EDGES MEMO #416

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To: EDGES group
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Subject: Study of further improvements in VNA accuracy

VNA accuracy is critical for the EDGES global 21-cm system. This was recognized and discussed in memos 84, 86, 90, 93, 97, 103, 114, 122, 124, 130, 131, 133, 135, 197, 319, 321, 322, 333, 351, 363, 368, 369, 411 and 412 as well as ASU memos 7, 8, 11, 12, 21, 22, 40, 85, 87, 100, 132, 134, 137, 138, 139, 143 and 181. The method of testing VNA accuracy and the accurate determination of the Short Open and Load (SOL) standards using a passive asymmetric 2-port network is described in memo 133 and

Monsalve, R.A., Rogers, A.E., Mozdzen, T.J. and Bowman, J.D., 2016. One-port direct/reverse method for characterizing VNA calibration standards. *IEEE Transactions on Microwave Theory and Techniques*, *64*(8), pp.2631-2639.

A key finding is that a VNA is very temperature sensitive with temperature coefficients for the directivity (00e) mismatch (11e) and tracking (10e) of about 5e-4 fractional units per deg K as described in memo 93. This is a serious problem for EDGES-3 which has to use a handheld VNA owing to the limited space in the antenna. Tests of the N9923A is the EDGES-3 prototype show that the temperature of the VNA increases from 25 C to 50 C during the 90 minute “warm-up” needed to reach a fairly constant temperature. However in the current installation of EDGES-3 at the MRO the air flow has significant diurnal temperature variation. To ameliorate this problem it was decided to reduce the time difference between the device measurement and the SOL measurements by limiting the number of scans to 2 per VNA s1p measurement as described in memo 411. While most VNAs have specifications for the dynamic range and other general parameters the overall accuracy is not usually specified. Consequently VNAs need to be tested and some units with added features like spectrum analyzers have been found to have significant I/Q cross-talk as discussed in memos 333 and 351. For EDGES a fractional accuracy of 1e-4 is needed which is more difficult to achieve from a handheld than for a benchtop in a temperature controlled room.

Tests made using the EDGES-3 prototype are in table 1 using a 6dB attenuator as antenna.

tests	comparison	num scans	warm-up	num repeats	sequence of s1p measurements	difference
1,2	2 - 1	10, 10	yes, yes	1,1	antSOLLOSant,antSOLLOSant	2e-5
2,3	3 - 2	10,10	yes,yes	1,1	antSOLLOSant,antSOLLOSant	4e-5
3,4	4 - 3	10,10	yes,no	1,1	antSOLLOSant,antSOLLOSant	1e-2
5,6	6 - 5	1,1	no,no	10,10	antSOLLOSant,antSOLLOSant	1e-4
7,8	8 - 7	1,1	no,no	10,10	antSOLantSOL,antSOLantSOL	3e-4
5a,6a	6a - 5a	2,2	yes,yes	25,25	antSOLLOSant,antSOLLOSant	6e-5
7a,8a	8a - 7a	2,2	yes,yes	25,25	antSOLantSOL,antSOLantSOL	6e-5

Table 1. Measured differences of calibrated S11 measurements using Keysight N9923A VNA

Table 1 shows that repeatability at the level of a few parts in 1e5 can be obtained with warm-up in the lab but measurements during which the VNA is warming up or in an environment with changing temperature need to be taken with the shortest time between antenna and SOL. The test shows that repeating the measurements with the reverse order improves the repeatability in an environment whose temperature is changing in a linear manner in the sequence of time which includes ant,S,O,L,L,O,S,ant which corresponds to about 80 seconds since each scan takes about 10 seconds. Tests 6 and 7 have the combination positive and negative time differences between the antenna and SOL which cancels some of the temperature effects when the temperature changes slowly due to the thermal mass of the VNA. Tests 5a,6a,7a,8a were run on the prototype using script with 25 repeats of 2 scans per VNA s1p measurement described in memo 411 with the following changes:

1] The internal open cable was used instead of the 6 dB on the antenna port
2] The regular and reverse order run

In this case little change is seen using the reverse order and the overall conclusion is that the reverse order makes little difference. What is very important is the warm-up which needs to be long enough to ensure that the VNA has reached an equilibrium with the air and is not going to continue heating up when the actual data is being taken.

The antenna S11 measurements made following the averaging method in memo 411 have an rms difference from day to day range from about 5e-4 to 1e-3 fractional units. Figure 1 shows the calculated effects of these errors on the spectrum at GHA=12 hours with 5-terms removed. The changes from day to day are significant below 60 MHz. Some of these changes may be due to real changes in the antenna S11 due to small changes in the separation of the antenna boxes. FEKO simulations show that a 200 mK rms residual for 5-terms removed from 55 – 100 MHz results from a 2 mm change in box separation so that it would take only about 0.2 mm of antenna separation change to produce the changes in Figure 1. We plan replace the temporary strap currently being used to maintain box separation with new mechanical parts to ensure a constant box separation.

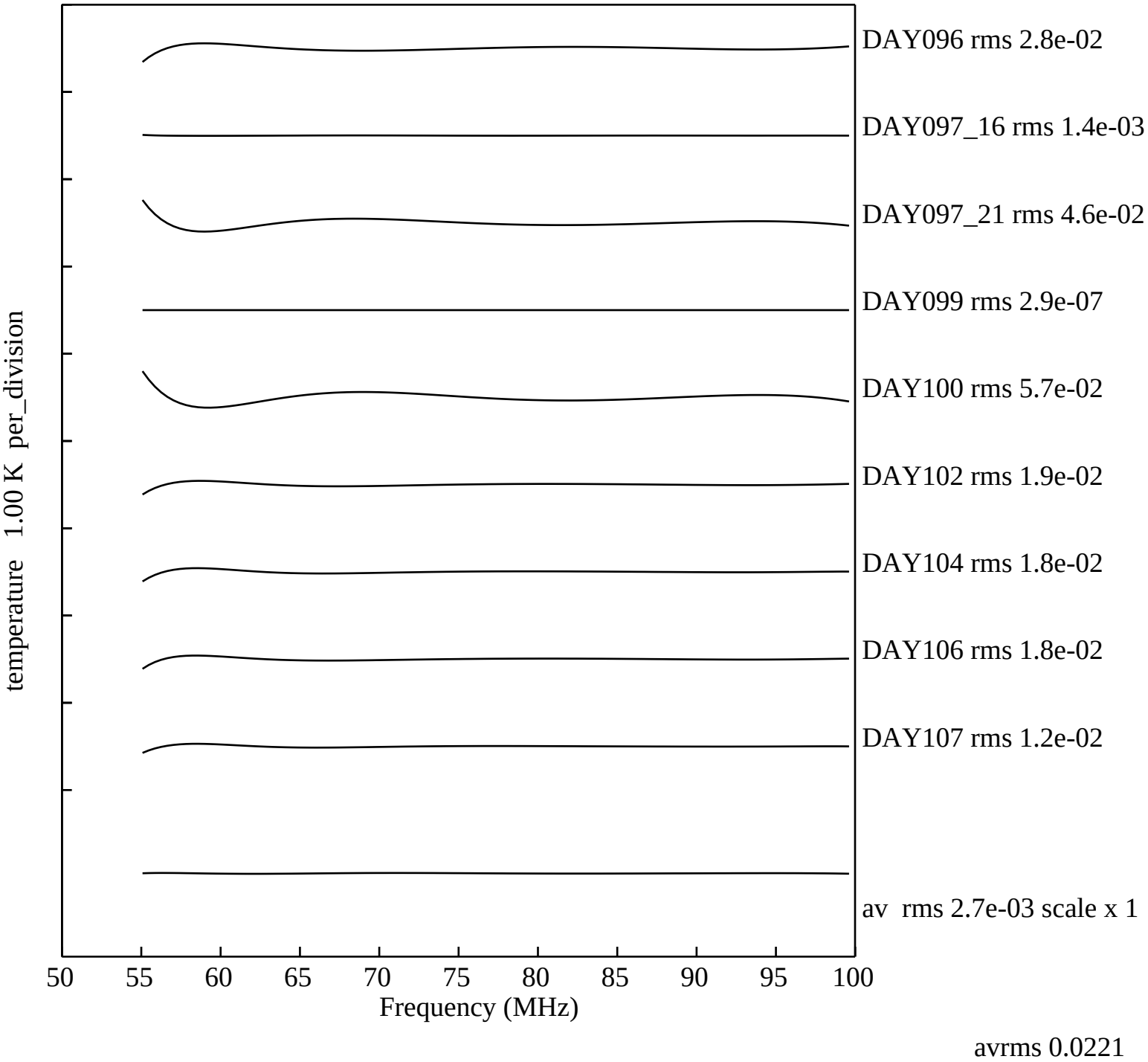

Figure 1. Simulations of the effect on the sky noise spectrum of antenna s11 measurements of different days in 2023 for EDGES-3 at the MRO at GHA=12hrs with 5-physical terms removed. The antenna S11 on day 99 is used as the reference.