Summary

Beginning with version 6.5.0.2 of the SPARQ software, users have the option of limiting the impulse response time as part of the S-parameter calculation process. Prior to 6.5.0.2, users had the option of limiting impulse response, but only in conjunction with enforcing causality. Limiting the impulse response time has the main benefit of eliminating noise from the S-parameters returned by the SPARQ. When limiting the impulse response, the S-parameters measured by the SPARQ are smoother, and a better match to VNA results. Use of this feature is especially recommended when using devices with very short electrical lengths, (e.g. < 500ps). Via impulse response time limiting, users can also avoid “time domain aliasing” that can occur when using too few points in the S-parameter measurement. Lastly, Impulse response limiting can be used in conjunction with causality enforcement feature to return S-parameters that meet a simulator’s causality requirement.

Configuring to Limit the Impulse Response

The settings to configure the feature to limit the impulse response are on the extended view of the main Setup dialog. This dialog is displayed by clicking the Setup button at the top of the application, and then by clicking any of the “+” buttons to expand the dialog to show the additional settings. Figure 1 shows both Limit Impulse Response and Enforce Causality enabled. (These two features now operate independently, which was not the case in previous software versions.)

Algorithm to Limit the Impulse Response

The limiting of the impulse response time (and the enforcement of causality, which is an independent setting) are the last steps in the algorithm to calculate the S-parameters returned to the user. The algorithm takes as input the S-parameters calculated after all de-embedding has been applied, as well as after passivity and reciprocity enforcements have been applied. If either the Enforce Causality or Limit Impulse Response checkboxes in the extended Setup dialog are enabled the following steps are performed:

1. Each S-parameter is converted to the time-domain via the iFFT function to determine the corresponding impulse responses waveforms. Figure 2 shows the impulse response derived from the S11 S-parameter of a SPARQ demo board. The measurement was taken with 40GHz end frequency, resulting in an iFFT with a time interval of 40ns between impulses.
SPARQ Impulse Response Limiting

2. Each impulse response waveform is truncated as follows:

   a. If only **Limit Impulse Response** is enabled, the resulting impulse responses include both the positive and negative time specified in the entry box for the impulse response time. Figure 3 shows the limiting of the impulse response using an impulse response time of 6ns. The waveform is truncated to include times from \(-6\text{ns} \leq t \leq 6\text{ns}\).

   ![Figure 3: The impulse response used when configuring a limiting time of 6ns is shown.](image)

   b. If only **Enforce Causality** is selected, only the positive region is retained, as shown in Figure 4. For this example, the truncated waveform includes only times \(0 \leq t < 20\text{ns}\). This ensures that the impulse response waveform is causal by excluding all vestiges of an impulse response from before the impulse time \((T=0)\).

   ![Figure 4: The impulse response used when enforcing causality and without limiting the impulse response time is shown.](image)

   c. If both **Enforce Causality** and **Limit Impulse Response** are enabled, then the negative region of the impulse response is truncated, along with the positive time beyond the response time specified, as shown in Figure 5 which is 6ns in this example.

   ![Figure 5: The impulse response used when both enforcing causality and when limiting the response to 6ns is shown.](image)
3. The waveforms output from step 2 are converted back to the frequency domain, and are the final S-parameters displayed to the user and that are available be saved to a Touchstone file (either manually or automatically.) Figure 6 shows before/after plots when setting the impulse response limiting time to 6ns. After limiting the impulse response, the waveforms show a smaller amount of noise. The waveforms are clearly smoother in the second half of the plot. The ripple on the insertion loss plots in the lower grids is a real effect due to coupling to an unterminated trace rather than due to noise; this will be discussed further later in this application note.

![Waveform Comparison](image)

*Figure 6: Before and after S-parameter curves when limiting the impulse response time to 6ns. Top grids: S11. Bottom grids: S21. The curves are smoother, especially in the second half of the plot. The ripple on the S21 plots is due to coupling to a neighboring unterminated trace.*

(See the “Avoid Overlimiting” section below for an example of how excess limiting can lead to incorrect results.)

The effect of the impulse response limiting algorithm can easily be seen when comparing the impulse responses with and without the feature enabled. Figure 6 above shows the comparison; the waveform on the left is the impulse response without limiting in place, and the waveform on the right is with limiting set to 6ns. The left-side waveform is displayed by configuring the Result Display dialog to have trace S1 show the S11 parameter with the result type **Impulse**. This result type returns the iFFT of the selected S-parameter convolved with a user-selectable risetime (set to 0 for this screenshot).

![Waveform Comparison](image)

*Figure 7: Time-domain waveforms derived from S11 measurements with and without applying impulse response limiting. The plots have been zoomed vertically to clearly show that the response time has successfully been limited in the right-hand plot.*
The right-side waveform uses the S-parameter that is output from step 3 above; the zero-values for time $T > 6$ns is now "encoded" in the S-parameter result. (To show the response with limiting in place, the S-parameters were first saved to a Touchstone file, and then loaded using the "SParamImport" feature; the SPARQ truncates the Sx waveforms based on the impulse response time setting, whereas the time-domain results that can optionally be shown when using imported S-parameter files will have a time length of $(\text{NumPoints})/(2\times\text{End Frequency})$, which $= 20$ns in this example.)

**Using Impulse Response Limiting on DUTs with Short Impulse Responses**

The limiting feature can help in the generation of S-parameters for short lossless devices. Figure 9 shows the measurement of a calibration standard that is embedded in a PCB for the purpose of de-embedding a cable test fixture (Figure 8). The embedded short is at the end of a “1X” length trace of about 2 inches. The right-hand grid shows the S11 measurement both with and without applying impulse response limiting; the thin green trace shows how the algorithm eliminates the noise in the red waveform. The upper and lower left plot shows the before and after plots for the step response. (The lower plot shows trace S1 configured to be the Step result type using S11; the upper plot is a memory trace saved from the S1 plot before limiting the impulse response). This waveform can help determine the correct time to use in conjunction with limiting the impulse response. From the cursor, we can see that the time to out to the short and back is approximately 450ps. We make use of this value in the section “Determining the Limiting Time” below.

![Figure 8: Calibration board for cable test fixture de-embedding using cal standards at the end of a “1x” length of trace.](image)

![Figure 9: Impulse response time limiting on a DUT with short electrical length. The DUT is an embedded “Short” calibration standard used for fixture de-embedding. The green trace in the left grid is after limiting the impulse response to 2 ns.](image)
Determining the Limiting Time
The time to use when limiting the impulse response should be, as a rule of thumb, about 5x the DUT’s electrical length. (Two times the electrical length is the time needed to include the reflection from the far-end of the DUT, but a longer time length is needed to account for multiple reflections.) To determine the DUT’s electrical length, SPARQ operators can first make the S-parameter measurement with limiting turned off, and by examining one or more of the time-domain views of the results. Figure 10 shows the result from Figure 6 on page 5 along with the associated S21 step response. The time of the step is the left side grid is ~1.6ns. This corresponds to the electrical length of the DUT, since the S-parameter measurement was taken with cable de-embedding enabled, placing the reference plane at ends of the SPARQ port cables, i.e. the DUT ports. Figure 9: (page 2) shows the Step result type from a 1-port measurement of a short; the electrical length for this DUT is ~225ps. This is ½ of the 450ps time measured by the cursor; 450ps includes the reflection, since it is a TDR measurement.

Users can also use the “live TDR” SPARQ feature to make a measurement of the DUT length without first measuring the S-parameters of the DUT. Appendix A shows how to calculate the DUT length when using this approach.

Avoid Overlimiting
Care should be taken to not to over-limit the response time. This can have the undesired consequence of excluding reflections, or perhaps even the transmitted edge on the TDT waveform. The effect of overlimiting will be S-parameters that are not a correct characterization of the DUT. Figure 11 below shows measurements taken with 6, 4 and 1.5ns as the limiting time. At first glance, the 4ns limiting looks cleaner than when using 6ns, but the ripple that has been eliminated is not noise, but rather expected behavior due to coupling to neighboring unterminated traces. The bottom grids show an extreme case, where the value chosen is 1.5ns. This is just less than the 1.6ns DUT length. With this setting, the S-parameters no longer correctly characterize the DUT; the impedance profile derived from the S11 measurement no longer includes the far-end of the DUT, and the S21 measurement no longer bears any resemblance to the correct result.

Displaying Results on the SPARQ
Users configure the Result Display dialog to setup S-parameters and time-domain results for display. Up to 16 results can be displayed, in waveforms named S1, S2, S3, etc. (“Sx” in general). For each Sx, an S-parameter is selected, along with a result type.
Time-domain Aliasing

Time domain aliasing can be avoiding by using Impulse Response Limiting to reduce the impulse response time. In the same way that undersampled time-domain waveforms can lead to frequency-domain aliasing (i.e., when an oscilloscope is configured to sample at a sampling rate less than Nyquist), undersampled S-parameters can result in time-domain aliasing. This occurs when the user chooses too few points to use for the S-parameter measurement given the end-frequency selected. This results in an under-sampled S-parameter curve, with the consequence that the conversion to the time-domain via an iFFT can result in aliasing. In Figure 12, (next page) the middle trace shows the how such aliasing can show up in an impedance profile. The larger ripple in the 4th horizontal division shows up when using 400pts in the S-parameters. This ripple is aliased from another position in time, in the same way that frequency-domain aliasing can relocate spectral peaks. The time length for the middle trace, which was the result of a 40GHz, 400pt S-parameter measurement, is 5ns. If instead the user selects 1600 pts with no time limiting, the result is the top trace. When applying impulse response limiting with time = 5ns, the result is the bottom trace. Neither of these traces show time-domain aliasing since the S-parameters are sufficiently sampled at 25MHz/pt. Both the middle and bottom trace are S-parameters with impulse length=5ns, but since impulse response limiting was used in the bottom trace, time-domain aliasing has been avoided.

Figure 11: Results after for 3 response time limits: Top grids: 6ns; middle grids: 4ns; bottom grids 1.4ns. Plots on the left are with the Z result type; on the right is S21. The 4ns and 1.5ns results show signs of overlimiting.
Conclusions
The SPARQ's Limit Impulse Response feature can be used to eliminate noise in calculated S-parameters, and to avoid time-domain aliasing. The feature is especially useful when applied to short DUTs. The resulting S-parameters are smoother and a better match to VNA-generated S-parameters. The SPARQ also includes all the tools required to understand the time-domain behavior of the calculated S-parameters, including Step, Impulse, Rho and Z result types.
Appendix A: Quick Procedure to Measure DUT Length using TDR/TDT

Using TDR alone to measure DUT length can be difficult because of degradation of the reflection from the far end of the DUT. The following procedure employing both TDR and TDT measurements can be used to estimate DUT length.

**Step 1:**
For a configuration similar to the figure below, disconnect the cable from the DUT that is connected to port 1, and turn on live TDR with TDR → Port 1. And TDT → Port 2. Place the one of the horizontal cursors at the TDR reflection point, which in Figure A is in the 3rd horizontal division.

The time measured by this cursor is twice the time to get from the pulser to the end of the cable, or $2 \times \text{Tin}$ (see diagram below).

When the cables in and out are equal, this measurement = **Tin + Tout**

**Step 2:**
Reconnect the cable. Place the other horizontal cursor on rising edge of the TDT signal. This measures time Tdut, as shown in Figure B.

The time of this edge is the complete time from the TDR pulser/sampler to the TDT sampler, or **Tin + Tdut + Tout**.

**Step 3:**
Read Delta-X value (lower right corner). This is the approximate length of the DUT, calculated by subtracting the time measured in Step 1 from Step 2: Tin + Tdut + Tout – (Tin + Tout) = Tdut.

The above result = 1.269ns

**Figure A:** Time of the left cursor is $= 2 \times \text{Tin}$, which nominally $= \text{Tin} + \text{Tout}$.

**Figure B:** Time of the right cursor is $= \text{Tin} + \text{Tdut} + \text{Tout}$. DUT length is the time between cursors.

**Figure C:** Simplified schematic.