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High Dynamic Range Digital Audio Playback

High dynamic range digital audio is the next frontier in audio reproduction. Achieving it means removing the many errors that typically compromise accuracy and thus the sense of realism that enthusiasts desire. High dynamic range starts with the power supply, then the digital-to-analog conversion, and continues right through to the speakers' output. If the DAC is flawed then nothing that follows can replace the lost and compromised signal. In fact the source is the most critical element in a high dynamic range playback system.

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

Audio

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.[2] 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.[3]

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:

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

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:[4]

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

The maximum achievable SNR Signal-to-noise ratio for a digital audio system with *Q*-bit uniform quantization is

$$\mathrm{SNR_{ADC}} = (1.76 + 6.02 \cdot Q)\ \ \mathrm{dB}$$

The 16-bit Compact Disc has a theoretical dynamic range of about 96 dB[5] (or about 98 dB for sinusoidal signals, per the formula[4]). 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.[2] 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.[5]

Dynamic range in analog audio is the difference between low-level thermal noise in the electronic circuitry and high-level signal saturation resulting in increased distortion and, if pushed higher, clipping.[2] Multiple noise processes determine the noise floor of a system. Noise can be picked up from microphone self-noise, preamp noise, wiring and interconnection noise, media noise, etc. Early 78 rpm phonograph discs had a dynamic range of up to 40 dB,[6] soon reduced to 30 dB and worse due to wear from repeated play. German magnetic tape in 1941 was reported to have had a dynamic range of 60 dB,[7] though modern day restoration experts of such tapes note 45-50 dB as the observed dynamic range.[8] Ampex tape recorders in the 1950s achieved 60 dB in practical usage,[7] though tape formulations such as Scotch 111 boasted 68 dB dynamic range.[9] In the 1960s, improvements in tape formulation processes resulted in 7 dB greater range,[9] and Ray Dolby developed the Dolby A-Type noise reduction system that increased low- and mid-frequency dynamic range on magnetic tape by 10 dB, and high-frequency by 15 dB, using companding (compression and expansion) of four frequency bands.[10] The peak of professional analog magnetic recording tape technology reached 90 dB dynamic range in the midband frequencies at 3% distortion, or about 80 dB in practical broadband applications.[9] The Dolby SR noise reduction system gave a 20 dB further increased range resulting in 110 dB in the midband frequencies at 3% distortion.[11] Compact Cassette tape performance ranges from 50 to 56 dB depending on tape formulation, with Metal Type IV tapes giving the greatest dynamic range, and systems such as XDR, dbx and Dolby noise reduction system increasing it further. Specialized bias and record head improvements by Nakamichi and Tandberg combined with Dolby C noise reduction yielded 72 dB dynamic range for the cassette. Vinyl microgroove phonograph records typically yield 55-65 dB, though the first play of the higher-fidelity outer rings can achieve a dynamic range of 70 dB.[12] The rugged elements of moving-coil microphones can have a dynamic range of up to 140 dB (at increased distortion), while condenser microphones are limited by the overloading of their associated electronic circuitry.[2] Practical considerations of acceptable distortion levels in microphones combined with typical practices in a recording studio result in a useful operating range of 125 dB.[13]

In 1981, researchers at Ampex determined that a dynamic range of 118 dB on a dithered digital audio stream was necessary for subjective noise-free playback of music in quiet listening environments.[14]

Several interesting observations from the information above:

1) While the theoretical maximum dynamic range for the human ear is up to 140dB the perceived dynamic range of an orchestra in a concert hall environment is on the order of 80dB which represents the dynamic range we wish to achieve in our replay environment after taking into account all factors that limit dynamic range.
2) Modern DAC and ADC technology using 24-bit technology can achieve over 120dB dynamic range for the Analog-to-Digital Converter (ADC) and nearly 130dB 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 encompasses the 80dB dynamic range requirement for playback of audio, but there are other considerations requiring greater than 16-bit performance for the best playback of even 16-bit source material. These issues are covered later 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 D-to-A 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. Consequently the old concerns of quantization noise dominating playback 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 such as resistors can lead to dynamic range exceeding 125dB and approaching 130dB. 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 125-130dB dynamic range very low levels of jitter are more audible. Jitter on the DAC clock modulates the signal and causes audible signal artifacts. It's a given that clock jitter must be reduced to levels at or below

10 picoseconds RMS. This isn't a simple task as running a clock through even 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 analog electronics is required to insure full dynamic range without external noise and signal artifacts.
4) Out of Band noise: High frequency noise created by the DAC process itself must be effectively filtered to insure no modulation of the audio signals occurs which would also limit the effective dynamic range.

Bel Canto addresses each of the issues above resulting in superb, low-noise and dynamic playback.

1) Analog Stages: We use the low noise, high speed amplifier devices for each critical analog stage. The I/V converter is 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 uses high-speed low-noise devices. The DAC and analog output section operate in a fully balanced differential mode, and the output device is a fully balanced amplifier with extremely low noise and distortion levels. All of our analog output stages are biased into 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 placed near the DAC circuit to provide an extremely low jitter environment for the DAC. The jitter filter starts attenuating at 10Hz, filtering jitter components by more than 80dB by 100Hz and increasing beyond that frequency.
3) Power Supply Noise is effectively dealt with by our new Virtual Battery Supply technology. The VBS1 generates a highly-isolated low-noise voltage supply with less than 6uV RMS noise over the audio band. This is lower noise than an analog preamplifier's output. It forms the foundation of all the internal supplies used in the DAC and insures that power supply-related audio signal modulation is minimized. The effective isolation of the incoming AC power insures that the audio signal is optimized no matter the quality of the AC power. Remarkably the power supply filtration offered by our VBS1 provides more than 100dB of isolation and filtration starting well below 100 Hz.
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 make sure that no out-of-band signals compromise dynamic range.

5) 24-bit digital level control: Insuring full dynamic range performance we provide a 24-bit dithered volume control. It's the most transparent means to control the volume level of the signal as even the best analog preamplifiers compromise the dynamic range potential of our DAC, adding layers of noise and distortion you can hear. Because quantization noise of the dithered 24-bit DAC is no longer a subjective quality issue, the best means to control volume level is through the digital word. This technique 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 ratios are now truly optimized throughout the entire playback chain.

Summarizing the many advantages of Bel Canto DAC technology:

1) Bel Canto's DAC technology achieves >125dB dynamic range; the DAC now becomes the lowest-noise signal source even quieter than the best analog preamplifiers.
2) Bel Canto's high-definition 24-bit volume control is essentially transparent, neither adding nor subtracting from the original signal. The dithered 24^{th} bit is 10-15dB below the noise floor of the extremely low analog noise floor of our DAC electronics.
3) Bel Canto's 24/192 A/D converters have arguably less sonic signature than a 1 meter analog interconnect.
4) Bel Canto's 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's ultra-low jitter clocks render the conversion to and from analog in an extremely pure manner.
6) Bel Canto's 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.

With all elements working in concert, with high dynamic range conversion occurring in an environment isolated from outside jitter and noise, the result is sonic purity that renders discussion of Analog vs Digital moot and what remains IS the music.