

November, 2011

Summary

Both LeCroy's ERES (Enhanced Resolution) math operation and the Tektronix HiRes (High Resolution) acquisition mode are FIR (Finite Impulse Response) filters. Their function is to remove high bandwidth components of the signal and high bandwidth components of acquisition noise from a waveform. Beyond that basic similarity the two operations are completely different on both a mathematical and operational level.

How Do They Work ? (ERES)

ERES is a post-acquisition processing function available in many LeCroy oscilloscopes. The user controls the amount of filtering desired. In the examples in Figure 1a and 1b, the dialog box in the lower right hand corner shows the user is requesting 2.5 additional bits of vertical resolution. The user can request 0.5, 1, 1.5, 2, 2.5 or 3 bits of enhanced resolution. Of course extra resolution comes at a cost. The tradeoff is shown in the dialog box. The bandwidth of the ERES math waveform is less than the bandwidth of the originally acquired waveform. The dialog box shows the bandwidth of the math waveform is 36.25 MHz. This is 0.029 x the Nyquist bandwidth of the original acquisition. The original acquisition was done at 2.5 GS/s (note the Timebase rectangle near the lower right corner of Figure 1a) for which Nyquist criteria would say the scope could capture signal frequencies up to 1.25 GHz. But the filter reduces the bandwidth of the math waveform. The operation trades bandwidth for vertical resolution. Shorter filters offer less vertical enhancement and give up less bandwidth. Table 1 shows the choices available when using the LeCroy ERES math operation.



Figure 1a: The ERES setup dialog as a math function in the lower right corner. The full bandwidth trace of ADC samples is the upper trace. The lower bandwidth ERES trace is below.

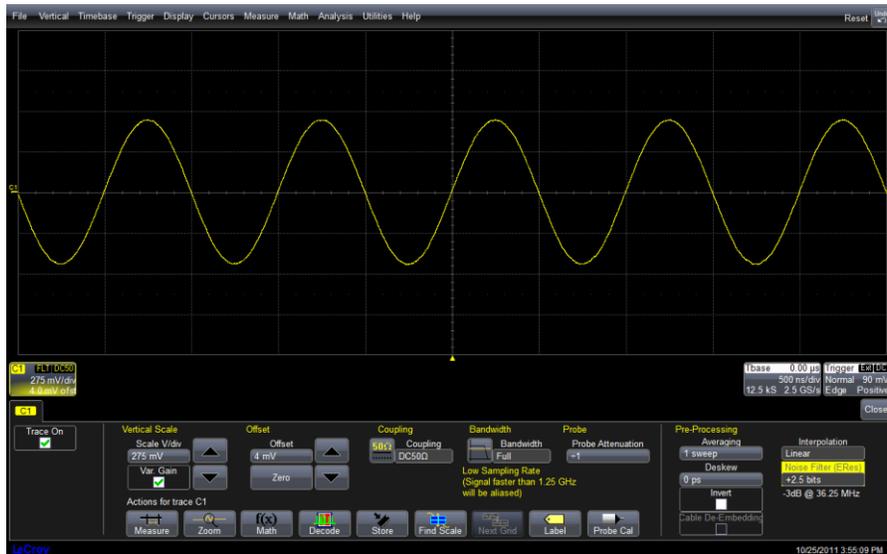


Figure 1b: ERES is accessed via the setup menu for channel 1. The ERES trace is displayed. If desired, the channel 1 trace can also be viewed/measured. Using either the method in Figure 1a or 1b the user has control of the filter length, extra vertical resolution and the resulting bandwidth of the new waveform

A crucial factor in any filter is the mathematical shape of the filter that is applied. In the case of ERES, the math function creates a new waveform in which each point is computed from a weighted average of the original ADC samples. Each of the new “math” samples is computed by giving the “raw” sample that was acquired at a certain point in time the most weight, the two samples which were acquired one sample period previous and one sample period after that time are given less weight, the two samples that were acquired at +2 and -2 sample periods are given even less weight in computing the new sample and so forth for the length of the filter (see Figure 2).

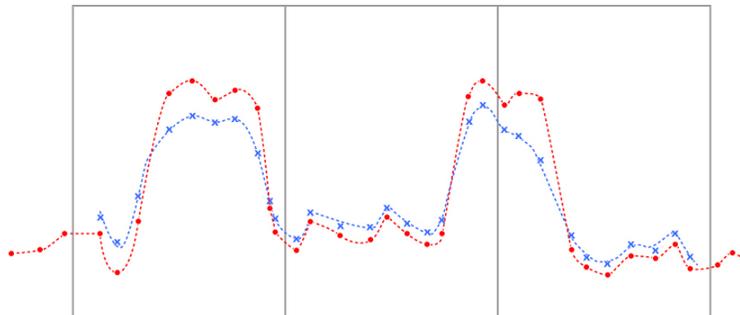


Figure 2: This artist's rendition shows the process followed by ERES. The original waveform is captured and displayed (if desired) – red line. The ERES filter (blue line) replaces each point of the original waveform with a new point. The ERES waveform has lower bandwidth

Essentially, the raw data samples acquired closer to a particular point in time are given more weight and those acquired farther away in time are given less weight. Mathematically, each new point is the sum from $-N/2$ to plus $N/2$ of the ADC data samples times a bell shaped weighting curve (where N is the filter length). The new math waveform has the same number of points as the originally acquired waveform except that at the beginning and end of the waveform there are not enough points to compute the filtered result. So the math waveform has N points less than the original ADC samples. For a 100,000 point acquisition and a vertical resolution enhancement of 2 bits the filter length is 25 (Table 1) and so the resulting ERES math waveform is 99,975 points in length. Typically this reduction in record length is too short to be noticeable to the user.

Table 1 The Enhanced Resolution Filter Parameters		
Resolution Enhancement [Bits]	-3 dB Bandwidth [x Nyquist]	Filter Length [samples]
0.5	0.5	2
1	0.241	5
1.5	0.121	11
2	0.058	25
2.5	0.029	52
3	0.016	106

As a final note concerning LeCroy’s implementation of ERES it should be noted the set of filters are linear phase FIR filters which are optimized for fast computation, excellent step response and minimum bandwidth reduction. The linear phase response means the filters do not distort the relative positions of different features of the waveform even if the frequency content of the two features is different. Since the math is done as a post-acquisition math process, the user can view both the original ADC sampled waveform as well as the ERES, filtered waveform. If desired, the user could even display the raw waveform and a selection of several waveforms that incorporate different levels of filters.

How Do They Work ? (HiRes)

HiRes is an acquisition mode (not a math function). When the user selects HiRes Acquisition mode a Tektronix scope runs its ADC at maximum rate and performs a “boxcar” filter which averages several sequential samples and saves the averaged number into memory. The number of ADC sample points input into the filter/average process is the ratio of the total ADC samples available at max sample rate to the number of samples requested by the user for the displayed waveform. For example, if a scope is running at its maximum sample rate and acquires 100,000 samples and the user requests a waveform of 100,000 samples then no filtering occurs but if the user requests only 10,000 samples in the displayed waveform then HiRes will average each group of 10 ADC samples into one HiRes sample. There is no weighting curve to the averaging – it is a simple summation of N samples, divided by N. The averaging occurs “on the fly” as the samples are acquired. The original ADC samples are not available to the user – they are lost in the process of HiRes filtering. See Figure 3.

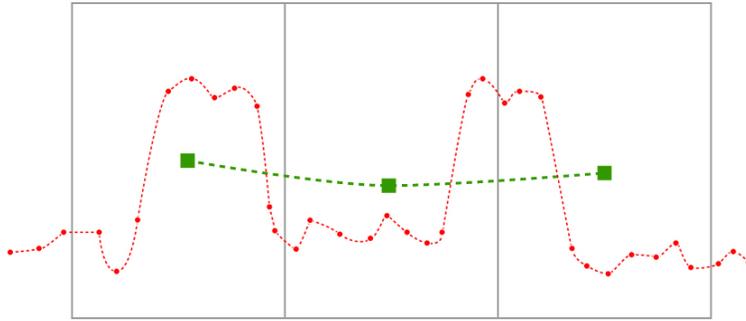


Figure 3: The same ADC sample points (red) as in Figure 2. In this artist's rendition, HiRes averages each group of 10 ADC sample points to produce one HiRes waveform point. The HiRes waveform has lower bandwidth and 10 times fewer points

Examining Figure 3 shows that of the first 10 points there are 5 which are “high.” In the second group of 10 points 2 are “high” and in the final group 3 are “high”. If the first five points in the first set of ten were high or if the last five points were high (and in both cases the other five points are low), then HiRes puts the same number onto the display – the position of the signal feature, the five high points, has no effect. In the case of the second set of five “high” points, two are in the middle set of 10 points and affect that value of the HiRes waveform and three are in the final set of 10 points and affect a different point of the HiRes waveform. The signal feature formed by the 5 consecutive “high” samples gets split up. Part is moved forward in time and part is moved backward.

The user has very little control of HiRes mode. It can be turned on or off. If it is turned on, the user has a limited amount of control by selecting the number of samples in the displayed waveform. The scope does not tell the user whether any filtering is being done, does not list the length of the filter or report the loss in bandwidth due to the filter implementation.

Many oscilloscope users have become accustomed to thinking of the record length as a way to increase horizontal resolution. For a certain timebase, adding more samples to a waveform by using a larger memory can allow an increased ADC sampling rate and give better horizontal resolution. When using HiRes mode there is a much different effect to changing record length. If the user activates HiRes acquisition mode, then for a certain timebase, decreasing the requested waveform record length will increase the vertical resolution of the waveform – at the cost of decreasing the number of horizontal points and decreasing the bandwidth. In the discussion of ERES above we looked at the example of 100,000 ADC samples and a filter length of 25 points. The resulting waveform was 99,975 points. As a contrast, in HiRes mode with 100,000 ADC samples and a filter length of 25 the displayed waveform is 4,000 points (each group of 25 ADC sample points gets averaged into one point). If the user tried to tell a Tek scope to acquire 100,000 ADC samples and display a HiRes acquisition of 99,975 points then HiRes would do nothing. As a minimum, HiRes needs to decimate the ADC record length by at least a factor of 2 (i.e. it needs to average at least 2 ADC samples to create a new point).

Readers who are familiar with filter techniques or who are mathematically inclined have already figured out the bandwidth reduction from a boxcar shaped FIR filter is larger than for a bell shaped filter of the same length. As cited in the Tektronix application note on acquisition modes:

One drawback of High Resolution mode grows from the use of a “boxcar” averaging technique that causes the frequency response to roll off quickly. The low pass filter acts like a one pole filter, with -3dB bandwidth at the displayed sample rate divided by 2.5.

Table 2a shows the bandwidth reduction of Tek’s HiRes acquisition mode as a function of filter length. This table comes from the Tektronix web site. Table 2b restates the information in Table 2a in a way that makes it easier to compare with Table 1. The reader can see the difference in bandwidth reduction for various filter lengths and for various numbers of extra vertical bits.

Table 2a HiRes example results at 5 GS/s base sample rate 8 bit oscilloscope

Sample Rate	Bits of Resolution	3 dB Bandwidth Limit (0.44 x Sample Rate)
2.5 GS/s	8.5 bits	1.1 GHz *
1 GS/s	9 bits	440 MHz
250 MS/s	10 bits	110 MHz
50 MS/s	11 bits	22 MHz
10 MS/s	12 bits	4.4 MHz
2.5 MS/s	13 bits	1.1 MHz
1 MS/s	14 bits	440 KHz
250 KS/s	15 bits	110 KHz
25 KS/s	>15 bits	11 KHz
250 S/s	>15 bits	110 Hz
25 S/s	>15 bits	11 Hz
2.5 S/s	>15 bits	1.1 Hz

*This is the filter bandwidth, oscilloscope bandwidth will be determined by the analog bandwidth of the 1 GHz front end amplifier.

Table 2b Reduction in Bandwidth of a HiRes Filter For 5 GS/s ADC scope (Nyquist 2.5 GHz)			
Resolution Enhancement [Bits]	-3 dB Bandwidth of scope (GHz)	-3 dB Bandwidth (x Nyquist)	Filter Length [samples]
0.5	1.0	0.4	2
1	0.44	.176	5
2	0.11	.044	20
3	.022	.0088	100

There is also a more subtle effect that users should watch out for when applying the HiRes mode. All oscilloscopes make estimates of a waveform shape by using the numbers in the memory that describe the waveform (either ADC numbers or filtered/processed numbers) and then connecting those points using an interpolation algorithm that displays an estimated waveshape on the screen. Both LeCroy and Tektronix oscilloscopes allow the user to choose either linear or Sin(x)/x interpolation. In LeCroy scopes, linear is the default while in Tek scopes Sin(x)/x is the default. There is a mathematical artifact called “Gibb’s Ears” which will

occur when trying to display an undersampled edge using $\text{Sin}(x)/x$ interpolation. The Gibb's Ears show overshoot and ringing before and after an edge – even when the actual waveform has no overshoot and ringing. In Figure 4 (upper trace) a waveform is acquired at 5 GS/s, the maximum rate of the ADC – no HiRes filtering. In Figure 4 (lower trace) the same waveform is acquired in HiRes mode but the user has asked for increased vertical resolution by setting the displayed sample rate to 500 MS/s by changing the displayed memory length. Note the pre-shoot and ringing the scope now shows before each edge.

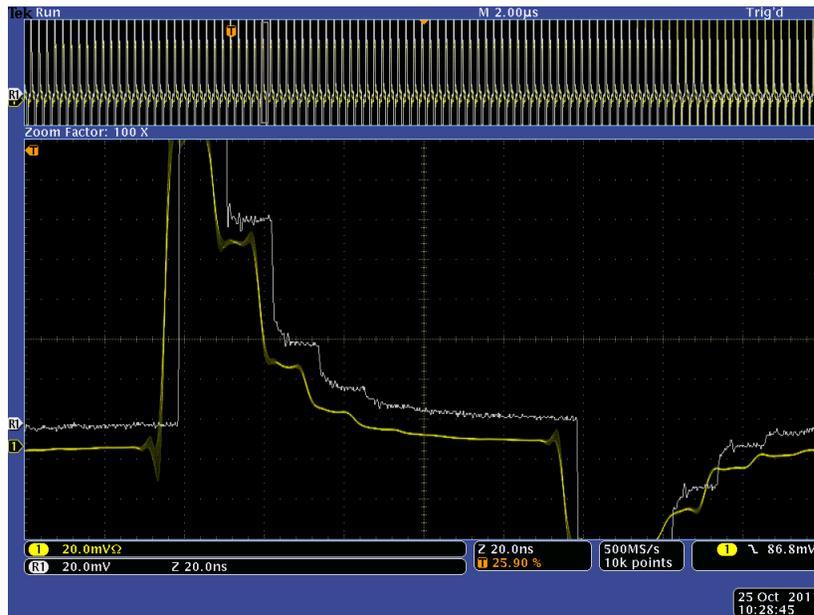


Figure 4: A waveform acquired using first 5 GS/s normal acquisition (grey/upper) and then with HiRes mode (yellow/lower). HiRes keeps the ADC running at 5 GS/s but compacts each group of ten ADC samples into one sample making the effective sample rate 500 MS/s. Note the HiRes view of the waveform has Gibb's Ears artifacts (preshoot) added prior to the edges. Also, even with a short filter length of 10 samples the pulses are much more rounded – a substantial loss of bandwidth

An uninformed user might think there is real overshoot on the signal but actually the signal edges are fine- the overshoot is a mathematical artifact from using $\text{Sin}(x)/x$ interpolation on an undersampled edge. If an ADC captures 10 samples on an edge the shape of the edge is very precisely determined and any interpolation algorithm will show an excellent view of the edge shape. But if the scope now applies a boxcar average that decimates the sample record by a factor of 10 then there remains only one sample on the edge – resulting in Gibb's Ears. In general, less than 2 samples on an edge will result in Gibb's Ears if $\text{Sin}(x)/x$ interpolation is applied.

As a contrast, recall that ERES replaces each of the ADC samples with a new computed sample. There is no reduction in the number of samples in the waveform except at the very beginning and end of the record.

Figure 5 shows a single acquisition in a LeCroy scope which is then filtered with 3 different filter lengths; 3 different ERES filters that add 1, 2, and 3 bits of additional resolution. The filter lengths are 5, 25 and 106 points. You will notice that no Gibb's Ears appear.

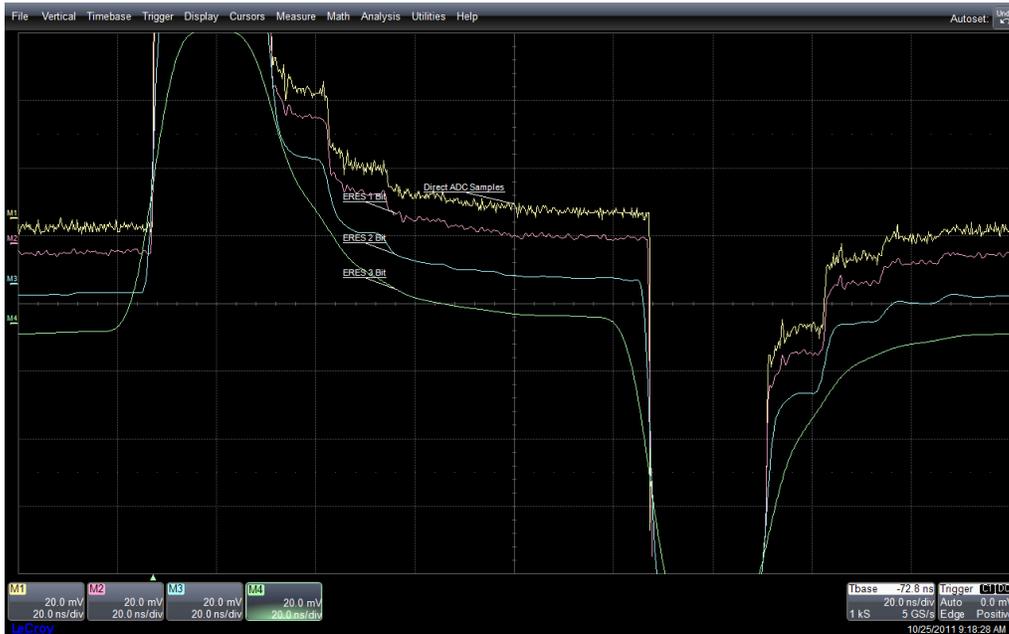


Figure 5: The same signal as in Figure 2. This time it is captured on a LeCroy 8 bit oscilloscope using the same 5 GS/s sample rate. The top trace is the ADC samples, then 1, 2 and 3 bits of ERES. ERES maintains the 5 GS/s sample rate (no compaction). Note there are no Gibbs Ears artifacts and also that the noticeable loss of bandwidth does not come until the 3 bit enhancement (106 point length filter)

Advanced Applications of Filtering

Suppose you would like to eliminate the low bandwidth portion of a waveform in order to get a better view of the high frequency components. Perhaps you have a signal that looks much too noisy and you would like to investigate the cause of the noise. Figure 6 shows an example in which ERES is used to filter out the high frequency components of a waveform. Since the scope also still has the original ADC waveform in memory, the two traces can be subtracted. The result is a waveform that contains only the high frequency noise. In this case the noise looks like pickup of bursts of noise at a stable frequency. This is excellent insight which will likely help in troubleshooting the source. This type of troubleshooting technique is not available using HiRes since the original ADC sampled waveform is not available. Even if the user saved an ADC acquisition in memory and subtracted from it a subsequent HiRes acquisition this would be problematical since HiRes can move signal features and because the user would be subtracting two different waveforms (different acquisitions of the signal).

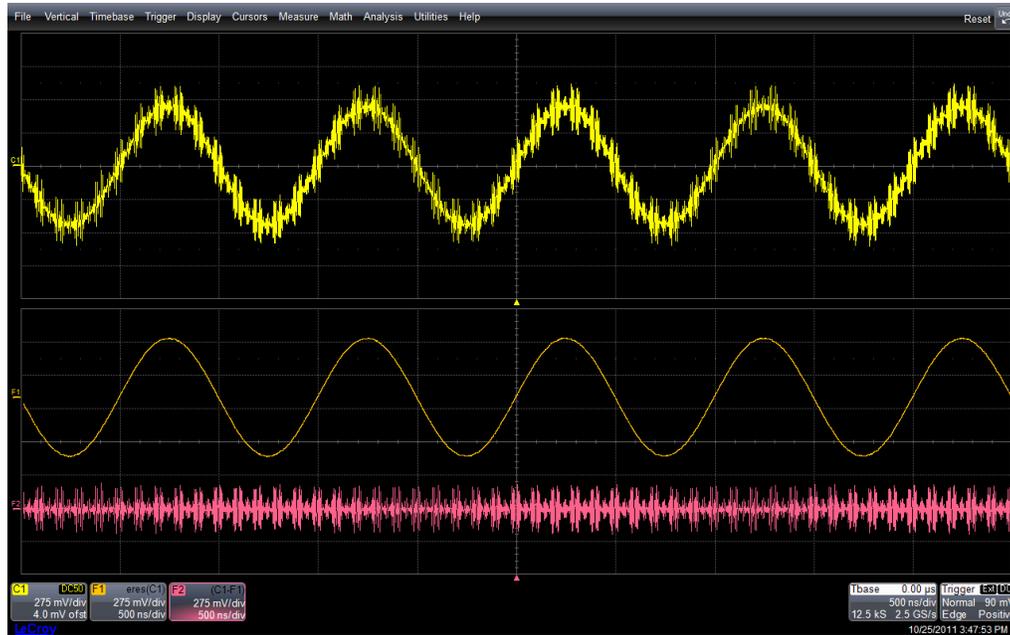


Figure 6: The raw signal, C1, is in the top trace. F1 is an ERES filtered view of C1. F2 is channel 1 minus F1. The high bandwidth noise looks like cross talk of noise bursts at a fairly stable frequency

In addition to ERES, which is standard in many LeCroy scopes, LeCroy offers an optional digital filter package (DFP2) which allows the user to easily create FIR and IIR (infinite impulse response) filters. The user can select a wide variety of filter shapes including high pass, low pass, notch, Butterworth, Bessel, Chebyshev and Inverse Chebyshev. A variety of application notes on the use of filters is available in the technical library at www.LeCroy.com.

Final Note

Keep in mind that all filters change the shape of a waveform. If your basic desire is to see your waveform as clearly as possible, the best solution is to acquire it with as little added noise as possible from the acquisition process. Keep in mind that removing noise by applying a filter may mislead you if the scope performs any type of measurement of signal quality – because your filter has removed a part of the signal. Obviously this includes measurements such as signal to noise ratio, eye diagrams and jitter measurements (where a primary source of jitter is often the vertical noise in the signal). But a filter can also affect measurements of pulse width, risetime, overshoot and other signal qualities because noise on an edge affects its position. If you find yourself using a (common) 8 bit oscilloscope with filters and hoping the filters are not affecting your measurements it may be a good idea to try a very low noise HRO (high resolution, low noise 12 bit oscilloscope).

ERES Summary

- Math function which creates a new, filtered waveform by computation on the ADC samples
- Filter coefficients are bell shaped
- As with all filters, ERES will remove some portion of the true signal content.

Advantages

- ADC sampled waveform is still available for view/measurement
- Preserves more bandwidth than boxcar filter
- Oscilloscope allows user control of filter length, extra resolution and new bandwidth
- Other math functions can be applied before or after ERES
- Will not cause shift in time of waveform features
- Cannot cause Gibb's Ears (false overshoot)

Disadvantages

- For a filter length of N, the ERES waveform is N points shorter than the ADC waveform
- Requires substantial processing power (but this is easily available in modern scopes)

HiRes Summary

- An acquisition mode which replaces ADC samples with a new, filtered waveform
- Each group of N ADC samples creates one point of the new waveform via boxcar filter/average
- As with all filters, HiRes will remove some portion of the true signal content

Advantages

- Very little processing power required

Disadvantages

- Original ADC samples are lost – not available for view or measurement
- For a filter length of N, the HiRes waveform decimates the ADC samples by a factor of N times
- Can cause Gibb's Ears signal artifacts (false overshoot)
- Decreases bandwidth faster (relative to extra bits of vertical resolution) than bell shape filter
- Oscilloscope does not give controls for filter length, extra resolution or new bandwidth to the user
- No math function can be applied prior to HiRes.
- HiRes can cause a shift in time of signal features