Verification of LRRM Calibrations with Load Inductance Compensation for CPW Measurements on GaAs Substrates

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Abstract

The on-wafer microwave measurement community has been searching for a mechanism to quantify S-parameter calibration inaccuracies. A powerful verification technique developed by the National Institute of Standards and Technology (NIST) has enabled the determination of calibration error bounds for a working calibration by comparison with a benchmark calibration, the NIST multi-line GaAs TRL calibration [1]-[5]. A series of automated Line-Reflect-Reflect-Match (LRRM) calibrations with load inductance compensation are performed on commercially available alumina coplanar waveguide (CPW) standards from 1 to **40 GHz.** These calibrations are then compared with a benchmark NIST calibration. The calculated error bounds are determined and compared in order to assess both the relative accuracy and the repeatability of the automated calibrations.

Introduction

Traceability of on-wafer calibration standards has long been an issue among the microwave measurement community. The great diversity of calibration standards and calibration methods currently in use throughout the industry has made traceability of these standards to some physical reference impractical. Instead, the NIST has developed a calibration procedure and software package which enables calibration verifications to be performed [2]. Thus, it is possible to demonstrate traceability of a calibration, rather than traceability of the individual calibration standards.

The purpose of this paper is to investigate the accuracy, variation, and repeatability of LRRM wafer probe calibrations with load inductance compensation performed with a commercially available semi-automatic probe station and alumina-based CPW impedance standard substrate (ISS). Two experiments are performed using the NIST verification procedure and software in order to accomplish this. In the first experiment, ten automated calibrations are made using ten different sets of standards on the same ISS. In the second experiment, ten automated calibrations are made using a single set of standards. Each of the automated calibrations from the two experiments are then compared with a manual NIST multi-line GaAs CPW reference calibration. The worst case error bounds for each automated calibration are calculated using the NIST verification software [2]. These verification results are then used to assess both the variation and repeatability in the calibration accuracy. Presentation of the data is followed by a general discussion of the possible impact of instrument drift, contact repeatability, and ISS alignment on the verification experiments.

Probing System Configuration

Figure 1 illustrates the probing system configuration for the investigation. All equipment used in the investigation is commercially available. In both experiments, the automated calibrations are performed on a Cascade Microtech semi-automatic wafer probe station, capable of ±3 micron placement repeatability. All calibrations contain 51 data points and are performed with an HP8510C VNA from 1 to 40 GHz. The averaging factor is 256. Electronic alignment of the ISS, probe station control, VNA control, and the automatic load inductance compensation are all performed by the probe station's automatic VNA calibration software. For each calibration, raw data is read from the HP8510C. The calibration software then calculates the inductance compensated error coefficients and stores them back into the network analyzer. The two wafer probes used are standard ceramic tip ground-signal-ground (GSG) configuration with 100 micron pitch. Flexible 2.4 mm RF cables are used to connect these wafer probes to the HP85 1 OC.

Calibration Standards and Verification Technique

The standards used for the automated calibrations are commercially available alumina based CPW standards from Cascade Microtech. These consist of 1.15 psec long 50 ohm CPW lines, shorts (metallized bars), opens (open circuited probe tips in air), and precision 50 ohm loads. The load standards are trimmed at DC to be 50 ohm ± 0.3%. Alignment marks on the ISS set the contact force, separation, and initial position of the wafer probes. **Figure 2** shows a typical alumina ISS.

The NIST benchmark calibration standards consist of a 550 μm CPW thru line, an offset short, and four CPW lines of additional length 2.135 mm, 3.2 mm, 6.565 mm, and 19.695 mm respectively. These standards are fabricated on 500 μm thick GaAs [3]. The NIST software is run on an HP9000 series 300 computer under HP Basic 5.1. The specific programs used in the experiments are DEEMBED revision 4.04 and VERIFY revision 1.03 [5].

The first step in the verification procedure is to make an on-wafer calibration. With this correction applied to the VNA, an NIST benchmark calibration is then performed using the DEEMBED software. Each of the five NIST standards is measured, and the data is stored to disk. The program deembeds this data, calculating the effective dielectric constant and the "error boxes" for both port 1 and port 2 [3]. In effect, a two-tier calibration is performed, and the error coefficients represent the differences between the working calibration and the benchmark calibration. The VERIFY program is then calculates and plots the worst case deviation after the reference plane of the benchmark calibration is adjusted to be as close as possible to the reference plane of the working calibration [5].

LRRM Calibration Verification Results

In the first experiment, ten automatic LRRM calibrations with load inductance compensation are performed using ten different sets of standards on the same alumina ISS. In the second experiment, an automatic LRRM calibration with load inductance compensation is performed ten times on a single set of standards. For each of these twenty working calibrations, the load inductance compensation value is recorded, and the VNA error coefficients are stored to disk. The time required to complete both sets of calibrations and store the data to disk is approximately 50 minutes.

Following the verification technique described earlier, a benchmark GaAs TRL calibration is then performed. Using the NIST calibration standards and the DEEMBED program, each of the six NIST standards is contacted with the wafer probes only once. Every standard is measured using each of the twenty stored calibration sets, and the measured data is stored to disk. This procedure minimizes the number of probe contacts required, thus reducing uncertainty in probe placement repeatability. After a!! of the standards are measured, there are 6 data files for each working calibration, or 120 files total. This portion of the verification procedure is particularly slow. The total time required to complete this process is about 2 hours and 45 minutes. Thus, 3 hours and 35 minutes is required to collect a!! of the verification data.

The NIST's DEEMBED program then uses the 6 data files for each working calibration to calculate new error coefficients. Three output files are stored to disk: the error box for port 1, the error box for port 2, and the effective dielectric constant. These three files are used by the VERIFY program to calculate the worst case deviations between each working calibration and the NIST benchmark calibration [2]. These deviations are expressed as the largest difference in $|Sij - Sij'|$, where Sij is the S-parameter from the LRRM working calibration and Sij' is the S-parameter from the NIST benchmark calibration as described in [2] and [5].

Figure 3 shows the results of verification experiment 1. In genera!, the calculated upper bounds increase linearly with frequency. The average worst case deviation is .067 and occurs at 34.5 GHz. The worst case deviation for any single calibration is observed to be .079 at 37.7 GHz. The worst case total variation from 1 to 40 GHz is observed to be less than .032. This also occurs at 37.7 GHz. The legend in Figure 3 indicates the row and column of the standards used on the ISS for each of the working calibration.

The load inductance compensation values calculated for each working calibration are shown in **Figure 4.** The average inductance compensation value is 5.63 pH with a variation of ± 15%. It is interesting to note that the inductance compensation values increased from column 1 to column 5 in both rows 7 and 8. In addition, the calibrations which exhibited the greatest deviations in Figure 3 also had the largest associated load inductance compensation values.

Figure 5 shows the results of verification experiment 2. Once again, the calculated upper bounds increase linearly with frequency. The average worst case deviation is .063 at 34.5 GHz, and the worst case variation is an impressive .00 at 28.3 GHz. The worst case deviation for any single calibration is observed to be .064 at 34.5 GHz. **Figure 6** shows the load inductance compensation values calculated for each working calibration in experiment 2. The average inductance compensation value is 5.66 pH with a variation of ± 5%.

Comments and Conclusions

When evaluating the results of the automated LRRM calibration verifications, it is helpful to compare this data with verification results from manual LRRM verification experiments. **Figure 7** presents results from [1] in which manual LRRM verification experiments were performed. Again, the calculated upper bounds are observed to increase linearly with frequency. The worst case deviation for these measurements ranged from .06 to .125. Although the accuracy in three of the four calibrations is comparable to the automated calibrations, the large variation suggests that repeatability in the manual calibrations is much more difficult to achieve.

Instrument drift is the biggest concern in both the manual [1] and the automated LRRM verification experiments. The automated verifications required nearly 4 hours to complete. The temperature and relative humidity in the room in which the measurements were performed was uncontrolled. In order to assess the possible impact of instrument drift on the results, a calibration stability test was performed at the end of each experiment and at completion of the verification procedure. This test determines the change in $|S11 - S11'|$ for an open circuited probe tip, where $S11'$ is measured periodically after the initial $S11$ data has been recorded.

Figure 8 shows the results of the calibration stability test. In general, the system will drift more at the higher frequencies. This is why the curves in Figure 8 all tend to slope upward. A new calibration would usually be performed when the worst case $|S11 - S11'|$ reaches -40 dB. This corresponds to a 1% error in the $S11$ measurement of the open circuited probe tip. At the completion of experiments 1 and 2, the system had a worst case stability of better than -40 dB. However, due to the extended period of time required to perform the verification procedure, the worst case system stability at completion of the verification was only -27 dB. This corresponds to a measurement accuracy of about 4.5%. Based on this data, it is quite likely that system drift did have a significant effect on the verification results. It is likely that reducing the time required to perform the verification would improve the results.

The results presented in Figure 5 indicate that the contact repeatability in the automated calibrations is very good. Thus, it seems likely that the impact on the verification results due to contact repeatability is very subtle. If the ISS is not properly aligned, probe placement errors will occur. These errors in conjunction with the subtle contact repeatability errors may help to explain the apparent increase in load inductance observed across the ISS in Figure 4. It has been observed in [4] that the load inductance varies by about .14 pH per micron change in probe placement. It is likely that slight ISS alignment errors contributed to the accuracy

variation observed in Figure 3. However, the data is probably representative of what a typical user would observe.

The NIST calibration verification procedure has been used to demonstrate the calibration accuracy of automated LRRM calibrations with load inductance compensation. Using commercially available wafer probes, a semi-automatic wafer probe station, and alumina-based CPW calibration standards, the calibration accuracy and repeatability have been shown to be quite good for use in measuring CPW structures on GaAs substrates. The accuracy is comparable to that achievable in manual LRRM calibrations, while the repeatability appears to be far superior. In addition, the accuracy variation using different standards across an ISS has been characterized and found to be quite acceptable.

References

[1] D. F. Williams, "Cascade Microtech LRRM Probe-Station Calibrations," NIST/ *Industrial MMIC Consortium Report No.* SR-813-28-93, August, 1993.

[2] D. F. Williams, R. B. Marks, and A. Davidson, "Comparison of On-Wafer Calibrations," *38th ARFTG Conference Digest,* December, **199 1.**

[3] D. F. Williams, R. B. Marks, "Calibrating On-Wafer Probes to the Tips," *40th ARFTG Conference Digest,* December, 1992.

[4] A. Davidson, K. Jones, and E. Strid, "LRM and LRRM Calibrations with Automatic Determination of Load Inductance," *36th ARFTG Conference Digest,* November, 1990.

[5] NIST Industrial MMIC Consortium Software Manuals

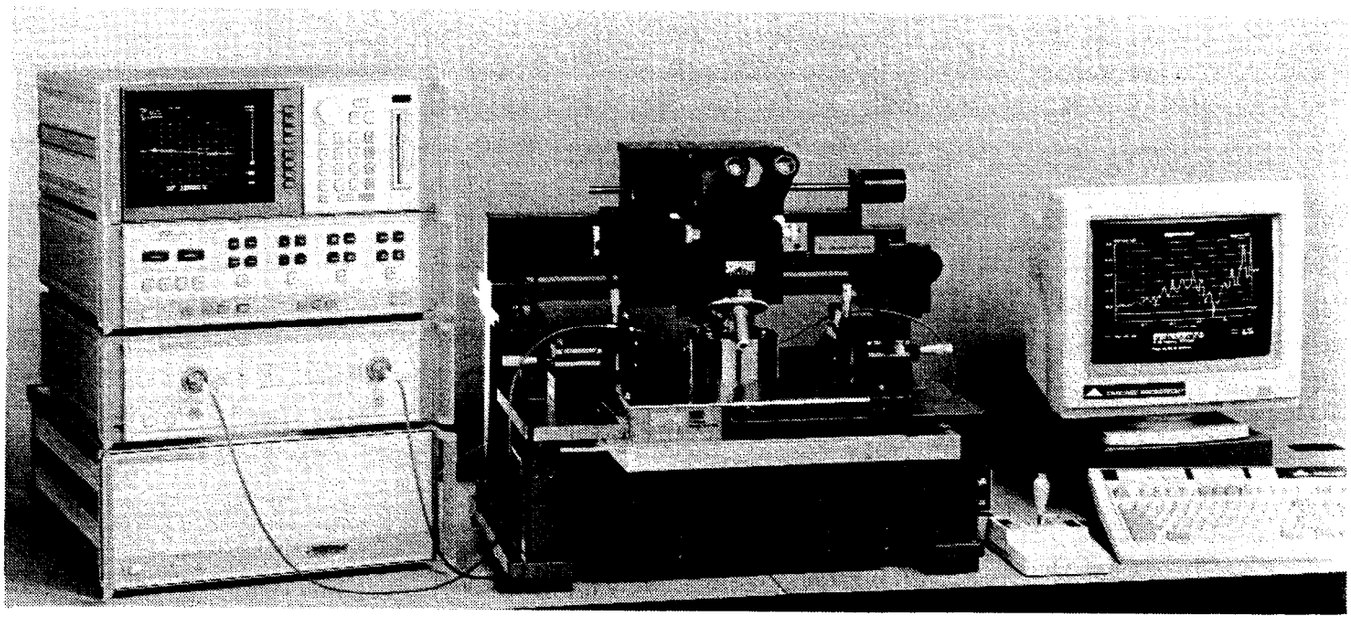


Figure 1: Cascade Microtech Semi-Automatic Wafer Probing System

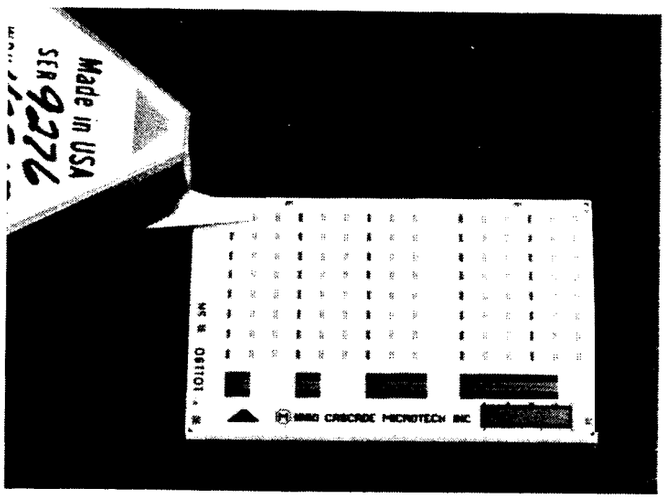


Figure 2: Typical Cascade Microtech Alumina CPW Impedance Standard Substrate

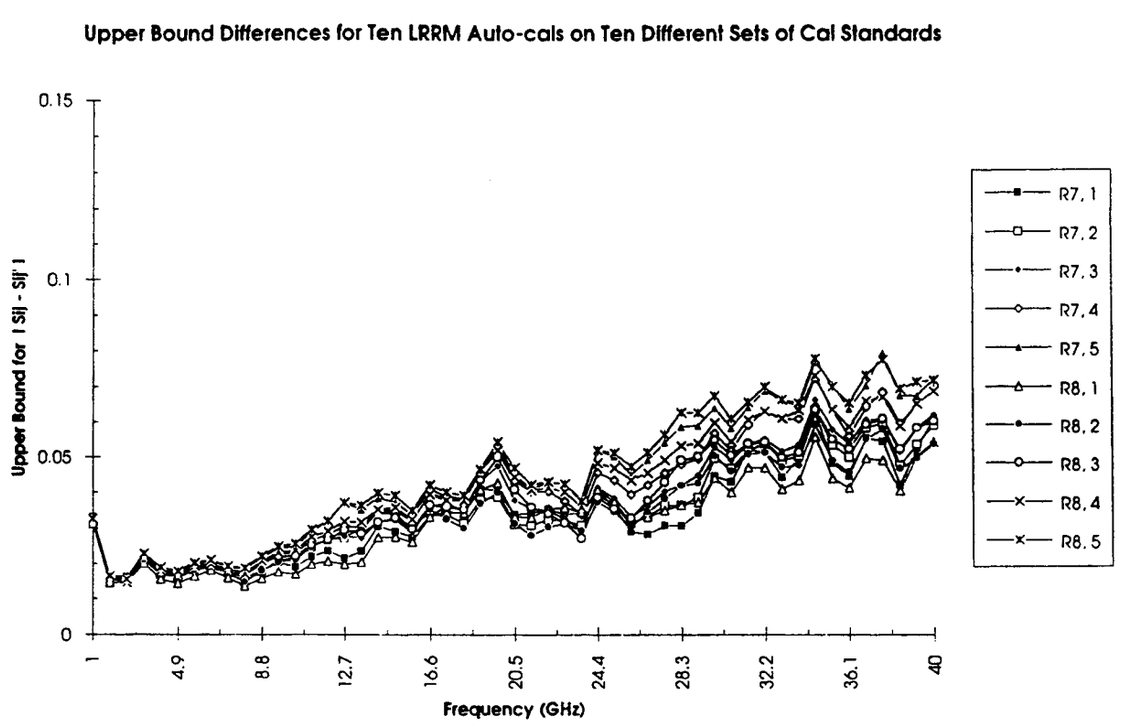


Figure 3: LRRM with Load Inductance Compensation Verification Results for Experiment 1

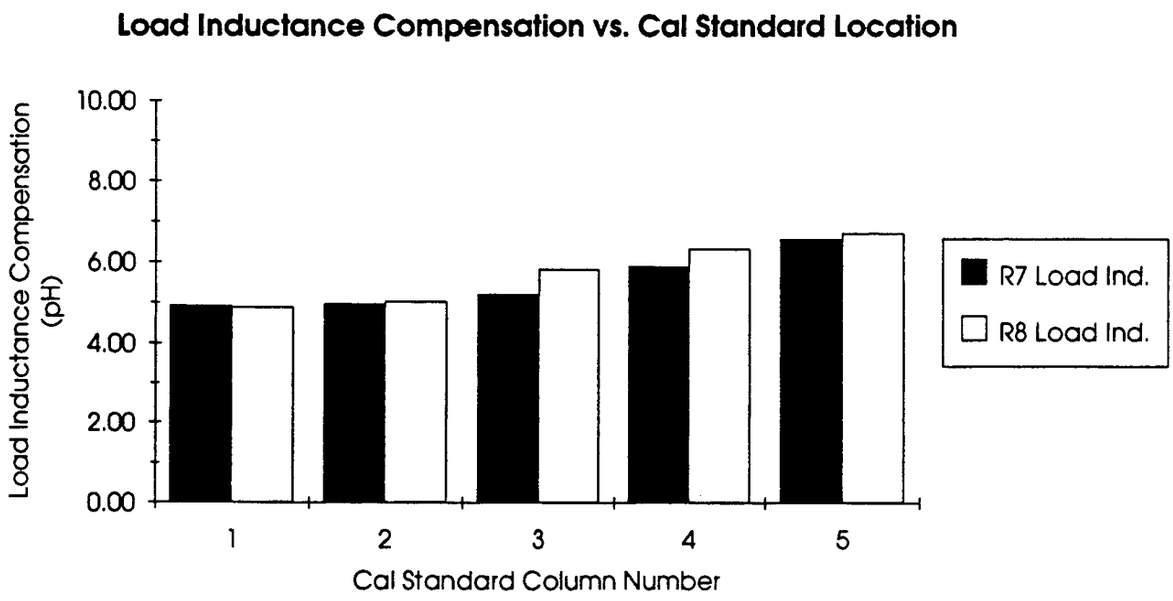


Figure 4: Calculated Load Inductance Compensation Values for Experiment 1

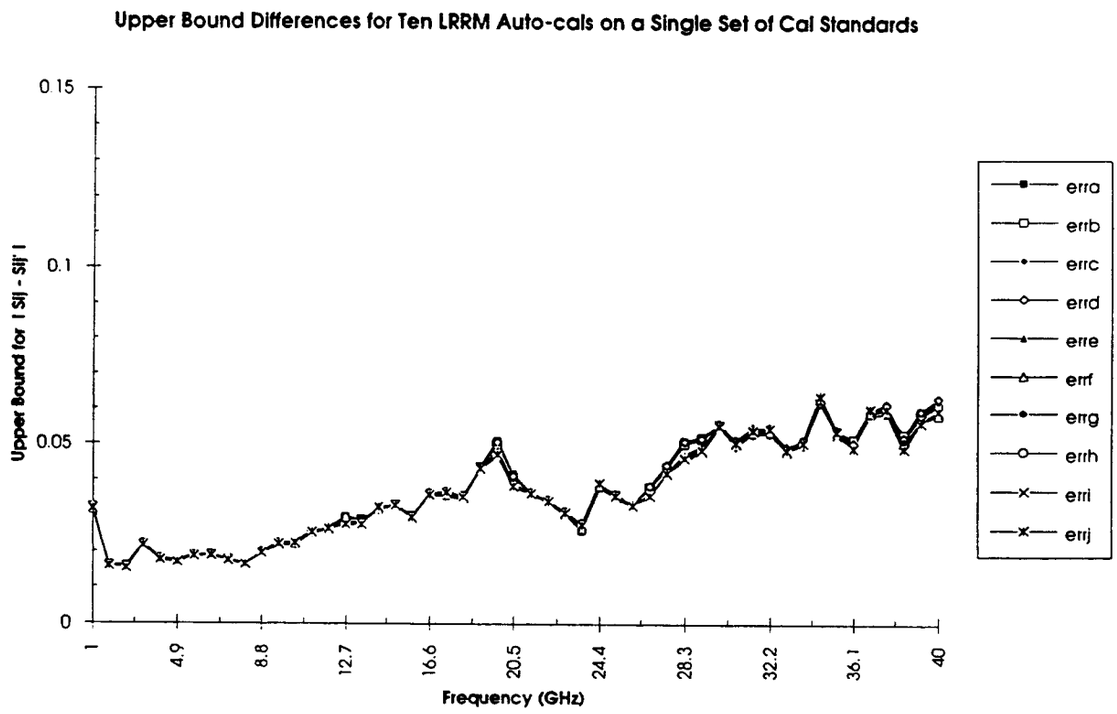


Figure 5: LRRM with Load Inductance Compensation Verification Results for Experiment 2

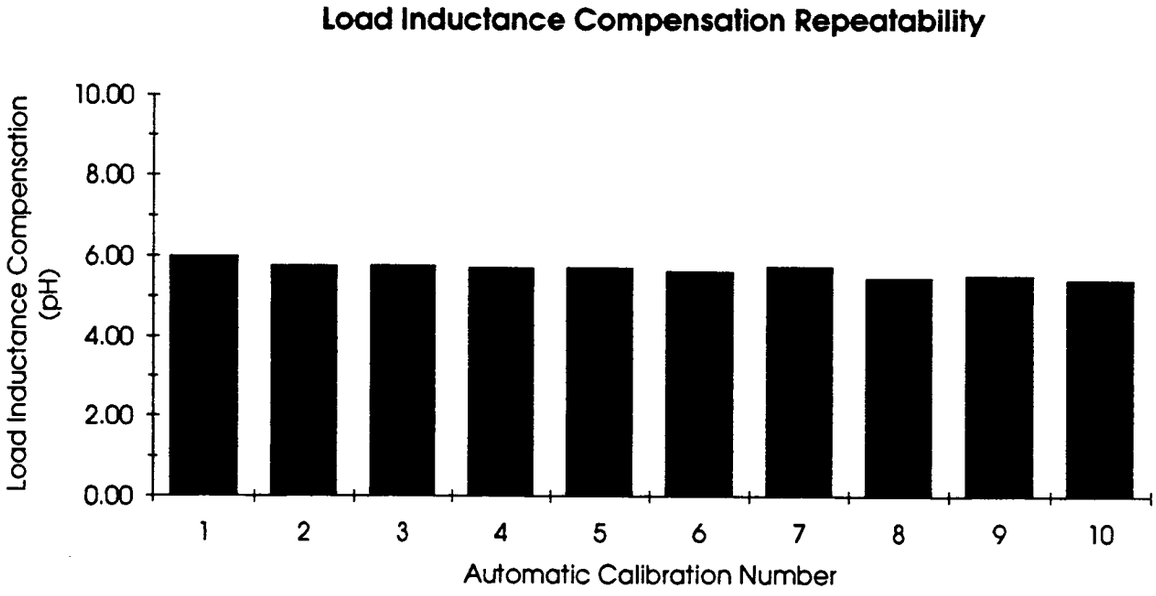


Figure 6: Calculated Load Inductance Compensation Values for Experiment 2

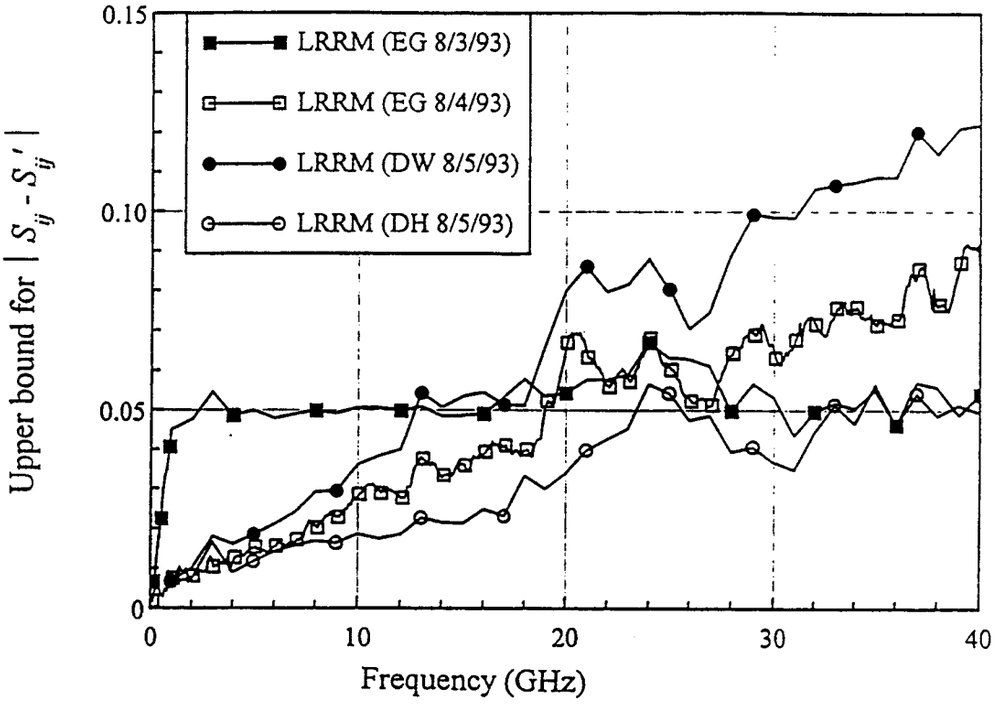


Figure 7: Upper Bound Differences for Manual LRRM Calibration Verifications

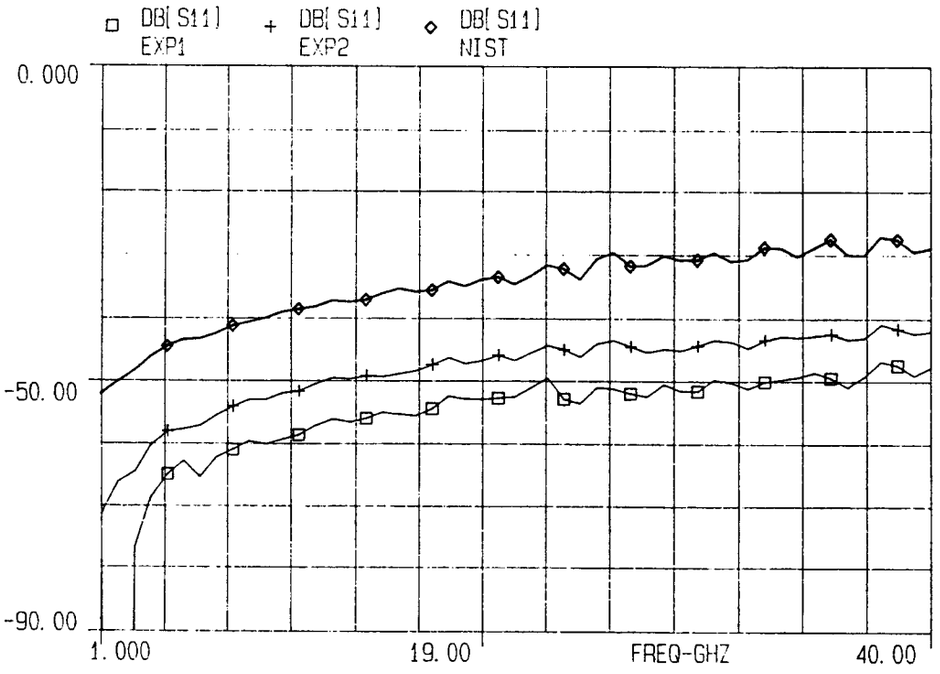


Figure 8: Calibration Stability Test Results