THE NEXT GENERATION AIRBORNE DATA ACQUISITION SYSTEMS.
PART 1 - ANTI-ALIASING FILTERS: CHOICES AND SOME LESSONS LEARNED

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ABSTRACT

The drive towards higher accuracy and sampling rates has raised the bar for modern FTI signal conditioning. This paper focuses on the issue of anti-alias filtering. Today's 16-bit (and greater resolution) ADC's, coupled with the drive for optimum sampling rates, means that filters have to be more accurate and yet more flexible than ever before. However, in order to take full advantage of these advances, it is important to understand the trade-offs involved and to correctly specify the system filtering requirements.

Trade-offs focus on:

- Analog vs. Digital signal conditioning
- FIR vs. IIR Digital Filters
- Signal bandwidth vs. Sampling rate
- Coherency issues such as filter phase distortion vs. delay

This paper will discuss each of these aspects. In particular, it will focus on some of the advantages of digital filtering various analog filter techniques. This paper will also look at some ideas for specifying filter cut-off and characteristics.

KEY WORDS

Aliasing, Digital Signal Processing, FIR, IIR, Butterworth, Bessel

1. INTRODUCTION

When sampling at Fs, any frequencies above the Nyquist rate (Fs/2) will alias back and appear as signals below Fs/2. In particular, it is impossible to differentiate (and hence remove) these aliased signals from signals within the band of interest. Consequently, it would be useful to have a filter that removes these higher frequencies.

The problem is that there are many trade-offs when choosing this filter:

- Too strong a filter may mean too large a delay

- Increasing the filter cutoff frequency causes the aliasing to increase
- Is acceptable aliasing ever better than no aliasing?
- Some filters types (e.g. Butterworth) distort the shape of the signal
- Some filters types (e.g. Bessel) attenuate all but a small band of frequencies
- Analog filters are familiar but are power- and real-estate hungry
- As ADC resolution increases so does the susceptibility to aliasing
- Digital filters can always beat analog filters except the delay may be slightly larger

This paper examines some of these trade-offs, in particular with respect to upgrading from a 10-bit system to a 12, 14 or 16-bit system.

2. FILTER SPECIFICATION - WITH NO ALIASING

In the past, a reasonable sounding request for a filter might be:

- My sensor has a bandwidth (Fm) of 1kHz and I do not want any signal from it attenuated by more than 1% FSR.
- I have a 10-bit ADC and I want any signal aliased to be less then 1 count.
- I want to use a 6th order Butterworth filter.

For a 6th order Butterworth Filter, the lowest possible setting for the filter cutoff is approximately 1.4kHz. With this filter, signal attenuation is less than 1% of FSR (87 mdB) up to 1kHz. This filter will have an attenuation of 1/1024 (60.2dB) at approximately 4.5kHz. Therefore, to prevent aliasing as specified above, we must sample at greater than 9ksps.

In other words, even for a 10-bit system and 1% attenuation we must sample at **9** times the bandwidth of interest.

Furthermore:

- For a 12-bit system and 0.1% attenuation from the anti-aliasing filter, we must sample at 14 times the bandwidth of interest.
- For a 14-bit system and 0.1% attenuation from the anti-aliasing filter, we must sample at 19.5 times the bandwidth of interest.

For those with bandwidth considerations, the question inevitable arises: is there a better approach?

3. FILTER SPECIFICATION - WITH ACCEPTABLE ALIASING

Acceptable aliasing is the situation where aliasing is allowed but not within the passband. Thus, revisiting the user requirement stipulated in Section 2:

- My sensor has a bandwidth (Fm) of 1kHz and I do not want any signal from it attenuated by more than 1% FSR.
- I have a 10-bit ADC and I want any signal aliased to be less then 1 count.
- I want to use a 6th order Butterworth filter.

we have the required attenuation at approximately 4.5kHz. However, to prevent aliasing **below 1kHz,** we must only sample at greater than 4.5kHz + Fm instead of twice 4.5kHz.

In other words: using this approach for a 10-bit system and 1% attenuation below 1kHz, we must sample at 5.5 times the bandwidth of interest rather than 9 times. This constitutes a 40% saving in data bandwidth required.

However, that's not all – the news gets better:

- For a 12-bit system and 0.1% attenuation below 1kHz, we must sample at 8 times the bandwidth of interest, constituting a 43% saving in the required data bandwidth.
- For a 14-bit system and 0.1% attenuation we must sample at 10.75 times the bandwidth of interest (a 45% saving in data bandwidth required).

The sampling rate advantages of allowing acceptable aliasing are illustrated in Figure 3.1 below. In the figure, the metrological band remains the same, as does the filter. However, by allowing aliasing (outside the metrological band), the sampling rate required is greatly reduced.

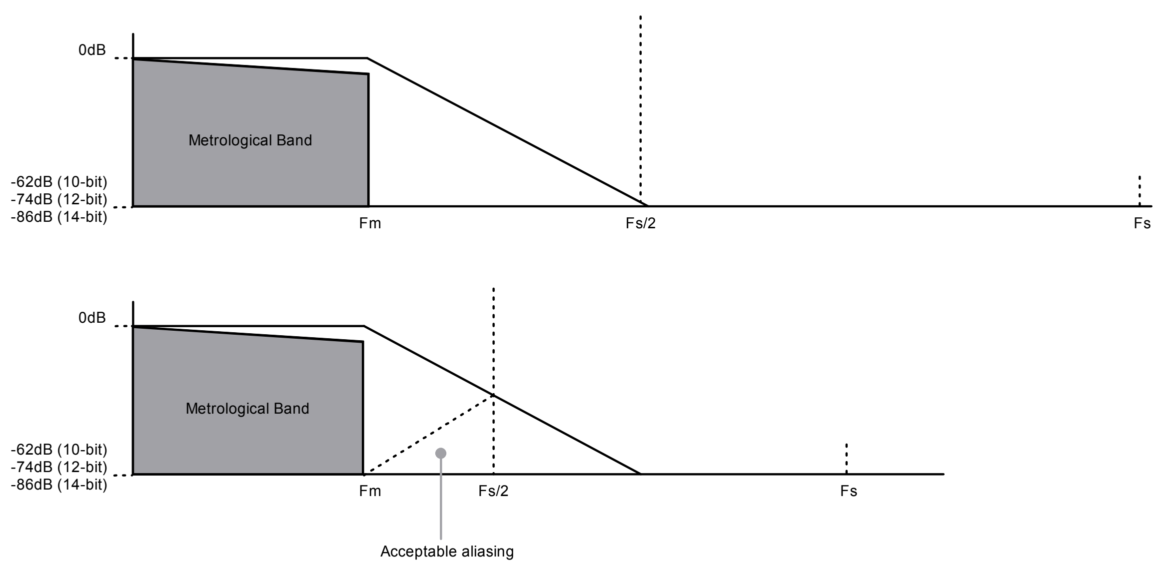

Figure 3.1 - Sampling rates required with and without "acceptable aliasing".

4. INCREASING THE FILTER ORDER FROM 6 TO 8

If, in section 3, the anti-aliasing filter was specified as an 8^{th}-order filter, then the resulting sampling rate would be as follows:

For an 8th order filter, the lowest possible setting for the filter cutoff is approximately 1.3kHz. Here the attenuation is less than 1% of FSR (87 mdB) up to 1kHz. This filter will have an attenuation of 1/1024 (60.2dB) at approximately 3.1kHz. Therefore, to prevent aliasing below 1kHz, we must sample at greater than 4.1ksps.

In other words:

- Even for a 10-bit system and 1% attenuation below 1kHz, we must sample at 4.1 times the bandwidth of interest (a 55% improvement from section 2 above).

- For a 12-bit system and 0.1% attenuation we must sample at 5.4 times the bandwidth of interest (a 61% saving in data bandwidth required).

- For a 14-bit system and 0.1% attenuation we must sample at 6.2 times the bandwidth of interest (a 69% saving in data bandwidth required).

5. SELECTING THE FILTER TYPE - IS BUTTERWORTH THE BEST?

There is no analog filter with a flatter amplitude response in the passband than Butterworth. However, one problem with a Butterworth filter is that, due to its non-linear phase response, signals of different frequencies are delayed by different amounts. This can distort the shape of a signal.

There is no analog filter with a more linear phase response then a Bessel filter. However, it has such a poor roll-off that the sampling rate would have to be many times higher than that required for Butterworth filter, in order to meet the anti-aliasing requirements. Other analog filters, such as elliptical and Chebychev filters are compromises, and are beyond the scope of this paper.

An eighth order analog filter typically requires 4 op-amps, 8 resistors and 8 capacitors, all of which are sources of gain error and non-linearity. Eighth order analog filters also require considerable PCB real estate and power. It is also difficult to have analog filters with programmable cut-off frequencies, especially with 12 or 14-bit systems. Perhaps the solution is to use digital filters?

6. DIGITAL FILTERS - FILTERING AFTER THE A/D

In a scheme whereby filtering is done digitally, a simple fixed 2nd or 4th order filter is placed before an ADC which samples at many times the required sample rate. The ADC values are then filtered using DSP techniques such as IIR (Infinite Impulse Response) or FIR (Finite Impulse Response) filtering.

There are many advantages to this technique:

- Digital filters require fewer analog components, and so there is considerably less drift with temperature and time than with analog filters
- Fewer analog components are used – hence there is less power required

- Fewer analog components are used - hence there is less PCB real-estate required
- ADC white noise is reduced (quantization noise and jitter) because it is spread over the sampling band and removed by the filtering
- Noise above the metrological band causes Dither[1] which actually increases the effective number of bits of the ADC
- Because filter cut-off is a function of the digital filter, many different cut-off frequencies are possible
- Digital filter techniques allow for a passband flatter than the flattest possible analog filter (Butterworth) and with less time distortion then the best possible analog filter (Bessel).

There are two disadvantages to this technique, however:

- Because, for the first time, people can set cut-offs as low as 2Hz, the filter delay is observable with the human eye. For example, an 8th order Butterworth at 2Hz has a delay of between 0.4s and 0.5s depending on the input frequency. This is not a disadvantage of digital filtering it would also happen with analog filters if you set the cutoff frequency to this value.
- The technique is new. Some people don't accept that an 8th order Butterworth filter implemented digitally is exactly the same as one implemented with analog components. They argue that the sample they read is not an ADC sample but is something derived from many ADC samples. In other words, it is not a "true" reading. This is analogous to saying that asking one person to measure the length of a football field gives a truer reading than asking 100 people and averaging the results.

Thus, there are many advantages to digital filtering. The disadvantages really become a question of perception and understanding. As the FTI world moves beyond 12-bit data acquisition and analysis systems, it is almost certain that digital filtering is the only way forward.

At this stage, it is worth looking at the last advantage of digital filtering as listed above, i.e. that digital filters can have a better repine than analog filters. Figure 6.1 compares the amplitude response of one type of digital filter (a 31-tap half-band FIR) with that of an 8th order Butterworth.

1 Dither is low power noise which is added to the system. The literal meaning of the word dither is to tremble or quiver - a reference to the least significant bits being turned on and off at random.

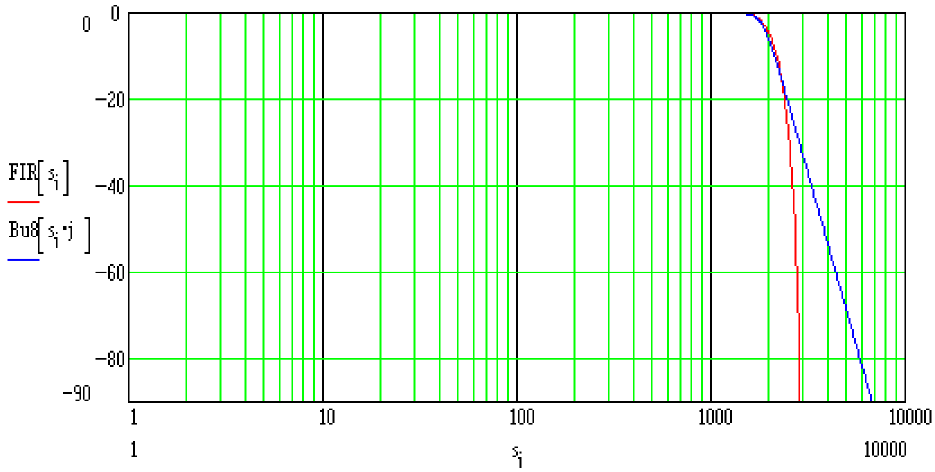

Figure 6.1 – Amplitude response of an 8th order Butterworth filter and a 31-Tap Halfband FIR Filter

Both filters have roughly the same passband (±10mdB). However the sampling rates required for each are very different, as illustrated below:

With no aliasing:
- The FIR requires sampling at 8192sps.
- The 8th order Butterworth requires sampling at 14,000sps (70% more than FIR).

With aliasing allowed down to 1kHz:
- The FIR requires sampling at 4096sps.
- The 8th order Butterworth requires sampling at 8,000sps (100% more than FIR).

7. DELAYS AND DATA BANDWIDTHS - FOR COMPLETENESS

The delay of the 8th order Butterworth filter in the example above varies from 440µs (at DC) to 540µs (at 1.8kHz). However the delay of the FIR filter at 4096sps is 1953µs (for all frequencies).

However, if the cut-off point of the 8th order Butterworth filter was moved down so that both could be sampled at 4096sps, then the graphs would look like those in Figure 6.2. In Figure 6.2, the bandwidth of the Butterworth filter has halved and the delay has increased to 1282µs.

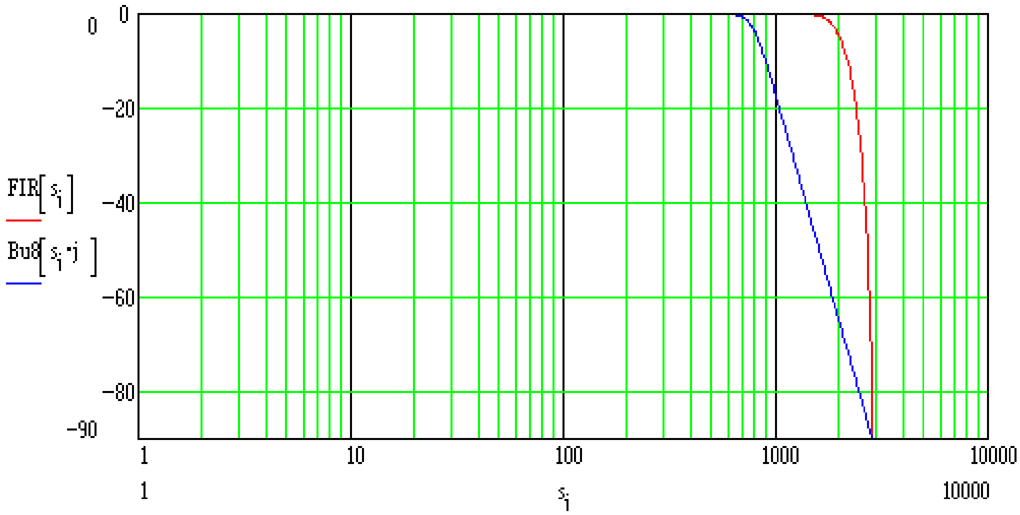

Figure 6.1 – FIR and 8th Order Butterworth filter with acceptable aliasing at 4096sps.

If 16-bit data is used instead of 12-bit data then there is an automatic 33% increase in the data bandwidth unless the sampling rate can be reduced.

8. CONCLUSION

As FTI moves beyond 10-bit and 12-bit systems, towards 14-bit and 16-bit systems, care has to be taken not to increase the volume of data transmitted unnecessarily. The extra data rate required is not only a function of the extra bits from each ADC sample, but from the faster sampling rates required to achieve the corresponding reduction in aliasing acceptable for those higher ADC resolutions.

This paper suggests that "acceptable aliasing" and higher order filters go some way towards reducing the data rate, but that digital filtering may also hold a vital key, as illustrated in this final example.

For a 14-bit system and 0.1% attenuation beneath 1kHz we must sample at:

- 19.5 times the bandwidth of interest (with 6th order filter and no aliasing)
- 10.75 times the bandwidth of interest (with 6th order filter and acceptable aliasing)
- 6.2 times the bandwidth of interest (with 8th order filter and acceptable aliasing)
- 4.1 times the bandwidth of interest (with a FIR filter and acceptable aliasing)