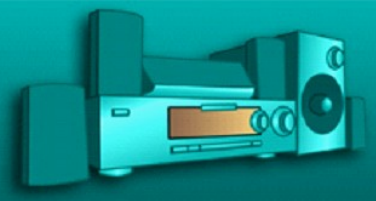
Noise Shaping Sigma Delta DACs

October 2011



Overview of this Presentation

- About ESS Technology
- Simple Noise Shaping
- The “magic” step...
- ΣΔ Modulators
- Beyond the ΣΔ modulator
  - ΣΔ artifacts and understanding what Audiophiles are hearing
  - What the ESS HyperStream does differently



Corporate Overview

- ESS was founded in 1984
  - Fabless semiconductor supplier
  - Market is consumer digital entertainment
  - Headquartered in Silicon Valley with worldwide branches

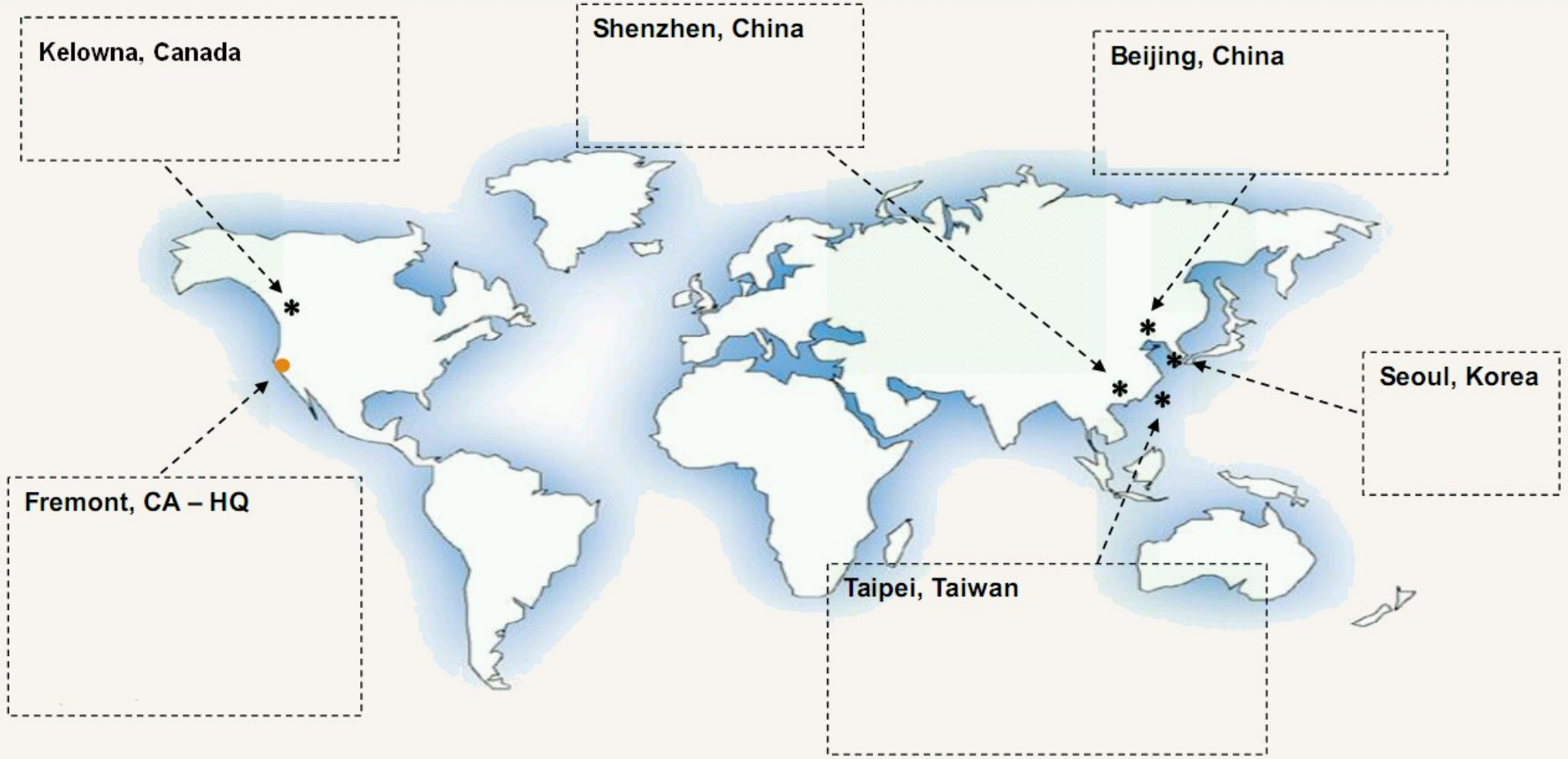
- ESS has a long history of being the market leader
  - 1989 #1 supplier: Sound chips for toy industry
  - 1995-1999 #1 supplier: PC Audio chips
  - 1998-2005 #1 supplier: Digital video chips
  - 2008 Sabre DAC: Highest Performance Audio DAC
  - 2011 Sabre ADC: Highest Performance Audio ADC



What we make at ESS

- Sound-bar Chips
  - You may already have a HyperStream modulator in your home:
    We make the chips used in many Sound-bars today.
- Home Theater Chips
  - If you purchased a Home Theater (or DVD player) you probably have a HyperStream modulator in your home.
    ESS chips were in about 30% of all DVD players, and in many Home Theater systems today.
- High Performance DAC
  - The Sabre product line of highest performance DACs (and lately ADCs) are in many high-end systems.

ESS Locations



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What is the price of Gas? (1)

- Apparently, it is 121.9 cents

  Before you start crossing the border to Canada to buy gas, this is per litre not per gallon!

What is the price of Gas? (2)

1	Mon	$1.22
2	Tue	$1.22
3	Wed	$1.22
4	Thu	$1.22
5	Fri	$1.22
6	Sat	$1.22
7	Sun	$1.22
8	Mon	$1.22
9	Tue	$1.22
10	Wed	$1.22
11	Thu	$1.22
12	Fri	$1.22
13	Sat	$1.22
14	Sun	$1.22
15	Mon	$1.22
16	Tue	$1.22
17	Wed	$1.22
18	Thu	$1.22
19	Fri	$1.22
20	Sat	$1.22

- Buy one litre per day for a few days. What do you have to pay?
- Because that 0.9 is less than one cent, the cashier must charge you the nearest possible price: $1.22
- Had you not seen the sign, you would conclude that the price, based on buying gas 20 times, was $1.22

What is the price of Gas? (3)

1	Mon	$1.22
2	Tue	$1.22
3	Wed	$1.22
4	Thu	$1.22
5	Fri	$1.22
6	Sat	$1.22
7	Sun	$1.22
8	Mon	$1.22
9	Tue	$1.22
10	Wed	**$1.21**
11	Thu	$1.22
12	Fri	$1.22
13	Sat	$1.22
14	Sun	$1.22
15	Mon	$1.22
16	Tue	$1.22
17	Wed	$1.22
18	Thu	$1.22
19	Fri	$1.22
20	Sat	**$1.21**

- What's happening here? You are not getting the same price each day, something is wrong – why does the price differ on day 10 and day 20?
- Interestingly, you would now conclude that the price is 121.9 based on your 20 samples. Which is actually correct..

The cashier is keeping track of the accumulating error in the price you are paying

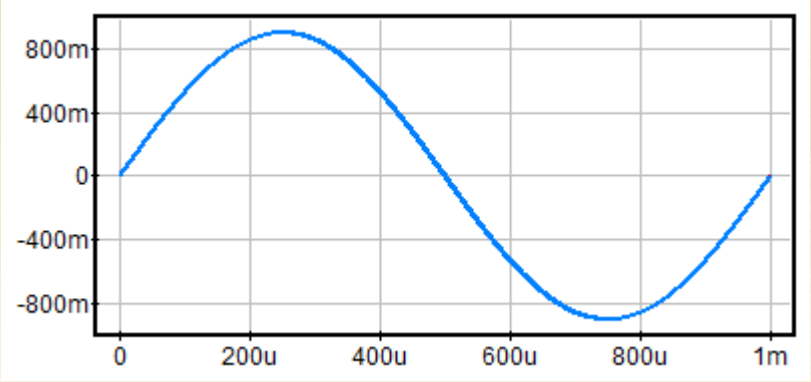


The Trick is “Noise Shaping”

- This method of making the error average out to zero is called “Noise Shaping”
  - It is so called because it does not just ignore the quantization noise: it keeps track of it, and reduces the average to zero
- In the “Gas Price” example, the cashier adds up the error and gives you back a penny every now and again to stop the error accumulating

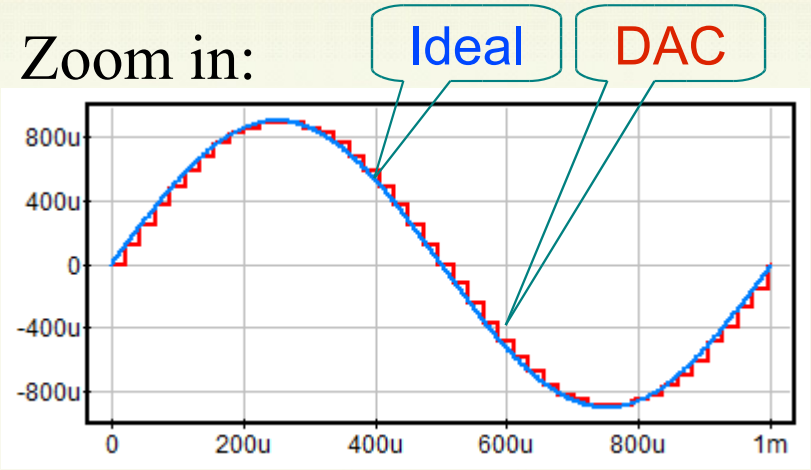


Does Noise Shaping help Audio?



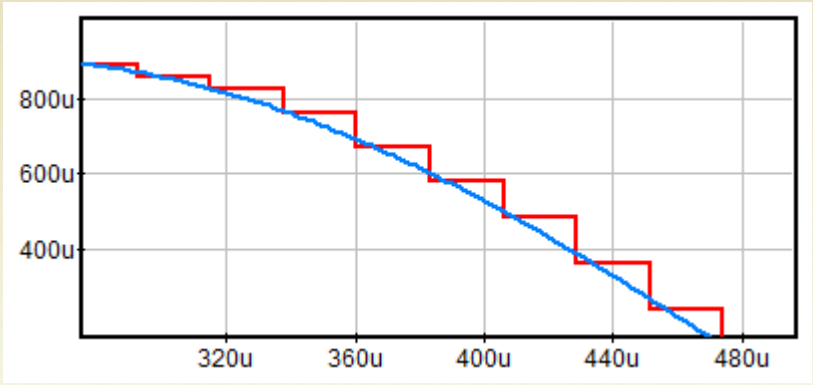
- This is a conventional 16bit DAC
  It is very good indeed, even before we try this noise shaping trick...

Zoom in:

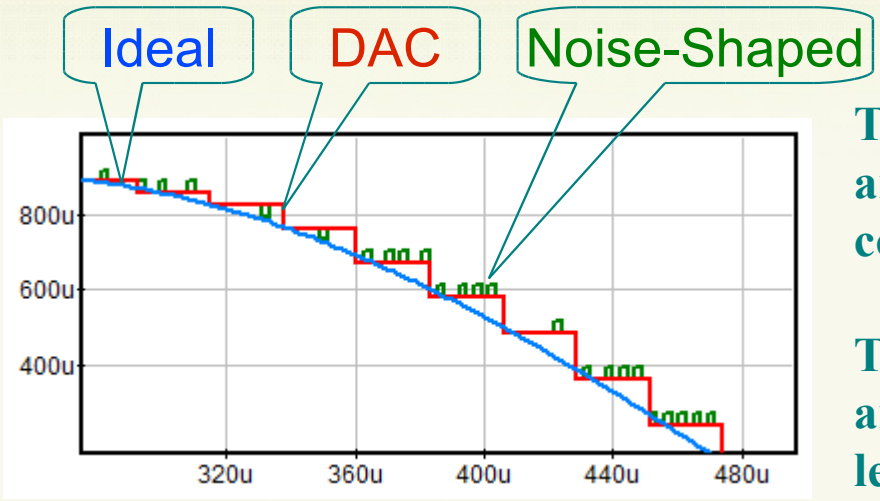


- We have to look at a tiny signal to see where it differs from the mathematical ideal

Does Noise Shaping help Audio? (2)



- Zoom in even more – we can now see the quatization steps clearly.
- Now we allow the DAC to shape the noise: we allow it to give us not just one number, but two, such that the average number is closer to the ideal



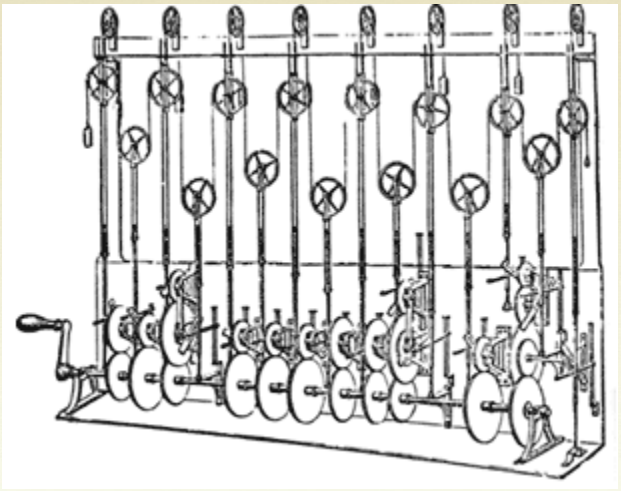
This is still a NOS* DAC: it has not generated another sample, it is simply not making a constant value from that sample.

This is still a 16 bit DAC: it has not created any more output levels, it is simply using the levels it already has.

*NOS DAC: Non-Oversampling Digital to Analog Convertor

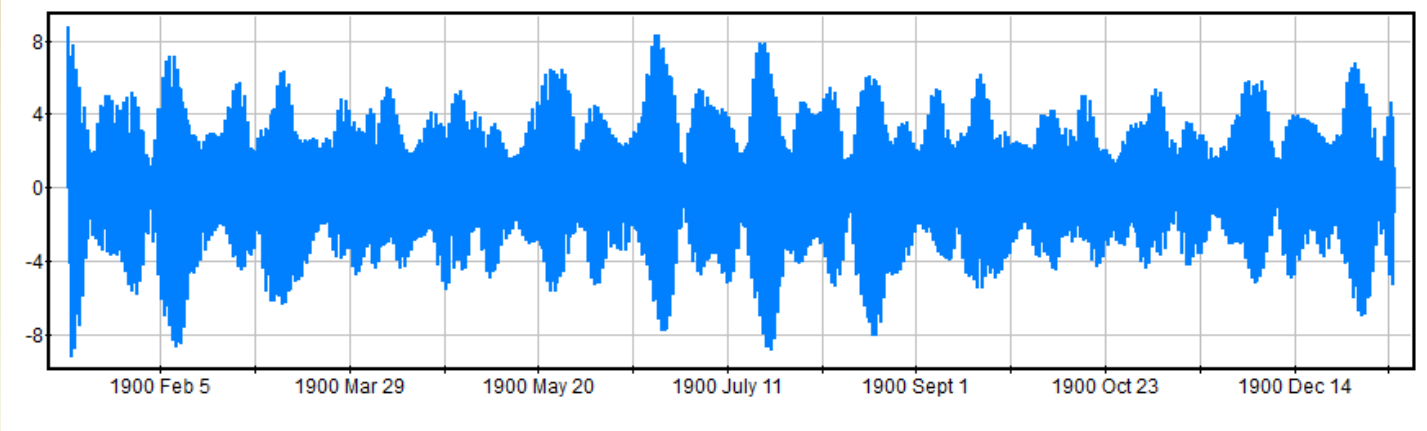
How do we know which is best?

These marvellous Victorian machines will help us: these are Fourier Analysis machines and were designed to predict the tides



William Thomson (later Lord Kelvin) tells us:
"The mechanical method which I have utilised in this machine is primarily due to the Rev. F. Bashforth ... 1845, ... 'A Description of a Machine for finding the Numerical Roots of Equations and tracing a Variety of Useful Curves,' ..."

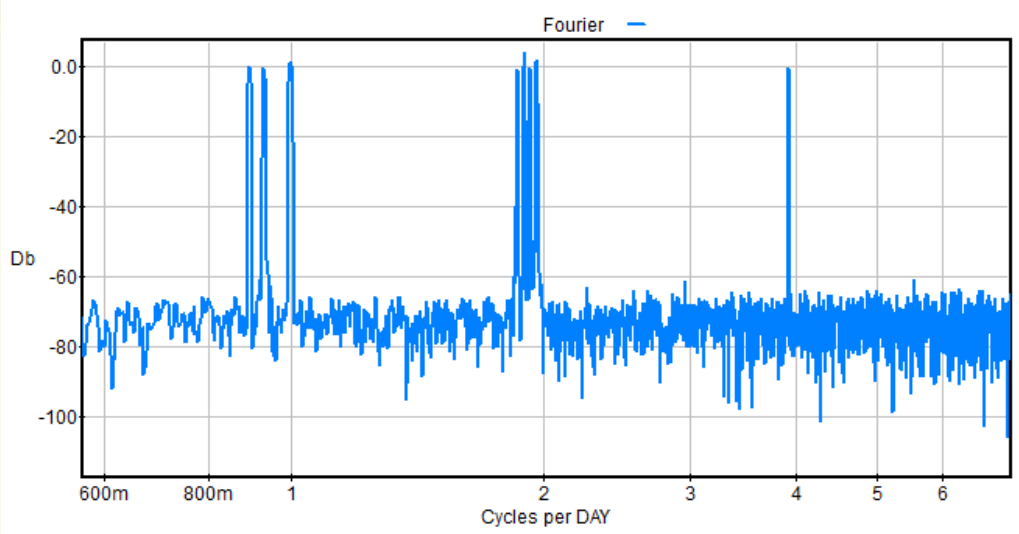
Victorian Analysis machines



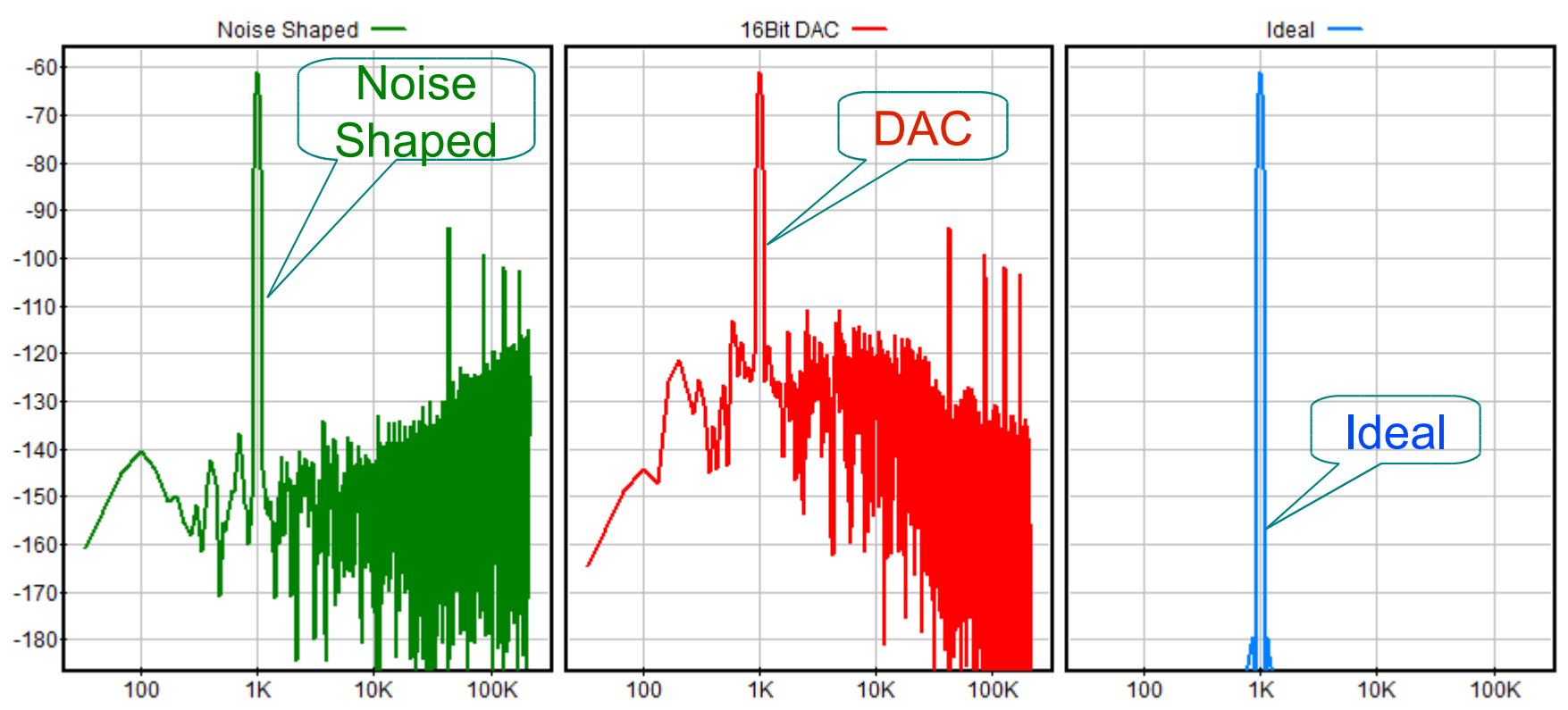
The graph above is the height of the tides at a certain Indian port in the British Empire in 1900

Kelvin's (Thomson's) machine breaks the signal down into components: mostly just under two cycles per day as we see

This is “Fourier Analysis”



We look in the Frequency Domain

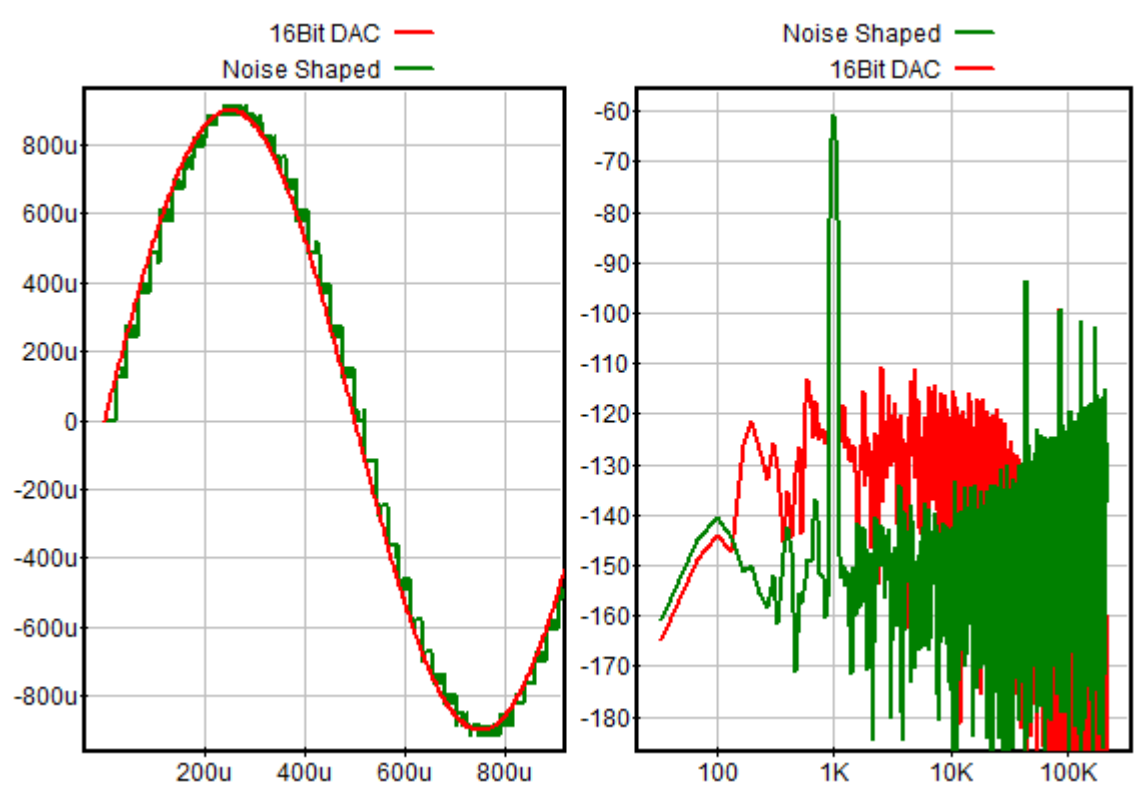


To find which is best, we need to look in the frequency domain. Here are those results from the noise shaped DAC slide after transformation into the frequency domain.

Look how effective those little "dithers" are on the otherwise fixed levels: the region of 1kHz has improved by about 20dB (factor of 10)

It's the “Gas Price” trick in Audio

- So far nothing too surprising: the “Gas Price” trick is just a means to stop the error from growing by keeping track of it, so that “on average” it is correct.
- We understand it as being mostly a DAC, with a little noise-shaping trick.



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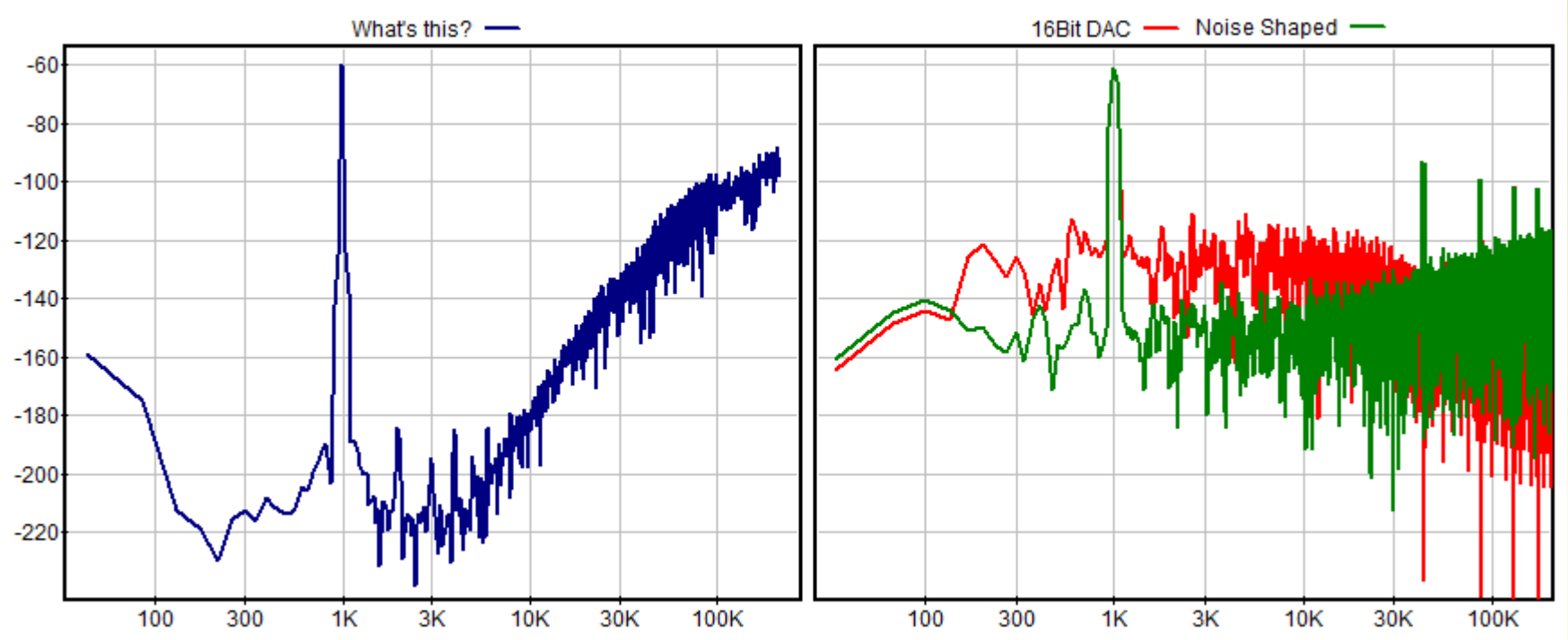
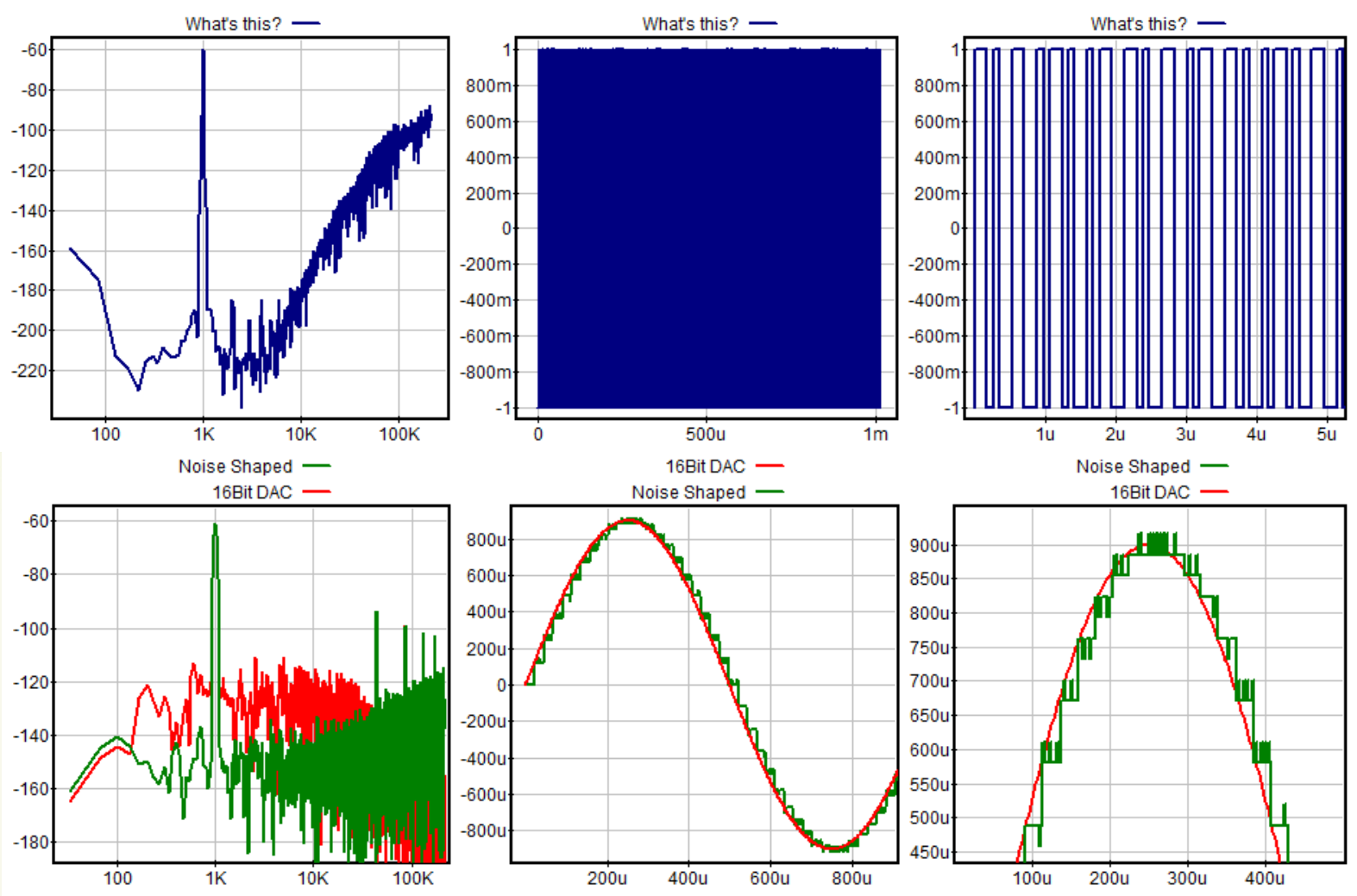
Very interesting FFT Plot...



- If you accept the red and green plots,
  what do you think of the blue one?
  It appears to have much, much lower noise in the Audio band...

This is a valuable technology....



The really low noise graph has only two levels!

It's all noise shaping and no DAC

We don't need the expense of making a DAC

Beginnings of a ΣΔ modulator

- Clearly, there is something much more than the “Gas Price” trick going on here.
  - The “magic” is to do with how you give that penny back: you can do it such that the error is very small indeed
- The name “ΣΔ modulator” has come to generically describe these advanced forms of noise shaping loops.
  - Being Audiophiles, you can probably accept the simple noise shaping on the 16bit DAC levels, it's still a DAC after all.
  - But, what are we to make of a “DAC” that has only two levels? It's all noise-shaping and no DAC!



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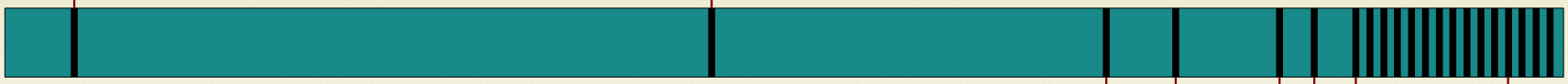
Delta Modulator in the 11th Century

- In about 1079 Omar Khayyam (an Islamic astronomer) in Iran, instituted a scheme of leap years that was actually a first order ΣΔ modulator!
  - His procedure was accurate, and did not accumulate errors, unlike the one proposed 500 years later...



Modulators



Omar Khayyam uses error minimizing algorithm in the Iranian Calendar: a 1st order ΣΔ

The Gregorian Calendar uses the SN7497 algorithm for leap years

France: video encoder

Bendix Digital Differential Analyzer

TI Sync. Binary Rate Multiplier SN7497

UK Post Office/Ferranti PCM1/PCM2 and the Consumer Micro-Circuits FX209

Crystal Semiconductor ΣΔ – many products

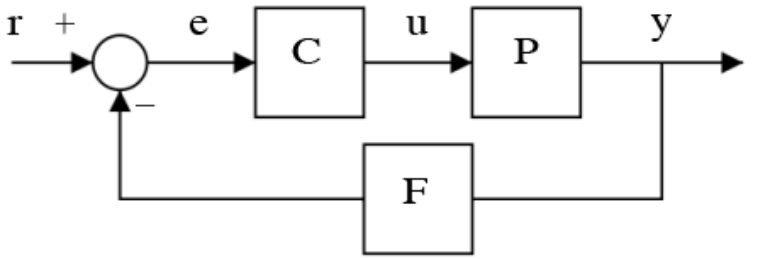
Many other companies (ADI, TI, Wolfson etc.) start to make ΣΔ's

ESS Technology HyperStream Modulators

There may well be more: these are the ones that have come to my attention over the years.

What is the magic of a ΣΔ?

It's control loop theory. And again we find it in Victorian machines



The “order” of a control system

No suspension

First order suspension: springs on chassis

Second order suspension: springs on chassis and in seats

- More springs, more comfort. A higher order control system suppresses bumps (noise) much better than a low order one. You can go over very bumpy roads if you have a high order suspension system.
- High order noise shaping suppresses the error much better than a low order noise shaping. You can let in a lot of noise (ie use a simplified DAC) if you have high order noise shaping.

The Magic is the ΣΔ + Filter

- The ΣΔ works only with a filter!
  It needs the filter to reconstruct the signal.
  - We need all the techniques of signal processing, mostly in the frequency domain, to understand precisely how a ΣΔ works...
  - The best description is that the control loop shapes the noise to be out of the filter response...
  - The total output noise is the convolution of the noise spectrum through the reconstruction filter...
  - A ΣΔ is a high order “noise shaping” control loop...



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ΣΔ's are very good, but...

- The surprising reality is that a ΣΔ can be audibly distinguished from a conventional DAC, despite measuring very much better than that DAC
  - Our customers often have one person who gives the final "thumbs up/down" after a listening test (he is not at all interested in the measurements)
  - Often, this audiophile plays a 16bit 44.1k CD through the system
    - Often that song is Frank Sinatra "New York New York", some Organ Music from Europe, or Rebecca Pidgeon singing "Spanish Harlem"
  - This reminds us of an important point:
    The human ear detects signals well below the noise level of the DAC



ESS HyperStream Modulator

- The HyperStream modulator is:
  - A collection of techniques applied to a noise-shaping loop that empirically remove the listener's ability to hear any difference between a noise shaping and a conventional DAC
- ► When the final artifact is removed, the listener starts to choose the HyperStream modulator (in blind tests) as being better than the conventional DAC
  - It begins with one HyperStream patent, but there are many more “tricks”
  - I will describe just two of these differences...



None Periodic Steady State Noise

- The ear is exquisitely sensitive to “unusual” noise sources
  - Your ancestors camped by a waterfall (white noise) and yet their “ears pricked up” when they heard a hint of a predator moving in the undergrowth. (The equivalent visual phenomenon is “seeing something out of the corner of your eye”)
  - Noise, to a large degree, can be accommodated in the ear and is not troubling, but the tiniest “anomalous” noise is raised to the conscious level
- ► ΣΔ modulators create none-periodic steady state noise (None-PSS) artifacts; the HyperStream modulator does not



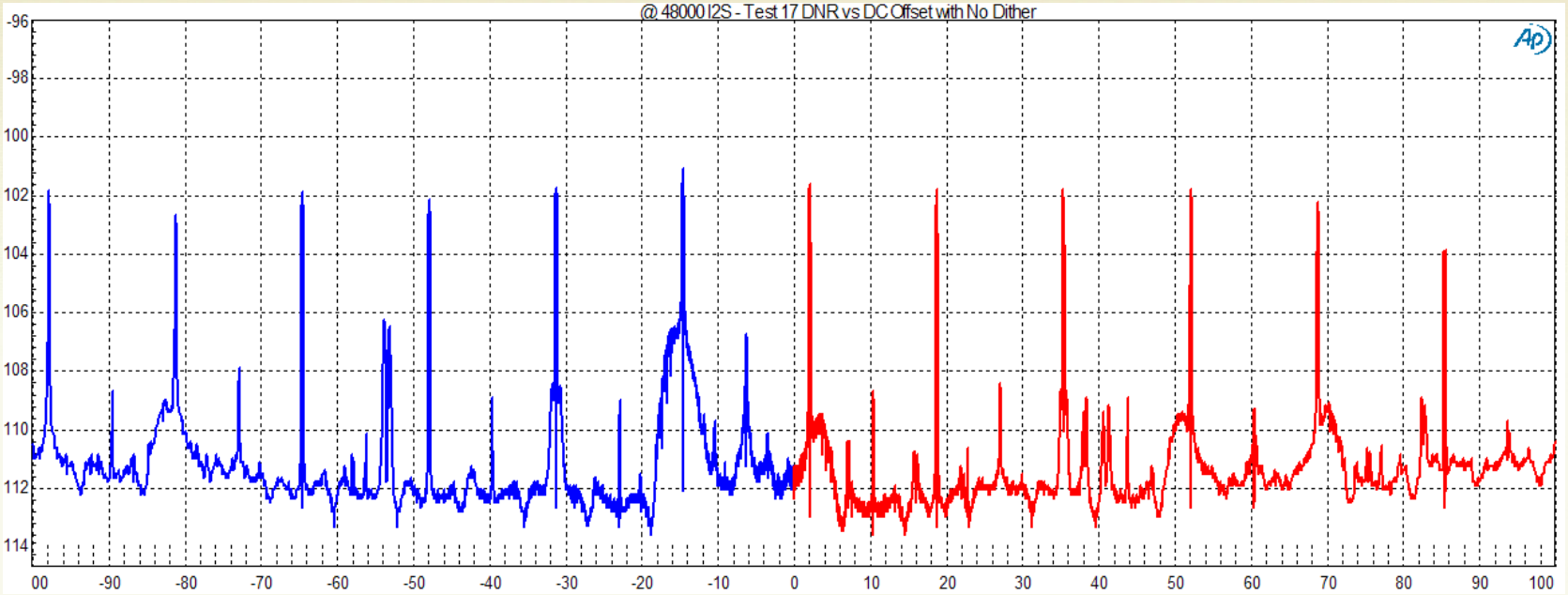
What is None PSS Noise?

- Periodic Steady State analysis is common in RF circuits:
  - It means that the system is forced to repeat a pattern of behaviour over and over again with a certain time period
  - Any artifact is presumed to also repeat in this time period
- Audio measurements such as THD and DNR are done in the Periodic Steady State
  - Therefore, they will not activate None-PSS noise
- ► You will not find None-PSS noise by looking at THD, DNR and SNR



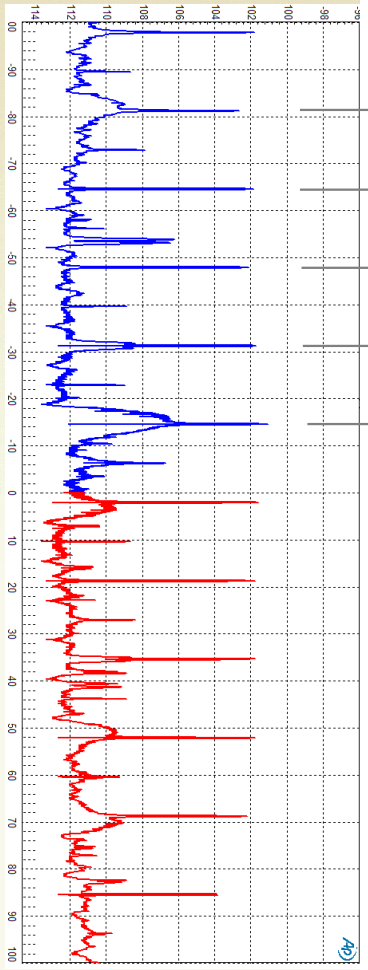
Source of None-PPS Noise

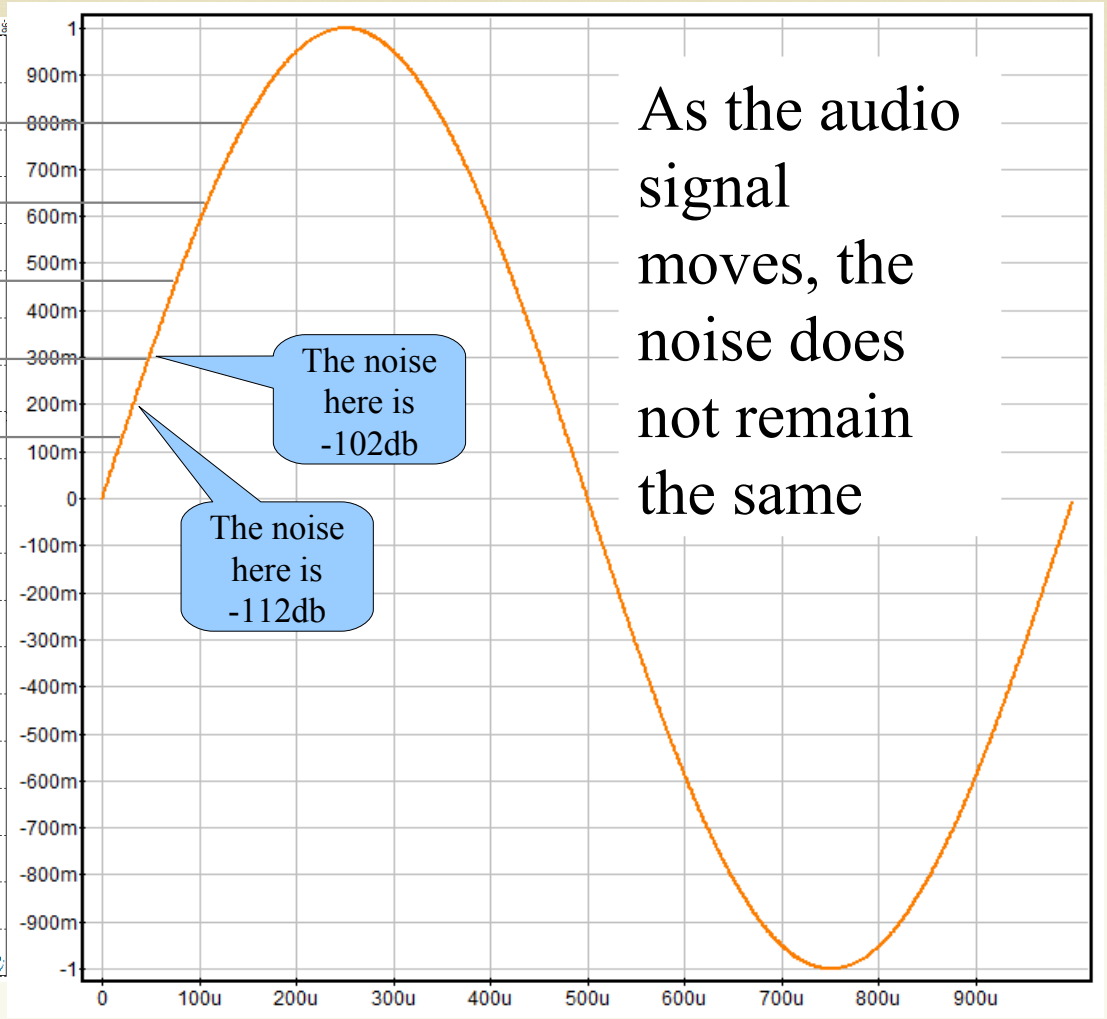
- A clue can be seen in the Noise-vs-DC offset graph of a ΣΔ modulator:



(This is one of our competitors ΣΔ parts)

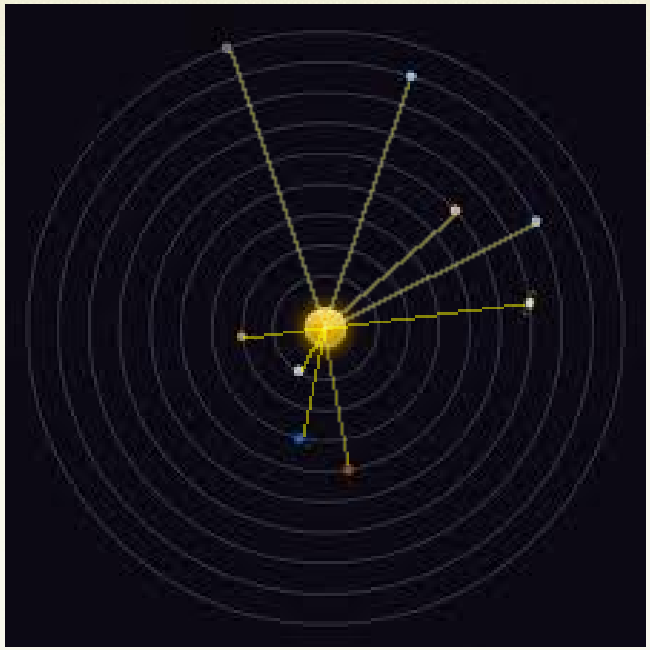
This makes the noise vary





Source of None-PPS Noise (2)

- In fact, noise does not just vary with input, but with every “state variable”
  - What is a “state variable”?
    - They are the elements in the list of values you need to know “where the machine is”. For example, if you know the position of Mecury, Venus, Earth, ... Nepture (8 angles) you now know the complete state of the Solar System
    - If you know the values on all the integrators in the noise shaping loop, and the input value, you now know the complete state of the modulator.



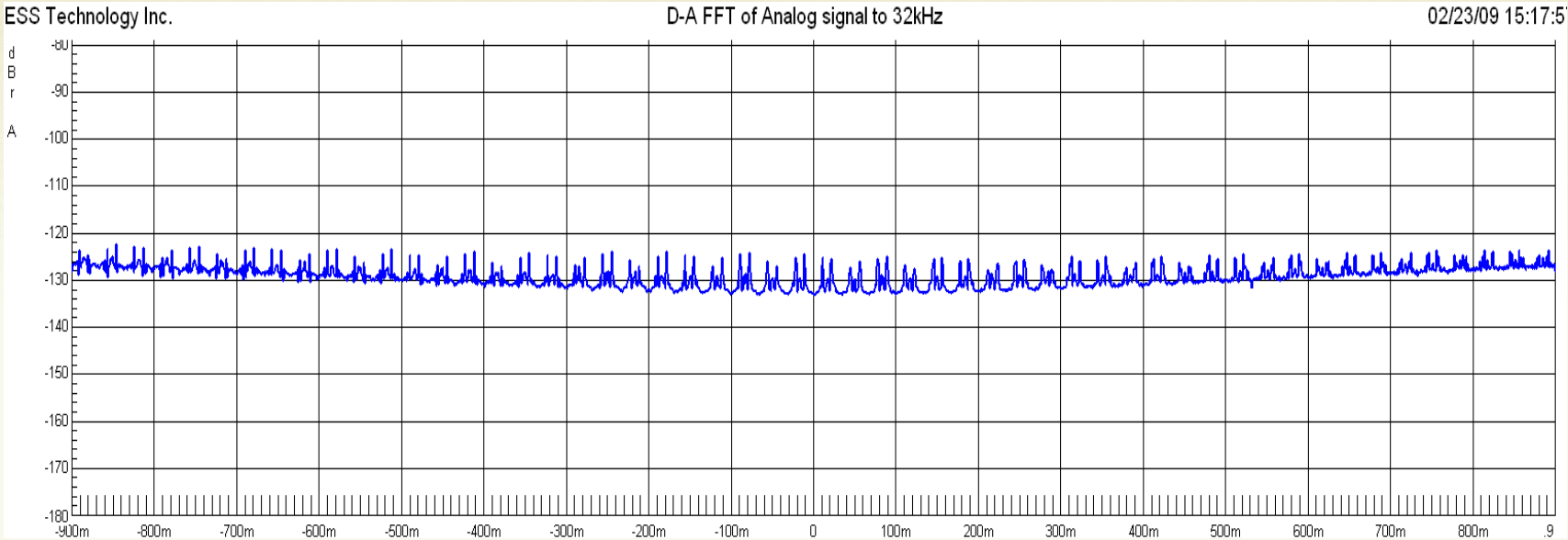
Source of None-PPS Noise (3)

- And here is the point: the noise varies depending where those state variables are:
  - As the modulator makes a transition from outputting say 1kHz -30db, to say 20kHz -10db, the state variables move from the repeating pattern needed to make 1k, to the repeating pattern needed to make 20k. And as they do, they move through regions of high and low noise
  - In the background, as the modulator chages between two PSS's it generates a variable pattern of noise
  - ►ΣΔ makes a variable (but still very low) amplitude “ffssst” noise as the state variables transition though noisy space



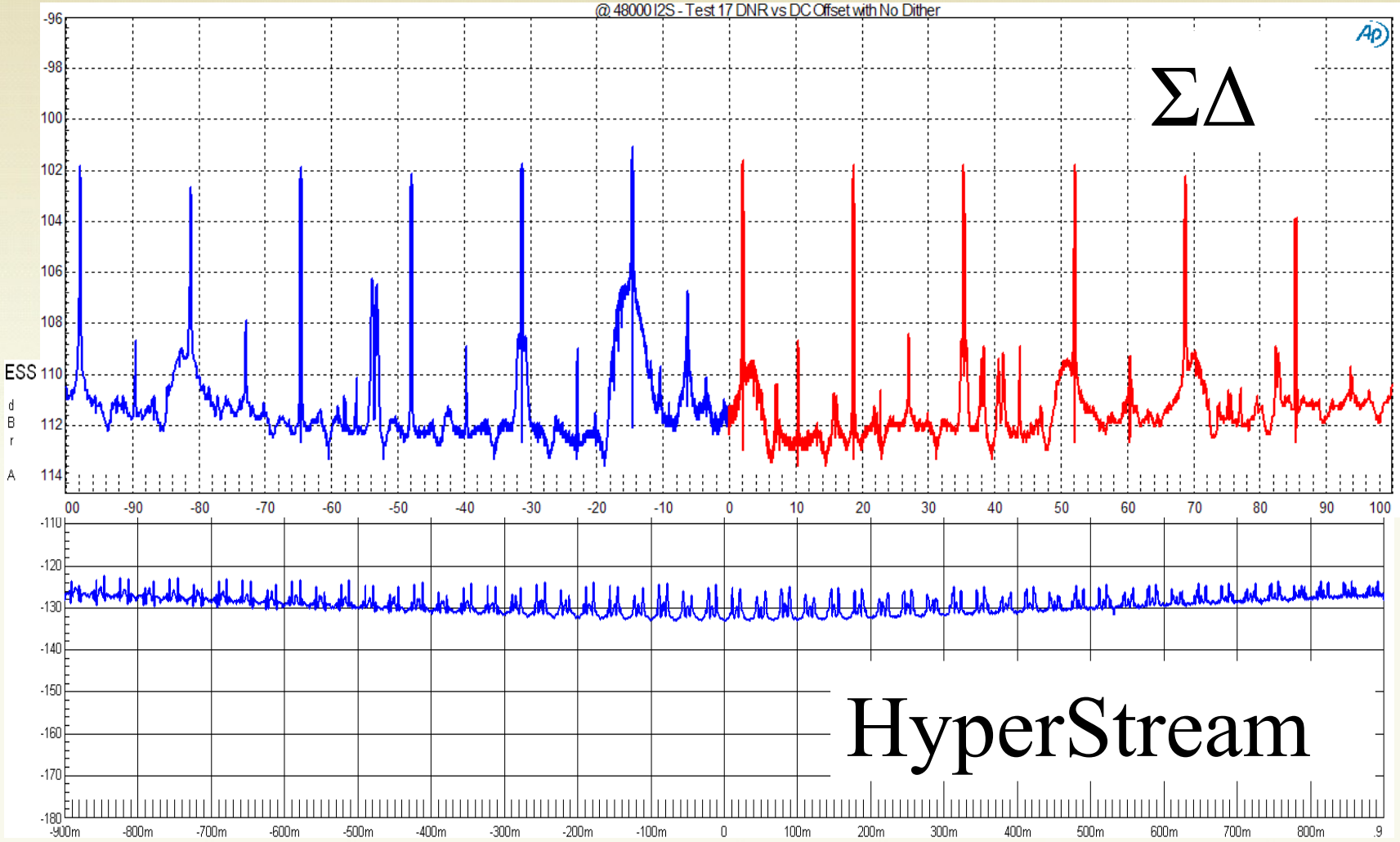
Source of None-PPS Noise (4)

- How does the HyperStream avoid this problem?
  - 1: The HyperStream loop is designed to minimize variation of noise in the state variable space.



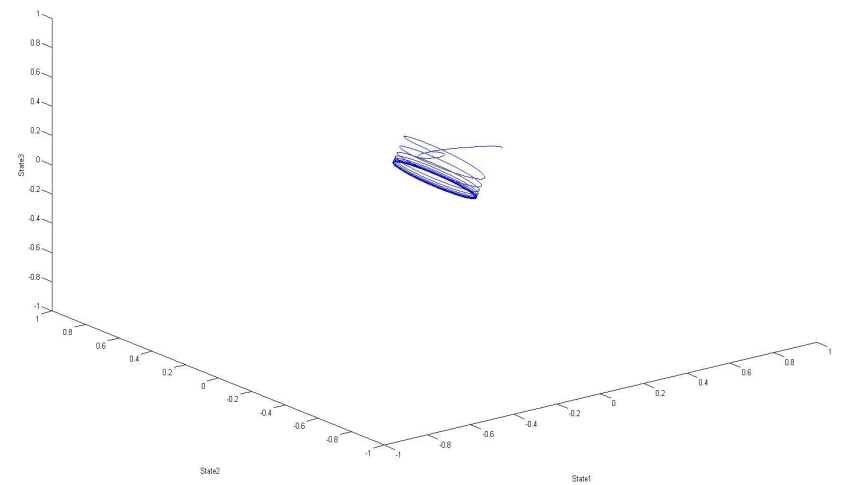
Note how little variation there is of noise with DC level in the HyperStream modulator (and it is much lower to begin with)

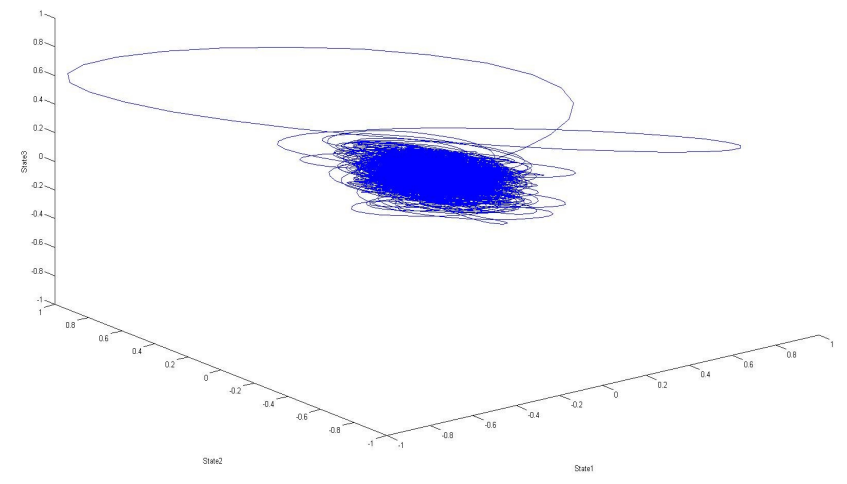
Noise vs DC input



Source of None-PPS Noise (5)

- How does the HyperStream avoid this problem?
  - 2: *This is the most important slide in the whole presentation*
    The HyperStream loop rapidly "quenches" the state variable excursions:





The left plot shows three of the HyperStream state variables as the loop adjusts to a new output signal of 20kHz. The right plot shows three state variables of a typical ΣΔ modulator.

The ΣΔ modulator visits much more of the state space and is "chaotic" - it bumps into regions of higher noise and the listener can detect this.

Non-linear Excess Phase

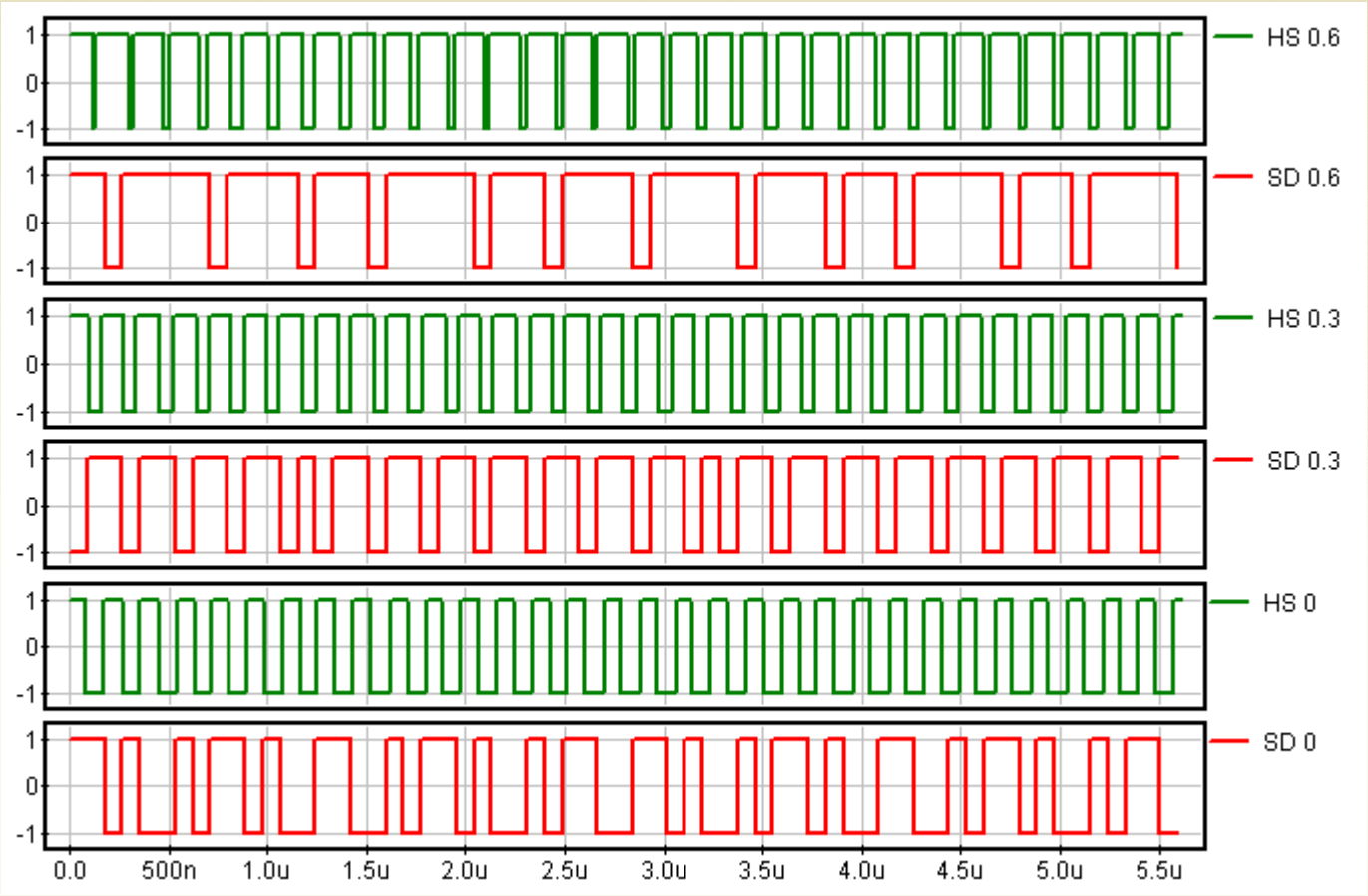
- None-PSS noise is the biggest issue, but experiments suggest there are more problems. For example:

  Audiophiles rate as inferior systems that have variable excess phase

  - ΣΔ modulators have stability criteria that vary with amplitude and ultimately they become unstable as the signal reaches full-scale.
  - The HyperStream modulator is unconditionally stable up to full scale because the excess phase does not change with signal level



What is Non-linear Excess Phase?



Note how the times between edges in ΣΔ (red) are increasing as the DC offset increases, but not in HyperStream (green)

Increasing Signal

The ΣΔ must wait for an edge to come back around before it can make any correction: this average delay changes with signal level

What is Non-linear Excess Phase?

- Because the phase is well controlled (and also due to careful loop design) the HyperStream can be made unconditionally stable
- And this is the point:
  - **►We find that an unconditionally stable loop sounds better in listening tests**

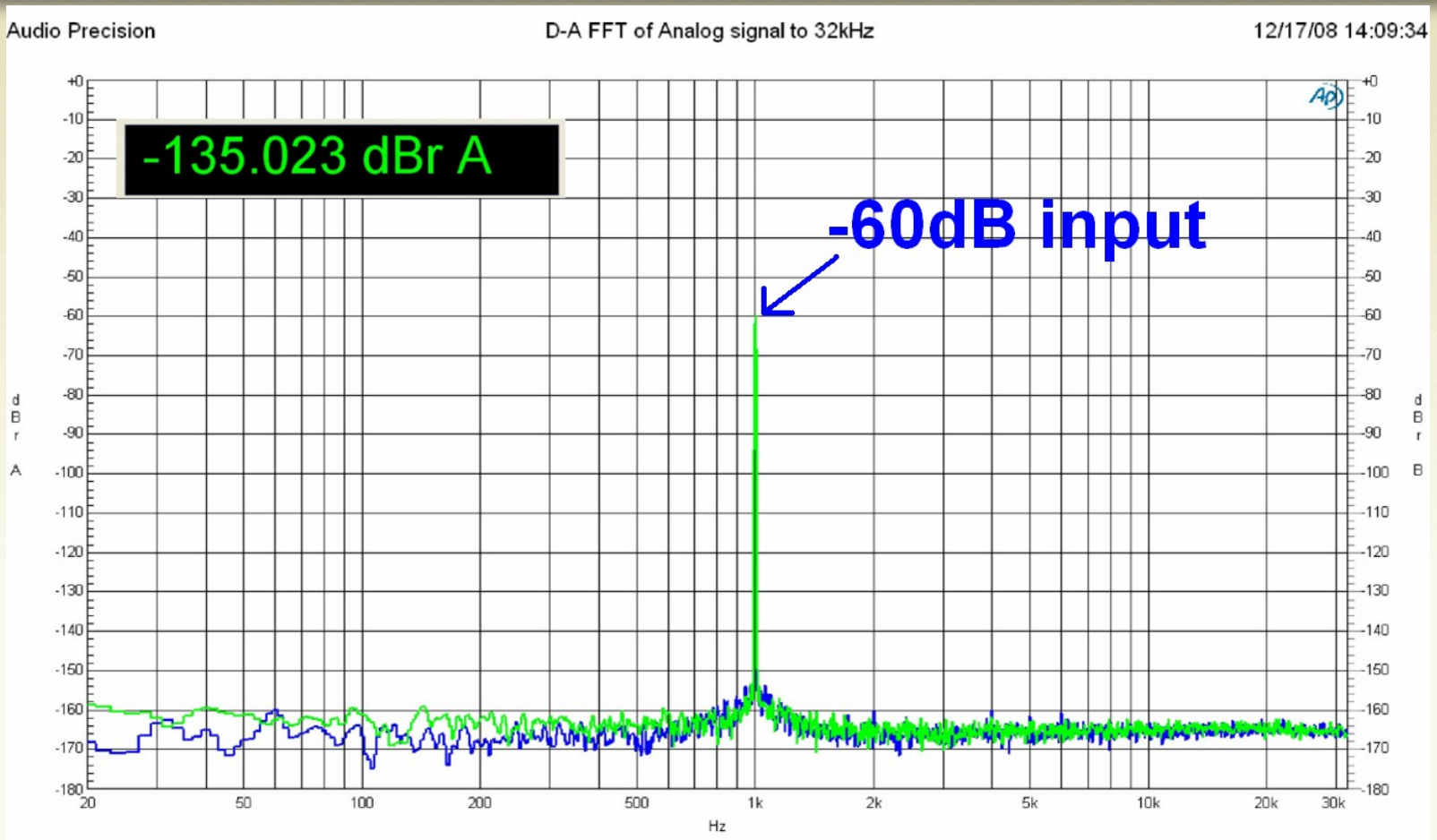


Briefly more

- Multi-bit versions of the ΣΔ and HyperStream exist
  - ΣΔ multiple-bits are in Amplitude
  - HyperStream multiple-bits are in Time
  - (None-PSS noise does not depend on the bits in the feedback)
- ESS uses HyperStream in all audio products.
  - The highest performance parts use the “Sabre” product name
- Both ESS DACs and ADCs use HyperStream
- Many more innovations...



The Sabre DAC



- But, engineering for specifications is secondary to engineering for exceptional sound fidelity...

End of ΣΔ/HyperStream Presentation

Thank you for attending the ΣΔ/HyperStream Presentation

[For more technical information from ESS email to wendy.chafer@esstech.com - mention RMAF]