MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS 01886

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Telephone: 617-715-5533
Fax: 781-981-0590

To: EDGES Group

From: Alan E.E. Rogers and John Barrett

Subject: Testing VNA for I/Q crosstalk

A test for VNA I/Q crosstalk has been simulated. This test is made by measuring the S11 of a low loss 1-port network consisting of a capacitor across a SMA connector which provides a S11 in quadrature with the open and short calibration loads. In order to make a very sensitive detection a cable is used to extend the VNA measurement port in order to make I/Q crosstalk show up as a ripple in the calibrated S11 of the capacitor.

The test is as follows:

The calibration SOL plus 1-port network are measured on the VNA port as a check followed by adding an extension cable to VNA port and running the VNA with SOL plus 1-port network on the end of the cable which is a total of 8 measurements.

The calibrated S11 of the 1-port network with the added cable on the VNA should only show ripples if the VNA has I/Q crosstalk or some other defect. Without using the added cable the calibrated S11 of the 1-port network will have a very small offset in the presence of I/Q but it will be hard to distinguish from other sources of VNA error.

For a frequency range of 50 to 200 MHz a very simple acceptable 1-port network was found to be a 33 pf chip capacitor soldered from the center pin to the ground on a SMA connector. This provides a S11 in quadrature to the SOL over the 50 to 200 MHz which maximizes the sensitivity. A good choice of cable is the 10ft Molex “temp-flex” part number 89762-1372.

Figure 1 is a simulation which shows the ripples in the calibrated measurement of the 1-port with the cable in the presence of 6e-4 I/Q crosstalk while the ripples should not be present when VNA is run with SOL plus 1-port network without the cable as a check whether or not the VNA has I/Q crosstalk.

The value of 33 pf is not critical nor is the length of the cable. A shorter cable will just result in fewer ripples vs frequency. It is however very important that the cable be clamped so that it does not move between measurements of SOL and 1-port. Also a stable temperature environment while making the measurements. The peak ripple is only 0.02 dB peak to peak and 0.05 degree peak to peak in phase for 6e-4 I/Q crosstalk. However, this level of I/Q crosstalk is seen in low2-45 data as discussed in memo 333 and applying a correction is seen to make an improvement in the low2-45 signature consistency of the signature vs GHA reported in memo 339 and memo will be updated to include the recent data which is currently still being acquired at the MRO.

Figure 2 shows the difference between the S11 of the 1-port network from the calibration with the 10ft cable and the S11 of the 1-port network calibrated on port 1 of the Fieldfox (N9917A) without cable extension. This is a new Fieldfox with spectrum analyzer (SA) option similar to the new Fieldfox currently taking the low2-45 antenna S11 data at the MRO. A test of the old Fieldfox used for EDGES-3 shows that it’s performance listed in the first entry of table 1 is about 5 times better than new Fieldfox.

Figure 3 shows the results of the same test using the Keysight (N5222A) benchtop VNA which shows that much better is achieved with the benchtop VNA.

Table 1 summarizes the results of the tests on the 3 different VNAs. In each case a grid search is made to find the value of I/Q crosstalk that minimizes the S11 difference.

VNA	aver difference dB	aver difference deg	I/Q crosstalk	comments
EDGES-3	0.011	0.14	< 2e-4	Fieldfox w/o SA
N9917A	0.045	0.4	-10e-4	similar to MRO
N5222A	0.004	0.03	< 1e-4	short integration

Table 1. Average differences of 1-port S11 determined with and without VNA port extension cable.

Table 2 shows the sensitivity of low2-45 Nature absorption signature amplitude at GHA = 0 to errors in S11 showing that VNA accuracy of 0.01 dB and 10 ps (0.3 degrees of phase at 75MHz) is needed for an effect of less than 100 mK in the 500 mK amplitude or generate a false absorption at the 100 mK level.

S11	error dB	amplitude K	delay error ps	amplitude K
antenna	0.1	0.4	100	0.7
LNA	0.1	0.3	100	0.6

Table 2. Effects of error in S11 measurement of antenna and LNA S11

These effects are linearly dependent on the VNA error and the sky temperature so that the VNA accuracy is less critical at GHA=12 hours by a factor of about 3 but the table emphasizes the need for better that VNA accuracy better than 0.01 dB and 10 ps is needed in order to get better results showing that the signature is global with constant amplitude with GHA using the EDGES lowband antenna.

The effects of extending the VNA port on a long cable has been studied in memo 103 and ASU memos 22 and 74. Memos 84, 86, 131, 135, 262, 321 and ASU memos 134, 138 and 143 look at VNA accuracy and the effects of VNA error. Memos 245 and 246 look at systematics. Memo 254 looks at a check of the S11 accuracy of low2-EW (configuration H5 in the Nature paper) with a comparison of the antenna S11 measured using a VNA taken into the "pit" below the antenna. Memo 247 looks at using the change of the spectrum at transit of the Galactic center to derive the absorption under the assumption that the absorption is global as another check to be sure the signature is not the result of an error in the remote measurement of the S11 on the long cable extension of the VNA port from the electronics hut to the receiver.

An important factor in understanding the ripple in the remote antenna S11 measurements is that the ripple period may be "aliased" owing to the spacing of the measurement frequencies. For example using a 1 MHz frequency spacing on a 50 m cable with dielectric 2.05 for which the 4-way cable delay results in 344 degrees of rotation per MHz which is aliased to a ripple spacing of 22 MHz instead of the 1.048 MHz spacing which would be present in a fine frequency spacing. The factor of 4 arises from the doubling of the ripple period with I/Q cross-talk. A consequence of the aliasing is that depending on the cable length aliasing can result in ripple which is not easily smoothed without introducing significant error so that a different or more closely spaced frequency sequence may be needed to obtain better accuracy from the effects of the 12 or 13 term polynomial used to smooth the antenna S11 to minimize the addition of systematic errors from the VNA into the calibrated spectrum.

In summary while the original Fieldfox VNA without the spectrum analyzer feature may be adequate the N9917A Fieldfox has inadequate performance for EDGES and should be replaced with a more accurate VNA.

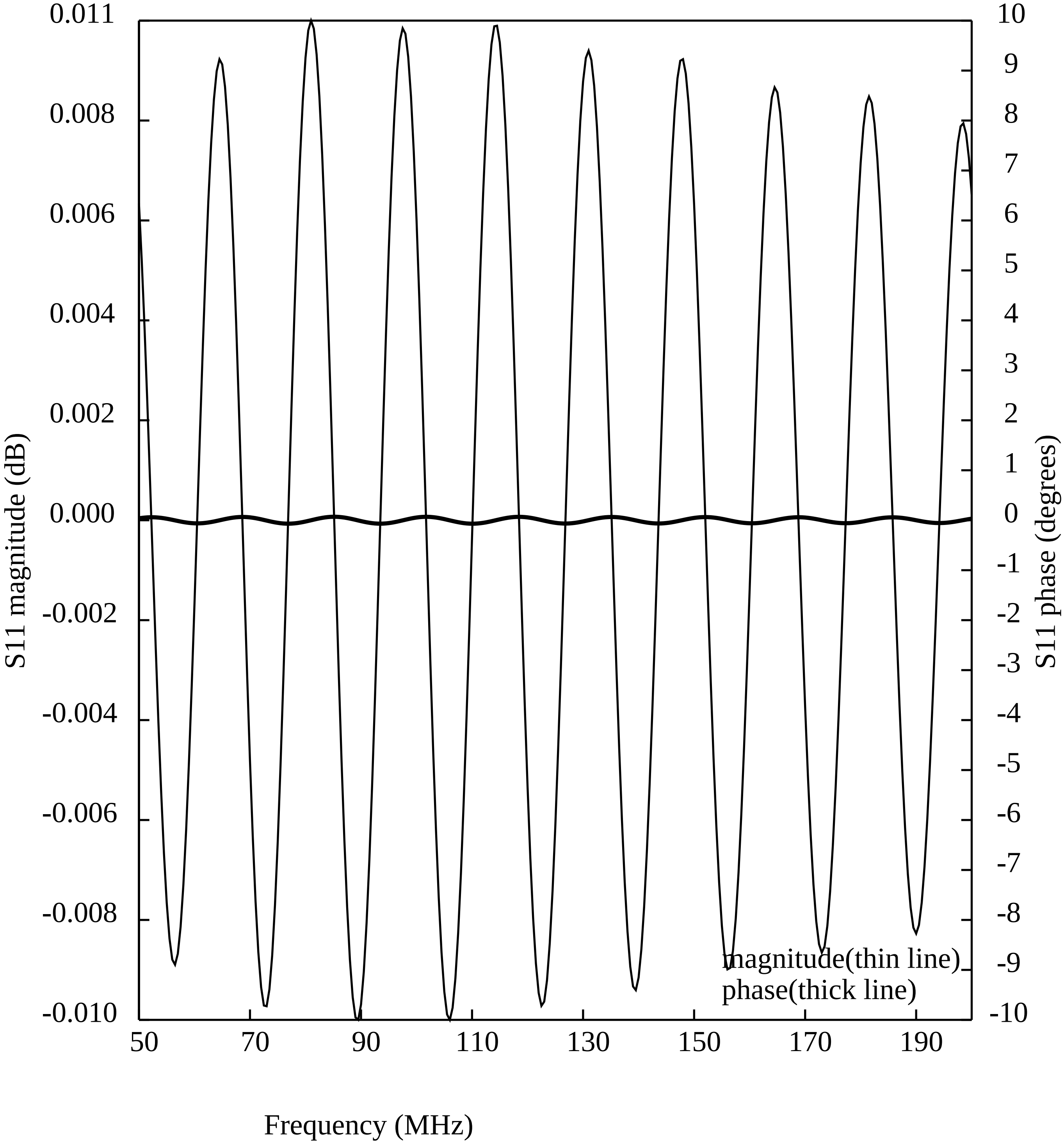

Figure 1. Simulation of I/Q cross-talk at the level of 6e-4 on difference of calibrated S11 with and without 10 ft cable extension.

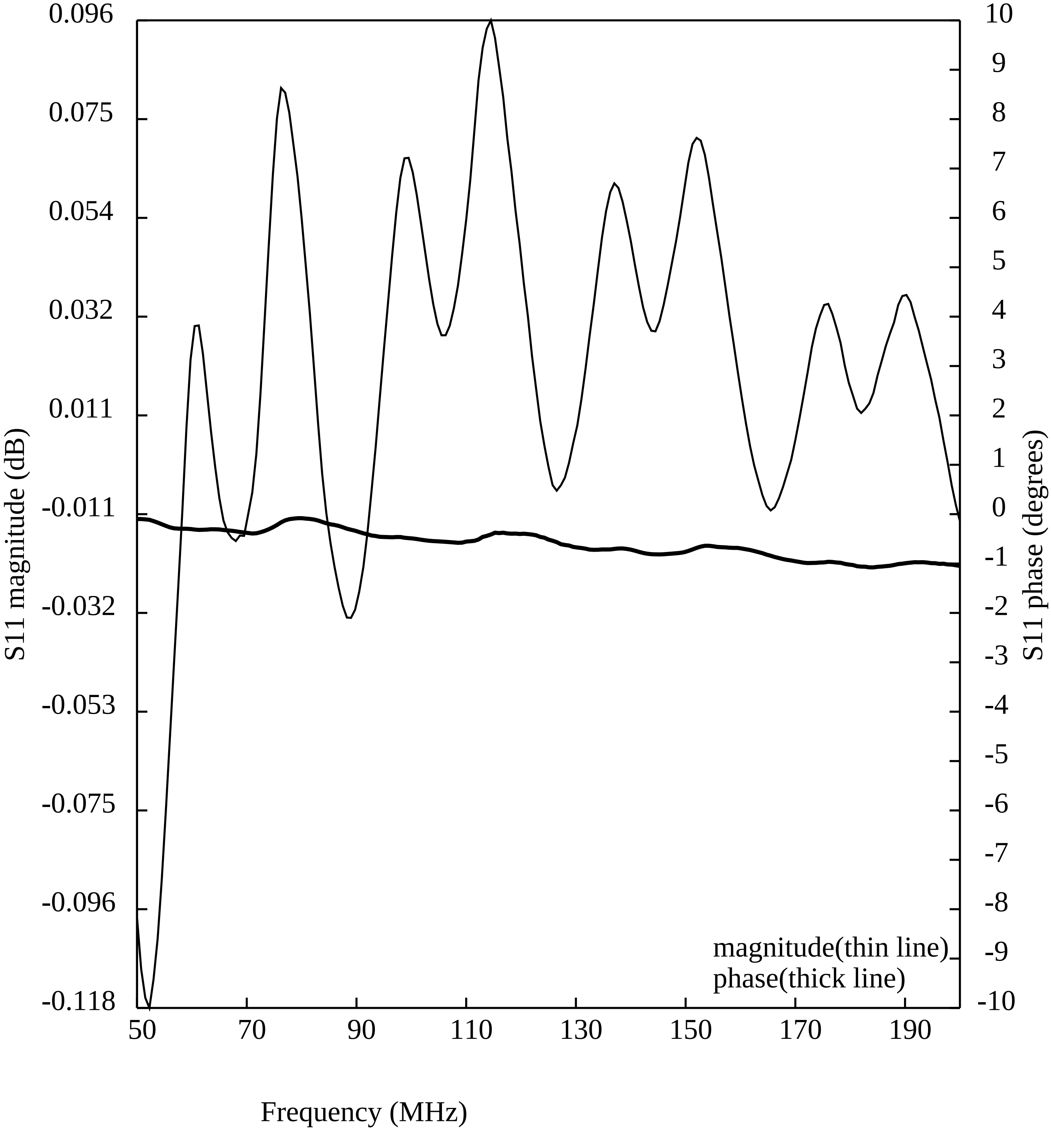

Figure 2. Difference of calibrated S11 of 33pf capacitor calibrated with and without a 10 ft cable on a Fieldfox N9917A VNA.

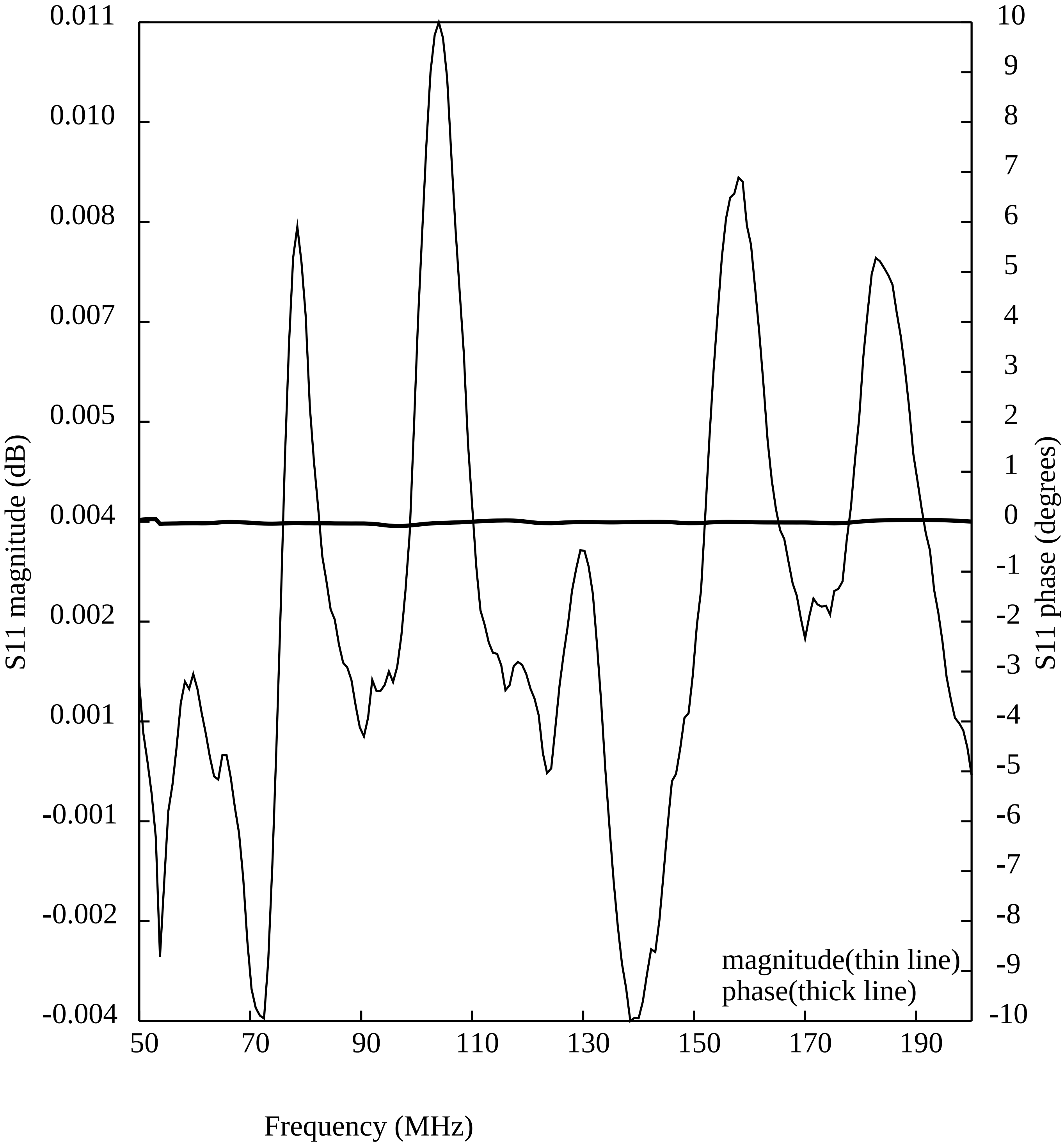

Figure 3. Difference of calibrated S11 of 33pf capacitor calibrated with and without a 10 ft cable on a Keysight N5222A benchtop VNA.