CHARACTERIZATIONS OF LOW-CUT FILTERS IN HANDHELD DIGITAL RECORDERS USING LONG-TERM AVERAGE SORTED SPECTRUM ANALYSIS

by

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Characterizations of Low-Cut Filters in Handheld Digital Recorders Using Long-Term Average Sorted Spectrum Analysis

Thesis directed by Associate Professor Catalin Grigoras

ABSTRACT

An audio signal's long-term average sorted spectrum can be used to reveal information about the source of a recording, which, in the case of this study, will focus on the low-cut filter option of small handheld digital recording devices. These devices are small, affordable, easy to operate and often come equipped from the manufacturer with a myriad of useful features, such as the low-cut filter. The shape of the low-cut filter slope could be a potential source of data in an authentication exam. It is the intention of this study to determine the forensic strength of applying long-term average sorted spectrum analysis to an audio signal to observe the slope of a low-cut filter in order to make comparisons and determine whether they may lead to an identification or an exclusion of a device. Three hypotheses will be examined:

- It is possible to identify whether or not the LCF option of a recorder was on or off.
- Low-cut filter signal processing differs significantly between recorders.
- LTASS/LCF analysis can be used as a means of eliminating a device from a pool of suspected recorders.

The form and content of this abstract are approved. I recommend its publication.

Approved: Catalin Grigoras

DEDICATION

To my family for their love, unyielding support, and genuine enthusiasm in whatever shiny thing I may be interested in that week.

To my beautiful wife Monica, whose assistance in my completion of this degree program cannot be understated. I love you so much. Thank you for watching the farm while I was off becoming a scientist.

To our pets, Kingston, Lady, Sherpa, Billie, Duke, Buster, Levi and Midnight. Were it not for your relentless appeals for affection, this thesis would have been completed in half the time.

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TABLE OF CONTENTS

CHAPTER

I. INTRODUCTION 1

Scope and Intention 1

II. PERSPECTIVE 2

Digital Recorders 2

Audio Formats 2

Low-Cut Filters 2

Fast Fourier Transform 3

Power Spectral Density 3

Long-Term Average Spectrums 4

Sorted Spectrums 5

III. MATERIALS & METHODS 6

Digital Recorders 6

FFmpeg 8

MATLAB 8

Testing Procedure 8

IV. ANALYSIS 12

V. RESULTS 25

Hypothesis One 25

Hypothesis Two 26

Hypothesis Three 27

VI. DISCUSSION & FUTURE RESEARCH 29

REFERENCES 30

APPENDIX 31

LIST OF TABLES

TABLE

1 – Technical Characteristics of the Digital Recorders Used 7

2 – CC Values of Olympus VP–10 vs Sample Database..... 13

3 – CC Values of Olympus WS–802 vs Sample Database..... 15

4 – CC Values of Sony ICD–PX370 vs Sample Database 17

5 – CC Values of Sony ICD–UX523 vs Sample Database..... 19

6 – CC Values of Zoom H4N 80Hz vs Sample Database..... 21

7 – CC Values of Olympus WS–700M vs Sample Database 23

8 – CC Test Results..... 28

LIST OF FIGURES

FIGURE

1 – Example of PSD Analysis 4

2 – Example of LTAS Analysis 4

3 – Example of LTASS Analysis 5

4 – Example of PSD, LTAS, and LTASS Plots Derived from MATLAB 11

5 – ZOOM H4N Sorted Power Values of all LCF Options 26

6 – Olympus DM-520 LCF On/Off Comparison 31

7 – Olympus DM-620 LCF On/Off Comparison 31

8 – Olympus DM-901 LCF On/Off Comparison 32

9 – Olympus DS-40 LCF On/Off Comparison 32

10 – Olympus VN-8100PC LCF On/Off Comparison 33

11 – Olympus VP-10 LCF On/Off Comparison 33

12 – Olympus WS-600S LCF On/Off Comparison 34

13 – Olympus WS-700M LCF On/Off Comparison 34

14 – Olympus WS-852 LCF On/Off Comparison 35

15 – Phillips DVT-5500 LCF On/Off Comparison 35

16 – Sony ICD-PX312 LCF On/Off Comparison 36

17 – Sony ICD-PX370 LCF On/Off Comparison 36

18 – Sony ICD-UX512 LCF On/Off Comparison 37

19 – Sony ICD-UX523 LCF On/Off Comparison 37

20 – Sony ICD-UX533 LCF On/Off Comparison 38

21 – Sony ICD-UX560 LCF On/Off Comparison 38

22 – Sony ICD-TX50 LCF On/Off Comparison 39

23 – Tascam DR-05 40Hz LCF On/Off Comparison 39

24 – Tascam DR-05 80Hz LCF On/Off Comparison 40

25 – Tascam DR-05 120Hz LCF On/Off Comparison 40

26 – Tascam DR-07 40Hz LCF On/Off Comparison 41

27 – Tascam DR-07 80Hz LCF On/Off Comparison 41

28 – Tascam DR-07 120Hz LCF On/Off Comparison 42

29 – Zoom H1 LCF On/Off Comparison 42

30 - Zoom H4N 80Hz LCF On/Off Comparison 43

31 – Zoom H4N 98Hz LCF On/Off Comparison 43

32 – Zoom H4N 115Hz LCF On/Off Comparison 44

33 – Zoom H4N 133Hz LCF On/Off Comparison 44

34 – Zoom H4N 150Hz LCF On/Off Comparison 45

35 – Zoom H4N 168Hz LCF On/Off Comparison 45

36 – Zoom H4N 185Hz LCF On/Off Comparison 46

37 – Zoom H4N 203Hz LCF On/Off Comparison 46

38 – Zoom H4N 220Hz LCF On/Off Comparison 47

39 – Zoom H4N 237Hz LCF On/Off Comparison 47

40 – Olympus DM-901 vs Olympus DS-40 - LCF On 48

41 – Olympus DM-520 vs Olympus DM-620 - LCF On 48

42 – Zoom H1 vs Zoom H4N 237 - LCF On 49

43 – Tascam DR-05 120Hz vs Tascam DR07 120Hz - LCF On 49

44 – Sony ICD-UX560 vs Tascam DR-05 120Hz - LCF On 50

45 – Sony ICD-UX523 vs Sony ICD-UX533 - LCF On 50

46 – Sony ICD-UX512 vs Sony ICD-UX523 - LCF On 51

47 – Sony ICD-PX370 vs Sony ICD-TX50 - LCF On 51

48 – Phillips DVT-5500 vs Sony ICD-PX312 - LCF On 52

49 – Olympus WS-802 vs Olympus WS-852 - LCF On 52

50 – Olympus WS-600S vs Olympus WS-700M - LCF On..... 53

51 – Olympus VN-8100PC vs Olympus VP-10 - LCF On..... 53

52 – Olympus DM-520 vs Sony ICD-PX370 - LCF On 54

GLOSSARY OF TERMS & ABBREVIATIONS

LCF – Low–Cut Filter

LTAS – Long–Term Average Spectrum

LTASS – Long–Term Average Spectrum

PSD – Power Spectral Density

CC – Correlation Coefficient

FFT – Fast Fourier Transform

DFFT – Discrete Fast Fourier Transform

SWGDE – Scientific Working Group on Digital Evidence

I. INTRODUCTION

Handheld digital recorders are small, affordable, easy to operate and often come equipped from the manufacturer with a myriad of useful options and features. One of those features is the low-cut filter, an equalization tool with the primary function of reducing noise in a recording to help make the intended source more intelligible. The shape of the low-cut filter slope, or the pattern of its frequency attenuation, could be a potential source of data in an authentication exam. Manufacturers such as Sony, Olympus, Tascam, et al., choose a frequency and a slope, generally expressed in decibels per octave, to assign to the numerous models they manufacture each year. If the LCF pattern can be observed, or identified with LTASS, the analysis could be a powerful tool in an examiners toolbox to apply in conjunction with other analysis methods.

Scope and Intention

The scope of this examination was limited to digital handheld recorders that have a low-cut filter option. Recording samples were created in realistic "real-world" settings, quiet rooms with uncomplex ambient tone. It was not within the scope of this study to use pink noise or other similar calibration techniques. It is the intention of this study to determine the forensic strength of applying long-term average sorted spectrum analysis to an audio signal to observe the LCF slope in order to make comparisons and determine whether these comparisons may lead to an identification or exclusion of a device. Three hypotheses will be examined:

- It is possible to identify whether or not the LCF option of a recorder was on or off.
- Low-cut filter signal processing differs significantly between recorders.
- LTASS/LCF analysis can be used as a means of eliminating a device from a pool of suspected recorders.

II. PERSPECTIVE

Digital Recorders

The digital handheld recorders used in this study are generally consumer-level devices marketed for recording speeches, depositions, lectures and other types of close proximity conversations. Law enforcement officers may even carry these devices to help document their interactions with citizens, suspects and witnesses [1]. Some models used have extra features for the audio production market, such as external XLR inputs, high sample rates or filtering options. These handheld recorders are particularly commonplace in the field of criminal and civil investigations. Most current models offer removeable/expandable storage and have built in USB plugs or ports for easy file transfers. They are relatively inexpensive, compact, easy to operate and can be relinquished as evidence far more easily than one's personal mobile phone or tablet [2].

Audio Formats

The recording devices used in this study record digital audio in a variety of formats, both lossy and uncompressed. In the SWGDE document *Best Practices for Forensic Audio*, whenever performing a forensic examination it is always recommended to avoid degradation of the audio by limiting unnecessary conversions. When transcoding is necessary, one should convert to or between uncompressed formats, such as .WAV, and maintain the sampling rate and bit depth of the original recording [3]. Transcoding is the process of de-coding and re-encoding to convert a file into another format [4].

Low-Cut Filters

A low-cut filter, also sometimes referred to as a high-pass filter, is a type of audio filter which removes low frequencies from a signal, usually with the intent of improving the

intelligibility of a source in a recording. Frequencies are removed below a determined frequency, and the shape of the frequency attenuation is referred as the slope. Handheld digital devices use these filters quite effectively, and generally the only option available is to turn the filter on or off. It is typical that the slope will begin at a frequency pre-determined by the manufacturer and may or may not be included in the device documentation. In some cases, manufacturers will give the user frequency options for the frequency where filtering should begin, as is the case with Tascam and Zoom brand models included in this examination.

Fast Fourier Transform

The FFT spectrum (Fast Fourier Transform) changes the time domain audio signal into the frequency domain. With the audio represented in this way, data can be plotted with frequency on the horizontal axis and amplitude along the vertical axis [5]. The examiner has the option to display the signal as a spectrogram, a waterfall plot, or narrow band frequency display. The analysis can be useful to observe the frequency limits of a recording system, identify precise frequencies and pitches, along with many other characteristics of an audio signal [6].

Power Spectral Density

Power Spectral Density analysis (PSD) is one of the different ways to display a Fourier transform. Also often referred to as a signal's frequency spectrum, it is a representation of that signal in the frequency domain, presented as magnitude (dB) versus frequency (Hz) [7]. Spectral analysis can be helpful in identifying traces of file recompression or inconsistencies between the recorded evidence and the claimed recording device [8].

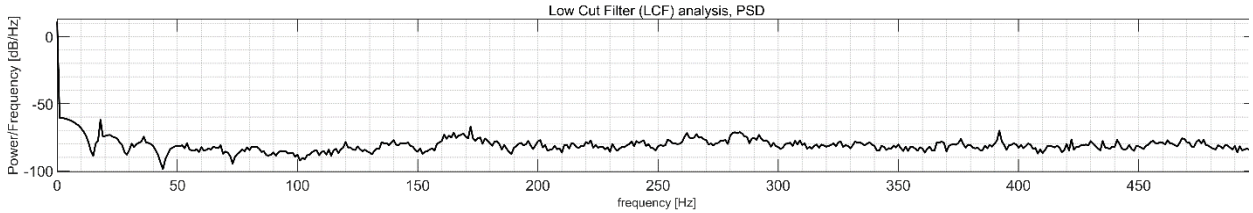

Figure 1 – Example of PSD Analysis

Long-Term Average Spectrums

The long-term average spectrum (LTAS) is an analysis method which can reveal additional information about a signal related to the environment and acoustics of the recording, the equipment used to create the recording and potential traces of re-compression or processing. It is a mathematical computation that can be used for purposes such as statistical comparisons of different signals. The LTAS is derived by dividing a signal into short time windows, typically overlapping by 50%, then frame functions are applied, FFT and PSD are computed for each frame and the results for each frame are averaged. The product of these processes is a two-column vector consisting of frequency and amplitude. From these values a histogram can be derived to show the number of appearances of each energy level. The global spectrum of the signal can be viewed to verify whether the curve is consistent with a typical recording obtained with the same methods, equipment and settings claimed by the recording operator [4] [6].

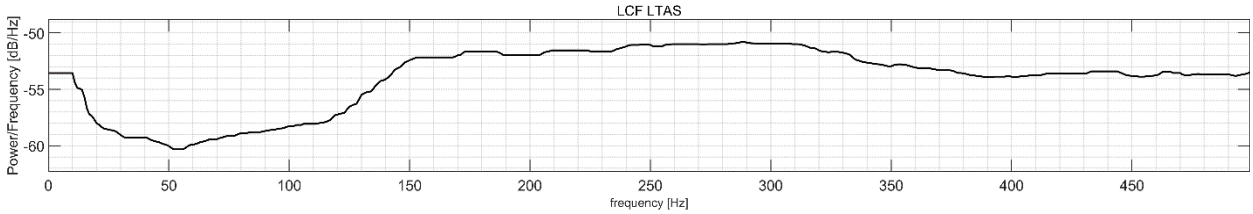

Figure 2 – Example of LTAS Analysis

Sorted Spectrums

Discrete Fast Fourier Transform (DFFT) computes the minimum, maximum and mean frequencies across all the frames in a recorded signal. These are known as M3 values. A perceptually coded signal will display a steep drop off in magnitude above a certain frequency, which is indicative of a lossy, or compressed, signal, whereas an uncompressed signal will be more consistent across the full range of available frequencies. In a sorted spectrum, the x-axis represents the signal's frequency range and the y-axis represents their power values. Values can be sorted on a descending order to show signs of lossy compression amongst higher frequencies. When values are sorted on an ascending order, the characterizations of a low-cut filter's slope can be observed [4] [7].

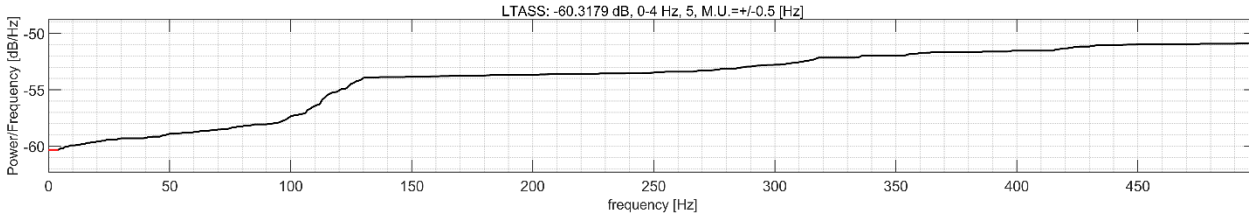

Figure 3 – Example of LTASS Analysis

III. MATERIALS & METHODS

Digital Recorders

Audio samples were collected from twenty-two different models of digital recorders from a variety of manufacturers. The devices were procured from the collections of three examiners and were chosen based on two primary requirements: the device must have an LCF option and access to transfer the digital file sample directly to a computer. The following table shows the record characteristics of each recorder as they were used in this study.

Table 1 – Technical Characteristics of the Digital Recorders Used

Recording Characteristics of Digital Recorders Used							
Manufacturer	**Model**	**Recording Format**	**Bit Rate (kbps)**	**Sample Rate (kHz)**	**Bit Depth**	**Channels**	**LCF Options (Hz)**
Olympus	DM-520	.WAV PCM		44.1	16	2	
Olympus	DM-620	.WAV PCM		48	16	2	
Olympus	DM-901	.WAV PCM		44.1	16	2	
Olympus	DS-40	.WMA	128	44.1	16	2	
Olympus	VN-8100PC	.MP3	192	44.1		2	
Olympus	VP-10	.WAV PCM		22.05	16	2	
Olympus	WS-600S	.MP3	192	44.1		2	
Olympus	WS-700M	.WAV PCM		44.1	16	2	
Olympus	WS-802	.WAV PCM		44.1	16	2	
Olympus	WS-852	.MP3	128	44.1		2	
Phillips	DVT-5500	.WAV PCM		44.1	16	2	
Sony	ICD-PX312	.MP3	192	44.1		2	
Sony	ICD-PX370	.MP3	192	44.1		2	
Sony	ICD-TX50	.WAV PCM		44.1	16	2	
Sony	ICD-UX512	.WAV PCM		44.1	16	2	
Sony	ICD-UX523	.WAV PCM		44.1	16	2	
Sony	ICD-UX533	.WAV PCM		44.1	16	2	
Sony	ICD-UX560	.WAV PCM		44.1	16	2	
Tascam	DR-05	.WAV PCM		96	24	1	40, 80, 120
Tascam	DR-07	.WAV PCM		48	24	2	40, 80, 120
Zoom	H1	.WAV PCM		96	24	2	
Zoom	H4N	.WAV PCM		44.1	16	2	80, 98, 115, 133, 150, 168, 185, 203, 220, 237

FFmpeg

FFmpeg is a command line tool useful for converting, creating, manipulating and streaming digital audio. In this case, it was used for splitting a stereo signal into multiple mono streams and for transcoding a lossy compressed format file into an uncompressed .WAV file. Two commands were primarily used during this examination.

Transcode audio into an uncompressed .WAV format:

```
ffmpeg -i .\input.mp3 -acodec pcm_s16le -ar 44100 -ac 1 OUT.wav
```

Splitting a stereo audio stream into two mono streams:

```
ffmpeg -i .\input.WAV -map_channel 0.0.0 OUTPUT_LEFT.wav -
map_channel 0.0.1 OUTPUT_RIGHT.wav
```

MATLAB

MATLAB is programmable software that can be used to create custom scripts, algorithms and workflows that incorporate peer-reviewed authentication techniques. It served as the backbone of this examination and provided critical comparative data. In this examination, MATLAB was used to calculate a signal's PSD, LTAS and LTASS, plot the spectrums to a visual figure and save the sorted power values to a document which was later used to create additional comparative periodogram figures as well as determine the correlation coefficient (CC) between two signals.

Testing Procedure

The test recordings were produced only on handheld digital recorders which had an LCF option. The recorders were set to the highest native resolution offered for each device, .WAV

PCM if available, but, if not, then the highest resolution of .MP3 or .WMA was selected. The recordings were made in a realistic quiet room environment consisting of uncomplex ambient room tone. Each recording was approximately five to ten minutes in length. It was decided that lengthier file durations would help to eliminate the effects of extremes when averaged. Recording samples were made with the LCF both on and off, and often multiple samples of the same device were taken. When more than one device of the same make and model were available, samples were recorded and labeled as a duplicate. In the cases where there were LCF options, samples were taken for each frequency.

Once recorded, the sample recordings were transferred directly to the examination computer either through an attached USB plug or via a mini USB cable connection. The files were renamed to follow a standardized naming convention:

MAKE_MODEL_DUPLICATE (WHEN APPLICABLE)_LCF ON/OFF_LCF FREQ_SAMPLE

This convention allowed for easy file sorting to find all instances of samples taken on a specific device.

Once named, the recording samples were evaluated to see whether the files were recorded in a compressed format, and whether they were mono or stereo. If the file was in a compressed format, it was necessary to transcode the file in an uncompressed .WAV format. This was accomplished using FFmpeg in Windows PowerShell. If the ensuing .WAV file was stereo, it was then split into two mono files, with the Left channel (channel 0) being renamed with the addition of _MONO at the end and retained for testing, while the Right channel (channel 1) was deleted.

The remaining mono .WAV file for each recording sample was then imported into the initial MATLAB script created for this examination. In brief, the script calculation steps were as follows:

- Input a mono .WAV audio signal.
- Calculate a one-sided spectrum to display the PSD.
- Divide the spectrum into short time windows, one second in length and overlapping each other by 50%.
- Compute the FFT and PSD for each resulting frame. The FFT order was determined by the sampling frequency of the file being analyzed.
- After splitting a signal on *N* short time windows and computing FFT and PSD, compute the min, max, mean and std values for the *N* vector.
- Sort the power values of the LTAS signal on an ascending scale and save to a text document for separate analysis purposes.
- Separately plot the three spectrums, PSD, LTAS and LTASS, to a figure with a limited frequency range up to 500Hz.

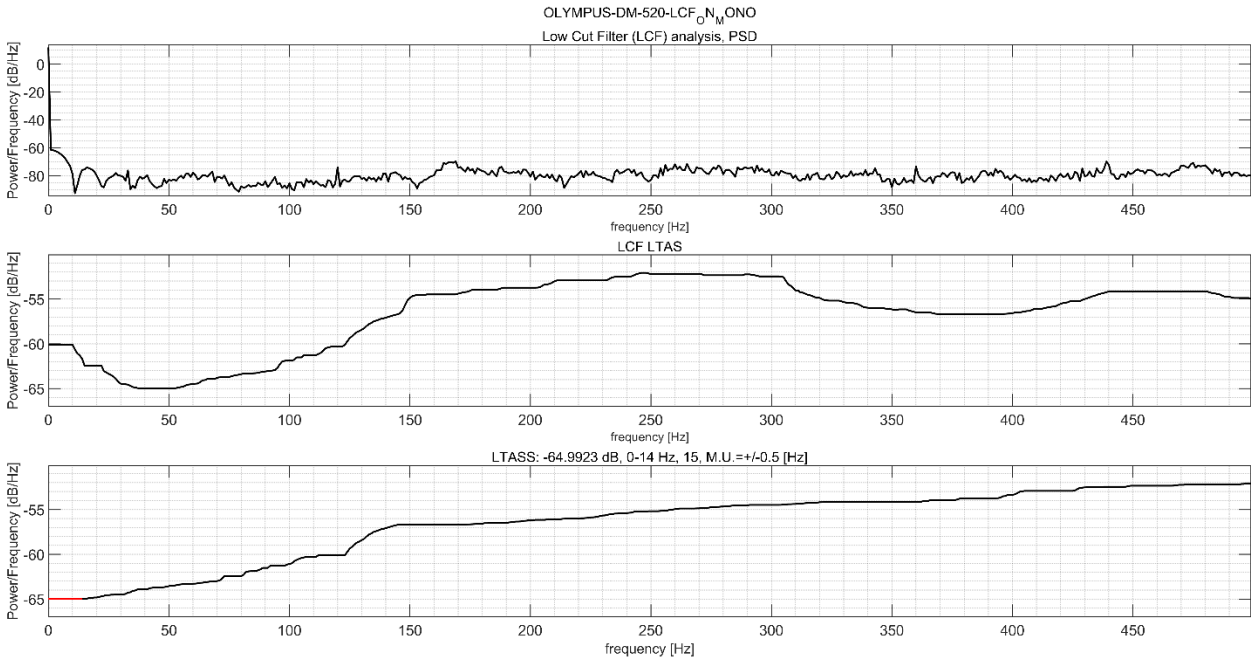

Figure 4 – Example of PSD, LTAS, and LTASS Plots Derived from MATLAB

A second MATLAB script was utilized to determine the correlation coefficient between two signals using the sorted power values exported by the initial MATLAB process to measure the statistical relationship between the two variables. This is expressed by a number between 0 and 1 with 1 meaning the variables are identical and 0 representing no correlation whatsoever. These values were then placed in a table to show the CC values of the entire testing database against a chosen exemplar sample.

Additionally, the sorted power values were utilized to plot two spectrums to a figure to create a visual comparison of two audio signals representing a single recorder with the LCF both on and off and of two audio signals from different recorders comparing the LCF slope for each.

IV. ANALYSIS

Figures 6 – 39, see Appendix, show the intra-variability of a recorders output signal by comparing the LTASS values of samples taken with the LCF function both on and off for each recording device used in this examination. The intention is to show how LTASS analysis can identify whether or not the LCF function was active while recording. The frequency range is limited to 500Hz, and power values vary for each plot to reflect the minimum value represented in each computation. The solid line represents the spectrum of the signal that had the LCF feature turned off, and the dotted line represents when the LCF feature was instantiated.

Figures 40 – 52, see Appendix, compare the inter-variability of the LTASS values of samples taken from two different recording devices, both with the LCF function on, with the intention of showing how the slope of the LCF differs significantly between recorders. Again, the frequency range is limited to 500Hz, and power values vary for each plot to reflect the minimum value represented in each computation. A legend in the figure identifies which recorder is represented by the solid or dotted line.

Tables 2 – 7 list the CC value of an exemplar, named at the top of column B, compared with each of the LCF On audio samples created for this examination, all of which are listed in column A. The CC value is a means to show the level of inter-variability within the database. CC values were limited to the fourth digit. The results are sorted in descending order with the cell containing the highest CC value shaded gray, identifying the device whose sorted spectrum has with the highest mathematical relationship to the exemplar.

Table 2 – CC Values of Olympus VP-10 vs Sample Database

LCF-On Data Set	Correlation to OLYMPUS_VP10-LCF_ON_A_MONO.wav
	Standard Deviation: .0387
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.9969
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.9953
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.9944
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9918
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.9859
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.9856
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9849
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.9809
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.9806
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.9767
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.9738
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.9736
ZOOM-H1-LCF_ON_MONO.wav	0.9722
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.9718
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.9661
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.9631
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.9607
SONY-ICD-PX312-LCF_ON_MONO.wav	0.9562
SONY-ICD-UX523-LCF_ON_A_MONO.wav	0.9559
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.9552
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.9549
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.9547
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.9545
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.9543
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.9531
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.9528
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.9524
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.9523
SONY-ICD-PX370-LCF_ON_A_MONO.wav	0.9499
SONY-ICD-UX533-LCF_ON_MONO.wav	0.9492
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.9478
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.9460
OLYMPUS-WS-700M-LCF_ON_MONO.wav	0.9356
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.9352
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.9339
SONY-ICD-TX50-LCF_ON_MONO.wav	0.9282
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.9279
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.9275

Table 2 Continued	
LCF-On Data Set	**Correlation to OLYMPUS_VP10-LCF_ON_A_MONO.wav**
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.9255
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.9243
OLYMPUS-WS-802-LCF_ON_A_MONO.wav	0.9237
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.9233
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.9227
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.9199
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.9122
ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	0.9002
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.8920
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.8910
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.8855
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.8578
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.7797

Table 3 – CC Values of Olympus WS-802 vs Sample Database

LCF-On Data Set	**Correlation to OLYMPUS-WS-802-LCF_ON_A_MONO.wav**
	Standard Deviation: .0716
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.9997
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.9993
OLYMPUS-WS-700M-LCF_ON_MONO.wav	0.9965
SONY-ICD-TX50-LCF_ON_MONO.wav	0.9951
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.9888
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.9881
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.9872
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.9869
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.9862
SONY-ICD-UX533-LCF_ON_MONO.wav	0.9839
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.9816
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.9772
SONY-ICD-PX312-LCF_ON_MONO.wav	0.9771
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.9769
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.9769
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.9756
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.9743
SONY-ICD-UX523-LCF_ON_A_MONO.wav	0.9723
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.9632
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.9533
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.9531
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.9519
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.9482
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.9347
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9336
OLYMPUS-VP10-LCF_ON_A_MONO.wav	0.9237
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.9173
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.9140
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.9127
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9097
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.9092
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.9073
ZOOM-H1-LCF_ON_MONO.wav	0.9045
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.8963
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.8943
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.8916
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.8859
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.8858

Table 3 Continued	
LCF-On Data Set	**Correlation to OLYMPUS-WS-802-LCF_ON_A_MONO.wav**
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.8816
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.8787
SONY-ICD-PX370-LCF_ON_A_MONO.wav	0.8726
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.8644
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.8574
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.8490
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.8460
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.8238
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.8136
ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	0.7861
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.7739
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.7308
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.6955

Table 4 – CC Values of Sony ICD-PX370 vs Sample Database

LCF-On Data Set	**Correlation to SONY-ICD-PX370-LCF_ON_A_MONO.wav**
	Standard Deviation: .0724
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.9908
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.9901
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.9892
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.9864
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.9775
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.9773
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.9754
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.9684
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.9649
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.9617
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.9601
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.9588
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.9545
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.9542
OLYMPUS-VP10-LCF_ON_A_MONO.wav	0.9499
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.9453
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.9427
SONY-ICD-PX312-LCF_ON_MONO.wav	0.9364
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.9322
SONY-ICD-UX533-LCF_ON_MONO.wav	0.9317
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9232
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.9221
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.9215
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.9177
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.9149
SONY-ICD-UX523-LCF_ON_A_MONO.wav	0.9135
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.9100
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.9096
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9012
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.9007
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.9001
ZOOM-H1-LCF_ON_MONO.wav	0.8995
SONY-ICD-TX50-LCF_ON_MONO.wav	0.8974
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.8974
OLYMPUS-WS-700M-LCF_ON_MONO.wav	0.8948
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.8948
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.8828
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.8773

Table 4 Continued	
LCF-On Data Set	**Correlation to SONY-ICD-PX370-LCF_ON_A_MONO.wav**
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.8727
OLYMPUS-WS-802-LCF_ON_A_MONO.wav	0.8726
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.8709
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.8587
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.8301
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.8255
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.7851
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.7806
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.7757
ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	0.7718
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.7425
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.7335
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.6817

Table 5 – CC Values of Sony ICD-UX523 vs Sample Database

LCF-On Data Set	**Correlation to SONY-ICD-UX523-LCF_ON_A_MONO.wav**
	Standard Deviation: .0483
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.9987
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.9971
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.9907
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.9878
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.9850
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.9835
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.9790
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.9788
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.9786
SONY-ICD-UX533-LCF_ON_MONO.wav	0.9783
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.9768
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.9747
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.9737
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.9728
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.9728
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.9728
OLYMPUS-WS-700M-LCF_ON_MONO.wav	0.9724
OLYMPUS-WS-802-LCF_ON_A_MONO.wav	0.9723
SONY-ICD-TX50-LCF_ON_MONO.wav	0.9723
SONY-ICD-PX312-LCF_ON_MONO.wav	0.9703
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.9651
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.9593
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.9569
OLYMPUS-VP10-LCF_ON_A_MONO.wav	0.9559
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9545
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.9515
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.9508
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.9473
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9473
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.9468
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.9467
ZOOM-H1-LCF_ON_MONO.wav	0.9447
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.9427
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.9369
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.9359
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.9285
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.9259
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.9248

Table 5 Continued	
LCF-On Data Set	**Correlation to SONY-ICD-UX523-LCF_ON_A_MONO.wav**
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.9190
SONY-ICD-PX370-LCF_ON_A_MONO.wav	0.9135
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.9110
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.9065
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.9062
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.8831
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.8788
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.8786
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.8681
ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	0.8650
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.8424
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.8179
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.7630

Table 6 – CC Values of Zoom H4N 80Hz vs Sample Database

LCF-On Data Set	Correlation to ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav
	Standard Deviation: .0818
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.9914
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.9895
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.9828
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.9812
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.9811
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.9692
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.9690
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.9496
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.9482
ZOOM-H1-LCF_ON_MONO.wav	0.9450
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9322
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.9317
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9278
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.9211
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.9135
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.9035
OLYMPUS-VP10-LCF_ON_A_MONO.wav	0.9002
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.8889
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.8880
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.8829
SONY-ICD-UX523-LCF_ON_A_MONO.wav	0.8650
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.8649
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.8641
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.8595
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.8585
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.8487
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.8469
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.8360
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.8339
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.8328
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.8297
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.8112
SONY-ICD-PX312-LCF_ON_MONO.wav	0.8047
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.8023
SONY-ICD-TX50-LCF_ON_MONO.wav	0.7971
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.7936
SONY-ICD-UX533-LCF_ON_MONO.wav	0.7915
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.7910

Table 6 Continued	
LCF-On Data Set	**Correlation to ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav**
OLYMPUS-WS-700M-LCF_ON_MONO.wav	0.7890
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.7882
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.7880
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.7880
OLYMPUS-WS-802-LCF_ON_A_MONO.wav	0.7861
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.7777
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.7761
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.7759
SONY-ICD-PX370-LCF_ON_A_MONO.wav	0.7718
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.7560
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.7193
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.7043
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.6500

Table 7 – CC Values of Olympus WS-700M vs Sample Database

LCF-On Data Set	**Correlation to OLYMPUS-WS-700M-LCF_ON_MONO.wav**
	Standard Deviation: .0710
SONY-ICD-TX50-LCF_ON_MONO.wav	0.9976
OLYMPUS-WS-802-LCF_ON_C_MONO.wav	0.9970
OLYMPUS-WS-802-LCF_ON_A_MONO.wav	0.9965
OLYMPUS-WS-802-LCF_ON_B_MONO.wav	0.9960
OLYMPUS-WS-700M-DUP-LCF_ON_MONO.wav	0.9927
OLYMPUS-WS-600S-LCF_ON_MONO.wav	0.9910
SONY-ICD-UX533-LCF_ON_MONO.wav	0.9905
SONY-ICD-UX512-LCF_ON_C_MONO.wav	0.9883
SONY-ICD-UX512-LCF_ON_B_MONO.wav	0.9865
SONY-ICD-PX312-LCF_ON_MONO.wav	0.9860
SONY-ICD-UX512-DUP-LCF_ON_MONO.wav	0.9849
SONY-ICD-UX512-LCF_ON_A_MONO.wav	0.9845
OLYMPUS-DM-520-LCF_ON_MONO.wav	0.9844
OLYMPUS-WS-802-DUP-LCF_ON_MONO.wav	0.9843
SONY-ICD-PX370-LCF_ON_B_MONO.wav	0.9835
SONY-ICD-UX523-LCF_ON_C_MONO.wav	0.9778
SONY-ICD-UX523-LCF_ON_B_MONO.wav	0.9759
OLYMPUS-DM-620-LCF_ON_MONO.wav	0.9752
SONY-ICD-UX523-LCF_ON_A_MONO.wav	0.9724
OLYMPUS-DS-40-LCF_ON_MONO.wav	0.9644
OLYMPUS-DM-901-LCF_ON_MONO.wav	0.9614
TASCAM-DR-07-LCF_ON_120Hz_A_MONO.wav	0.9593
OLYMPUS-VP-10-LCF_ON_C_MONO.wav	0.9403
SONY-ICD-UX560-LCF_ON_C_MONO.wav	0.9397
OLYMPUS-VP10-LCF_ON_A_MONO.wav	0.9356
OLYMPUS-VP10-LCF_ON_B_MONO.wav	0.9356
SONY-ICD-UX560-LCF_ON_B_MONO.wav	0.9315
ZOOM-H4N-LCF_ON_168Hz_MONO.wav	0.9291
ZOOM-H4N-LCF_ON_133Hz_MONO.wav	0.9273
ZOOM-H4N-LCF_ON_185Hz_MONO.wav	0.9254
OLYMPUS-WS-852-LCF_ON_B_MONO.wav	0.9239
ZOOM-H4N-LCF_ON_150Hz_MONO.wav	0.9205
ZOOM-H4N-LCF_ON_203Hz_MONO.wav	0.9162
ZOOM-H1-LCF_ON_MONO.wav	0.9127
ZOOM-H4N-LCF_ON_220Hz_MONO.wav	0.9120
SONY-ICD-UX560-LCF_ON_A_MONO.wav	0.9106
ZOOM-H4N-LCF_ON_237Hz_MONO.wav	0.9065
OLYMPUS-VN-8100PC-LCF_ON_MONO.wav	0.8961

Table 7 Continued	
LCF-On Data Set	**Correlation to OLYMPUS-WS-700M-LCF_ON_MONO.wav**
SONY-ICD-PX370-LCF_ON_A_MONO.wav	0.8948
ZOOM-H4N-LCF_ON_115Hz_MONO.wav	0.8865
TASCAM-DR-05-LCF_ON_80Hz_MONO	0.8836
OLYMPUS-WS-852-LCF_ON_A_MONO.wav	0.8796
TASCAM-DR-05-LCF_ON_120Hz_MONO	0.8769
TASCAM-DR-07-LCF_ON_80Hz_B_MONO.wav	0.8500
TASCAM-DR-05-LCF_ON_40Hz_MONO.wav	0.8481
ZOOM-H4N-LCF_ON_80Hz_B_MONO.wav	0.8244
TASCAM-DR-07-LCF_ON_80Hz_A_MONO.wav	0.8185
ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	0.7890
ZOOM-H4N-LCF_ON_98Hz_MONO.wav	0.7771
TASCAM-DR-07-LCF_ON_40Hz_A_MONO.wav	0.7335
PHILLIPS-DVT-5500-LCF_ON_MONO.wav	0.6934

V. RESULTS

The aim of this study was to determine whether sufficient salient data could be derived from the LCF effects in audio recordings made with handheld digital recorders using LTASS analysis to reliably make comparisons, exclusions or possible identifications. Three hypotheses were examined using the data created for this examination.

Hypothesis One

It is possible to identify whether or not the LCF option of a recorder was on or off.

This hypothesis has been confirmed to be true. Samples were made with the LCF both on and off for each recorder used in the study. When processed with the initial analysis script in MATLAB, the power values of the LTASS were exported and saved to a text document. The on and off power values were then plotted to a periodogram. These figures show the inter-variability of a recorder's output, LCF on vs off.

As can be visually observed in figures 6 – 39, the signal with the LCF turned on differs greatly from the signal with the LCF turned off, with varying degrees of significant differentiation. Figure 21, showing the spectrums of a Sony ICD-TX50 recorder, is an excellent example to show a clear distinction of LCF on vs. off. Other examples are more subtle, such as figure 10, showing the spectrums of an Olympus VP-10. All devices tested from manufacturers Olympus, Sony, Phillips and Zoom exhibited expected results. An interesting characteristic of the Zoom H4N model, the device with the highest number of frequency roll-off options, did not seem to exhibit any substantial difference in frequency among the samples, only changes in the slope severity (figures 30 - 39). Below is a figure showing the overlaid sorted power values of all the LCF options; 80Hz, 98Hz, 115Hz, 133Hz, 150Hz, 168Hz, 185Hz, 203Hz, 220Hz, and 237Hz.

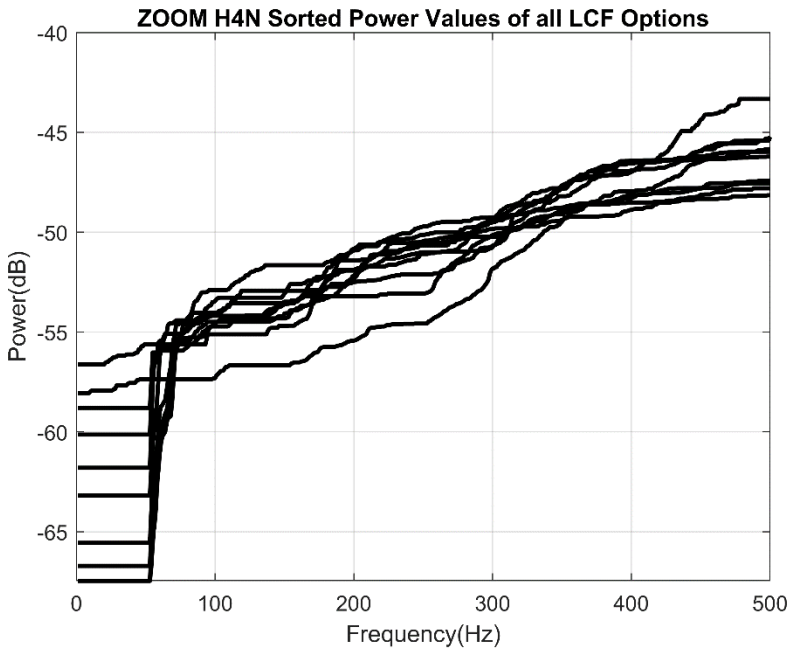

Figure 5 – ZOOM H4N Sorted Power Values of all LCF Options

Additionally, the Tascam DR-05 model showed less low frequency activity in the LCF off sample than in the samples taken with the LCF on and set to the three frequency options of 40Hz, 80Hz, and 120Hz, seen in figures 23 - 25. Additional samples or even additional DR-05 devices in a future study could help understand this anomaly. However, visually, there was a clear frequency slope drop seen in figure 25 which shows the sorted spectrum with the LCF set to 120Hz.

Hypothesis Two

Low-cut filter signal processing differs significantly between recorders.

This hypothesis has been confirmed to be true. To compare the inter-variability of the LTASS values of samples taken from two different recording devices, sorted power values from two different recorders, both with the LCF on, were overlaid in a single periodogram. As shown in figures 40 – 52, in most cases, there is a clear distinction between the LCF processing of one

recorder to the other. It is particularly evident in figure 47, which shows the spectrums for the Sony ICD-PX370 and the Sony ICD-TX50. A more subtle example of LCF slope distinction can be seen in figure 41 where the Olympus DM-520 and Olympus DM-620 are compared.

Some inter-variability comparisons displayed interesting results. In figure 46, the Sony ICD-UX512 spectrum is very similar to that of the Sony ICD-UX523. A similar event is seen in figure 50 between the spectrums of the Olympus WS-600S and the Olympus WS-700M. A possible explanation is that the manufacturers copied much of the processing architecture to a subsequent model, giving them similar LCF functionality.

Hypothesis Three

LTASS/LCF analysis can be used as a means of eliminating a device from a pool of recorders.

This hypothesis has been confirmed to be true. To test whether LTASS analysis can reliably identify the LCF signature of a purported recording device, correlation coefficients were calculated for a single device sample against all of the sample library used in this study. CC values were charted for six comparative studies shown in tables 2 – 7. The highest CC value was highlighted to show which recorder sample had the highest mathematical relationship to the exemplar. The results are as follows:

Table 8 – CC Test Results

	Exemplar Recorder	Recorder with Highest CC Sample
Test 1	OLYMPUS_VP10-LCF_ON_A_MONO.wav	SONY-ICD-UX560-LCF_ON_B_MONO.wav
Test 2	OLYMPUS-WS-802-LCF_ON_A_MONO.wav	OLYMPUS-WS-802-LCF_ON_B_MONO.wav
Test 3	SONY-ICD-PX370-LCF_ON_A_MONO.wav	OLYMPUS-WS-852-LCF_ON_A_MONO.wav
Test 4	SONY-ICD-UX523-LCF_ON_A_MONO.wav	SONY-ICD-UX523-LCF_ON_B_MONO.wav
Test 5	ZOOM-H4N-LCF_ON_80Hz_A_MONO.wav	ZOOM-H4N-LCF_ON_98Hz_MONO.wav
Test 6	OLYMPUS-WS-700M-LCF_ON_MONO.wav	SONY-ICD-TX50-LCF_ON_MONO.wav

Tests 2, 4 and 5 were accurately able to determine which recording device was used to create the exemplar recording because another audio sample made with the same recorder measured the highest CC values. However, tests 1, 3 and 6 resulted in a make and model of recorder other than the exemplar as having the highest CC value.

While LTASS analysis cannot reliably identify the LCF signature of specific handheld digital recorders, it may still be used to make an exclusion through spectrum comparisons on a periodogram. The scope of this study only included recorders with the LCF option, but there are numerous recorders on the market that do not have this option. Should a signal after analysis show evidence of an LCF, but the purported recorder does not have this option, this information could be useful to an examiner.

VI. DISCUSSION & FUTURE RESEARCH

This study was able to show that LTASS analysis can be a very useful technique when analyzing the effects of an LCF on an audio signal from a handheld digital recorder. Its use does have limitations, but when used in conjunction with other recommended techniques can provide valuable data for an investigation.

Possible areas of interest for future research could be:

- Samples may be created in a calibrated environment involving pink noise or frequency sweeps.
- Samples may be created in more varied "real-world" situations to test how background noise effects the reliability of LTASS analysis.
- Samples may be created at the extremes of available resolution in a recorder to further test intra-variability.

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6. Grigoras, C., D.L. Rappaport, and J.M. Smith, *Analytical Framework for Digital Audio Authentication*, in *AES 46th International Conference: Audio Forensics*. 2012: Denver, CO, USA.

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8. Grigoras, C. and J.M. Smith, *Audio Enhancement and Authentication*, in *Encyclopedia of Forensic Sciences*. 2013. p. 315-326.

APPENDIX

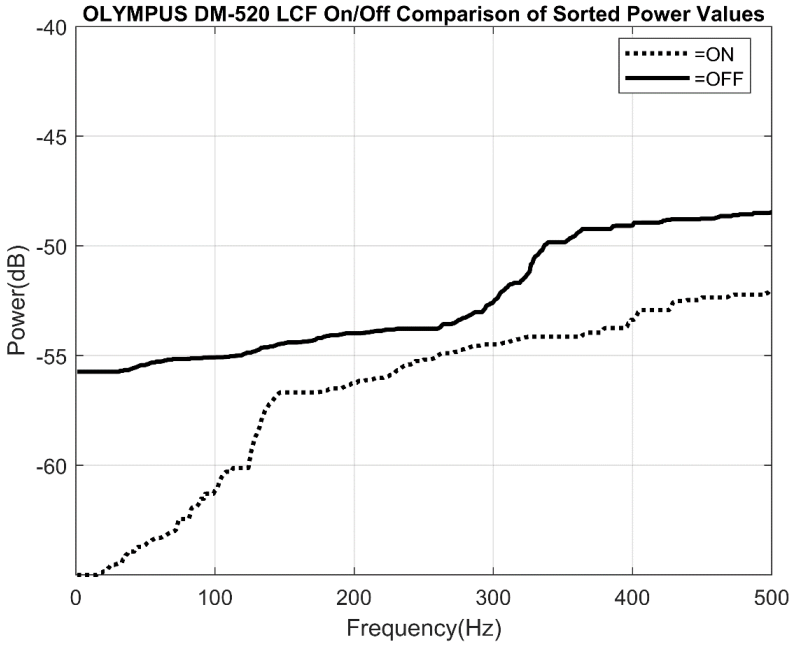

Figure 6 – Olympus DM-520 LCF On/Off Comparison

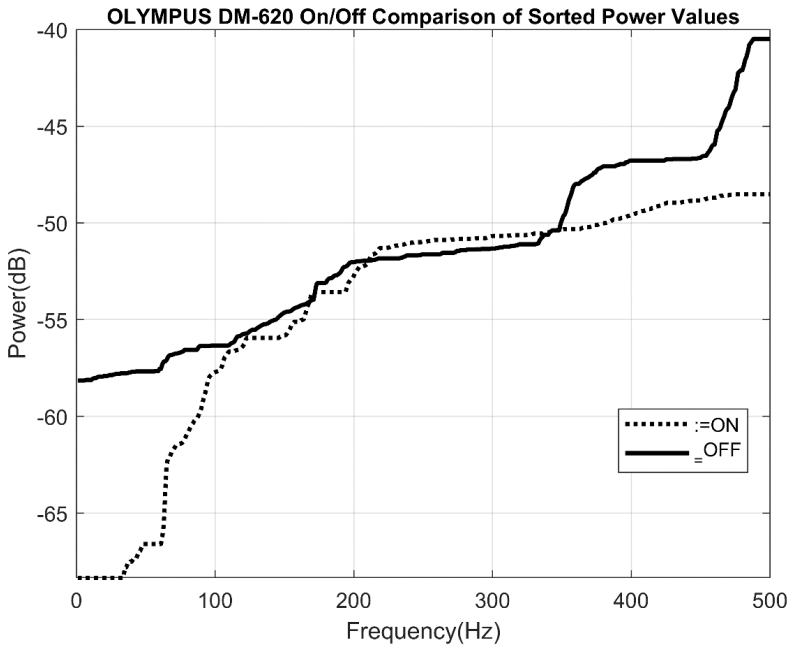

Figure 7 – Olympus DM-620 LCF On/Off Comparison

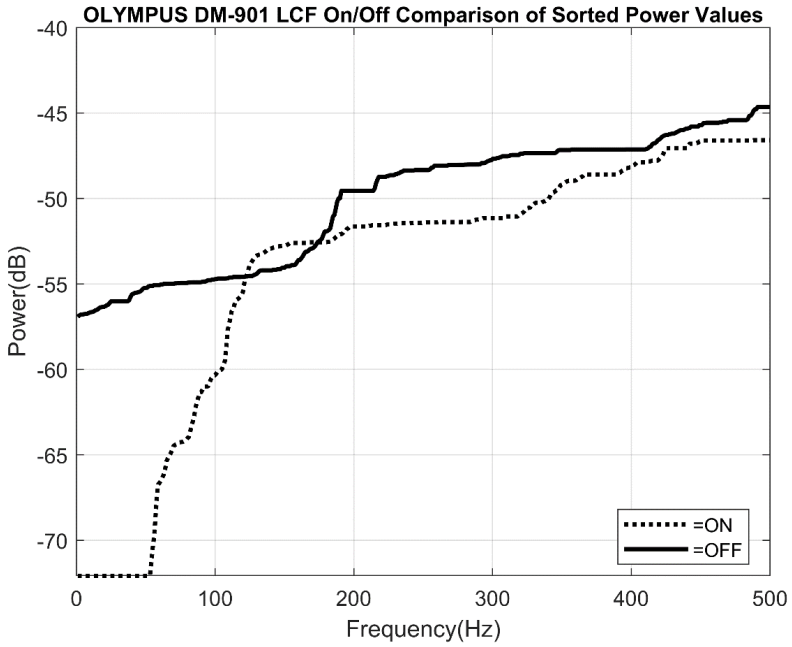

Figure 8 – Olympus DM-901 LCF On/Off Comparison

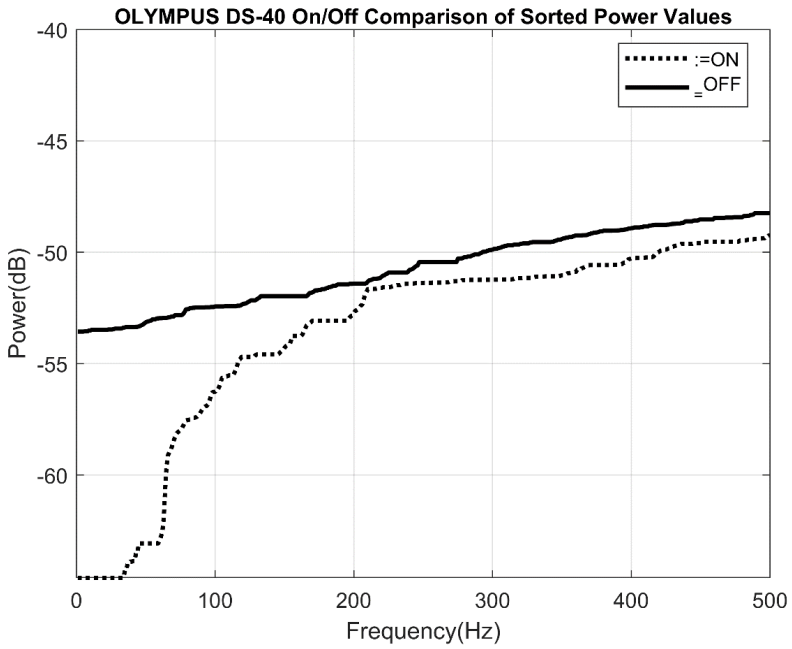

Figure 9 – Olympus DS-40 LCF On/Off Comparison

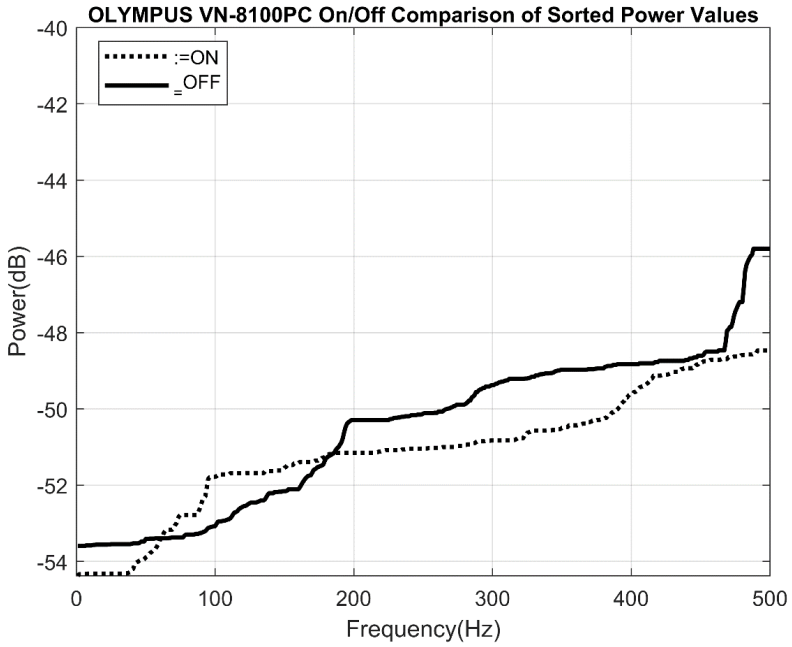

Figure 10 – Olympus VN-8100PC LCF On/Off Comparison

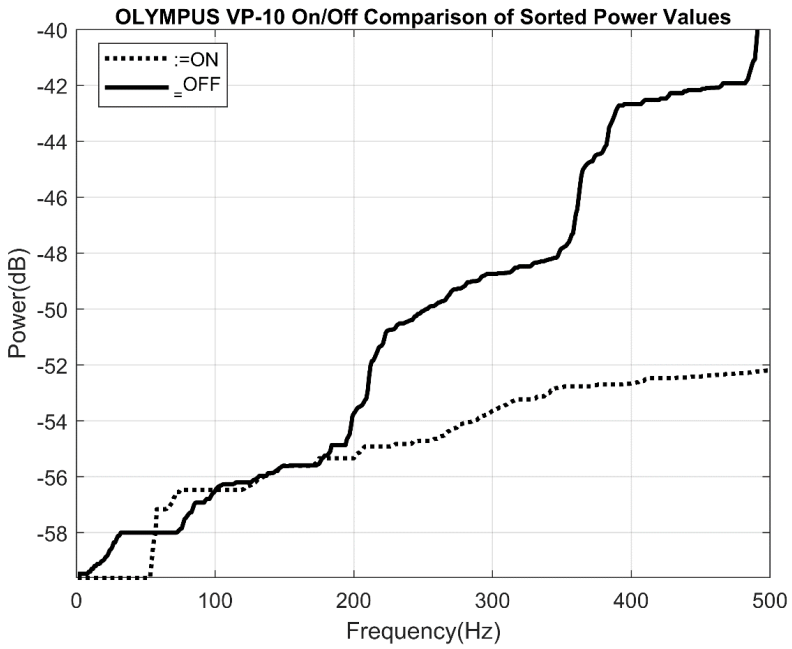

Figure 11 – Olympus VP-10 LCF On/Off Comparison

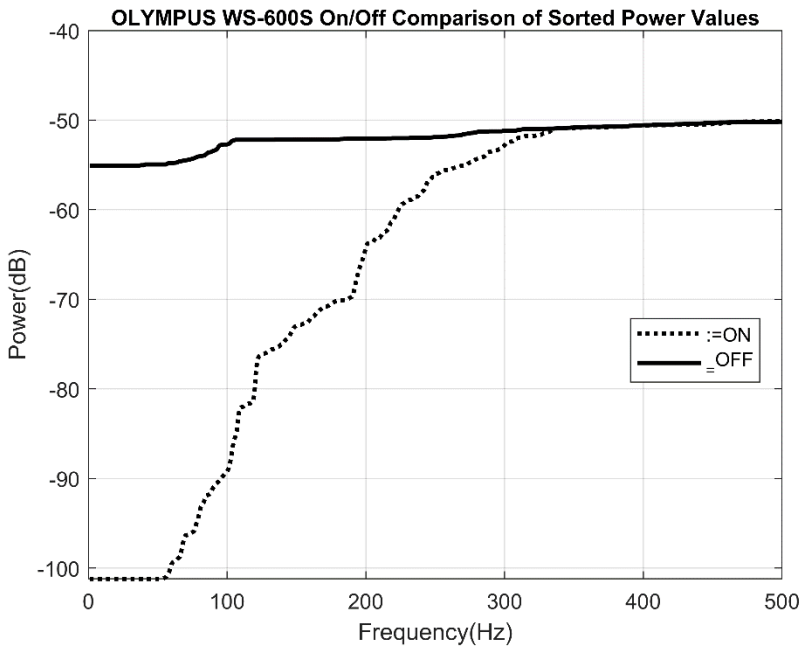

Figure 12 – Olympus WS-600S LCF On/Off Comparison

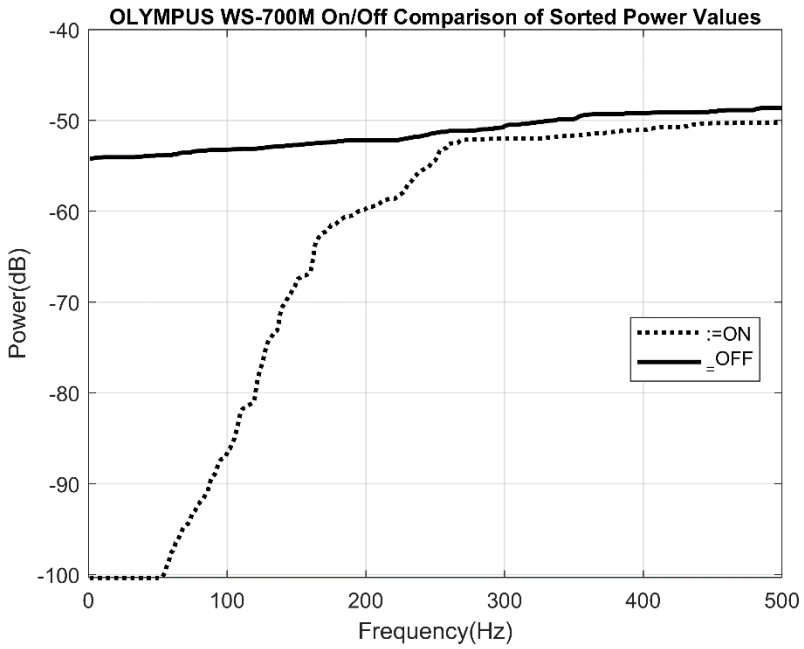

Figure 13 – Olympus WS-700M LCF On/Off Comparison

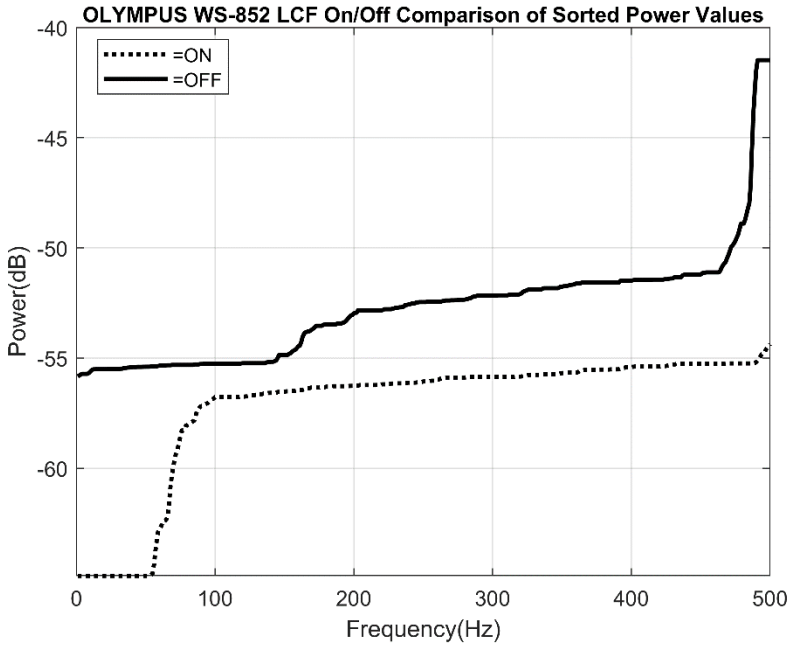

Figure 14 – Olympus WS-852 LCF On/Off Comparison

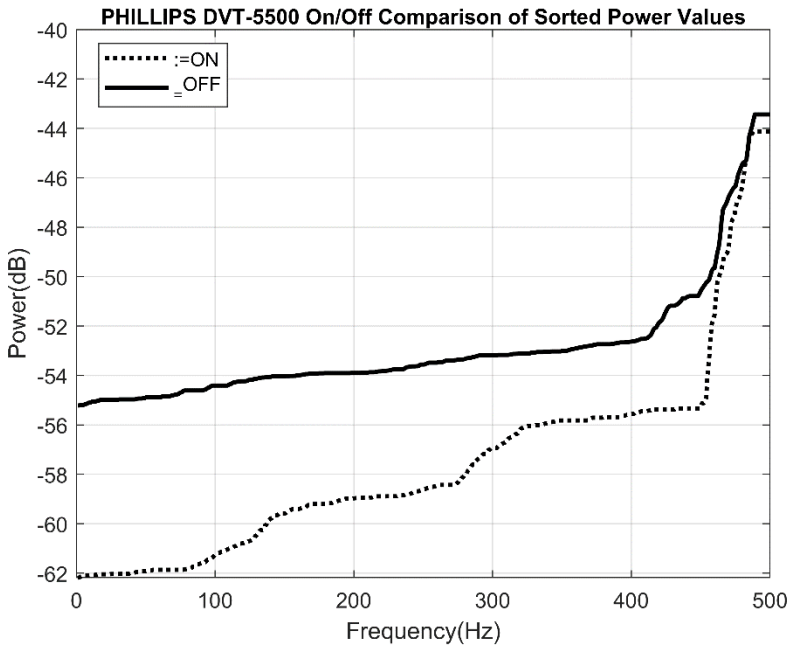

Figure 15 – Phillips DVT-5500 LCF On/Off Comparison

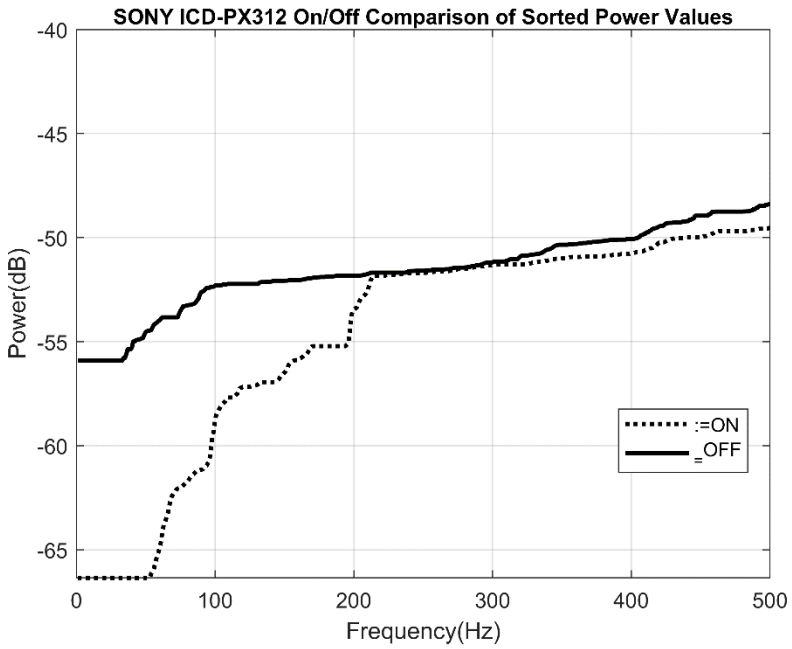

Figure 16 – Sony ICD-PX312 LCF On/Off Comparison

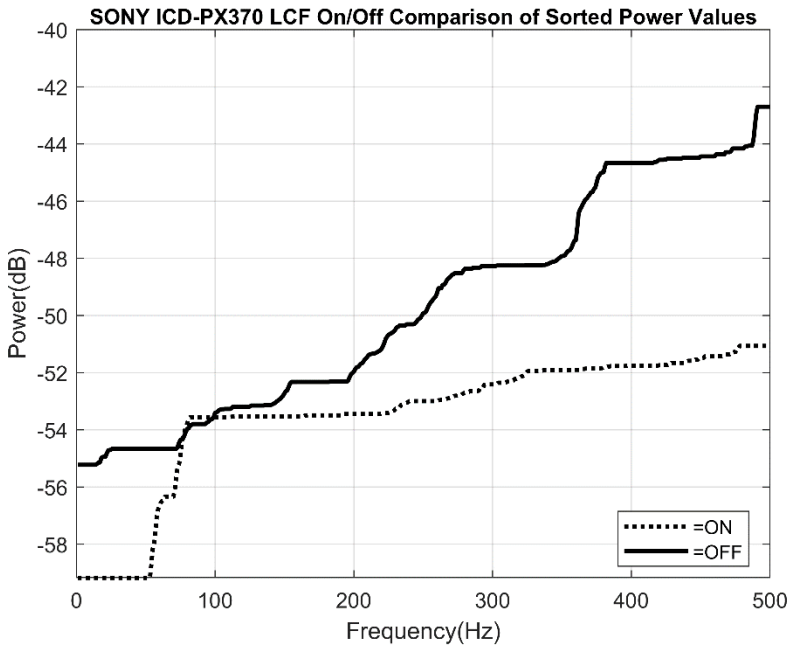

Figure 17 – Sony ICD-PX370 LCF On/Off Comparison

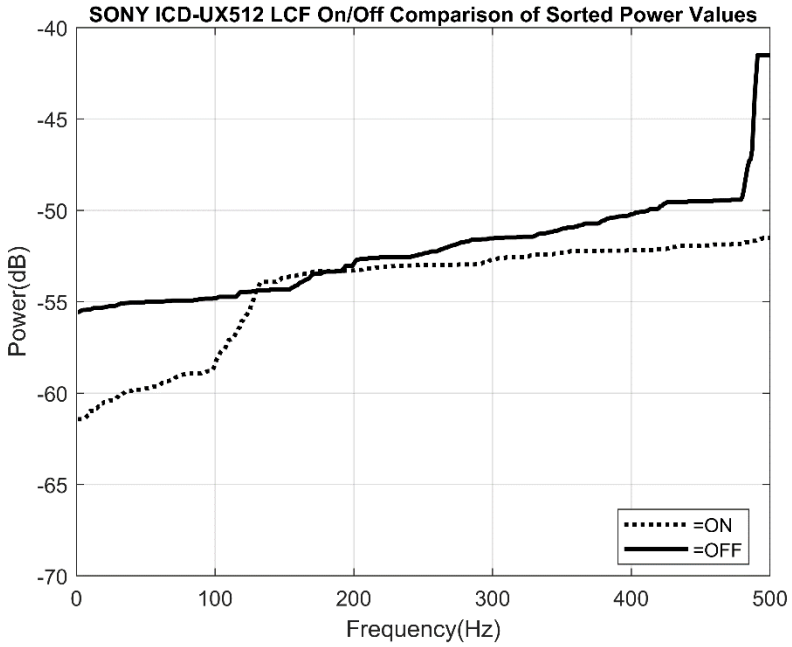

Figure 18 – Sony ICD-UX512 LCF On/Off Comparison

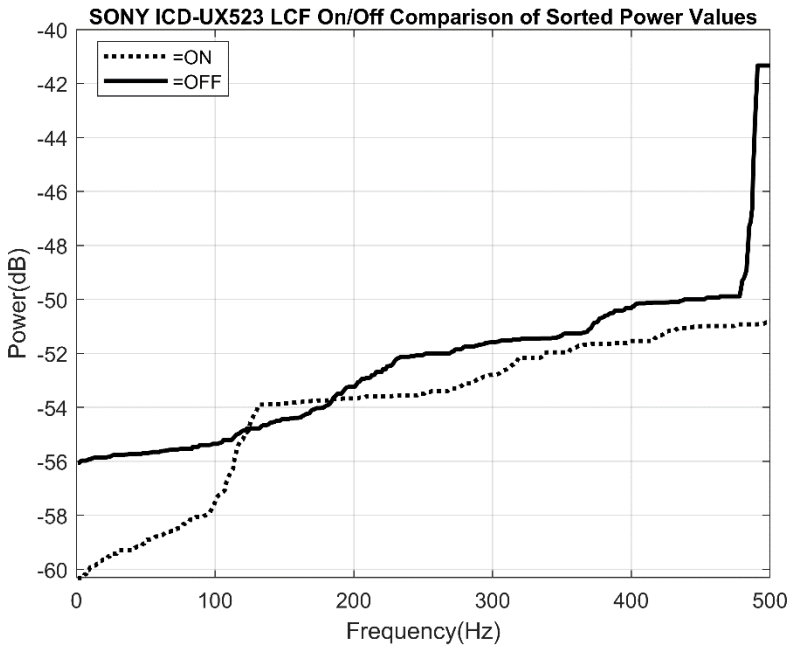

Figure 19 – Sony ICD-UX523 LCF On/Off Comparison

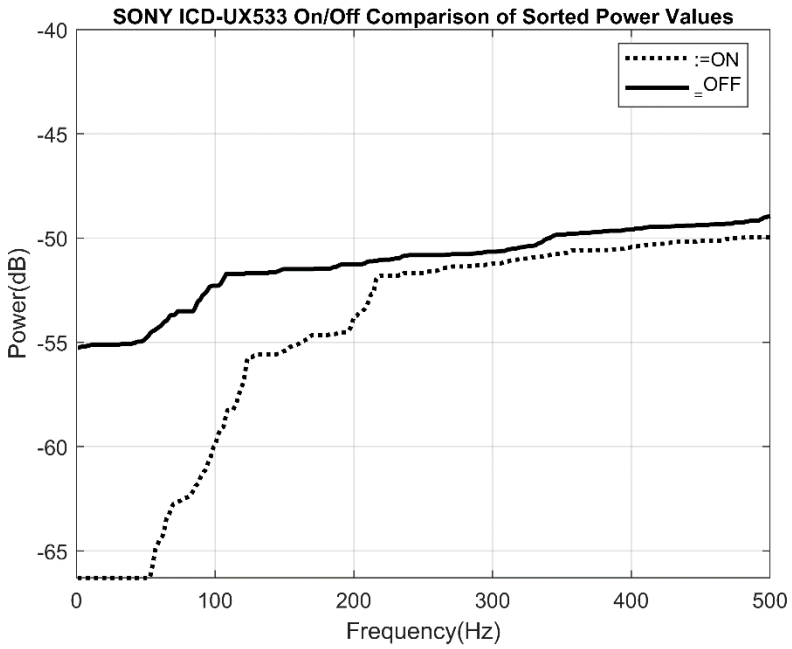

Figure 20 – Sony ICD-UX533 LCF On/Off Comparison

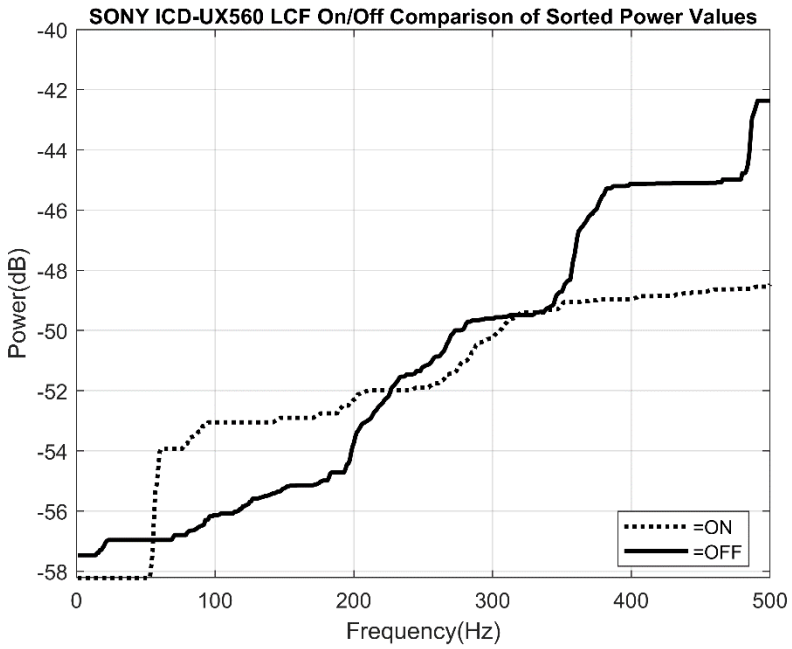

Figure 21 – Sony ICD-UX560 LCF On/Off Comparison

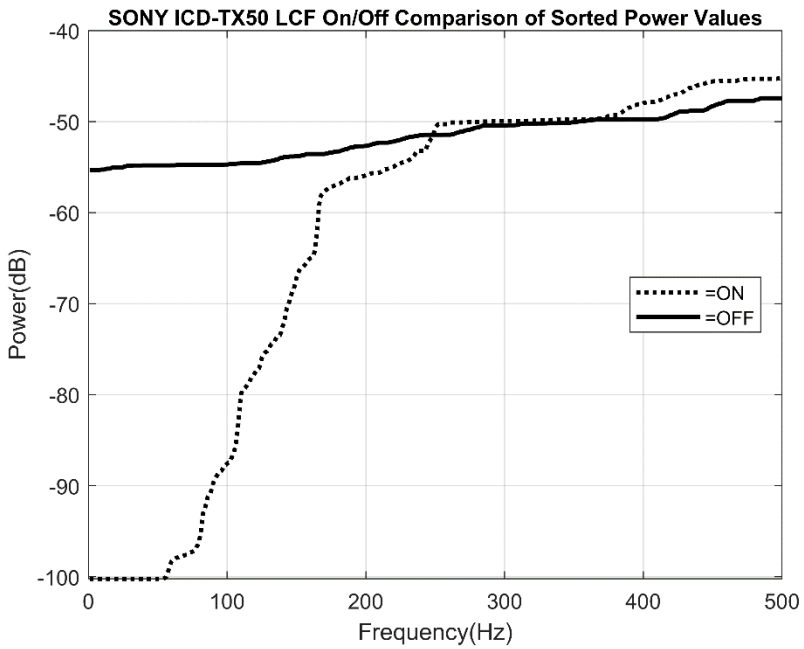

Figure 22 – Sony ICD-TX50 LCF On/Off Comparison

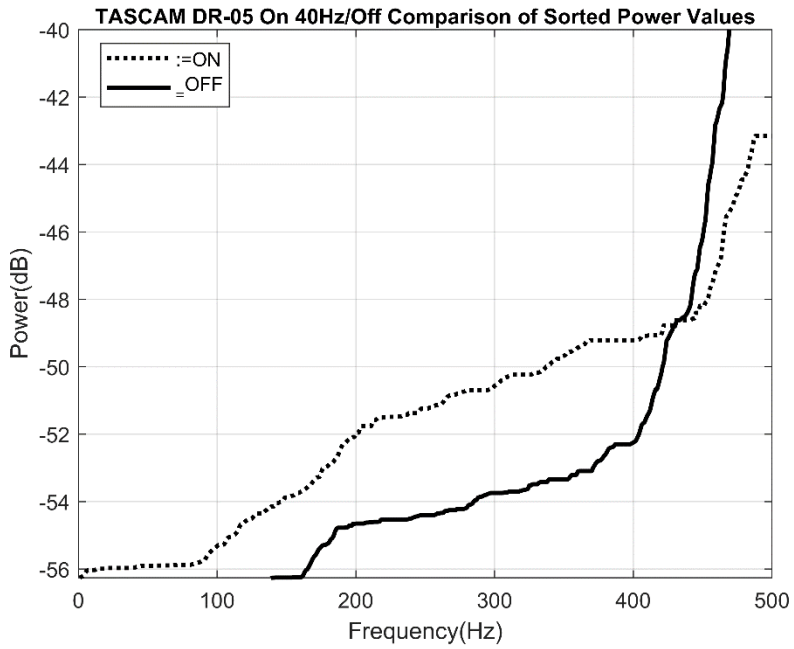

Figure 23 – Tascam DR-05 40Hz LCF On/Off Comparison

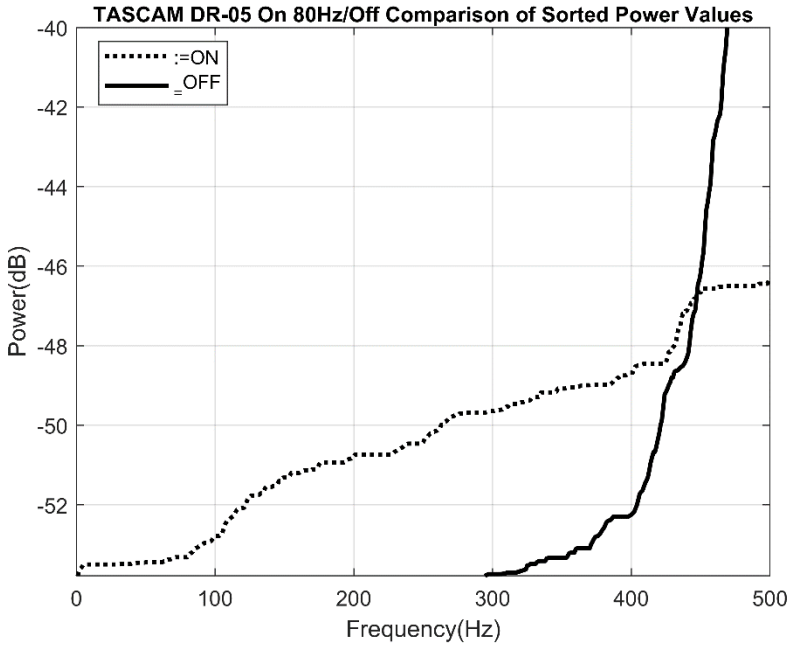

Figure 24 – Tascam DR-05 80Hz LCF On/Off Comparison

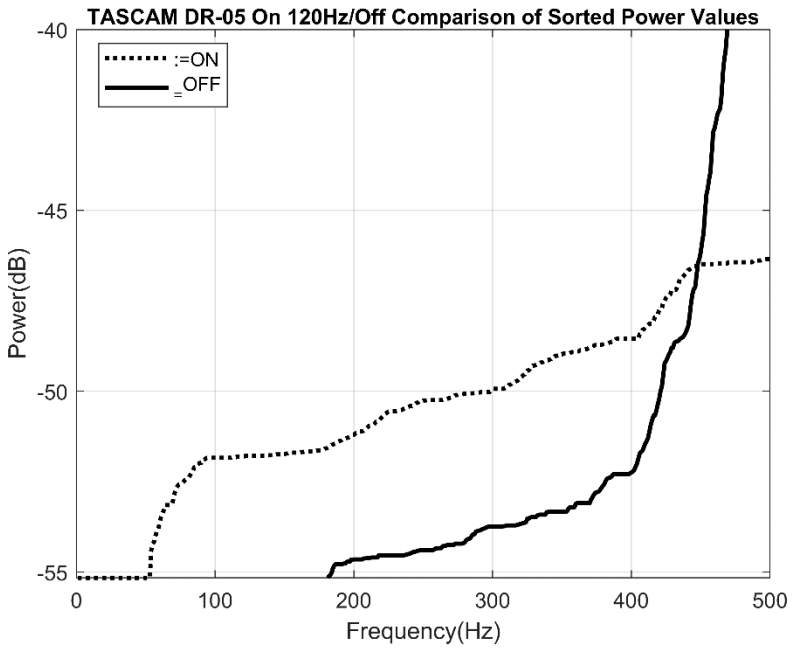

Figure 25 – Tascam DR-05 120Hz LCF On/Off Comparison

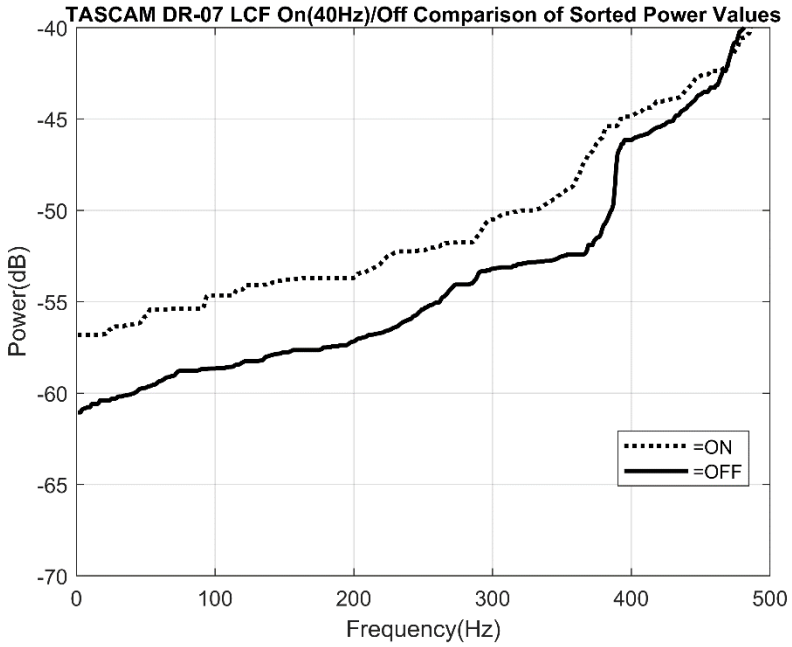

Figure 26 – Tascam DR-07 40Hz LCF On/Off Comparison

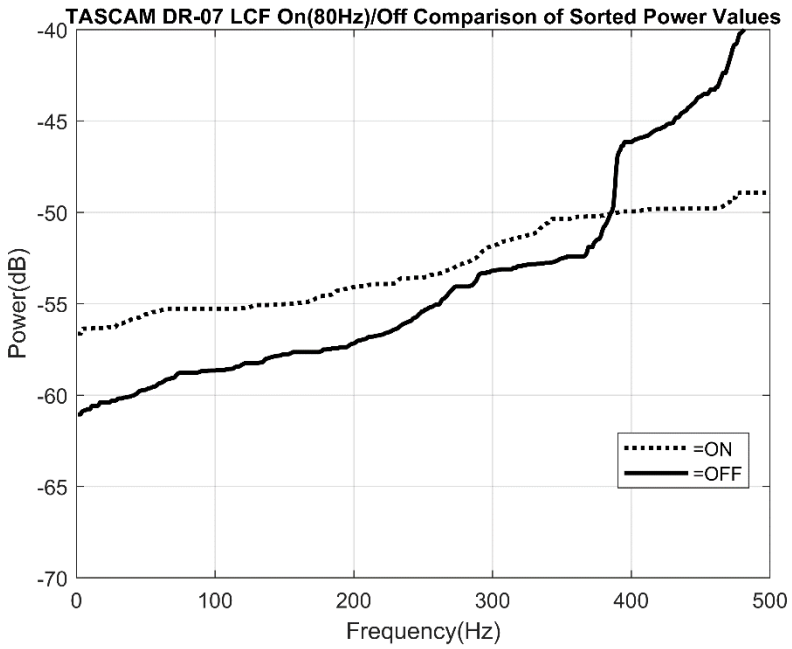

Figure 27 – Tascam DR-07 80Hz LCF On/Off Comparison

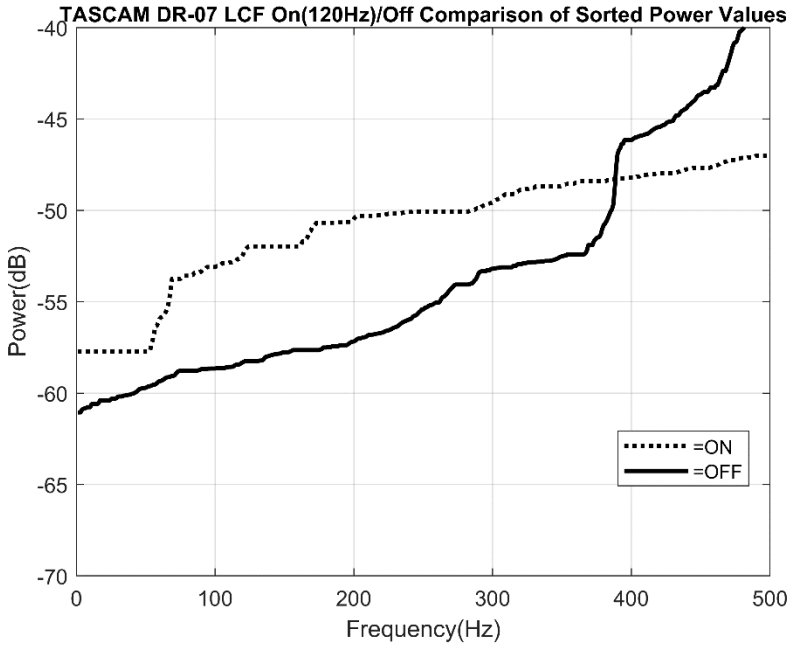

Figure 28 – Tascam DR-07 120Hz LCF On/Off Comparison

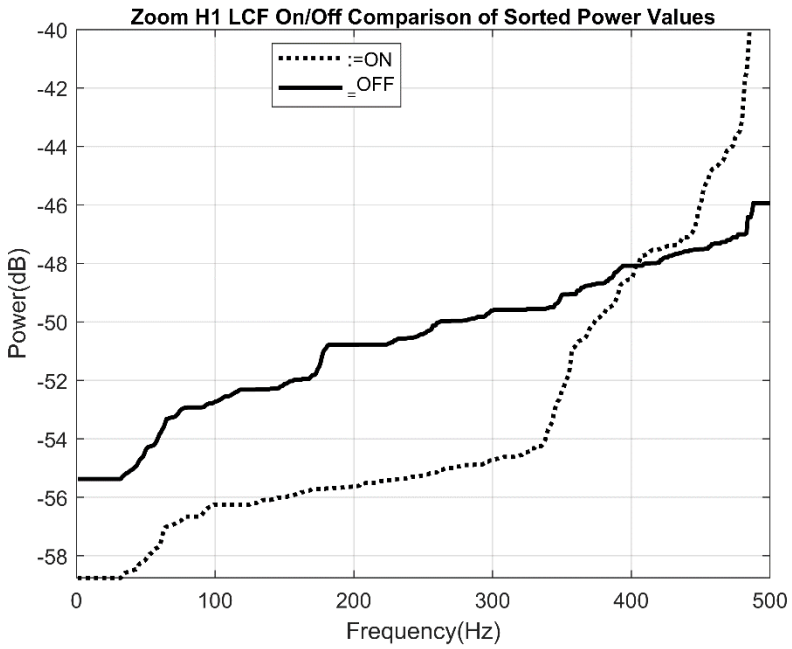

Figure 29 – Zoom H1 LCF On/Off Comparison

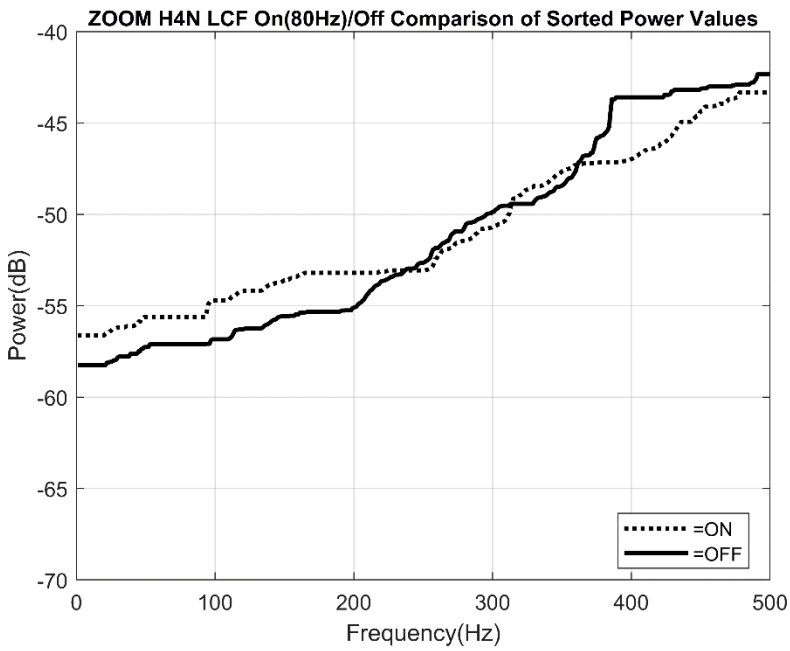

Figure 30 – Zoom H4N 80Hz LCF On/Off Comparison

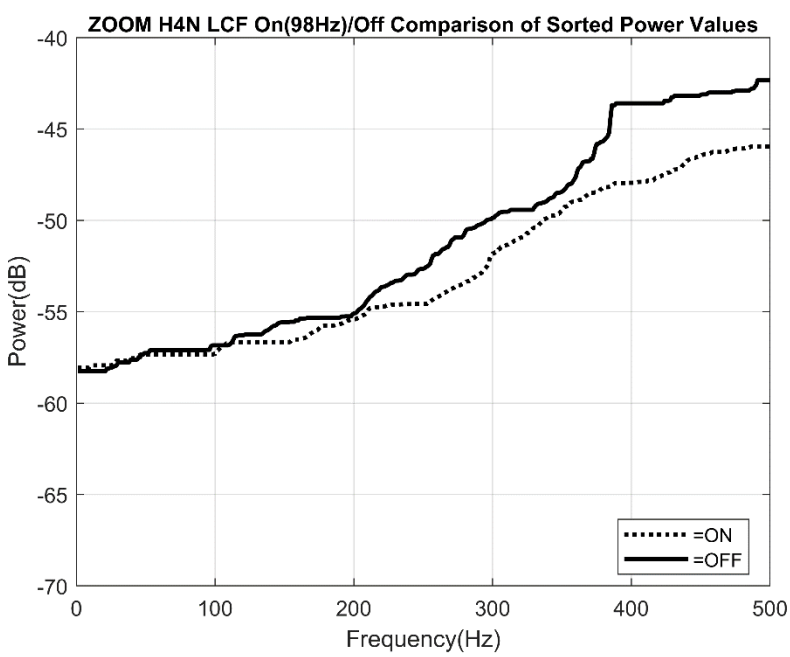

Figure 31 – Zoom H4N 98Hz LCF On/Off Comparison

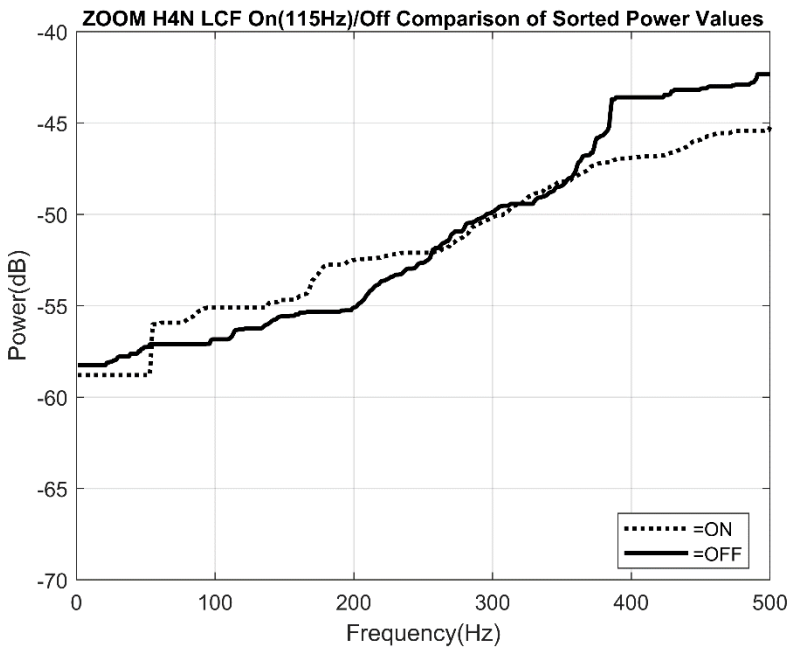

Figure 32 – Zoom H4N 115Hz LCF On/Off Comparison

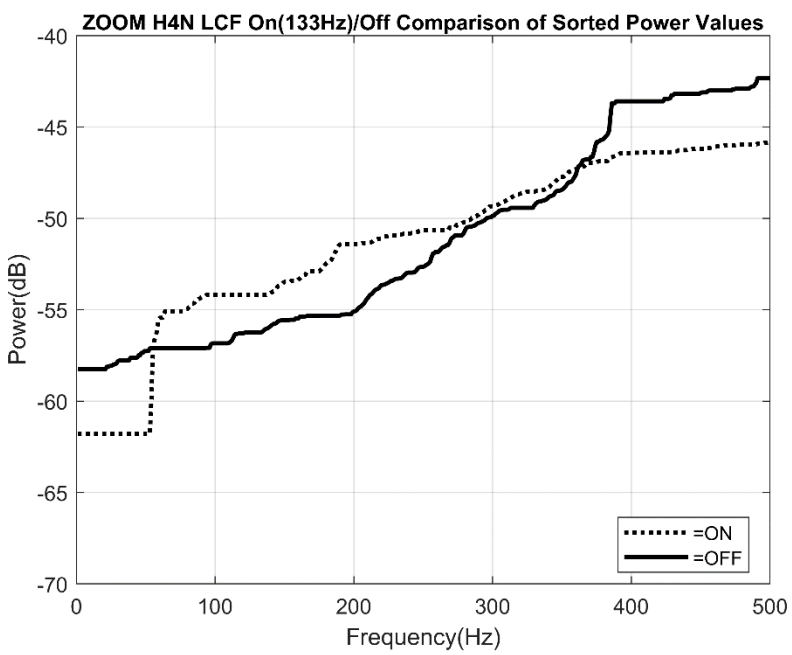

Figure 33 – Zoom H4N 133Hz LCF On/Off Comparison

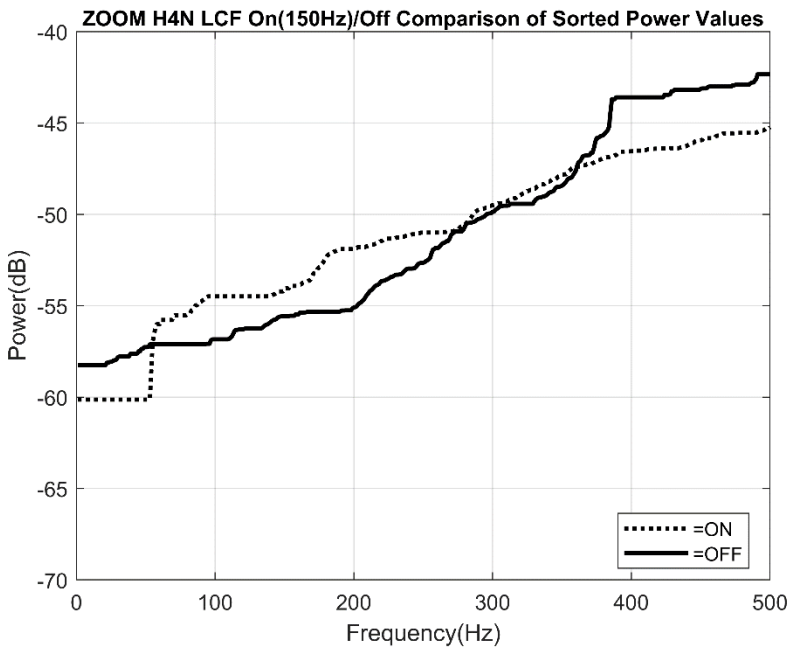

Figure 34 – Zoom H4N 150Hz LCF On/Off Comparison

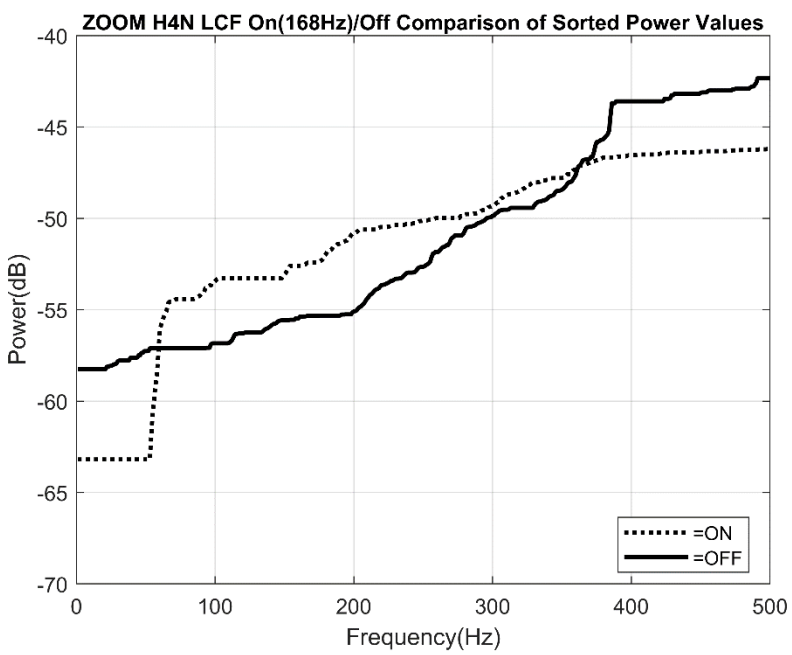

Figure 35 – Zoom H4N 168Hz LCF On/Off Comparison

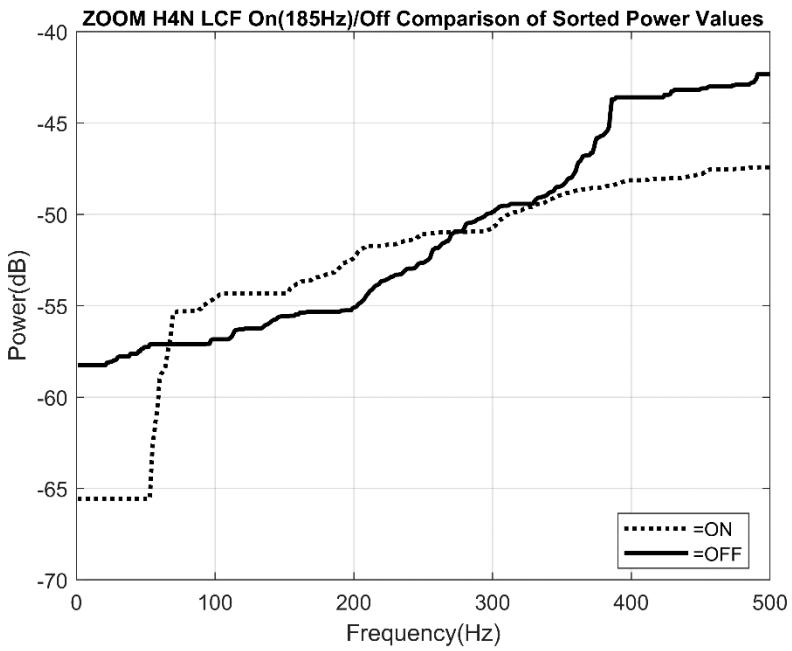

Figure 36 – Zoom H4N 185Hz LCF On/Off Comparison

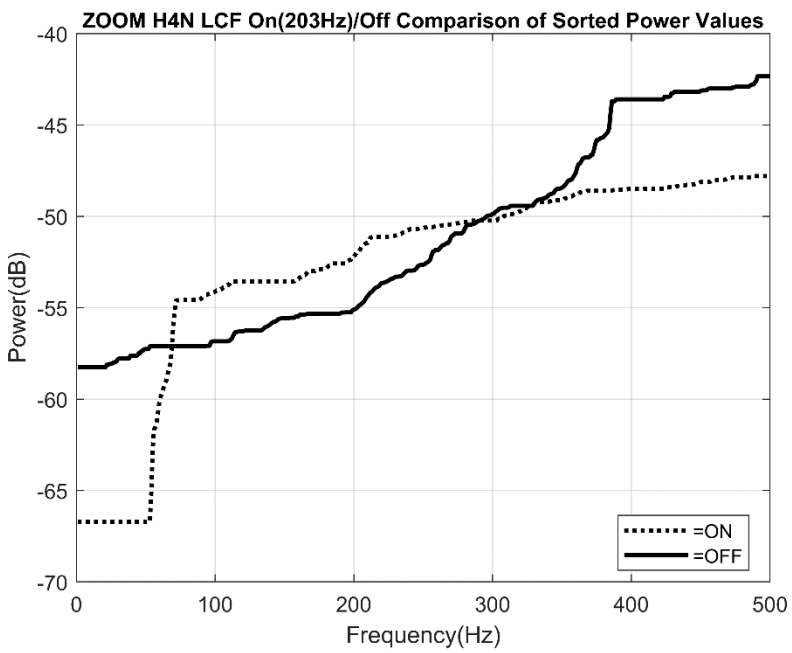

Figure 37 – Zoom H4N 203Hz LCF On/Off Comparison

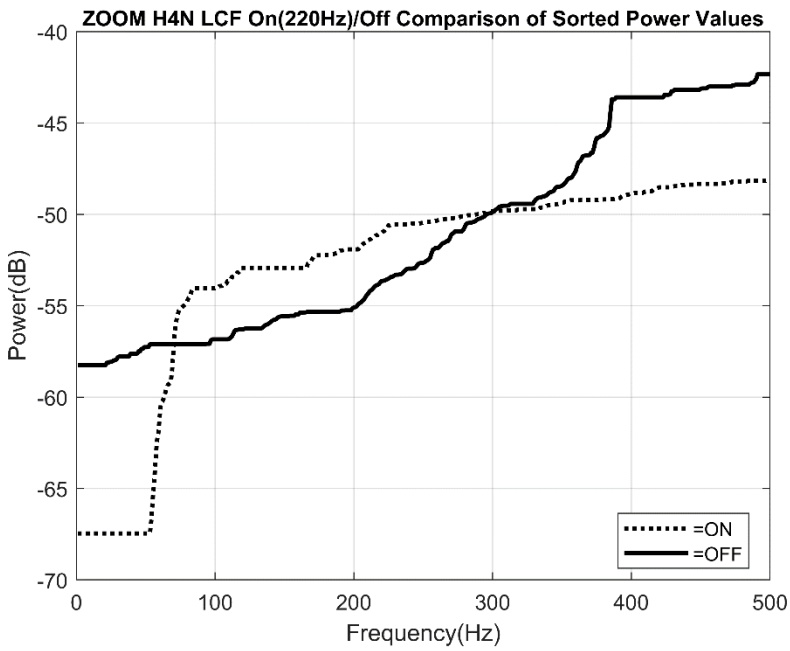

Figure 38 – Zoom H4N 220Hz LCF On/Off Comparison

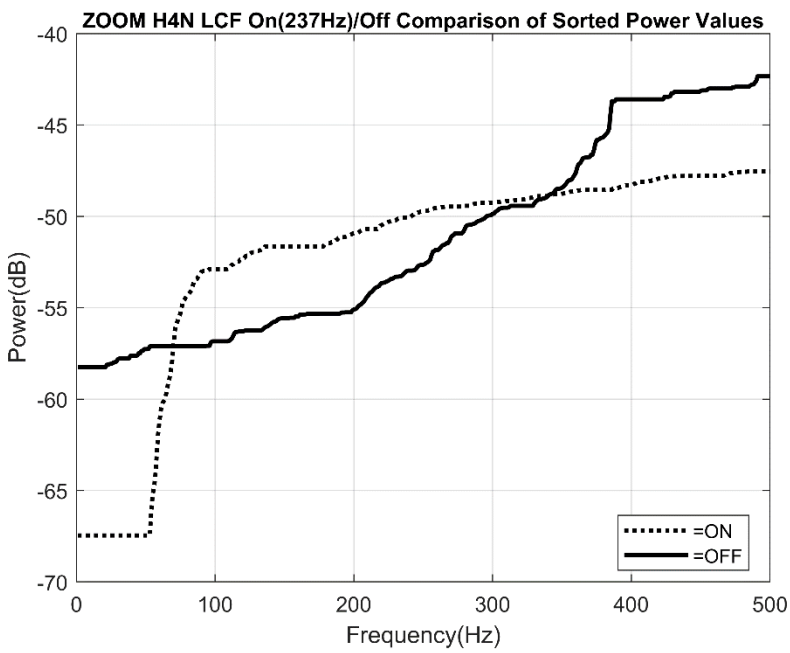

Figure 39 – Zoom H4N 237Hz LCF On/Off Comparison

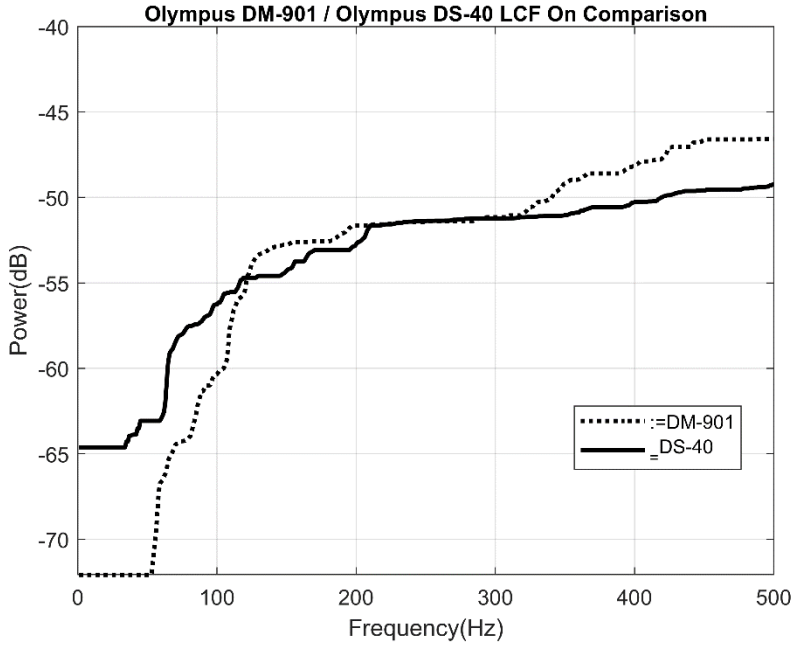

Figure 40 – Olympus DM-901 vs Olympus DS-40 - LCF On

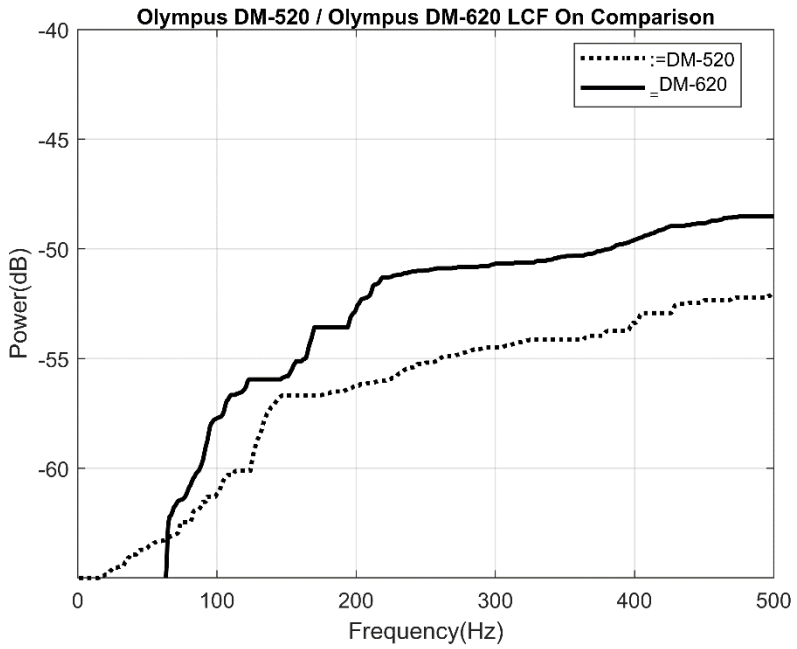

Figure 41 – Olympus DM-520 vs Olympus DM-620 - LCF On

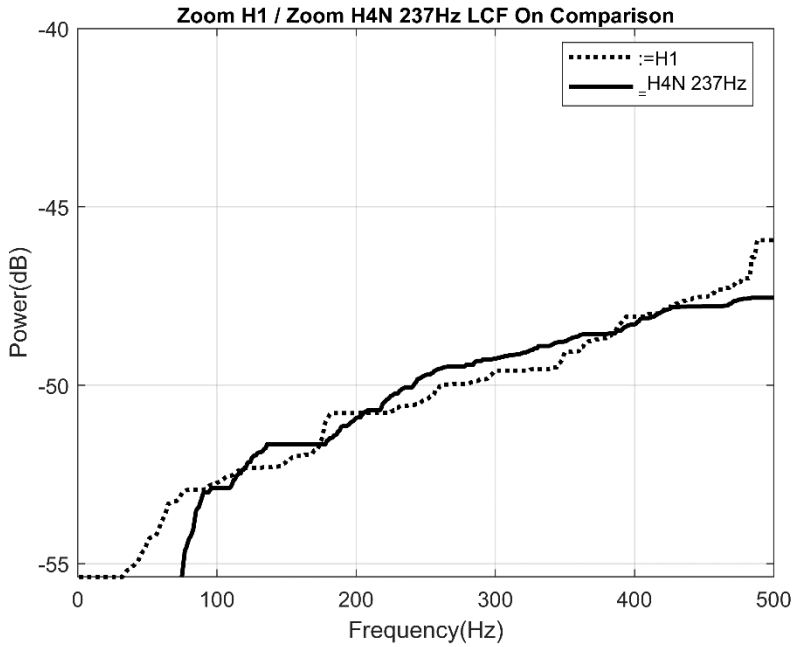

Figure 42 – Zoom H1 vs Zoom H4N 237 - LCF On

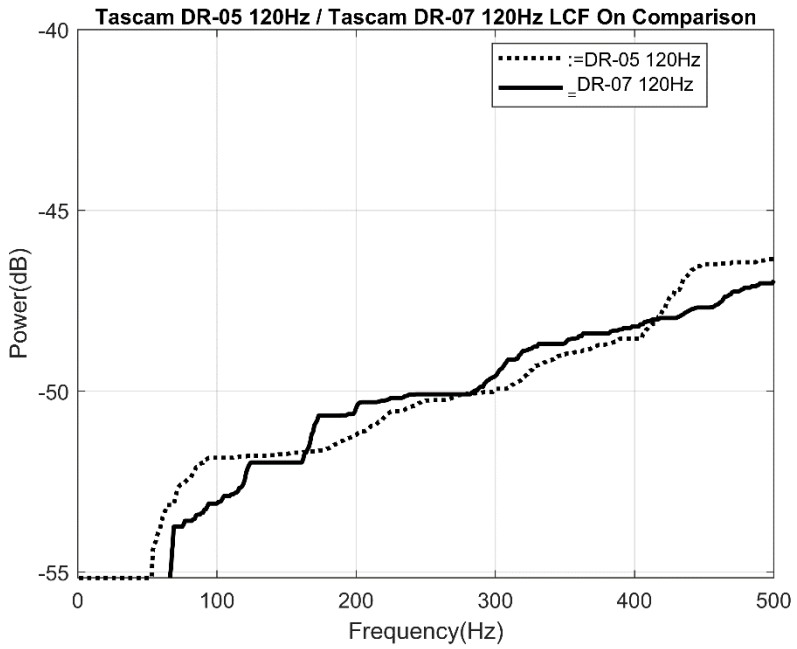

Figure 43 – Tascam DR-05 120Hz vs Tascam DR07 120Hz - LCF On

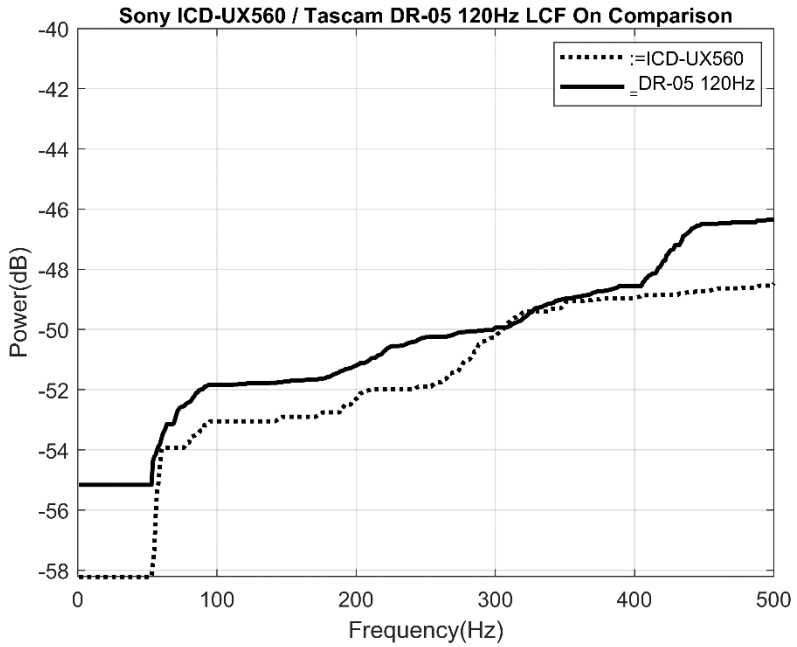

Figure 44 – Sony ICD-UX560 vs Tascam DR-05 120Hz - LCF On

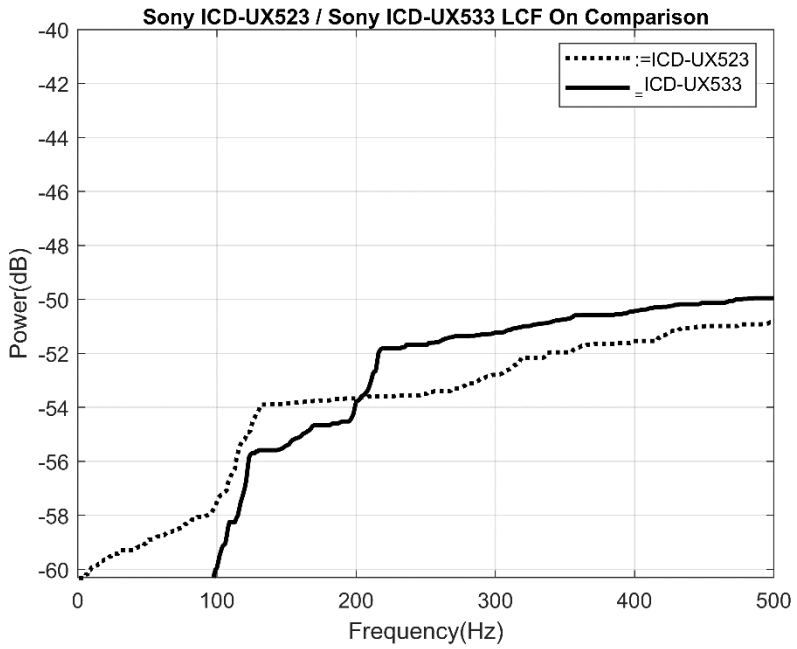

Figure 45 – Sony ICD-UX523 vs Sony ICD-UX533 - LCF On

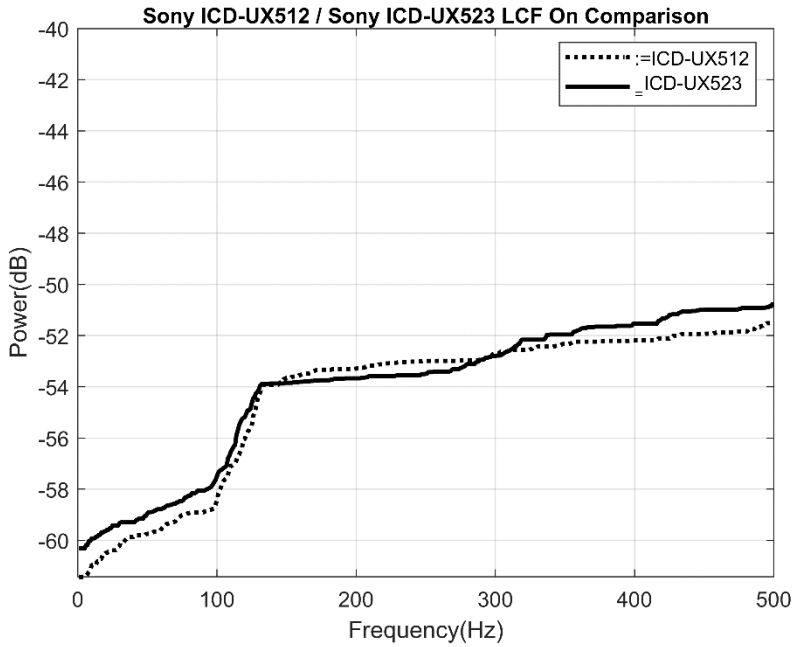

Figure 46 – Sony ICD-UX512 vs Sony ICD-UX523 - LCF On

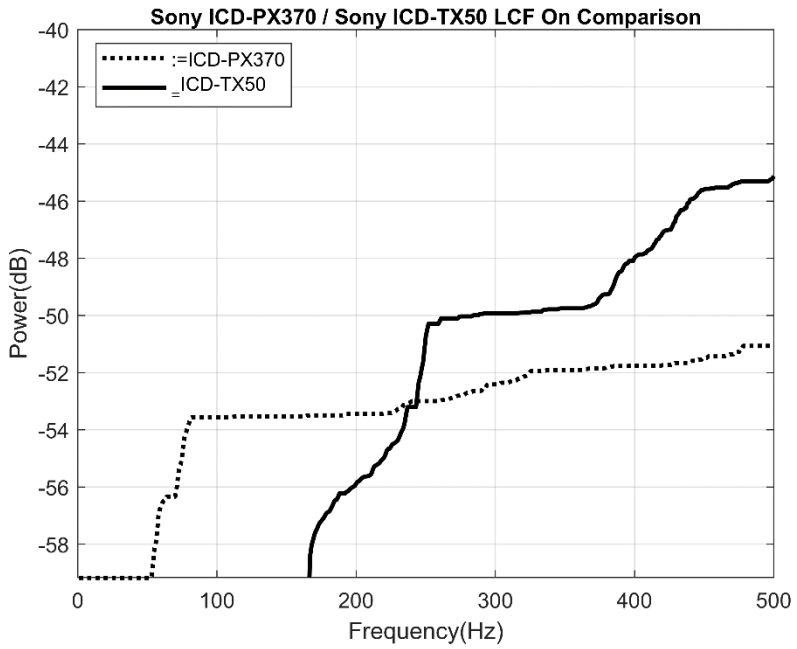

Figure 47 – Sony ICD-PX370 vs Sony ICD-TX50 - LCF On

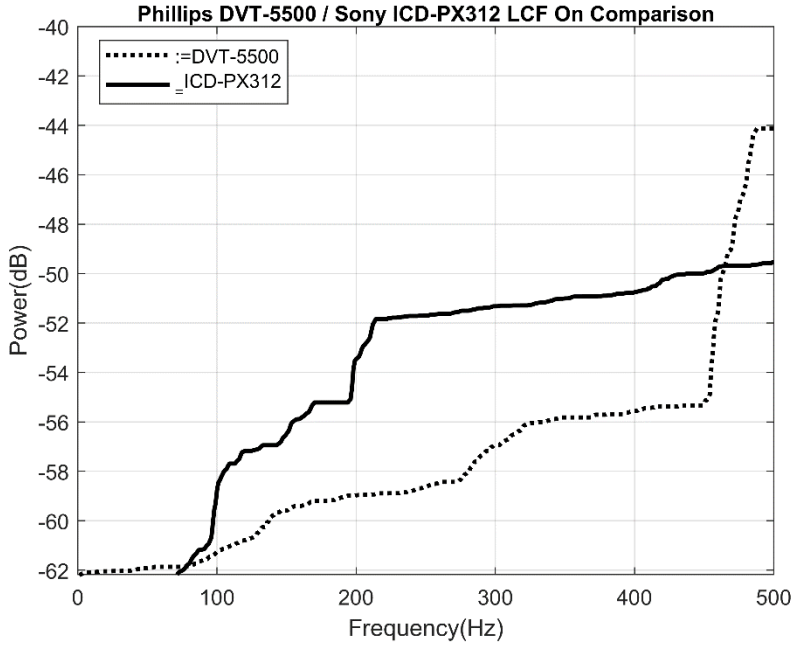

Figure 48 – Phillips DVT-5500 vs Sony ICD-PX312 - LCF On

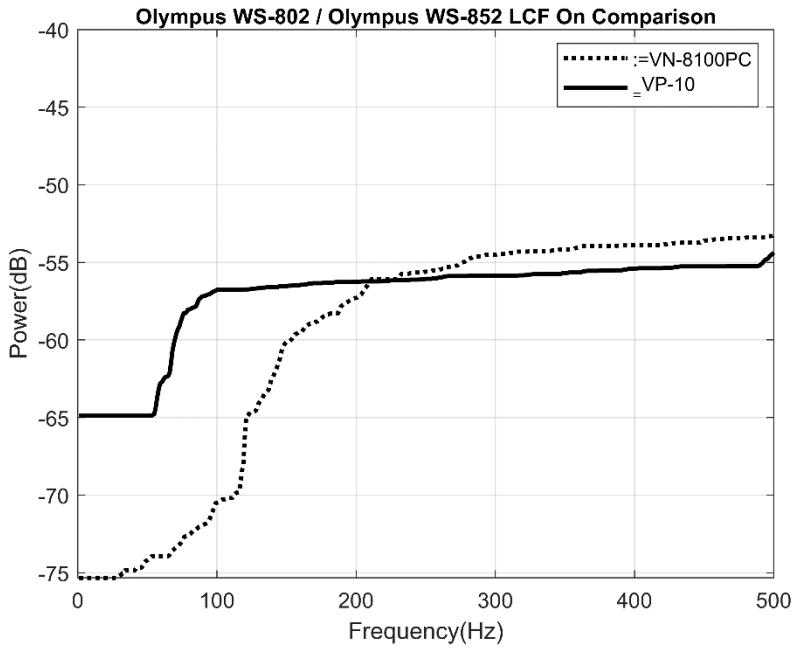

Figure 49 – Olympus WS-802 vs Olympus WS-852 - LCF On

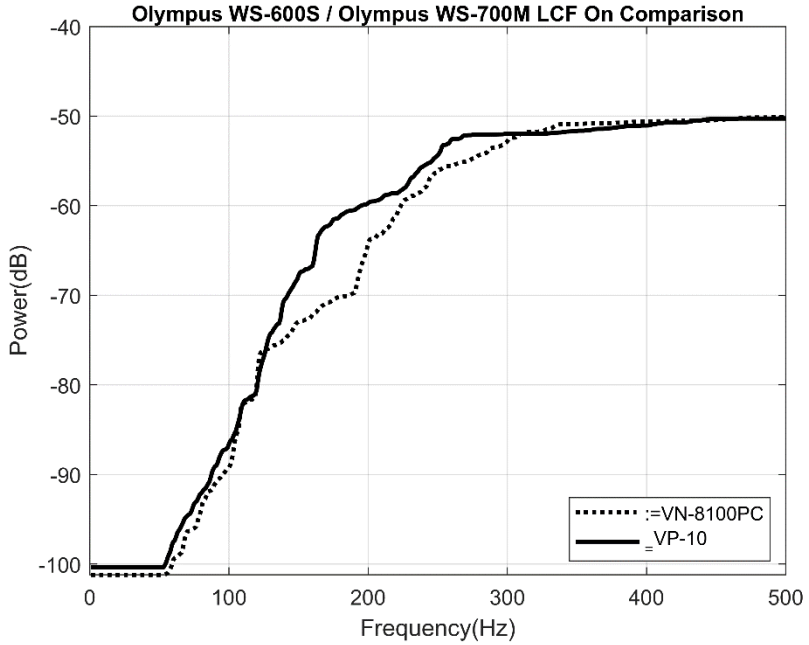

Figure 50 – Olympus WS-600S vs Olympus WS-700M - LCF On

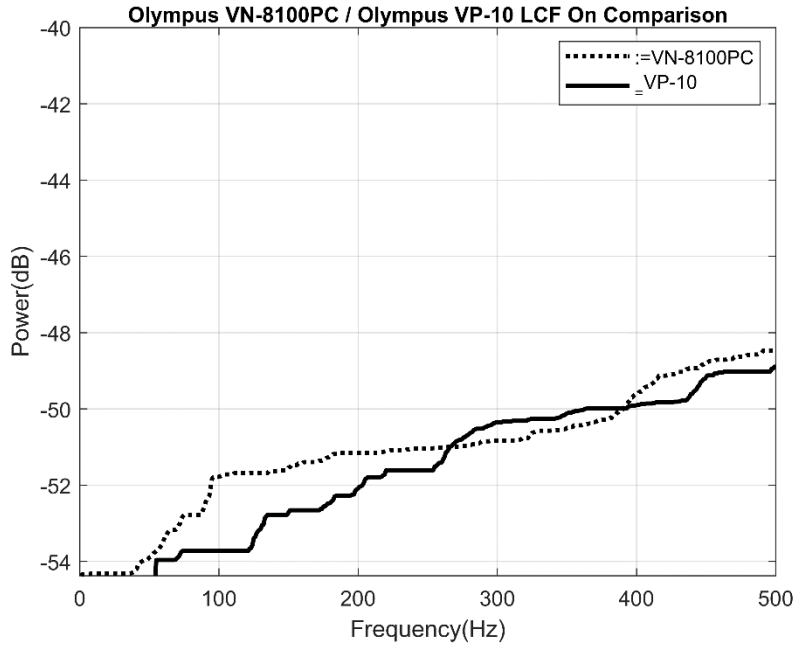

Figure 51 – Olympus VN-8100PC vs Olympus VP-10 - LCF On

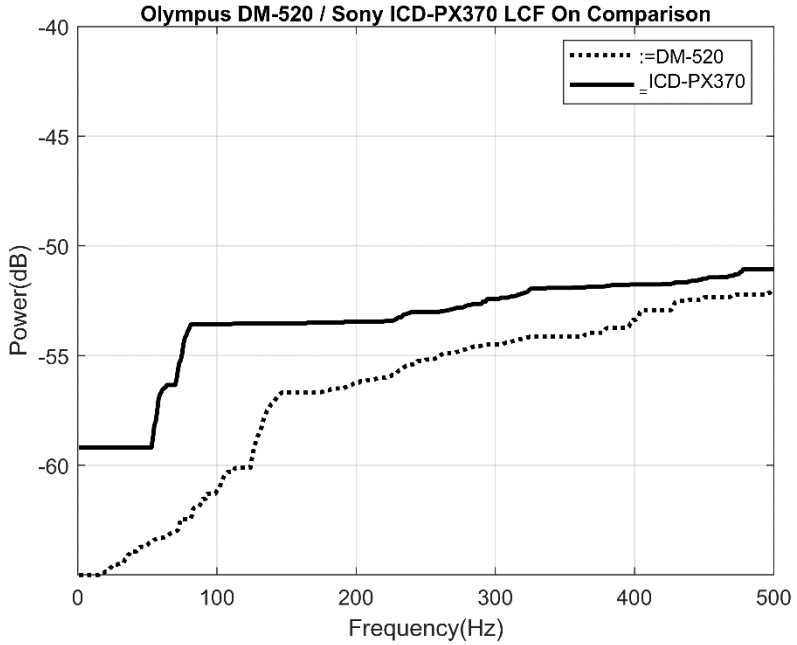

Figure 52 – Olympus DM-520 vs Sony ICD-PX370 - LCF On