Optimization of automatic exclusion algorithm of the vector network analyzer measuring equipment

D A Bolshakov, N N Burdukovskaya and K V Shugurova
JSC “Academician M F Reshetnev Information satellite systems”, 52 Lenin street, Zheleznogorsk, Krasnoyarsk region, 662972, Russia
E-mail: burdukovskayann@iss-reshetnev.ru

Abstract. Automatic elimination of measuring equipment (deambedding) in measuring S-parameters has become widespread with the development of modern vector network analyzers. This handy feature allows to get the measurement results in the "ready form", eliminating the need to perform calculations manually with the transformation of S-parameters matrices many times (by the number of points in the source *.s2p file). At the same time, this function has certain limitations that become critical with the exclusion of measuring equipment with large (more than 30 dB) losses. This paper describes the experience of determining the limitations of the applicability of the deambedding operation, provides an analysis of the reasons for their existence, and also suggests a method for eliminating these limitations.

The appearance of vector network analyzers (VNA) of the function of automatic exclusion of a calibrated measuring tool (deambedding) in the functional significantly simplified the measuring process. This circumstance is associated with eliminating the need for post-processing of measurement results using specialized software (for example, Agilent Genesis) and additional mathematical analysis of measurement results. Particularly vividly, the advantage of using deambedding is manifested in the organization of complex multiport measurement systems (for example, control and test equipment of the payload of a spacecraft), where real-time streaming processing is required with control of the result obtained.

In his paper, the author encountered the incorrect operation of the deambedding operation with the exclusion of equipment with a significant (more than 30 dB) attenuation. The need to use technological equipment with such large losses is due to the peculiarities of the device under test (the spacecraft onboard repeater). The connection of the VNA to the repeater is carried out by means of directional couplers (DC) with typical branch loss of about 28 dB (for all applicable frequency bands). In addition to CD, increased losses are due to long (up to 13m) test cables and the presence of a waveguide or coaxial switching matrix. A typical scheme of connecting the VNA as part of the test equipment (TE) to the onboard transponder (OBT) is shown in a simple form in figure 1.
Cables 3 and 4 are connected directly to ports 1 and 2 of the VNA, they are involved in the calibration process (before the measurement starts) and do not require an exception. In this case, the measurement result should reflect the S-parameters of the OBT equipment. Denote the boundaries of the calibration and the measured device as “slices”.

Thus, all technological equipment located between the "slices" of calibration and measurement should be excluded from the measurement result. In the considered scheme, the excluded accessories include: switching matrices, test coaxial cables up to 10 m long, as well as a BUT branched channel. To obtain accurate results, all the equipment between the "slices" of measurement and calibration should be pre-measured in the required frequency range and with the results saved in the *.s2p format. Losses in a snap will be defined as:

\[
L_{in} = L_{mch1} + L_1 + L_{wic1}
\]
\[
L_{out} = L_{mch2} + L_2 + L_{woc1},
\]

where: \(L_{in}\), \(L_{out}\) are total losses of input and output, respectively (dB); \(L_{mch1}\), \(L_{mch2}\) are switching matrix losses (dB); \(L_{wic1}\), \(L_{woc1}\) are branch loss in DC (dB); \(L_1\), \(L_2\) are losses in long text cables (dB).

In (1) and (2) losses in transitions between connectors are not taken into account, because loss measurement is performed with the same transitions that will be used in the measuring circuit.

Let us consider the situation when receiving equipment (OBT input) operates in the Q frequency range, and transmitting equipment (OBT output) operates in the Ka frequency range. The measured attenuations in the tooling elements are presented in table 1 (test cables 10 m long were used).

| Частота, ГГц | 20.1 (Ka) | 44.5 (Q) |
|-------------|-----------|-----------|
| \(L_{mch1}\), дБ | - | 6,0 |
| \(L_{mch2}\), дБ | 3,2 | - |
| \(L_{wic1}\), дБ | - | 32,6 |
| \(L_{woc1}\), дБ | 28,6 | - |
| \(L_1\), дБ | - | 27,3 |
| \(L_2\), дБ | 14,4 | - |
| \(L_{in}\), дБ | - | 65,9 |
| \(L_{out}\), дБ | 46,2 | - |

The calculation shows that in the described case the input loss, which will be eliminated using the deambedding operation, exceeds 65 dB, i.e. the test signal, reaching the measuring slice, will weaken by 107 times. Taking into account the capabilities of modern VNA (own noise of measuring receivers
at the level of minus 150 dBm), the total path loss (112.1 dB) does not make it impossible to measure correctly. It is also necessary to take into account that the OBT may have a gain of up to 130 dB, that is:

\[ P_{mr} = P_{rs} - L_{in} - L_{out} - L_{cal} + G, \]  

(3)

where \( P_{mr} \) is input receiver power (dBm); \( P_{rs} \) is port source power (dBm); \( L_{in}, L_{out} \) are snap-in loss (dB); \( L_{cal} \) are calibrated area losses, including internal VNA loss (dB); \( G \) is OBT amplification (dB).

However, such a weakening of the test signal leads to incorrect operation of deambedding.

Let us consider the following test. A full two-port calibration was performed using the SOLT method for cutting test phase-stable cables (the author used SUCOFLEX101PEA NMD 2.4 mm (f) - 2.92 mm (m) 600 mm, on both VNA ports and electronic calibration module) in the frequency range 22.0 GHz - 23.0 GHz over 1601 points, with 50 averagings, with a source power of 0 dBm. After calibration, the S-parameters of the step attenuator 0–70 dB were measured, thus eight *.S2P files were obtained. The resulting files are used as a snap-in, eliminated with the help of deambedding. The described scheme is explained in figure 2.

![Figure 2. Experimental scheme: 1,2 - SUCOFLEX101PEA cable assemblies.](image)

Figure 2 shows that for any set value of losses in the attenuator, the equipment excluded by one of the ports corresponds in S-parameters to the device under test (attenuator). Under ideal conditions in such a test, after the deambedding operation, the measurement result S21 should always be the same: S21 = 0 in the entire frequency range.

In practice, the following results are obtained (see figure 3).

Taking into account the modern requirements for errors measurement when testing equipment of communication systems (especially OBT), the measurement error of amplitude characteristics (frequency response, AM-AM, compression point) should not exceed 0.5 dB.

The results obtained allow us to draw the following conclusions (see table 2).

| No | Attenuation snap, dB | Measurement error, dB | Evaluation and comments                      |
|----|---------------------|-----------------------|---------------------------------------------|
| 1  | 10                  | \( \leq 0.03 \)       | Fine. Result is at calibration error level   |
| 2  | 20                  | \( \leq 0.12 \)       | Good                                         |
| 3  | 30                  | \( \leq 0.33 \)       | Satisfactory                                 |
| 4  | 40                  | \( \geq 8 \) dB       | Unacceptable. It is impossible to use in work|
| 5  | 50                  | \( \leq \text{minus 18} \) |                                             |
| 6  | 60                  | \( \leq \text{minus 39} \) |                                             |
Figure 3. Measurement results with an exception: 1 - 10 dB; 2 - 20 dB; 3 - 30 dB; 4 - 40 dB; 5 - 50 dB; 6 - 60 dB.

Considering that the self-noise of the measuring receivers used by the VNA is not worse than minus 163 dBm, according to the formula (3) losses in the measured device at minus 60 dB at the source level of 0 dBm could not create a significant obstacle to their operation.

The algorithm of the VNA software operation when performing the deambedding operation is described in [1]. According to [3], the logic of operation and the mathematical apparatus of the VNA software are based on the representation of the test circuit as three two-pole devices connected in series (see figure 4).

Figure 4. Presentation of the VNA measurement scheme in deambedding mode: DUT - the device under test; FA<sub>xx</sub> - equipment parameters on port 1; FB<sub>xx</sub> - equipment parameters on port 2; S<sub>xx</sub> - parameters of the device under test.

Everything on figure 4 to the left and right of the calibration slices is taken into account during calibration and does not need to be excluded from the measurement results. What lies between the calibration and measurement sections is considered to be a measuring tool and is excluded by deambedding means. Taking into consideration that scalar operations can be performed only with transfer coefficients (S12 and S21) and only under certain assumptions, to exclude a snap-in, a conversion to T-parameters is used [2, 3]:

\[
\begin{bmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{bmatrix} = \begin{bmatrix}
S_{11} S_{22} - S_{12} S_{21} \\
S_{21} S_{22} - S_{12} S_{21} \\
S_{11} S_{21} \\
S_{21} S_{21}
\end{bmatrix}, \quad \text{или} \quad (4)
\]
\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{11} & S_{22}
\end{bmatrix} = \begin{bmatrix}
T_{12} & T_{12}T_{22} - T_{12}T_{21} \\
T_{22} & T_{22} - T_{21}
\end{bmatrix}
\]

(5)

The parameters of the device under test, taking into account the transformation, are defined as:

\[
[T_{DUT}] = [T_A]^{-1} \cdot [T_M] \cdot [T_B]^{-1}
\]

(6)

where \(T_{DUT}\) - true parameters of the device under test; \(T_M\) - measured parameters (without exception equipment); \(T_A\) - snap parameters on the first port; \(T_B\) - snap-in options on the second port.

It can be seen from formulas (4) and (5) that the reflection coefficients \(S_1\) and \(S_2\) participate in the calculations of the transfer coefficients \(T_{12}\) and \(T_{21}\). Such a calculation is convenient, however, does not take into account the measurement error due to the mismatch, which becomes significant at the microwave. Those, in ideal conditions, when the return loss on the slices of the measurements is infinitely small, you can use this method of calculation without analyzing the errors. In real conditions, there are always losses due to mismatch (see figure 5).

\[
\varepsilon_{\text{rf}} = \frac{\varepsilon_{\text{rf}} F A_{12}}{1 - \varepsilon_{\text{rf}} F A_{11}}
\]

(7)

\[
\varepsilon_{\text{df}} = \frac{\varepsilon_{\text{df}} F A_{22}}{1 - \varepsilon_{\text{df}} F A_{21}}
\]

(8)

\[
\varepsilon_{\text{sf}} = \frac{\varepsilon_{\text{sf}} F A_{22} F A_{21}}{1 - \varepsilon_{\text{sf}} F A_{21}}
\]

(9)

\[
\varepsilon_{\text{tr}} = \frac{\varepsilon_{\text{tr}} F A_{12} F B_{22}}{1 - \varepsilon_{\text{tr}} F B_{22}}
\]

(10)

\[
\varepsilon_{\text{rf}}' = \frac{\varepsilon_{\text{rf}} F A_{12} F A_{21}}{1 - \varepsilon_{\text{rf}} F A_{21}}
\]

(11)

\[
\varepsilon_{\text{df}}' = \frac{\varepsilon_{\text{df}} F A_{22} F A_{21}}{1 - \varepsilon_{\text{df}} F B_{21}}
\]

(12)

\[
\varepsilon_{\text{sf}}' = \frac{\varepsilon_{\text{sf}} F A_{22} F B_{21}}{1 - \varepsilon_{\text{sf}} F B_{21}}
\]

(13)

\[
\varepsilon_{\text{tr}}' = \frac{\varepsilon_{\text{tr}} F A_{12} F B_{22}}{1 - \varepsilon_{\text{tr}} F B_{22}}
\]

(14)

\[
\varepsilon_{\text{rf}}'' = \frac{\varepsilon_{\text{rf}} F A_{12} F A_{21}}{1 - \varepsilon_{\text{rf}} F A_{21}}
\]

(15)

\[
\varepsilon_{\text{df}}'' = \frac{\varepsilon_{\text{df}} F A_{22} F A_{21}}{1 - \varepsilon_{\text{df}} F B_{21}}
\]

(16)

\[
\varepsilon_{\text{sf}}'' = \frac{\varepsilon_{\text{sf}} F A_{22} F B_{21}}{1 - \varepsilon_{\text{sf}} F B_{21}}
\]

(17)

where: \(\varepsilon_{\text{df}}, \varepsilon_{\text{df}}\) - port source impact; \(\varepsilon_{\text{sf}}, \varepsilon_{\text{tr}}\) - input from the mismatch of the sources of the ports; \(\varepsilon_{\text{df}}, \varepsilon_{\text{tr}}\) - contribution from reflection from adapters on ports; \(\varepsilon_{\text{df}}, \varepsilon_{\text{tr}}\) - direct crosstalk between ports.

**Figure 5.** Measuring circuit taking into account the mismatch (above) and its equivalent circuit (below).
$E_d$, $E_o$ – contribution from source mismatch; $E_{df}$, $E_{fo}$ – contribution from the transmission coefficient by ports; $FA_{11}, FA_{21}, FA_{12}, FA_{22}$ – S-parameters snap on port 1; $FB_{11}, FB_{21}, FB_{12}, FB_{22}$ – S-parameters snap on port 2.

Relations (9-16) show that the parameters $FA_{22}, FB_{22}, FA_{11}, FB_{11}$, which reflect the return loss in the measurement tool, affect the error calculation equally with the components defined by $FA_{21}, FA_{12}, FB_{21}, FB_{12}$ which represent straight lines tooling loss.

If the direct loss is, for example, 60 dB (as in the case under consideration), the return loss from port 1 will be no worse than minus 120 dB [5, 6, 7], which corresponds to SWR:

$$SWR = \frac{1 + 10^{-\frac{S_{11}}{20}}}{1 - 10^{-\frac{S_{11}}{20}}} = 1,000002.$$

The value, which cannot be achieved in practice. At frequencies in the Ka range, a value of 1.2–1.3 is considered good, at best, 1.12, which corresponds, according to (18), to parameter $S_{11}$ equal to minus 25 dB. If the losses in the equipment, which is measured for subsequent elimination, significantly exceed this value, then the measurement result $S_{11}$ of this equipment will reflect the return loss of the adapter [4] rather than the directly measured equipment. What will affect the final result of the measurement using deambedding (see table 2). For a better understanding of this effect, we will conduct a mental experiment: a cable with a loss of 2.8 dB / m at a frequency of 45 GHz, 10 meters long, connected to the first port of the VNA in the measurement mode of VSWR at 45 GHz, the calibration measures of the SN, XX and KZ - the difference in SWR between the measures will not be noticeable.

The easiest way out of this situation is to stop using deambedding in favor of scalar post-processing on a PC. However, this is not always convenient (especially when creating automated measurement systems). Reducing losses is also not always possible (an example with measurements of the parameters of the OBT).

A possible solution to the problem may be the processing of *.s2p files used for deambedding. Processing consists in “replacing” the values of $S_{11}$ and $S_{22}$ with very low ones (for example, minus 200), which practically excludes their influence on the final result (according to (7) - (16)). Fragments of files before and after processing are presented in figure 6.

![Graph showing file processing with direct losses of minus 62 dB.](image)

This method is applicable for broadband (with respect to the strip of subsequent measurements) snap-in, which has no rejection in the strip. That is, if it is necessary to exclude from the measurement, for example, a filter with a pronounced out-of-band and in-band rejection, the result may turn out to be unreliable. As the practice of OBT testing shows, the excluded equipment consists of switching matrices.
cables, directional couplers, and the proposed method allows to obtain reliable results using the
deambedding function.

Figure 7 shows the results of repeated measurements of the attenuator with the exception of the
processed snap-in files.

![Image of Figure 7 with S21 dB vs Frequency for different attenuation levels]

Figure 7. The results of repeated measurements with the exception: 1 - 10 dB; 2 - 20 dB; 3 - 30 dB;
4 - 40 dB; 5 - 50 dB; 6 - 60 dB; 70 - 70 dB.

Analysis of the measurements before and after processing allows us to draw the following
conclusions (see table 3).

Table 3. Result express-analysis.

| No | Attenuation snap, dB | Measurement error before, dB | Measurement error after, dB | Evaluation and comments |
|----|----------------------|------------------------------|----------------------------|-------------------------|
| 1  | 10                   | ≤ 0,03                       |                            | Excellent               |
| 2  | 20                   | ≤ 0,12                       |                            |                         |
| 3  | 30                   | ≤ 0,33                       | ≤ 0,06                     | Excellent               |
| 4  | 40                   | ≥ 8                          |                            |                         |
| 5  | 50                   | ≤ minus 18                   | ≤ 0,08                     |                         |
| 6  | 60                   | ≤ minus 39                   | ≤ 0,12                     | Good                    |
| 7  | 70                   | -                            | ≤ 0,27                     |                         |

Provided that the excluded equipment does not have a non-uniformity of the group specification, it
is possible to carry out all types of measurements that are standard for VNAs, except for GD (absolute
value of the group specifications).

The proposed method allows with sufficient accuracy to measure S-parameters with the exception of
equipment with losses up to minus 70 dB.

References
[1] Dunsmore J P 2012 *Handbook of Microwave Component Measurements with Advanced VNA
Techniques* (New York: Wiley–Interscience)
[2] Hiebel M 2008 *Fundamentals of Vector Network Analysis* (Munich: Rohde &Schwarz)
[3] Agilent 2004 *De-embedding and Embedding S-Parameter Network Using a Vector Network
Analyzer* (Agilent Technologies)
[4] Dzhurinsky K B 2013 *Miniature RF Connectors* (Moscow: Radiant)
[5] Bolshakov D A 2010 Investigation of the resistance of shielding materials *SibSAU Vestnik 6*(32)
74-7
[6] Bolshakov D A 2009 Development of a system for EMC research of the onboard cable network
of spacecraft \textit{X Korolev Readings} 48-9

[7] Burdukovskaya N N and Bolshakov D A 2016 Method of measuring the shielding rate of high-frequency connectors without dismantling \textit{High School} 22 70-4