

Choosing the ISI Filter Size for EZJIT Plus Arbitrary Data Jitter Analysis

Application Note 1574

Introduction

RJ/DJ analysis is a relatively new technique for analyzing timing jitter that separates a signal's aggregate total jitter into random and deterministic components. This capability allows you to estimate peak-to-peak jitter values at very low bit-error-rate levels. Measuring these values directly is very time consuming. An added benefit of this technique is that it provides a basic diagnostic understanding of the jitter's underlying cause.

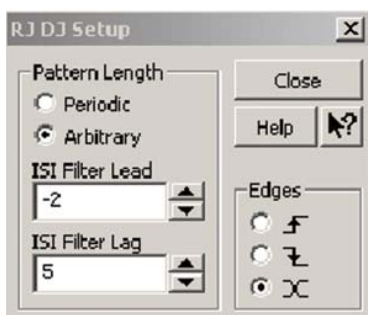


Figure 1. ISI filter controls in EZJIT Plus's RJ/DJ Setup menu



EZJIT Plus is an optional jitter analysis package that runs on Infiniium real-time oscilloscopes from Agilent Technologies, Inc. and performs RJ/DJ analysis. EZJIT Plus uses two different analysis techniques depending on whether you specify that the data pattern is periodic or non-periodic. Arbitrary Data mode is used to analyze signals with data patterns that are either not periodic or their pattern length is too long to be analyzed using the Periodic Data mode.

In Arbitrary Data mode, the EZJIT Plus GUI (graphical user interface) allows you to select the number of leading and lagging coefficients contained in EZJIT Plus' ISI Filter (see Figure 1). Selecting an appropriate number of coefficients is important because it allows you to trade-off accuracy and measurement time. However, selecting the best coefficients is not always easy. This document describes several methodologies for choosing appropriate ISI filter coefficient settings.

What Is ISI?

ISI is an acronym for “inter-symbol interference.” This term is loosely used to refer to any data-dependent signal distortion or signal distortion that is correlated to the transmitted data pattern. ISI is most-commonly caused by insufficient bandwidth of transmitters or transmission channels. However, it can be caused by anything that causes distortion of a transmitted data signal that is correlated to the data pattern itself, including transmission line discontinuities and poor power supply by-passing.

Figure 2 illustrates how non-flatness in a transmitter’s step response can cause ISI. The figure displays two transmitter output waveforms for each of the two serial data sequences, pattern A and pattern B. The red dotted traces represent the output of an ideal transmitter with a well-controlled step response, while the solid black traces represent the output of a poor transmitter with a non-flat step response. Notice that in pattern A the rising edges cross the threshold at the same time. Also notice that the rising edge of the poor transmitter in pattern B does not transition at the expected, or desired, position in time, but is delayed from that of the ideal transmitter. This erroneous delay is caused by ISI. The falling edge of the poor transmitter in pattern B “interferes” with the rising edge because the falling

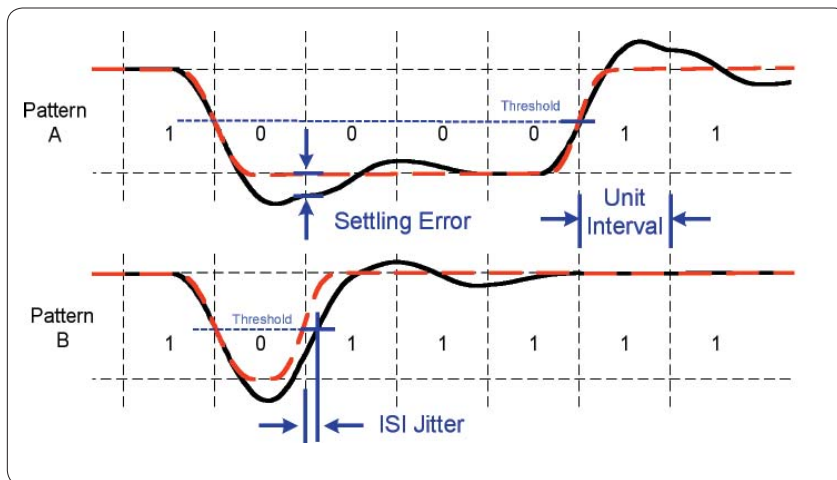


Figure 2. This figure illustrates how non-flatness in a transmitter’s step response can cause ISI jitter in its transmitted data signal. The red dotted traces represent an ideal transmitter, while the solid black traces represent a transmitter that produces ISI.

edge has not settled completely to the logic zero voltage before the next rising edge occurs. The rising edge of the non-ideal waveform in pattern A does not suffer from ISI because its transition occurs after the previous falling edge has had time to completely settle to the logic zero value.

It is important to note that ISI is not always linear. ISI that differs between rising and falling edges, for example, is not linear. ISI is not always causal either. Most ISI that appears on a particular edge of a data pattern (victim edge) is caused by other transitions in the pattern (aggressor edges) that were transmitted prior to the victim edge. However, in buffered or pipelined systems, it is possible for the ISI of an aggressor edge to affect a victim edge that precedes it in the transmitted data pattern.

The above description is a general definition of the term ISI. Be careful not to confuse this with the very specific definitions of measurement results that EZJIT Plus reports. EZJIT Plus reports three jitter values that are all correlated to the data pattern, and therefore are related to the above definition of ISI. These three values, DDJpp, ISJpp and DCD are explicitly defined as follows:

- Data-dependent jitter peak-to-peak, DDJpp, is equal to the peak-to-peak range of time errors that are correlated to the source waveform’s serial data pattern.
- Inter-symbol interference peak-to-peak, ISJpp, is the range of DDJ (data-dependent jitter) from rising edges or the range of DDJ from falling edges, whichever is greater.

- Duty-cycle distortion, DCD, is defined as the absolute value of the difference of the mean of the DDJ from rising edges and the DDJ from the falling edges.

What Is an ISI Filter?

EZJIT Plus's Arbitrary Data mode analysis uses a linear regression technique to extract the data-dependent component of jitter from the total jitter. The linear regression used in EZJIT Plus is similar to that used in echo cancellation or other adaptive filtering applications. A by-product of this linear regression analysis is a set of coefficients that describe how the data-dependent jitter can be calculated from the transmitted data pattern. EZJIT Plus refers to this set of coefficients as the ISI filter.

EZJIT Plus's ISI filter is similar to a standard FIR (finite impulse response) digital filter in that the ISI filter is convolved with the input data pattern in order to calculate the data-dependent jitter function. The ISI filter differs from a standard FIR filter in that its output is a TIE (time- interval error) function, or a time error vs. time function that is sampled at the input signal's voltage transitions. The ISI filter also differs from an FIR filter in that its input function represents data transitions (rising edge, falling edge) instead of data amplitudes (logic 0 level, logic 1 level). Standard FIR filters are

linear operators, but DDJ can be a non-linear function of the data pattern. So the ISI filter is actually comprised of four separate sets of linear coefficients, each corresponding to one of the four combinations of 1) rising edge victim, rising edge aggressor, 2) rising edge victim, falling edge aggressor, 3) falling edge victim, rising edge aggressor, 4) falling edge victim, falling edge aggressor.

Figure 3 shows an example ISI filter generated within the EZJIT Plus jitter analysis application. Similar to a conventional filter impulse response, the leading coefficients represent pre-shoot, while the lagging coefficients represent over-shoot and ringing. You can see in this ISI filter that all four sets of coefficients are

closely aligned with one another, indicating very little non-linearity in the signal's DDJ.

EZJIT Plus finds the optimum ISI filter from which it can calculate a DDJ function that matches the measured total jitter with the least mean-squared error. EZJIT Plus can find this optimum ISI filter using any number of positive or negative coefficients, but there are trade-offs to be made between using ISI filters of different sizes (numbers of coefficients). If you use an insufficient number of coefficients, the resultant DDJ function will not include all the true DDJ in the measured signal. Conversely, if you use too many coefficients, the time required to make an accurate measurement becomes excessive.



Figure 3. This ISI filter graph shows how the transitions surrounding each bit affect that bit's data-dependent jitter.

Modeling with the Step Response

Choosing the appropriate number of leading and lagging ISI Filter coefficients is easy if your transmission system's ISI is dominated by a single signal step response and you already know something about its shape. If you know, for example, that your system's dominant step response is causal (DDJ on each bit is only affected by other bits that have already been transmitted) then you can choose to use zero leading coefficients. If you know that the transmission channel has a large discontinuity that produces echoes (re-reflections) 20 unit intervals after a voltage transition, then you need to use at least 20 lagging coefficients. However, if you know that your step response settles sufficiently in two unit intervals, then you should only use two lagging coefficients.

Now, before you ask what "settles sufficiently" means, consider this simple estimate. A settling error of E from an aggressor transition will produce a timing error of approximately $J = M / E$ on a victim transition with a slew rate of M , where E is in percent of the nominal logic swing, J is in time, and M is in percent of logic swing per unit time. Keep in mind that this equation estimates the time displacement of a single aggressor edge on the victim edge. If the actual

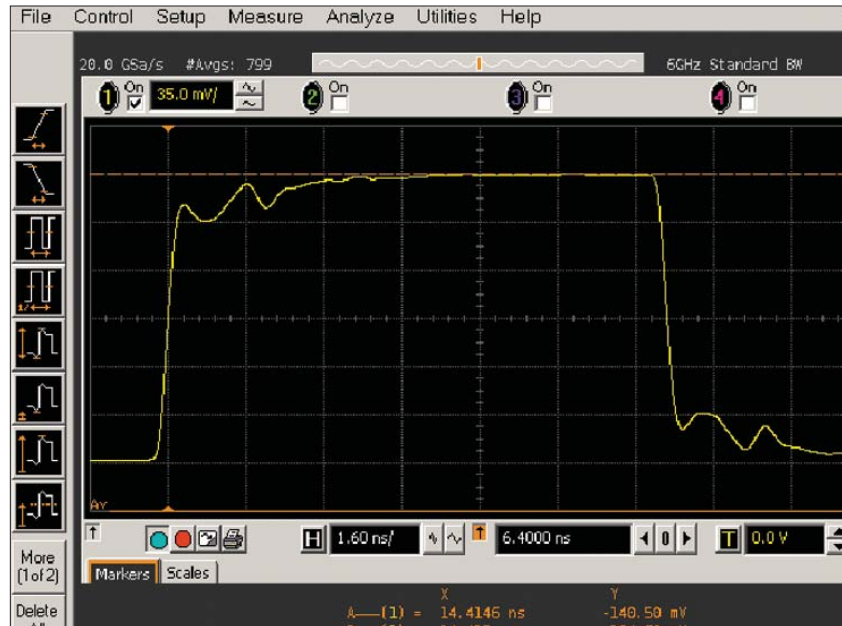


Figure 4. Step response analysis showing poor channel characteristic

ISI extends for multiple unit intervals, the total DDJ will be the aggregate of time displacements from all appreciable aggressor edges.

Although it is not always practical, sometimes you can measure or simulate the system step response by transmitting a repeating long sequence of logic zeros followed by a long sequence of logic ones. The settling time of the step response can then be evaluated with respect to integer numbers of the signal's unit interval. Figure 4 is an example of a step response measurement on a 3.125-Gb/s system with a poor transmission channel. This step response was generated by transmitting an alternating

pattern of 32 logic zeros followed by 32 logic ones. The horizontal scale of the oscilloscope's display was chosen such that there are 5 unit intervals per major division on screen.

Since there appears to be no pre-shoot, or perturbations before the rising edge, no leading ISI filter coefficients should be needed to measure the jitter of this signal. Since the step response appears to settle within a few percent after about 10 or 11 unit intervals, 10 or 11 lagging coefficients is probably enough to use for the ISI filter.

Iterative Technique

In cases where you know nothing about the system's step response, you can usually find the optimum ISI filter by evaluating jitter measurement results while sweeping the ISI filter settings. Theoretically, making the ISI filter longer (adding coefficients) gives the ISI filter more degrees of freedom with which to model the DDJ. If you use too few coefficients, the measurement results will be incorrect. If you use too many coefficients, the measurement results will be correct, but it will take much longer to calculate them.

Minimizing RJ

It turns out that the RJrms value is the best indicator for evaluating the effectiveness of the ISI filter. This is because using too few coefficients does not allow the ISI filter to calculate all the DDJ in the signal. Any DDJ that is not calculated by the ISI filter and then is removed from the TJ (total jitter), is treated by EZJIT Plus as RJ (random jitter) and PJ (periodic jitter). Assuming that the data pattern is not a short periodic pattern, this residual DDJ will appear to EZJIT Plus

as RJ, increasing the reported RJrms value. Of course this residual DDJ would appear to EZJIT Plus as PJ if a short periodic data pattern were used, but in that case you would be using the Periodic Data mode of EZJIT Plus instead of the Arbitrary Data mode.

Normally the reported RJrms value decreases monotonically as the number of ISI filter coefficients is increased. Since the measurement time increases exponentially as the number of ISI filter coefficients is increased, it is best to use the smallest number of coefficients that produce an acceptably small RJrms value.

Sometimes (e.g., very large PJ with very small RJ) using too many ISI filter coefficients can actually increase the reported RJrms value. This happens because the number of waveform acquisitions required to resolve the ISI filter becomes very large, and small errors in the ISI filter convert some of the input PJ to RJ. In these situations the optimum number of filter coefficients is easy to choose because it is simply the number of coefficients that produces the minimum reported value of RJrms.

Maximizing DDJ

In rare cases, the amount of RJ in the signal is much larger than the amount of DDJ in the signal. For these signals the reported value of RJrms may be insensitive to ISI filter size. Normally, you would be satisfied with a very short ISI filter because the DDJ's contribution to the TJ is negligible. However, you can often improve the accuracy of the reported DDJpp value by increasing the number ISI filter coefficients. Just make sure you don't use so many that they increase the reported RJrms value or increase the measurement time excessively.

Averaging measurement results

The variance in EZJIT Plus's Arbitrary mode measurement results decreases with the number of acquisitions that are allowed to accumulate. So comparing small differences in RJrms, for example, often requires waiting for several acquisitions to accumulate. In fact, it is sometimes useful to average the results of a few measurements, where each measurement is comprised of several acquisitions. It is also sometimes useful to increase the waveform memory depth of your acquisitions. Even though each acquisition will take longer to compute, the variance of your measurement results can actually converge faster.

Putting It All Together

The optimum number of leading and lagging coefficients that you should use when performing EZJIT Plus measurements in Arbitrary Data mode is the minimum number that allows the ISI filter to correctly model the DDJ in the measured signal. So if you know the time duration (in unit intervals) of the DDJ, you can enter those values directly. If you don't have any prior knowledge of the DDJ in the signal, you can use the following procedure to determine an appropriate number of coefficients:

1. Set both the lead and lag values to zero.
2. Perform three measurements accumulating five acquisitions each, and record the average of the three RJrms values.
3. Increase the lag value by one and repeat step 2.
4. Repeat steps 2 and 3 until the average RJrms value hits a minimum value or settles to an acceptable accuracy.
5. Decrease the lead value by one and repeat step 2.
6. Repeat steps 2 and 5 until the average RJrms value hits a minimum value or settles to an acceptable accuracy.
7. If the variance of the three RJrms measurements using the final ISI filter settings seems too large, repeat steps 1-6 using 5 more measurements of 10 acquisitions each.

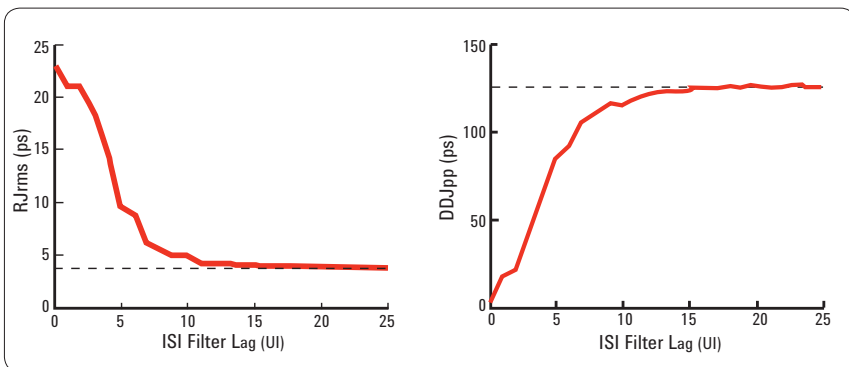


Figure 5. These two graphs plot the intermediate RJrms and DDJpp measurement results from sweeping the number of lagging ISI filter coefficients while holding the number of leading coefficients equal to zero.

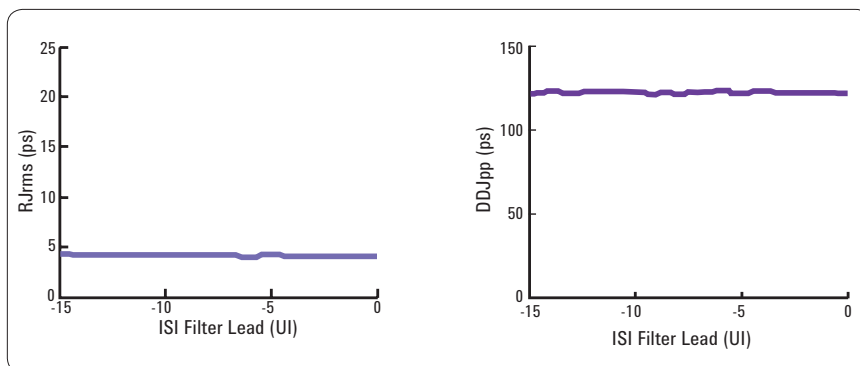


Figure 6. These two graphs plot the intermediate RJrms and DDJpp measurement results from sweeping the number of leading ISI filter coefficients while holding the number of lagging coefficients equal to 11.

Note that averaging three iterations of five acquisitions each can be a bit time consuming and is not usually necessary, but is recommended here because it almost always works the first time.

Figure 5 and **Figure 6** graph the intermediate results of using the above procedure on the same transmitter used in the example of **Figure 4**. Both graphs in **Figure 5** were generated by sweeping the number of lagging

ISI filter coefficients while keeping the number of leading coefficients fixed at 0. It is apparent from these two graphs, that 11 lagging coefficients should be enough to model the DDJ accurately. The graphs in **Figure 6** were generated by sweeping the number of leading ISI filter coefficients while keeping the number of lagging coefficients fixed at 11.

These graphs show that the measurement results are independent of the number of leading coefficients. Since using more coefficients makes the measurement take longer, zero leading coefficients should be chosen.

Conclusion

In this application note, we explained how EZJIT Plus uses the ISI filter to model DDJ within a measured data signal and explored several different approaches to choosing ISI filter lead and lag settings. We showed examples of two of these methods that produced approximately the same answer (lead = 0, lag = 11) for the same transmitter signal. **Figure 7** at right shows the resultant ISI filter that EZJIT Plus generated for the same example signal using a lead value of 0 and a lag value of 11.

Compare the ISI filter in **Figure 7** to the one in **Figure 8**, which is comprised of coefficients from -5 to 25. Note that although EZJIT Plus had more coefficients with which to model the DDJ in **Figure 8**, it did not need them to model the DDJ significantly better. We can conclude from this that both methods that were suggested produced an optimum ISI filter size because it modeled the DDJ accurately without increasing the measurement time excessively.

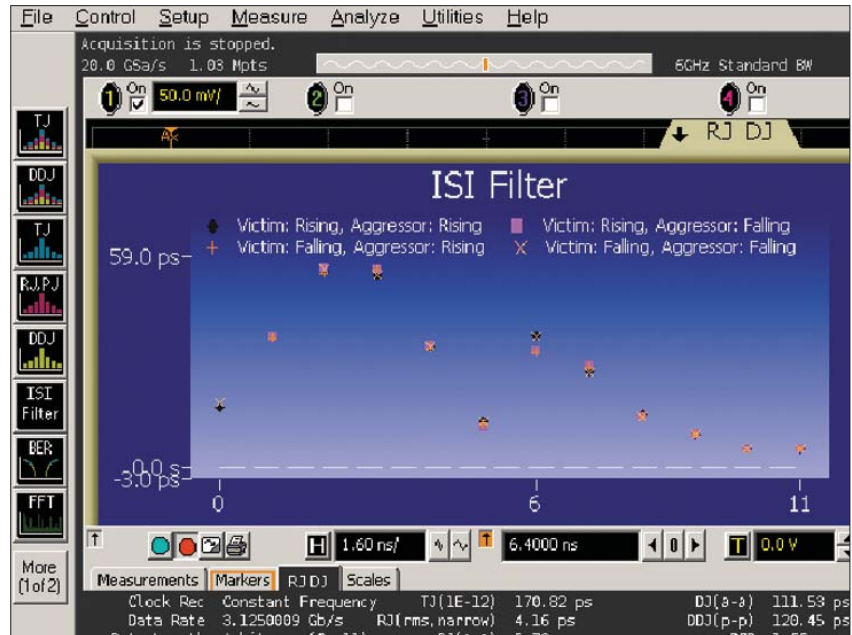


Figure 7. EZJIT Plus modeled the example signal’s DDJ with this ISI filter when the lead value was set to 0 and the lag value was set to 11.

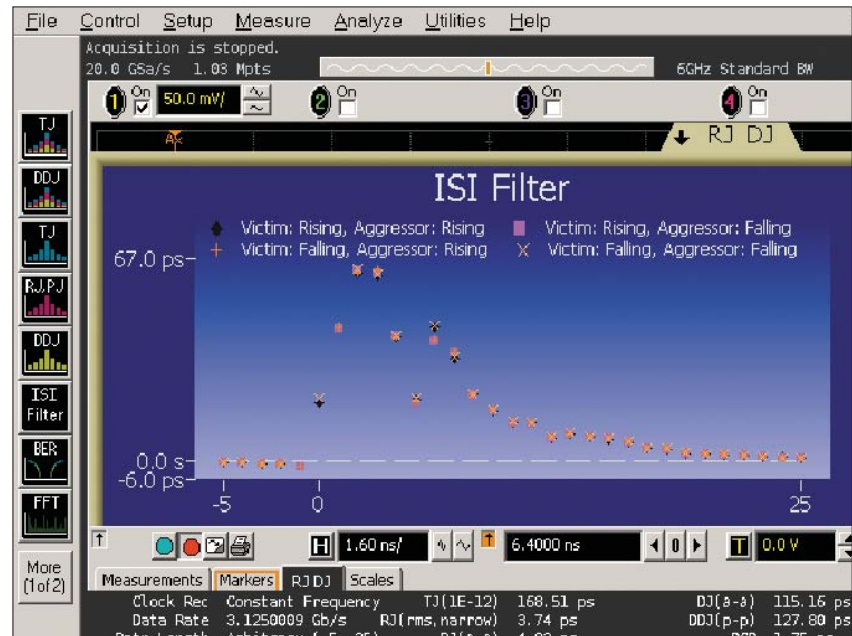


Figure 8. EZJIT Plus modeled the example signal’s DDJ with this ISI filter when the lead value was set to -5 and the lag value was set to 25.

Related Agilent literature

Publication Title	Publication Type	Publication Number
EZJIT and EZJIT Plus Jitter Analysis Software for Infiniium Series Oscilloscopes	Data sheet	5989-0109EN
Analyzing Jitter Using Agilent EZJIT Plus Software	Application Note	5989-3776EN

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