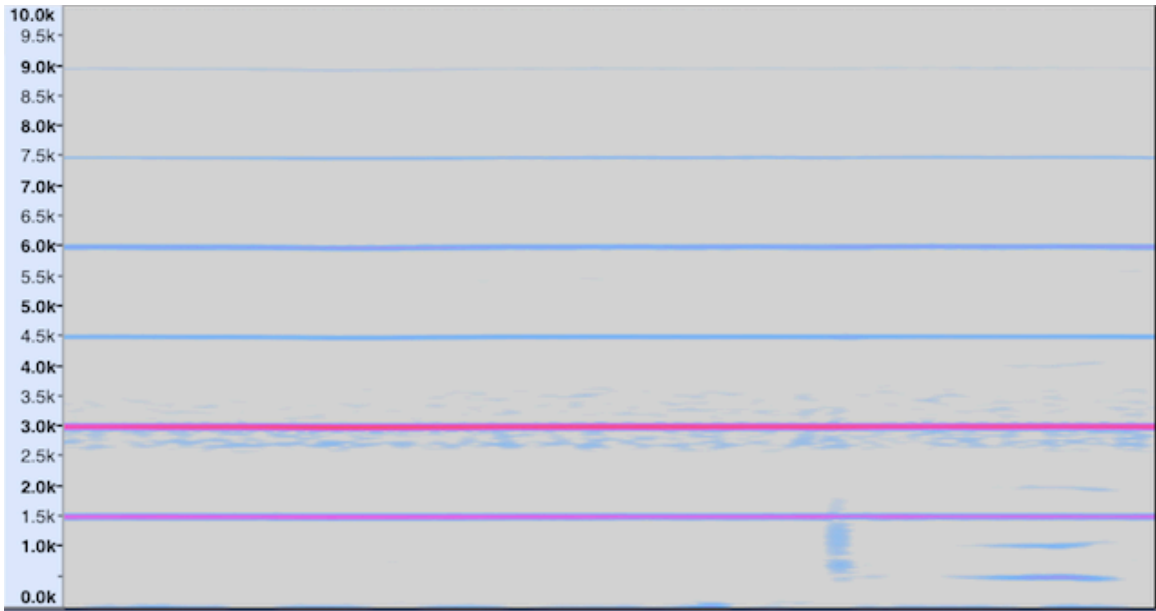
BAR Port



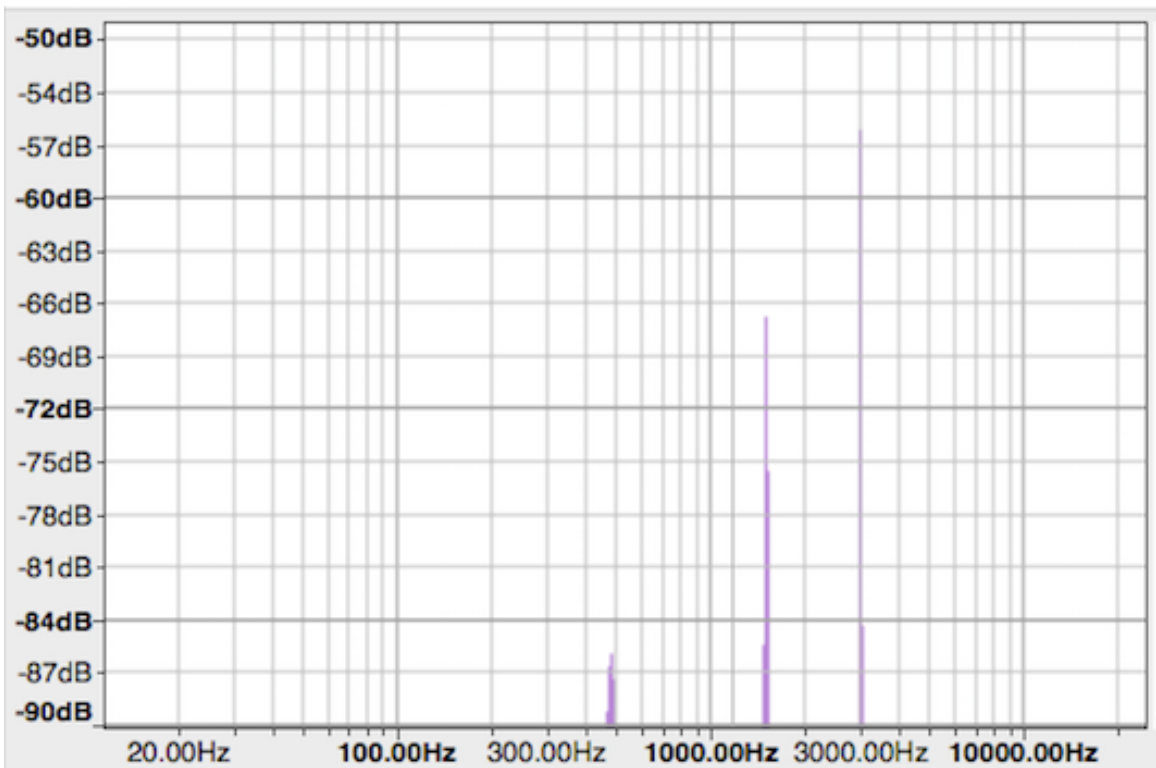
BAR Surf



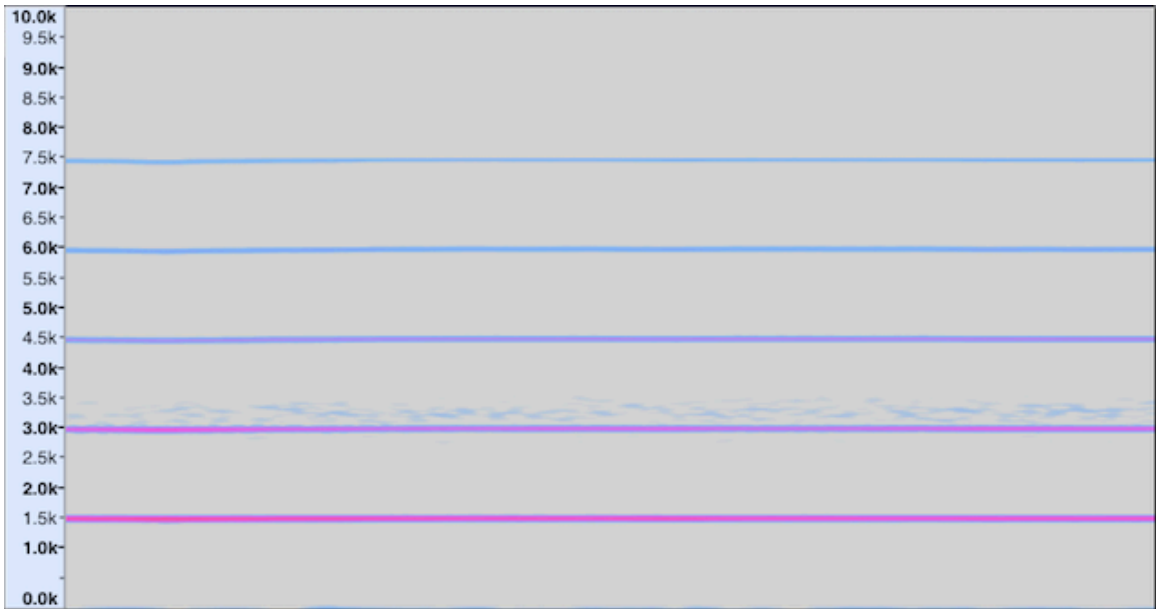
BAR Surf



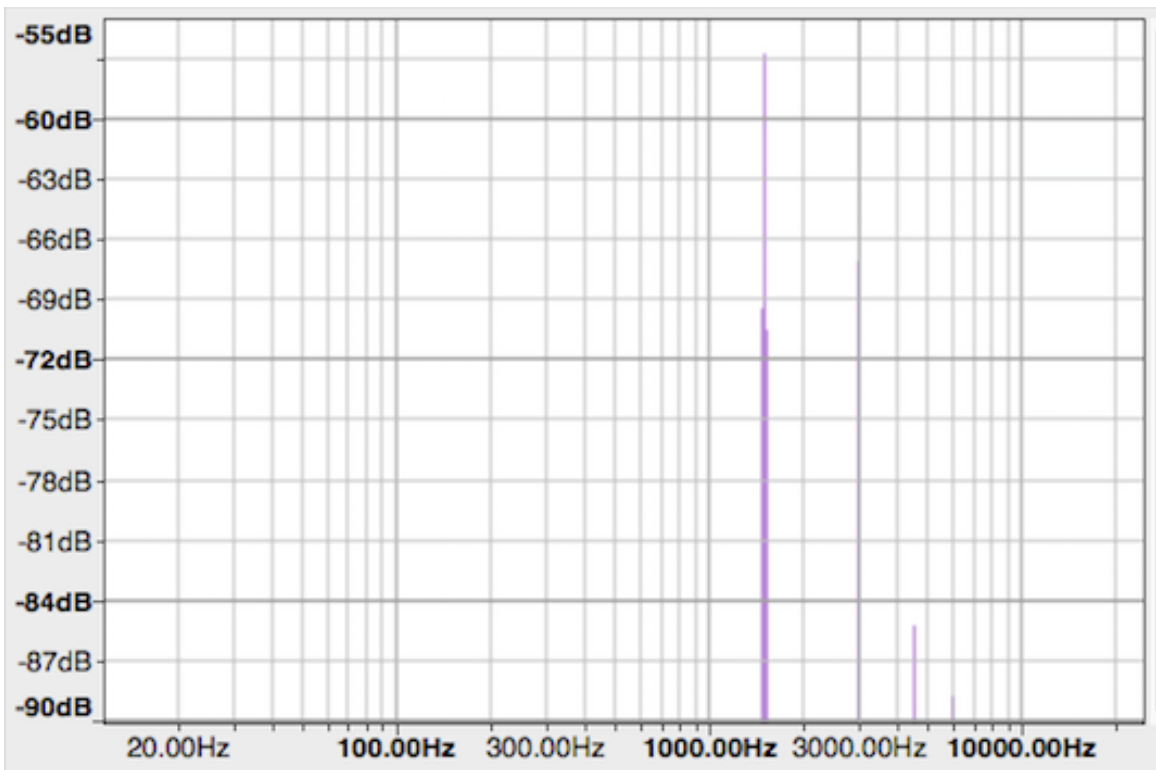
LF MPB



LF MPB



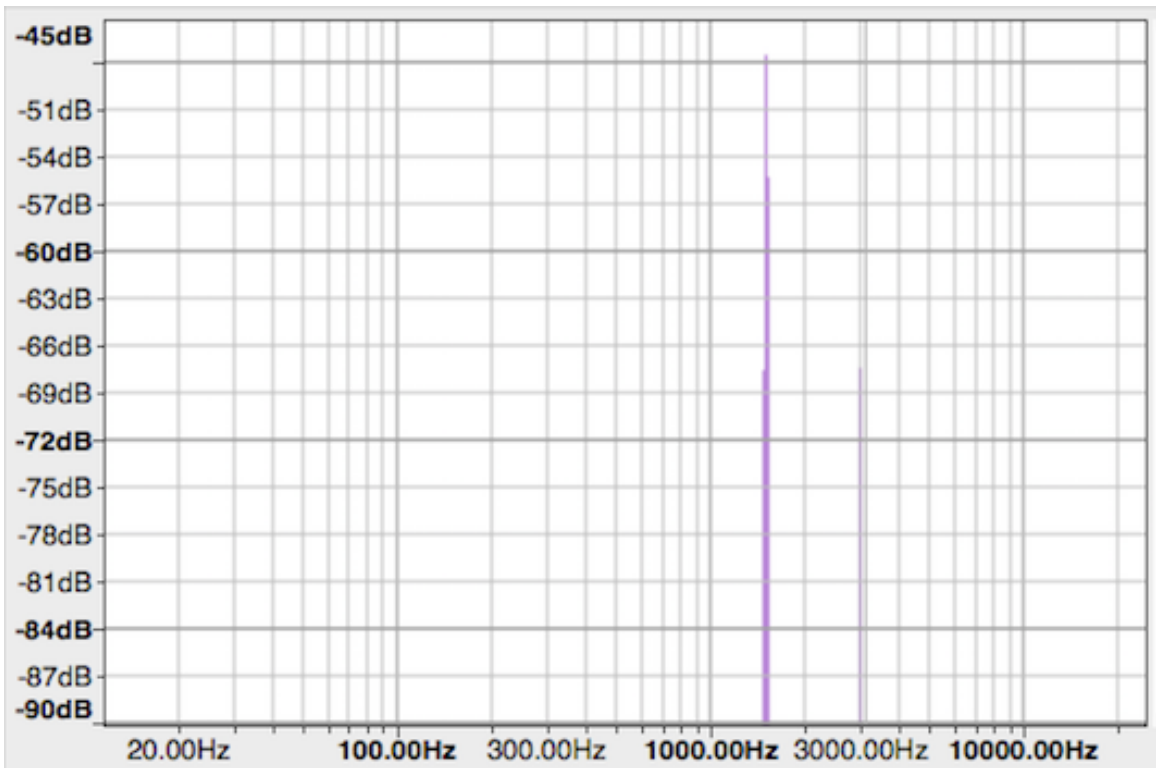
LF BUJ



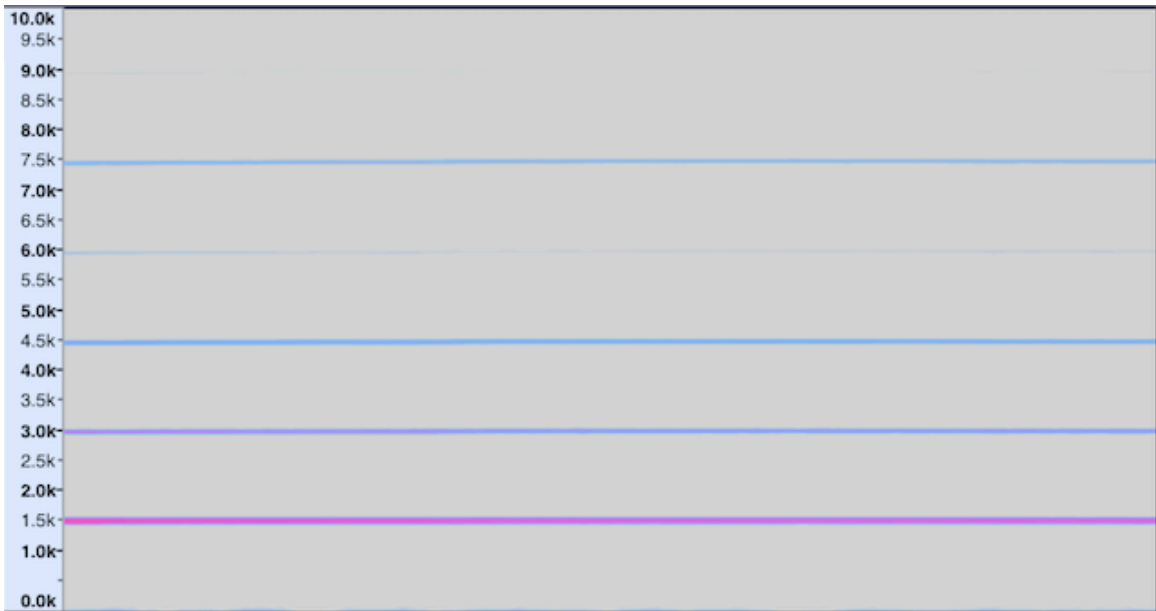
LF BUJ



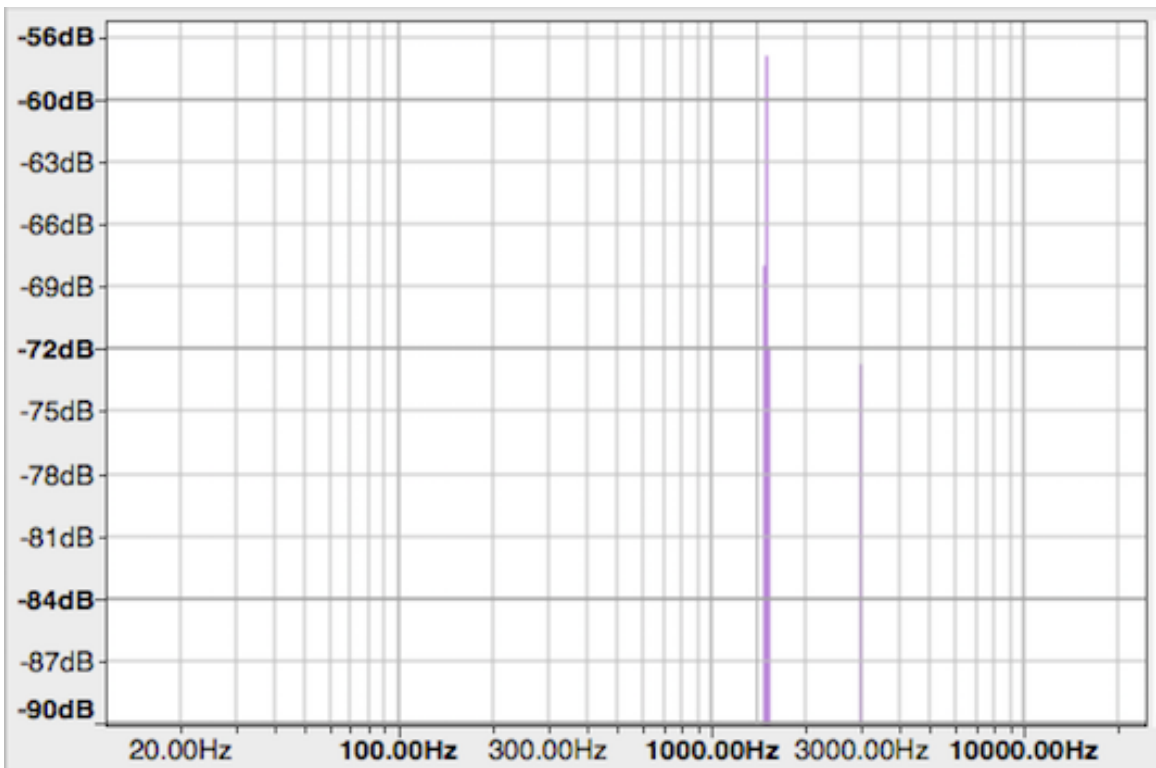
UJ



UJ



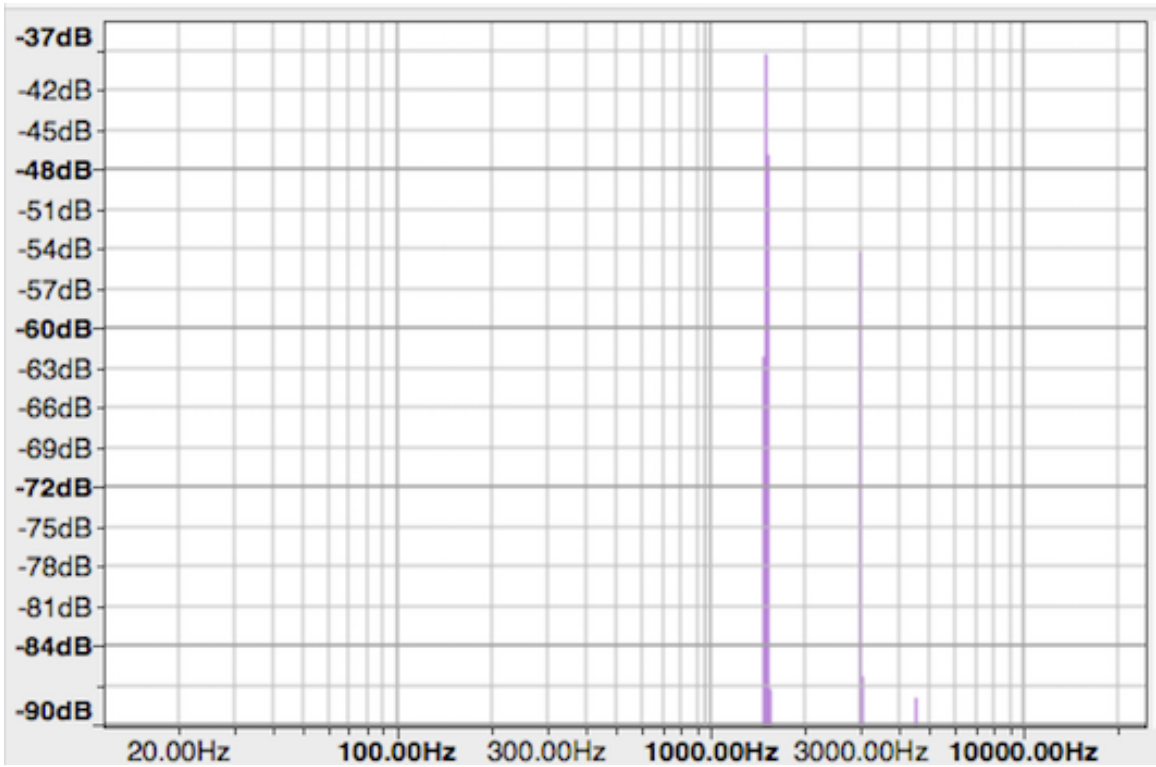
CTR



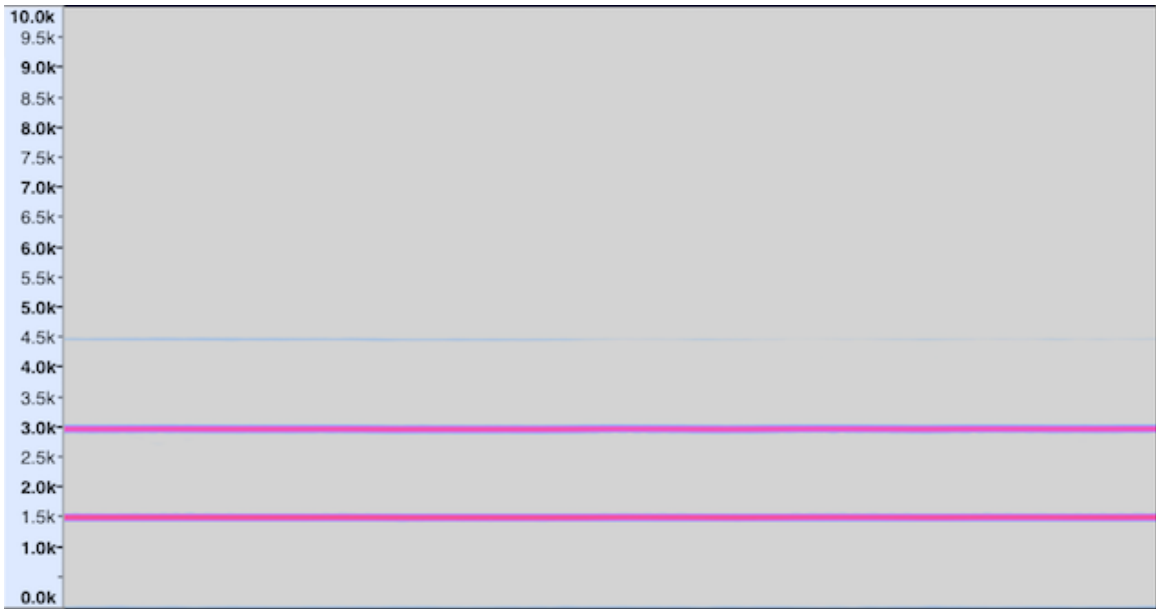
CTR



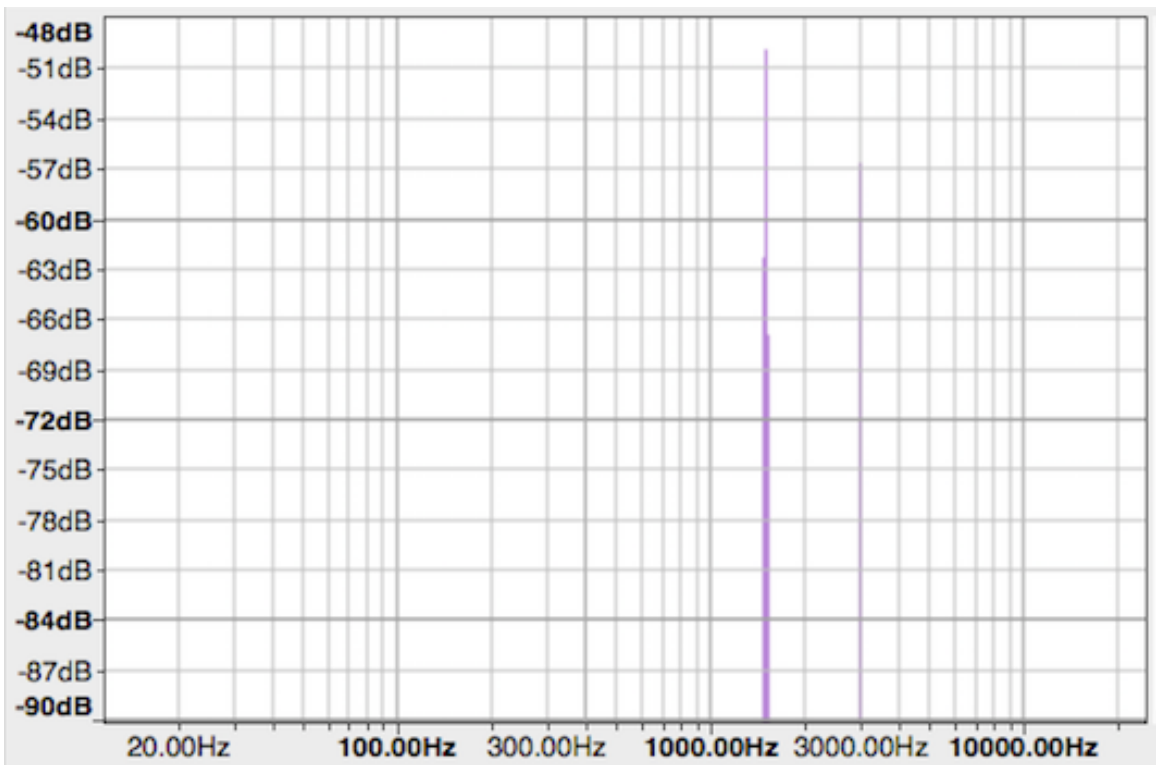
LJ



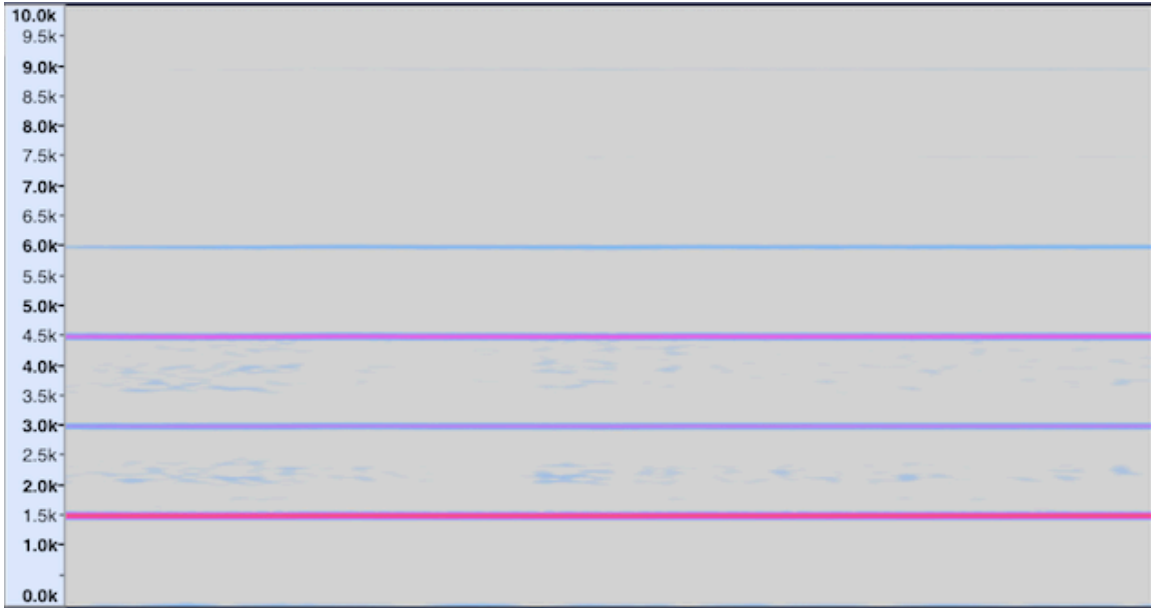
LJ



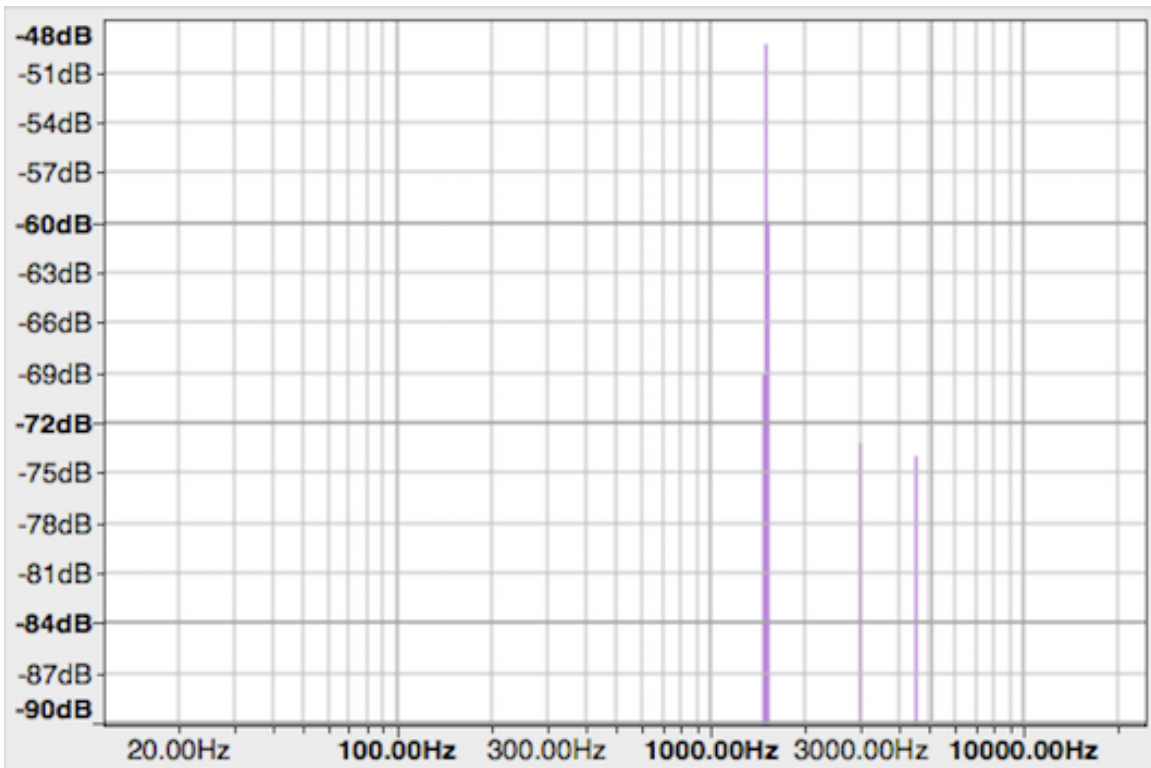
BELL Out



BELL Out

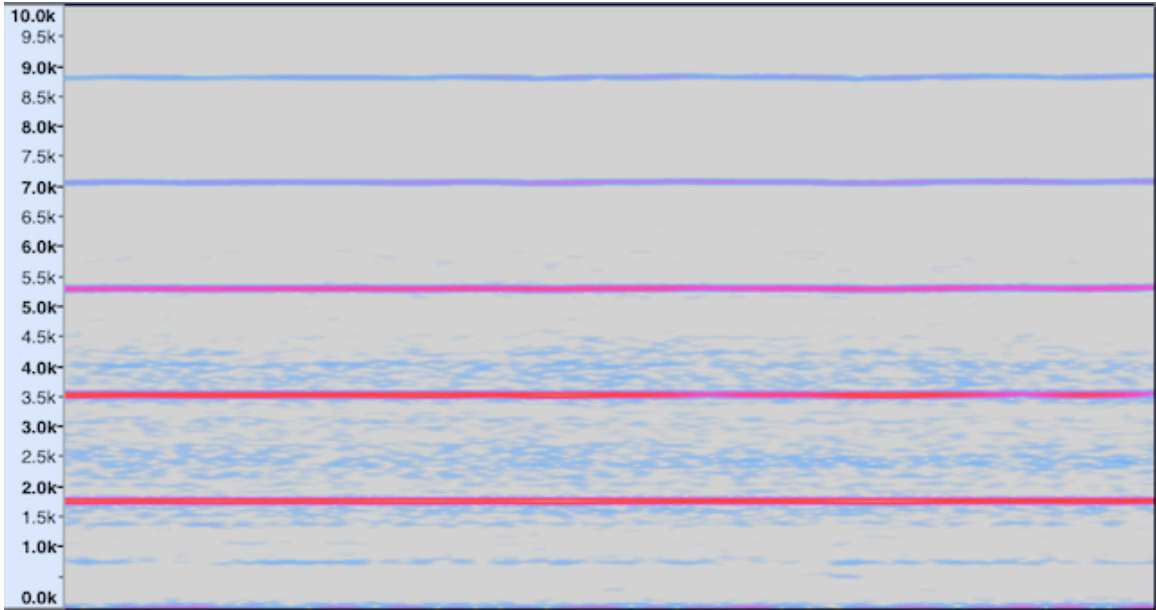


BELL End

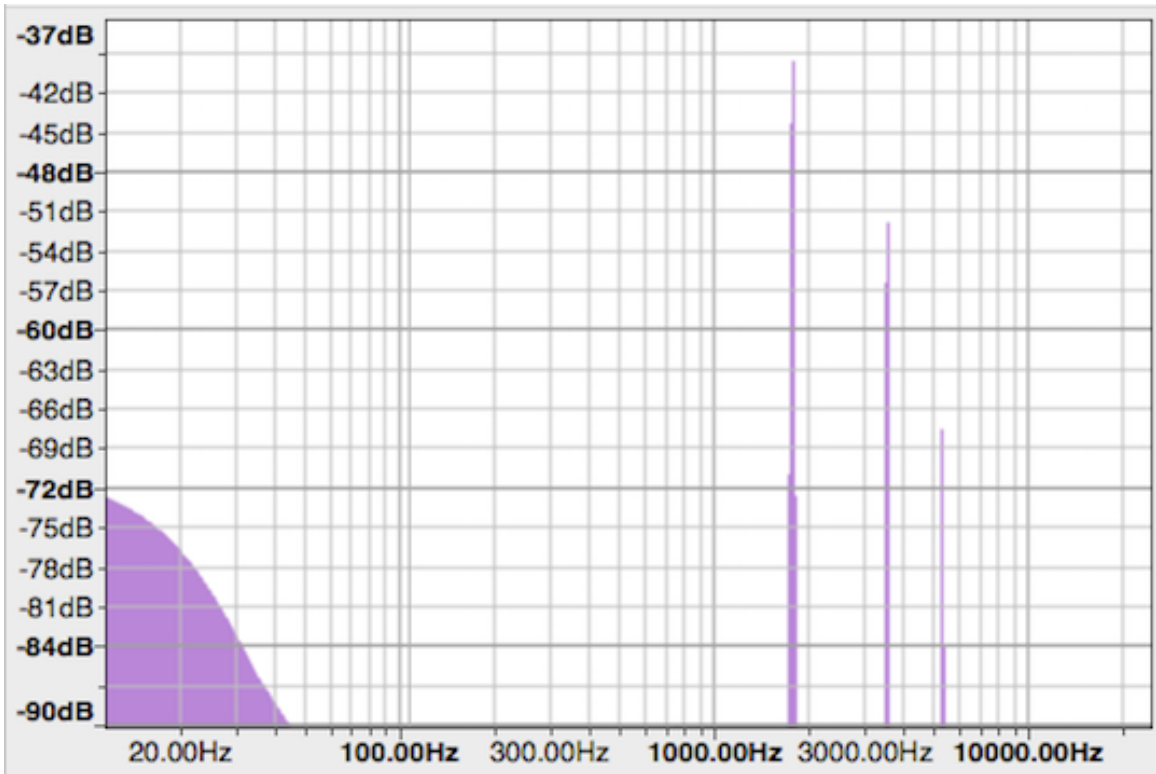


BELL End

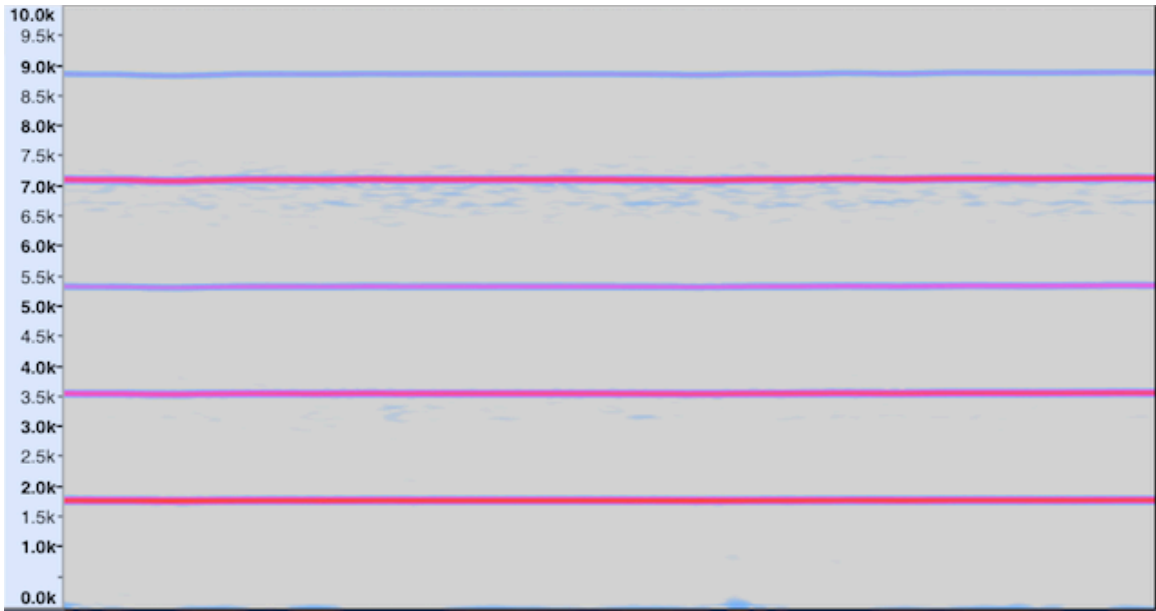
APPENDIX P  
SAMPLE DATA B6



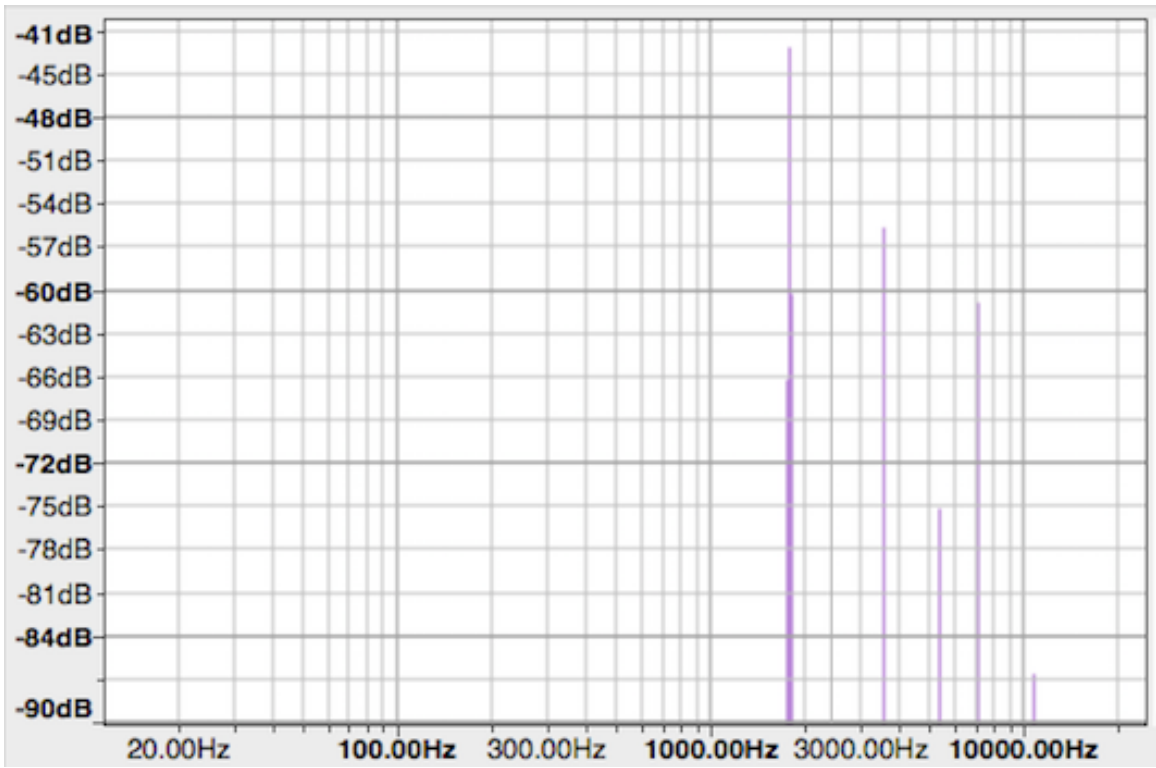
M30 (Reference)



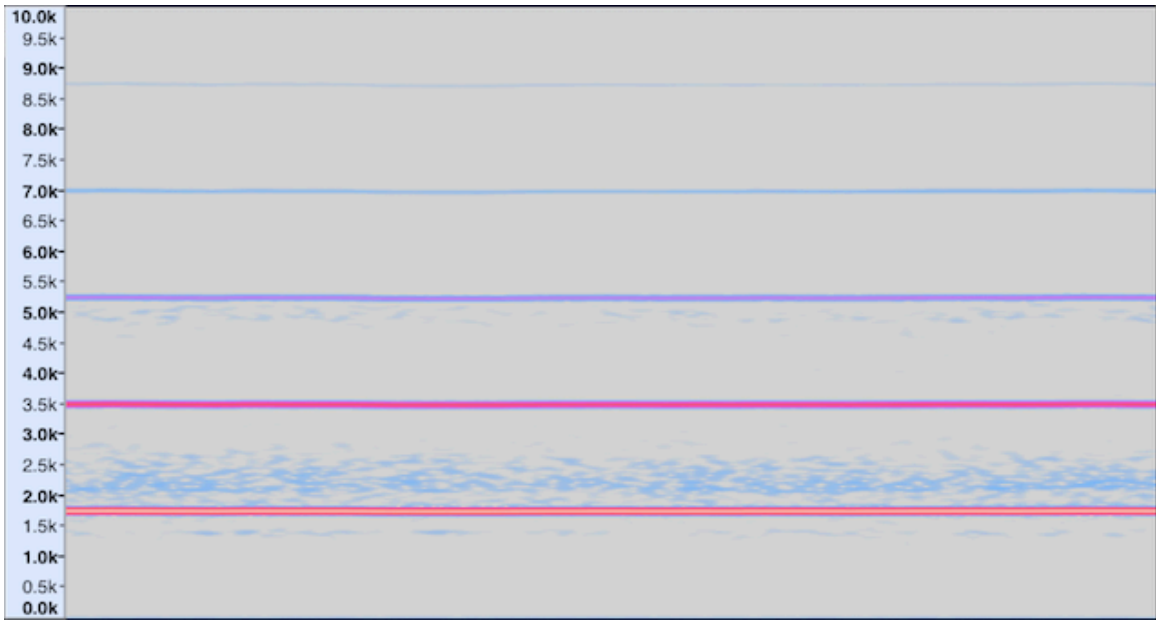
M30 (Reference)



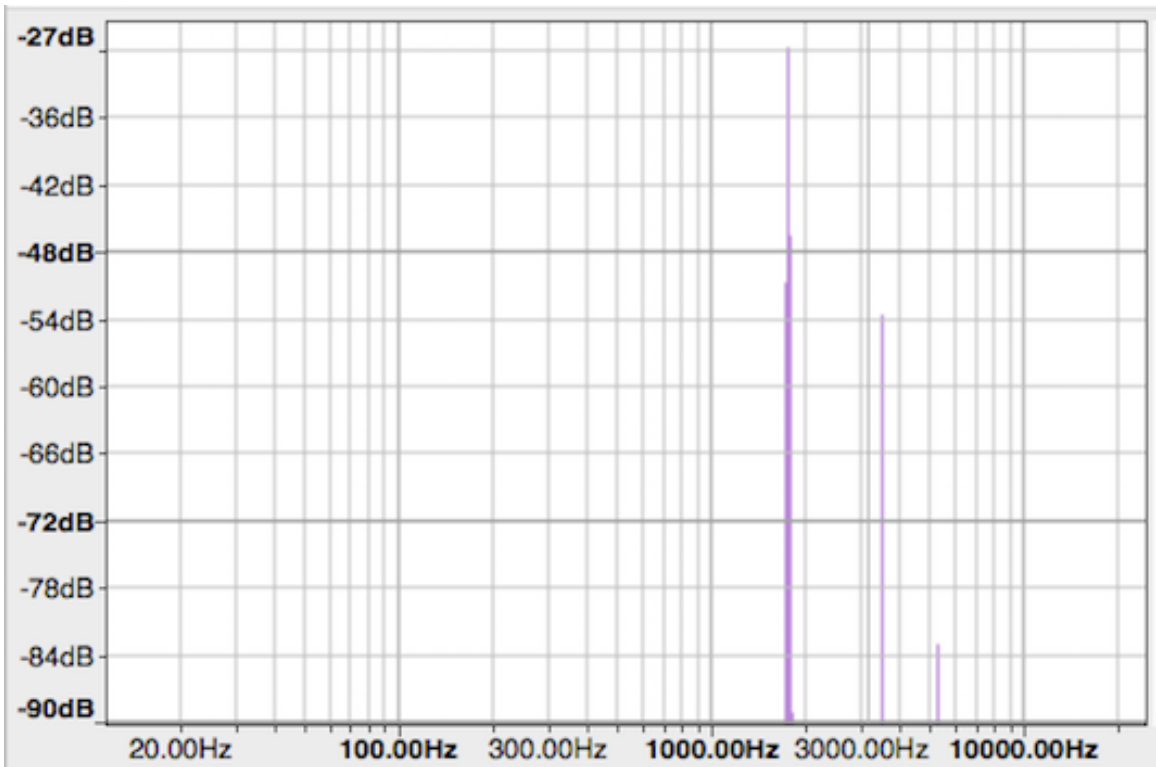
LIG



LIG



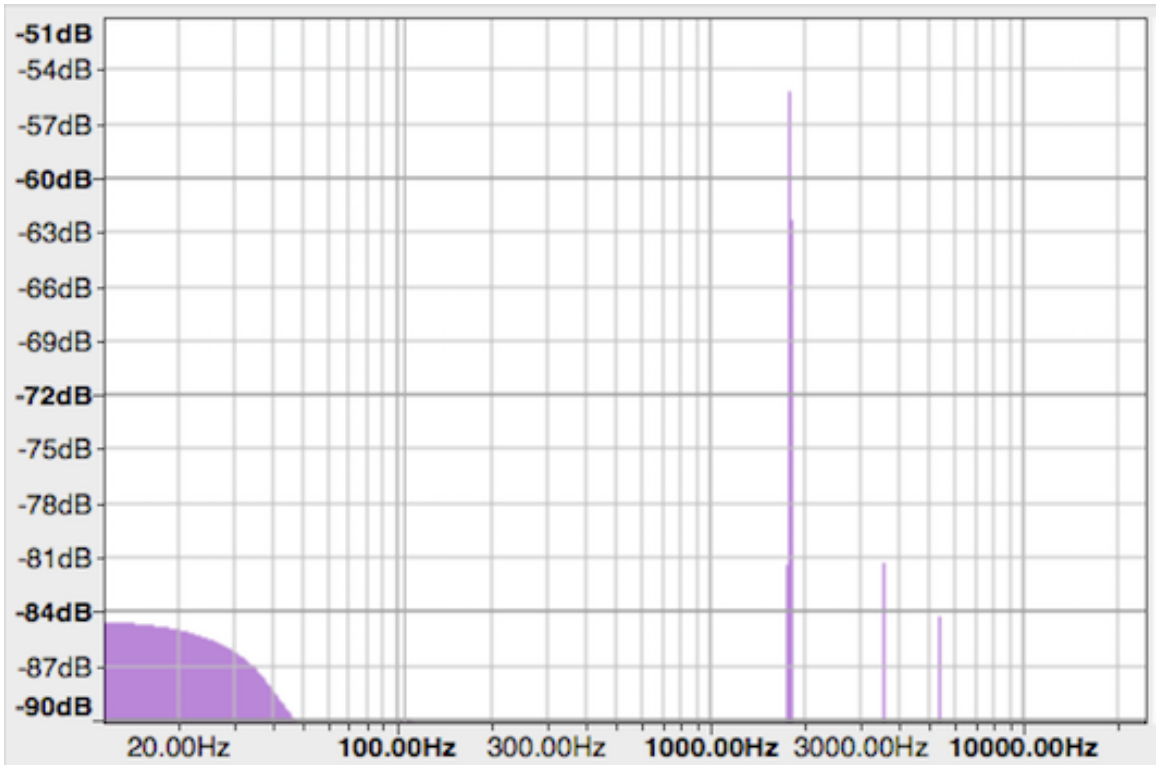
BAR Port



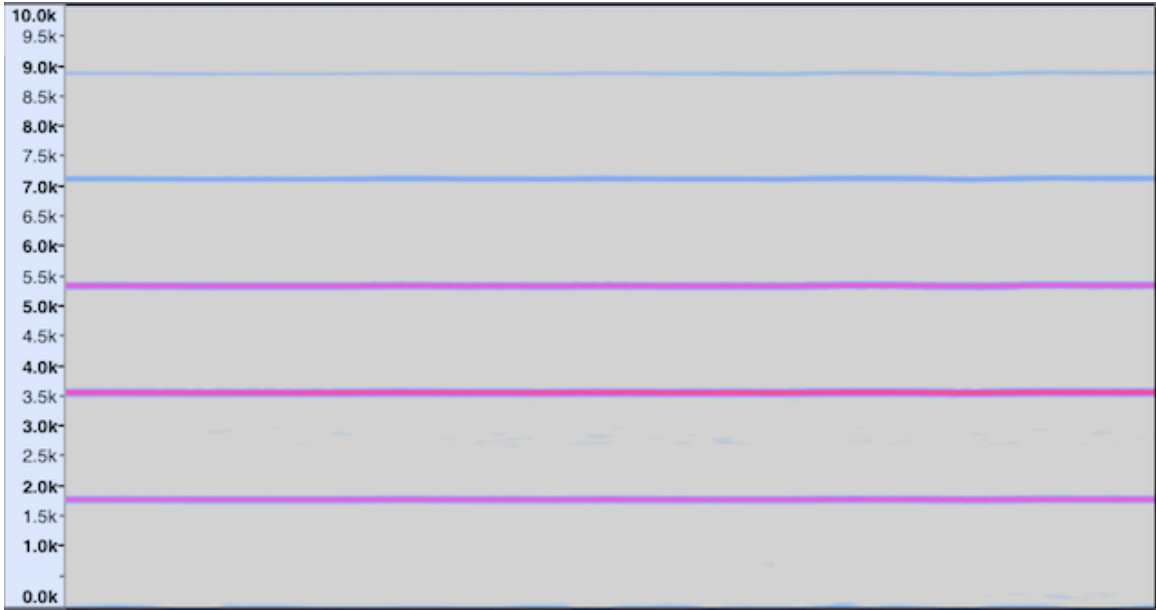
BAR Port



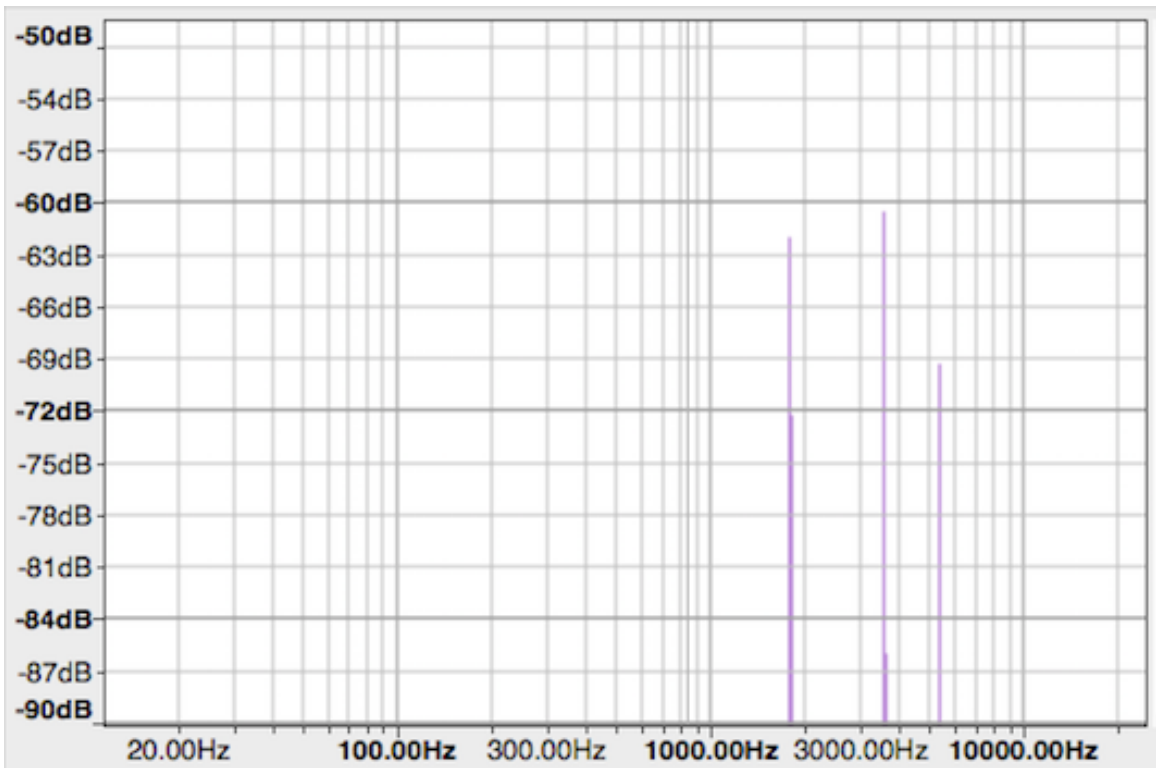
BAR Surf



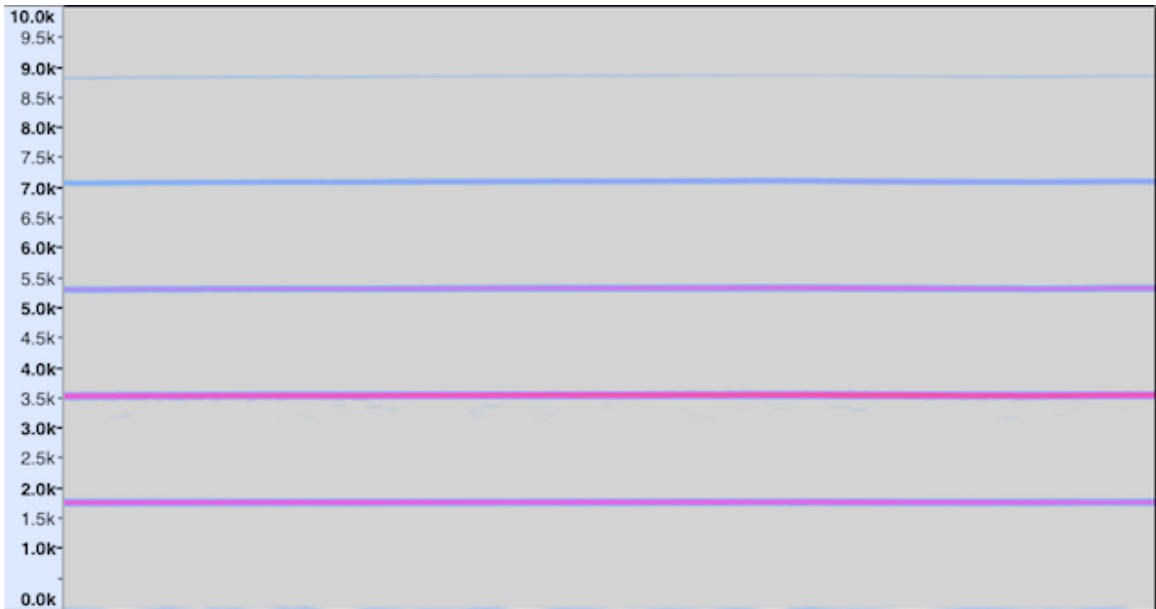
BAR Surf



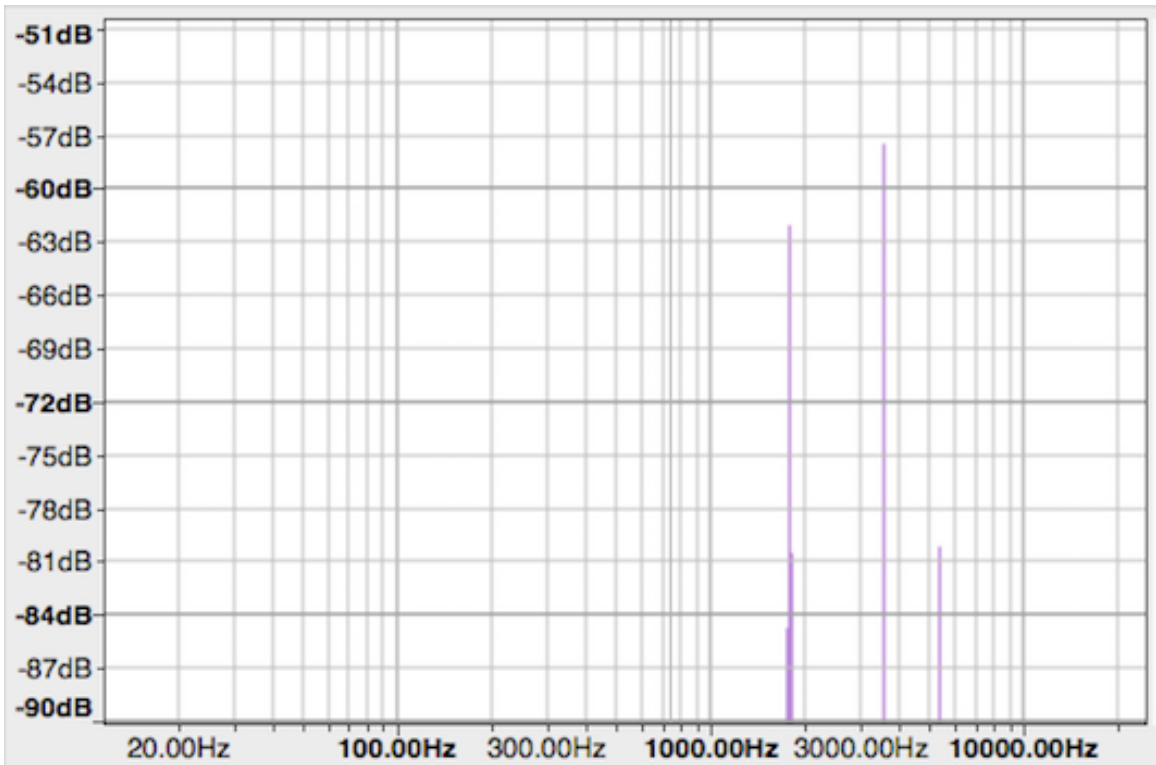
LF MPB



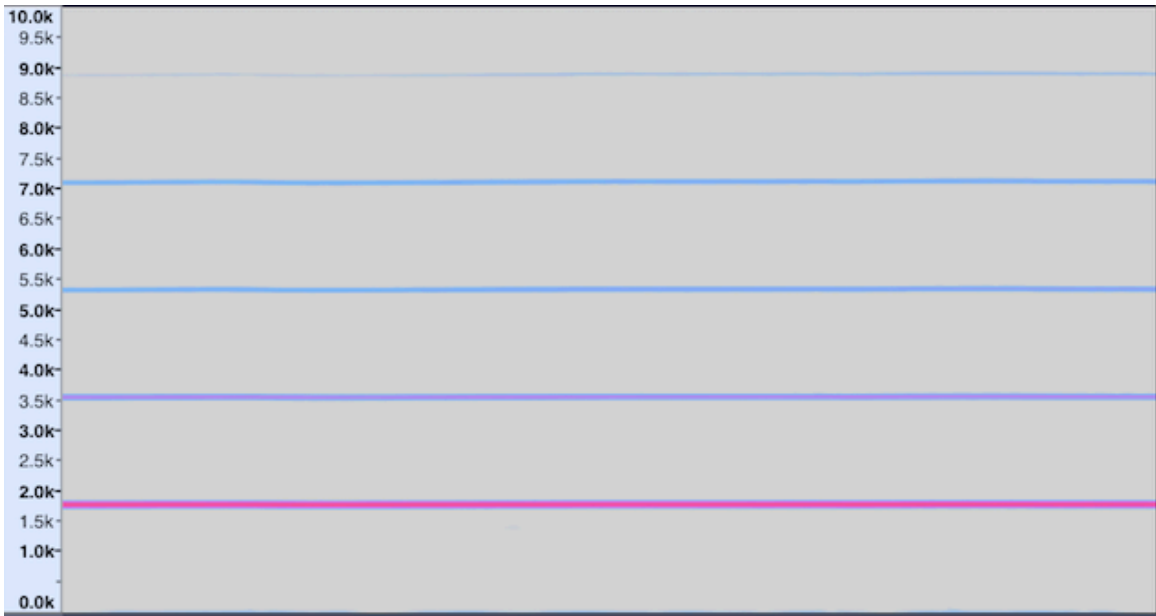
LF MPB



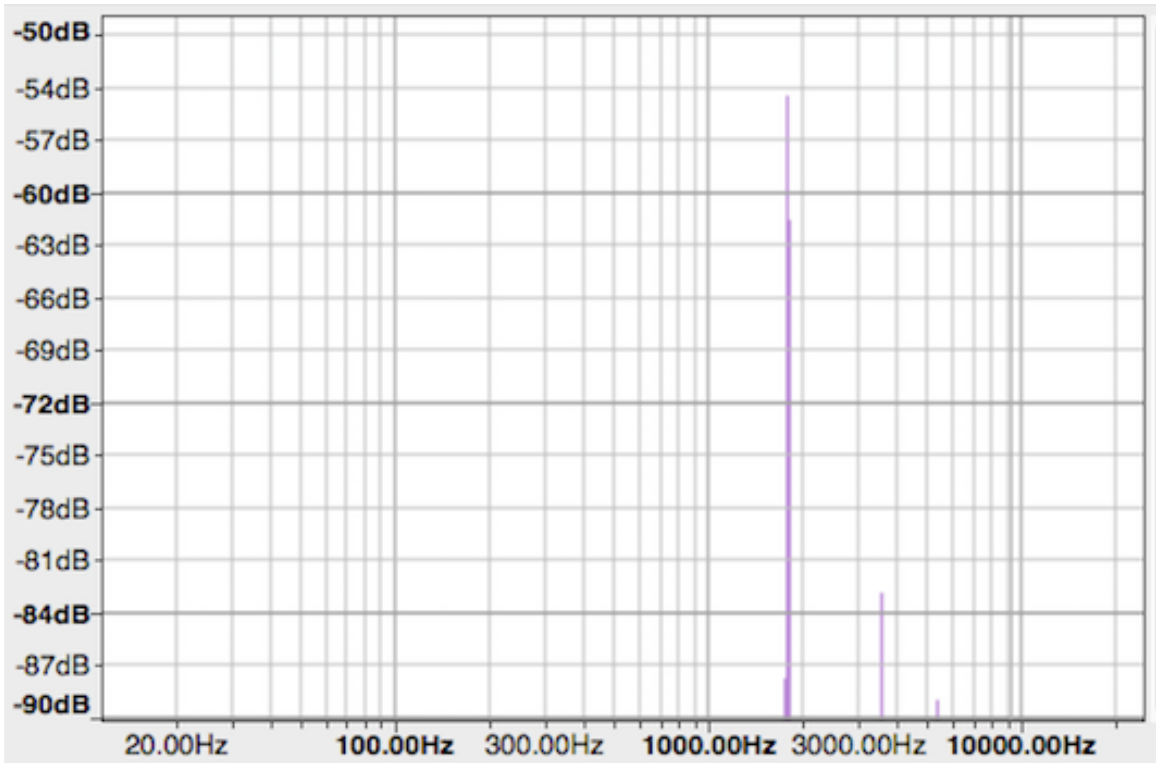
LF BUJ



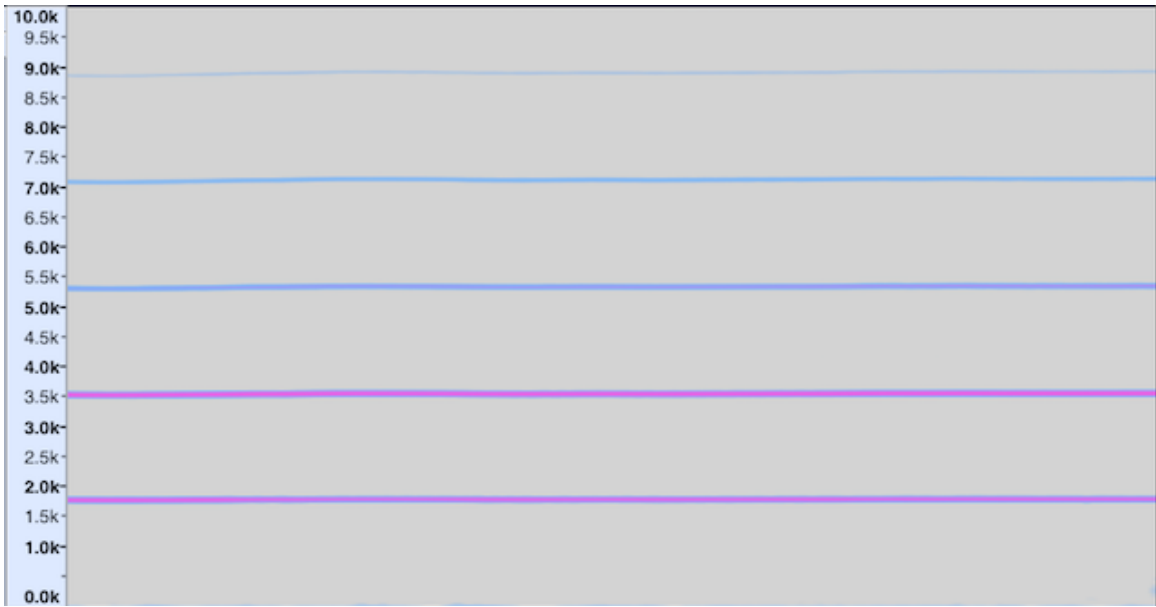
LF BUJ



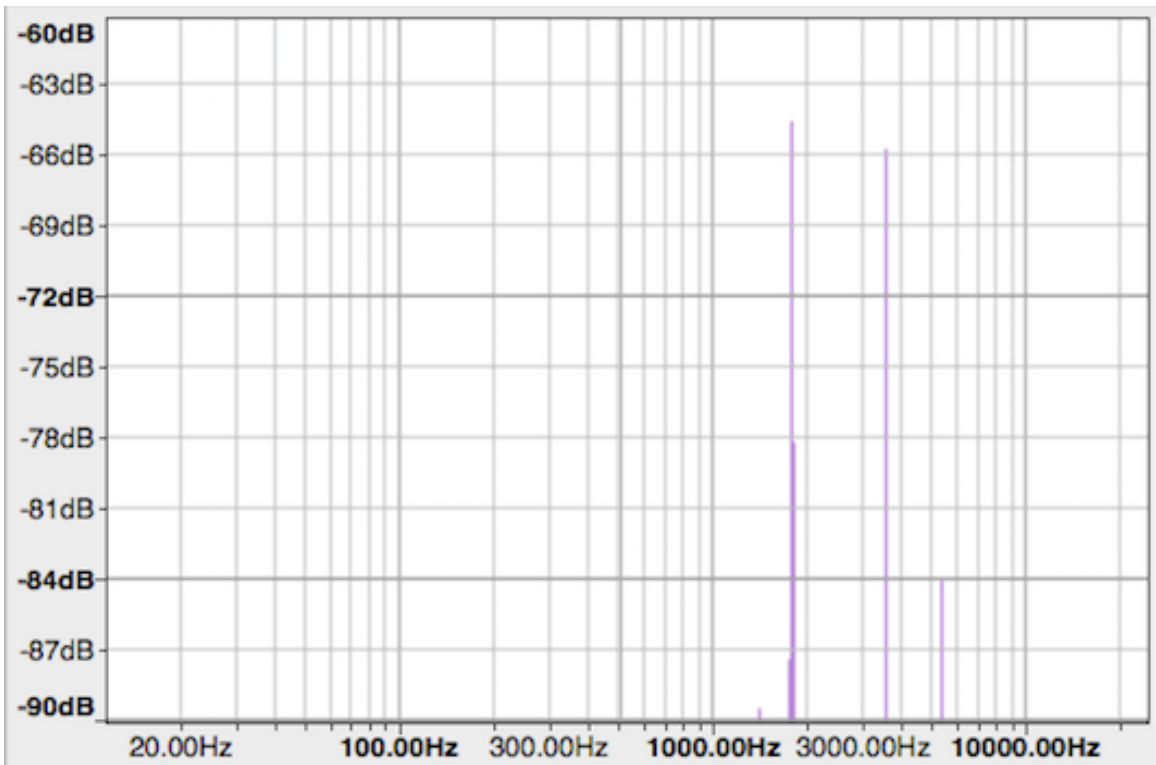
UJ



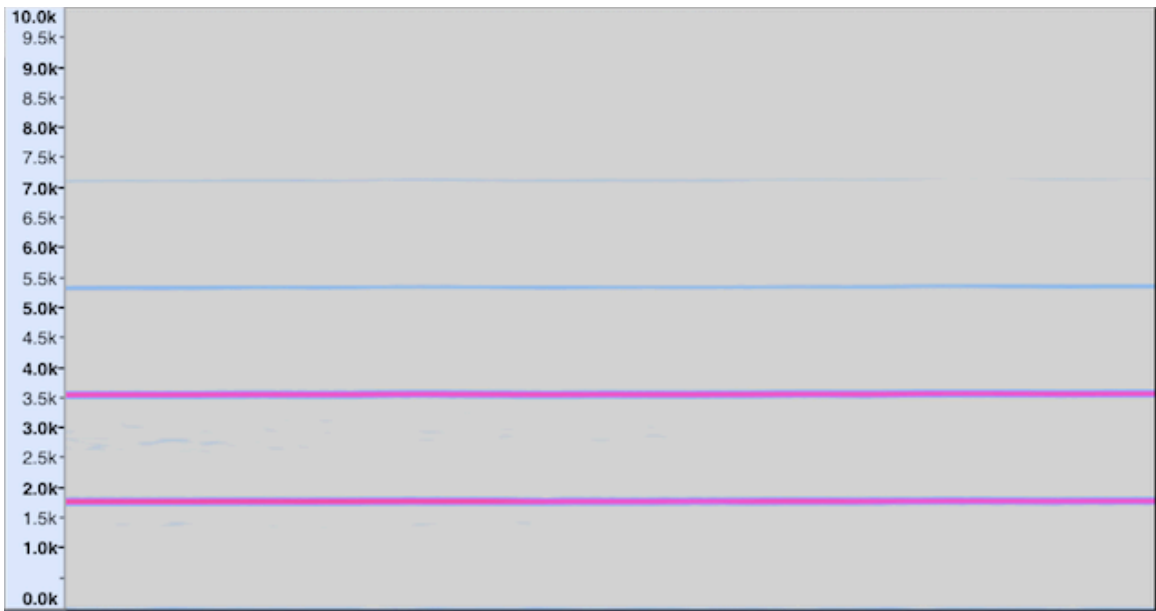
UJ



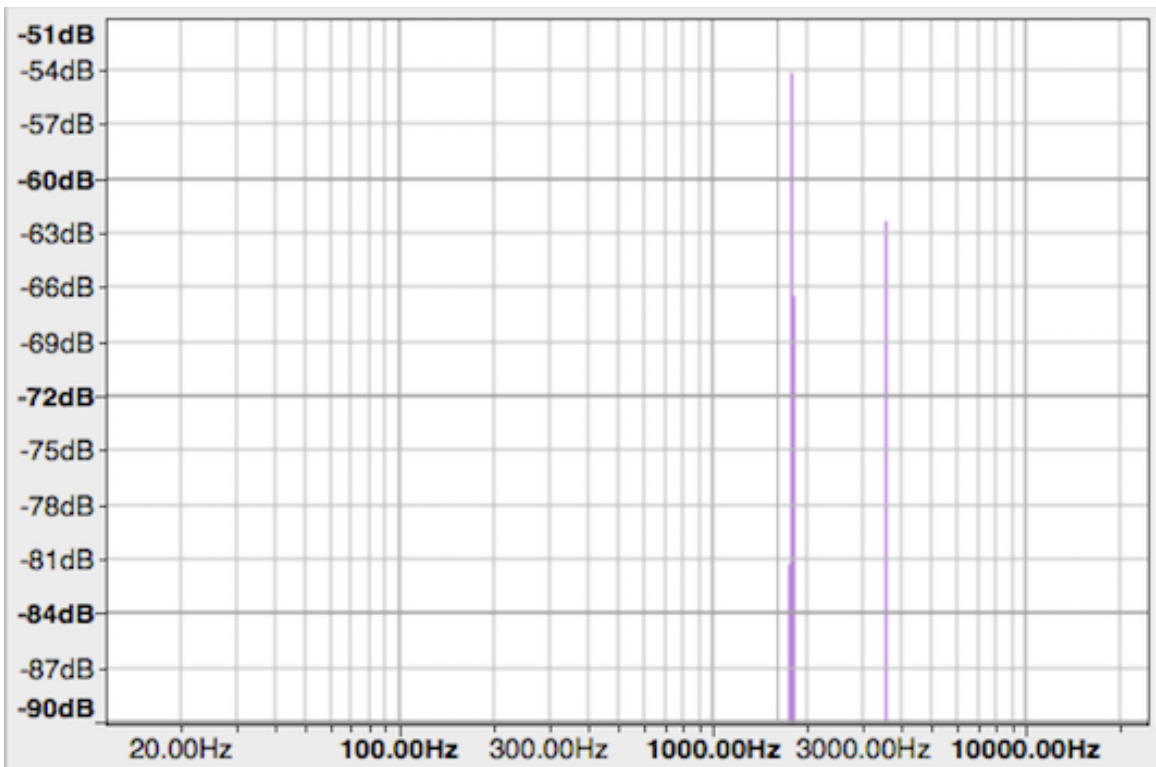
CTR



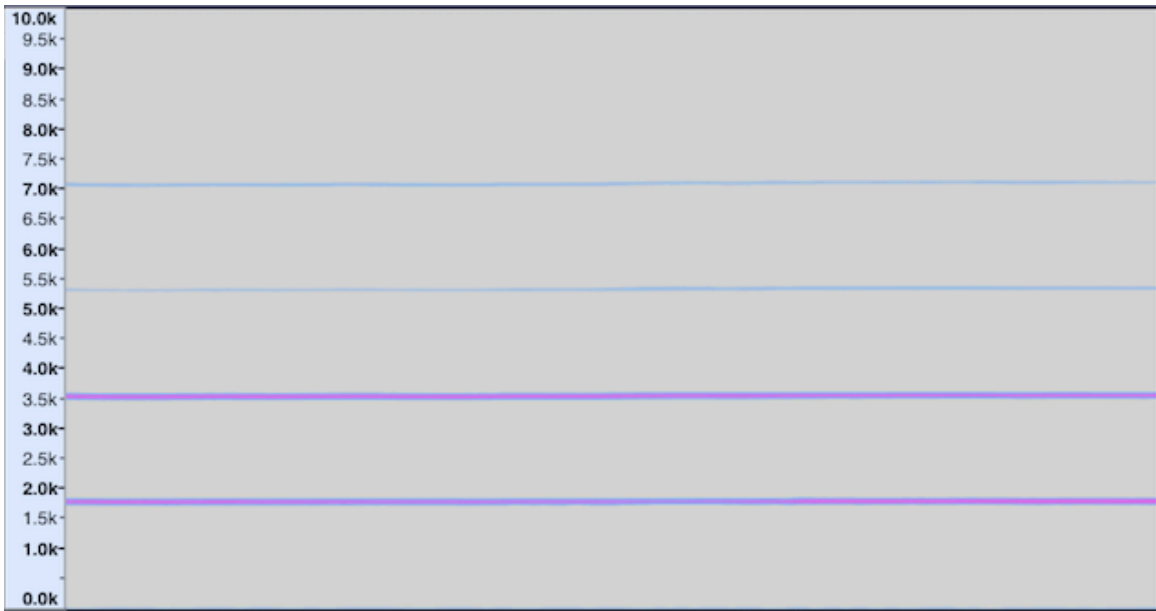
CTR



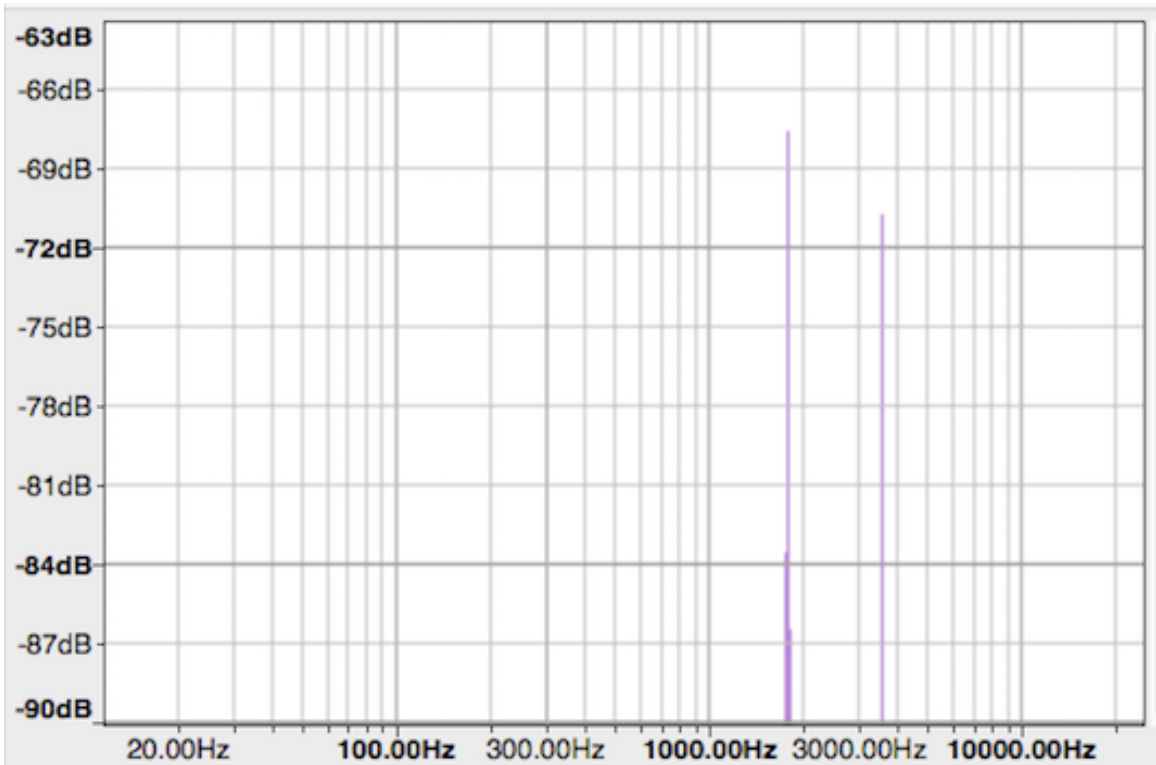
LJ



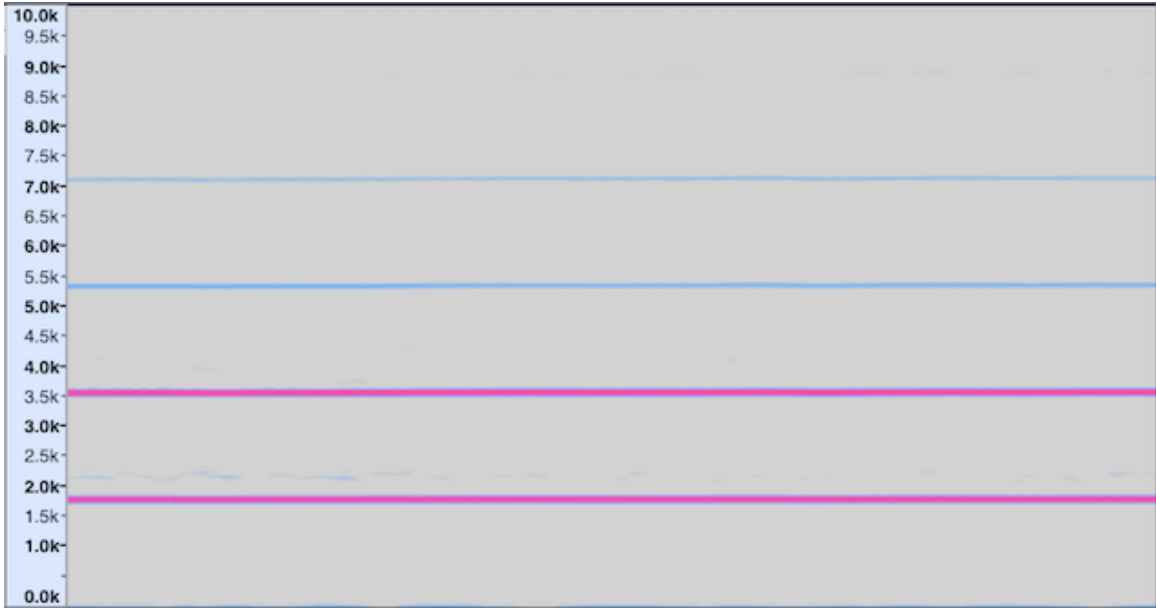
LJ



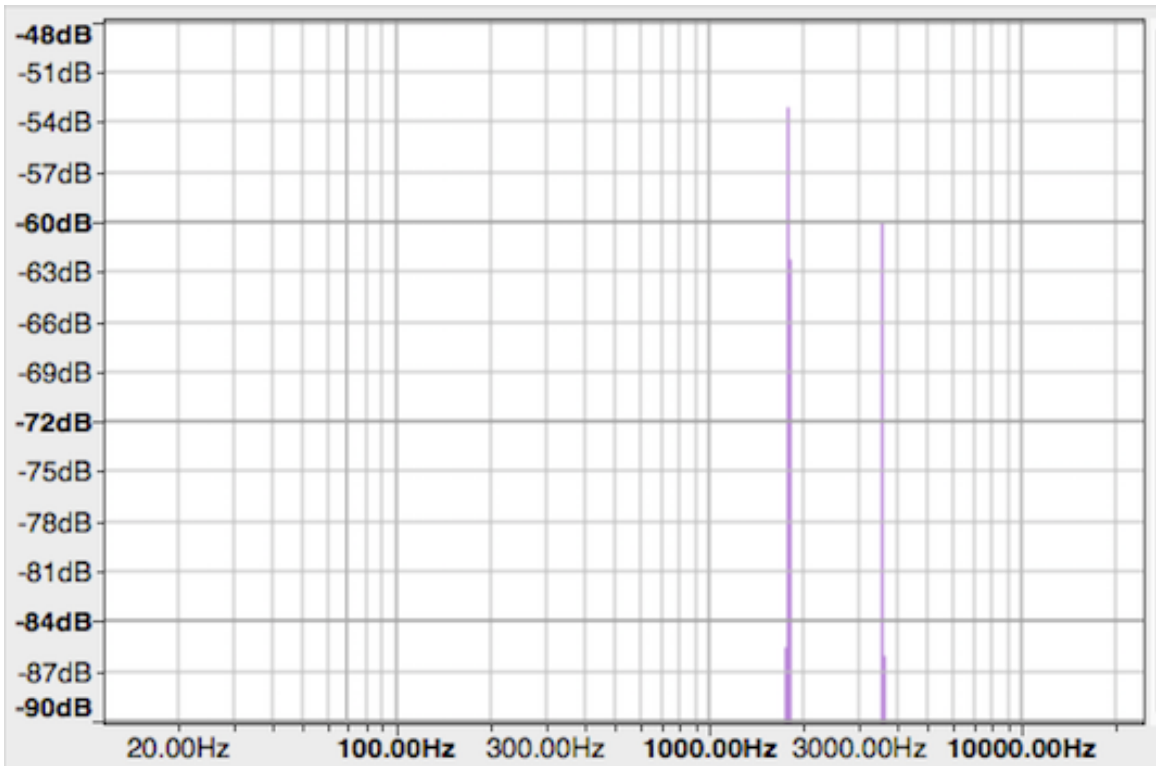
BELL Out



BELL Out

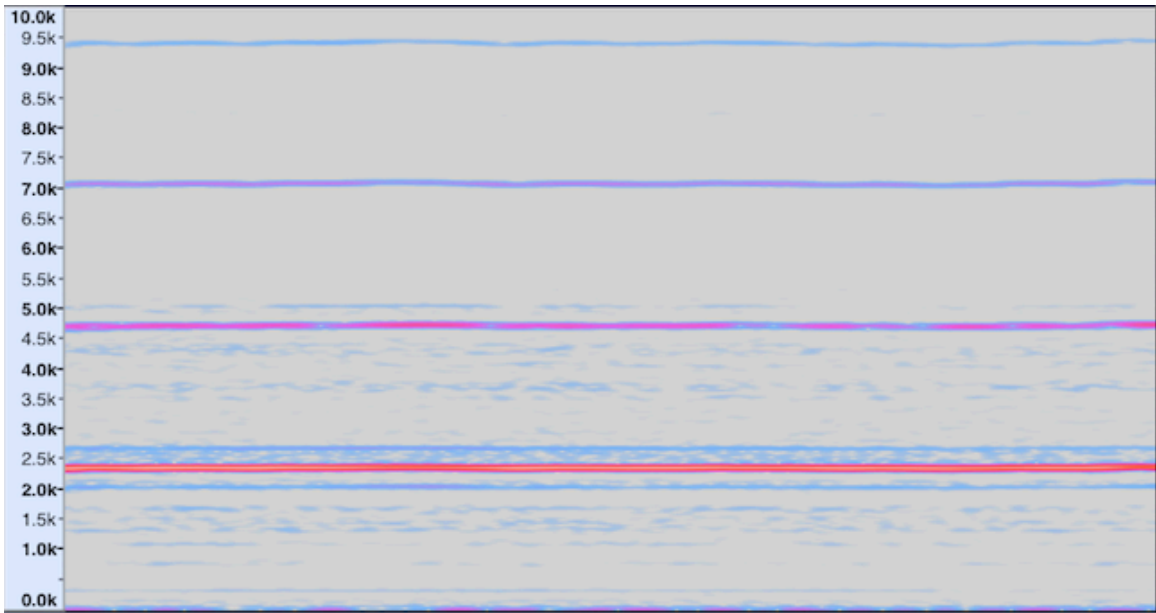


BELL End

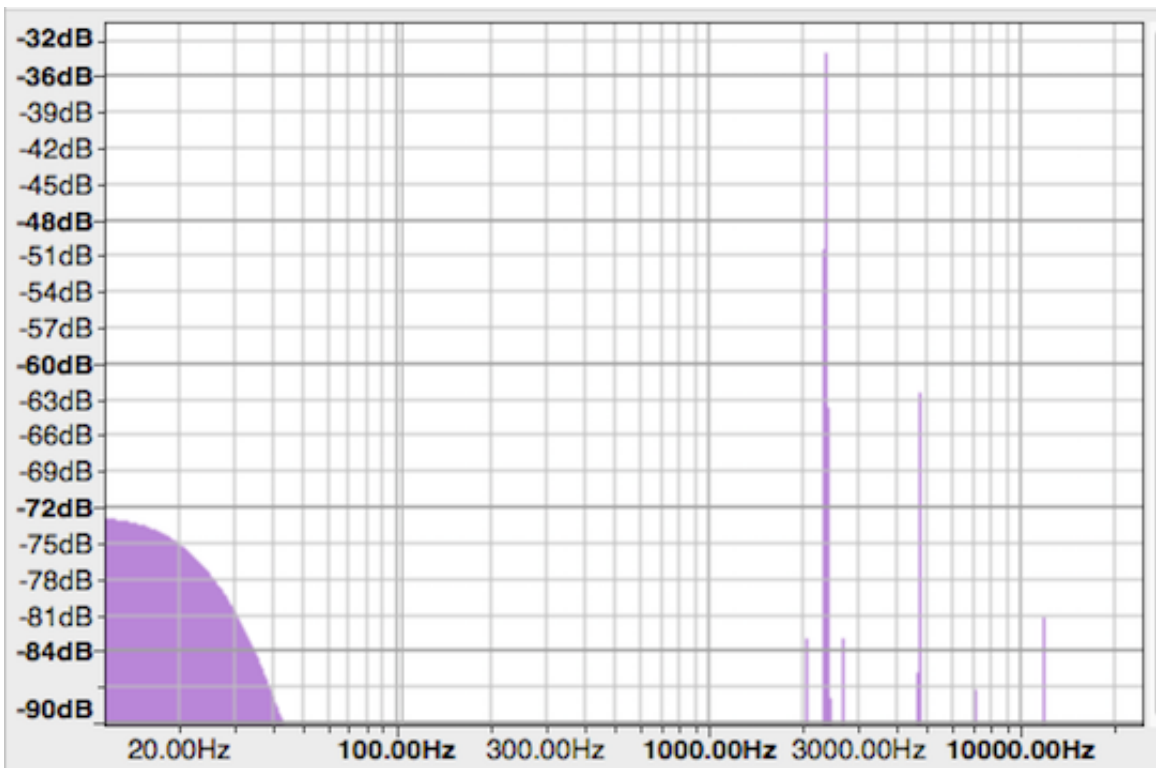


BELL End

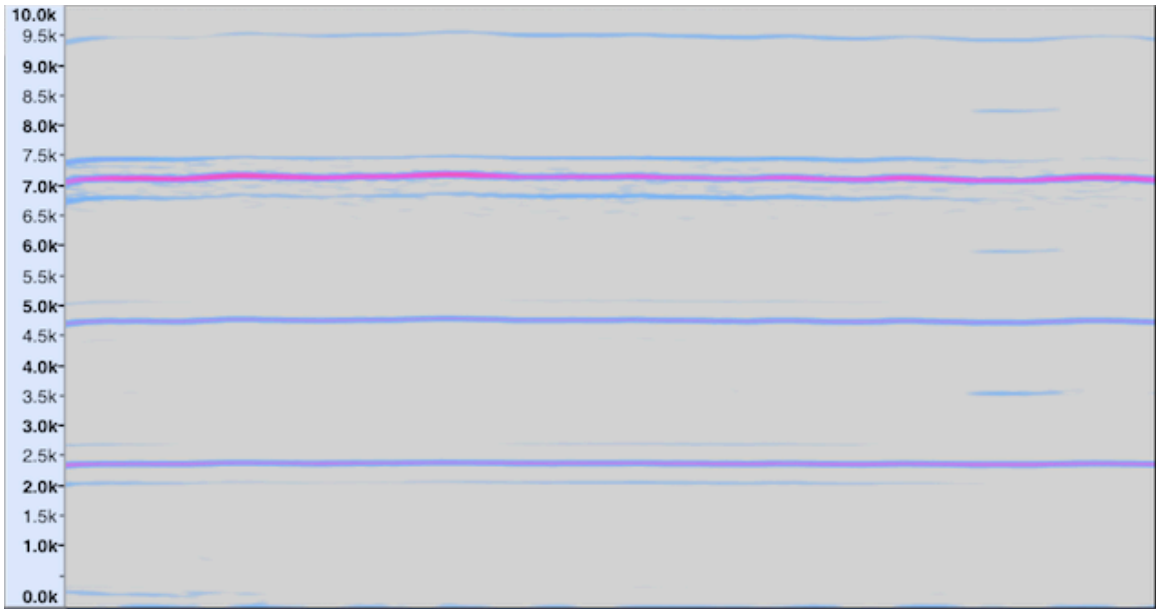
APPENDIX Q  
SAMPLE DATA E7



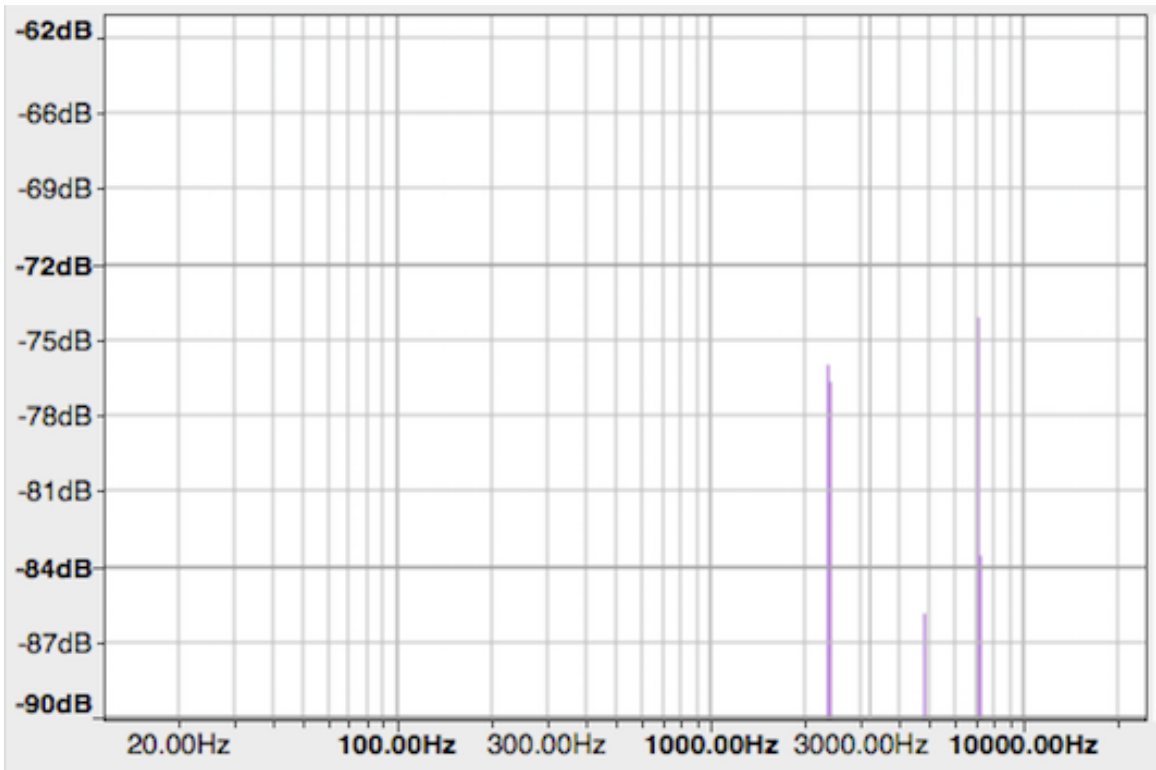
M30 (Reference)



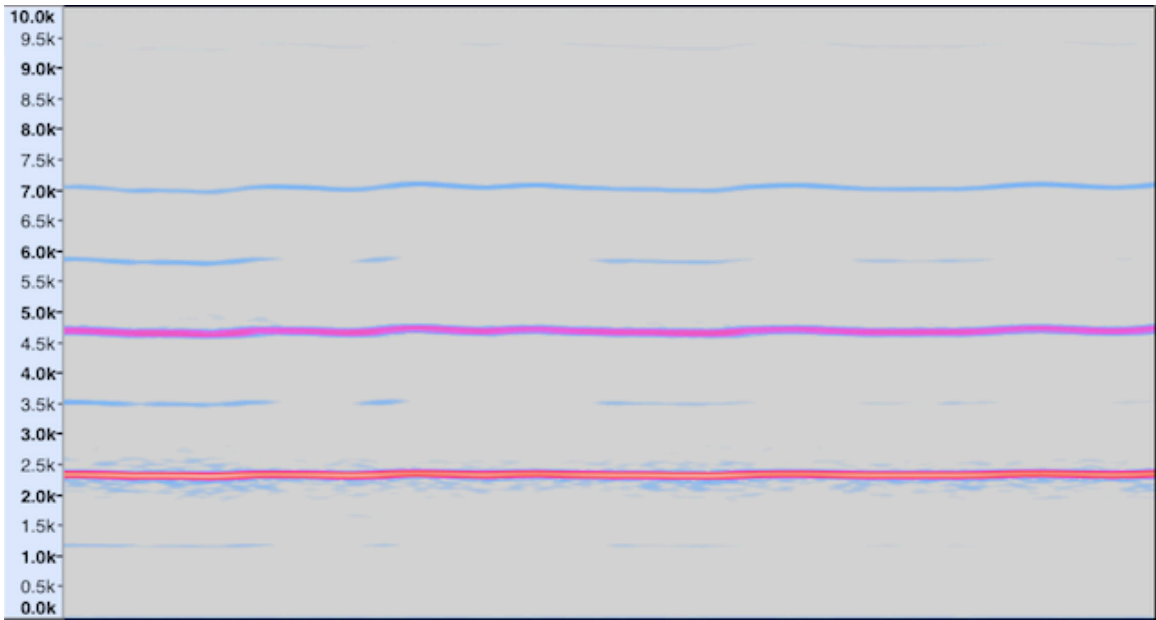
M30 (Reference)



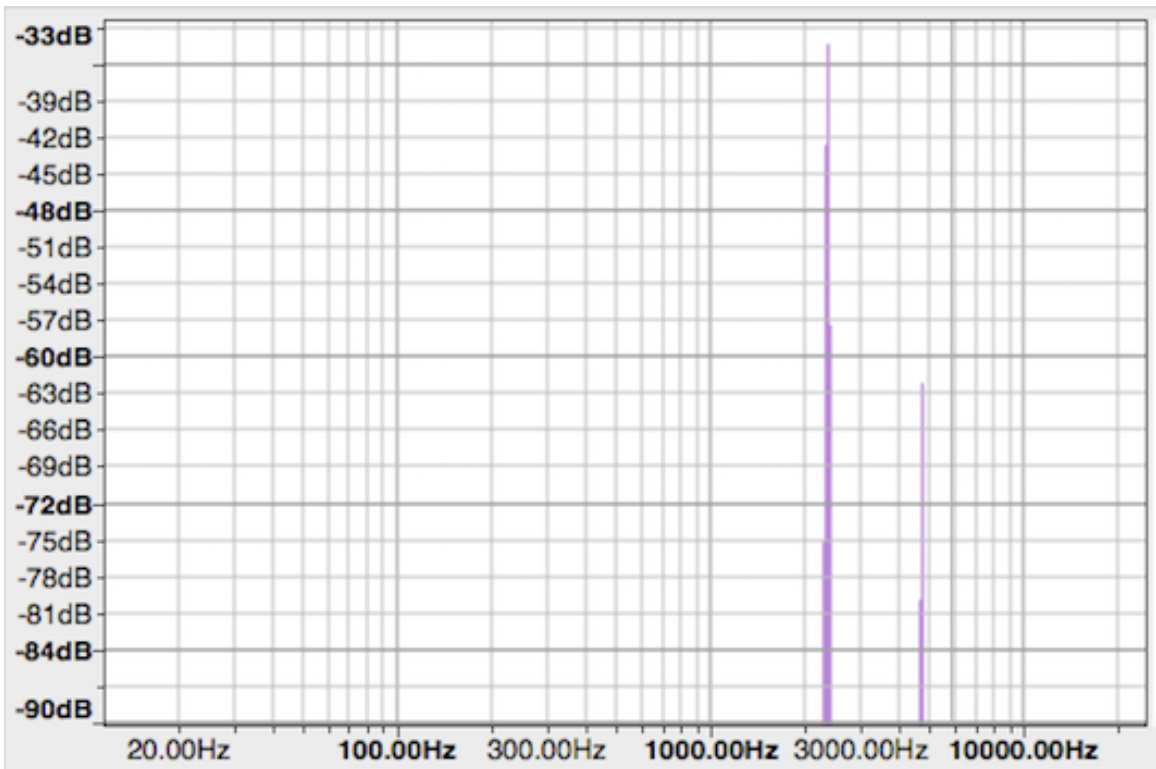
LIG



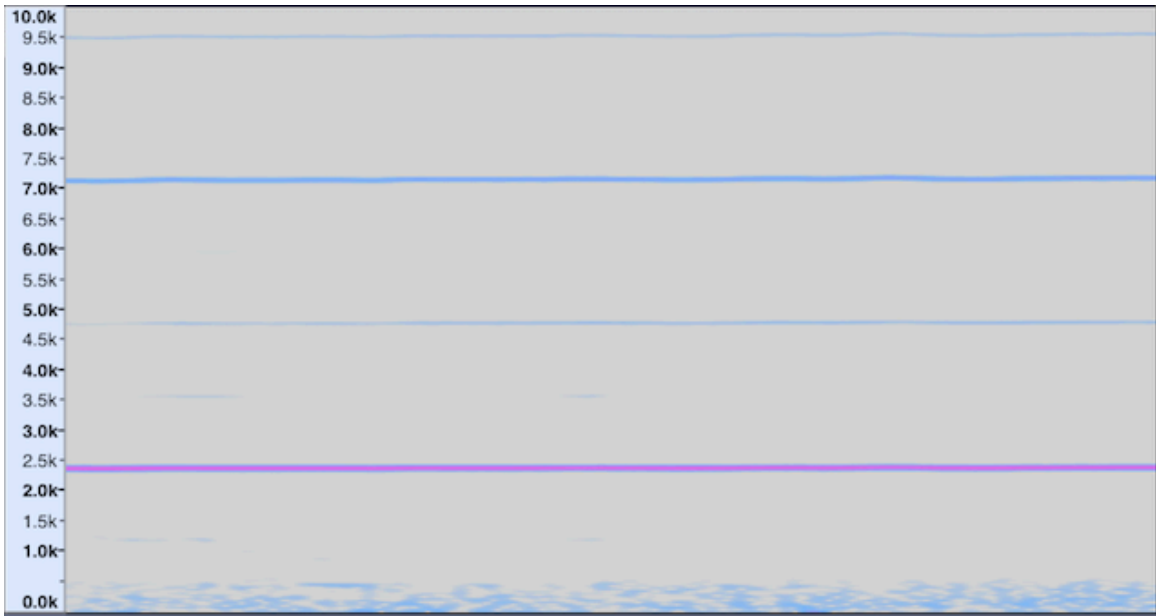
LIG



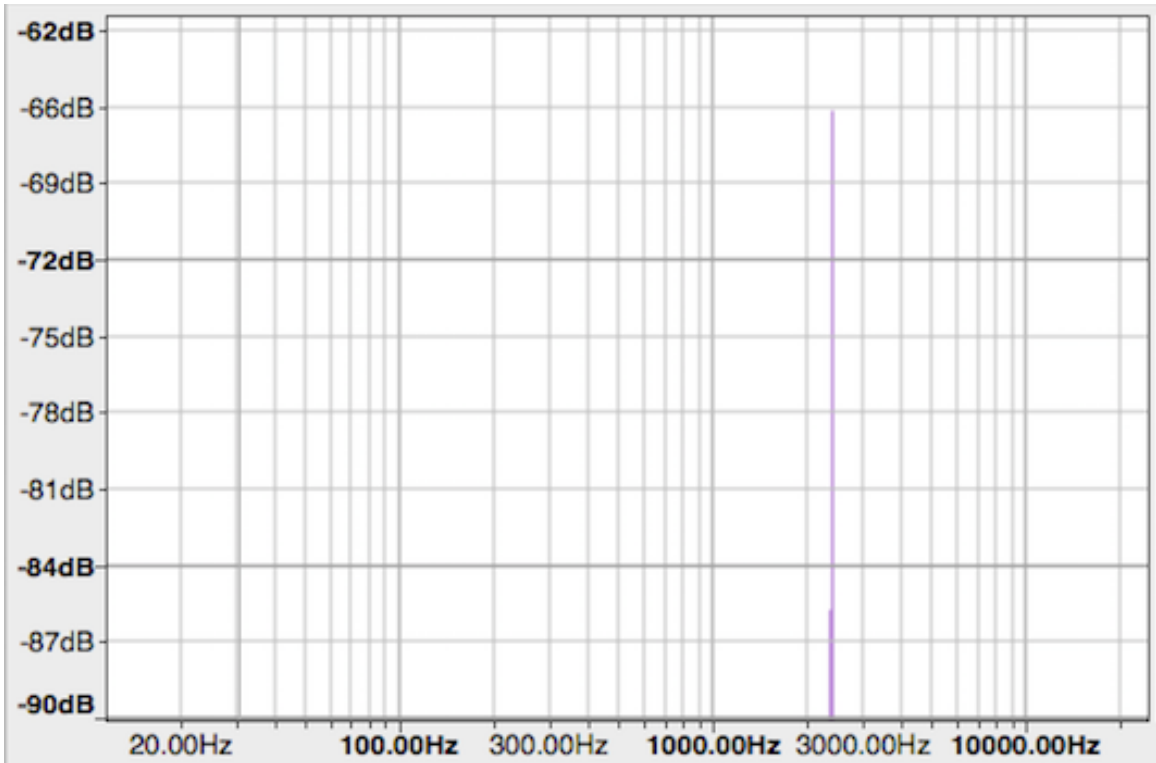
BAR Port



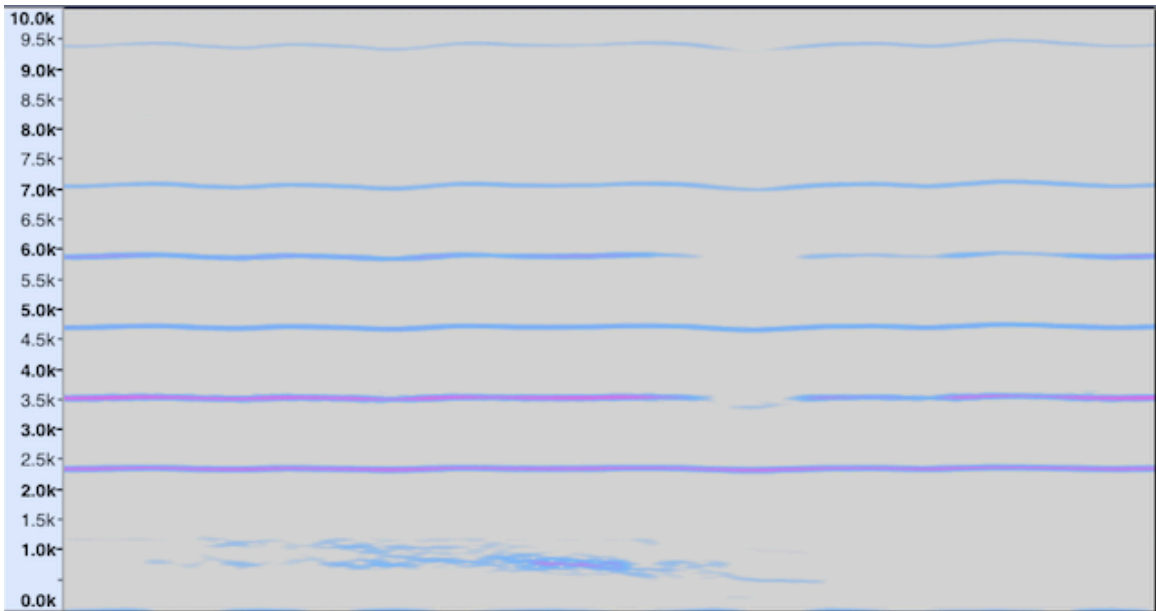
BAR Port



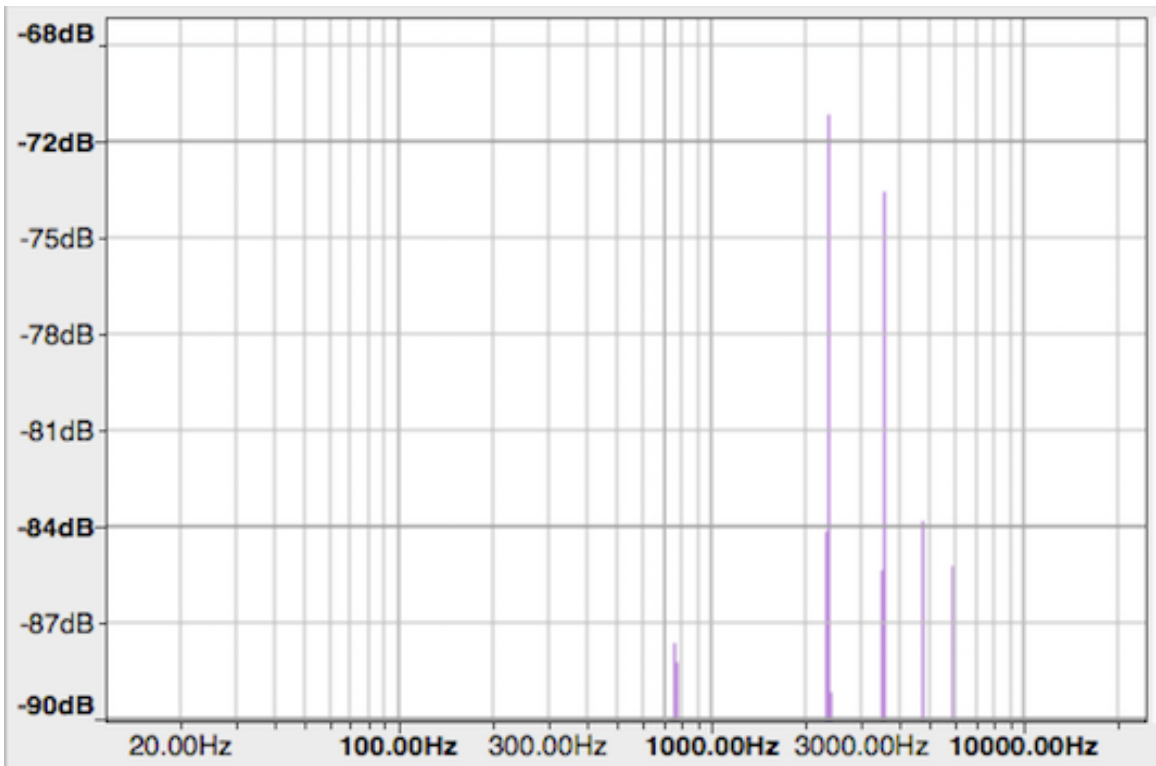
BAR Surf



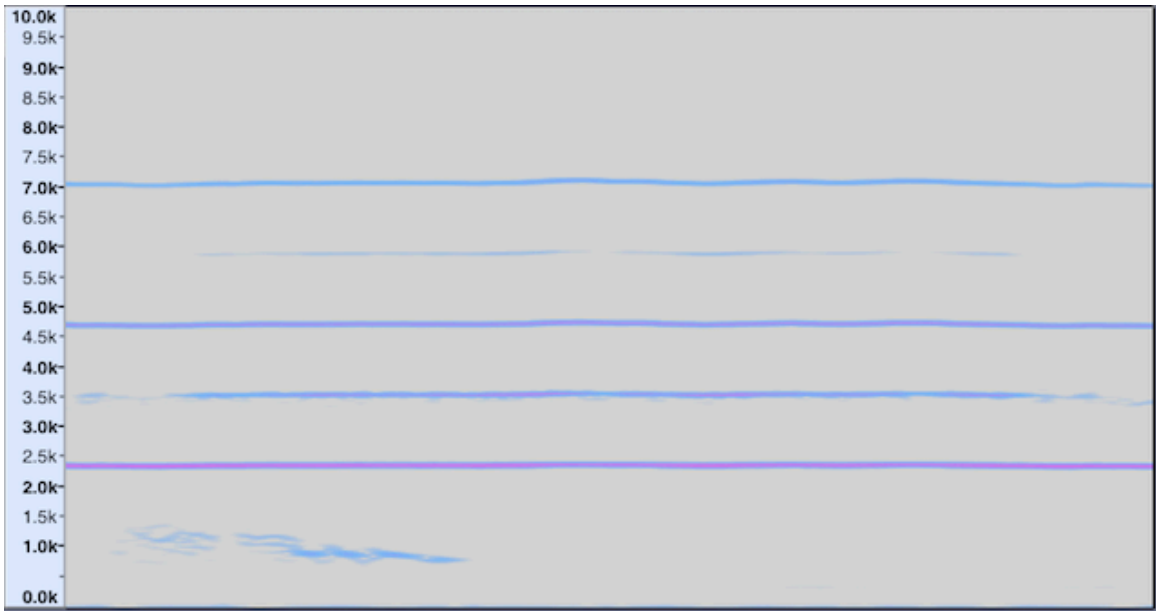
BAR Surf



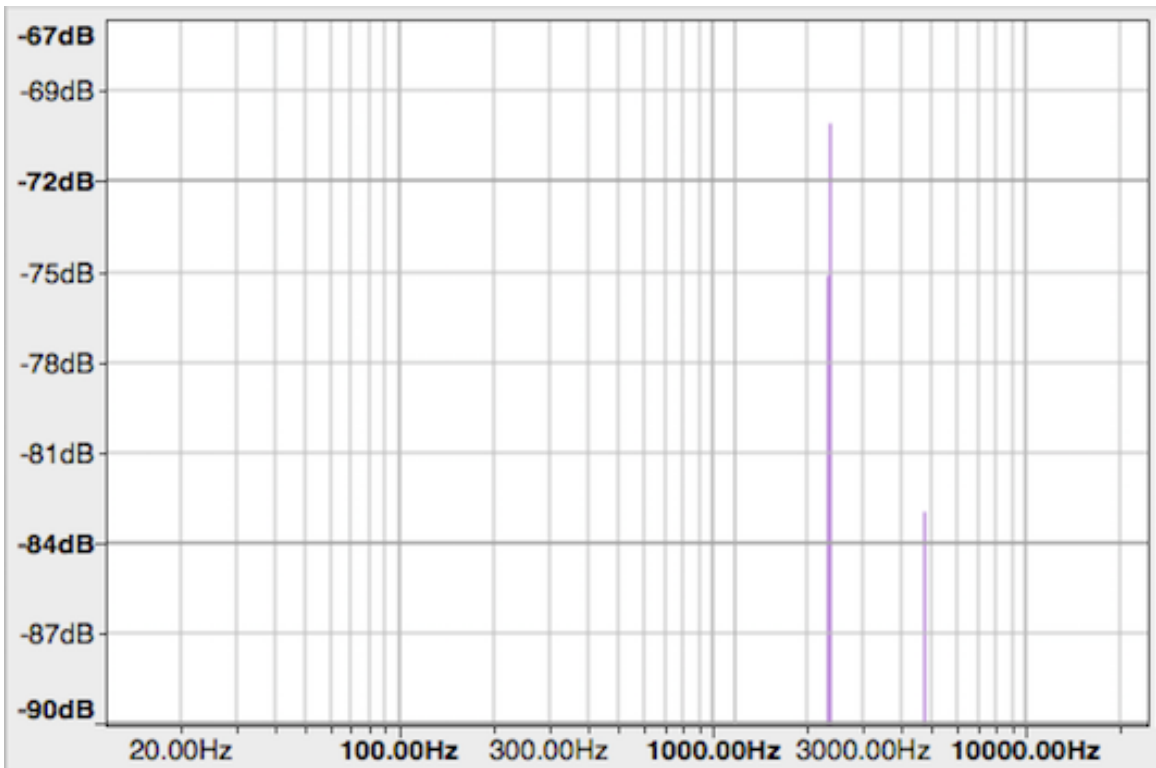
LF MPB



LF MPB



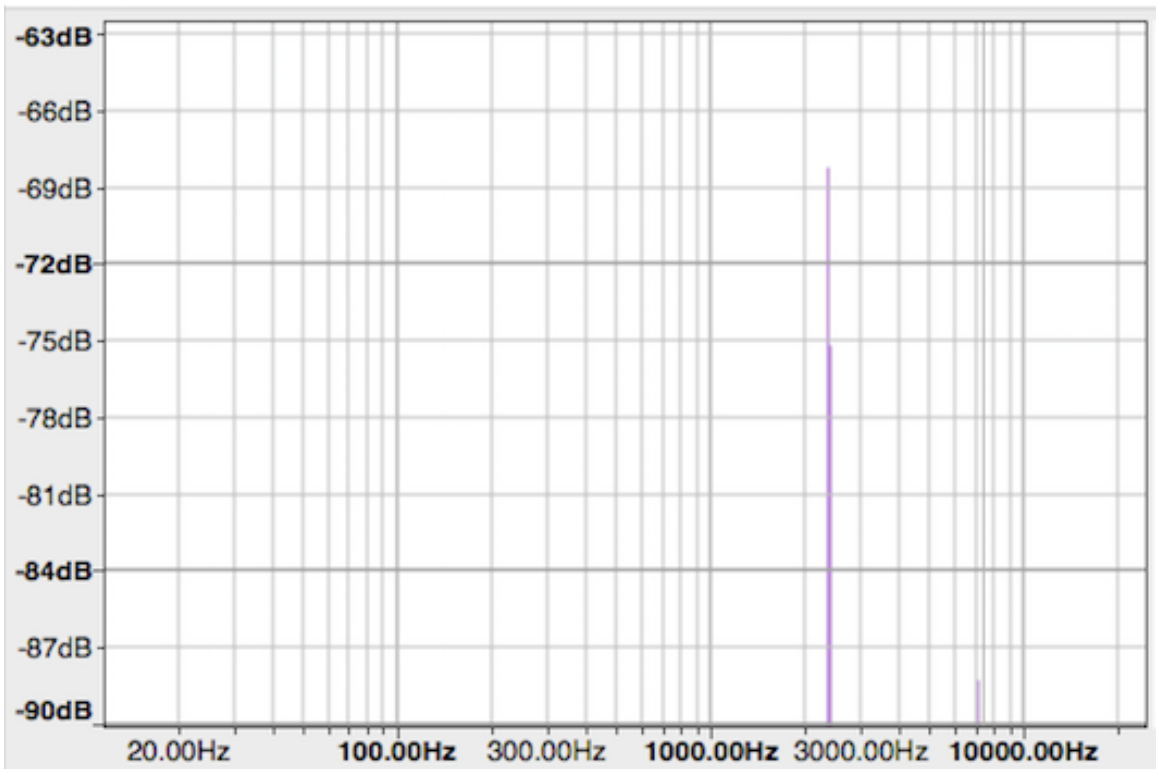
LF BUJ



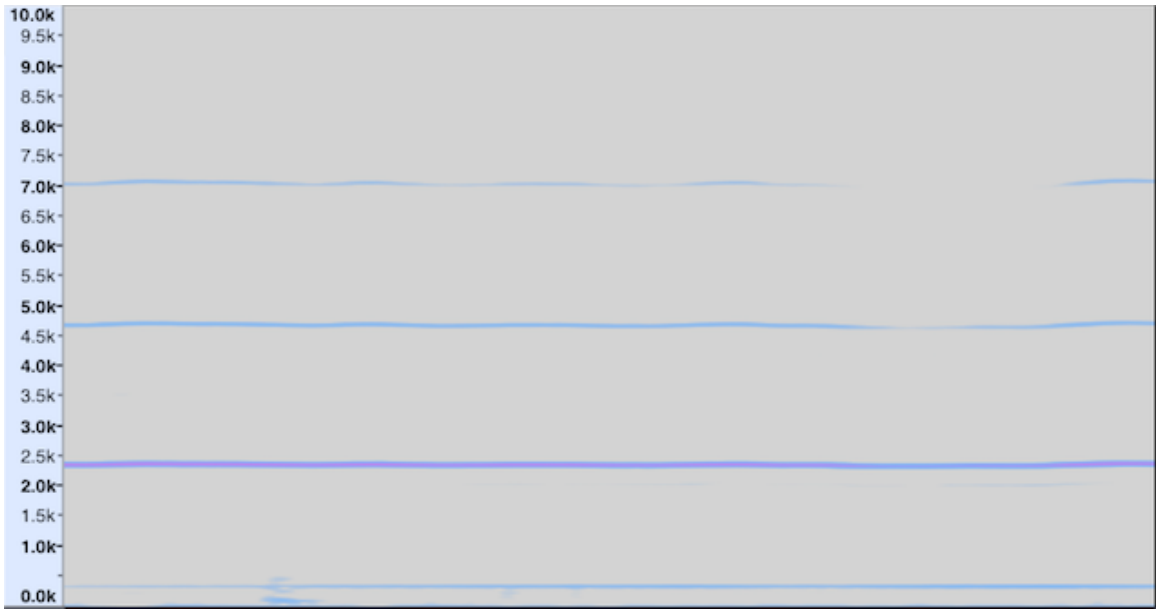
LF BUJ



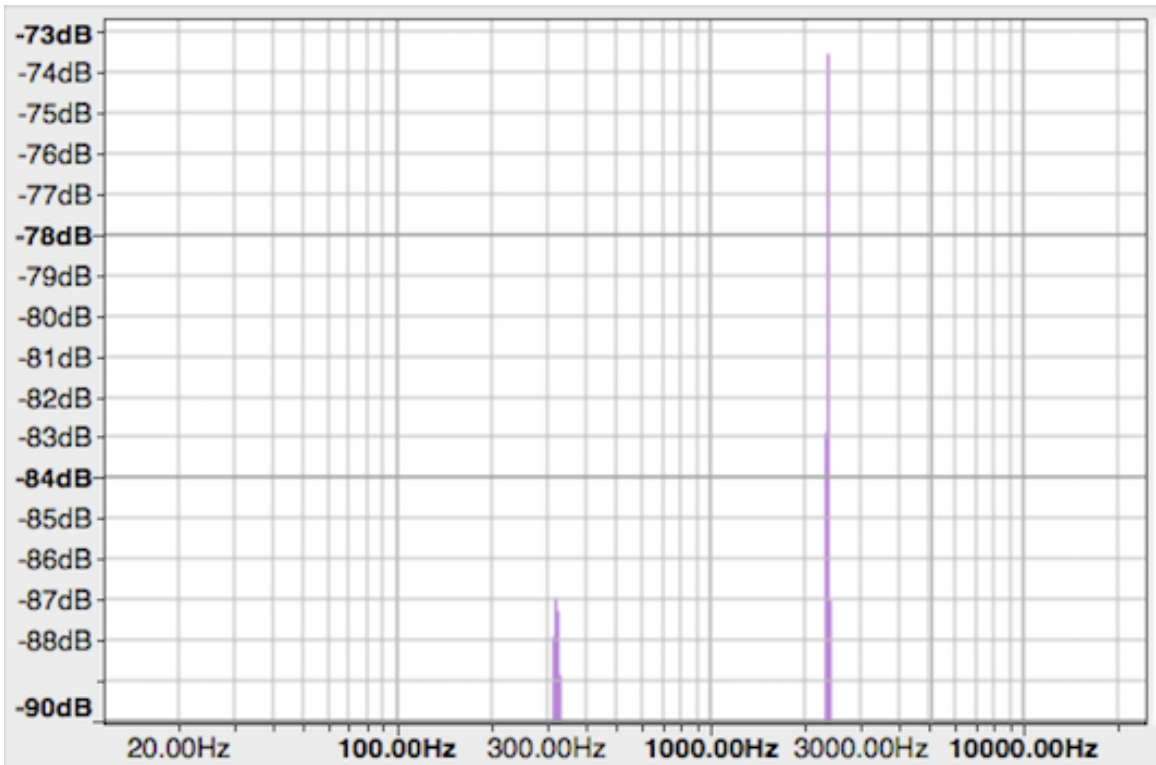
UJ



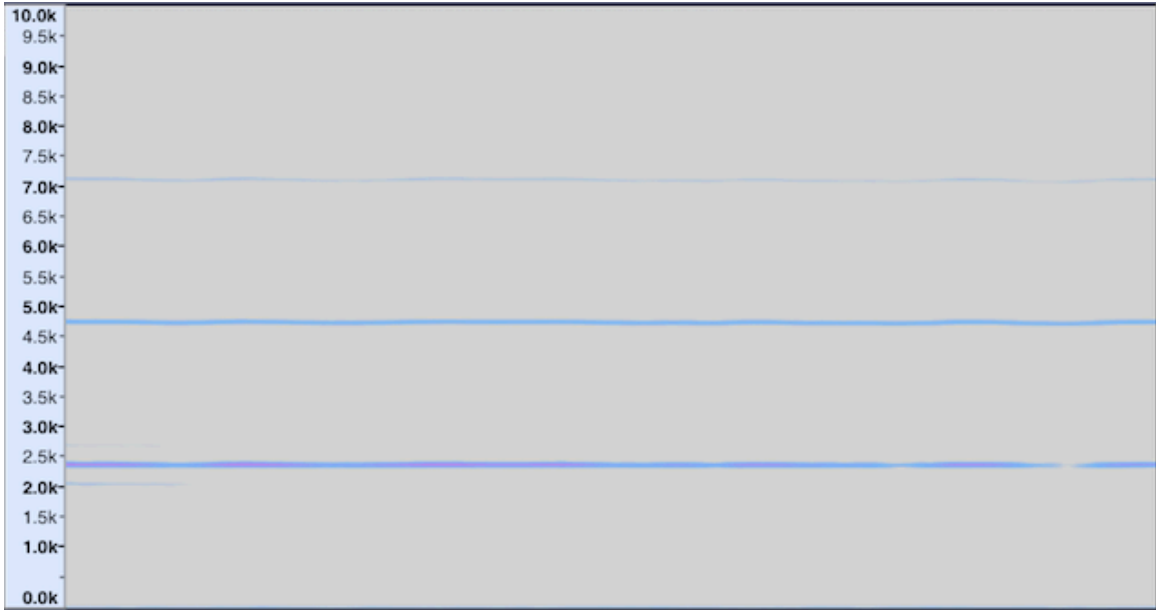
UJ



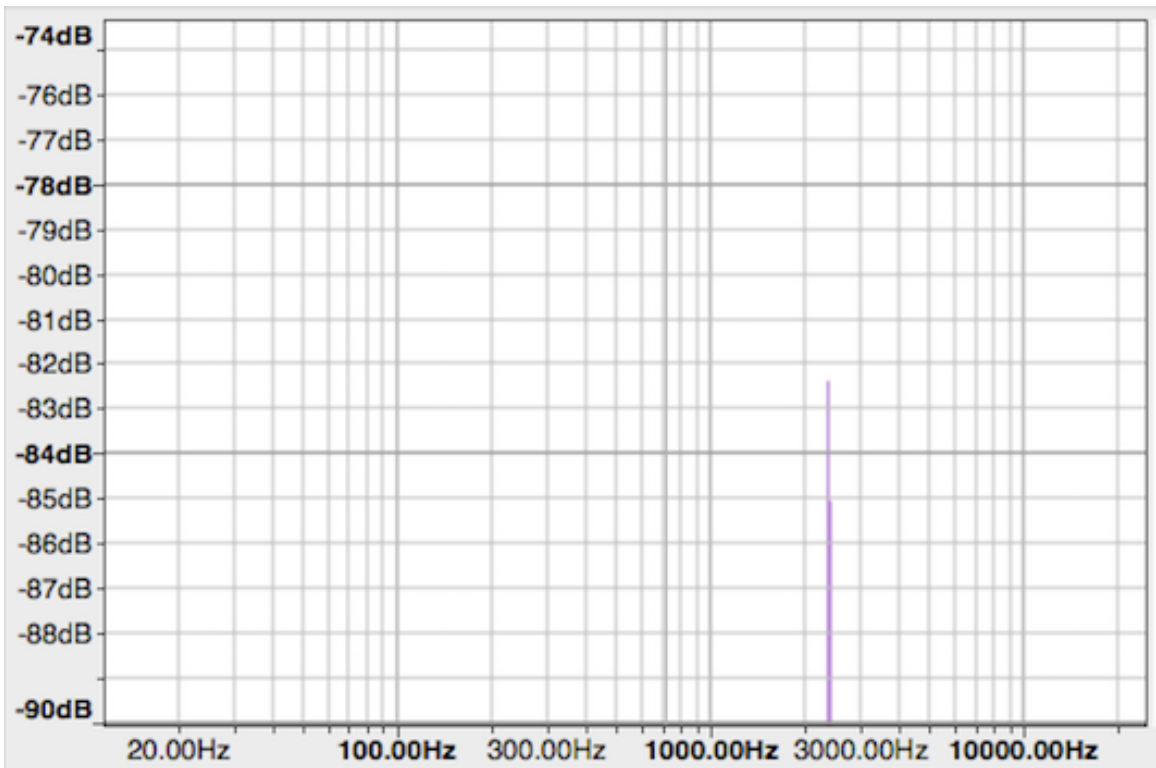
CTR



CTR



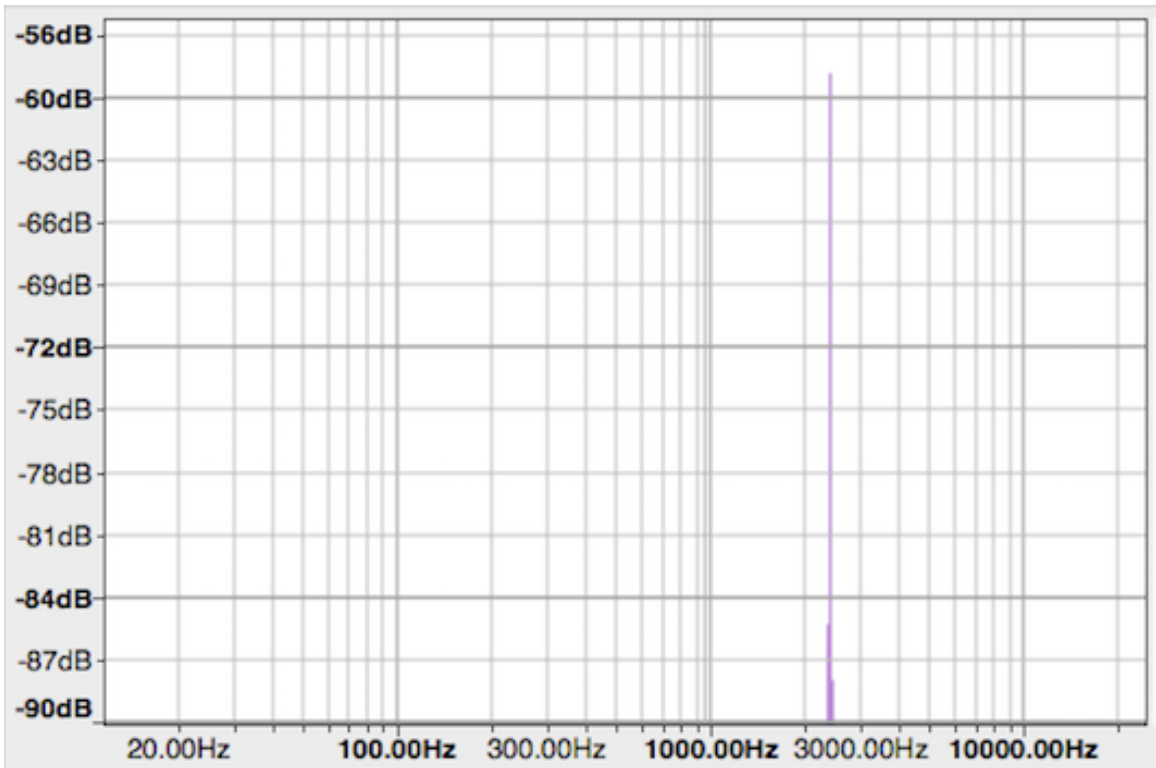
LJ



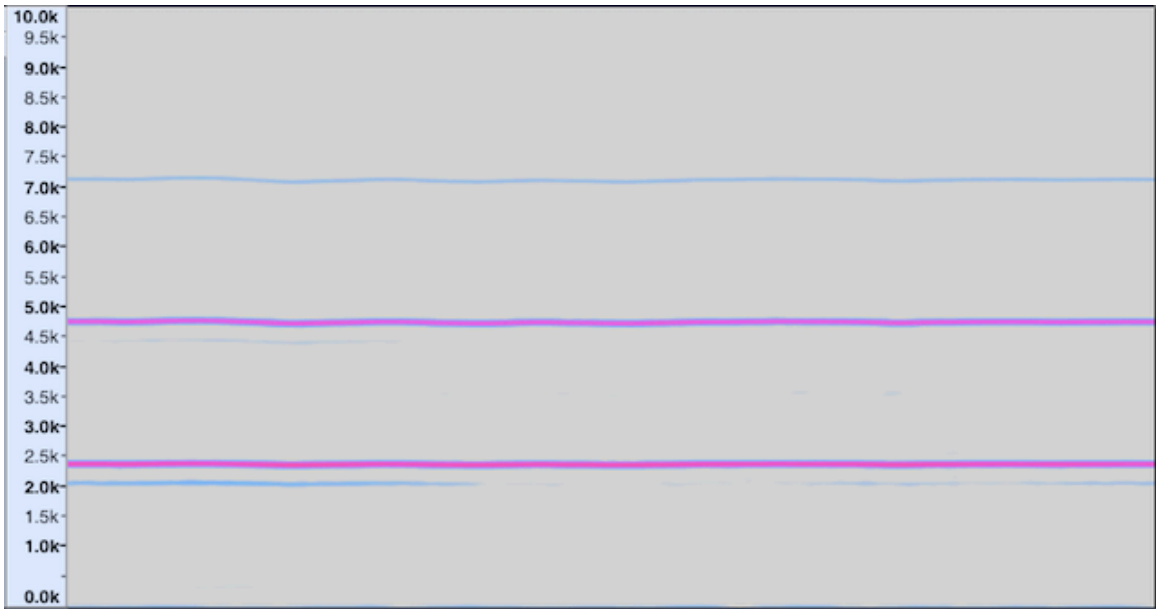
LJ



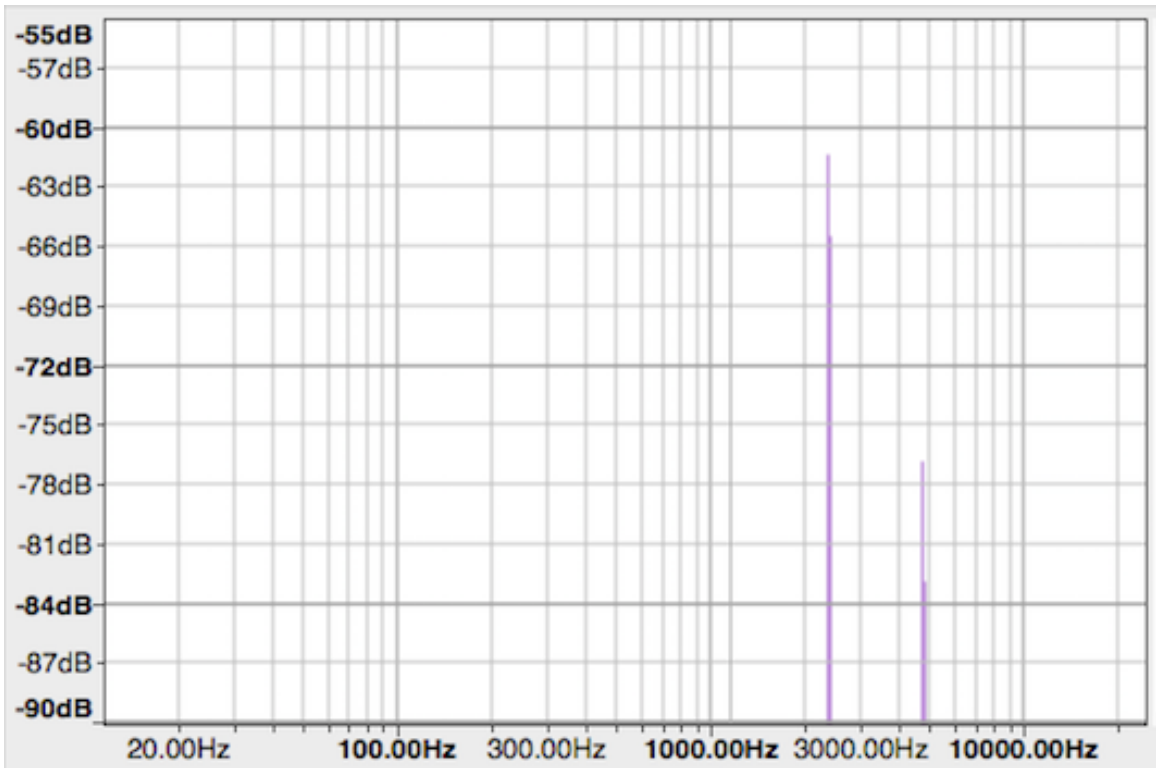
BELL Out



BELL Out



BELL End



BELL End