

# Using 2<sup>nd</sup> Tier Calibration for Cable Fixture De-embedding

APPLICATION NOTE

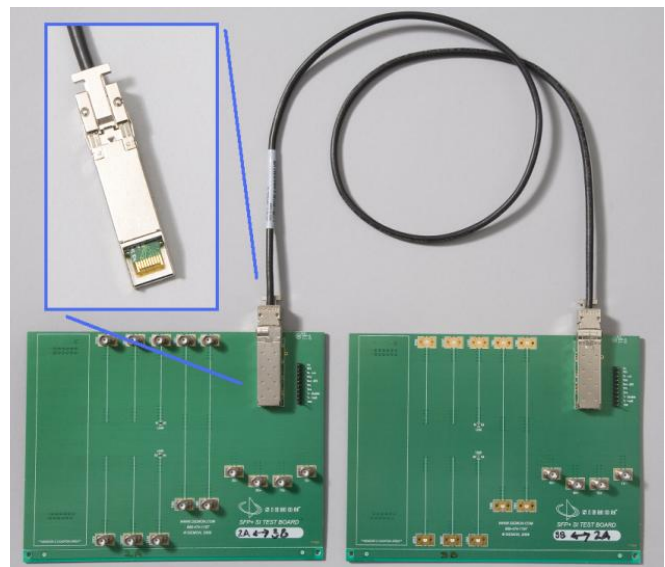
*Dr. Alan Blankman, SPARQ Product Manager*

## Summary

Beginning with SW Release 6.5.x.x (available May/June 2011), the SPARQ software includes the capability of performing a **user-generated 2nd-tier calibration**. When a user 2nd-tier calibration is used, error terms from a secondary manual calibration is applied “on top” of the automatic OSLT and factory calibrations. One application of this feature includes de-embedding of fixtures used for cable measurements including SFP+, QSFP+, DisplayPort and USB3.0 fixtures by using calibration structures included with the cable testing fixtures. This application note describes how to perform a user 2nd-tier calibration that de-embeds the test fixture.

## Cable Testing Challenges

Measuring S-parameters of an arbitrary cable is a non-trivial task due to the simple fact that most cables and interconnects do not have connectors that mate to the port cables of the SPARQ or other S-parameter measuring instrument such as a VNA. Carefully designed interfaces or fixtures are employed to breakout the signal pins of the cable under test to SMA or 2.92 mm connectors suitable for connecting to the S-parameter-measuring instrument, allowing insertion loss and return loss and other S-parameter results to be measured without the need for expensive probing systems that would connect to the cable connector’s pins directly. The consequence of using a fixture is that the reference plane of the S-parameter measurement is at the inputs to the fixture, rather than at the inputs to the mating receptacle mounted on the fixture. Cable testing requirements, however, often require that S-parameter and/or impedance measurements be referenced at the pins of the mating connector. The process of moving the reference plane from the fixture inputs to the receptacle inputs is referred to as **de-embedding**. On the SPARQ, de-embedding can be done in two ways 1) by employing a the SPARQ’s S-parameter de-embedding capability to de-embed either the connector & trace that interfaces the port cable to the receptacle or that de-embeds the fixture as a whole entity, or 2) via the User 2nd-Tier Calibration capability. For cable measurement applications, option (2) above will typically be used since the S2P S-parameters of the fixture are generally not known. This application note describes how to use the user 2nd-tier calibration to accomplish this task by using the SOLT structures that are included on the cable testing fixtures or on a separate calibration board. By performing an SOLT calibration using these structures, the input connector and trace leading to the receptacle can be de-embedded.



*SFP+ SI test board courtesy of The Siemon Company*

## User 2<sup>nd</sup>-Tier Calibration Overview & Benefits

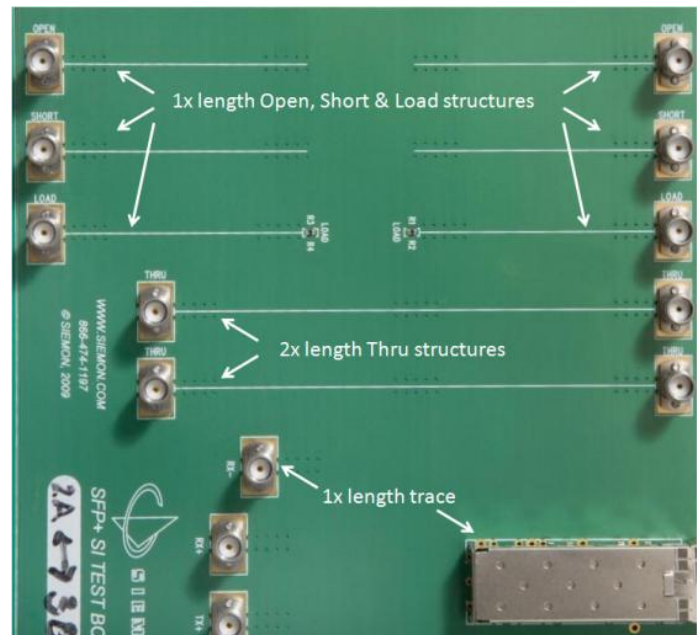
To perform a 2<sup>nd</sup>-tier cal, the user measures the SOLT structures on the fixture in a manner that is similar to how the SPARQ measures any other DUT, and then invokes the “Convert” feature in the SPARQ software to generate a L12T file (LeCroy 12-term error model). The conversion process uses the SOLT measurements along with S-parameters that describe the SOLT calibration structures. The L12T file contains an error model that is applied after the factory calibration and automatic calibration that is performed using the internally connected OSLT calibration kit at the time of measurement. This is why it is called a 2<sup>nd</sup>-tier calibration; it acts to refine the calibration used given the calibration structures embedded in the fixture.

LeCroy’s 2<sup>nd</sup>-tier calibration methodology has several benefits for fixture de-embedding and for other applications that utilize a 2<sup>nd</sup>-tier calibration such as probe de-embedding. The biggest benefit is that when performing a user 2<sup>nd</sup>-tier calibration the SPARQ is operating in a calibrated mode; it has already calibrated out all of the internal & active components that require calibrating whenever the instrument is powered up. This is done using the automatic internal calibration capability. The 2<sup>nd</sup>-tier calibration determines error terms for what is external to the SPARQ, which typically will be purely passive components. Thus the 2<sup>nd</sup>-tier calibration results for a cable test fixture only need measuring once, and can be re-used from day-to-day.

## Fixture De-embedding Using a 2<sup>nd</sup>-Tier Calibration: How it Works

The process of performing a 2<sup>nd</sup>-tier calibration using the SOLT structures in the cable test fixtures in [figure] has the action of de-embedding the connector and trace leading up to the receptacle. This occurs since the SOL structures are at the end of a net that is designed to have identical electrical behavior to the structure being de-embedded, i.e. a “1x” trace length, where x is the length of the trace from the connector to the receptacle mounted to the fixture. The T structure consists of two connectors and a “2x” length trace, and, thus accounting for the connector and trace seen when in 2-port measurements. When performing an SOLT calibration using models for SOL structures in isolation of the 1X trace and modeling the T as zero-length, the result is a de-embedding of the connector and 1x trace length.

Note, however, that the de-embedding is not exact, for two main reasons: 1) the S-parameters of each connector + 1x run will vary to some degree, and 2) The exact S-parameters of the SOL structures at the ends of the 1x run are not known precisely, and fixture manufacturers typically do not include a model for them. Thus these structures are typically modeled as ideal. Since, however, they are not ideal, the resulting calibration will have some resulting error.



**1x length open, short, load and 2x length thru structures are included for de-embedding.**

## Methods for Performing a User 2<sup>nd</sup>-Tier Calibration

There are several ways to run the 2<sup>nd</sup>-tier calibration. For this application, the **Single-Port** method is typically sufficient.

### **Single-Port Method:**

In this method the user measures the fixture's short, open load and thru structures once. Each of these measurements can be done using the same SPARQ port (e.g. port 1), or they can be done on different ports with the assistance of a script (See Appendix A) that programs the SPARQ to run each measurement in succession using a specific port. The SPARQ will use either user-supplied S-parameters for the SOLT calibration structures, or, if none are provided, the SPARQ will model them as ideal, and for the thru, zero-length.

If the user can provide S-parameter models for the S, O and L structures at the ends of the 1x run, they should be named short.s1p, open.s1p, load.s1p and placed in the same folder as the measurements taken in B below. The user should include an S-parameter file for the thru that is zero-length, with filename thru.s2p.

### **Full-Port Method** (Note: this method is not required for this application)

In this method, the user measures the SOL structures on ports that will be used for the DUT measurement, and the Thru on all combinations of ports. The SOLT measurements for the 2<sup>nd</sup>-tier calibration should be saved with the following naming convention:

- Short: **SMx.s1p**, where x is the port used, with x= 1, 2... up to the # of ports used for the cal
- Open: **OMx.s1p**, where x is the port used, with x= 1, 2... up to the # of ports used for the cal
- Load: **LMx.s1p**, where x is the port used, with x= 1, 2... up to the # of ports used for the cal
- Thru: **TMxy.s2p**, where x and y are the ports used, with x<y (e.g. thru13.s2p and thru24.s2p)

A 4-port 2<sup>nd</sup>-tier calibration using the full-port method would require a total of 18 measurements; 4 short measurements, with filenames SM1.s1p, SM2.s1p, etc. similarly, 4 opens and 4 loads, and 6 thru measurements. (Only one thru measurement is needed for each pair of ports, so thru measurements would be taken as follows: ports 1&2, 1&3, 1&4, 2&3, 2&4, and 3&4.)

The calibration structures should be modeled/measured as S-parameter files with the following naming convention, and the files should be saved in the same folder as the above measurements. The user has three choices for the definitions of the calibration structure:

1. Provide an S-parameter file for a single set, i.e for the short, open, load and thru to be used, with the following filenames: Short.s1p, Open.s1p, Load.s1p, Thru.s1p
2. Provide S-parameters individual SOLT standards used on each port. Employ this approach when using multiple SOLT structures with different S-parameter models or measurements)

**Short[x].s1p**, where [x]=1,2... up to the # of ports used for the calibration  
**Open[x].s1p**, where [x]=1,2... up to the # of ports used for the calibration  
**Load[x].s1p**, where [x]=1,2... up to the # of ports used for the calibration  
**Thru[x].s1p**, where [x]=1,2... up to the # of ports used for the calibration

3. Provide no S-parameter files for the standards, in which case the SPARQ will model the standards as ideal, with the thru being zero-length.

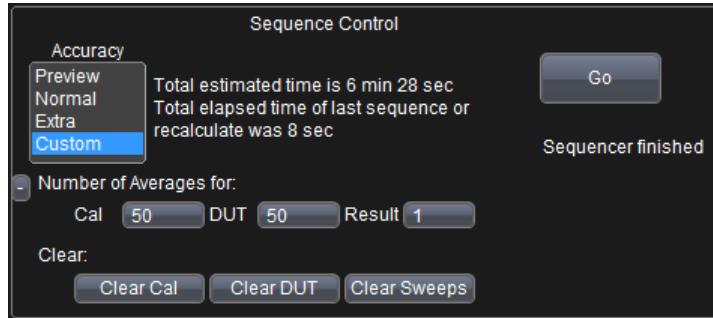
## Performing a User 2nd-tier Calibration Using the Single-Port Method

Here are step-by-step instructions for performing a 2nd-tier calibration using the Basic method:

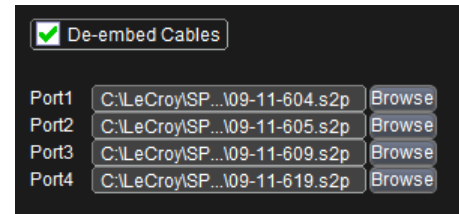
### Configuration Phase:

A. Always start with a Recall Defaults via the **File → Recall Setup...** dialog.

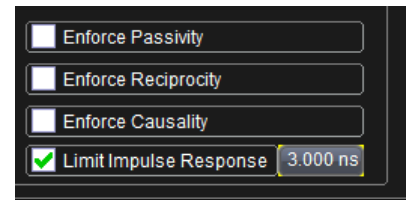
B. In the main SPARQ setup dialog, which can be invoked via the **Setup** button at the top of the application), configure the SPARQ's accuracy mode to Custom, with the number of averages set to Cal=50, DUT=50. (This corresponds to 50 sets of averages, with each set = 250 averaged waveforms). The **Cal** setting configures the automatic internal calibration; the **DUT** setting is for the measurements to be made on the fixture's SOLT structures for the 2<sup>nd</sup>-tier calibration. Since the calibration is the foundation upon which all successive measurements are made, using a higher number of averages than the SPARQ's "Normal" accuracy mode is recommended, although the amount of averaging to employ is up to the user. The amount of averaging used affects the dynamic range of the measurement.



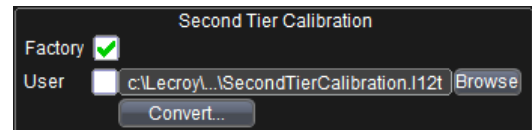
C. Configure the SPARQ's cable de-embedding in the **Instrument Setup** tab to be active. This allows the resulting 2<sup>nd</sup>-tier calibration to be used with port cables different than those used for the measurements taken in the **Measurement Phase**.



D. Configure the SPARQ to make a 1-port measurement with an end frequency and number of points that is at least as large as the measurement you plan to make. You may wish to use the SPARQ's full range when running the calibration to ensure enough range for subsequent DUT measurements.



E. Limit the impulse response length to a time that is about 5x the electrical length of the standard being measured. This is done via the selector in the advanced view of the setup dialog.



F. Lastly, and importantly, configure the 2nd-tier calibration settings in the Calibration tab as follows:

1. **Factory: Checked**
2. **User: Unchecked** (This setting should be checked when using a user-defined 2nd-tier cal; it should be unchecked when performing a 2nd-tier cal.)

Name	Type	Size
<input type="checkbox"/> LM.cal	CAL File	3,385 KB
<input type="checkbox"/> OM.cal	CAL File	3,385 KB
<input type="checkbox"/> SM.cal	CAL File	3,393 KB
<input type="checkbox"/> TM.cal	CAL File	6,205 KB
<input checked="" type="checkbox"/> LM.s1p	S1P File	67 KB
<input checked="" type="checkbox"/> OM.s1p	S1P File	68 KB
<input checked="" type="checkbox"/> SM.s1p	S1P File	67 KB
<input checked="" type="checkbox"/> TM.s2p	S2P File	198 KB

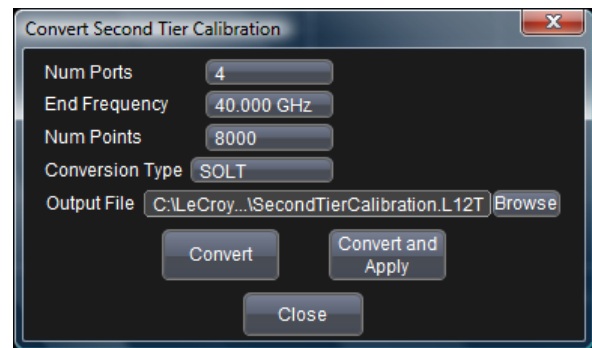
### Measurement Phase:

A. Connect the fixture's Open structure to port 1, and click **Go** to run the measurement. The SPARQ will perform an automatic calibration first, followed by the Open. When the measurement is complete:

1. Save the S-parameter to the filename OM.s1p, in the folder of your choice (e.g. C:\LeCroy\SPARQ\SPARQ\SecondTierCalibration).
  2. Save a .cal file via the floppy disk icon in the Calibration tab. This is always a good practice; the resulting file includes all of the time-domain acquisitions used for the measurement, and can be recalled if you wish to re-make the 2<sup>nd</sup>-tier calibration file with different settings.
- B. Perform step A above with the Short and then the Load structures connected to port 1, saving to SM.s1p and LM.s1p. Remember to also save the .cal file as well.
- C. Connect the Thru structure (use the Thru that is twice the length of the O, S and L) between ports 1 and 2, change NumPorts to 2, and then click Go. Save the measurement to TM.s2p, and save a .cal file as well.

### Calculation of the 2<sup>nd</sup>-tier Calibration Error Model:

- A. If desired, prepare a text file called "ConvertSettings.vbs" that configures variables used for the conversion. See Appendix B for an example, and how to find the variables to use.
- B. Click **Convert** in the Second-tier calibration section of the Calibration tab to open pop-up window for the conversion of the SOLT measurement to a 2<sup>nd</sup>-tier calibration LeCroy 12-term model.
1. Configure the end frequency and number of points to match the settings used for the SOLT measurements.
  2. Set Conversion Type = SOLT
  3. Click Browse to open the window to select a file path and name. For the file path, select the folder where the S-parameters measurements were saved in section B above. The filename to use is arbitrary, but must have the extension ".L12T"; e.g. UserSecondTierCal.L12T
  4. Click either **Convert** or **Convert and Apply** to begin the conversion process. This process can take just a few seconds or up to a minute depending on the number of points used and if the end frequency and number of points match the settings used when making the SOLT measurements.
- C. During the conversion process, the options in the Convert Second Tier Calibration window are grayed out. When the conversion is complete, the options become active again.



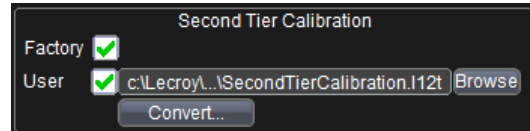
### Confirming the Results

- A. Open a Windows Explorer window, and navigate to the folder containing your SOLT measurements. A successful conversion generates several additional files:
1. **<filename>.L12T**; <filename> being the selected filename in step C-1-iii above)
  2. **Second\_Tier\_x.s8p**, where X=1 through the number of ports used. These are S-parameters files that include the error terms for the 2<sup>nd</sup>-tier calibration. See Appendix C for additional information about these files.
  3. **ConversionLog.txt**: log file containing the actions performed by the conversion.
- B. Open **ConversionLog.txt** and quickly confirm that it includes no errors.
1. Errors are denoted by an "!" at the beginning of a line, and indicate that the conversion was not successful.
  2. Warnings are denoted by a "w" at the beginning of a line, and are typically informative
- C. The goodness of the calibration can be determined by repeating the 2<sup>nd</sup>-tier calibration as described in the sections above but, this time:
1. Select to use the User 2<sup>nd</sup>-tier calibration L12T file created above. (See section on "Using the 2<sup>nd</sup>-Tier calibration below).

2. Repeat the measurements of the SOLT structures, and save them in a new directory (e.g. C:\LeCroy\SPARQ\SecondTierCalibration\Checkout)
3. Repeat the steps above in “Calculation of the 2<sup>nd</sup>-tier Calibration Error Model” above, using the new “Checkout” directory.
4. The resulting error terms in the Second\_Tier\_x.s8p files are now the **residual errors**, and should be close to ideal. The ER<sub>i</sub> and ET<sub>ij</sub> terms should be close to unity, and the ED<sub>i</sub>, EL<sub>ij</sub> and ES<sub>ij</sub> should be close to 0. **See Appendix D** for more information.

## Using the 2<sup>nd</sup>-Tier Calibration

To use the user 2<sup>nd</sup>-tier calibration, check the checkbox in the Second-Tier Calibration section of the Calibration dialog, and select the L12T file to use. (This is done automatically when clicking **Convert and Apply** in section C above.). The SPARQ will apply the User 2<sup>nd</sup>-tier calibration as the last step in the S-parameter calculation algorithm, and the reference plane for the measurement is the inputs to the receptacle.



To see results without the fixture de-embedding in place, uncheck the **User** checkbox, and click Recalculate at the top of the application to return the S-parameters without applying the 2<sup>nd</sup>-tier calibration.

## User 2<sup>nd</sup>-Tier Calibration and Cable De-embedding

Users should make sure to replicate the cable de-embedding setup used when generating the 2<sup>nd</sup>-tier calibration when making measurements using the generated L12T file. I.e., if cable de-embedding is enabled when saving the SM.s1p, OM.s1p etc. files, cable de-embedding should also be enabled when making cable measurements that use the resulting L12T file. If the de-embedding setup is not kept consistent, then the resulting S-parameters will not have the de-embedding accomplished correctly.

## Re-usability of User 2<sup>nd</sup>-Tier Calibration Files

A 2<sup>nd</sup>-tier calibration characterizes the fixture in a manner that is re-usable, insofar as the electrical behavior of the fixture is stable. There is no requirement to re-run a 2<sup>nd</sup>-tier calibration unless the user suspects that the previous calibration led to poor results when performing the “Confirming the results” step.

## Portability of User 2<sup>nd</sup>-Tier Calibration L12T Files

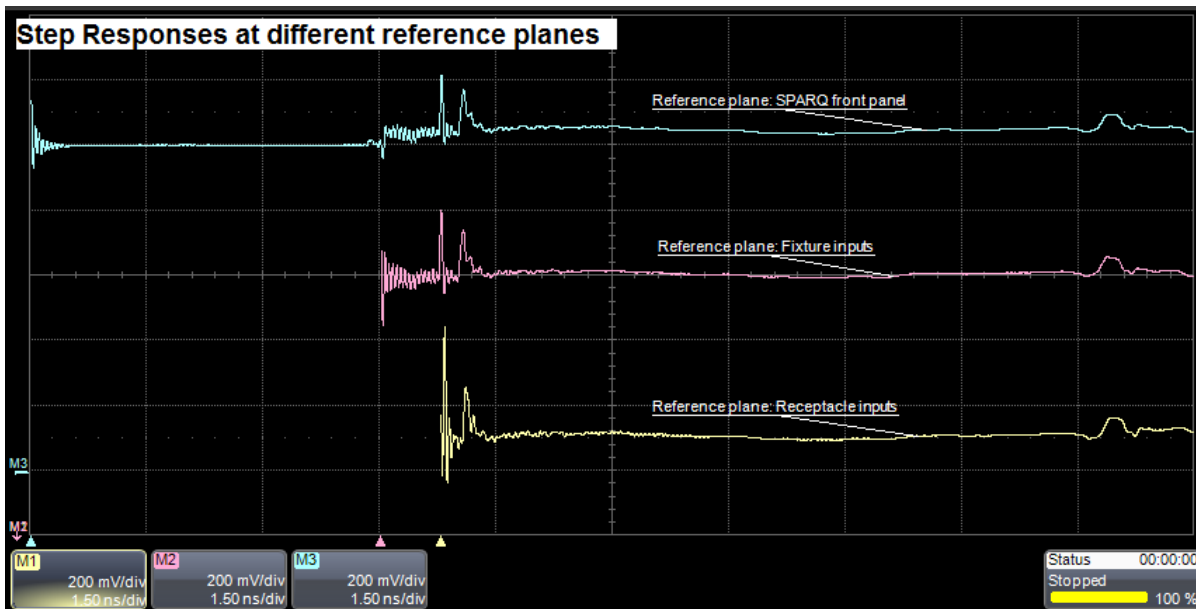
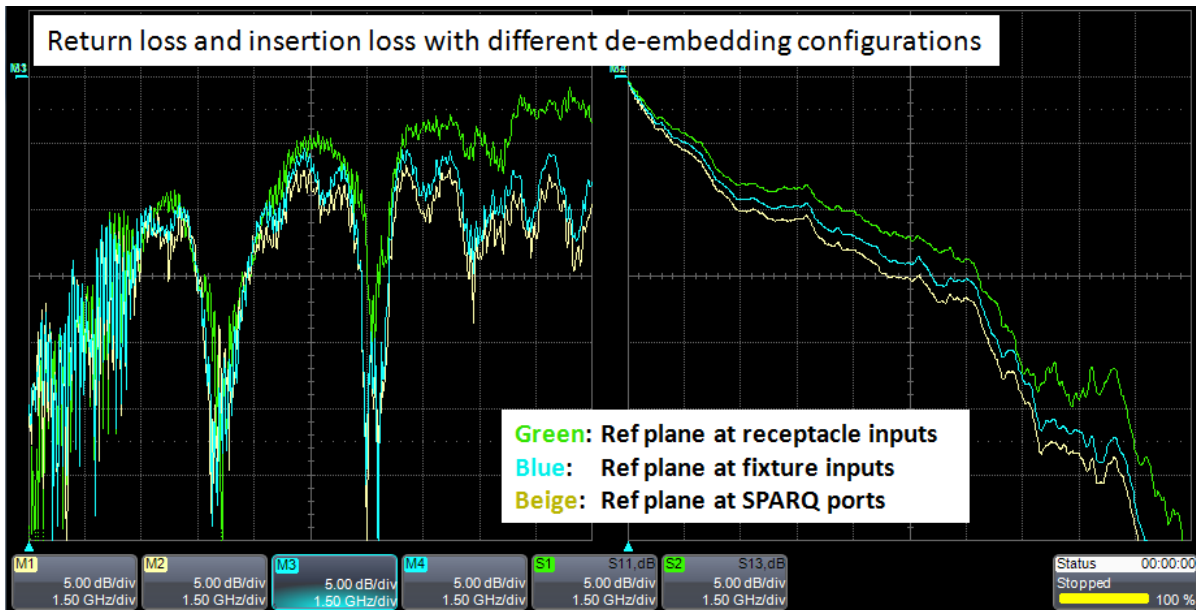
The L12T file can be also used with a different SPARQ than the one used to perform the calibration. If the user creates the L12T file with SOLT measurements that **include cable de-embedding**, then the L12T file is an error model of the fixture in isolation; the cables used were de-embedded such that the S-parameters of the SOLT structures do not include the cable. When using the L12T file, be sure to turn on cable de-embedding so that the SPARQ cables are properly de-embedded when using either the SPARQ that generated the L12T file, or when using another SPARQ.

## Other Applications for the User 2<sup>nd</sup>-Tier Calibration

The 2<sup>nd</sup>-tier calibration method can be used to de-embed probes; look for a separate application note on this topic. It is also used to generate a “Factory” calibration that is applied after the automatic calibration. This method facilitates the performance of a performance verification procedure that fine-tunes the automatic OSLT calibration, and leaves the reference plane at the SPARQ front panel ports. (It is subsequently moved to the ends of the port cables via **Cable De-embedding** that is configured in the Instrument Setup dialog, and further de-embedding is accomplished as described in this application note, or by using the **Adaptor** and/or **Fixture** S-parameter de-embedding that is configured in the expanded view of the **Setup** dialog.)

### Results

The following plots show the results of a measurement of a SFP+ cable when using the L12T file that is the result of the 2<sup>nd</sup>-tier calibration process, in both the time and frequency domains. The effect of the de-embedding is most easily seen when looking at insertion loss and step response plots. The IL plots in the screenshot below show reduced IL when first applying cable dembedding (blue curve), where the reference plane is at the inputs to the fixture. When including the fixture de-embedding by using a 2<sup>nd</sup>-tier calibration, the IL is further reduced as show in the green trace. In the second screenshot below, The impedance profile is measured using S-11. Here, the effect of de-embedding the fixture can be seen by comparing the pink and yellow traces. The blue trace shows the impedance with the reference plane at the SPARQ ports by having cable de-embedding turned off as well.



## Appendix A: VBScript Code

The following VBScript code can be copied into a file called "Perform 2nd Tier Calibration.vbs", and executed via a double-click from a Windows Explorer screen. Files generated by the script will be placed in the same folder. Check the LeCroy website for any updated version of this code. (The latest version should be accessible on the page containing this application note.)

**Note:** Users do not need to use this code to perform a 2<sup>nd</sup>-tier calibration; the purpose of this code is to semi-automate the process. The calibration can be done simply via the SPARQ user interface.

```
'Version 1.0, March 2011
'VBScript to automatically perform the 2nd-tier calibration using the basic method described
'in the application note "Using a 2nd-Tier Calibration for Fixture De-embedding"

set app = CreateObject("LeCroy.SparqApp.1")
set objShell = Wscript.CreateObject("WScript.Shell")

app.SaveRecall.Setup.DoRecallDefaultPanel

'Setup dialog configuration - modify as needed.
app.SPARQ.EndFrequency = 40e9
app.SPARQ.NumPoints = 8000
app.SPARQ.NumPortsInMeasurement = 2 'start with 2-port to do full OSLT internal cal below.
app.SPARQ.ConvertToUserSPParameters = True
app.SPARQ.CausalityImpulseResponseLimitingEnabled = True
app.SPARQ.CausalityMaxImpulseLength = 2e-9
app.SPARQ.AccuracyPreset = "Custom"

'Using the following setting for averaging is highly recommended.
app.SPARQ.CustomAccuracyNumAveragesForCal = 50
app.SPARQ.CustomAccuracyNumAveragesForDut = 50
app.SPARQ.CustomAccuracyNumAveragesForResult = 1

'Calibration dialog configuration
app.SPARQ.AutoCalPolicy = "RecalibratePeriodically"
app.SPARQ.AutoCalTimeout = 10

'Result Actions dialog configuration
app.SPARQ.AppendTimestampToResultsFilename = False
app.SPARQ.Actions.Enable = 1
app.SPARQ.Actions.Beep = 1
app.SPARQ.Actions.Save = 0
app.SPARQ.Actions.Mode = "OnSeqCompleteAndRecalc"

'Instrument Setup dialog configuration
app.SPARQ.DeEmbedCables = True
app.SPARQ.SecondTierCalibrationFactoryEnabled = True
app.SPARQ.SecondTierCalibrationUserEnabled = False
app.SPARQ.ParkRelays

Msgbox "Connect the Open, Short and Load standards to ports 1, 2 and 3, then click OK"

'Perform internal calibration
app.SPARQ.ClearCalibrationMeasures
app.SPARQ.CalibrateNow
app.SPARQ.WaitForSequencer(3600)
Wscript.Sleep(1000)

'Measure O,S,L as 3 independant 1-port measurements, but using ports 1, 2, 3
RunOne 1, "OM"
RunOne 2, "SM"
RunOne 3, "LM"

'Measure T as 2-port on ports 1 & 2
Msgbox "Connect Thru from port 1 to port 2, then click OK to continue"
RunTwo 1,2
```

'Convert OSLT measurements to 2nd-tier calibration  
 'If the user has S-parameters for the OSLT structures, they should be placed in the folder  
 'containing the SOLT measurements taken.

```
app.SPARQ.ConvertSecondTierCalibration.NumPorts = 4
app.SPARQ.ConvertSecondTierCalibration.EndFrequency = 40e9
app.SPARQ.ConvertSecondTierCalibration.NumPoints = 8000
app.SPARQ.ConvertSecondTierCalibration.Type = "SOLT"
app.SPARQ.ConvertSecondTierCalibration.CausalityMaxImpulseLength = 2e-9
app.SPARQ.ConvertSecondTierCalibration.CausalityImpulseResponseLimitingEnabled = True
fname = objShell.CurrentDirectory + "\" & "second_tier_cal_name.L12T"
app.SPARQ.ConvertSecondTierCalibration.Filename = fname
app.SPARQ.ConvertSecondTierCalibration.ConvertAndApply
Stop
```

```
'-----
Function RunTwo(n,m)
'Configures and runs a 2-port measurement for a thru between 2 ports.
set objShell = Wscript.CreateObject("WScript.Shell")
spfilename = objShell.CurrentDirectory + "\TM.s2p"
cfilename = objShell.CurrentDirectory + "\TM.cal"
```

```
'Configure for 2-port on port n,m
app.SPARQ.NumPortsInMeasurement = 2
app.SPARQ.DutSparqPortMapping = CStr(n) & "," & CStr(m)
app.SPARQ.ConverterDefinitions = "1,2"
app.SPARQ.UserPortDefinitions = "1,2"
app.SPARQ.DutToConverterPinDefinitions = "1,2"
app.SPARQ.SParameterResultsFilename = spfilename
app.SPARQ.CalFilename = cfilename
app.SystemControl.PersistentMessage = "Running TM"
app.SPARQ.Go
app.SPARQ.WaitForSequencer(3600)
Wscript.Sleep(1000)
app.SPARQ.SaveSParameterResults
app.SPARQ.SaveCalToFile
app.SystemControl.PersistentMessage = ""
End Function
```

```
'-----
Function RunOne(n, stdtype)
set objShell = Wscript.CreateObject("WScript.Shell")
spfilename = objShell.CurrentDirectory + "\" & stdtype & ".s1p"
cfilename = objShell.CurrentDirectory + "\" & stdtype & ".cal"
```

```
'Configure for 1-port on port n
app.SPARQ.NumPortsInMeasurement = 1
app.SPARQ.DutSparqPortMapping = CStr(n)
app.SPARQ.ConverterDefinitions = "1"
app.SPARQ.UserPortDefinitions = "1"
app.SPARQ.DutToConverterPinDefinitions = "1"
app.SPARQ.SParameterResultsFilename = spfilename
app.SPARQ.CalFilename = cfilename
app.SystemControl.PersistentMessage = "Running " & stdtype & " on port" & CStr(n)
app.SPARQ.Go
app.SPARQ.WaitForSequencer(3600)
Wscript.Sleep(1000)
app.SPARQ.SaveSParameterResults
app.SPARQ.SaveCalToFile
app.SystemControl.PersistentMessage = ""
End Function
```

## Appendix B: Example ConvertSettings.vbs file

The Convert Second Tier Dialog configures the number of ports, end frequency, number of points, conversion type and output file. Users who wish to configure other settings can create a file called **ConvertSettings.vbs** that will be executed. Here is an example file:

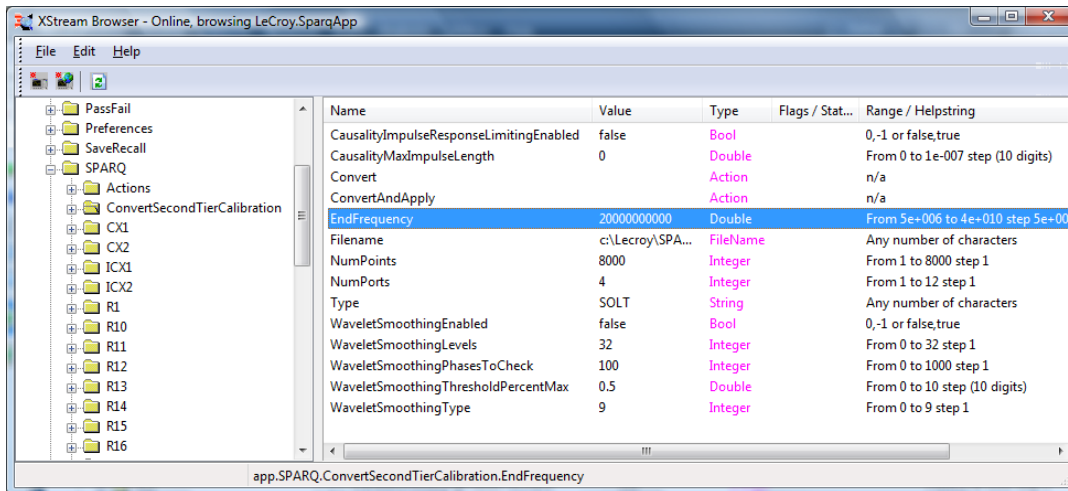
---

```
'Example ConvertSettings.vbs file that limits the impulse length for the error terms
set app = CreateObject("LeCroy.SparqApp.1")
```

```
'For the length below, use the same value as in the measurement step of the 2nd-tier cal procedure.
app.SPARQ.ConvertSecondTierCalibration.CausalityMaxImpulseLength = 3e-9
app.SPARQ.ConvertSecondTierCalibration.CausalityImpulseResponseLimitingEnabled = True
```

---

The application **SPARQBrowser** can be used to view the control variables. A shortcut for this application is installed on the desktop. Right-click on a line, and select **Copy Path...** to easily copy the line, and then paste it into your ConvertSettings.vbs file. See the SPARQ manual for information on what each control variable does.



## Appendix C: Layout of the 2<sup>nd</sup>-Tier Calibration Error Term S-param Files

An N port measurement will generate N s8p files containing error terms as shown below. (Cells with no entry are 0; “n” maps to index number of the s8p file.)

- ED\_n: Directivity error term when pulsing from port n
- ER\_n: Reflection error terms when pulsing from port n
- ES\_n: Source match error term when pulsing from port n
- ET\_in: Transmission error term from port i when pulsing from port n
- EL\_in: Load match error term from port i when pulsing from port n

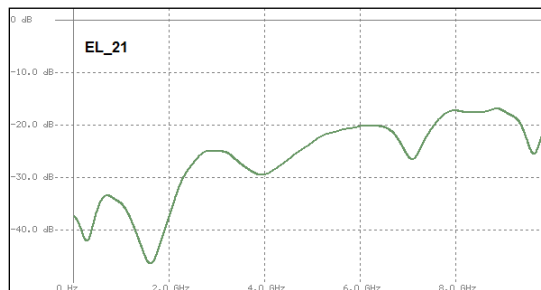
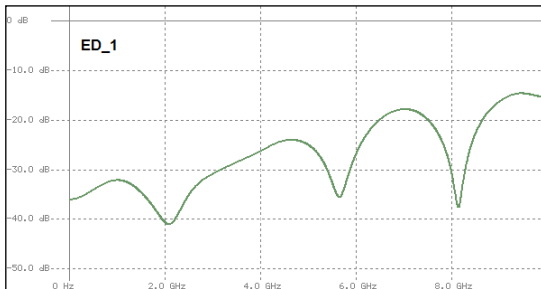
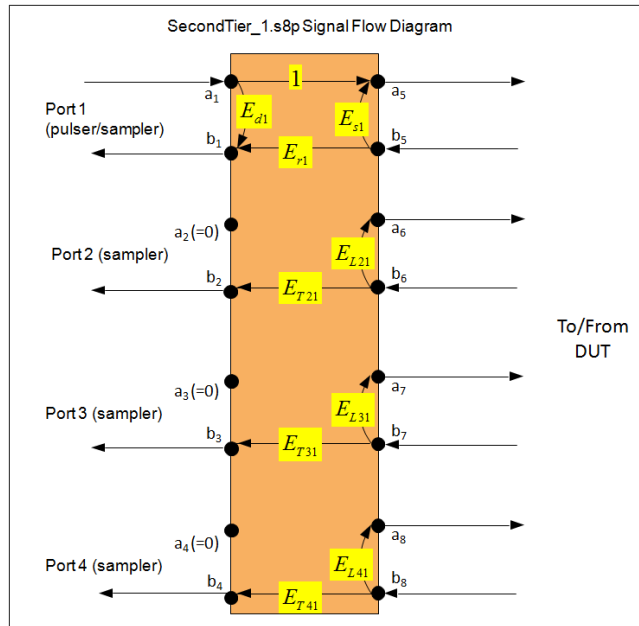
SecondTier_1.s8p	1	2	3	4	5	6	7	8
1	ED_1				ER_1			
2						ET_21		
3							ET_31	
4								ET_41
5	1				ES_1			
6						EL_21		
7							EL_31	
8								EL_41

SecondTier_2.s8p	1	2	3	4	5	6	7	8
1					ET_12			
2		ED_2				ER_2		
3							ET_32	
4								ET_42
5					EL_12			
6		1				ES_2		
7							EL_32	
8								EL_42

SecondTier_3.s8p	1	2	3	4	5	6	7	8
1					ET_13			
2						ET_23		
3			ED_3				ER_3	
4								ET_43
5					EL_13			
6						EL_23		
7			1				ES_3	
8								EL_43

SecondTier_4.s8p	1	2	3	4	5	6	7	8
1					ET_14			
2						ET_23		
3							ET_34	
4				ED_4				ER_4
5					EL_14			
6						EL_24		
7							EL_24	
8				1				ES_4

The signal flow diagram for SecondTier\_1.s8p is shown below. In the other files, error terms change to reflect the port being stimulated by the pulser (e.g. in SecondTier\_3.s8p, the pulser is input to port 3.)



### Appendix D: Validating the 2<sup>nd</sup>-tier Calibration

Section C of “Confirming the Results” describes how to re-run the measurements on the standards using the 2<sup>nd</sup>-tier calibration, and then using those measurements to generate another 2<sup>nd</sup>-tier calibration. The result of this calibration (effectively a 3<sup>rd</sup> tier call) are residual error terms, and should be very small. Here are example error terms of such a calibration.

