High Dynamic Range Audio

High Dynamic Range Audio is the next frontier in audio reproduction. Bel Canto is achieving dynamic range greater than 125dB using our new DAC architecture. Achieving high dynamic range in the audio playback system removes the errors that typically compromise the sonic quality and sense of realism that a playback system can achieve. This dynamic range needs to start from the Digital to Analog conversion in the playback system and flow through to the output of the Loudspeaker. If the critical first stage DAC in this process is compromised then nothing that follows will replace the lost and compromised signal. Indeed the source is most critical in a high dynamic range playback system.

The Wikipedia definition for Dynamic Range as applied to an audio system follows:

**Audio Dynamic Range**

Audio engineers often use dynamic range to describe the ratio of the amplitude of the loudest possible undistorted sine wave to the root mean square (rms) noise amplitude, say of a microphone or loudspeaker.

The dynamic range of human hearing is roughly 140 dB. The dynamic range of music as normally perceived in a concert hall doesn’t exceed 80 dB, and human speech is normally perceived over a range of about 40 dB.

The dynamic range differs from the ratio of the maximum to minimum amplitude a given device can record, as a properly dithered recording device can record signals well below the rms noise amplitude (noise floor).

For example, if the ceiling of a device is 5V (rms) and the noise floor is 10uV (rms) then the dynamic range is 500000:1, or 114 dB:

$$20 \times \log_{10} \left( \frac{5V}{10uV} \right) = 20 \times \log_{10}(500000) = 20 \times 5.7 = 114 \text{ dB}$$

In digital audio theory the dynamic range is limited by quantization error. The maximum achievable dynamic range for a digital audio system with $Q$-bit uniform quantization is calculated as the ratio of the largest sine-wave rms to rms noise is:

$$\text{DR}_{\text{ADC}} = 20 \times \log_{10} \left( \frac{2^Q}{1} \right) = (6.02 \cdot Q) \text{ dB}$$

The maximum achievable SNR, Signal-to-noise ratio, for a digital audio system with $Q$-bit uniform quantization is
The 16-bit Compact Disc has a theoretical dynamic range of about 96 dB (or about 98 dB for sinusoidal signals, per the formula). Digital audio with 20-bit digitization is theoretically capable of 120 dB dynamic range; similarly, 24-bit digital audio calculates to 144 dB dynamic range. All digital audio recording and playback chains include input and output converters and associated analog circuitry, significantly limiting practical dynamic range. Observed 16-bit digital audio dynamic range is about 90 dB.

Several interesting observations can be made from the information above:

1) While the theoretical maximum dynamic range for the human ear is up to 140 dB the perceived dynamic range of an orchestra in a concert hall environment is on the order of 80 dB. This 80 dB number represents the kind of dynamic range we wish to achieve in our replay environment, this is after taking into account all factors that limit dynamic range.

2) Modern DAC and ADC technology using 24 bit technology can achieve over 120 dB dynamic range for the Analog to Digital Converter (ADC) and nearly 130 dB for the Digital to Analog Converter (DAC) while the quantization noise floor is now 144dB below the maximum signal level.

3) Even 16 bit audio can encompass the 80 dB dynamic range requirement for playback of audio-however there are other considerations that require greater than 16 bit performance to insure the best playback of even 16 bit source material. These issues will be discussed in this paper.

Factors that limit Dynamic Range in a DAC based playback system:

1) DAC Analog Noise: The analog noise floor is the fundamental limit of dynamic range in a Digital to Analog converter. Modern DACs using multi-bit sigma-delta architectures can reduce quantization noise to levels well below the thermal noise floor of the analog electronics. The consequence of this is that the old concerns of quantization noise dominating the playback quality are gone. Careful design of the analog output electronics, including the Current to Voltage (I/V) converter stage and the output buffer stage are critical in determining the ultimate dynamic range of the DAC. Careful design using the best DAC devices, amplifiers and carefully chosen passive components like resistors can lead to a dynamic range exceeding 125 dB and even approaching 130 dB. The represents a noise level of 2.84microVolts RMS for a DAC with a 9Volt RMS output capability. A high quality audio preamplifier will have a noise floor of 3-10 times this or 10 to 20dB higher noise level.

2) Jitter: When operating at 125-130 dB dynamic range very low levels of jitter can become more and more audible. Clock jitter on the DAC clock will modulate with the original signal and cause very audible signal artifacts-It is absolutely necessary to reduce clock jitter to levels at or below 10 picoseconds RMS. This is not a simple task when you
realize that even running a clock through 1 Meter of cable can add significant jitter to a signal.

3) Power supply noise: Power supplies become even more critical as dynamic range capabilities increase. Power supply noise levels on par with the noise floor of the analog electronics become necessary to insure that all of the dynamic range is realized without external noise and signal artifacts.

4) Out of Band noise: High frequency noise created by the DAC process must be effectively filtered in the playback system to insure that no modulation of the audio band signals occurs. This would also limit the effective dynamic range of the playback.

Bel Canto has designed its DACs to insure that dynamic range is optimized. We address each of the issues above-resulting in the highest dynamic range DAC product line.

1) Analog Stages: We use low noise, high speed amplifier devices for each critical analog stage. The current to voltage amplifier operates as a single-ended device with high slew rate, fast settling time and low noise and distortion. This insures that the DAC operates to its full potential. We also use audio grade resistors and capacitors in this critical amplification stage. The output stage also uses high speed low noise devices. The DAC and analog output section operate in a balanced differential mode, the output device is a fully balanced amplifier with extremely low noise and distortion levels. All of our analog output stages are biased in Class A operation for optimum distortion and thermal modulation performance.

2) Jitter: We employ a state of the art digital Phase Lock Loop architecture coupled with an Asynchronous Sample Rate Converter to filter clock jitter from any of the incoming digital audio data. This works in tandem with our ultra-low jitter clock sited locally near the DAC circuit to provide an extremely low jitter environment for the DAC. See appendix A for measured results.

3) Power Supply Noise is dealt with by our new Virtual Battery Supply. See Appendix C.

4) We deal with out of band noise in the DAC process by running the DAC at the highest rate possible, 192 KHz, and using a high performance linear phase, slow roll-off digital filter. This optimizes both the time domain and the frequency domain performance of the filter and only requires a simple analog filter in the analog output stage to insure that out of band signals do not compromise the dynamic range performance.

5) 24 Bit digital level control: To insure that the full dynamic range potential of our DAC technology is used we provide a 24 bit dithered volume control. This is the most transparent means to control the volume level of the signal—-even the best analog preamplifiers will compromise the dynamic range potential of our DAC—-adding layers of noise and distortion that will effect the perceived signal quality. Because quantization noise of the dithered 24 bit DAC is no longer a subjective quality issue the best means to control level is through the digital word—-indeed—-this insures that the entire analog system is minimally stressed—-with just enough analog voltage level generated as needed for the desired playback level issues such as distortion and signal to noise are now optimum in the entire playback chain.
Advantages of a Bel Canto High Dynamic Range DAC:

1) Bel Canto DAC technology achieves >125dB dynamic range, the DAC now becomes the lowest noise signal source, quieter than the best analog preamplifiers.

2) Bel Canto High Definition Volume control in the 24 bit domain is essentially transparent, neither adding nor subtracting from the original signal. The dithered 24\textsuperscript{th} bit is 10-15 dB below the noise floor of the extremely low, analog noise floor of our DAC electronics.

3) Bel Canto 24/192 A/D converters have arguably less sonic signature than a 1Meter analog interconnect.

4) Bel Canto jitter filtration methods remove jitter as an error source. All digital inputs now sound equally pure and dynamic without audible jitter signature.

5) Bel Canto ultra-low jitter clocks render the conversion to and from analog extremely pure.

6) Bel Canto Virtual Battery Technology isolates the converters from power line noise and insures low impedance power delivery to and isolation of the analog and digital electronics for best dynamic range and definition.

7) Bel Canto’s Class A analog electronics maintain ultra-low noise and distortion.

When all of these elements work in concert, with the high dynamic range conversion occurring in an environment isolated from outside jitter and noise sources, the result is sonic purity that captures the original musical intent to such a high degree that discussions of Analog VS Digital are rendered moot-what remains IS the musical experience.

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Appendix A

DAC3.1 Jitter Test Results

The following graphs indicate the level of jitter rejection that our jitter filtration delivers under measured conditions using the well known Miller Test. Figure 1 shows the results of this test at the Analog Output of the new DAC3.1. Figure 2 is a digital to digital result with no jitter or analog noise floor in the measurement. The difference between the theoretically perfect Figure 2 graph and the DAC3.1 result in Figure 1, is the analog noise floor at -150dBFS on the DAC3.1.

There are no jitter components present in the DAC3.1 analog output, the side spurs are virtually identical in level and shape to the theoretical and there is only a very slight spreading of the fundamental near the analog noise floor to indicate very slight low frequency clock noise or other 1/f noise source in the analog output. There are no indications of any clock jitter. This test was done from a Mac computer source driving the USB Link with ST LightLink output through 50 feet of ST-glass fiber cable.

Figure 1. Miller Test Results for DAC3.1 driven from USB to Lightlink Converter, 16/44.1 test signal through 15 meters of fiber cable.
The high dynamic range of our new DAC architecture requires effective jitter filtration to insure that the full potential of these new circuits is experienced in all playback conditions. Extensive digital-digital testing of the jitter filter and subjective evaluation on a high dynamic range playback system has confirmed that even high jitter sources can be played back with no audible jitter errors compromising the sonic performance.
Appendix B. High Dynamic Range Computer Audio

These are exciting times of change in the music world. With CD sales dropping and downloaded MP3 music, streamed music and digital music players taking over there is no consensus for what the future will look like. It could make an audiophile and music lover despair. However, along with all of the change there are positive forces emerging in the market. Numerous sources of High Definition digital audio downloads have emerged on the WEB, great music mastered in high definition audio ranging from traditional CD rates of 16 bits at 44.1 KHz ranging up to 24 bits at 192 KHz are available with several rates in between.

The question at this juncture is not will the computer be used for high performance audio playback but how to get the best from this new music source. I have used the iMac in our main audio system to play back my CD library, download and play high definition music, DVD-A discs, DVD movies, stream radio from around the world, watch streamed television and even play back original live recordings at 24/96. The iMac in my system has over the past 3 years become at least as important as any other source of music, CD player or Turntable and is used daily. This primer will explain an approach that has proven to work well and to provide pointers on what to look for in a quality audio playback system based on a computer.

High Dynamic Range Playback of Digital Audio

Most of the issues relating to quality digital audio playback are essentially the same for playback of traditional media such as the CD, SACD or DVD. There are, however, several important differences that will be discussed.

1) Which Computer to Use?

I will primarily focus on the Mac as a preferred platform to store, access and play back quality audio. Some may find this limiting, although given the fact that a Mac Mini can be had for around $600 it seems short sighted to not consider this route, given the advantages over the relative mine-field that awaits the PC/Windows user. I personally have had an iMac feeding my audio system and have had no issues related to operation. It is quiet, reliable, I know what to expect when I use it. Indeed it is as reliable an audio source as any CD player or turntable that I have used in the past 30+ years.

2) Ripping your CDs

This is easily done- with the Mac systems the quality of the drives and integration of the software and hardware makes ripping music from your CDs into the computer a transparent and reliably efficient operation. Just set the Options within iTunes to insure error correction in ripping of the CDs and the system takes care of the rest. Even damaged CDs that may skip on a very good CD player will be corrected and ripped into the computers hard drive quickly. I would recommend using Apple Lossless to rip your CDs as this does indeed result in a Bit Perfect playback and saves nearly 50% on space. However, given the ever decreasing cost of hard drive space you could save the data in a
completely uncompressed format if you wish. With adequate playback hardware to address issues of jitter there is no audible difference in these storage formats. Just be sure to choose and USE a good method for backing up your music library-a RAID type hard drive setup or some other method should be used for backing your library up. Again-the latest Mac operating system has some very useful software to address backups.

**Digital Links for Audio Playback**

There are several digital links available from the computer to your audio DAC:

In each case the critical issues to pay attention to are:

1) **Bit Errors**
   a. Bit errors are discussed often but are really not a major concern in digital audio playback—uncorrected errors occur rarely and when they are not corrected they are accompanied by silence or clicks and pops—quite obvious, if they occur you will know it. Using the correction algorithms within iTunes when ripping my CDs I have found digital errors to be a non-issue, even with CDs that would not play back clean on my CD player.

2) **Jitter**
   a. Jitter is a very critical issue that must be addressed with any audio DAC—no matter if the source is a computer, a CD/SACD player or a DVD player. Any digital link can easily impose levels of jitter that are easily heard in a high dynamic range playback system. At Bel Canto we address jitter right in the DAC with a robust jitter filter that attenuates the jitter components starting below 10 Hz, has jitter rejection of 80 dB (10,000 times reduction) by 100 Hz and filtration increases even more at higher frequencies. With this filter we can insure jitter free audio playback from all digital sources.

3) **Galvanic Isolation**
   a. Galvanic isolation is when the power and grounds between two components are isolated. This is critical for connecting to a computer as the power and ground system are not clean, first of all, and the ground loops that can occur when connecting a computer to an audio system can create noise levels that severely compromise the dynamic range potential of the system. We engineer galvanic isolation into all digital inputs on our high dynamic range DACs and deem this to be essential for quality playback.

**USB-Universal Serial Bus:**

USB is a reliable link to get audio date from the computer. It is being used more and more because it works reliably and simply. There are several methods for implementing a USB link. While some claim that superior jitter performance can be had using an Asynchronous method where the critical DAC clock is located on the DAC side of the link
Asynchronous design is a good approach for jitter but it does leave open other critical issues such as galvanic isolation as discussed above. The USB interface in our high dynamic range DAC products has galvanic isolation built in to insure optimum performance under all system conditions and our jitter filtration insures optimum jitter performance at the DAC clock for USB as well as all of the other digital inputs.

**Issues related to the USB interface:**

1. Bandwidth limits using current USB 1.1 links limits operation to 24/96 audio streaming
2. No inherent galvanic isolation built in to USB links.
3. Maximum wire length of 14.8 feet sets a limit on where you can site your computer. I have used a USB 1.1 compatible optical extender from Opticis to get around this limitation. Bel canto is demonstrating a USB to SPsIF link that uses glass ST optical fiber for the SPsIF transmission that both provides galvanic isolation and allows running 100s of meters of small diameter, rugged optical cable.
4. Future USB links will use USB 2.0 technology. Today Mac computers support USB 2.0 operation for multiple 24/192 digital streams!
5. Software compatibility: Bel Canto USB links are compatible with the native software drivers in both Mac and PC computers and are therefore transparent to use. They also can achieve bit perfect playback on both Mac and PC platforms.

**Firewire:**

This link has been used for pro audio applications for many years and is well proven. It is typically more expensive than USB but can work well—it has not been as popular for home audio computer playback but certainly can perform well in this application. Galvanic isolation can be achieved within the Firewire standard but it must be designed into the link. There are no real limits to bandwidth for audio streaming with Firewire. Jitter filtration still needs to be designed into the DAC system and Firewire has similar limitation on maximum wire length as USB—about 15 feet.

**SPDIF and TOSLINK:**

Mac computers and some PCs have built in SPDIF or TOSLINK interfaces. These function much like the same outputs on a CD player. The Mac TOSLINK can operate at up to 24/96 data rates and with our jitter filter can provide excellent performance—also TOSLINK cables can run to over 20 feet and provide galvanic isolation. Beware that with DACs that do not provide adequate jitter filtration there will be a noticeable reduction in dynamic range using TOSLINK. If you are using a desktop, tower PC or Mac computer you can also consider aftermarket professional
SPDIF SPI bus cards—these are complex to use and require software installation and can be expensive, especially for the pro level products. However they can work very well and the pro level software can insure bit perfect playback.

**Ethernet:**

Ethernet can provide very good performance but it is early days for this interface to stream audio—there is a new standard emerging called Ethernet AVB that promises to be an excellent option in the future. It will provide galvanic isolation, low jitter and long cable runs. So keep an eye out for this in the future.

**Wireless:**

This is an exciting future option also. Today I have used the Apple Airport Express with a TOSLINK output to get excellent performance with our new jitter filtration method, note that without the jitter filtration of our new products the performance of the Airport Express is marginal. Also, Airport Express is limited to 16/44.1 data rates so it is not compatible with the new 24/88.2 high definition downloads.

The bottom line when connecting to the computer is that any of the above options can work well if used with an audio DAC that filters any incoming jitter. We have chosen to support USB for interfacing to the computer although our SPDIF, TOSLINK and AES inputs also support other options for streaming from the computer.

**Bit Perfect Playback**

Perhaps the biggest potential quality trap related to computer playback is related to the fact that the processing power of the computer allows the original digital data to be modified, either through volume control, equalization or, sample rate conversion. The built in software in either the Windows or Mac operating systems is not designed for the highest quality performance. It is best to set up and use your computer so that the original data is not modified before being transmitted to the audio DAC. To insure the best playback steps need to be taken to insure that the computer is not modifying the original data. This can be done easily on the Mac/iTunes platform, while the PC can achieve Bit Perfect playback it is rather more complex given the vagaries of Windows and the many different software options available on the PC platform.

This first step in bit perfect playback is to insure that the system volume control is at maximum. The Bel Canto USB Link disables the system volume and EQ controls when it connects to the computer’s operating system so this eliminates this problem. Within iTunes or Windows Media make sure that the volume control is set to maximum, you do not want the computer changing volume level on the 16 bit words that make up the original CD data—this will absolutely degrade the sound. Let the Bel Canto DAC do this on the 24 bit word with correct dither, insuring a transparent volume control.
Finally make sure to disable any ‘sound enhancement’ settings within iTunes or any other playback software.

**Sample Rate Conversion**

Both PC and Mac can play back the original sample rate of the digital file, however the system can alter the sample rate depending on the Midi setting on the Mac, and depending on numerous factors on different PC/Windows setups. In any case, when the computer performs sample rate conversion the software adds noise and distortion to the signal, causing a softening of the sound and loss of timbre accuracy and dynamic realism. Within iTunes on the Mac playback can be managed to insure that the built in software Sample Rate Converter does not turn you audio into mush. Just use the smart playlist application to group your library into same sample rate groups and use the MIDI controller software in the System settings to insure that the Mac is feeding the correct sample rate to the DAC. You may also want to monitor sample rate on the DAC to insure that you are getting what you expect. With the MIDI application on the Mac you can insure the correct sample rate playback. The operation is not as transparent on the PC and you will need to watch your DAC display more carefully.
Appendix C. The Power Supply and High Dynamic Range Audio

Virtual Battery Supply Technology

Offering low noise, high current and isolation from the AC Line supply, the battery is often seen as an absolute reference power source for sensitive audio circuitry. Bel Canto revisits this ideal power source with our Virtual Battery Supply (VBS) technology. Combining low noise switching technology, multiple stages of isolation, filtration and regulation, the VBS1 provides a highly stable, isolated and low noise base for our precision digital and analog audio circuitry. The VBS1 with internal VB board is designed to provide this ideal power source for all signal sources and control electronics in the Bel Canto e.One line.

Technical Approach

Our first VBS was based on a traditional 50/60 Hz transformer and linear regulation scheme with abundant local LC filtration and energy storage. Our experiments proved that while providing excellent overall performance it still did not approximate the noise levels that a quality battery could provide. It also suffered from the typical inefficiencies of a linear regulation scheme, especially when required to operate over the AC power line voltage variations, interference and noise encountered in real world operation. We decided to explore alternative technologies that gave us higher inherent efficiency and more control over the specific performance of the power supply.

Switch Mode Power Supplies

The Switch Mode Power Supply (SMPS) provides great levels of efficiency, over 90%, great control over specific operating parameters of the supply design and potentially greater levels of isolation and lower audio band noise. Their weakness is in the high frequency noise generated. This weakness was addressed in the design of the VBS1 and it became obvious that it is much more effective to filter high frequency noise than to attempt filtration of low frequency noise.

Later prototypes approached the problem by using a quality SMPS to generate 12Volts DC from the incoming AC line voltage. We included extensive input filtration, low noise rectification and high energy storage prior to the SMPS. This is followed by a massive bank of LC filtration using compound inductors, parallel electrolytic capacitors and final stage polypropylene capacitors to insure hundreds of amperes of peak current capability and low noise across a wide frequency spectrum. There is nearly ½ of a FARAD of total capacitance (500,000 microfarads) and over 100 Joules of energy storage in the VBS1.
Spectrum analysis of this design from the low audio frequencies to well beyond the audio frequency band revealed a noise floor within a few decibels of the spectrum analyzer noise floor. This represented a 10X to 100X reduction of the noise floor of the traditional linear approach. This reduction in noise was particularly evident in the lower region of the audio frequency band, the critical midrange where the ear is most sensitive. Over the 20 kHz audio band the unweighted noise of the VBS1 is only 6μVrms. This is lower than the output noise from the best analog preamplifiers. We found that this extremely low level of noise coupled with low impedance, transient current delivery provides absolute sonic advantages in a high dynamic range DAC front end.

Isolation/Filtration

Perhaps the only area where a battery is potentially superior is in the isolation from power line noise. However, this isolation is not a given. The only time that a battery is ‘totally’ isolated is if it is not being charged, even then there is likely to be some kind of charger circuitry in the supply that is connected to the wall outlet, and its isolation may be quite poor. Also when a battery is NOT being charged it is in discharge mode and the voltage, noise and regulation is constantly changing as it discharges. In the VBS1 we have several advantages that we apply to insure a VERY high degree of isolation.

LC filtration provides over 100 dB (100,000 times filtration) isolation starting below 100 Hz, and on top of this the very small power transformer in the SMPS happens to provide several advantages over the traditional line frequency transformer, much less copper and much less parasitic capacitance, both of these factors provide better performance and better isolation for the transformer, especially at low frequencies.

We have confirmed this isolation by performing listening tests with the VBS1 where you literally UNPLUG the VBS1 from the wall and listen for any change in the audio performance-there is no change-nor is there much, if any, sensitivity to the specific type of power cord used to drive the VBS1, providing further proof of the quality of isolation from AC power born noise. The VBS1 is acting like a local low noise power station for your front end electronics-rendering many power filters, regenerators and such unnecessary or even counter productive.

Internal VB board

The 12VDC provided by the VBS1 supply needs to be further acted upon to deliver the needed supply voltages for the internal digital and analog sections of the e.One equipment. This necessitated further technology development. We designed the new VB board that converts the ultra-isolated, ultra-low noise 12V supplied by the VBS1 to the needed voltages for the digital and critical analog power stages of the e.One equipment. Our approach uses a tiny SMPS to optimally generate the voltage for the
digital sections an SMPS transformer isolated, ultra-low noise symmetrical supply for the critical analog audio section. The noise floor of the analog power supply now is close to that of the audio circuitry that it is driving! With our new VB board the VBS1 is complete.

The sum total of the VBS1 is an obvious increase in resolution from all audio sources. What was most surprising was the great increase in how NATURAL the images and sounds are within the larger, deeper soundstage when the VBS is used to power the front end electronics. With the VBS1 you have the best of both worlds as the increase in resolution and detail are accompanied with an even more naturally beautiful sound quality. As if this weren’t enough, the system efficiency is higher, with the Dac3V with the VBS using only 7 watts of power instead of 12-14 watts for the Dac3 and its traditional linear supply.