At What Price Fidelity?

A Comparison of Transfer Quality in Audio Analog-to-Digital Converters

Caitlin Hammer / Video Preservation I / January 2, 2012

Archivists are often confronted with the difficult choice between expensive, high-end digitization equipment and more affordable equipment of dubious quality. This tension is amplified by the fact that the allocation of funds towards equipment is often carried out at the expense of collection maintenance and care. When facing this problem, archivists need strong data to support their decisions and ensure that they are making the best decisions for their collections. In short, they need to be able to identify the minimum level of quality (and expense) necessary to create a quality archival transfer. Nowhere is this conundrum more apparent than in the selection of analog-to-digital converters (ADCs). An essential element of the reformatting workflow, ADCs vary in the price and quality from $20 converters meant for home use to professional versions costing as much as several thousands of dollars. While the minimum acceptable quality of the ADC will depend on the type of content and purposes of transfer, any ADC used in an archival setting should be as transparent as possible. This experiment tests the impact of the quality of the ADC upon the converted signal by evaluating a professional converter (the Benchmark ADC1, retail price $1800) and a prosumer version (M-Audio FireWire Solo, $150) which is intended for home recording but would likely be attractive to archivists because of its low price and claims of quality.

Evaluating Audio Analog-to-Digital Converters

While there are many components in the chain of an archival transfer, all of which have a bearing upon the resultant recording, the ADC is the most crucial factor in determining fidelity.[1] In a perfect world, the converter would not leave any footprint on the signal as it was transferred from analog to digital; however, all ADCs introduce some element of quantization error resulting from the difference between the analog and digital signals. ADC performance can be evaluated using both static and dynamic factors. Common dynamic measurements include the signal-to-noise-and-distortion ratio (SINAD), effective number of bits (ENOB), signal-to-noise ratio (SNR), total harmonic distortion (THD), total harmonic distortion plus noise (THD+N), and spurious free dynamic range (SFDR).[2] The static accuracy of an ADC can be measured by the occurrence of three major categories of errors: offset errors, gain errors, and integral nonlinearity. Of these three, integral nonlinearity is the most difficult to correct. Although most commercial ADC manufacturers do not include static measurements in published converter specifications, they can have a direct impact upon dynamic factors, and should thus be included in any evaluation of an ADC.[3]

The table below offers a summary comparison of the differences between the two converters tested in this experiment. While not all dynamic measurements were readily available, the difference in quality is already apparent from the disparities in dynamic range, THD+N, and SNR. While the Benchmark ADC1 has the capability to sample at 192kHz, all recordings for this experiment were recorded at 96 kHz, thus the sample rate has no bearing on the results. Another important factor to note is that the M-Audio

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[1] Bradley, Kevin, ed. "IASA TC-04 Second Edition. Guidelines on the Production and Preservation of Digital Audio Objects." Section 2.4.3

[2] Kester, Walt. "Tutorial MT-003: Understand SINAD, ENOB, SNR, THD, THD + N, and SFDR so You Don't Get Lost in the Noise Floor"

[3] Kester, Walt. "Testing Data Converters"

FireWire Solo uses an unbalanced ¼" input cable while the Benchmark ADC1 uses a balanced XLR. This will significantly impact the findings of this experiment by making it impossible to determine how much noise is being introduced by the connector and how much is being generated by the ADC. For complete specifications for both models, see Appendix A.

ADC1 and FireWire Solo Specification Comparison

	M-Audio FireWire Solo	Benchmark ADC1 USB
Price	$150	$1800
Target Market	Home Audio	Professional Audio
Input	¼" Unbalanced	XLR
Output	FireWire	USB / BNC / XLR, Toslink
Sample Rate	96kHz	192kHz
Bit Depth	24-bit	24-bit
THD	Not published	Not published
THD+N 1kHz @ -1 dBFS	-84dB (0.0061%)	-101dB (0.00089%)
Dynamic Range	102 dB @ 48kHz A-weighted	> 120 dB A-weighted
SNR	-107 dB @ 48 kHz (a-weighted)	121dB @ 0dBFS and 108 @Max gain
ENOB	Not published	Not published
SINAD	Not published	Not published
SFDR	Not published	Not published

Methodology

This experiment attempted to recreate the conditions of a typical in-house archival transfer. The analog signal was generated from ¼ inch open reel audio played back on a Studer 807 reproducer. The analog signal was then run through an RSXa audio switcher and Coleman Audio MS2 active monitor switcher with VU meters via balanced connections. Input from the monitor to the ADC was determined by input interfaces available on each switcher. In the case of the Benchmark ACD1, input was via XLR; the M-Audio FireWire Solo (ADC2) was connected via ¼" unbalanced cable. Output too was determined by ADC specifications: the digital signal from the ADC1 was fed into a desktop PC running WaveLab by a USB connection while ADC2 was connected by FireWire. Due to technical difficulties, some of the test recordings were captured directly onto a laptop running WaveLab using the same connections. All samples were captured as 96kHz / 24-bit WAV files.

The experiment was designed to test the performance of ADCs based on factors relevant their signal-to-noise ratio (SNR) and dynamic range. Of the six dynamic measurements of ADC performance, SNR and dynamic range are the most immediately apparent, easiest to calculate, and the most widely understood. In order to test these factors, two test recordings were made for each ADC, one at normal levels (-10dBFS) and one at extremely low levels (-40dBFS). The purpose of these tests was to monitor how each converter handles the signal in different dynamic ranges. This design also reflects the

IASA TC-04 recommendations for testing frequency response for 96kHZ recordings be measured differently for different output levels (± 0.1 dB for the range 20Hz to 20 kHz, and ± 0.3 dB for the range 20 kHz to 40 kHz).[4]

In order to assure consistency within the experiment and isolate the introduction of noise, a commercially manufactured test tone tape with tones at 1kHz, 10kHz, and 50Hz was used as the analog audio source. Inconsistencies at the head of the test tape made the first fifteen seconds unsuitable for use in this experiment, so samples analyzed here start about fifteen seconds after the beginning of the first tone and run until the end of the recording. Likewise, inconsistencies in the execution of the experiment resulted in each recording starting at a slightly different time, but all samples used are roughly three minutes long and include all three of the test tones.

Before initiating the experiment, the playback heads and transport were cleaned, the output from the Studer was calibrated, and finally the azimuth was adjusted to assure optimum transfer. Steps of testing for Test 1 and Test 2 are detailed below. As the table demonstrates, every effort was made to replicate the same testing conditions in Tests 1 and 2; the only variable is the output level from the analog reproducer.

Procedure for Tests 1 and 2

Step #	Test 1: Regular Output Levels	Test 2: Low Output Levels
1	Calibrated output to -10 dBFS @ 1khz tone	Calibrated output to -40 dBFS @ 1khz tone
2	Recorded the entire test tape to 96kHz/24-bit WAV using WaveLab using Benchmark ADC1	Recorded the entire test tape to 96kHz/24-bit WAV using WaveLab using Benchmark ADC1
3	Repeated using M-Audio FireWire Solo	Repeated using M-Audio FireWire Solo
4	Preliminary monitoring and analysis Using WaveLab	Preliminary monitoring and analysis Using WaveLab
5	Performed signal analysis performed using Audacity	Performed signal analysis performed using Audacity
6	Subjective hearing test using MacBook and Logitech speakers	Subjective hearing test using MacBook and Logitech speakers

Results and Analysis

Since all transfers were created from the same master test tape, this analysis compensated for the slight differences in the length and timing of the captured recordings by identifying the tone change from 1kHz to 10kHz (which remains constant) and assigning all test points in relation to that point. Also important to note here is the, due to the inconsistencies between left and right channels of the original tape, all visual and spectrogram analyses refer only to the top (left) channel.

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[4] Bradley, Section 2.4.1.3

Selection of Sampling Points for Samples 1, 2, and 3

Test Point	Location Relative to 1st Tone Change	Tone	Time stamp ADC1_10	Time Stamp ADC1_40	Time Stamp Firewire_10	Time Stamp Firewire_40
Tone Change	0:00	n/a	0:24	0:48	0:24	0:43
1	- 0:10	1kHz	0:14	0:38	0:14	0:33
2	0:30	10kHz	0:54	1:18	0:54	1:13
3	1:35	50Hz	1:59	2:23	1:59	2:18

Once identified, the waveform of each test point was analyzed visually, then the sample was analyzed using Audacity 1.3.13 beta on a MacBook Pro running OSX 10.7.2. Finally, samples were played back on both internal MacBook speakers and external Logitech X-230 speakers with a frequency response of 40Hz ~ 20kHz and a signal to noise ratio of >96dB.

Visual Analysis

At first glance, the waveforms of these samples reveal obvious differences, the most apparent of which is in how the two converters record silence. The two signals below were captured at the end of the -40dBFS recordings. Note that a significant amount of noise is present in the FireWire Solo signal, even when there is no information coming in from the reproducer.

Silence Recorded by ADC1 and FireWire at -40dBFS
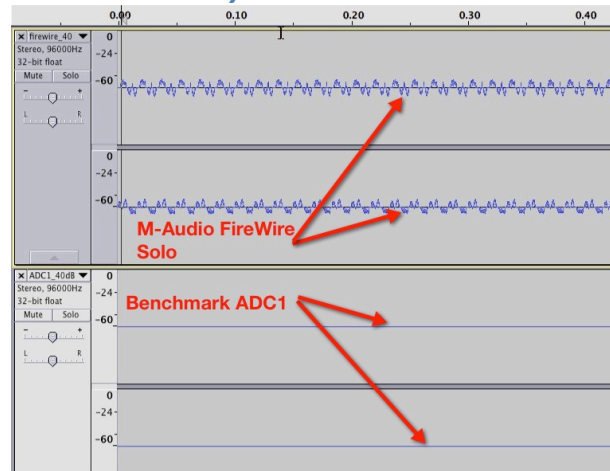
Another immediate observation was the apparent differences in phase between the output of the ADC1 and FireWire Solo at -40dBFS. While at -10dBFS, the waveforms seem to be in phase, a comparison of the recordings at -10dBFS show a subtle shift, indicating that one of the converters, most likely the FireWire Solo, is either interpreting frequency inconsistently or has slightly distorted the frequency throughout the recording.

*Phase Differences Between ADC1 and FireWire Solo at -10dBFS*
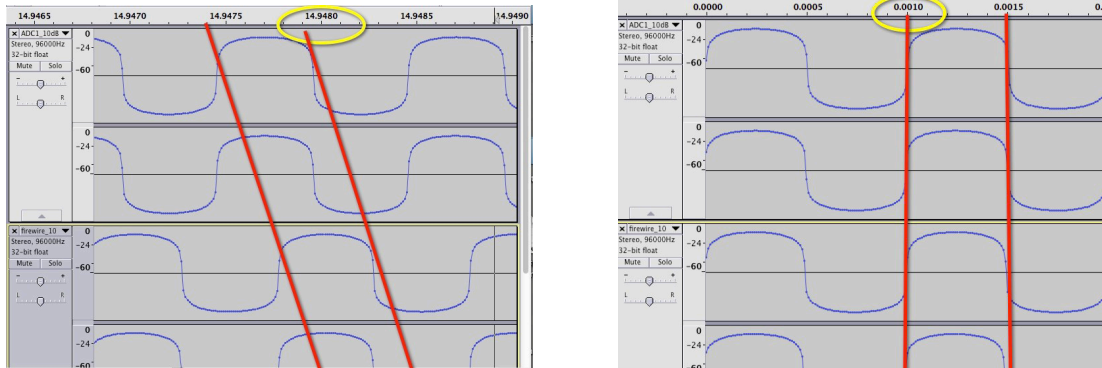
Visual analysis of individual sample waveforms did not prove particularly useful; however, comparisons of waveforms at points where the frequency of the analog signal changed yielded interesting results, particularly in the -10dBFS recordings (see below). The left channel (location of tone change – right channel lags by several cycles) shows a more defined shift from 1kHz to 10kHz in the ADC1 sample while the change demonstrated by the FireWire Solo waveform is more gradual. On a side note, note the distinctive shape of the waveform as it approaches the tone change in the right (bottom) channel. Both the ADC1 and FireWire Solo show the same pattern, but they are mirror images of each other.

Tone Change from 1kHz to 10kHz at -10dBFS
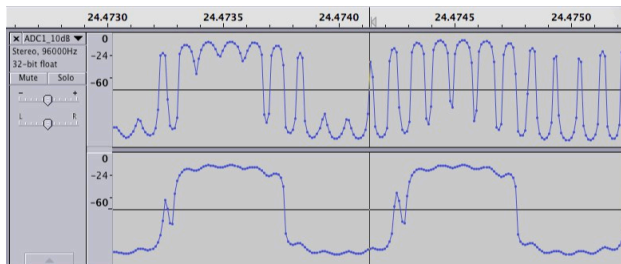
**ADC1**   **FireWire Solo**
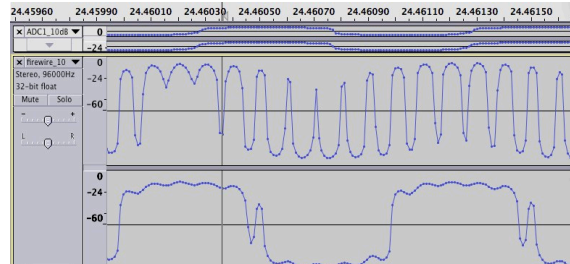
Spectrogram Analysis

Analysis of the spectrograms of samples 1, 2, and 3 revealed telling patterns in the introduction of noise. At 1kHz, there was little appreciable difference between output levels; there was, however, a significant amount of noise visible in the FireWire Solo -40dBFS sample at 16kHz, 20 kHz, and 31.5 kHz. Sample 2 showed slight noise at 20kHz in all samples and 30kHz in all but the FireWire -40dBFS sample, which showed noise at 31.5 kHz as well as just under 16kHz. This sample also shows a possible introduction of very low-frequency noise. Finally, sample 3 displayed similar result to sample 1: little appreciable difference except in the FireWire Solo -40dBFS sample, which again showed noise at just under 16kHz, 20kHz, and 31.5 kHz. These findings are also corroborated by a spectrogram of the two ADCs recording silence: while the ADC1 spectrogram is completely

blank, indicating the total absence of signal, the FireWire Solo spectrogram (below) shows noise similar to that found in sample 2. For complete spectrograms, see Appendix B.

FireWire Solo 0:00-0:01 (silence)
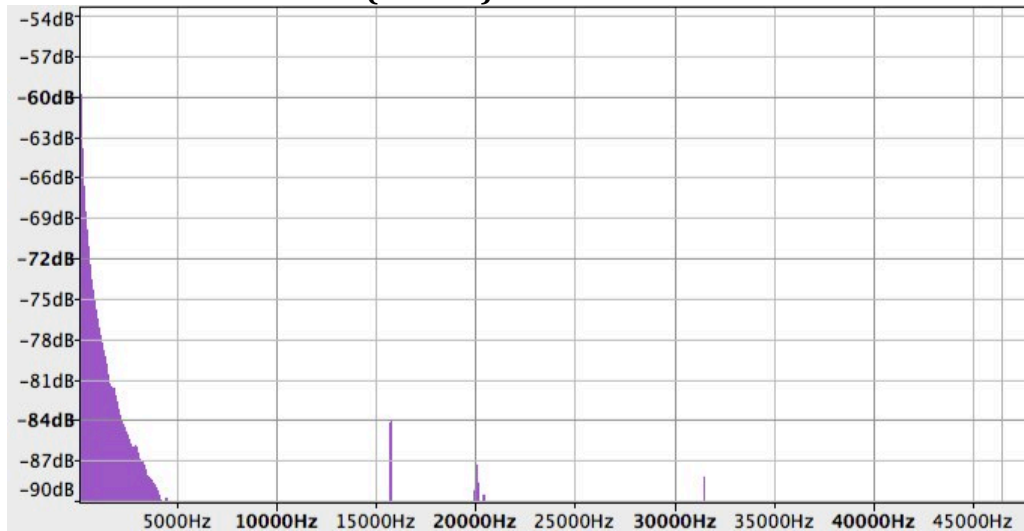
Subjective Listening Test

The listening test was carried out by selecting five-second excerpts at each sample point and pasting them together in succession within a separate 24-bit WAV file. A very small amount of time was left between excerpts, creating a barely audible "blip" to denote change between source samples. One-half second was left between each of the three sampling frequencies. The resulting file is embedded below.

Time	Source Sample
0:00-0:05	1kHz ADC1 @ -10dBFS
0:05-0:10	1kHz FireWire Solo @ -10dBFS
0:10-0:15	1kHz ADC1 @ -40dBFS
0:15-0:20	1kHz FireWire Solo @ -40dBFS
0:20.5- 0:25.5	10kHz ADC1 @ -10dBFS
0:25.5-0:30.5	10kHz FireWire Solo @ -10dBFS
0:30.5-0:35.5	10kHz ADC1 @ -40dBFS
0:35.5-0:40.5	10kHz FireWire Solo @ -40dBFS
0:41-0:46	50Hz ADC1 @ -10dBFS
0:46-0:51	50Hz FireWire Solo @ -10dBFS
0:51-0:56	50Hz ADC1 @ -40dBFS
0:56-1:01	50Hz FireWire Solo @ -40dBFS

Although different results might be obtained under more optimal listening conditions, I was not able to discern a difference between the ADC1 and the FireWire Solo at any of the sample levels.

Conclusions

These results indicate that, while the 20kHz noise common to all four recordings or sample 2 could be inherent to the tape, the noise at kHz, 20kHz, and 31.5 kHz that consistently visible in all samples from the FireWire Solo at -40dBFS is definitely being introduced by the ADC. One can also deduce that this noise is not a product of the unbalanced FireWire Solo input connection, since both the -10dBFS and -40 dBFS use the same connection and only the -40dBFS recording shows noise. Also, the amount of noise introduced to the signal seems to be directly proportional to the frequency of the analog signal. Finally, since the noise is introduced to the FireWire recording only when the input levels are very low, it is safe to say that this recorder does not perform well at low audio levels and should not be used for content requiring a large dynamic range. In fact, according to IASA TC-04, section 2.4, the FireWire Solo does not meet archival standards.

	IASA Recommendations	M-Audio FireWire Solo	Benchmark ADC1 USB
Sample Rate	32 kHz to 192 kHz +/- 5%.	96kHz	192kHz
THD+N 1kHz @ -1 dBFS	>-97 dB A-weighted	-84dB (0.0061%)	-101dB (0.00089%)
Dynamic Range	>117 dB A-weighted	102 dB @ 48kHz A-weighted	> 120 dB A-weighted

These results are not surprising given the FireWire Solo's narrower dynamic range. As the strength of the analog signal declines, the resulting digital signal runs the risk of getting lost in the noise floor of the converter.

Visual analysis of both samples and silence support these findings, as they show both noise and possible distortion of signal by the FireWire Solo at -10 dBFS that which was not immediately apparent in the spectrograms. The subjective listening test, however, did not reveal any discernible difference between these recordings, which means that, although the FireWire Solo did introduce noise into the signal, that noise was not detectable to the human ear.

Further Testing

These findings raise interesting questions for further research. While IASA's standards ensure the highest level of quality for archival transfers, the fact remains that the noise introduced by the FireWire Solo in this experiment was not audible. Might there be an acceptable level of error for archival some archival transfers with smaller dynamic range, such as spoken word? While such a suggestion might be anathema to the archival community, it deserves further exploration, especially since the inaudible difference in

quality between the ADCs tested in this experiment came at a savings of approximately $1,650. While spread over the extent of the collection being transferred, this is certainly not a large expense, creating a standard for "second-tier" class of ADCs might encourage those institutions that have limited funds to allocate to preservation to invest in a mid-quality ADC like the FireWire Solo instead of resorting to less expensive options.

However, further testing is needed to determine whether such a designation could be an option. First of all, a broader group of mid-range ADCs should be tested. It would be particularly instructive to test some that have balanced connectors to minimize noise. Also, in later stages of testing, more detailed experiments should be designed in order to test all six parameters of the impact of the ADC upon the signal, including THD, THD+N, SNR, ENOB, SINAD, SFDR. Finally, these tests should be replicated using a broad range of source material including various styles of music and spoken word. Although the impact of the FireWire's limited dynamic range was not audible when using test tones, it may become more apparent in the context of different kinds of sound.

Appendix A: Complete ADC Specifications

M-Audio FireWire Solo Specifications

http://www.m-audio.com/images/global/manuals/FWSolo_UG_EN01.pdf

Sample Rates
44.1, 48, 88.2, and 96 kHz

Line Inputs

Max Input
+2.2 dBV (1.3 Vrms)

Signal to Noise Ratio
-102 dB @ 48 kHz (a-weighted)

Dynamic Range
102 dB @ 48 kHz (a-weighted)

THD + N
0.0061% (-84 dB), 1 kHz, -1dBFS @ 48 kHz

Frequency Response
±0.2dB, 20 Hz to 20 kHz @ 48 kHz
±0.3 dB, 20 Hz to 40 kHz @ 96 kHz

Crosstalk
-116 dB, 1 kHz, channel-to-channel

Impedance
14kΩOhms

Microphone Input

Available Gain
40 dB

Input Range
-42 to -2 dBu (0.01 to 0.6 Vrms)

Signal to Noise Ratio (min gain)
-101 dB @ 48 kHz (a-weighted)

Dynamic Range (min gain)

101 dB @ 48 kHz (a-weighted)

THD+N (min gain
0.0049% (-86 dB), 1 kHz, -1dBFS @ 48 kHz

Frequency response (min gain)
±0.25 dB, 20 Hz to 20 kHz @ 48 kHz
±0.3 dB, 20 Hz to 40 kHz @ 96 kHz

Impedance
1.5kΩOhms

Instrument Input

Available Gain
40 dB

Input Range
 -28 to +12 dBV (0.04 to 4.0 Vrms)

Signal to Noise Ratio (min gain)
-101 dB @ 48kHz (a-weighted)

Dynamic Range (min gain)
101 dB @ 48kHz (a-weighted)

THD+N (min gain)
0.0079% (-82 dB), 1kHz, -1dBFS @ 48kHz

Frequency response (min gain)
 ±0.25dB, 20Hz to 20kHz @ 48kHz
±0.3 dB, 20Hz to 40kHz @ 96kHz

Impedance
270kΩOhms

Line Outputs

Max Output (balanced)
+10.2 dBu (2.5 Vrms)

Max Output (unbalanced)
+2.0 dBV (1.26 Vrms)

Signal to Noise Ratio
-107 dB @ 48 kHz (a-weighted)

Dynamic Range
107 dB @ 48 kHz (a-weighted)

THD + N
0.0024% (-92.5 dB), 1 kHz, -1dBFS @ 48 kHz

Frequency Response
 ±0.2dB, 20 Hz to 20 kHz @ 48 kHz
±0.3 dB, 20 Hz to 40 kHz @ 96 kHz

Crosstalk
-118 dB, 1 kHz, channel-to-channel

Impedance (balanced)
300ΩOhms

Impedance (unbalanced)
150ΩOhms

Headphone Outputs

Max Output
-2.0 dBV (0.8 Vrms) into 32Ω

Signal to Noise Ratio
 -106 dB @ 48 kHz (a-weighted)

Dynamic Range
105 dB @ 48 kHz (a-weighted)

Frequency Response
±0.2 dB, 20 Hz to 20 kHz @ 48 kHz
±0.3 dB, 20 Hz to 40 kHz @ 96 kHz

Crosstalk
-86 dB, 1 kHz, channel-to-channel

Output Impedance
75ΩOhms

Working Headphone Impedance
32 to 600ΩOhm

Benchmark ADC1 Specifications
http://www.benchmarkmedia.com/sites/default/files/documents/adc1_spec_sheet.pdf

Microphone Preamps
Number of Inputs (balanced)
2

Connector
Gold-Pin Neutrik™ female XLR

Impedance
200 k Ω

Sensitivity
-14dBu to +29 dBu (at 0 dBFS)

Direct Outputs

Format
Auto-detect AES/EBU, Word Clock, and
Super Clock (256x)

Impedance
75 Ω

Sensitivity
150 mV AES
200 mV Word Clock
750 mV Super Clock

Transformer Coupled
Yes

DC Blocking Capacitors
Yes

Transient and Over-Voltage Protection
Yes

Jitter Attenuation Method
Benchmark UltraLock™

Wordclock Reference Output

Impedance
75 Ω

Level
5 Vpp
2.5 Vpp into 75 Ω

Transformer Coupled
No

DC Blocking Capacitors
No

Transient and Over-Voltage Protection
Yes

Group Delay (Latency)

Delay (Analog Input to Digital Output)
1.20 ms at 44.1 kHz
1.09 ms at 48 kHz
0.75 ms at 88.2 kHz
0.67 ms at 96 kHz
0.63 ms at 176.4 kHz
0.59 ms at 192 kHz

Digital Audio Outputs

Number of Digital Outputs
1 XLR Main
1 TOSLINK Main
1 BNC Main
1 BNC Aux

Connectors
Gold-Pin Neutrik™ male XLR

Number of Audio Channels
2

Main Output Word Length
24 bits

Main Output Sample Frequencies
44.1, 48, 88.2, 176.4, or 192 kHz

Aux Output Word Length
16 or 24 bits

Impedance
110 Ω XLR
75 Ω BNC

Level
4 Vpp into 100 Ω XLR
1 Vpp into 75 Ω BNC

Transformer Coupled
Yes

DC Blocking Capacitors
Yes

Transient and Over-Voltage Protection
Yes

Audio Performance

SNR - A-Weighted, 0 dBFS = +8 to +29 dBu
121 dB

SNR - Unweighted, 0 dBFS = +8 to +29 dBu
119 dB

SNR - A-Weighted at max gain,
0 dBFS = -14 dBu
108 dB

THD+N, 1 kHz at -1 dBFS
-102 dBFS, -101 dB, 0.00089%

THD+N, 1 kHz at -3 dBFS
-107 dBFS, -104 dB, 0.00063%

THD+N, 1 kHz at -3 dBFS
-106 dBFS, -103 dB, 0.00071%

Frequency Response at 192 kHz Sample Rate
-3 dB, +0 dB, 2 Hz to 92 kHz
+/- 0.01 dB, 20 Hz to 20 kHz

-0.06 dB at 10 Hz
-0.01 dB at 20 Hz
-0.00 dB at 20 kHz
-0.18 dB at 88 kHz
-3 dB at 92 kHz
-100 dB at 108 kHz

Frequency Response at 96 kHz Sample Rate
-3 dB, +0 dB, 1 Hz to 46 kHz
+/- 0.01 dB, 20 Hz to 20 kHz
-0.06 dB at 10 Hz -0.01 dB at 20 Hz
-0.00 dB at 20 kHz -0.10 dB at 44 kHz
-3 dB at 46 kHz -108 dB at 54 kHz

Frequency Response at 48 kHz Sample Rate
3 dB, +0 dB, 1 Hz to 23 kHz
+/- 0.01 dB, 20 Hz to 20 kHz
-0.06 dB at 10 Hz
-0.01 dB at 20 Hz
-0.00 dB at 20 kHz
-0.10 dB at 22 kHz
-3 dB at 23 kHz
-110 dB at 27 kHz

Passband Ripple
+/- 0.008 dB

Crosstalk
-105 dB at 20 kHz
-130 dB at 1 kHz
-200 dB at 20 Hz

Jitter Tolerance (With no Measurable Change in Performance)
>12.75 UI sine, 100 Hz to 10 kHz
>3.5 UI sine at 20 kHz
>1.2 UI sine at 40 kHz
>0.4 UI sine at 80 kHz
>0.29 UI sine at 90 kHz
>0.25 UI sine above 160 kHz

Maximum Amplitude of Jitter Induced Sidebands
< -134 dB with
10 kHz 0 dBFS test tone
12.75 UI sinusoidal jitter at 1 kHz (measurement limit)

Maximum Amplitude of Spurious Tones with 0 dBFS test signal

-130 dBFS

Maximum Amplitude of Idle Tones
-145 dBFS

Maximum Amplitude of AC line related Hum & Noise
-130 dBFS

Interchannel Differential Phase (Stereo Pair)
+/- 0.5 degrees at 20 kHz

Interchannel Differential Phase (Between ADC1 Units)
+/- 0.5 degrees at 20 kHz

Maximum Lock Time after Fs change
< 1 s for frequency lock
< 5 s for phase lock

Mute on Sample Rate Change
Yes

Mute on Loss of External Clock
No

Mute on Lock Error
No

Mute on Receive Error
No

Soft Mute Ramp Up/Down Time
10 ms

Appendix B: Complete Spectrograms

Spectrograms: Sample 1
Sample 1.1: 1kHz tone / -10dBFS

ADC1
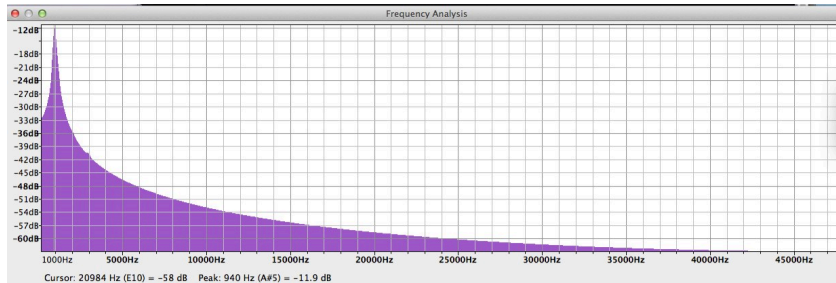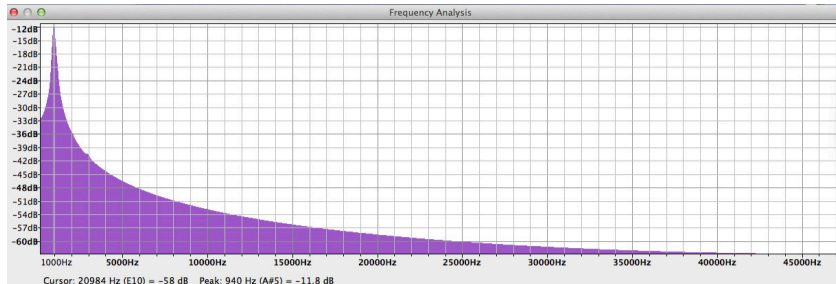
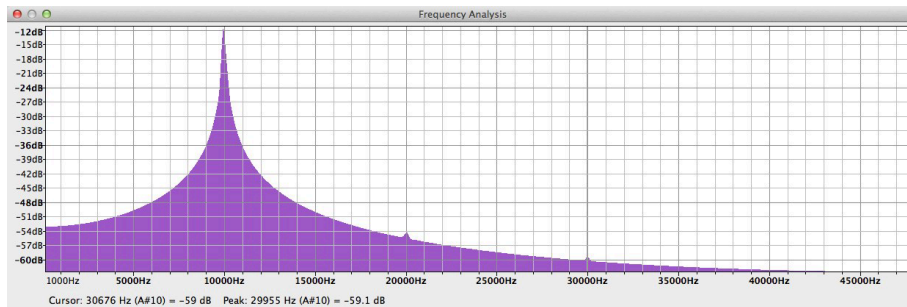### FireWire Solo

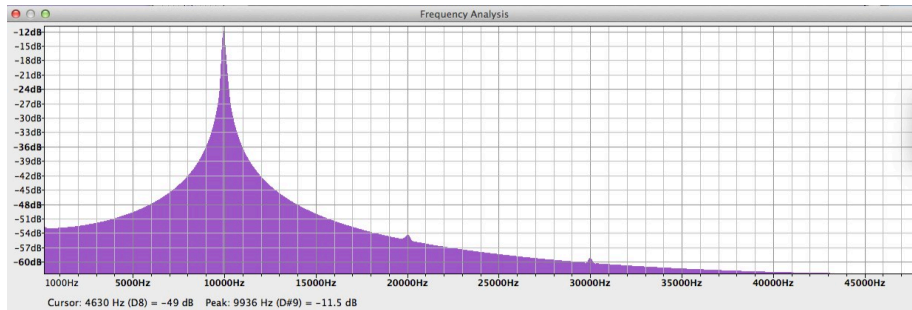## Sample 1.2: 1kHz tone / -40dBFS
ADC1
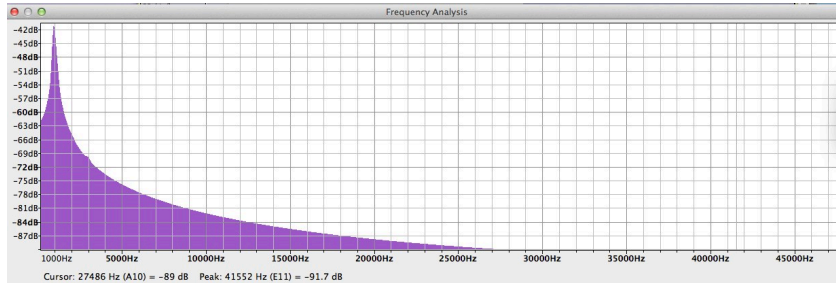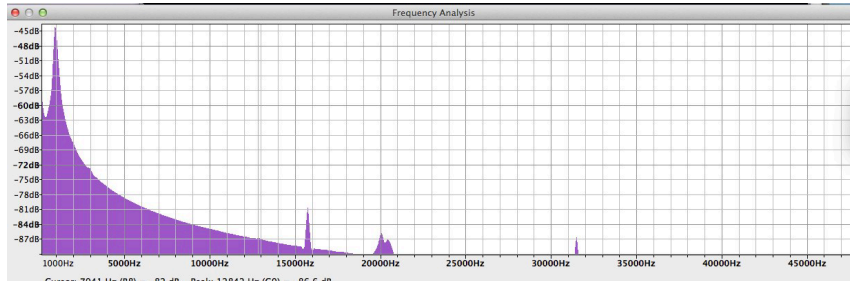
FireWire Solo

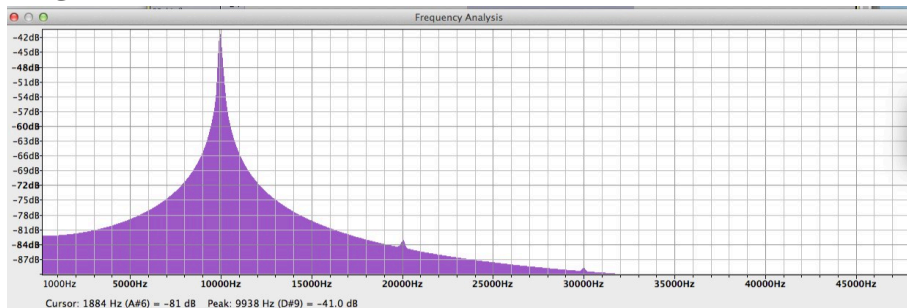## Spectrograms: Sample 2
Sample 2.1: 10kHz tone / -10dBFS
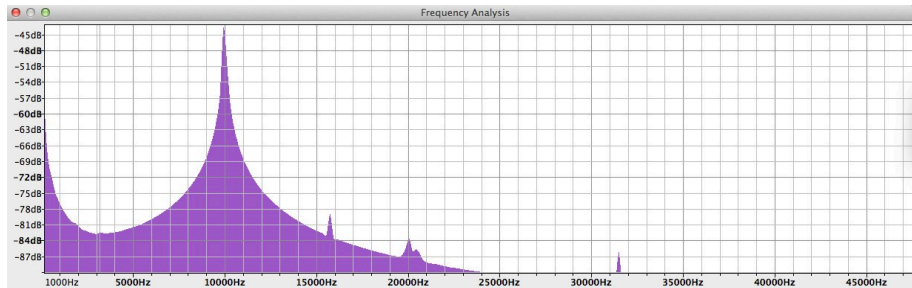### ADC1

FireWire Solo

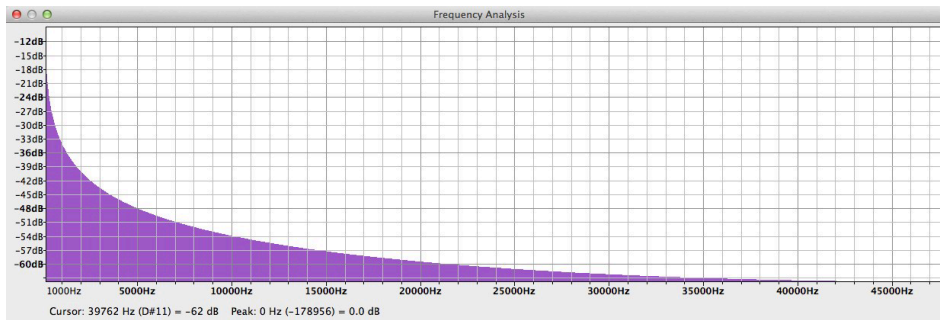### Sample 2.2: 10kHz tone / -40dBFS
ADC1

FireWire Solo

Spectrograms: Sample 3
Sample 3.1: 50Hz tone / -10dBFS
ADC1

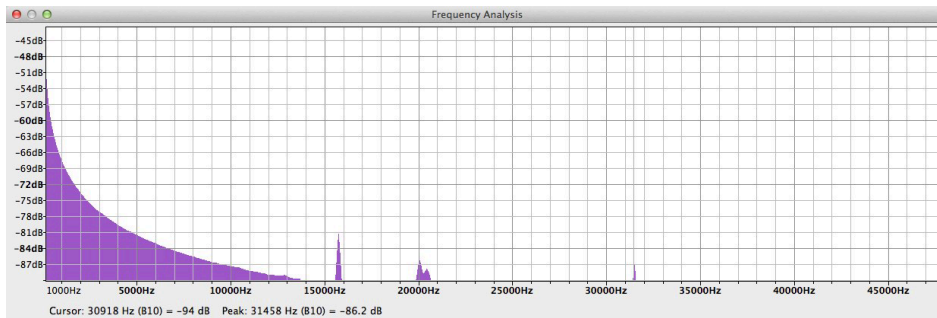Cursor: 39762 Hz (D#11) = −62 dB   Peak: 0 Hz (−178956) = 0.0 dB

FireWire Solo

Cursor: 41539 Hz (E11) = −62 dB   Peak: 38356 Hz (D11) = −63.1 dB
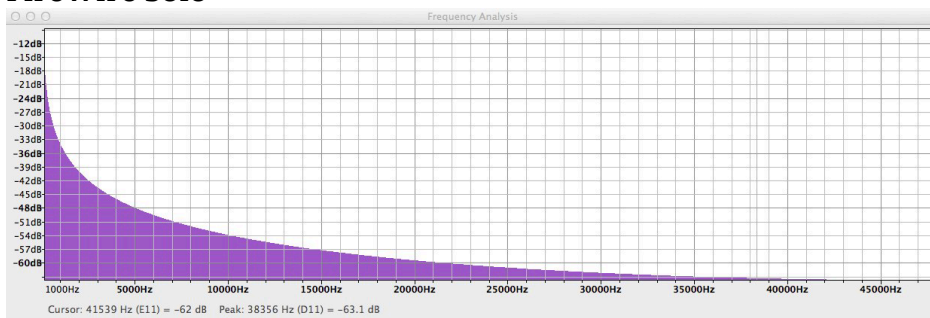
Sample 3.2: 50Hz tone / -40dBFS
ADC1

Cursor: 30918 Hz (B10) = −90 dB   Peak: 37419 Hz (D11) = −92.2 dB

FireWire Solo

Cursor: 30918 Hz (B10) = −94 dB   Peak: 31458 Hz (B10) = −86.2 dB
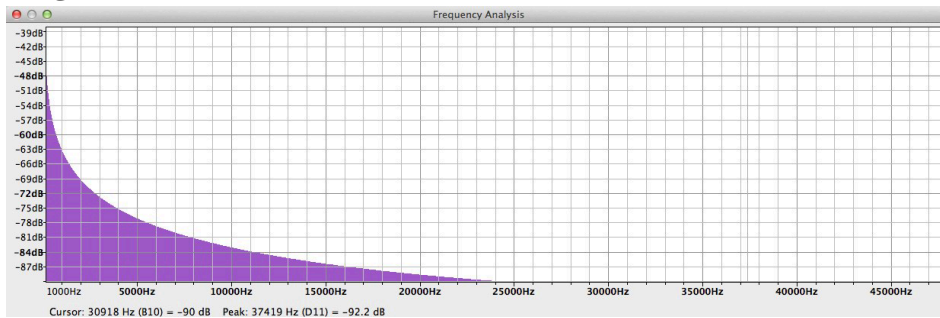
Appendix C: Resources for Audio ADC Measurement and Evaluation

ADC and DAC Glossary. Tutorial 641 on Maxim Innovation website. June 22,2002. Access December 31, 2011 at http://www.maxim-ic.com/app-notes/index.mvp/id/641/CMP/ELK-11

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