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*Application Note No 13*

# Calibration Techniques of Network Analyzers for Tuner Characterization

**This note compares commonly available techniques used to calibrate Vector Network Analyzers (VNA), knowing that Tuner characterization for Load Pull and Noise measurements requires the highest possible accuracy from VNA's.**
**We found that the best overall solution is TRL[1] (or LRL[2]) in coaxial, microstrip or waveguide media, because it yields excellent accuracy in short time using simple, affordable and easy to verify standards.**

## Introduction

Automatic Load Pull or Noise measurements require accurate knowledge of the tuner's parameters during the measurement. This is possible either using pre-calibrated tuners or measuring 'in-situ' by switching in and out a Vector Network Analyzer which is part of the measurement system.
In both cases the calibration of the VNA is the key issue of the operation, assuming the tuners or the RF switches used are repeatable enough.
Calibrating the VNA for measuring low loss - high reflection components, such as tuners, is not an easy task, especially at frequencies above 6 GHz.
Experience shows that in many practical cases inadequate or worn out calibration kits are used and that calibrations are often not properly verified. This may cause severe measurement errors especially at high VSWR's, which is what Load Pull measurements are about.

This note compares different common methods available in most laboratories to calibrate VNA's and makes certain recommendations on how to approach the problem.

[1] TRL = Thru Reflect Line, [2] LRL = Line Reflect Line

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# Comparison of VNA Calibration methods

**Vector Network Analyzer Calibration may be a difficult task, depending on the frequency range but even more on the Calibration Method and the Calibration Standards used.**
**There is no universal rule on which calibration standards are better, since their practical realization strongly depends on the transmission media used. In general terms a perfect load is more difficult to manufacture than a perfect short, but**
**even this depends on the medium used.**

**We can summarize the standard's performance related to the media as follows.**

| Calibration Standard | Transmission Media: Coaxial | Microstrip | Waveguide |
|---|---|---|---|
| Open (O) | - - | + | n/a |
| Short (S) | ++ | o | ++ |
| Load (L) | o | - | + |
| Sliding Load (SL) | + | n/a | o |
| Offset Short (OS) | ++ | o | ++ |
| Delay Line (DL) | ++ | ++ | ++ |

**Table 1: Degree of quality of known calibration standards.**
**Quality varies from Excellent (++) via Adequate (o) to Poor (- -).**

**The calibration method itself should be evaluated in relation to the standards required and their simple structure (= low cost and high reliability) in the corresponding transmission media.**
**The calibration methods themselves are sometimes based on assumptions about the standards and their repeatability, which makes them quite critical to employ and impossible to verify.**
**Manufacturing a good waveguide short at millimeterwave frequencies is very simple, but connecting it properly and repeatably may not be as simple.**

**Table 2 is an attempt to compare the obtained accuracies of commercially available calibration techniques [3].**

| **Calibration Method** | **Standards required** | **Transmission Media** | | |
|---|---|---|---|---|
| | | **Coaxial** | **Microstrip** | **Waveguide** |
| - Open-Short-Load | O,S,L | - | - | n/a |
| - Sliding Load | O,S,L,SL | + | n/a | o |
| - Short-Offset Short-Load | S,OS,L | n/a | n/a | o |
| - T R L | L,S(O),DL | ++ | + | ++ |

Table 2: Comparison of the accuracy obtained using different calibration methods (++ excellent, o adequate, - - poor).

The main conclusion from tables 1 and 2 is that **TRL** (Thru-Reflect-Line) is the most accurate and easy to employ method for all types of transmission lines, such as Coaxial, Microstrip (including Wafer) and Waveguide.

There is additional software required in the Network Analyzer system to permit TRL calibrations.
Some of the lower priced Analyzers like Hewlett Packard7 8720 A,B and 8753 do not have this option. The high end Vector Network Analyzers (HP 8510B, HP 8510C and Wiltron7 360 A and B) all include a TRL (Wiltron uses LRL) option. The HP 8720C is also available with TRL software.

[3] The recently from Hewlett Packard and ATN Microwave introduced ECal system provides similar accuracy as O,S,L,SL (Sliding Load) [3]. See also section 'Implemen-tation of VNA Calibration Techniques'.

## The TRL Method

The Thru-Reflect-Line (TRL) method was first proposed in 1979 [1].. Since then it has been enhanced to improve bandwidth and included as a standard calibration method in Hewlett Packard and Wiltron Network Analyzers.
According [2] the following conditions must be fulfilled by the TRL standards for a successful implementation.

| TRL Standard | Requirements |
|---|---|
| **REFLECT** | 1. Reflection coefficient Γ magnitude (optimally 1.0) need not be known<br>2. Phase of Γ must be known within ∀ λ /4<br>3. Must be the same Γ on both ports<br>4. May be used to set the reference plane if the phase response of the REFLECT is known and specified = 0 |
| **THRU** | 5. If Non-Zero THRU is used the Reference Plane is set at the centre of the THRU<br>6. If Zero THRU is used then the following assumptions are made: S11=S22=0 , S12=S21=1<br>7. Characteristic impedance $Z_0$ of the THRU and Non-Zero LINE must be the same<br>8. Attenuation of the THRU need not be known<br>9. Insertion phase or electrical length must be specified if the THRU is used to set the reference plane |
| **DELAY LINE** | 10. $Z_0$ of the LINE establishes the reference impedance after error correction is applied<br>11. Insertion phase of the LINE must never be the same as that of the THRU (zero or non-zero length)<br>12. Optimal LINE length is 1/4 wavelength or 90 degrees relative to the THRU at the centre frequency<br>13. Useable bandwidth of a single THRU/LINE pair is 8:1 (frequency span/start frequency)<br>14. Multiple THRU/line pairs ($Z_0$ assumed identical) can be used to extend the bandwidth<br>15. Attenuation of the LINE need not be known<br>16. Insertion phase or electrical length need only be specified within λ /4. |

## Discussion of TRL requirements

In the case of coaxial calibrations most of the above requirements can easily be satisfied. The use of a coaxial short satisfies conditions 1 and 3.
In GPC-7 the phase is 0 whereas in 2.9mm (K7) and GPC-3.5 systems the length of the offset short must be known within the $\lambda/4$ limit. (Condition 2).
Condition 6 is satisfied with any good coaxial THRU connection.
Conditions 8 and 9 are easily satisfied in the case of a coaxial line.
Conditions 7 implies some machining accuracy requirements for the non zero line. Since the characteristic impedance is given by $Z_o=(60/\varepsilon\ )\ \ln D/d$ and $\varepsilon = 1$ (air) the overall precision is related to the accuracy of manufacturing of the 2 diameters D and d of the outer and inner conductor of the coaxial line. For a simple structure like a centre conductor rod and an outer conductor tube high precision machining is easy within tolerances of ∀ 0.0002".

The requirements listed above for the LINE (10 to 16) are not all generally valid.
We never observed problems with requirement 11 and requirement 12 is easily fulfilled.
Condition 13 is not an absolute requirement. The TRL calkits of Focus Microwaves yield fmax/fmin ratios beyond 36:1 (0.5 to 18 GHz, or < 1 to 40 GHz), using a single Delay line.

The real limitation is at the high frequency end, where the phase of the Delay line should not exceed the phase of the Thru line by more than 180E. This is feasible when the delay line is dimensioned $\lambda/4$ at the mid frequency, as in our case.
Requirement 14 is therefore obsolete. The lack of a second delay Line may create some phase errors in the calibration for very narrow bands (Example 0.3 - 1 GHz).
For those low frequencies, however, different calibration standards, such as Open-Short-Load can be used and yield satisfactory calibrations.

## Implementation of VNA Calibration Techniques

There are several reasons why Engineers in different Laboratories do not always perform adequate VNA calibrations. Some of them are:

- Use the "wrong" calibration technique
- Use "worn out" calibration standards or connectors
- Take "shortcuts" to save time (not use sliding loads)
- Use "broken cables" (due to over-bending)
- "Avoid to re-calibrate" if the verification reveals problems.

There are a **few simple rules to follow that permit to avoid all the above problems without having to spend a lot of money in extra calibration kits**:

1- Use TRL (or LRL) method
2- Use Connector Savers and replace them regularly
3- Use long (3 feet or more) flexible or semi-rigid cables
4- Take your time to calibrate and verify
5- Never use a non-verified calibration

**The VNA calibration procedure is not the moment to save time.**
**It will, normally, be paid with measurement errors.**

The table below compares different calibration methods for the time needed to employ, and the cost, complexity and easy verification of the standards.

| Method | Standards | Time | Cost | Complexity | Verification[4] |
|---|---|---|---|---|---|
| TRL | DL,O/S | 5 min | 5-12 k$ | very low | immediate |
| SOT | O,S,L | 8 min | 5-8 k$ | low | problem with terminations |
| S-OS-T | S-OS-T | 5-15 min | 5-10 k$ | medium | problems with terminations if using sliding load |
| ECal | Tuner | 1.5 min | 8-20 k$ | high | in factory only |

Table 3: Implementation of different VNA calibration methods

[4] **Verification** in this context means the possibility that a trained person **can judge** by simple visual or electrical (Ohm-meter) inspection or mechanical verification **if a standard is damaged or not**.

# TRL Calibration kits of Focus Microwaves

The TRL calibration kits of Focus Microwaves have been developed in order to make wide band coaxial calibrations using one of the following Network Analyzers:
HP 8510 B and C, HP 8720 C and Wiltron 360 A and B.

- The TRL-7mm calibration kit can be used from 300 MHz to 18 GHz.

- The TRL-2.92mm calibration kit uses K7 connectors and can be used to calibrate
  - a Wiltron 360 with K7 connectors from 0.5 to 40 GHz.
  - a HP8510 B/C with 3.5mm connectors from 0.5 to 26.5 GHz.
  - any of the analyzers with SMA connectors from about 0.5 to 18 GHz.

# Components of the TRL Calibration Kits

The Focus Microwaves TRL calibration kits include the following standards

**GPC-7-TRL-CV** (figure 1)

- One 7mm short
- Two 50Ωloads
- One 50Ωline extension (Delay Line) including
  - One outer conductor cylinder
  - One centre conductor extension
- One 10cm 50Ωairline (for verification)

**GPC-2.92-TRL-CV (K7)** (figure 2)

- One offset short (male)
- One offset short (female)
- Two 50Ωloads (1 male, 1 female)
- One set of adapters (two male-female, one female-female).
- One 50 Ωextension line including
  - One outside conductor cylinder
  - Two centre conductor pins (one spare)
- One SMA or K7 connector fastener

For users of HP 8510-C network analyzers a 32" floppy is available in DOS or LIF format including the Calkit's parameters.
For users of Wiltron 360 this is not required because the Calkit's parameters can be introduced into the Analyzer very easily with a few keystrokes.

# Performance Verification of the TRL Calibration kits

There is some confusion, among Engineers, concerning the term **Verification**. In most cases the operator connects both connectors at the calibration reference plane and verifies the transmission (S21) or connects a short on either port and verifies the reflection (S11 or S22).

As a matter of fact this test does not say much about the validity of the calibration, this is rather a **Repeatability** test, since both standards (Thru line and Short) have already been used in the calibration procedure and we "told" the Analyzer: "this is a Short" or "this is a Thru" by pressing the corresponding Softkeys during the calibration. So the Analyzer **should** recognize the standards when we measure them again except if something is very wrong! If you have any problem recognizing the standards then you should verify the cables, the connectors and, if everything seems OK, repeat the calibration paying attention to **establish good mechanical connections** before you measure.

A reliable **Verification** procedure can be limited in measuring, in addition to the above
1- The **Ripple** of an OFFSET SHORT
2- The **Residual Reflection** of the THRU LINE

## Offset Short

To test an offset short use a 50Ω Airline, normally supplied with the Calkit, connected to a Short. Set the S11 (or S22) display on LOG MAG and the SCALE to 0.1 dB/DIV.

You should obtain on both ports graphs like figures 3 and 6. Both the HP and Wiltron Analyzers can be calibrated to generate offset short ripple of less than 0.1 dB over the 0.3 to 40 GHz frequency range using TRL calkits. A careful calibration of the HP-8510-C can provide ripple of less than 0.05 dB.
This residual ripple is due to residual directivity and test port mismatch of the Analyzers and cannot be improved by error corrections.

## Thru Line

When testing a THRU Line then S12 and S21 are the least significant parameters to observe. Anyhow if there is any problem with S12 or S21 then the calibration is useless and should be discarded.
The RESIDUAL REFLECTION should be verified and should generate a return loss of 50 to 70 dB over the entire frequency range. Figures 5 and 8 show examples of such measurements over the 0.5 to 18 and 1 to 40 GHz ranges made using the GPC-7 and GPC-2.92 Calkits correspondingly.

Figure 1
GPC-7 TRL Calibration Kit

Figure 2
GPC-2.92 (K7) TRL Calibration kit

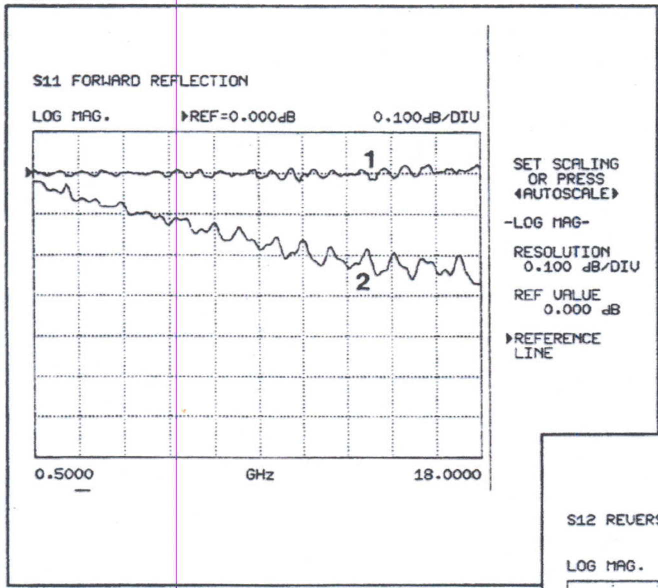


Figure 3
Short (1) and Offset Short (2)
Verification of GPC-7 kit

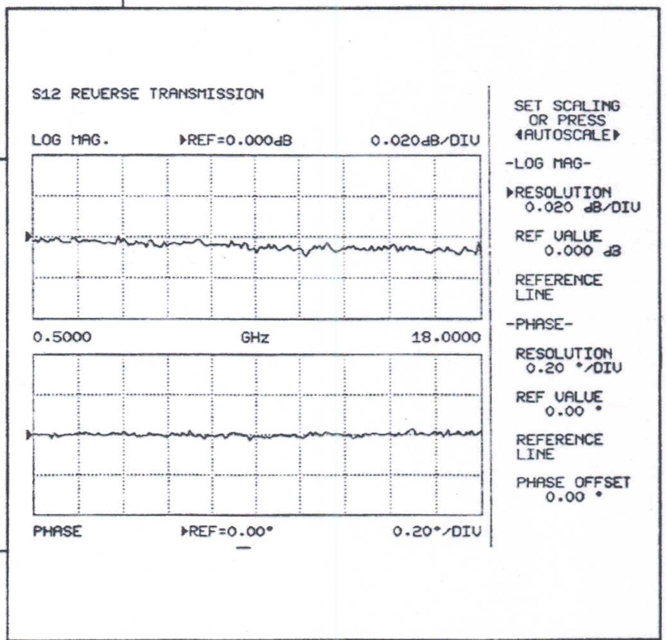


Figure 4
THRU Line Verification
of GPC-7 kit

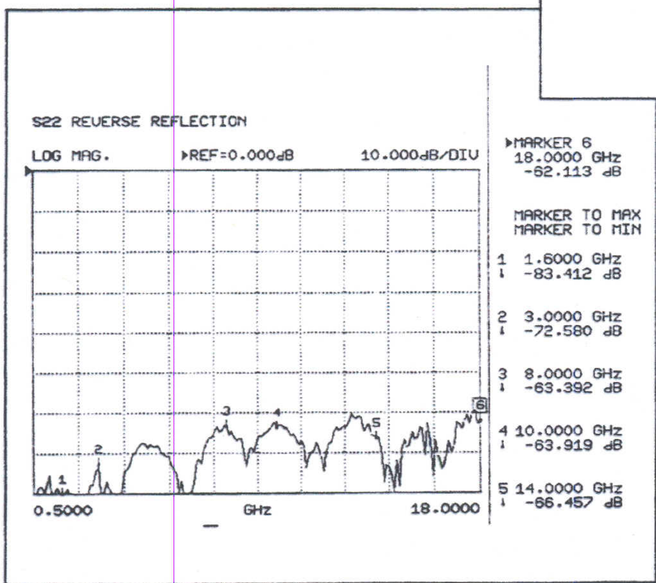


Figure 5
Residual Reflection
Verification of GPC-7 kit

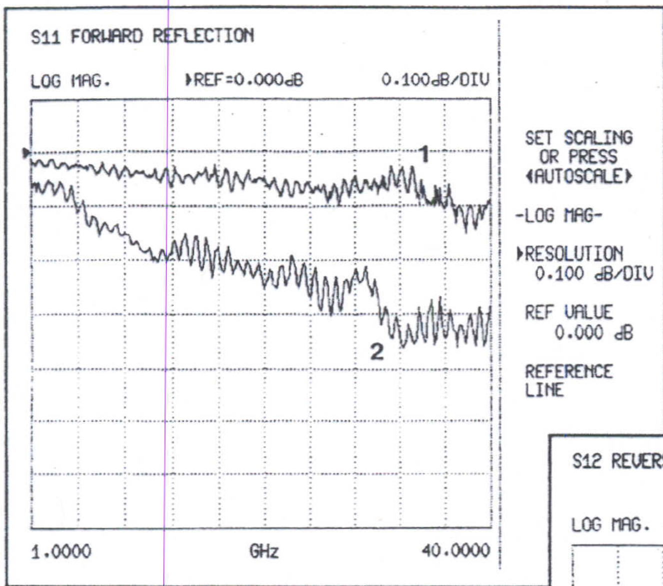


Figure 6
Short (1) and Offset Short (2)
Verification of GPC-2.92 kit

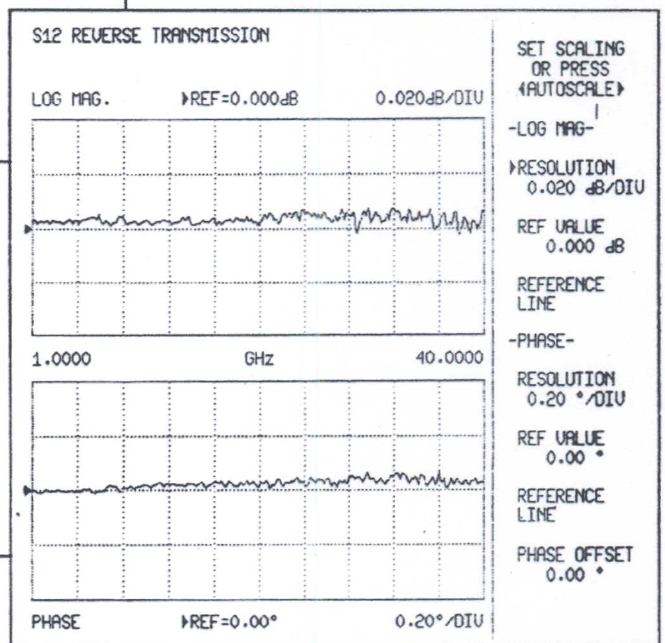


Figure 7
THRU Line Verification
of GPC-2.92 kit

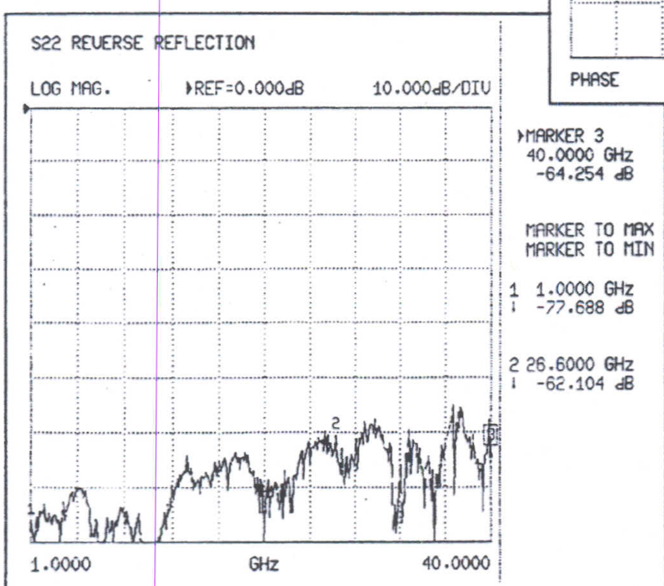


Figure 8
Residual Reflection
Verification of GPC-2.92 kit

# References


[1] GF Engen and CA Hoer, "TRL: an improved technique for calibrating the dual six-port automatic network analyzer", IEEE MTT, December 1979.

[2] Product Note 8510-8, Hewlett Packard, October 1987

[3] Product Overview, HP 85060 Family, Electronic Calibration System, Hewlett Packard, January 1994