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To: EDGES Group
From: Raul Monsalve
Subject: Effect of Error in the VNA Calibration Standards, on Measured Reflection Coefficient

1 Description

This memo provides estimates of error in reflection coefficient for loads of different values, due to error in the model of the standards used to calibrate the VNA using the one-port SOL method.

The errors are obtained through simulation. Measured values for the $open$, $short$, and $match$ are simulated using the models provided by the Agilent Application Note 1287-11, and the standard definitions of the Agilent 85033E 3.5-mm calibration kit. The true reflection coefficients of the standards are simulated by making perturbations to the $measured$ values, in magnitude and phase. This has the purpose of studying the scenario where the assumed model of one of the standards is incorrect.

With knowledge of the $measured$ and $true$ values of the standards, the scale of the VNA is taken from an uncorrected state to a corrected one. With the rescaling parameters at hand, it is possible to estimate the error for any measured load by computing the difference: *measured value* - *true value*. This is conducted for loads in the range 0 to -100 dB in magnitude, and 0 to 360° in phase.

Perturbations were applied sequentially to the magnitude and phase of the standards, one at a time. Therefore, the errors in the reflection coefficient of the load are the result of a single source of error every time, as opposed to a combination of them.

The errors in the standards are assigned as follows:

- Open magnitude: The fiducial model (used for the $measured$ trace) is flat below 200 MHz. $True$ profile is generated with the same curvature as that of the fiducial short magnitude. This error is unrealistically large and serves to put upper limits. Due to its nature, this is the only case with a one-sided error. All the others are studied as a plus/minus error band.
- Open phase: A constant error value of 0.55° obtained from the basic uncertainty specifications from Agilent.
- Short magnitude: The positive part of the error band corresponds to the distance between the fiducial model (used for the $measured$ trace), and a magnitude of 1 (0 dB). Same distance is used for the negative side of the error band, producing a larger curvature.
- Short phase: A constant error value of 0.48° obtained from the basic uncertainty specifications from Agilent.
- Match 1 magnitude: The error is specified as an error in resistance, of 0.01 Ω, relative to a reference of 50.008 Ω (-82 dB).
- Match 1 phase: An error of 90° is used. This value is chosen as the maximum that generates an error below 0.01 dB for a load at -20 dB.

- Match 2 magnitude: The error is specified as an error in resistance, of 0.01 Ω, relative to a reference of 50.1 Ω (-60 dB).
- Match 2 phase: An error of 5° is used. This value is chosen as the maximum that generates an error below 0.01 dB for a load at -20 dB.

As described above, two $match$ standards are simulated, referred to 1 and 2. Match 1 is used in most cases, except the last two where the purpose was to study the effect of error in a $match$ that departs significantly from 50 Ω, such as when its temperature is low (for a $match$ with negative temperature coefficient).

The appendices provide plots that illustrate key steps in the analysis. The first and second figures in each section depict the rescaling of the VNA using knowledge of the $measured$ and $true$ values. The third figure (heat map plots) shows the error propagated to the measurement of the load. For simplicity, heat maps are shown for a frequency of 200 MHz only. Errors for other frequencies are equal or lower, since the errors in magnitude of the $open$ and $short$ are largest at 200 MHz. Therefore, the results extracted from these maps correspond to the worst-case-scenario. The fourth figure presents cuts from its corresponding heat map, for a load with constant magnitude (-15 and -20 dB) and varying phase (from 0 to 360°). Below, Table 1 presents the largest errors for any phase, at a constant magnitude (-15 and -20 dB). This ensures that the quoted errors are the largest possible ones at those levels.

2 Results

The perturbation values are valid at 200 MHz, in particular the magnitude of the open and short. They were applied individually, one at a time. Here, the word *perturbation* refers to the distance between $true$ value and the fiducial ($measured$) value. If the $measured$ value is 0 dB and the $true$ value is -0.012 dB, the perturbation is negative. The same nomenclature is used in the plots, especially the heat maps.

As described above, the errors quoted in this table for magnitudes of -15 and -20 dB represent the worst value in the phase range 0 to 360°.

Table 1: Effect of Error in the VNA Calibration Standards, on Measured Reflection Coefficient.

Parameter	Perturbation	Error for -15 dB load	Error for -20 dB load	Comments
open mag	0.012 dB	0.0069 dB / 0.0069°	0.0065 dB / 0.0039°	
open phase	0.55°	0.0073 dB / 0.32°	0.0041 dB / 0.30°	
short mag	0.012 dB	0.0069 dB / 0.0069°	0.0065 dB / 0.0039°	
short phase	0.48°	0.0064 dB / 0.28°	0.0036 dB / 0.26°	
match 1 mag	0.01 Ω*	0.0047 dB / 0.033°	0.0086 dB / 0.058°	*for reference of 50.008 Ω
match 1 phase	90°	0.0055 dB / 0.036°	0.0098 dB / 0.065°	
match 2 mag	0.01 Ω**	0.0047 dB / 0.033°	0.0086 dB / 0.058°	**for reference of 50.1 Ω
match 2 phase	5°	0.0044 dB / 0.027°	0.0076 dB / 0.049°	

3 Conclusion

For the presented perturbations to the measured standards, the errors in a -15 or -20-dB load are always below 0.01 dB and 0.32° in magnitude and phase respectively. This is encouraging considering that the perturbations range between $conservative$ and $unrealistically\ large$. A full covariance analysis is still needed for assessing the combined effect of more realistic values.

A Perturbation in MAGNITUDE of OPEN

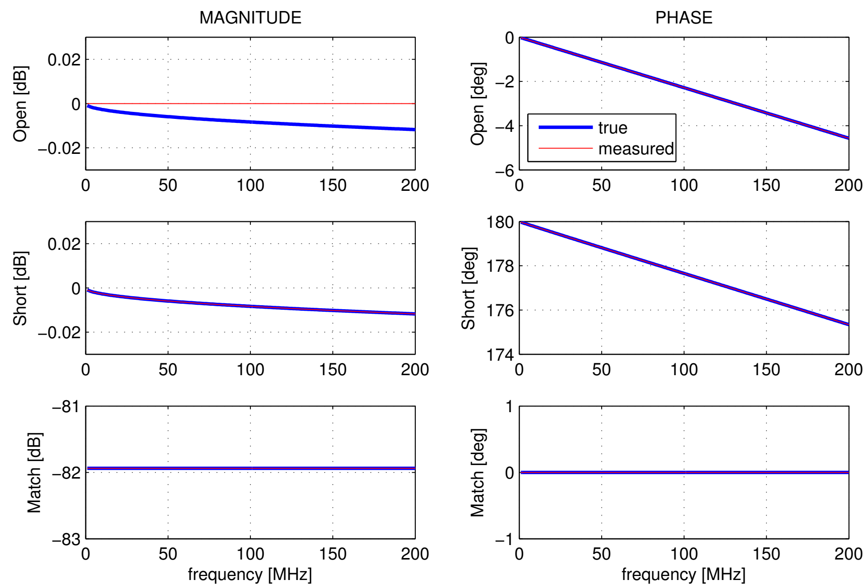

Figure 1: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the magnitude of the $open$ standard is off. Only a one-sided error is considered.

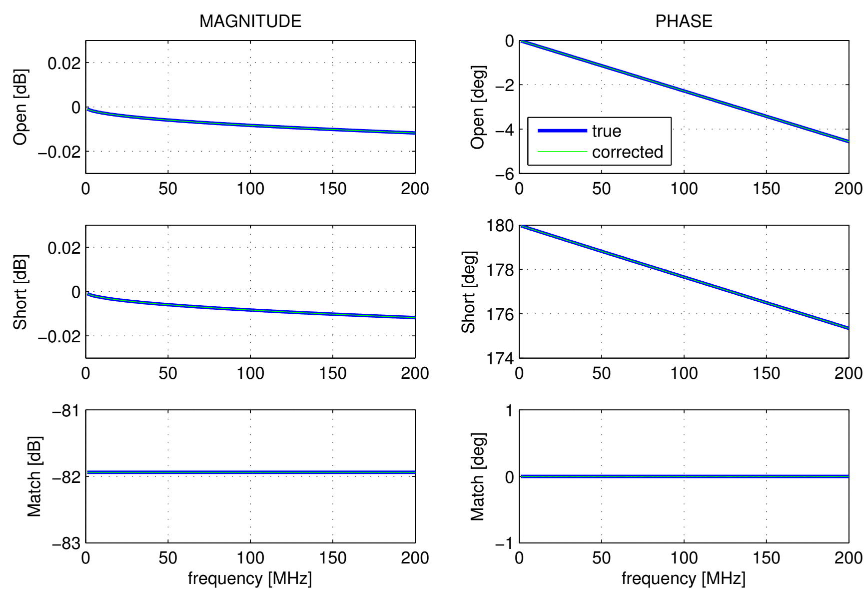

Figure 2: After correcting the VNA scale.

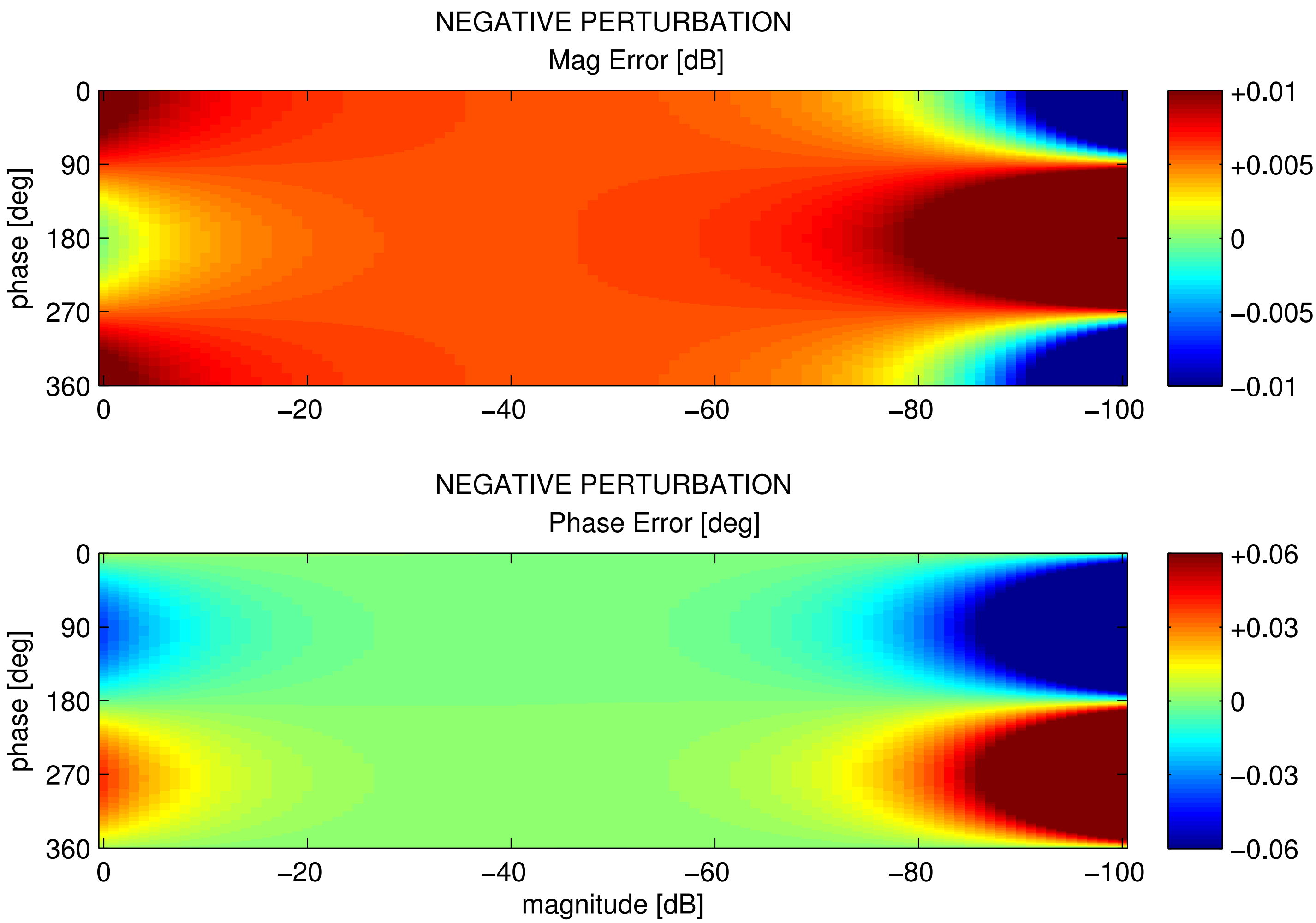

Figure 3: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Only results for negative perturbation here.

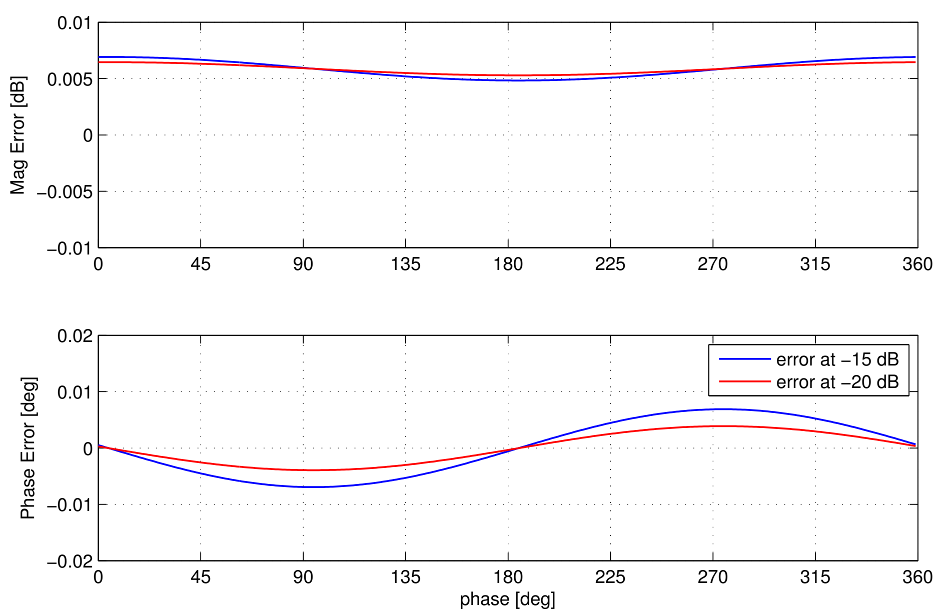

Figure 4: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

B Perturbation in PHASE of OPEN

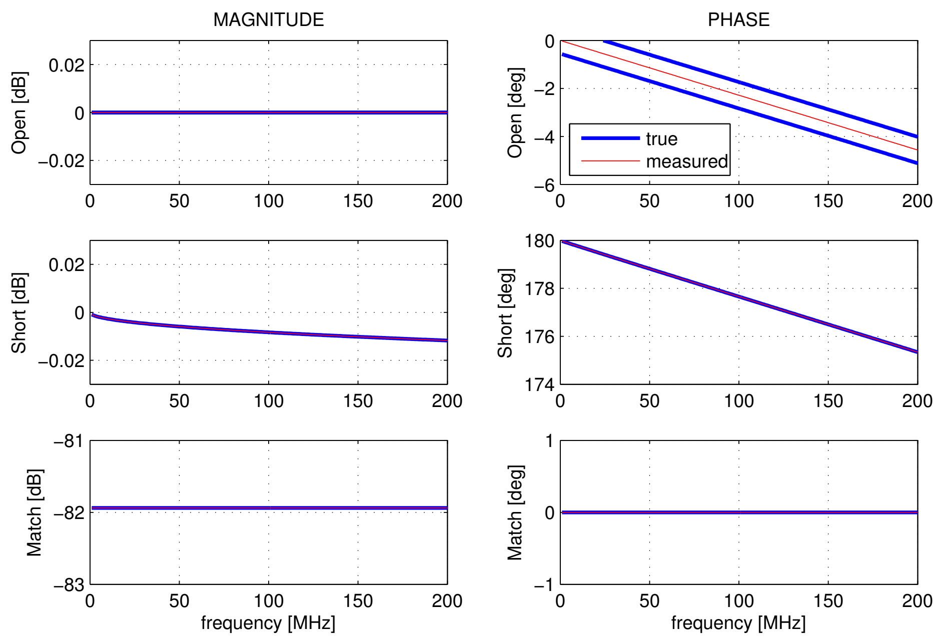

Figure 5: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the phase of the $open$ standard is off. Positive and negative perturbations are considered.

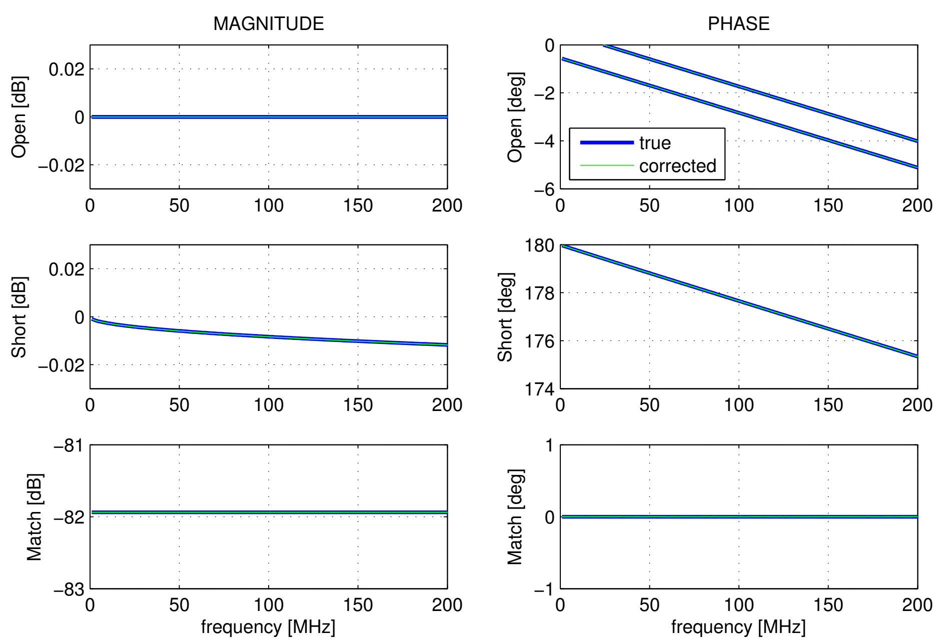

Figure 6: After correcting the VNA scale.

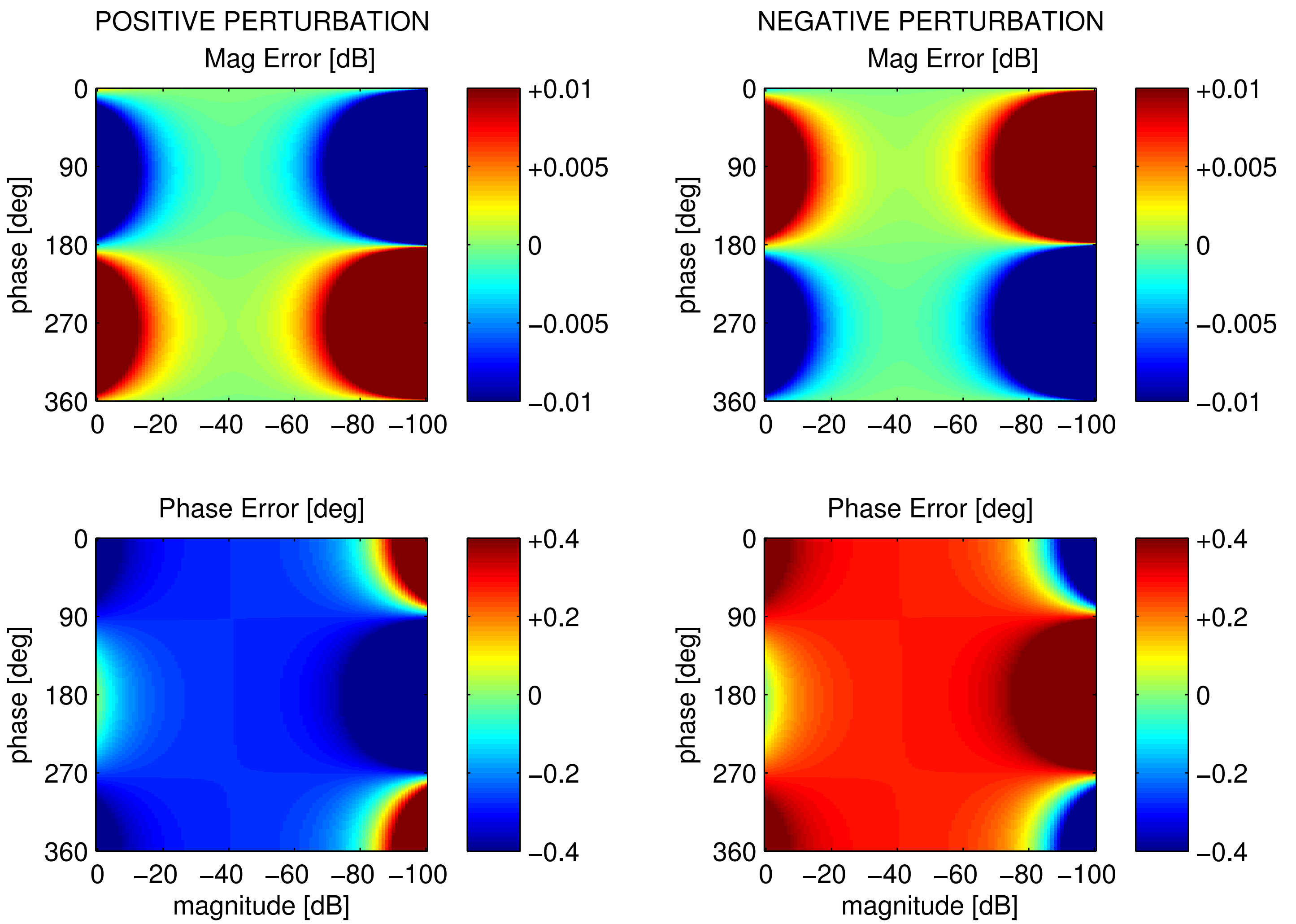

Figure 7: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

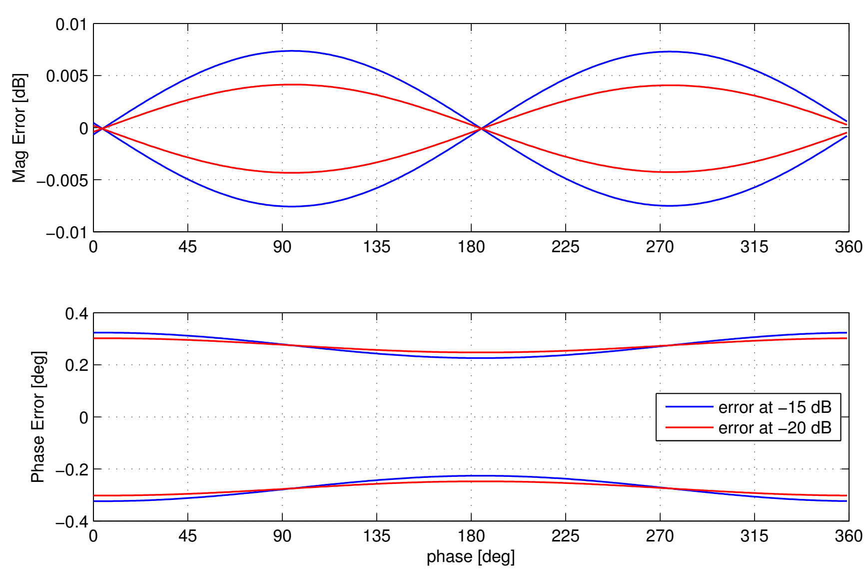

Figure 8: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

C Perturbation in MAGNITUDE of SHORT

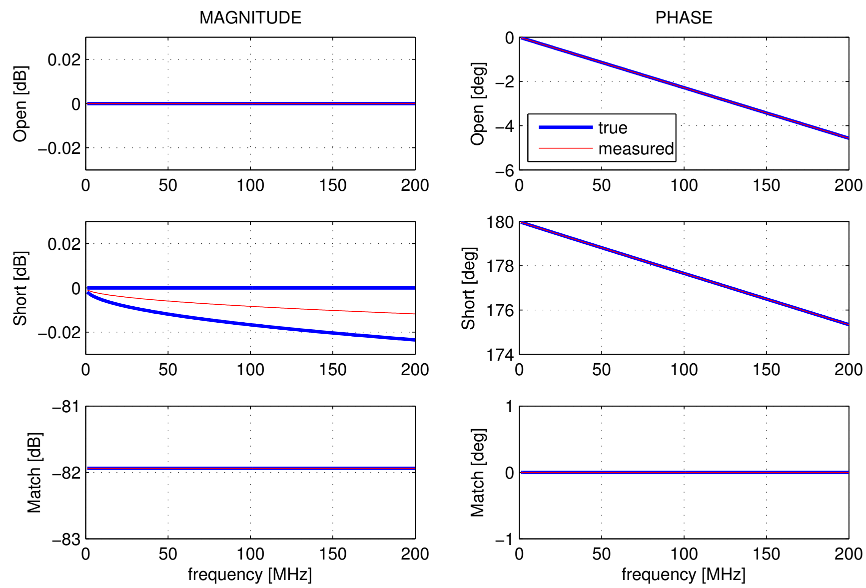

Figure 9: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the magnitude of the $short$ standard is off. Positive and negative perturbations are considered.

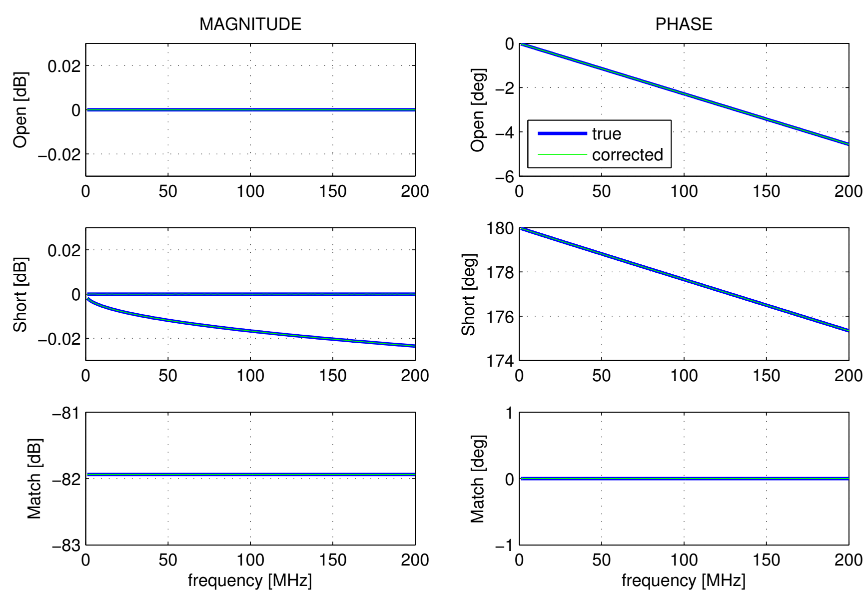

Figure 10: After correcting the VNA scale.

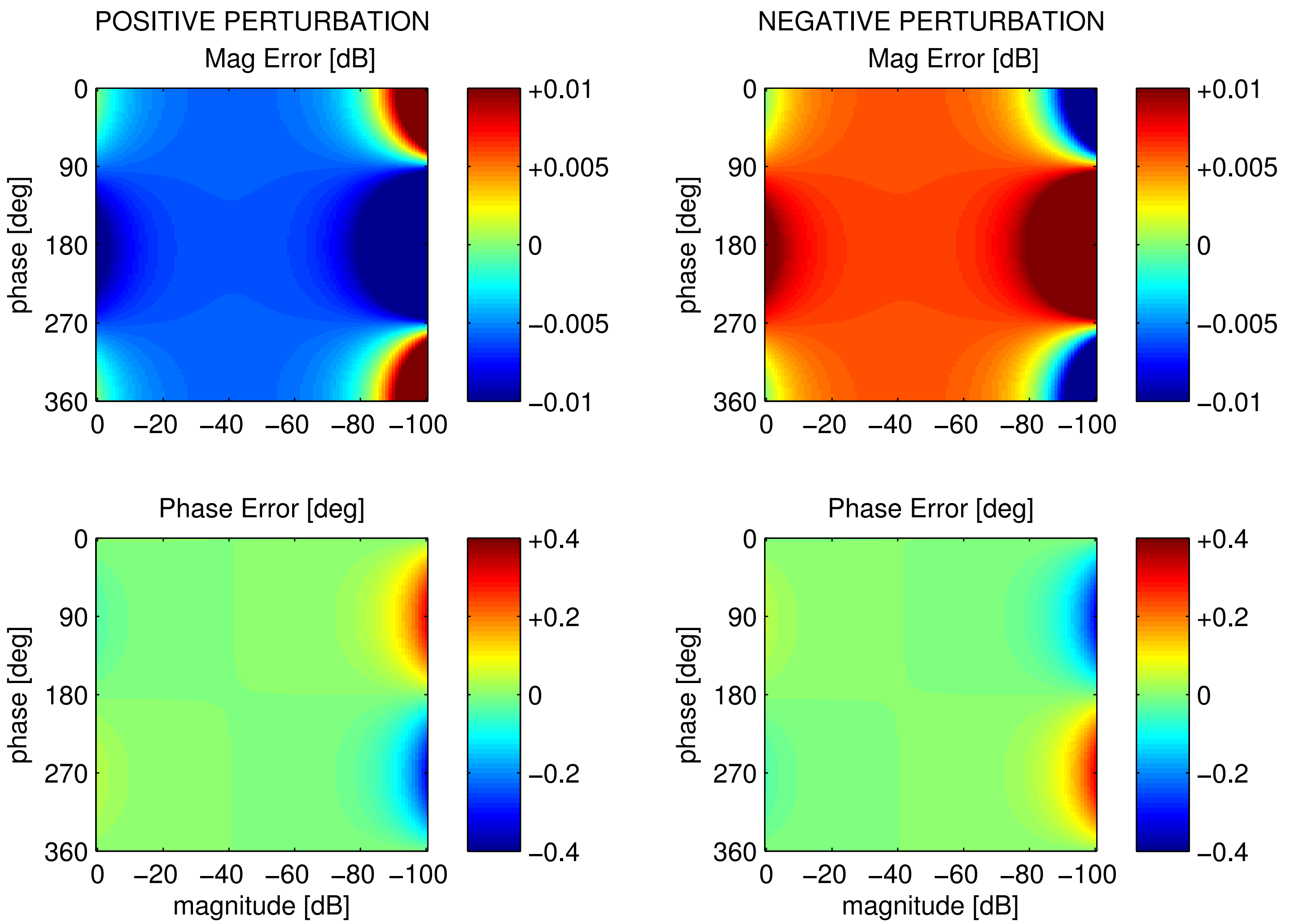

Figure 11: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

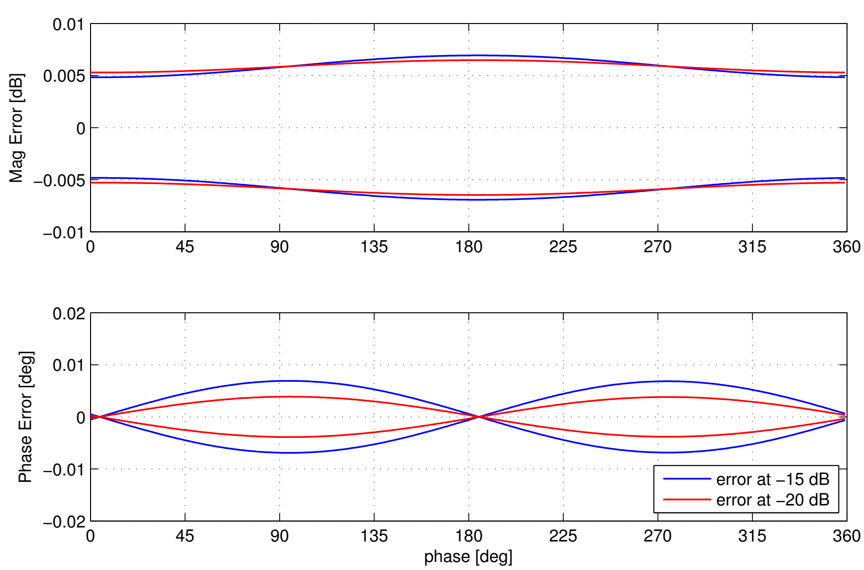

Figure 12: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

D Perturbation in PHASE of SHORT

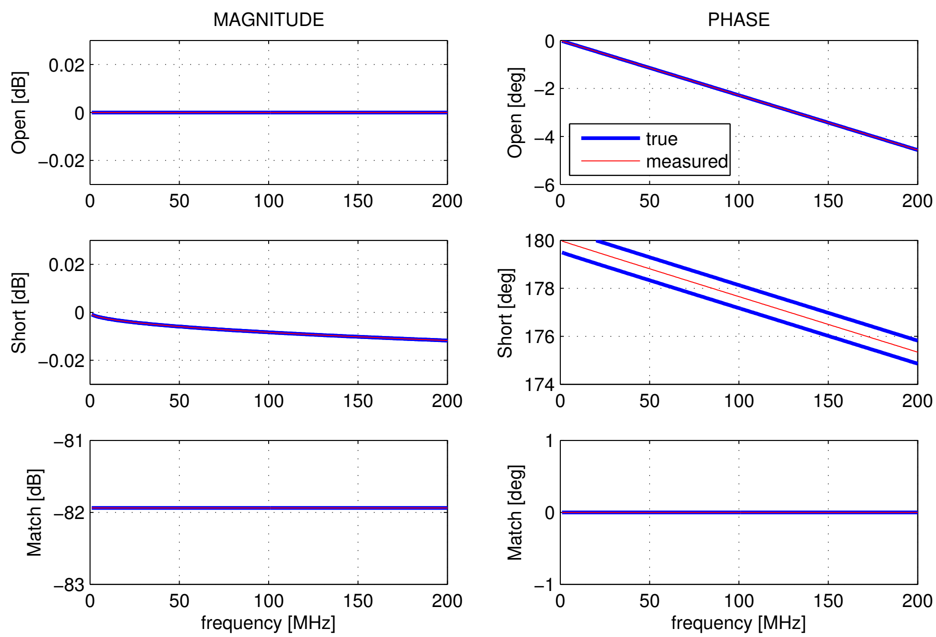

Figure 13: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the phase of the $short$ standard is off. Positive and negative perturbations are considered.

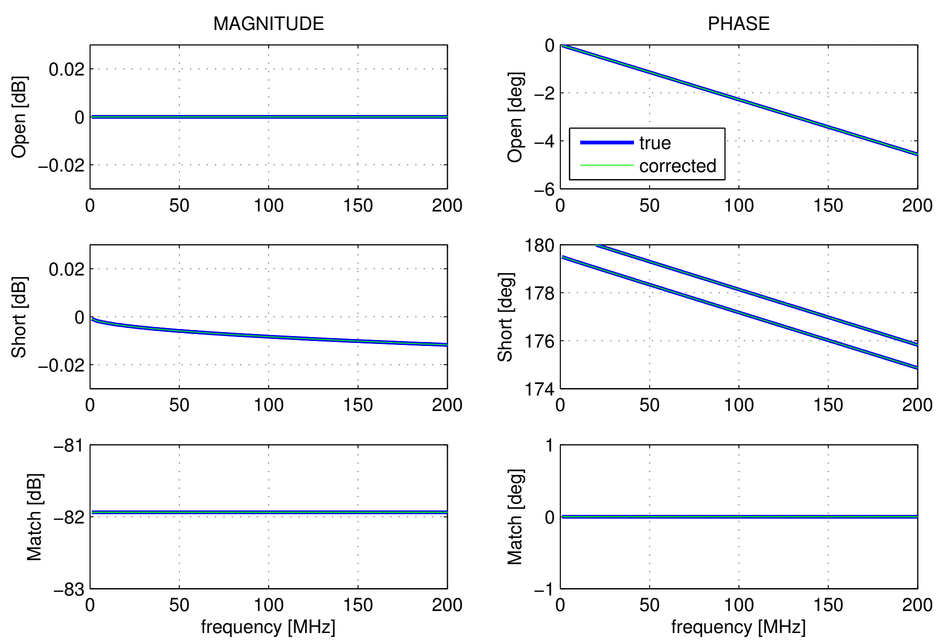

Figure 14: After correcting the VNA scale.

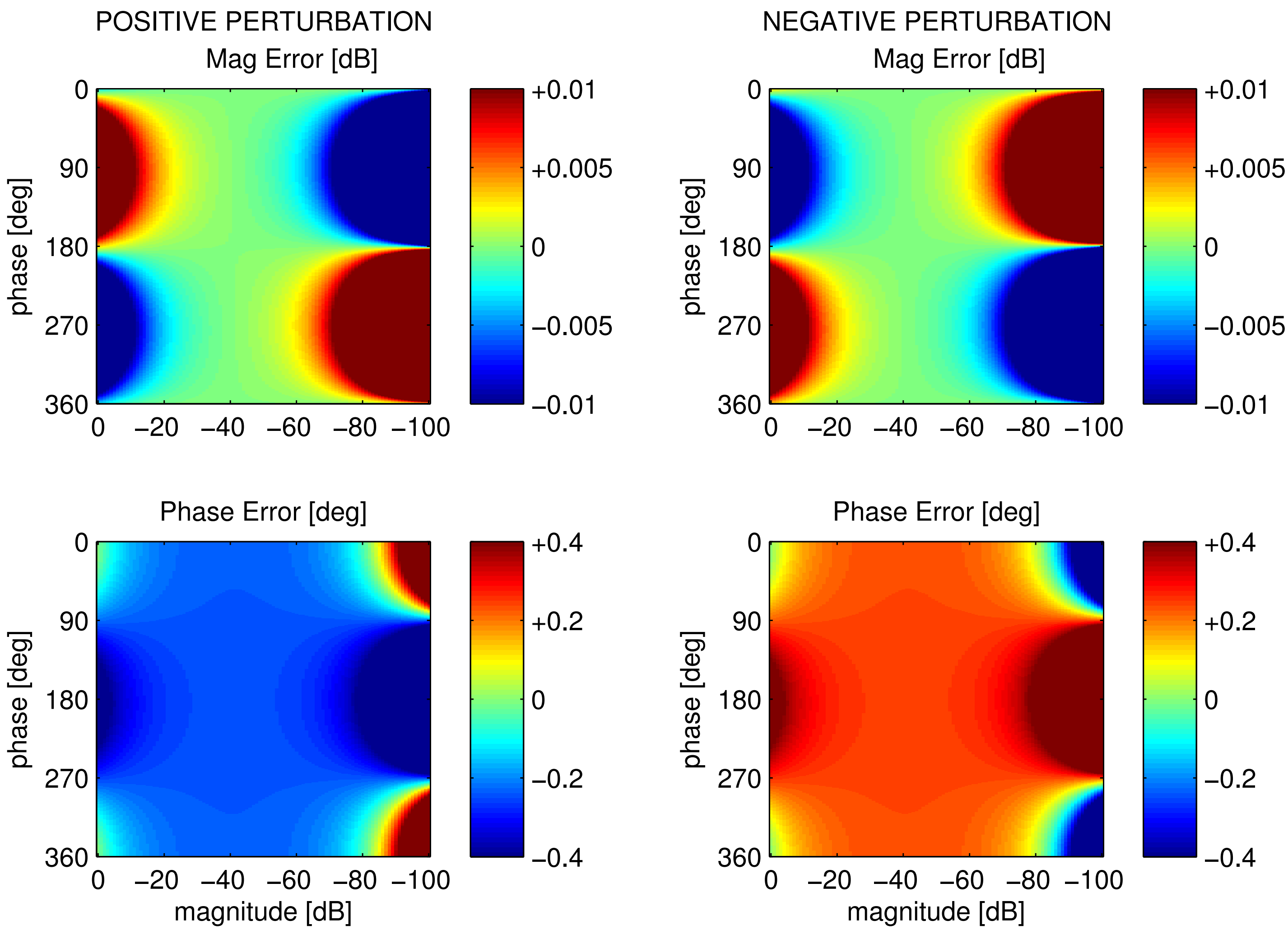

Figure 15: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

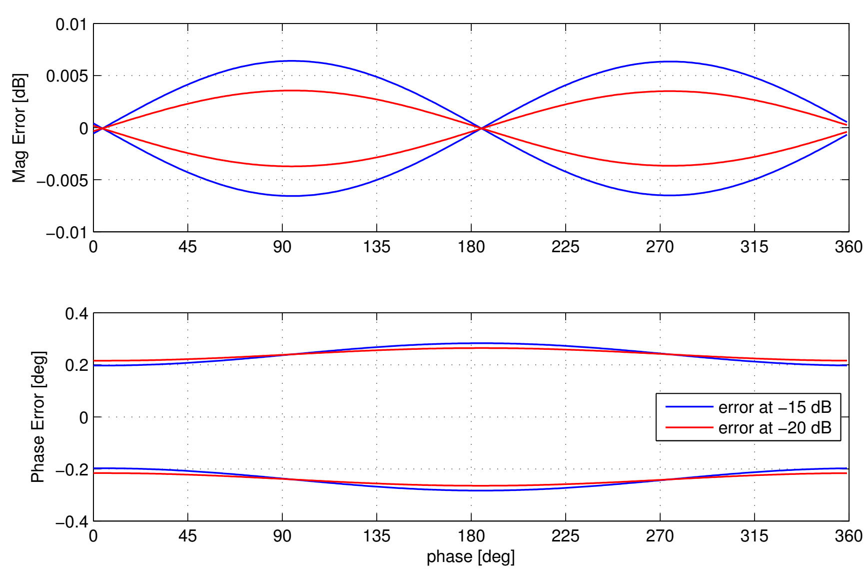

Figure 16: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

E Perturbation in MAGNITUDE of MATCH 1

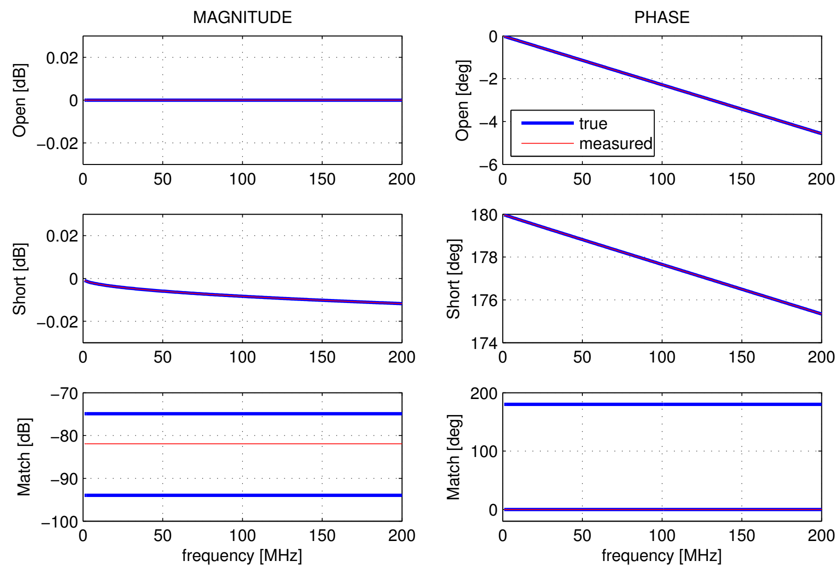

Figure 17: Comparison between *measured* and *true* traces before correcting the VNA scale. In this case, the magnitude of the *match* 1 standard is off. Positive and negative perturbations are considered. NOTE: the phase is 180° for the *match* 1 in one case because the resistance is slightly less than 50 Ω and therefore the reflection coefficient is negative.

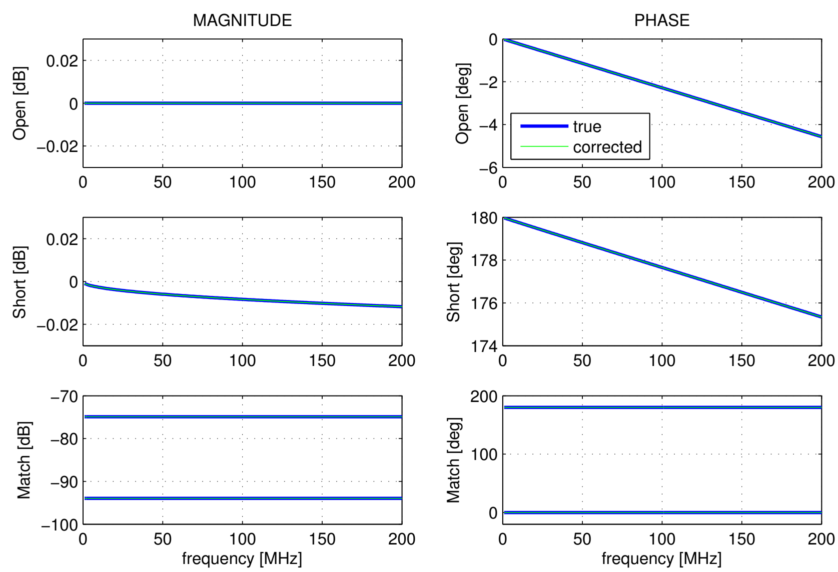

Figure 18: After correcting the VNA scale.

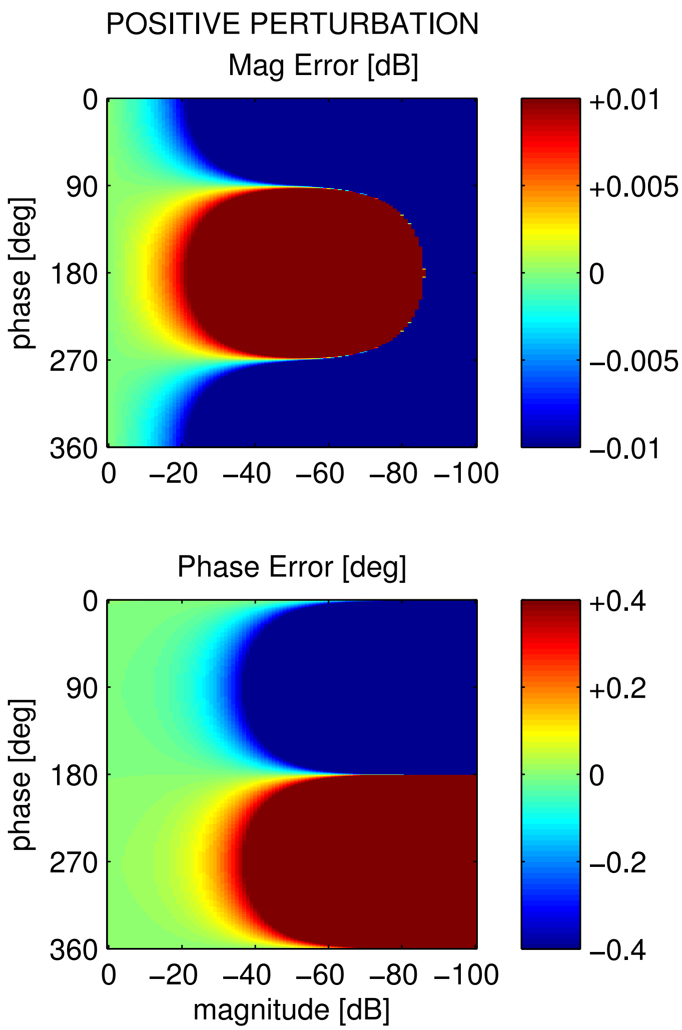

Figure 19: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

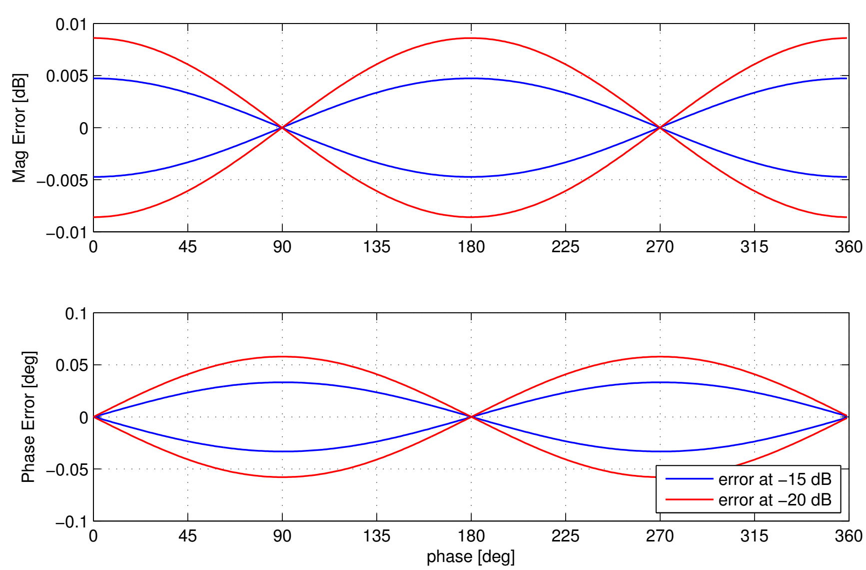

Figure 20: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

F Perturbation in PHASE of MATCH 1

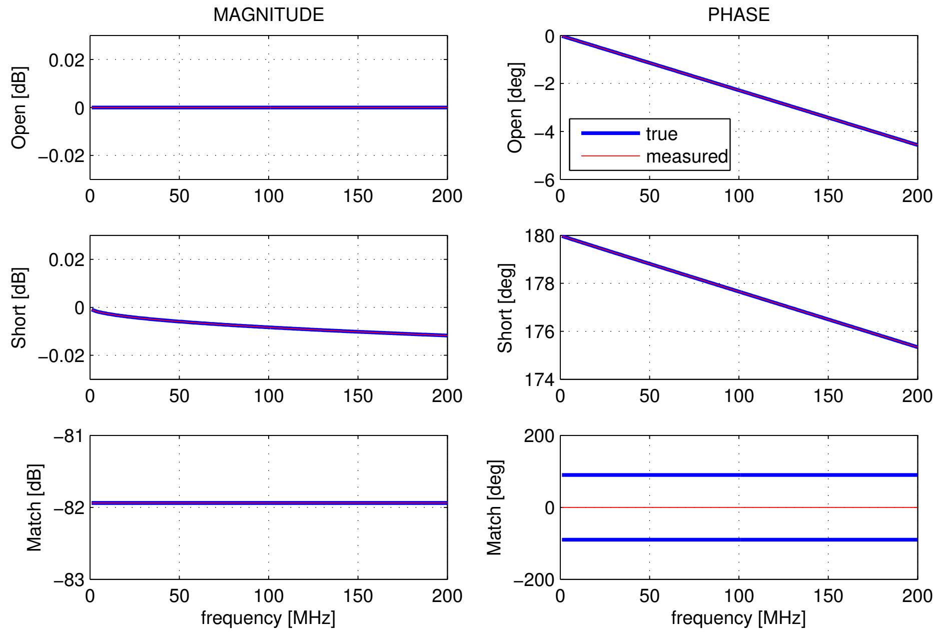

Figure 21: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the phase of the $match$ 1 standard is off. Positive and negative perturbations are considered.

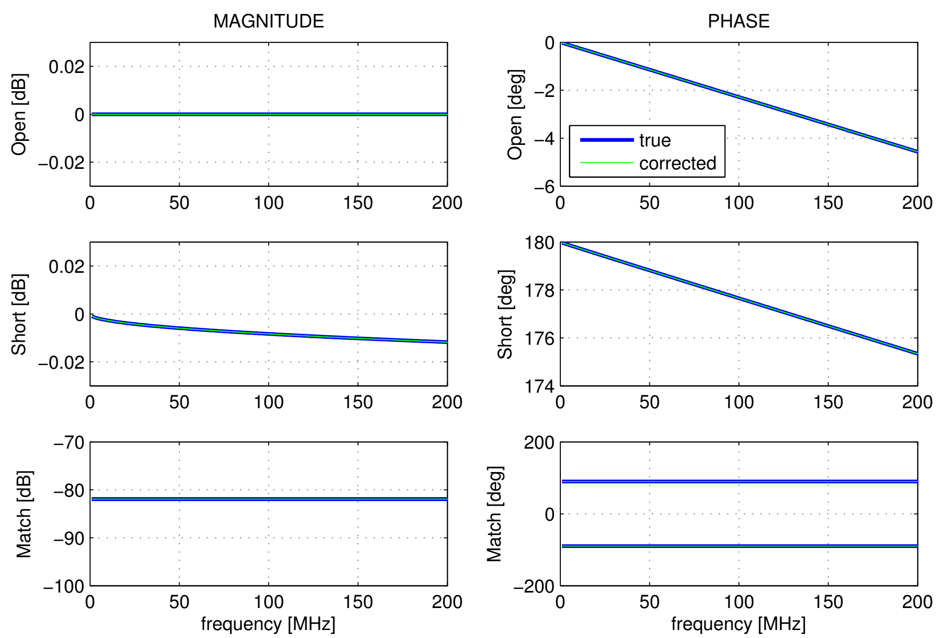

Figure 22: After correcting the VNA scale.

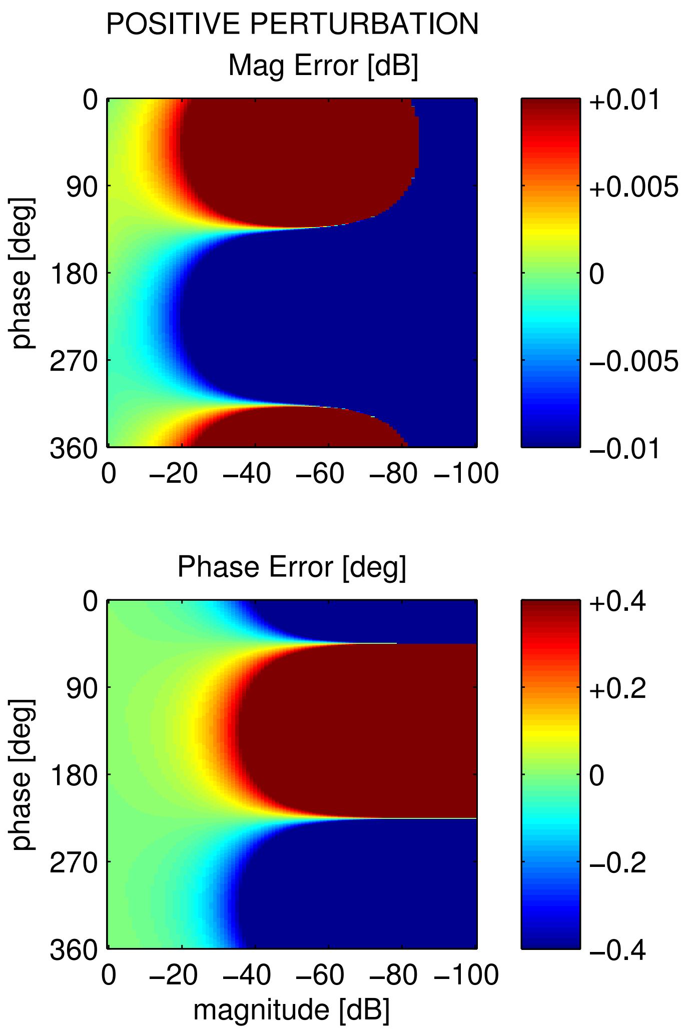

Figure 23: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

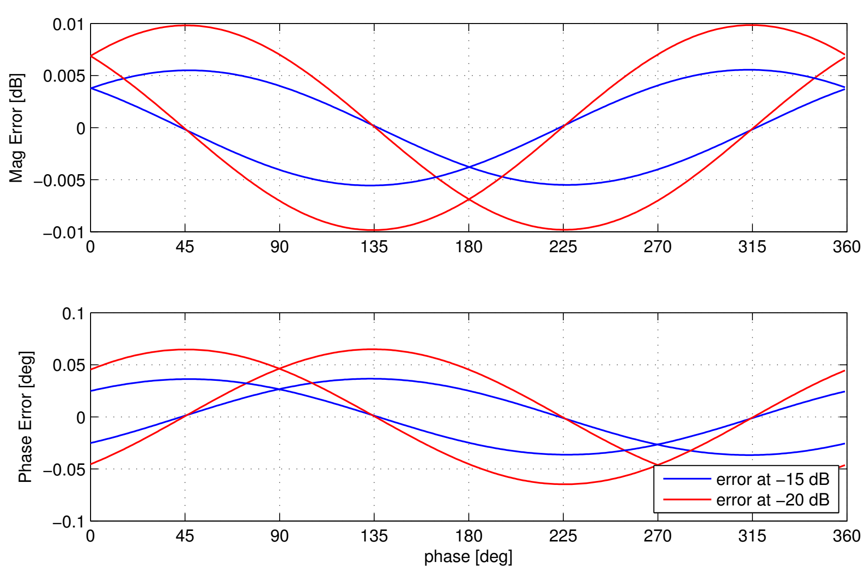

Figure 24: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

G Perturbation in MAGNITUDE of MATCH 2

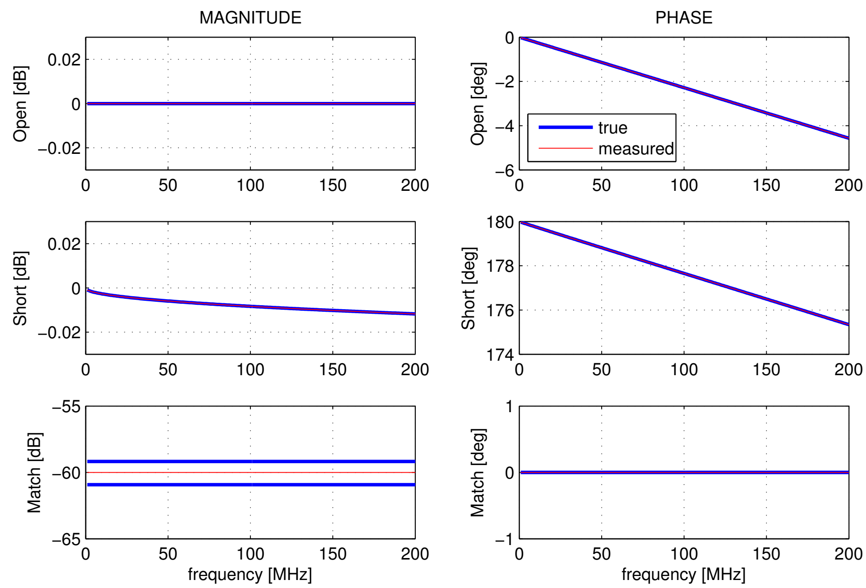

Figure 25: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the magnitude of the $match$ 2 standard is off. Positive and negative perturbations are considered.

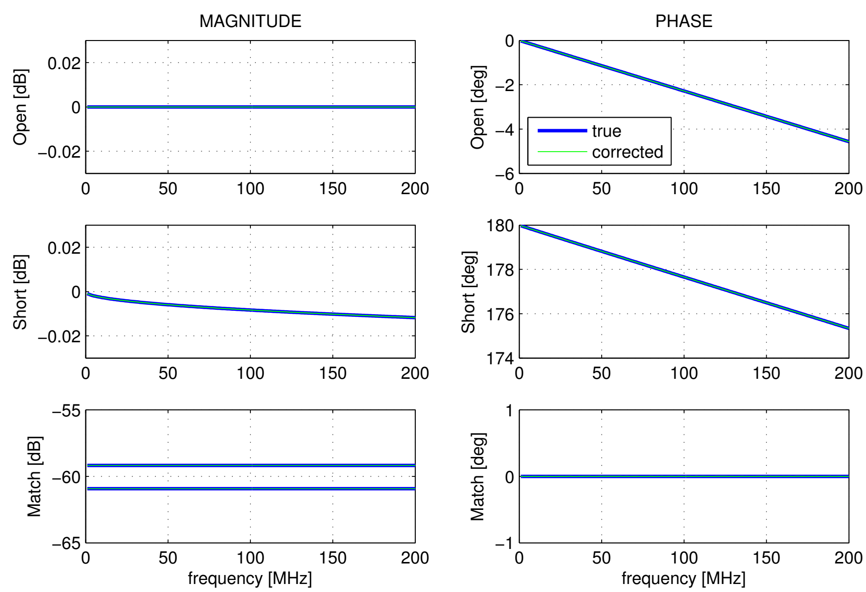

Figure 26: After correcting the VNA scale.

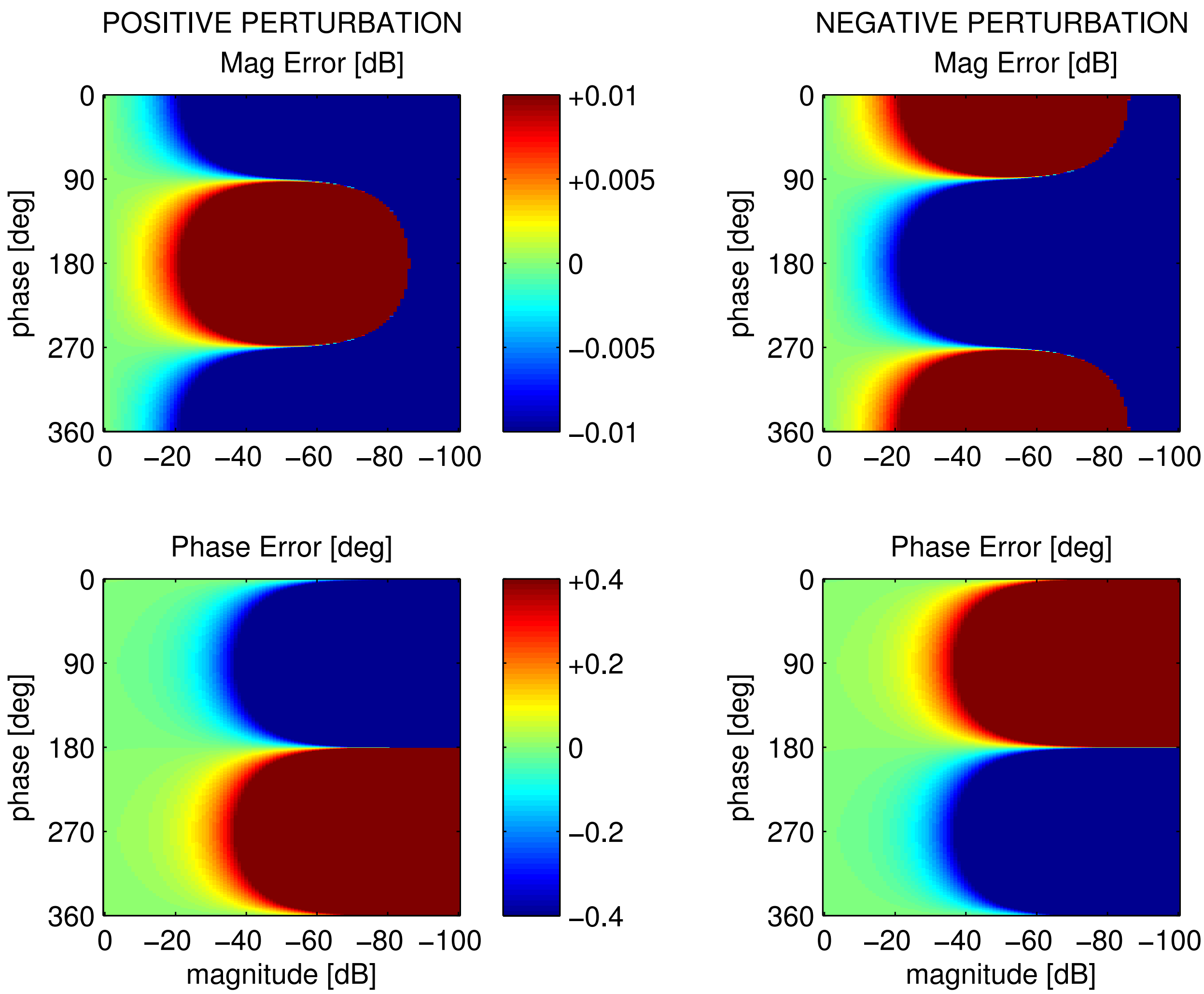

Figure 27: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

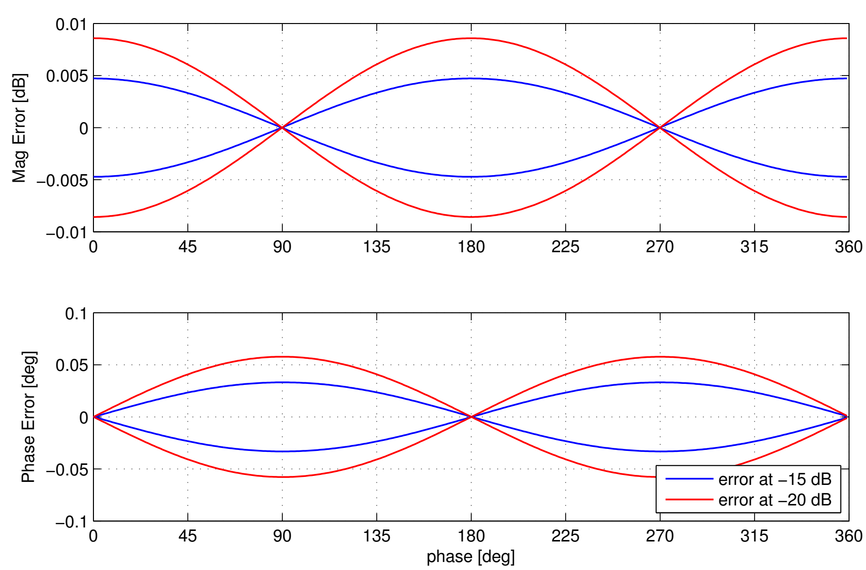

Figure 28: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.

H Perturbation in PHASE of MATCH 2

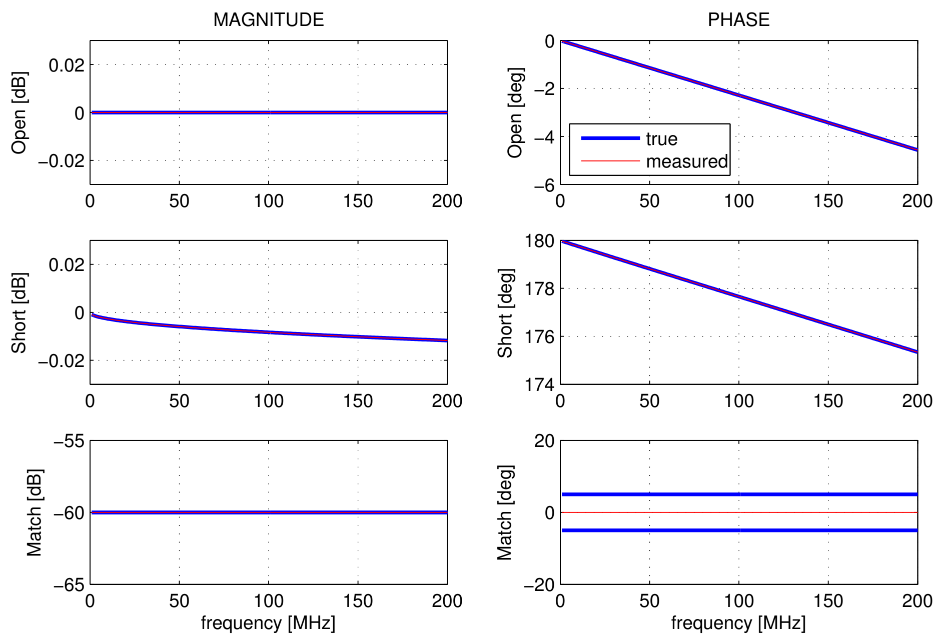

Figure 29: Comparison between $measured$ and $true$ traces before correcting the VNA scale. In this case, the phase of the $match$ 2 standard is off. Positive and negative perturbations are considered.

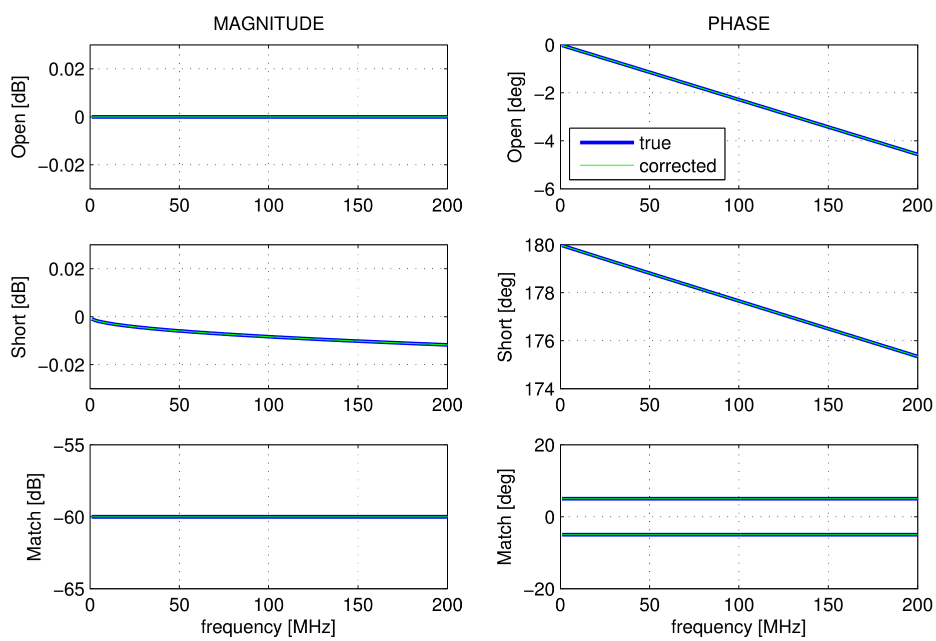

Figure 30: After correcting the VNA scale.

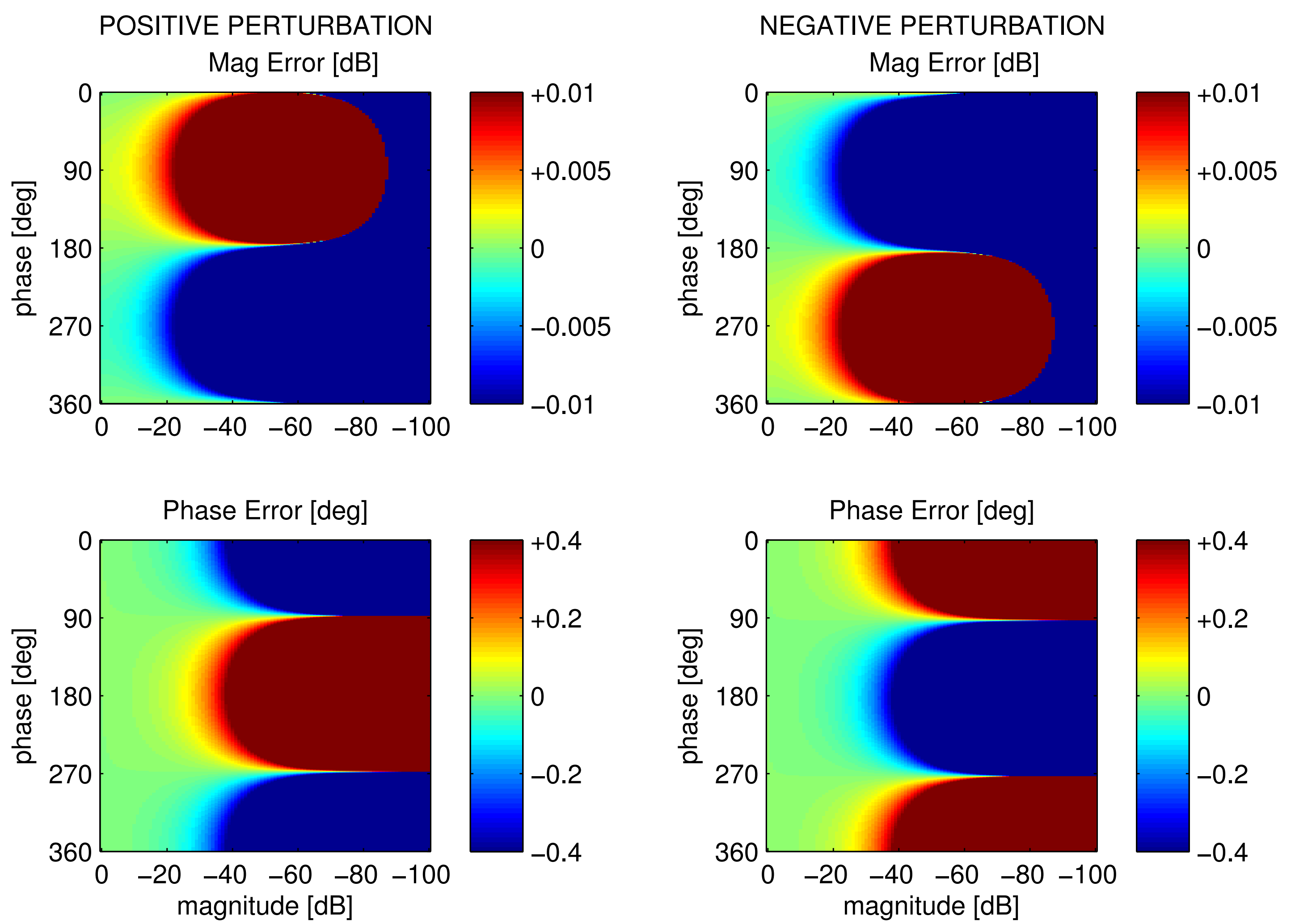

Figure 31: Error in magnitude (top) and phase (bottom) for a generic load whose magnitude and phase are represented by the x- and y-axis respectively. Valid at 200 MHz. Results for positive (left) and negative (right) perturbations.

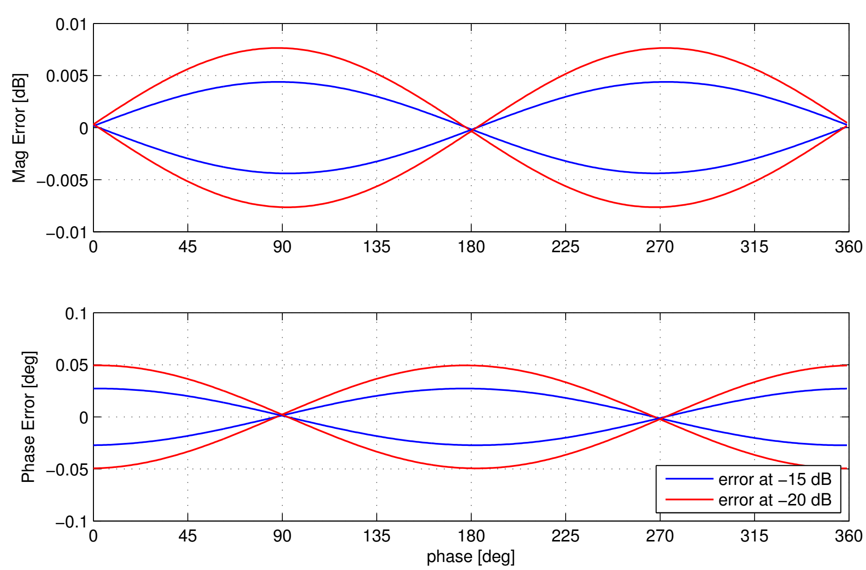

Figure 32: Cuts from the heat map plots above, for loads at -15 and -20 dB, with phase ranging between 0 and 360°. The highest absolute value of these traces is quoted in Table 1.