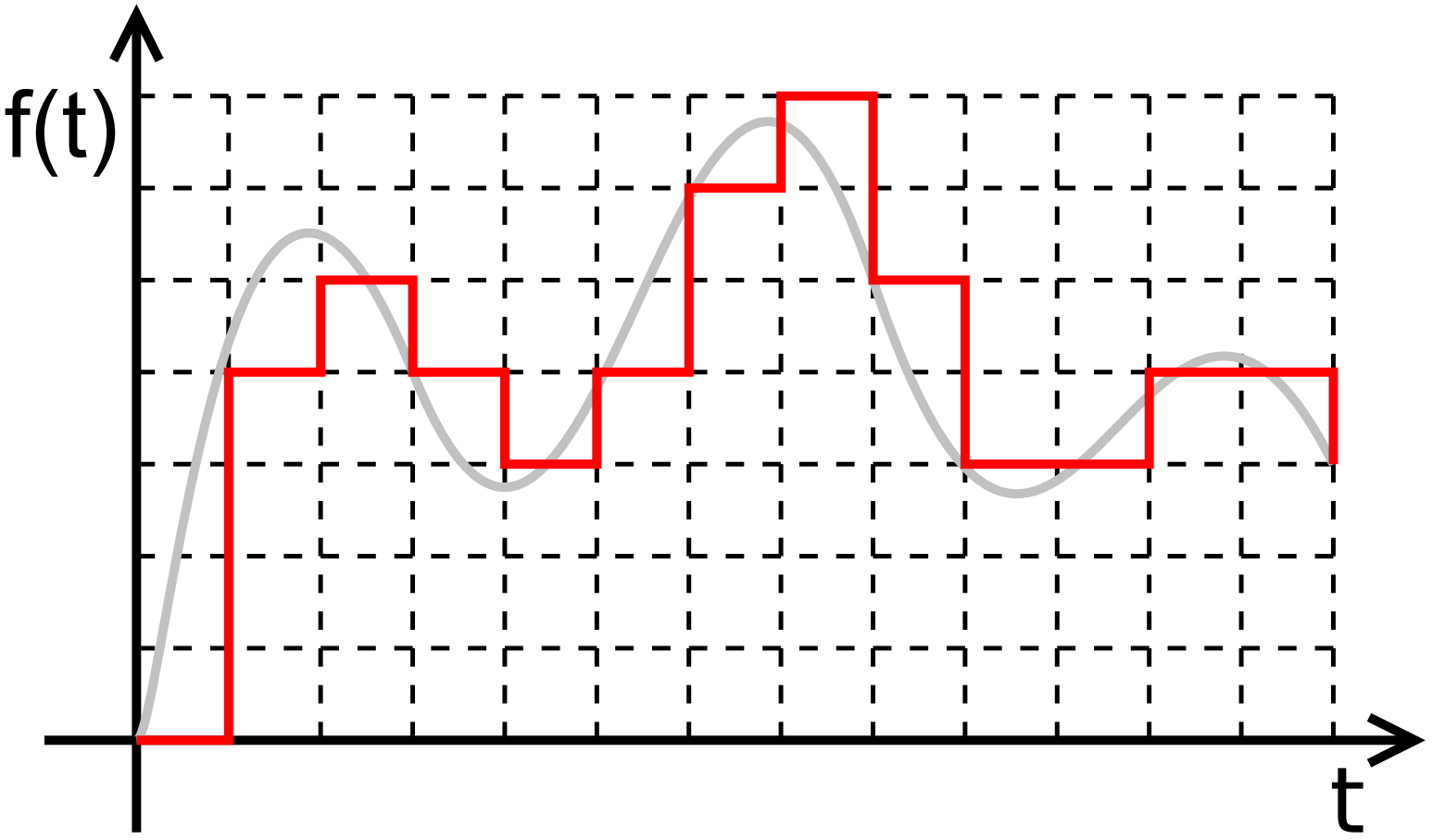
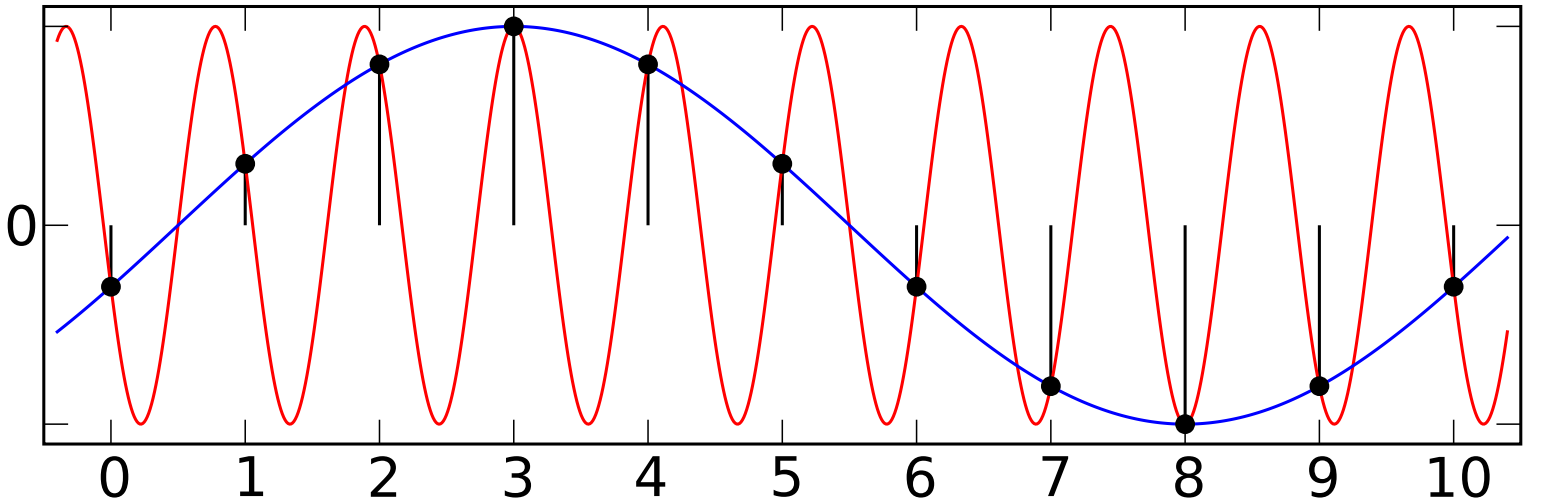
The illusion of continuity

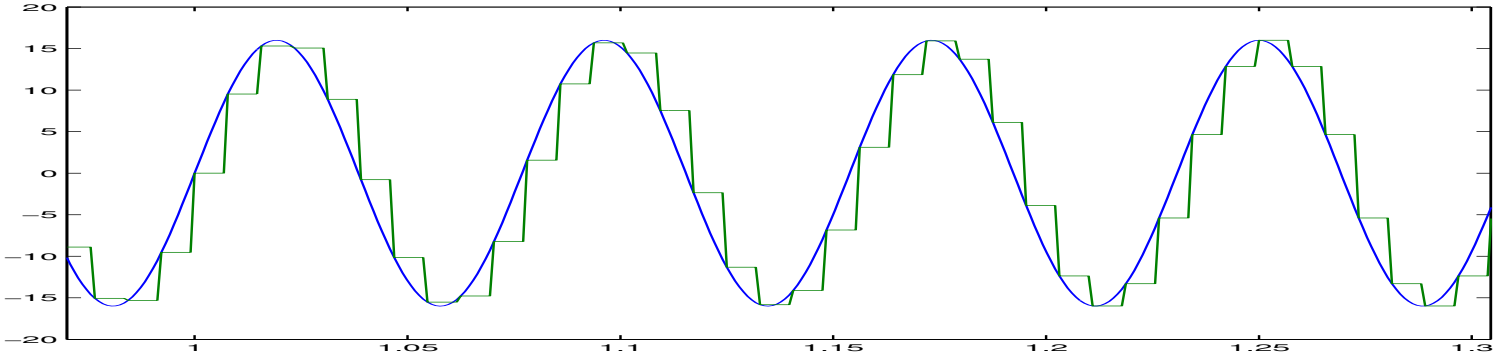


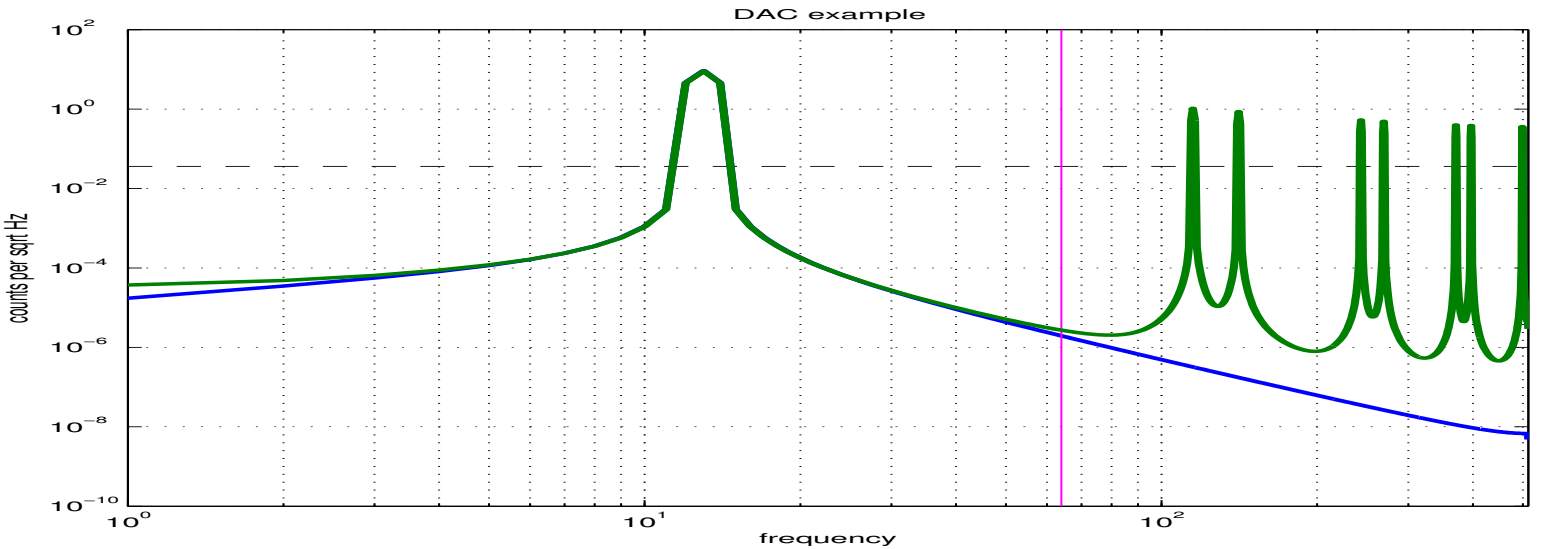
Aliasing (down)



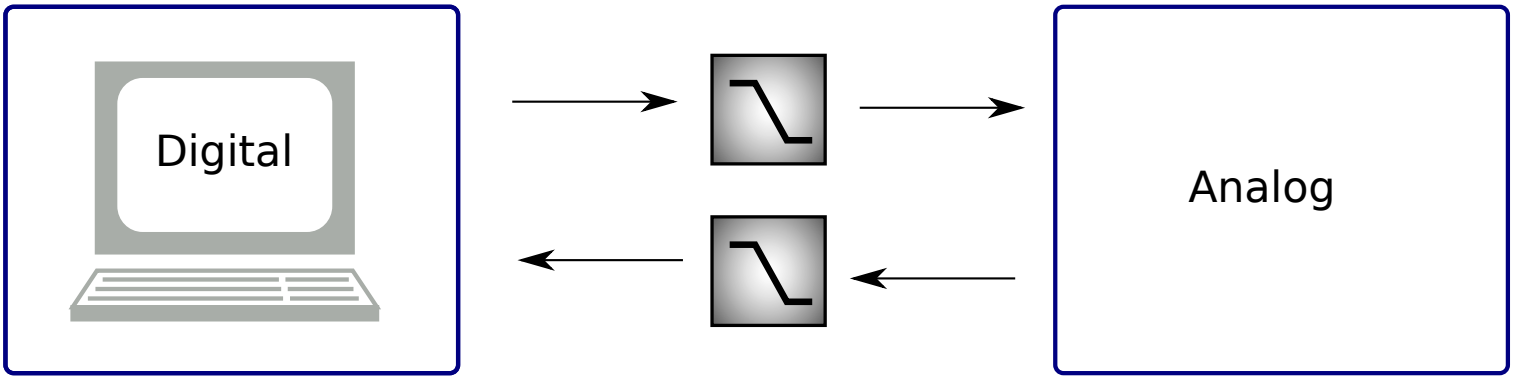
If you are sampling at f_s samples per second, you can't tell the difference between signals at $\frac{f_s}{2} + \Delta f$ and $\frac{f_s}{2} - \Delta f$.

Aliasing (up)


20
15
10
5
0
−5
−10
−15
−20
1
1.05
1.1
1.15
1.2
1.25
1.3

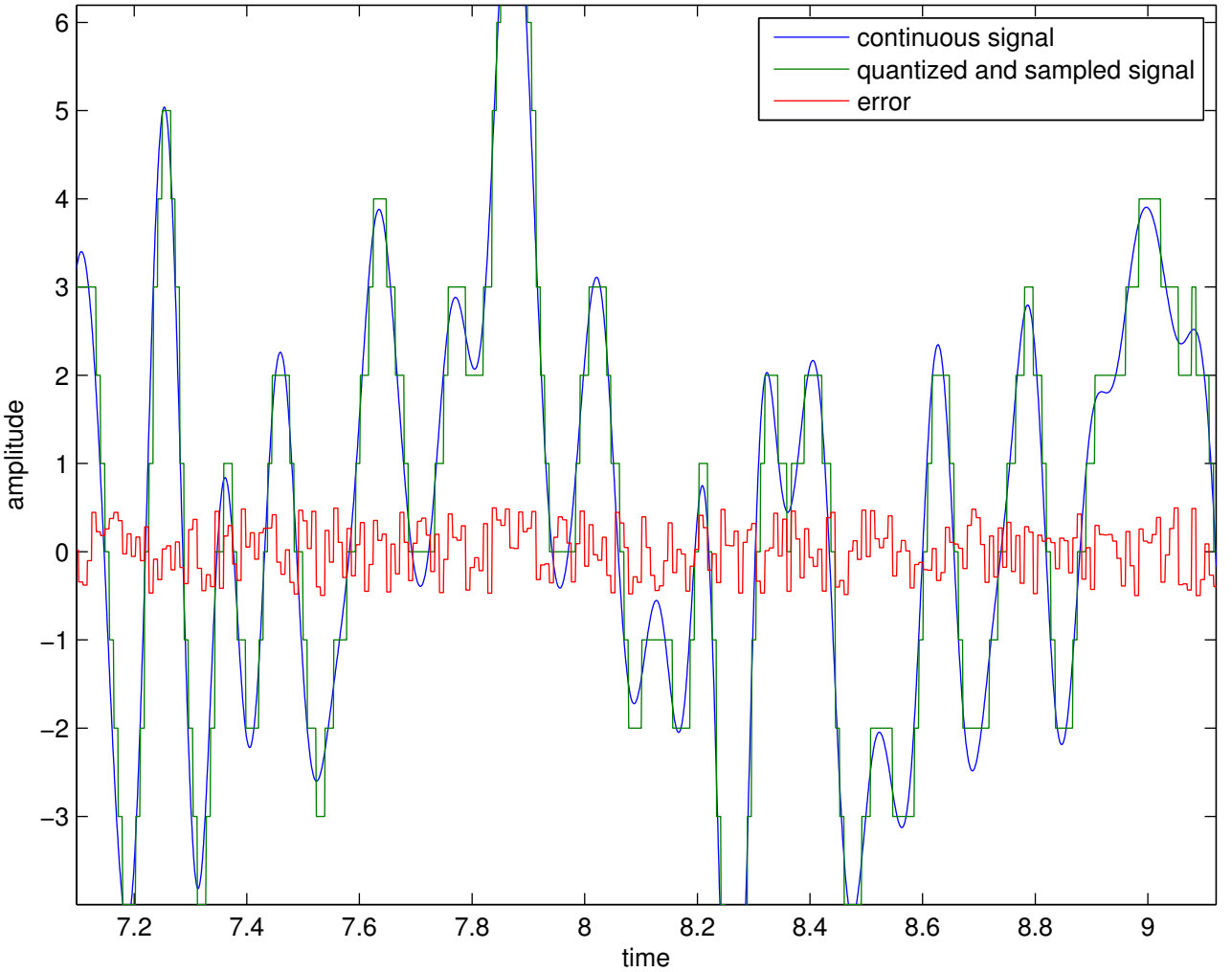

DAC example
counts per sqrt Hz
frequency
10^2
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^0
10^1
10^2

Anti-aliasing



The solution is to remove frequencies above $f_s/2$. This is done with an *anti-aliasing* filter on the input and an *anti-image* filter on the output.

Quantization noise



Calculating "ideal" quantization noise

Assume the quantization error comes from a uniform distribution, $x \in [-\frac{1}{2}, \frac{1}{2}]$.

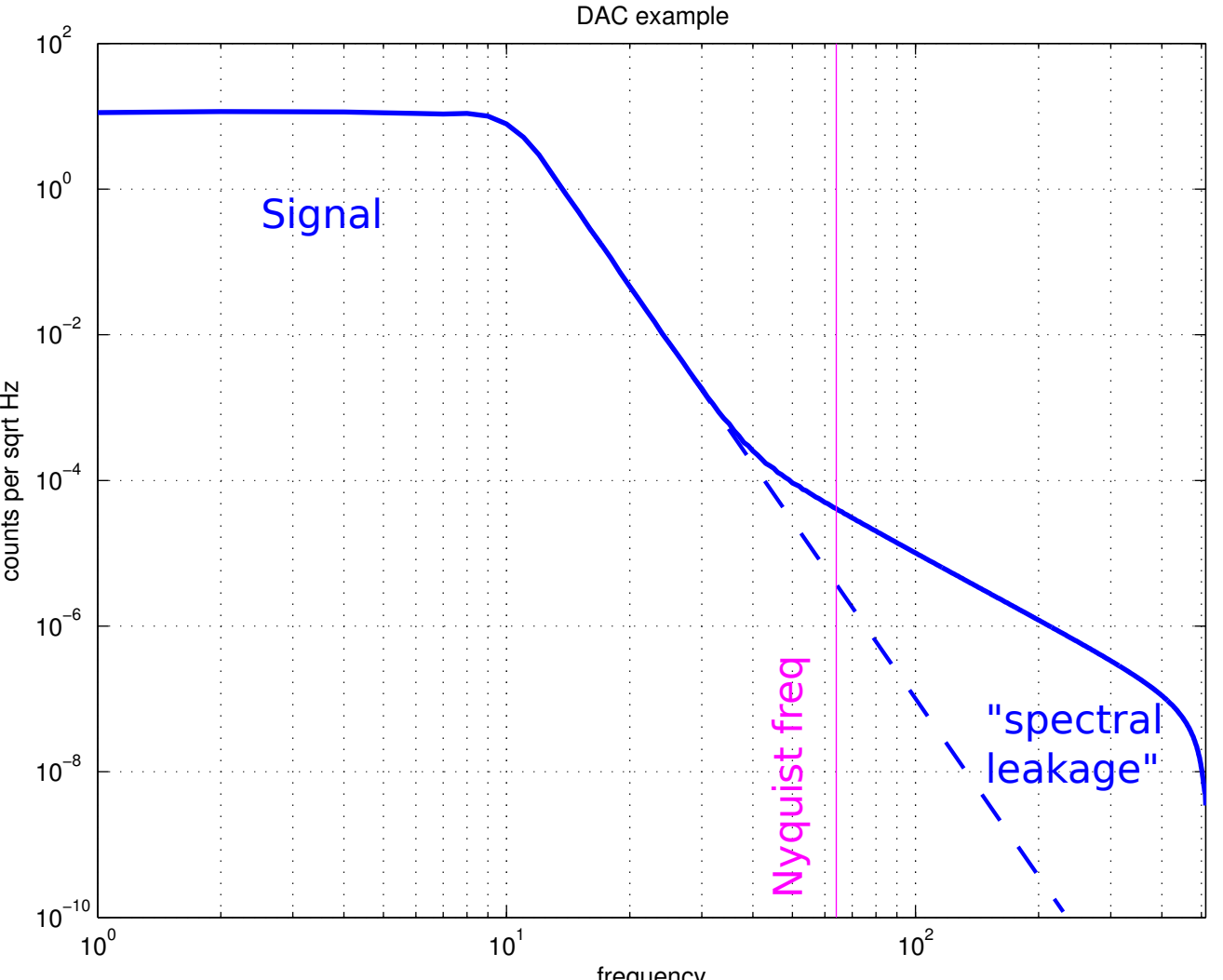
The variance is $\int x^2 \rho(x) dx = \frac{1}{12}$.

Apply Parseval's theorem.

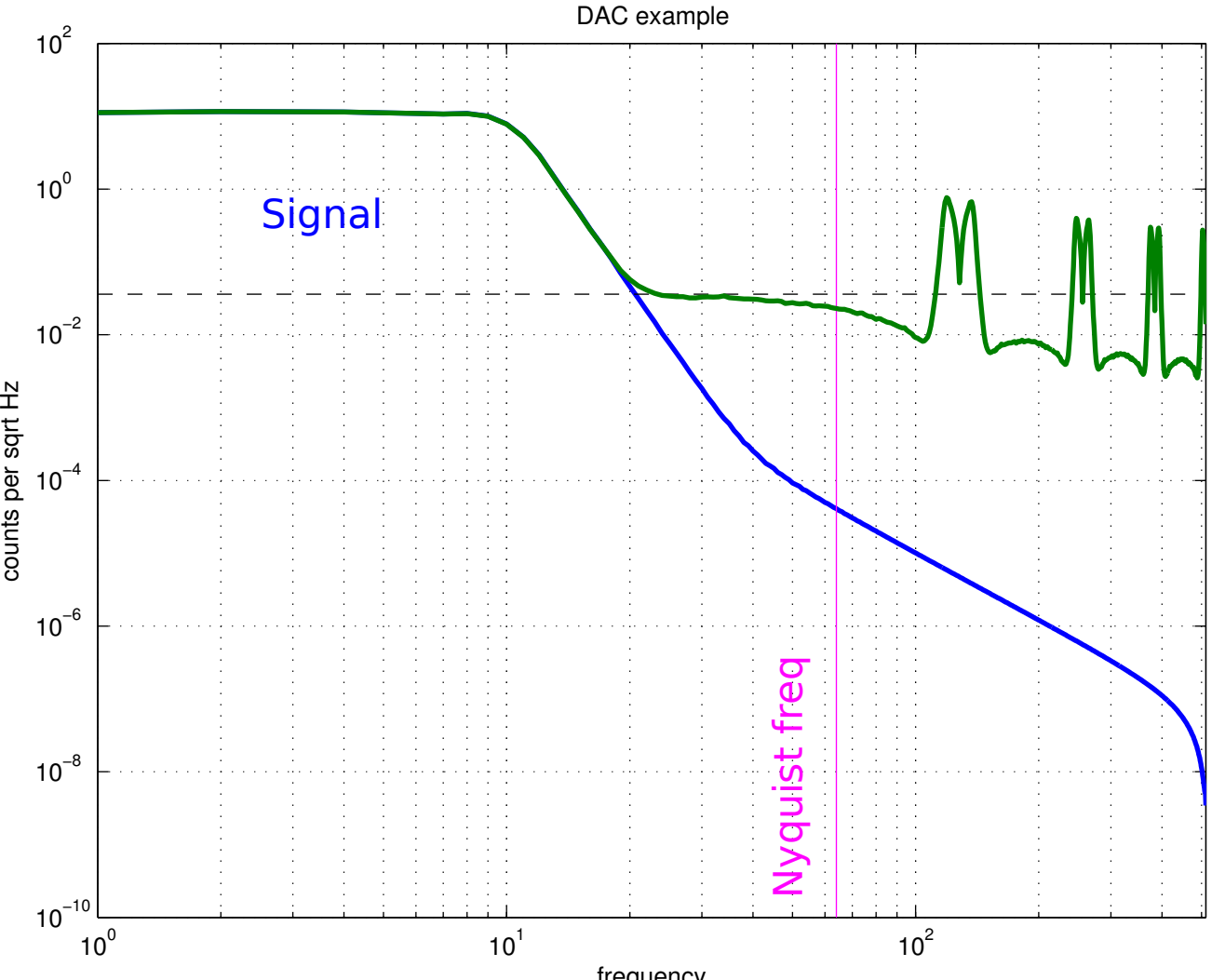
Bandwidth is $\frac{f_s}{2}$ Hz (Nyquist rate).

ASD is $\sqrt{\frac{1/12}{f_s/2}} = \boxed{\frac{1}{\sqrt{6 f_s}}}$ counts / $\sqrt{\text{Hz}}$.

DAC example

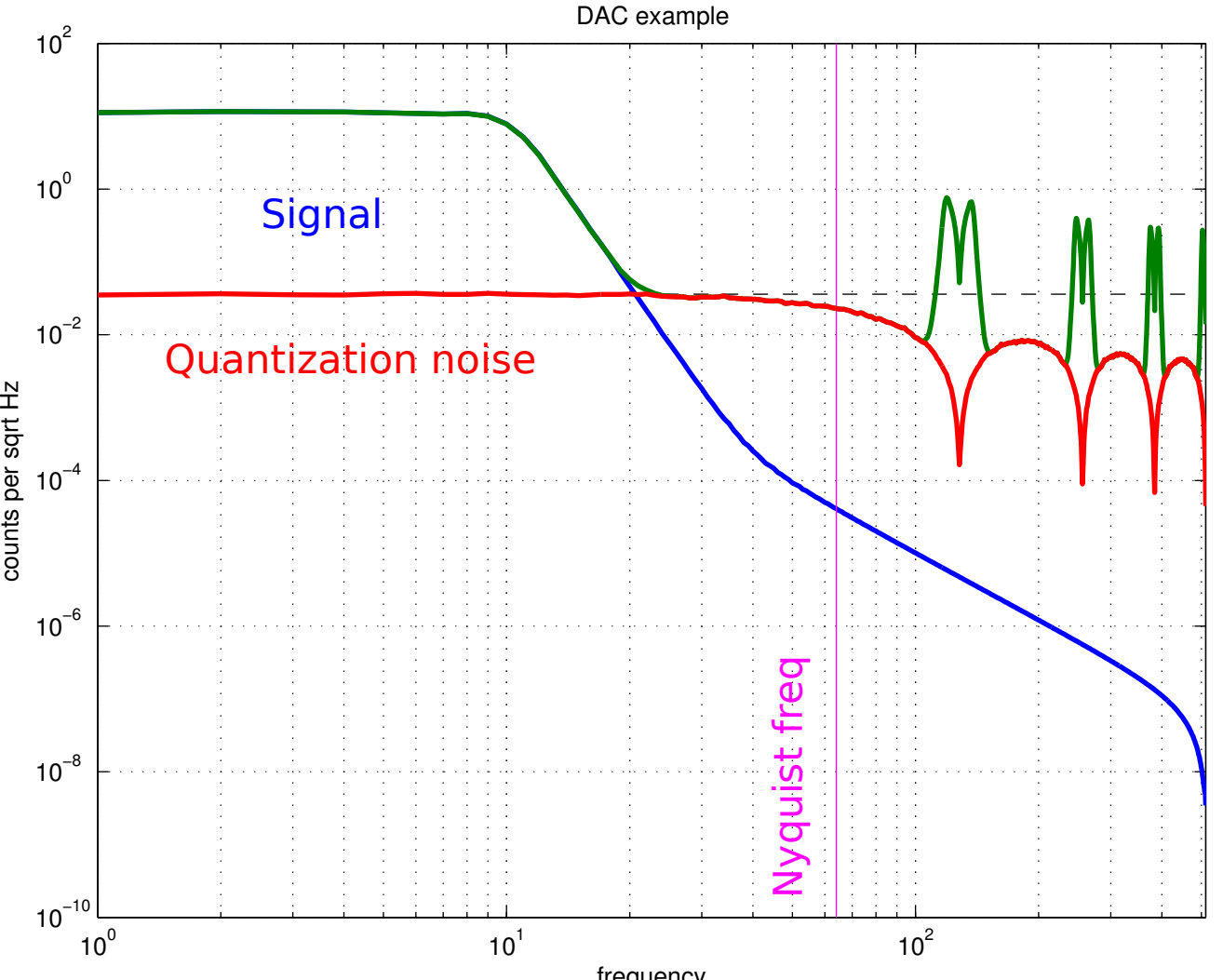

DAC example
counts per sqrt Hz
frequency
Signal
Nyquist freq
"spectral leakage"

DAC example II



What actually comes out.

DAC example III



warning!

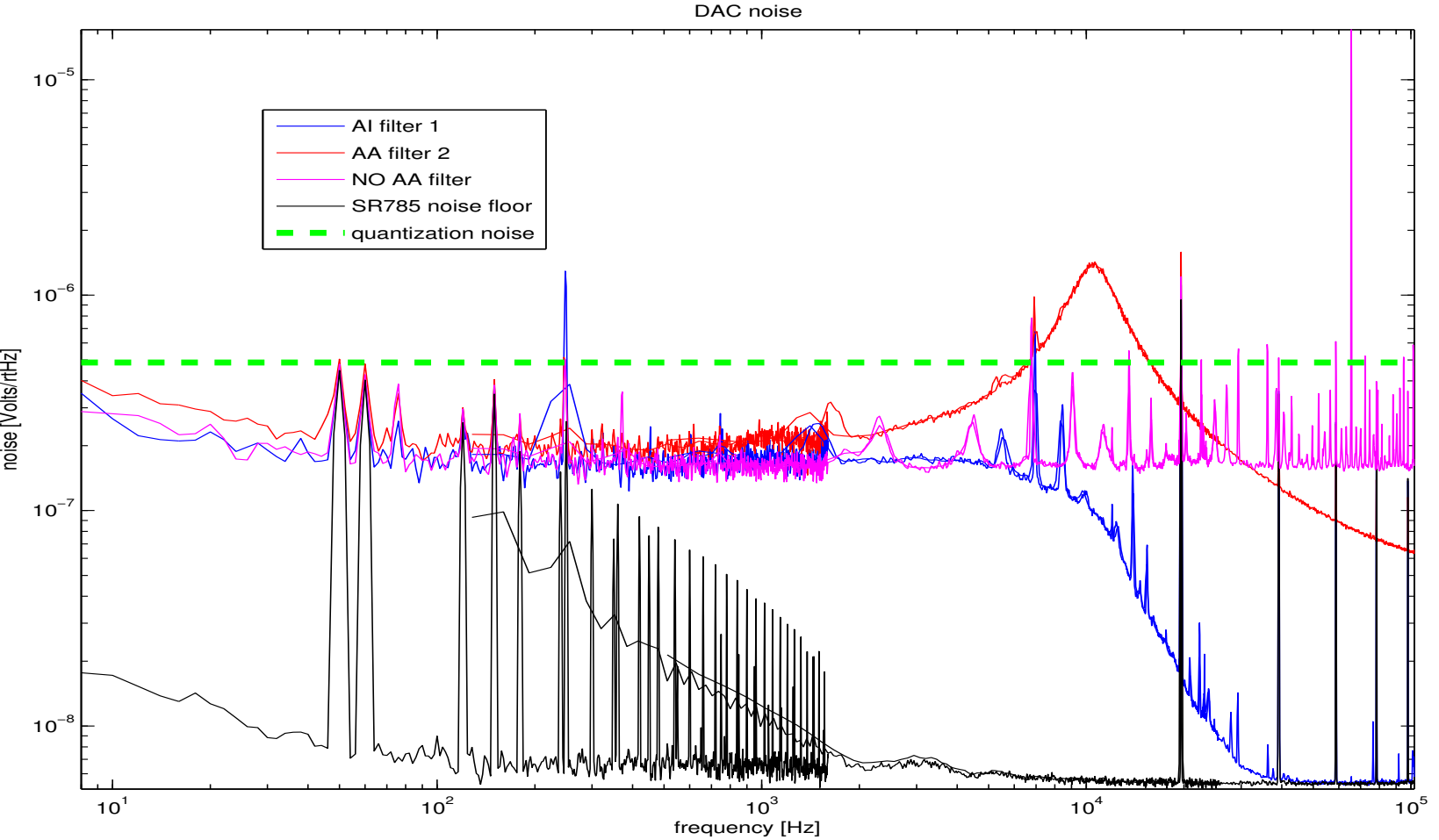
* Quantization noise is a nonlinear effect. It depends on the signal:

- No signal no noise...

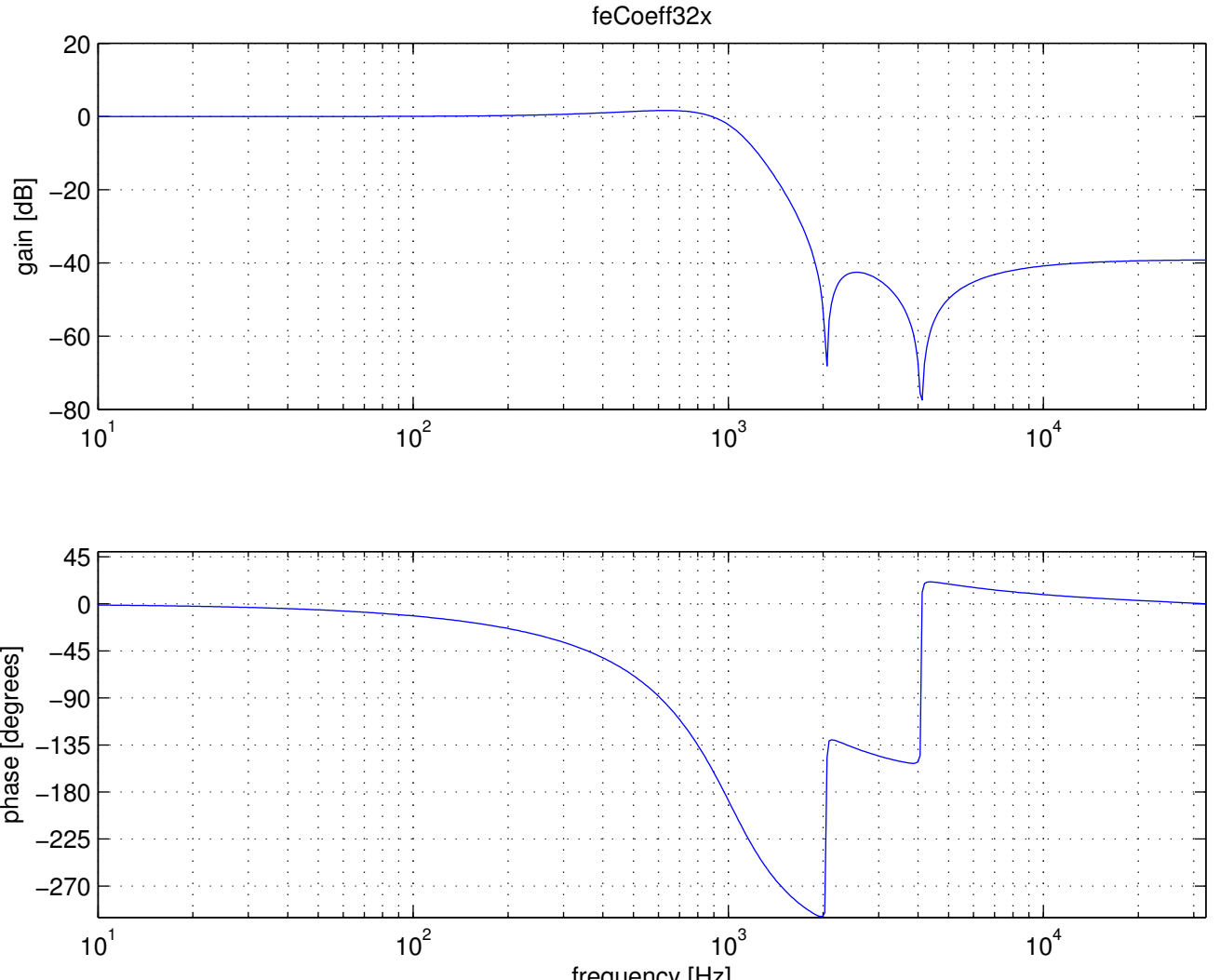
- If your signal is not complicated enough or big enough, then the spectrum of quantization noise will be much more complicated (worse)

It's easiest to just make sure your signal is big enough so that you don't have to worry about this.

Analog AA/AI filter



Digital AA/AI filter



Used for downsampling from 64 kHz to 2 kHz.

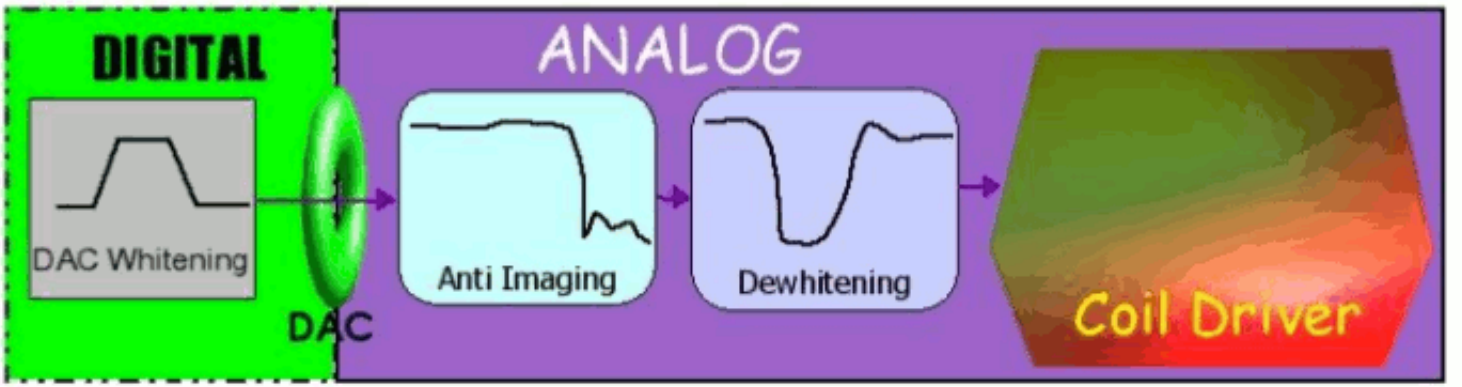
A control loop implemented in a 2 kHz CDS system will see this twice (one AA, one AI).

CDS

* The CDS ADCs are **not** limited by quantization noise.
(Their noise is higher)

* The CDS DACs **are** limited by quantization noise (0.5 uV/rtHz)

Whitening



(figure from Rana's thesis)

* Shape your signal to make best use of the ADC/DAC dynamic range

* Then undo the shaping on the other side

Summary

Sampling

* Anti-aliasing and anti-image filters are basically a complete solution, BUT...

* these filters can contribute non-trivial phase lag and perhaps noise

Quantization

* Estimate the quantization noise level and then stay away from it.

* Quantization noise is a non-linear effect and depends on the signal.

Saturation

* The ADC input / DAC output has a limit on signal amplitude.

Summary II

For signals that are not too small and not too big, and are bandlimited, the digital system provides an almost perfect illusion of continuity.

But occassionally you need to remember that it really is digital (sampled and quantized).