CCEM Key Comparison

CCEM.RF-K23.F

Measurement Techniques and
Results of an Intercomparison
of Horn Antenna Gain at Frequencies of
12.4, 15.0, 18.0 GHz

by

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1. Introduction

The CCEM international antenna gain comparison CCEM.RF- K23.F was initiated by the Working Group on Radio Frequency quantities (GT_RF) on the Consultative Committee for Electricity and Magnetism. This key comparison will measure on-axis gain of two pyramidal horns at Ku-band. Twelve national laboratories participated. The purpose of the comparison was to evaluate the consistency between the participating laboratories in the measurement of the boresight gain of horn antennas in the WR-62 band.

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3. Traveling Standards

Two nominally identical MI Technologies standard gain horns, model number: MI-12-12, part number: 093275, serial numbers: 3935 & 3936 were used for the key comparison. The dimensions of the antennas are, A = 35.7 mm, B = 15.6 mm, C = 12.9 mm, as shown in **Figure 1**.

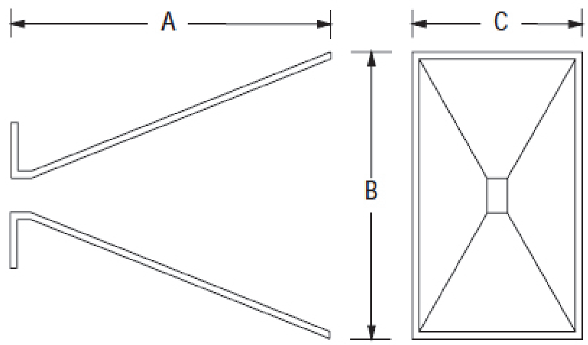

Figure 1. Dimension of the traveling standards.

4. Parameters for Measurement

Gain

The comparison consists of the measurement of boresight gain [1] of two MI Technologies pyramidal horn antennas at 12.4, 15, and 18 GHz. The boresight line was taken to be normal to the waveguide flange of the antenna and not normal to the aperture of the antenna. Treatment of outlier measurement values were determined in accordance with "Proposal for KCRV & Degree of Equivalence for GTRF Key Intercomparisons" GT_RF/2000-12 [2]. The Key Comparison Reference Value (KCRV) reported for the BIPM database are the three mandatory frequencies and non-weighted means after removal of outliers.

Reflection Coefficients

Participants making corrections for mismatch were asked to provide a table of the real and imaginary parts of the reflection coefficients of the antennas.

Swept or Stepped Frequency Measurements

Optionally, participants could measure the swept frequency gain from 12.4 to 18 GHz. Participants were free to choose the number of frequency points in this range, but were advised that the antennas were characterized by NIST from 12.4 to 18 GHz in 10 MHz steps.

On completion of the measurements, the comparison standards were forwarded to the next participant and finally returned to NIST.

Each laboratory submitted a report to the pilot laboratory (NIST) that provide the following information:

1) Antenna model and serial number.
2) Frequency [GHz].
3) Gain [dB].
4) Gain uncertainty with uncertainty budget [dB].
5) Swept frequency gain [dB] and step size (if measured).
6) Real and Imaginary Parts of Reflection Coefficients with their uncertainties (if measured).

A description of the measurement technique used and any theoretical corrections made were included for most of the participants.

5. The Comparison Schedule

The traveling standards were circulated to the participating National Measurement Institute (NMI) laboratories in the order listed in **Table 1**.

Table 1. Schedule for Traveling Standards.

Country	NMI	Date of Measurement
United States	NIST	February 2009
United Kingdom	NPL	April – May 2009
Sweden	SP	June 2009
Switzerland	METAS	September 2009
Korea	KRISS	January 2010
Australia	NMIA	August 2010
Japan	NMIJ	July – August 2010
France	LNE	September 2010
Turkey	TÜBİTAK-UME	December 2010
Russia	VNIIFTRI	February 2011
Czech Republic	CMI	June 2011
China	NIM	August – October 2011
United States	NIST	January 2013

6. Methods of Measurement

The NMI measurement methods are listed in **Table 2**. The details of each measurement method, as described by the NMI, are provided after the table.

Table 2. NMI Measurement Methods

Country	NMI	Measurement Method
Australia	NMIA	3 antenna, extrapolation
China	NIM	3 antenna, 7.07 m
Czech Republic	CMI	3 antenna, 2.4, 3.2, 4 m
France	LNE	reciprocity
Japan	NMIJ	3 antenna, extrapolation
Russia	VNIIFTRI	3 antenna, extrapolation
Korea	KRISS	3 antenna, extrapolation
Sweden	SP	gain transfer
Switzerland	METAS	3 ant., ANSI C63.5-1998
Turkey	TUBITAK-UME	3 antenna, 9 m
United Kingdom	NPL	3 antenna, extrapolation
United States	NIST	3 antenna, extrapolation

a. **NMIA** - *National Measurement Institute of Australia* - Australia

The antenna gain was determined using a three-antenna calibration method. The antenna was mounted in an anechoic chamber to measure the gain on an axis which was perpendicular to the waveguide flange. The antenna was moved along this axis to reveal finite separation effects. The antennas' test port was tuned for minimum reflection. From these measurements and the reflection coefficient of the antenna, the antenna gain was determined.

Description of antenna gain measurements

Measurements were performed in a 7 m x 5 m x 3 m anechoic chamber on an axis which was perpendicular to the waveguide flange. The antenna was moved along this axis to reveal finite separation effects. An extended three-antenna technique was used to a suite of three antennas which comprised the two travel standard antennas and a Ku-band antenna supplied by NMIA. The antenna separation range was chosen from $1D^2/\lambda$ to $4.5\ D^2/\lambda$.

The real and imaginary parts of the reflection coefficients of each antenna, pointed into an empty anechoic chamber, were measured by a calibrated vector network analyzer (VNA).

Discrete Frequency Measurements

Transmit and receive antennas were connected to matched ports which were tuned for minimum reflection, the gain products of distance-dependent antenna gains G_i and G_j for a finite antenna separation R can be expressed as

$$G_i G_j = \frac{P_{ij}^r(R)}{P^t F_{ij}(R)} \left(\frac{4\pi R}{\lambda}\right)^2 \frac{1}{(1-|\Gamma_i|^2)(1-|\Gamma_j|^2)} \quad ,$$

where P_{ij}^r is the power received by a measuring instrument when an antenna is connected to its port, P^t is the transmit power, F_{ij} is the near-field correction factor, and Γ_i and Γ_j are horn reflection coefficients.

The far-field gain product was obtained by applying a weighting factor that makes the gain product flat against the separation distance.

The simultaneous solutions of three gain product equations gave the gains of all three antennas.

Stepped Frequency Measurements

Transmit and receive antennas were connected to ports whose reflection coefficients were measured by a VNA. The measured power was corrected for mismatch. The gain products of distance-dependent antenna gains G_i and G_j for a finite antenna separation R can be expressed as

$$G_i G_j = \frac{P_{ij}^r(R)}{P^t} \left(\frac{4\pi R}{\lambda}\right)^2 \frac{|1-\Gamma_t \Gamma_i|^2 |1-\Gamma_r \Gamma_j|^2}{(1-|\Gamma_i|^2)(1-|\Gamma_j|^2)|1-\Gamma_t \Gamma_r|^2} \quad ,$$

where Γ_t and Γ_r are reflection coefficients at the transmit and receive ports, respectively.

Measurements for all frequencies were made at various separations and the extrapolation method was applied to the set of measurement results for each frequency. The periodic oscillations in the insertion loss between antennas due to horn mutual reflection were reduced by averaging measurements at uniform separations.

b. **NIM** – *National Institute of Measurements* - China

The horn antennas have been measured in the anechoic chamber (a semi-anechoic room paved absorber on the ground) at NIM, China. Its dimensions are: 8.2 m height x 16 m width x 20.0 m length. The measurement technique is a three-antenna method. Aside from the traveling standards, the two horn antennas, the third one is a same model horn, supplied by NIM.

The site insertion loss (SIL) between 3 pairs of 3 antennas is measured at the separation distance of 7.07 m between the apertures of the transmitting antenna and receiving antenna. A Network analyzer (Agilent PNA-X5244A) was used with port 1 used to supply the RF signal to the transmitting antenna through a cable and port 2 used to receive the microwave signal from the receiving antenna through another cable. The reflection coefficients of each antenna, the transmitter, and the receiver are measured using the network analyzer (Agilent PNX5244A) calibrated using the TRL method (cal kit P11644A). The settings of the network analyzer are as follows: IF = 100 Hz, POWER = 0.0 dBm, SWEEP TYPE = STEP, NUMBER OF POINTS = 601.

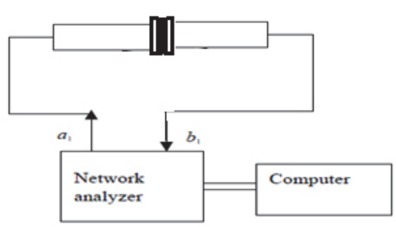

Figure 2. Network analyzer calibration measurement.

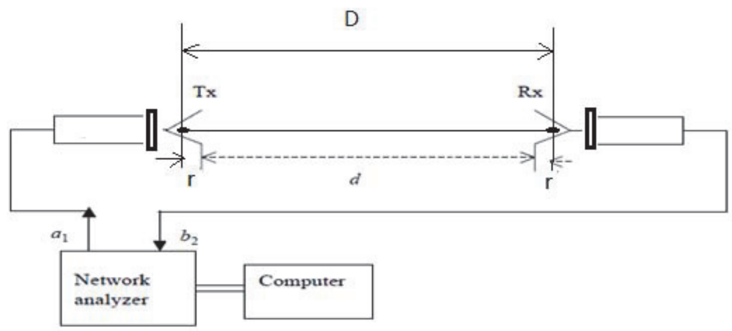

Figure 3. Network analyzer measurement horn antenna gain.

Three different combinations of three horns (MI-12-12-5057,-3935,-3936) were used during the investigation of the two DUTs: The series of measurements for each set-up consisted of three measurements in which one (MI-12-12-5057) horn was used for transmission only, another one (MI-12-12-3936) for receiving only and the last one (MI-12-12-3935) both for transmitting and receiving. The measurements were performed to measure the swept frequency gain over the frequency range 12.4 GHz to 18.0 GHz in step 10 MHz.

The gain of the horn antennas are calibrated by solving the following equations employing the three antenna method.

$$G_1 G_2 = (\frac{4\pi}{\lambda})^2 \frac{D^2 P_{12}}{P_D} M_{12}$$

$$G_1 G_3 = (\frac{4\pi}{\lambda})^2 \frac{D^2 P_{13}}{P_D} M_{13}$$

$$G_2 G_3 = (\frac{4\pi}{\lambda})^2 \frac{D^2 P_{23}}{P_D} M_{23}$$

Where G_1, G_2 and G_3 are the gains of the three antennas to be calibrated, respectively;
P_{ij} is the received power with the transmitting and receiving antenna connected to corresponding adapters;
P_D is the received power with the transmitting and receiving adapters directly connected;
M_{ij} is the mismatch correction factor that associated with the antenna reflection during the insertion loss measurement;
D is the distance between the phase centers of the two antennas;
d is the distance between the apertures of the transmitting and receiving antenna.

The gains can be derived as the following expressions

$$G_1(dB) = R_{12}(dB) + R_{13}(dB) - R_{23}(dB) + M_1(dB)$$

$$G_2(dB) = R_{12}(dB) + R_{23}(dB) - R_{13}(dB) + M_2(dB)$$

$$G_3(dB) = R_{13}(dB) + R_{23}(dB) - R_{12}(dB) + M_3(dB)$$

$$M_1 = \sqrt{\frac{M_{12}M_{13}}{M_{23}}} = \frac{|1-\Gamma_G\Gamma_1|^2|1-\Gamma_2\Gamma_L|}{(1-|\Gamma_1|^2)|1-\Gamma_G\Gamma_2||1-\Gamma_G\Gamma_L|}$$

$$M_2 = \sqrt{\frac{M_{12}M_{23}}{M_{13}}} = \frac{|1-\Gamma_G\Gamma_2||1-\Gamma_2\Gamma_L|}{(1-|\Gamma_2|^2)|1-\Gamma_G\Gamma_L|}$$

$$M_3 = \sqrt{\frac{M_{13}M_{23}}{M_{12}}} = \frac{|1-\Gamma_3\Gamma_L|^2|1-\Gamma_G\Gamma_2|}{(1-|\Gamma_3|^2)|1-\Gamma_G\Gamma_L||1-\Gamma_2\Gamma_L|}$$

Where, $R_{ij} = \lim_{D\to\infty}((4\pi/\lambda)\times\sqrt{D^2P_{ij}/P_D}$

M_i is mismatch correction factor;
Γ_1 is the reflection coefficient at the port of antenna MI-12-12, S/N: 5057;
Γ_2 is the reflection coefficient at the port of antenna MI-12-12, S/N: 3935;
Γ_3 is the reflection coefficient at the port of antenna MI-12-12, S/N: 3936;
Γ_G is the reflection coefficient looking into Vector Network analyzer (VNA) port1 connected with the adapter (P11644A);
Γ_L is the reflection coefficient looking into Vector Network analyzer (VNA) port2 connected with the adapter (P11644A).

c. **CMI** – *Czech Metrology Institute* – Czech Republic

Measurements have been performed in a fully anechoic chamber using a three antenna method for antenna aperture-to-aperture separations about 2.4 m, 3.2 m and 4 m. The ripple superimposed on the transmission curve due to interaction between antennas was eliminated by averaging. The near field corrections were calculated according to reference [3]. Reflection coefficients were measured by a vector network analyzer calibrated by the TRL method.

d. **LNE** – *Laboratoire national de metrologie et d'essais* - France

The antenna gain was determined by using a reciprocity method. The measurements were made in the vertical polarization in an anechoic chamber using a coaxial line of impedance characteristic equal to 50 Ohms with a VNA.

e. **NMIJ** – *National Metrology Institute of Japan* – Japan

The three antenna method based on the extrapolation technique was used to measure the gains of the antennas. Every surface of the anechoic chamber is covered with principally 0.6 m (in height) radiation absorbing material (RAM) blocks. In the chamber, the measurement area (8 m long, 4 m wide, 7 m high), where the measurement equipment for the extrapolation technique is placed, is made using 0.2 m RAM blocks and 0.3 m RAM blocks that cover the measurement equipment and the floor.
A vector network analyzer (VNA, Agilent Technologies E8364A) is used to measure the S parameters between the ports of two antennas under calibration. The setting calibration of the VNA is done with the combination of the SOLR method and the TRL method (for the coaxial to waveguide adapter removal) to measure the S parameters between the waveguide ports of the two antennas. The reflection coefficient of an antenna is measured by the VNA calibrated using the TRL method with the antenna being directed towards the ceiling of the anechoic chamber.

The separation distance between two antennas is varied from about 1.5 m to about 3.5 m. The number of measurement distances is 297, and they are grouped to 9 blocks, each of which is composed of 33 points separated by 1.5 mm. Therefore the end of each block is separated by 250.5 mm.

Figure 4 shows the measurement setup. The reference planes are defined at the antenna flanges as Port 1 at the fixed antenna and as Port 2 at the moving antenna. The S parameters between the antennas are measured between the Port 1 and Port 2.

One of the traveling standards (MI-12-12 SN 3935 and SN3936) and other two auxiliary antennas (MI-12-12) possessed by NMIJ as working standards are combined as a set of three antennas in the procedure of the three antenna measurement method. Therefore both of the traveling standards are not measured at the same time in a procedure of three antenna measurement. In the following explanation, one of the traveling standards is designated as the antenna 1 and two auxiliary antennas are designated as the antenna 2 and the antenna 3.

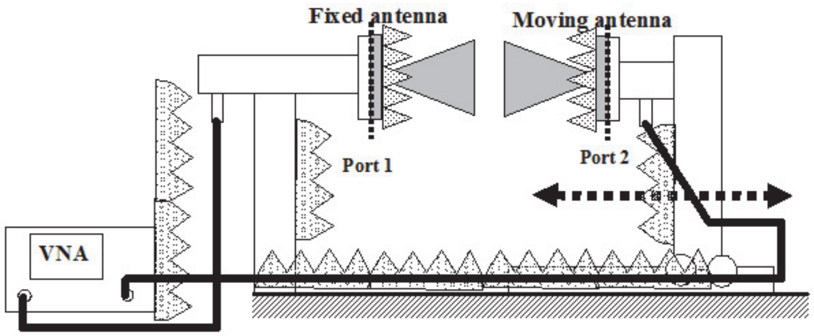

Figure 4. Measurement setup of three antenna method.

Taking the antenna *i* as the fixed antenna and the antenna *j* as the moving antenna from a group of three antennas, we obtain the gain product of the antenna pair (*i*,*j*) as

$$G_i G_j = \lim_{r\to\infty} \frac{16\pi^2 \left|rS_{ji}\right|^2}{\lambda^2 P_{ij}\left(1-\left|S_{ii}\right|^2\right)\left(1-\left|S_{jj}\right|^2\right)} = \frac{R^2_{ij}}{p_{ij}\left(1-\left|T_{(ij)ii}\right|^2\right)\left(1-\left|T_{(ij)jj}\right|^2\right)} \quad ,$$

where r , S_{ji} and P_{ij} are the distance between the apertures of the antennas, the S-parameters between the antenna i and the antenna j, and the polarization-mismatch factor, respectively. And further

$$\begin{aligned} R_{ij} &= \lim_{r\to\infty}\left|\frac{4\pi r S_{ji}}{\lambda}\right| \\ T_{(ij)ii} &= \lim_{r\to\infty} S_{ii} \\ p_{ij} &= \lim_{r\to\infty} P_{ij} \end{aligned} \quad ,$$

where R_{ij} is determined by the extrapolation method and $T_{(ij)ii}$ is obtained by the reflection coefficient measurement.

The gain of the antenna 1 under calibration (AUC) is obtained by

$$G_1 = \sqrt{\frac{(G_1G_2)(G_1G_3)}{(G_2G_3)}} = \frac{R_{12}R_{13}}{R_{23}}\sqrt{\frac{p_{23}}{p_{12}p_{13}}\frac{\left(1-\left|T_{(23)22}\right|^2\right)\left(1-\left|T_{(23)33}\right|^2\right)}{\left(1-\left|T_{(12)11}\right|^2\right)\left(1-\left|T_{(12)22}\right|^2\right)\left(1-\left|T_{(13)11}\right|^2\right)\left(1-\left|T_{(13)33}\right|^2\right)}} \quad .$$

Therefore, the gain in dB unit is given by

$$\begin{aligned} G_1(\mathrm{dB}) = 0.5\big[&R_{12}(\mathrm{dB}) + R_{13}(\mathrm{dB}) - R_{23}(\mathrm{dB}) + p_{23}(\mathrm{dB}) - p_{12}(\mathrm{dB}) - p_{13}(\mathrm{dB}) \\ &+ N_{23}(\mathrm{dB}) - N_{12}(\mathrm{dB}) - N_{13}(\mathrm{dB})\big] \end{aligned} \quad ,$$

where

$$G_1(\mathrm{dB}) \equiv 10 \log_{10} G_1$$
$$R_{ij}(\mathrm{dB}) \equiv 20 \log_{10} R_{ij}$$
$$p_{ij}(\mathrm{dB}) \equiv 10 \log_{10} p_{ij}$$
$$N_{ij}(\mathrm{dB}) \equiv 10 \log_{10} \left[\left(1 - \left|T_{(ij)ii}\right|^2\right)\left(1 - \left|T_{(ij)jj}\right|^2\right)\right]$$

f. **VNIIFTRI** – *Russian Scientific Research Institute of Physico-Technical Measurements - Russia*

The gains of the antennas were measured by the three antenna technique in anechoic chamber measuring: 10 m × 5 m ×4 m (L×W×H). An extrapolation measurement technique was used to evaluate and correct for near-zone and multiple reflection effects in the measured data. The gain and reflection coefficients were measured at the waveguide port of antenna. In addition to the two comparison antennas, the third antenna used was MI-12-12 horn serial number 4779. The gain was measured along an axis normal to the input flange of the antenna.

A Vector Network Analyzer R&S ZVB-24 with cables Rosenberger LU-7-039 and waveguide VNA calibration kits 7005E series was used to measure the complex reflection coefficients and the gain.

All measurements were performed at (23±2) ºC.

g. **KRISS** – *Korea Research Institute of Standards and Science* – Korea

The three-antenna method based on the extrapolation technique [4] is used to measure the gains of the antennas. The antenna chamber is covered with 48 in. electromagnetic wave absorbers and the dimensions are 13 m long, 10 m wide, and 7.5 m high.

The microwave measurement system for measuring the insertion loss between the transmitting and receiving antennas is based on an internal mixer configuration, as shown in **Figure 5**. A synthesized signal source (HP 83640A), an amplifier (AR 20ST1G18A), and a directional coupler (HP 11691D) are used to supply the RF signal to the transmitting antenna, and a microwave receiver (HP 8530A) is connected to the receiving antenna through a frequency converter (HP8511B). To correct for the impedance mismatches, the reflection coefficients of each antenna, the transmitter, and the receiver are measured using a network analyzer (Agilent E8361C) calibrated by the TRL method.

An additional horn antenna (Antenna 3, which is the same model as the traveling standards, Antenna 1 and Antenna 2) is used for the three-antenna method. The measurement data were taken over a distance range from 0.79 m to 4.57 m. A three-term polynomial is used for the curve fitting in the gain analysis.

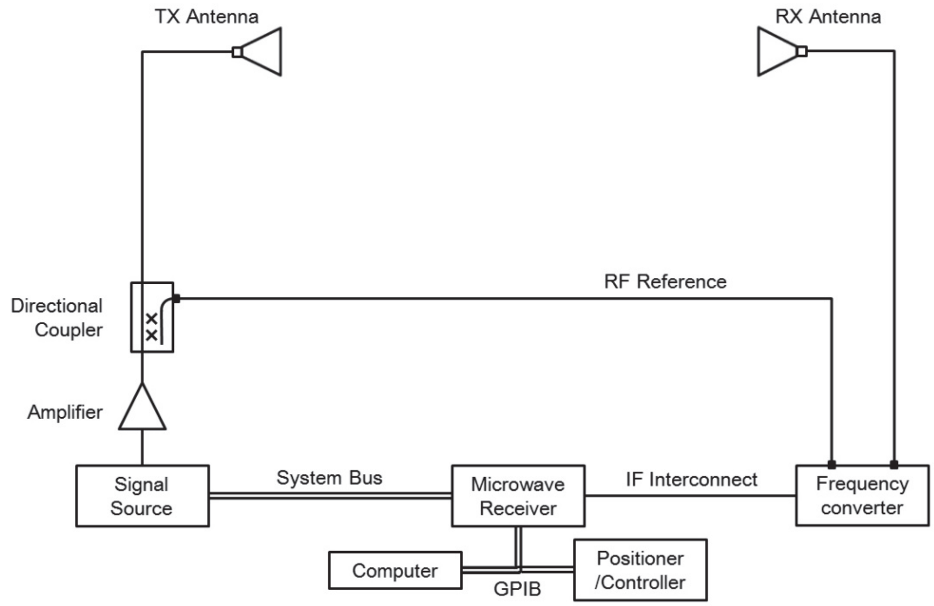

Figure 5. Block diagram of the measurement set-up at KRISS.

h. **SP** – *Technical Research Institute of Sweden* – Sweden

The gain of two almost identical horn antennas is determined using the method described in ref [5]. The gain was measured in the interval 12.3 GHz to 18 GHz using 10 MHz steps. The same waveguide to N-contact adapter was used for both horn antennas. The received power from a horn antenna is measured as function of frequency for two different configurations; one using a reference horn antenna (standard gain horn) and one using the test object. The known gain of the standard gain horn combined with the difference in obtained power from the reference horn antenna gives the gain of the test object.

The gain of the test object can be obtained by measuring the received power by the receiving horn (EMCO 3115) for the two cases; when the test object is transmitting and when the standard gain horn is transmitting. The transmitting antenna is fed by a signal generator through a 6 dB attenuator and the signal generator is having an output power of 10 dBm. The relation between the measured and sought quantities is presented in the equation below:

$$(G_T)_{dB} = (G_S)_{dB} + (P_T)_{dB} - (P_S)_{dB}$$

Where;
$(G_T)_{dB}$ = Gain of the test object;
$(G_S)_{dB}$ = Gain of the standard gain horn (known from calculation);
$(P_T)_{dB}$ = Received power when the test object is transmitting; and
$(P_S)_{dB}$ = Received power when the standard gain horn is transmitting.

i. METAS – *Federal Institute of Metrology* – Switzerland

The antenna factor was determined using the (ANSI C63.5-1998) three-antenna method [6], using the two traveling antennas and a double ridged horn antenna (Schwarzbeck, model BBHD 9120 D). However for proper determination of the site attenuation the technique described in annex C was not used and frequency smoothing was not performed on the data. Waveguide to coaxial adapters were used to accommodate the network analyzer. The antenna factors were corrected for the attenuation in the adapters. The reflection parameters of the waveguides were not good (25 dB to 35 dB) they were not made on the standard antennas. For the mismatch uncertainty calculations the S11 for each antenna was assumed to be better than
-20 dB.

Measure each horn combination

The site attenuation profile (measured from 1 m to 4 m every 2 cm) was determined. The measurements have been performed in the frequency range of 10 GHz to 18 GHz with a frequency step of 10 MHz. The phase center, as well the "normalized attenuation" was then determined for each individual frequency according to a fit of the site attenuation profile (measured from 1 m to 4 m every 2 cm) as:

$$A_{measured}(d) = \mathrm{x} + 20 \cdot \log_{10}(d + y)$$

Where:

- $A_{measured}(d)$ is the measured attenuation in dB.
- d is the distance between the aperture of both antennas. It is measured in meters.
- y is a fit parameter in the above equation. Its values after fitting are interpreted as the sum of the horn phase centers in meters, measured from the aperture of the horn.
- x is a fit parameter in the above equation. Its value after fitting is interpreted as the "normalized attenuation".

From the quality of the fit (standard deviation of the measured data to the fit data), we derived the reflection uncertainties that are reported in the uncertainty budget ("residual multi-path").

Calculation of the antenna factor

The antenna factors of each antenna are determined by solving the 3 equations:

$$nA_{i\text{-}j} = 32 - 20 \cdot \log_{10}(f) + AF_i + AF_j$$

for i,j = {1,2}, {1,3}, {2,3}

Where

- nA is the normalized attenuation in dB
- f is the frequency in MHz
- AF is the antenna factor is dB(1/m)
- i and j are 1,2, or 3, referring to the three horn antennas

Calculation of the gain

The gain of each antenna has been determined using the conversion formula between gain and antenna factor.

$Gain[dB] = -149.78 + 20 \log_{10}(f\,[Hz]) - AF[dB(1/m)]$

With

- $Gain$ is the gain in dB
- AF is the antenna factor in dB(1/m)
- f is the frequency in Hz

j. **TÜBİTAK-UME** – *The Scientific and Technological Research Council of Turkey* – Turkey

The antenna gain measurements were performed in accordance with the three antenna method in a semi-anechoic chamber with a cut-off frequency of 40 GHz. Before the measurements, the floor of the semi-anechoic chamber was covered with absorbers. The heights of the transmitting and receiving antennas were adjusted to 3 m. The distance between transmitting and receiving antennas was adjusted to 9 m in order to meet far field conditions. In the measurements, an EMI Receiver, a signal generator, adapters, a horn antenna as a third antenna, cables and attenuators were used. No extrapolation or near-zone corrections or other corrections have been applied to the results.

All measurements were realized at temperature of (23 ±2) °C and humidity (45 ± 10)% of the anechoic chamber.

After the measurements, the antenna gains were calculated by using the following equations,

$$(G_1)_{dB} + (G_2)_{dB} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{r2}}{P_{t1}}\right)$$

$$(G_1)_{dB} + (G_3)_{dB} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{r3}}{P_{t1}}\right)$$

$$(G_2)_{dB} + (G_3)_{dB} = 20\log_{10}\left(\frac{4\pi R}{\lambda}\right) + 10\log_{10}\left(\frac{P_{r3}}{P_{t2}}\right)$$

P_{t1}, P_{r2} : Transmitted/received power for horn 1 (transmitting) and horn 2 (receiving)
P_{t1}, P_{r3} : Transmitted/received power for horn 1 (transmitting) and horn 3 (receiving)
P_{t2}, P_{r3} : Transmitted/received power for horn 2 (transmitting) and horn 3 (receiving)
R : The distance between transmitting and receiving antenna
λ : Wavelength of the electromagnetic wave
G: Gain of the antenna

Figure 6. Measurement Setup.

k. **NPL** – *National Physical Laboratory* – United Kingdom

Gain

The gain of the horn antenna was determined by the three antenna extrapolation technique in a 15 m x 7.5 m 7.5 m anechoic chamber. Alignment of the source and test antenna was achieved by auto reflections using a micro-alignment telescope with a mirror placed over the waveguide flange. Thus the gain of the antenna was measured along the axis normal to the waveguide flange of the antenna. The polarization of the receiving antenna was adjusted, using a roll positioner, to match that of the transmitting antenna. The insertion loss was measured for antenna separations ranging from 1.5 m to 6.0 m, at a total of 2,143 positions. The separations were measured by a laser interferometer system. The data was digitally filtered to remove the effect of multiple reflections between the antennas before being filtered with a four term polynomial. A low-pass filter was include in the transmitting circuit to ensure freedom from errors due to unwanted source harmonics.

Two separate sets of three antenna extrapolation measurements were performed as indicated in the table below. The reported results are the average from the two sets of measurements.

	Antenna A (Tx only)	Antenna B (Rx and Tx)	Antenna C (Rx only)
Set 1	Narda 639 s/n A	Narda 639 s/n B	MI 12-12 s/n 3935
Set 2	Narda 639 s/n A	MI 12-12 3936	MI 12-12 s/n 3935

Swept Gain
Fixed distance, three antenna measurements were also carried out with a separation of 6.0 m between the antenna apertures, first using the Set 1 antenna combination indicated in the table above, then repeating these measurements but with the comparison horn s/n 3936 used for Antenna C, in place of s/n 3935.The measurements were carried out from 12.4 to 18.0 GHz in 20 MHz steps and the results were then corrected using the extrapolation gain values at 12.4, 15.0 and 18.0 GHz, with linear interpolation for intermediate frequencies. Mismatch correction was also applied.

The Set 2 antenna combination above was not used for the swept gain measurements, as the multiple reflections between the MI 12-12 antennas was significant, even at 6.0 m, and being a fixed distance measurement, the effect could not be removed.

Reflection Coefficients
A Hewlett-Packard 8510C automatic network analyzer was used to measure the complex reflection coefficients of the antennas and components used in the measurement circuit. Mismatch corrections were calculated using these reflection coefficient measurements.

All measurements were made in a temperature controlled electromagnetic chamber in a screened laboratory at a temperature of 23±2 ºC.

l. **NIST** – *National Institute of Standards and Technology* – United States

Gain
The on-axis gain [1] of the traveling standards were measured using a generalized three-antenna measurement technique [4]. A Narda, model 639, standard gain horn, serial number 12, was supplied by NIST as the third antenna. An extrapolation measurement technique was used to evaluate and correct for near-zone and multiple reflection effects in the measured data. A set of permanent scribe lines on the antennas apertures defined the axis of measurement which was

normal to the plane of the antenna aperture. The probe was aligned with the long wall of the waveguide flange horizontal. A "+Y" label was placed on the antenna near the aperture to define the orientation of the antenna for the measurements. The antenna was nominally linearly polarized.

Stepped Frequency Gain

Stepped frequency gain measurements were performed from 12.4 to 18.0 GHz in 10 MHz steps. The stepped frequency gain corrected using the fixed frequency gain values.

Reflection Coefficients

Reflection measurements were made with a network analyzer.

7. Measurement Results

On-Axis Gain at the Fixed Frequencies

The on-axis gain measurements were made at the waveguide port of the antennas. Each NMI generated a report of their determined gain values and uncertainties that were sent to NIST to be compiled. The reported uncertainties are based on a standard uncertainty coverage factor of k=2. As the pilot lab, NIST performed the measurements at the beginning and end of the measurement campaign. The two NIST measurements were averaged and entered as one measurement for the key comparison.

The gain values were converted from dB to linear for calculations using,

$$G_{linear} = 10^{\frac{G_{dB}}{10}} .$$

The gain uncertainty values were converted from dB to fractional uncertainty for calculations using eq. 24 & 25 [7], which gives the following for the fractional gain uncertainty value conversion,

$$u(y)_{fractional} = \left(1 - 10^{-\frac{u(y)_{dB}}{10}}\right) .$$

The determination and handling of outliers was performed and the non-weighted mean values and uncertainties were calculated according to [2]. Outlier does not necessarily mean bad, or wrong, or out of compliance. It just means that the point in question was not used in computing the mean. It may still be in agreement with the KCRV, depending on the uncertainties in each. For purposes of judging whether a lab's results are "good," one should refer to the degrees of equivalence, or to the plots that include uncertainties. This process is described in **Section 8**.

Theoretical gain values for the traveling standards were also computed at the three measurement frequencies using the Naval Research Laboratory model [8].

The NMI reported fixed-frequency on-axis gain results and respective uncertainties for the traveling standards S/N 3935 and S/N 3936 are listed in **Table 3** and **Table 4**, respectively. The outliers are shown in *red italic print* in the tables. The non-weighted means and uncertainties calculated after removing outliers are listed in **bold blue print** in the tables. The theoretical calculated gain values are listed in **bold purple print** in the tables. These results are also shown graphically in **Figure 7** and **Figure 8**, respectively. For ease in viewing, data reported in the graphs have been plotted nominally with respect to the measurement frequency.

The results are also graphed individually for each traveling standard, at each measurement frequency from **Figure 9** through **Figure 14**. The non-weighted mean value after outlier removal is shown as the solid black line and the respective uncertainty is shown as the light blue shaded area the figures. The theoretical calculated gain value for the traveling standard are shown as the dashed blue line in the figures.

Table 3. On Axis Gain Results for S/N 3935

Country	NMI	12.4 GHz	15.0 GHz	18.0 GHz
Australia	NMIA	23.63 ±0.05	24.44 ±0.05	24.82 ±0.05
China	NIM	23.63 ±0.20	24.46 ±0.20	24.84 ±0.20
Czech Republic	CMI	23.652 ±0.208	24.410 ±0.230	24.779 ±0.245
France	LNE	23.67 ±0.24	24.45 ±0.24	24.96 ±0.24
Japan	NMIJ	23.56 ±0.16	24.47 ±0.20	*25.09 ±0.26*
Russia	VNIIFTRI	23.612 ±0.094	24.374 ±0.140	24.800 ±0.150
Korea	KRISS	23.692 ±0.110	24.474 ±0.110	24.879 ±0.110
Sweden	SP	23.5 ±0.43	*24.0 ±0.5*	*23.9 ±0.5*
Switzerland	METAS	*23.75 ±0.35*	*24.62 ±0.53*	24.92 ±0.56
Turkey	TUBITAK-UME	23.59 ±0.84	*24.13 ±0.84*	*24.49 ±0.84*
United Kingdom	NPL	23.619 ±0.027	24.449 ±0.027	24.832 ±0.027
United States	NIST	23.67 ±0.07	24.48 ±0.07	24.88 ±0.07
	Non-weighted Mean Value	**23.63 ±0.10**	**24.44 ±0.05**	**24.86 ±0.08**
	Calculated Gain	**23.64**	**24.47**	**24.91**

Note: Significant digits are as reported by the NMI.

Table 4. On Axis Gain Results for S/N 3936

Country	NMI	12.4 GHz	15.0 GHz	18.0 GHz
Australia	NMIA	23.63 ±0.05	24.43 ±0.05	24.83 ±0.05
China	NIM	23.63 ±0.20	24.47 ±0.20	24.83 ±0.20
Czech Republic	CMI	23.645 ±0.208	24.410 ±0.230	24.788 ±0.245
France	LNE	23.63 ±0.24	24.45 ±0.24	24.89 ±0.24
Japan	NMIJ	23.56 ±0.16	24.44 ±0.20	*24.99 ±0.26*
Russia	VNIIFTRI	23.608 ±0.094	24.387 ±0.140	24.840 ±0.150
Korea	KRISS	23.695 ±0.110	24.473 ±0.110	24.881 ±0.110
Sweden	SP	*23.4 ±0.43*	*24.0 ±0.5*	*24.2 ±0.5*
Switzerland	METAS	*23.79 ±0.35*	24.52 ±0.53	*25.30 ±0.56*
Turkey	TUBITAK-UME	23.61 ±0.84	*24.14 ±0.84*	*24.51 ±0.84*
United Kingdom	NPL	23.624 ±0.027	24.444 ±0.027	24.863 ±0.027
United States	NIST	23.66 ±0.07	24.48 ±0.07	24.88 ±0.07
Non-weighted Mean Value		**23.63 ±0.10**	**24.45 ±0.08**	**24.85 ±0.06**
Calculated Gain		**23.64**	**24.47**	**24.91**

Note: Significant digits are as reported by the NMI.

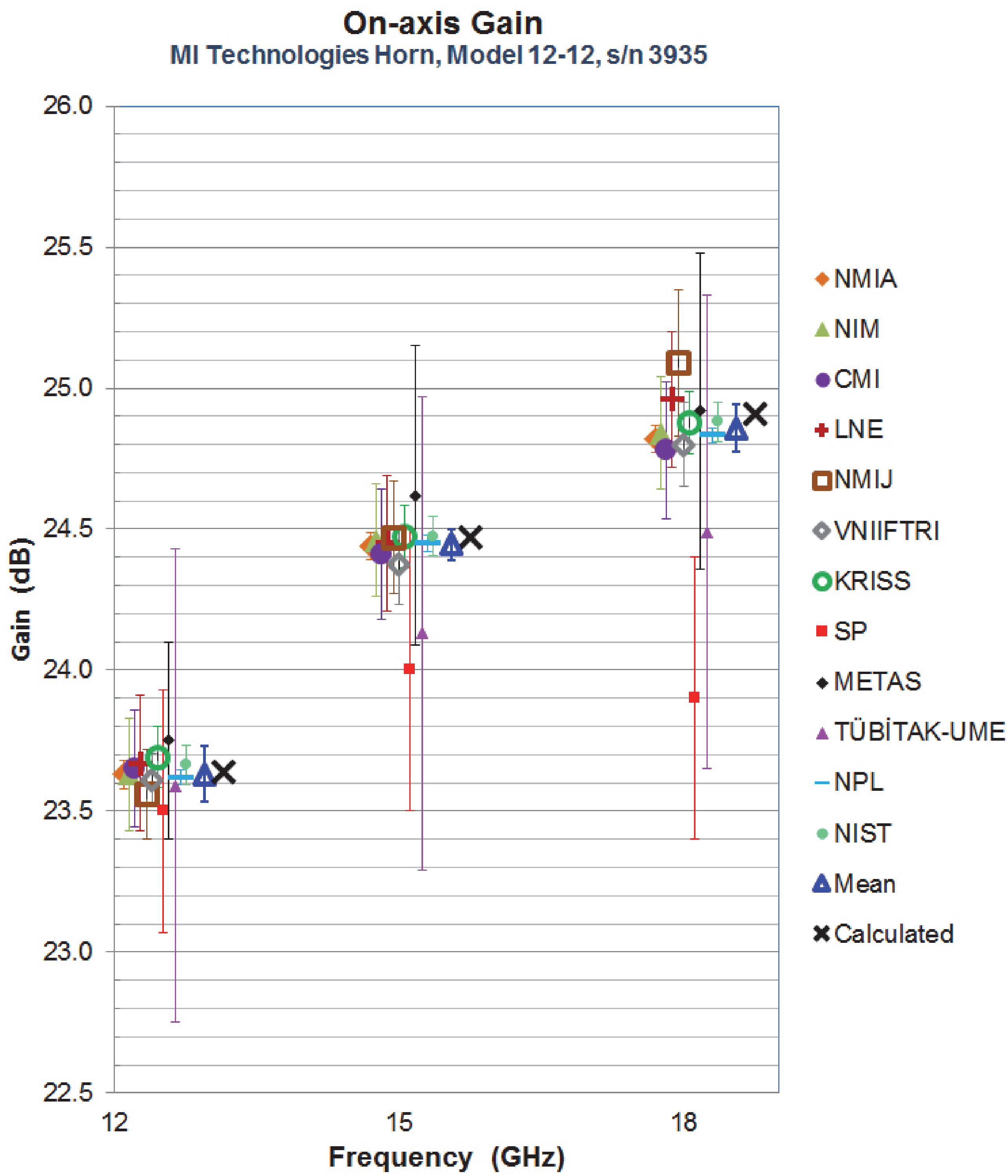

Figure 7. On axis gain measurement results for S/N 3935.

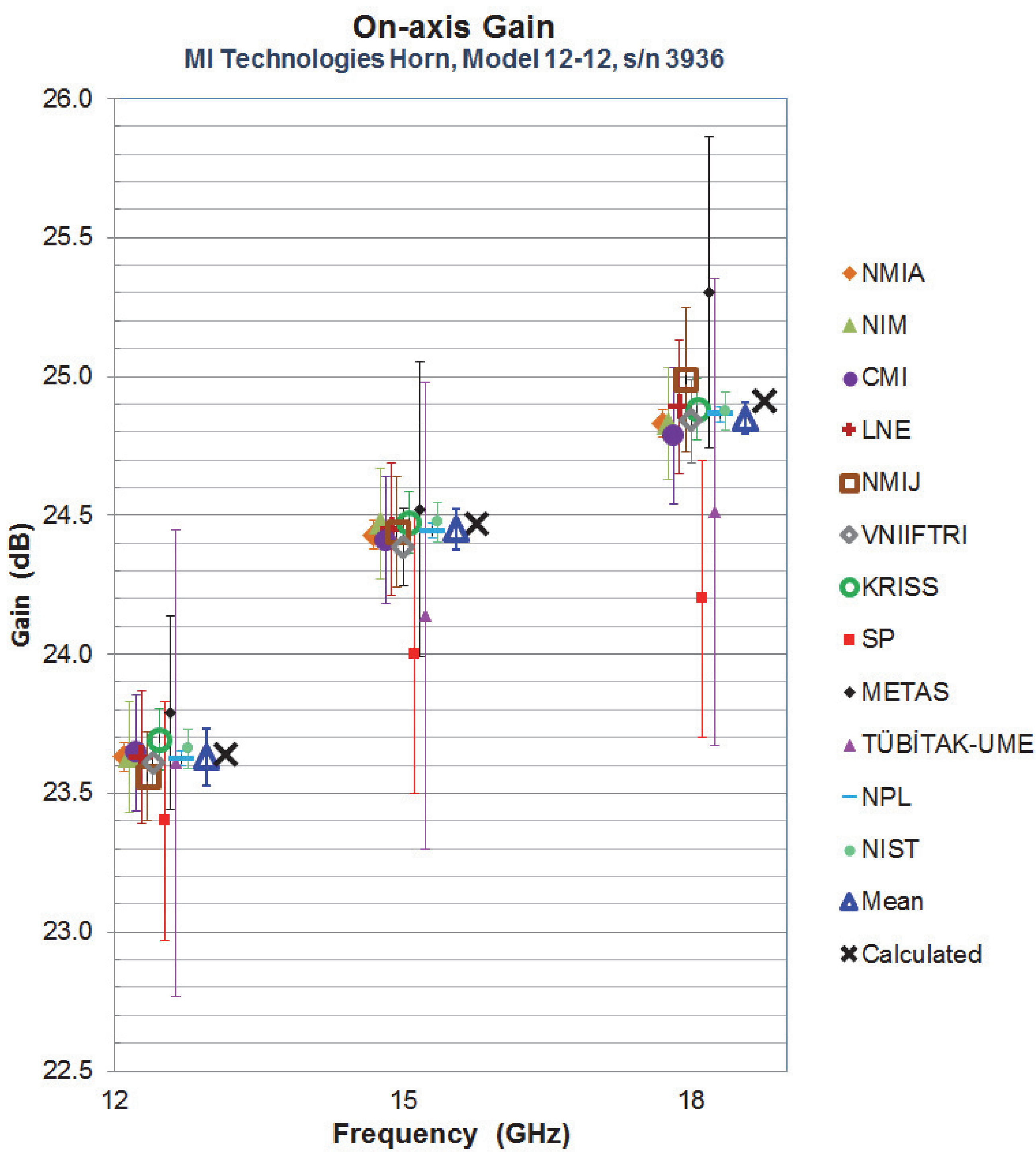

Figure 8. On axis gain measurement results for S/N 3936.

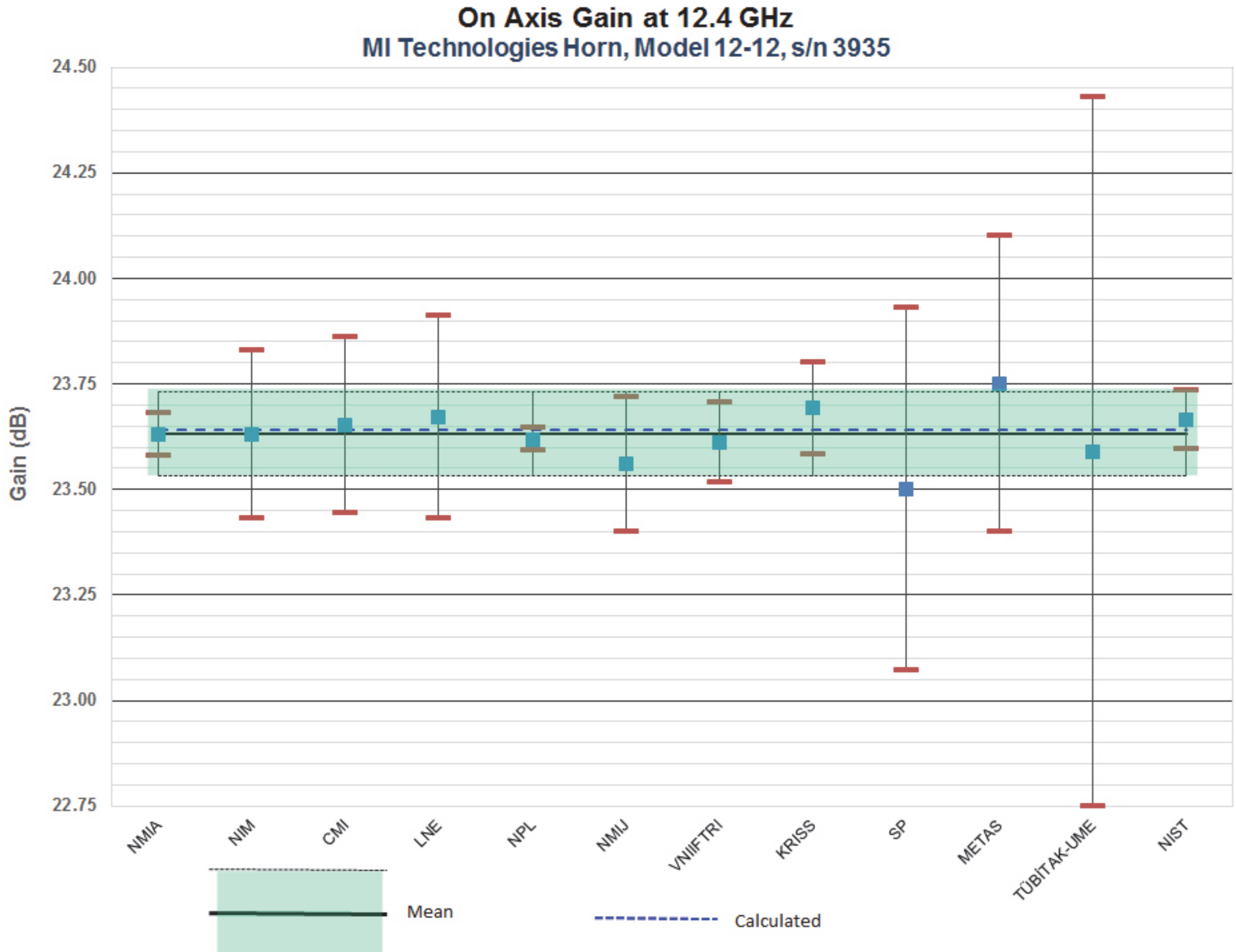

Figure 9. On axis gain measurement results at 12.4 GHz, for S/N 3935.

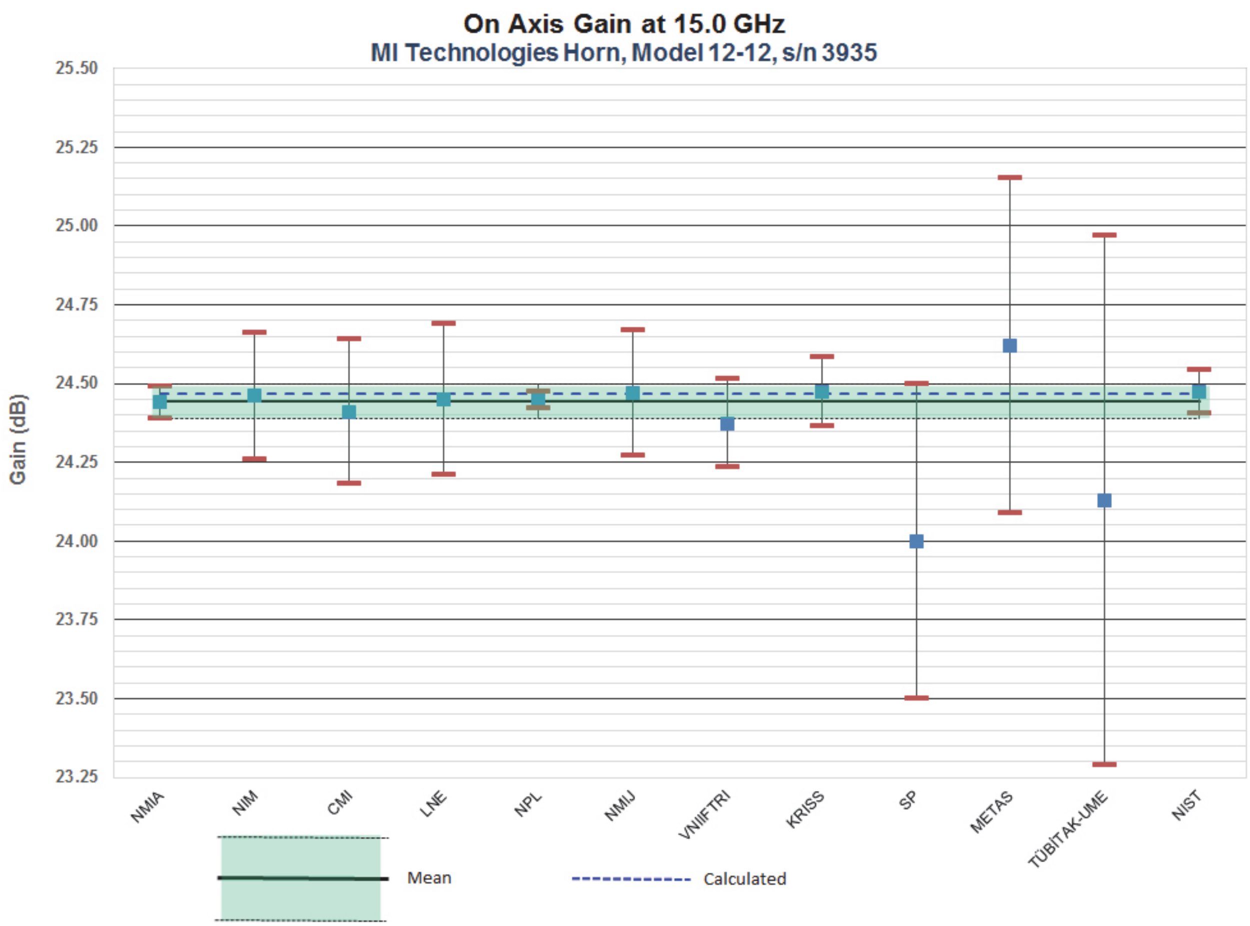

Figure 10. On axis gain measurement results at 15.0 GHz, for S/N 3935.

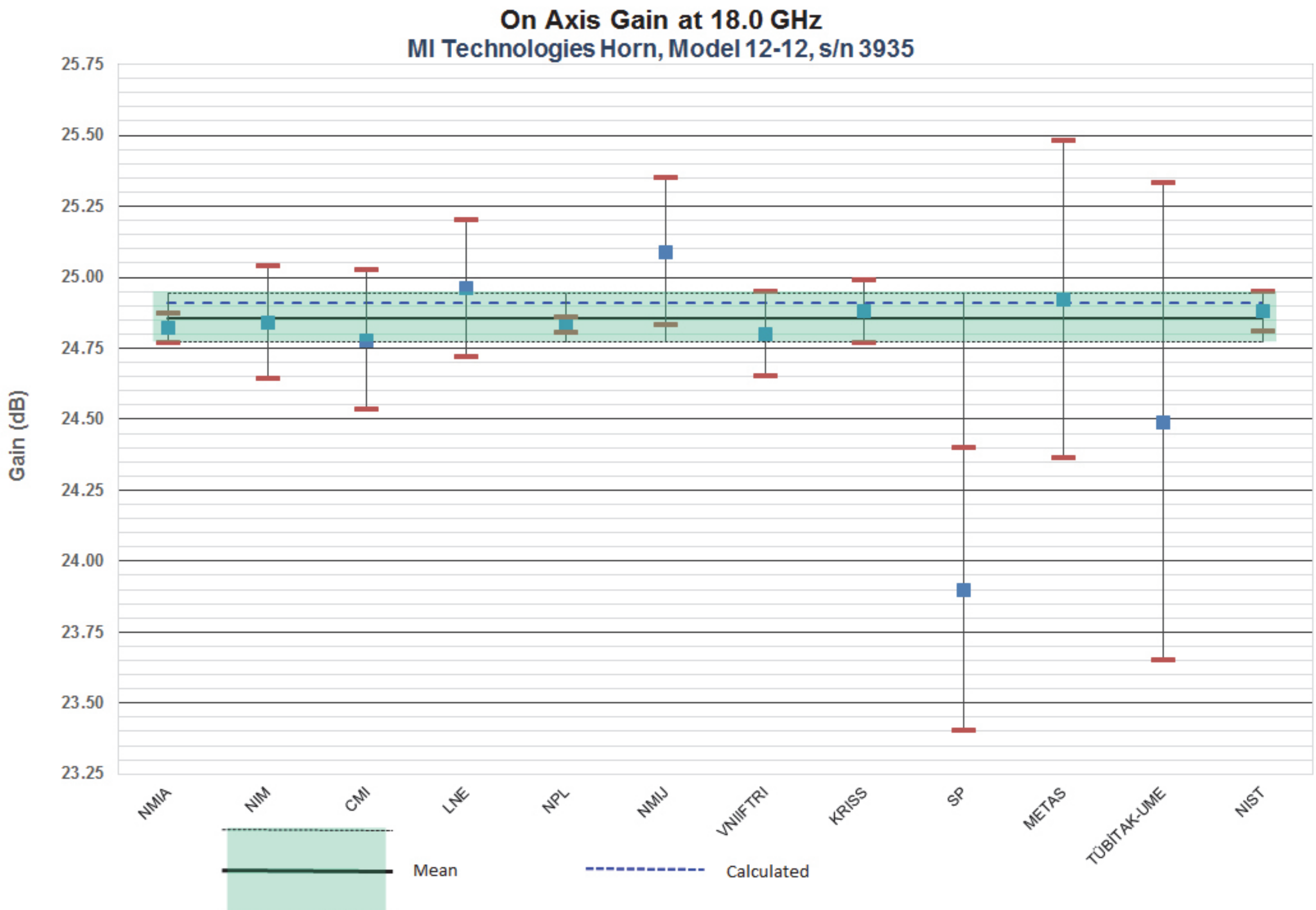

Figure 11. On axis gain measurement results at 18.0 GHz, for S/N 3935.

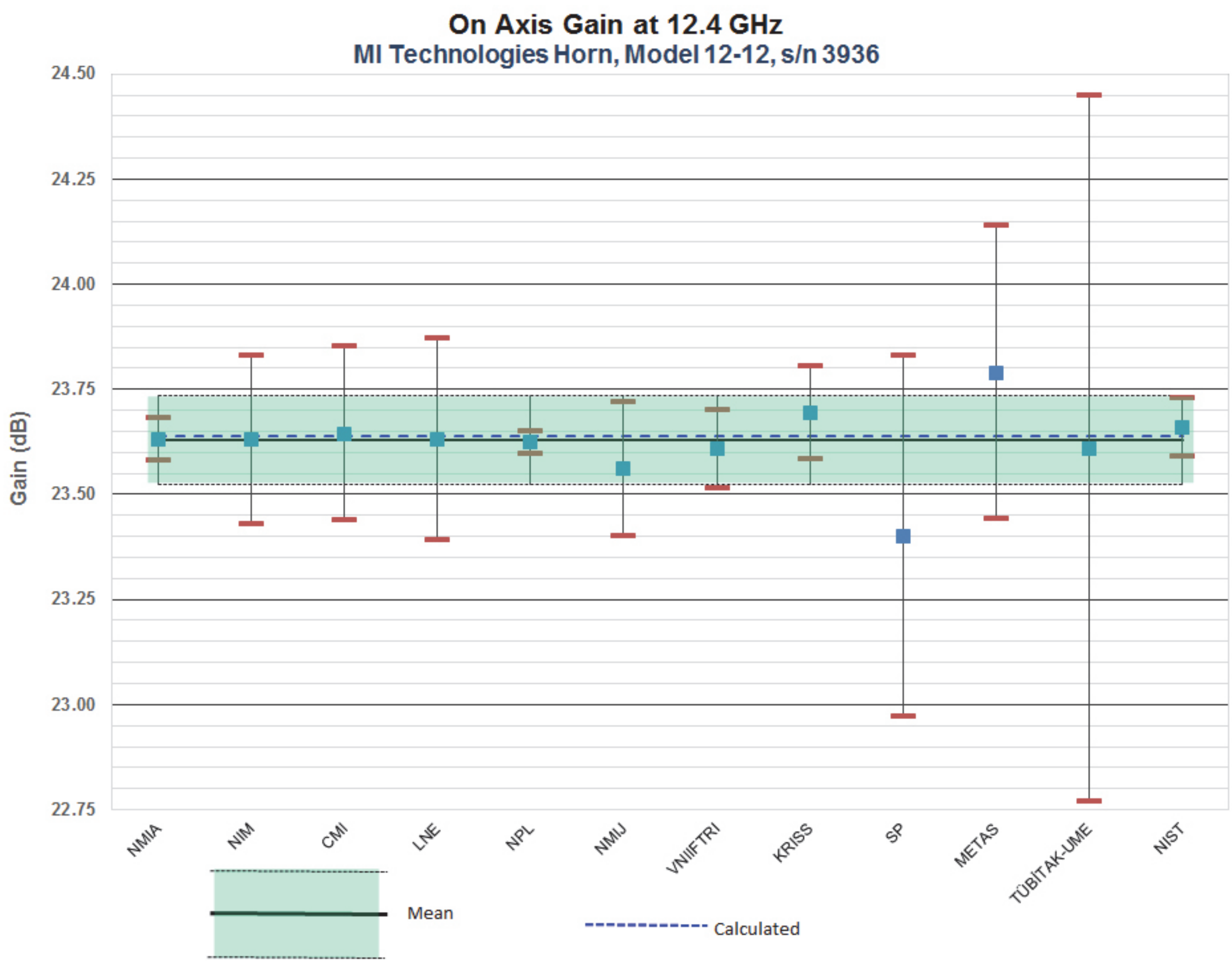

Figure 12. On axis gain measurement results at 12.4 GHz, for S/N 3936.

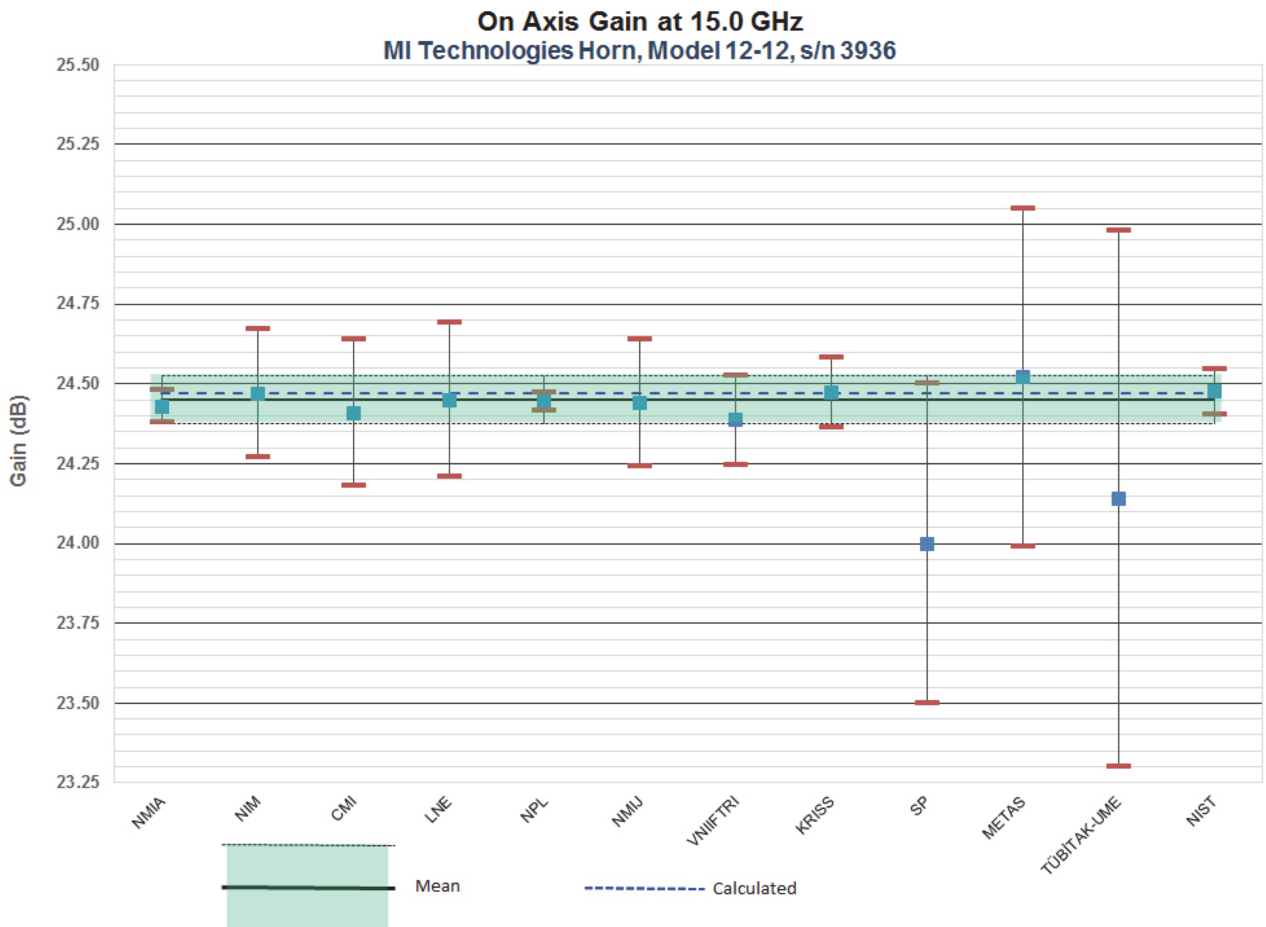

Figure 13. On axis gain measurement results at 15.0 GHz, for S/N 3936.

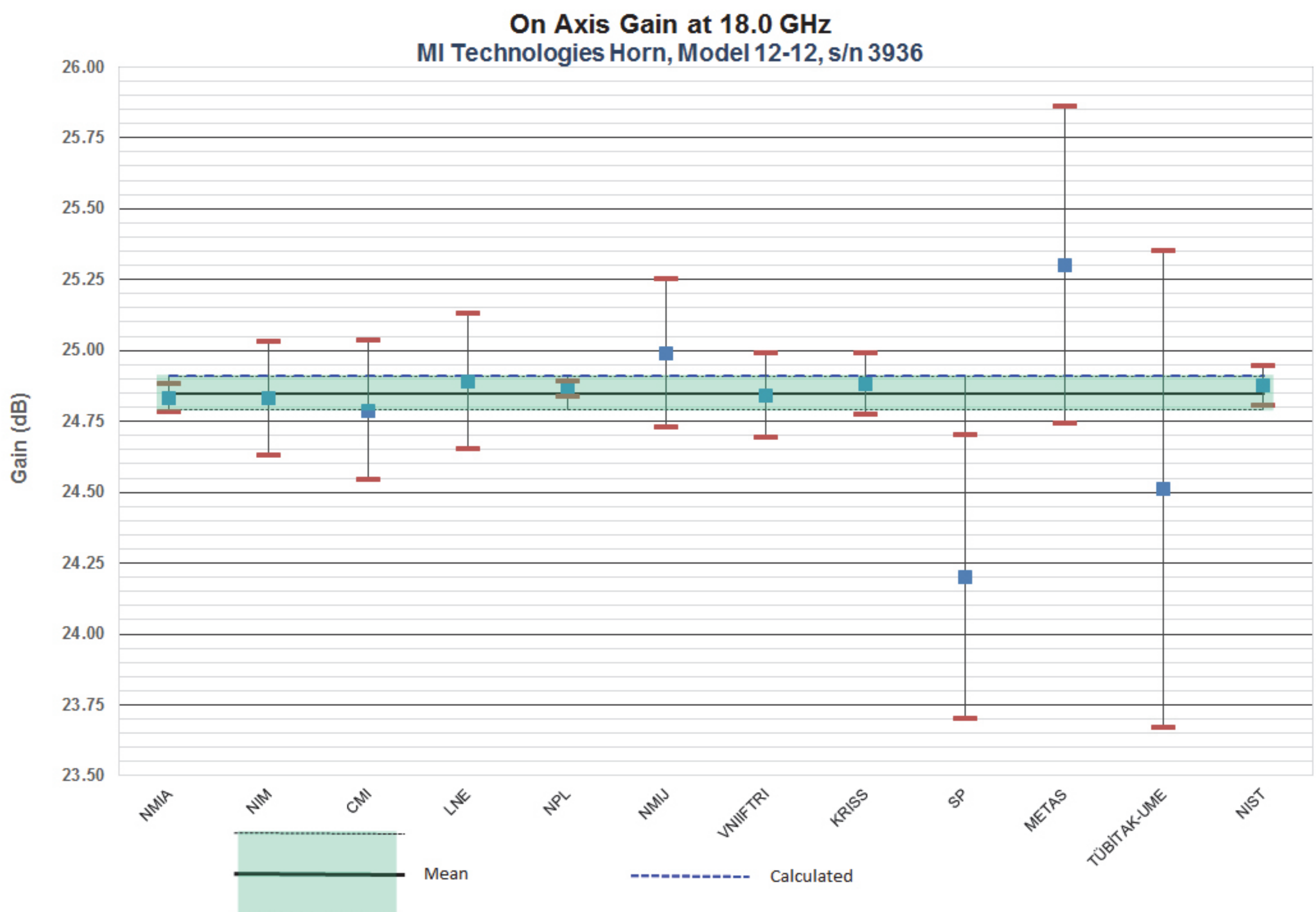

Figure 14. On axis gain measurement results at 18.0 GHz, for S/N 3936.

Reflection Coefficients

The reflection coefficient measurements were made at the waveguide port of the antennas. Reflection coefficients measurements were submitted by the participating countries NMIs, except for Sweden, Switzerland and Turkey. The reported uncertainties are based on a standard uncertainty coverage factor of k=2. As the pilot lab, NIST performed the measurements at the beginning and end of the measurement campaign. The two NIST measurements were averaged and entered as one measurement for the key comparison.

The determination and handling of outliers was performed and the non-weighted mean values and uncertainties were calculated according to [2]. Outlier does not necessarily mean bad, or wrong, or out of compliance. It just means that the point in question was not used in computing the mean. It may still be in agreement with the KCRV, depending on the uncertainties in each. For purposes of judging whether a lab's results are "good," one should refer to the degrees of equivalence, or to the plots that include uncertainties. This process is described in **Section 8**.

The NMI reported fixed frequency reflection coefficient measurement and respective uncertainties for the real and imaginary parts for S/N 3935 and S/N 3936 are listed in **Table 5** and **Table 8**, respectively. The outliers are shown in *red italic print* in the tables. The non-weighted mean values and uncertainties calculated after removing outliers are listed in **bold blue print** in the tables. These results are also shown graphically from **Figure 15** through **Figure 18**, respectively. For ease in viewing, data reported in the graphs have been plotted nominally with respect to the measurement frequency.

The results are also graphed individually for each traveling standard, at each measurement frequency from **Figure 19** through **Figure 30**. The non-weighted mean value after outlier removal is shown as the solid black line and the respective uncertainty is shown as the light blue shaded area the figures.

Table 5. Real part of reflection coefficients, and uncertainties (*k*=2), for S/N 3935.

NMI	S/N 3935					
	12.4 GHz		15.0 GHz		18.0 GHz	
	Real	Uncert.	Real	Uncert.	Real	Uncert.
NMIA	0.007	0.007	0.028	0.007	0.011	0.007
NIM	0.0067	0.0055	0.0268	0.0046	0.0132	0.0045
CMI	0.008	0.02	0.028	0.02	0.016	0.02
LNE	0.01	0.01	0.031	0.01	0.013	0.01
NPL	0.010	0.008	0.033	0.008	0.015	0.008
NMIJ	0.01	0.007	0.029	0.007	0.014	0.007
VNIIFTRI	0.009	0.006	0.028	0.006	0.011	0.008
KRISS	0.011	0.01	0.029	0.01	0.013	0.01
NIST	0.013	0.008	0.029	0.008	0.015	0.008
Non-weighted Mean Value	*0.009*	*0.003*	*0.029*	*0.003*	*0.013*	*0.003*

Note: Significant digits are as reported by the NMI.

Table 6. Imaginary part of reflection coefficients, and uncertainties (*k*=2), for S/N 3935.

NMI	S/N 3935					
	12.4 GHz		15.0 GHz		18.0 GHz	
	Imaginary	Uncert.	Imaginary	Uncert.	Imaginary	Uncert.
NMIA	-0.034	0.007	-0.009	0.007	0.006	0.007
NIM	-0.0334	0.0042	-0.015	0.0062	0.0042	0.0057
CMI	-0.036	0.02	-0.013	0.02	0.003	0.02
LNE	-0.035	0.01	-0.011	0.01	0.005	0.009/-0.003
NPL	-0.033	0.008	-0.010	0.008	0.007	0.008
NMIJ	-0.036	0.007	-0.012	0.007	0.006	0.007
VNIIFTRI	-0.035	0.006	-0.011	0.006	0.008	0.008
KRISS	-0.035	0.01	-0.01	0.01	0.006	0.01
NIST	-0.034	0.008	-0.011	0.008	0.006	0.008
Non-weighted Mean Value	*-0.035*	*0.003*	*-0.011*	*0.003*	*0.006*	*0.003*

Note: Significant digits are as reported by the NMI.

Table 7. Real part of reflection coefficients, and uncertainties (*k*=2), for S/N 3936.

NMI	S/N 3936					
	12.4 GHz		15.0 GHz		18.0 GHz	
	Real	Uncert.	Real	Uncert.	Real	Uncert.
NMIA	0.013	0.007	0.038	0.007	0.016	0.007
NIM	0.0143	0.0049	0.0361	0.0054	0.0168	0.0047
CMI	0.015	0.02	0.039	0.02	0.021	0.02
LNE	*0.003*	*0.009/-0.003*	0.036	0.01	0.02	0.01
NPL	0.016	0.008	*0.044*	*0.008*	0.019	0.008
NMIJ	0.016	0.007	0.04	0.007	0.018	0.007
VNIIFTRI	0.014	0.006	0.037	0.006	0.015	0.008
KRISS	0.017	0.01	0.04	0.01	0.018	0.01
NIST	0.018	0.008	0.039	0.008	0.020	0.008
Non-weighted Mean Value	***0.015***	***0.004***	***0.038***	***0.004***	***0.018***	***0.003***

Note: Significant digits are as reported by the NMI.

Table 8. Imaginary part of reflection coefficients, and uncertainties (*k*=2), for S/N 3936.

NMI	S/N 3936					
	12.4 GHz		15.0 GHz		18.0 GHz	
	Imaginary	Uncert.	Imaginary	Uncert.	Imaginary	Uncert.
NMIA	-0.032	0.007	-0.004	0.007	0.01	0.007
NIM	*-0.0276*	*0.0046*	-0.0056	0.0056	0.0107	0.0058
CMI	-0.032	0.02	-0.003	0.02	*0.006*	*0.02*
LNE	-0.032	0.01	-0.002	0.009/-0.003	0.009	0.009/-0.003
NPL	-0.031	0.008	-0.003	0.008	0.011	0.008
NMIJ	-0.032	0.007	-0.004	0.007	0.011	0.007
VNIIFTRI	-0.032	0.006	-0.004	0.006	0.013	0.008
KRISS	-0.031	0.01	-0.004	0.01	0.011	0.01
NIST	-0.031	0.008	-0.003	0.008	0.010	0.008
Non-weighted Mean Value	***-0.032***	***0.004***	***-0.004***	***0.003***	***0.011***	***0.003***

Note: Significant digits are as reported by the NMI.

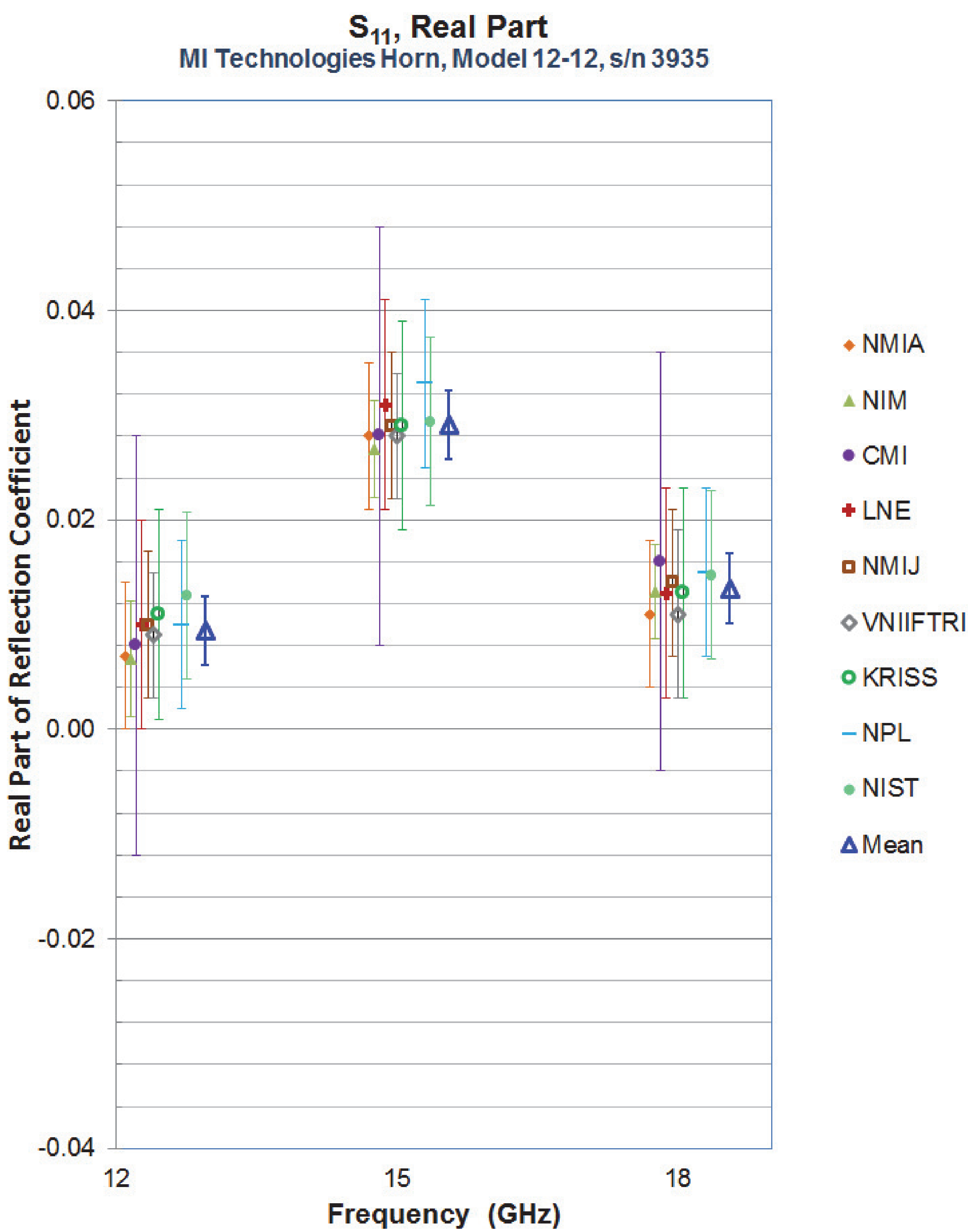

Figure 15. Real part of the measured reflection coefficients for S/N 3935.

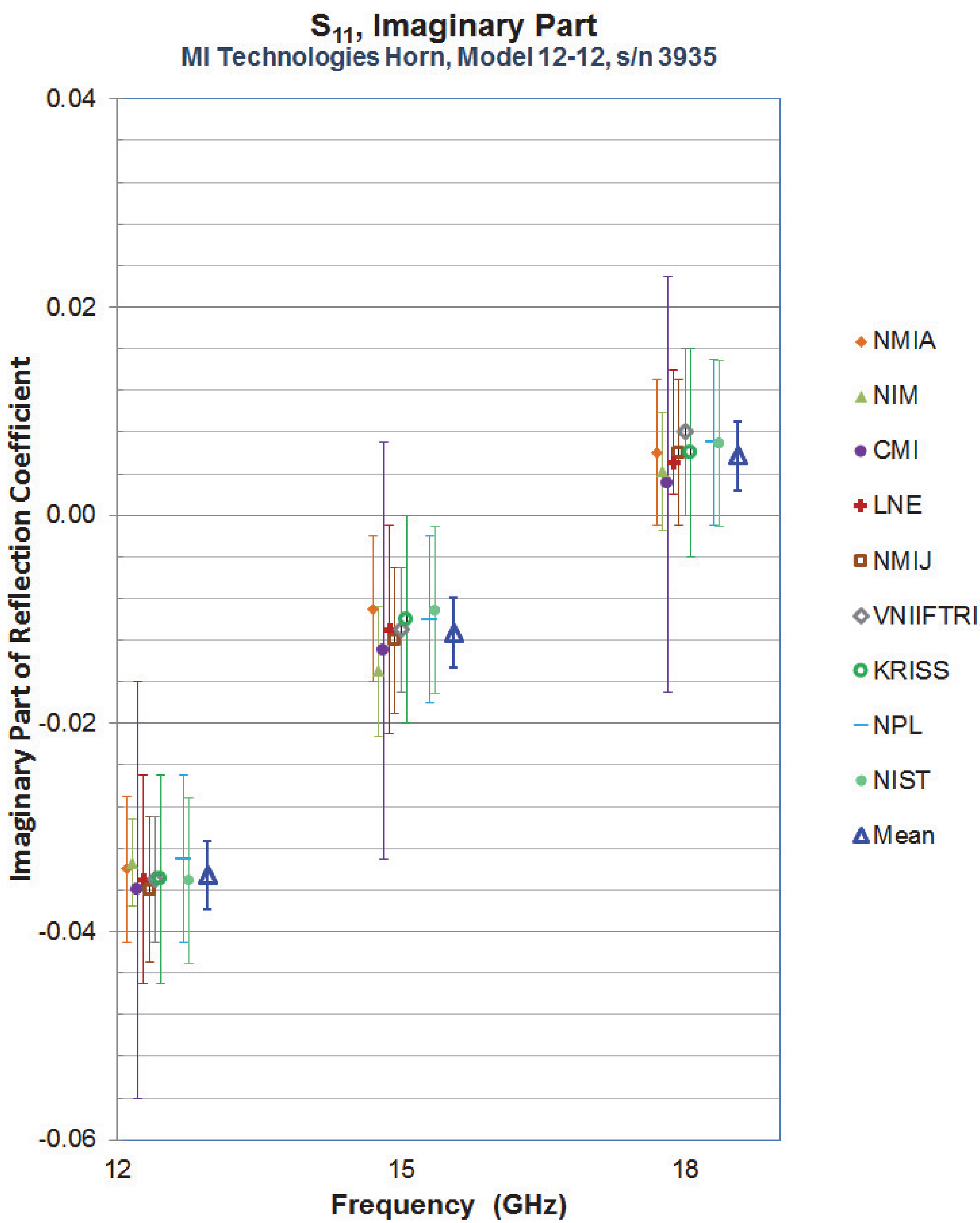

Figure 16. Imaginary part of the measured reflection coefficients for S/N 3935.

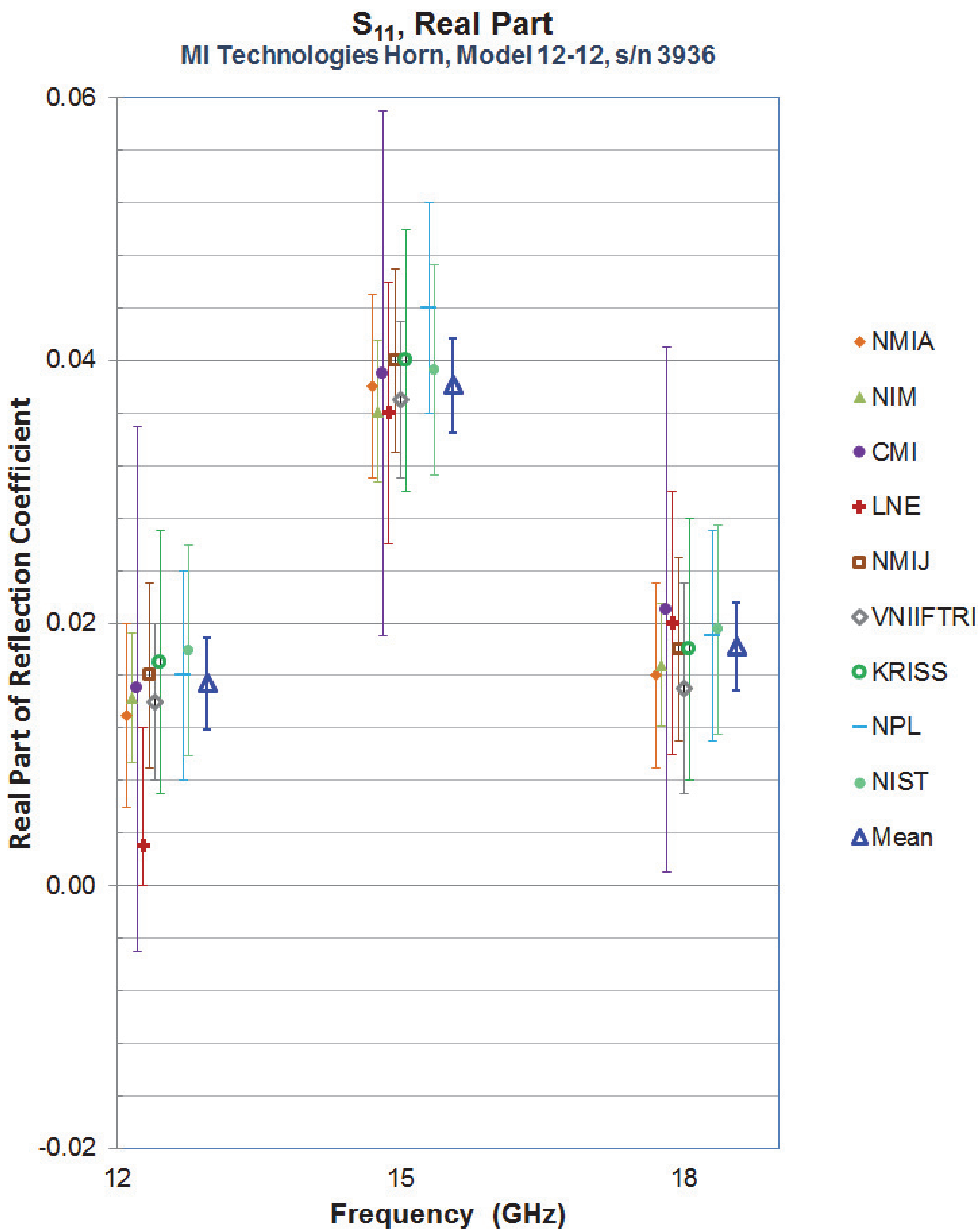

Figure 17. Real part of the measured reflection coefficients for S/N 3936.

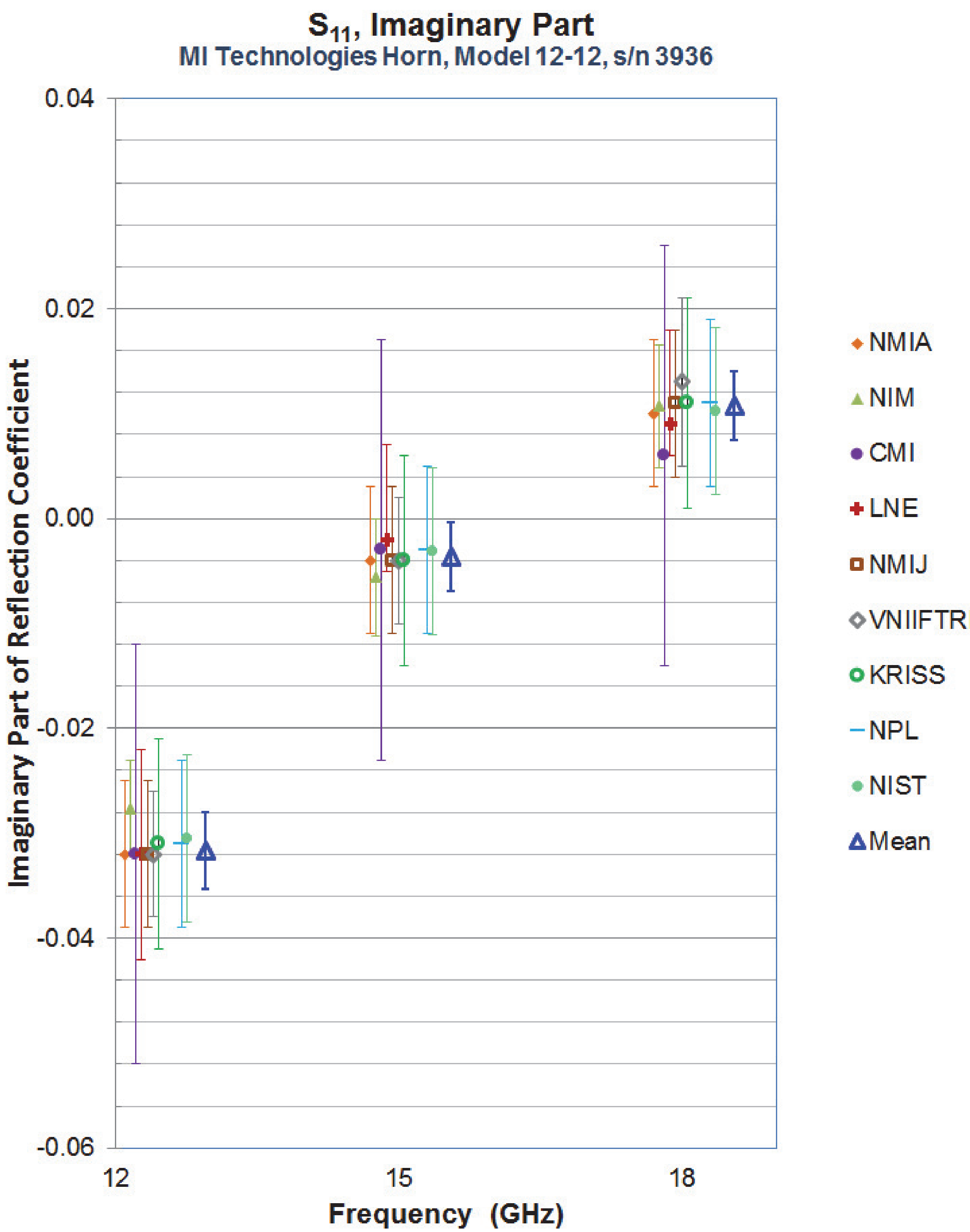

Figure 18. Imaginary part of the measured reflection coefficients for S/N 3936.

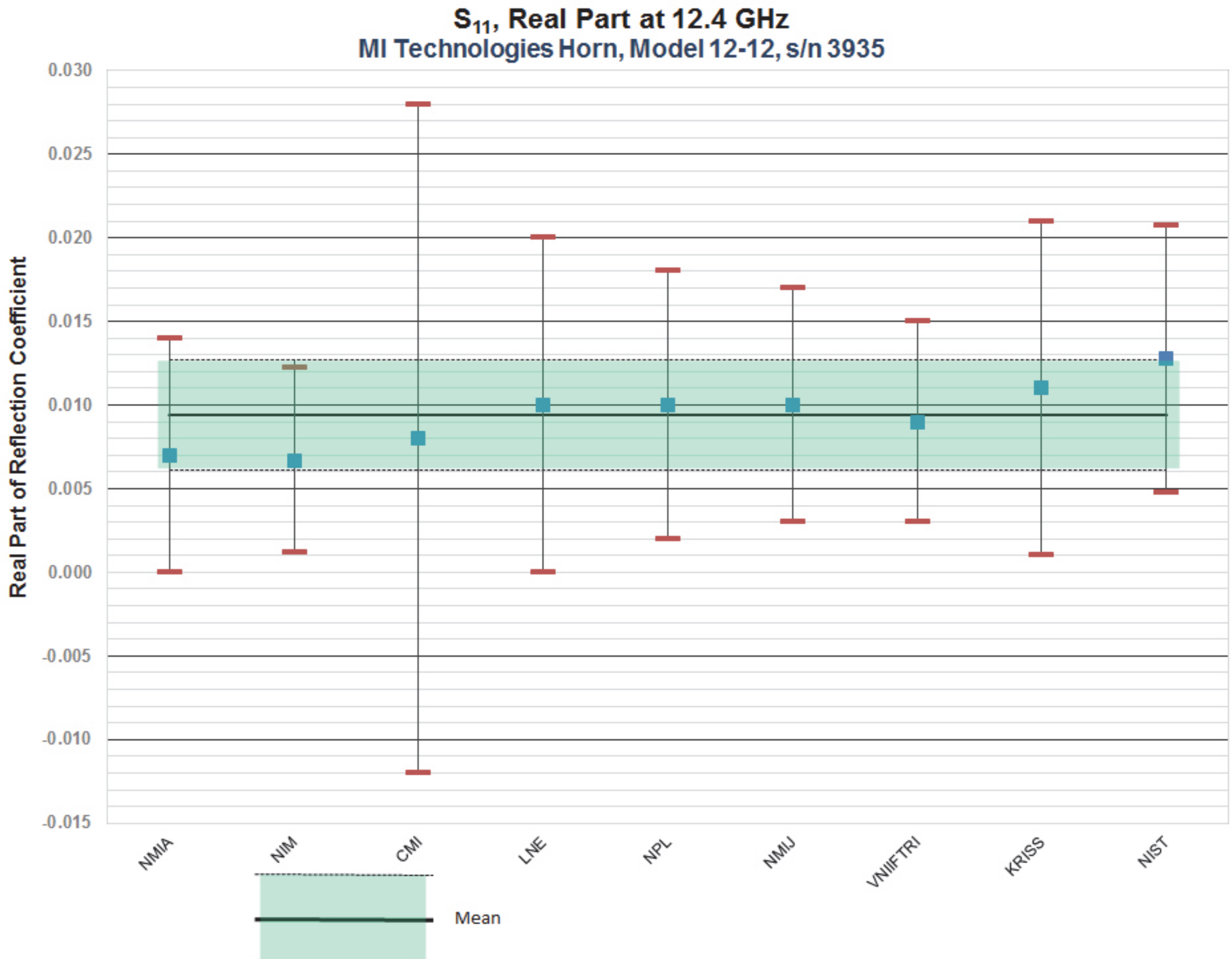

Figure 19. Real part of the measured reflection coefficient at 12.4 GHz, for S/N 3935.

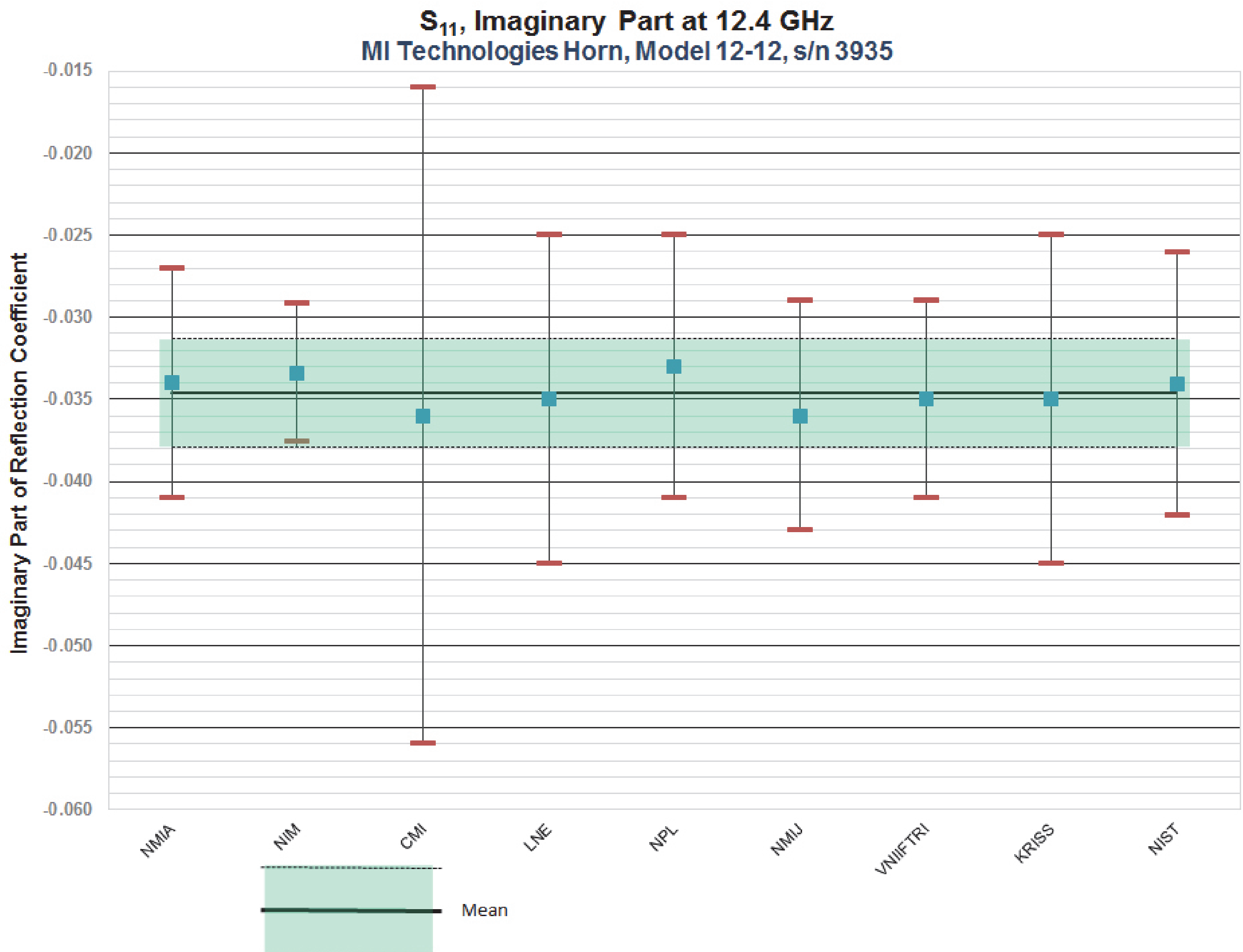

Figure 20. Imaginary part of the measured reflection coefficient at 12.4 GHz, for S/N 3935.

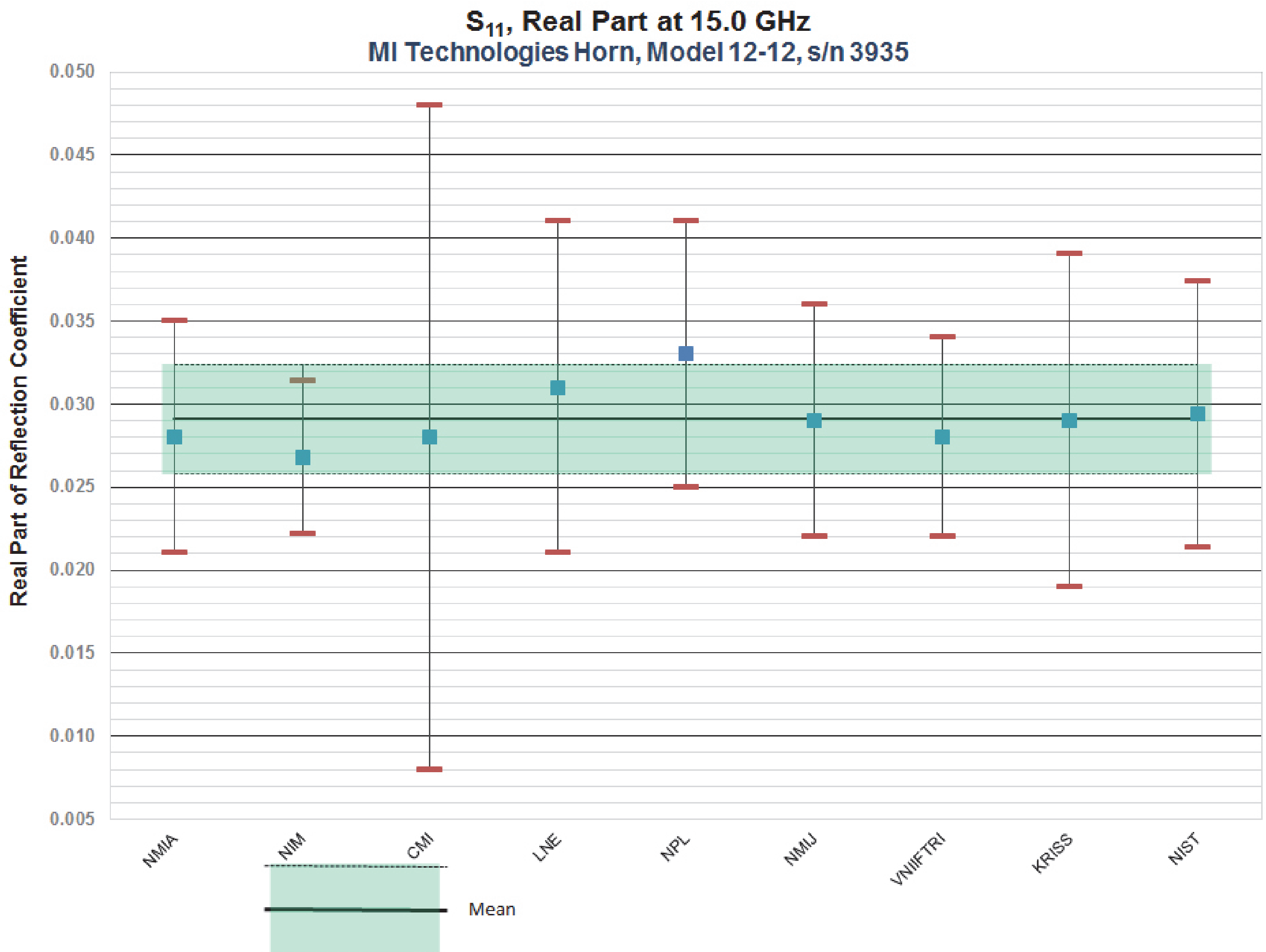

Figure 21. Real part of the measured reflection coefficient at 15.0 GHz, for S/N 3935.

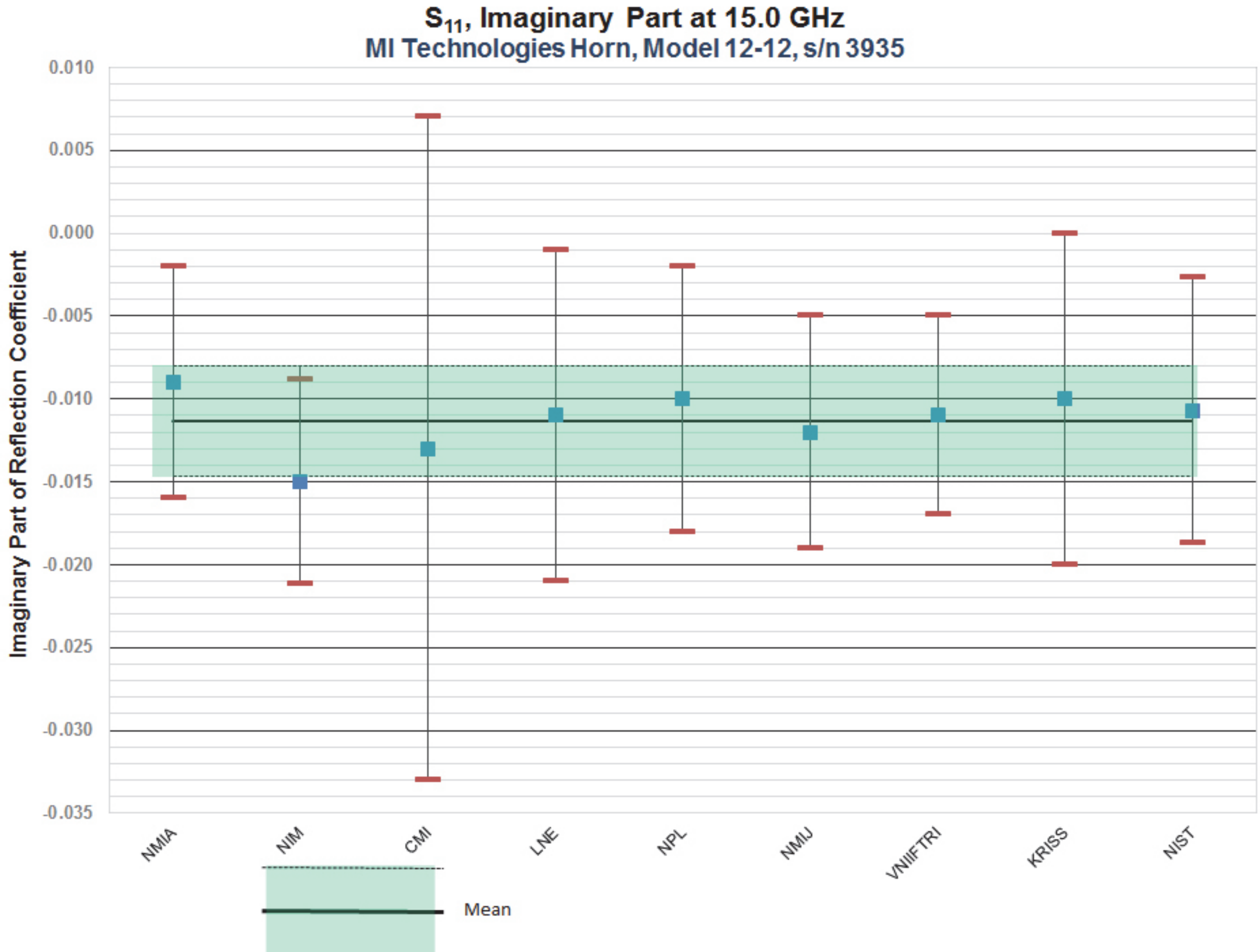

Figure 22. Imaginary part of the measured reflection coefficient at 15.0 GHz, for S/N 3935.

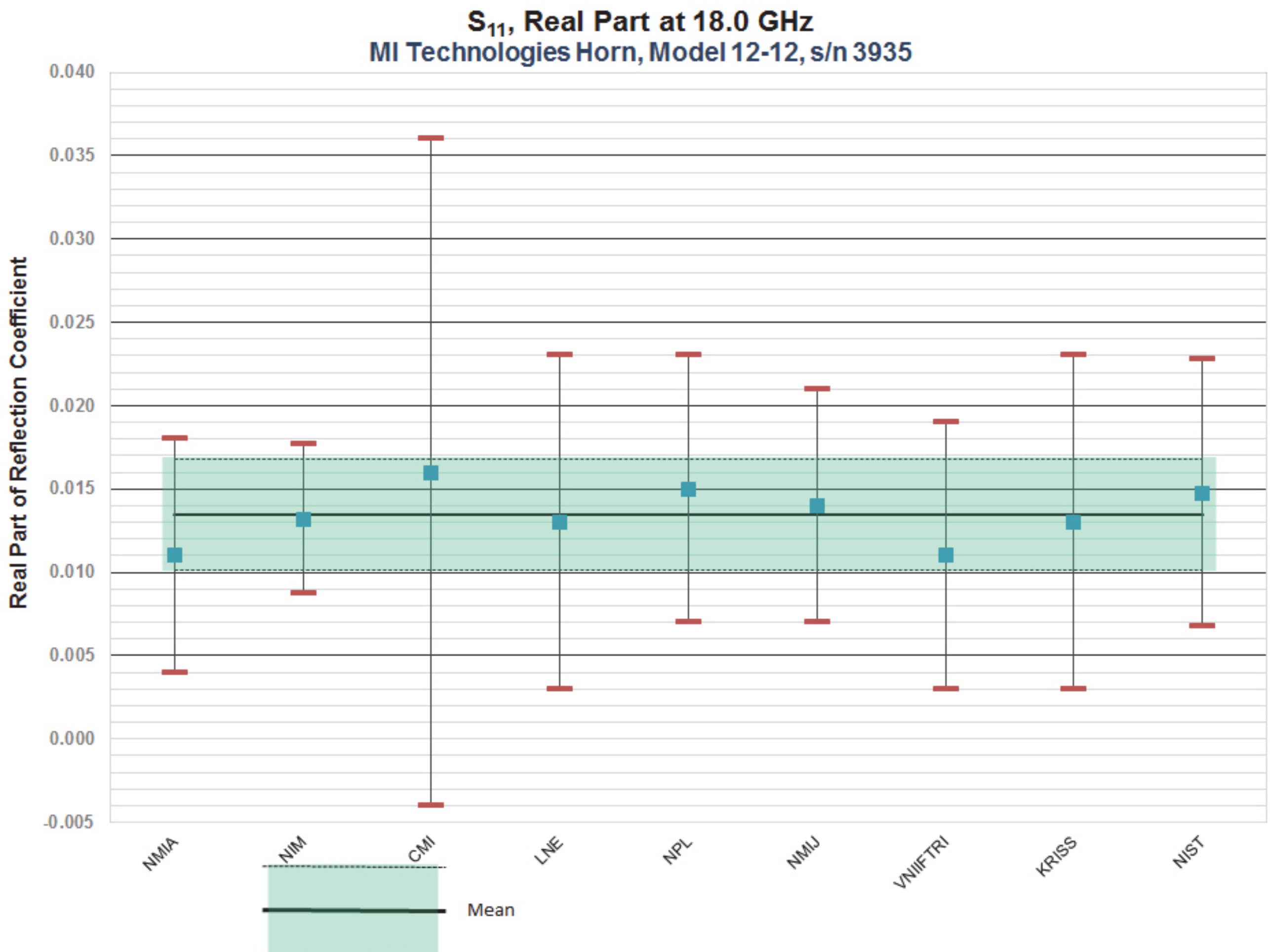

Figure 23. Real part of the measured reflection coefficient at 18.0 GHz, for S/N 3935.

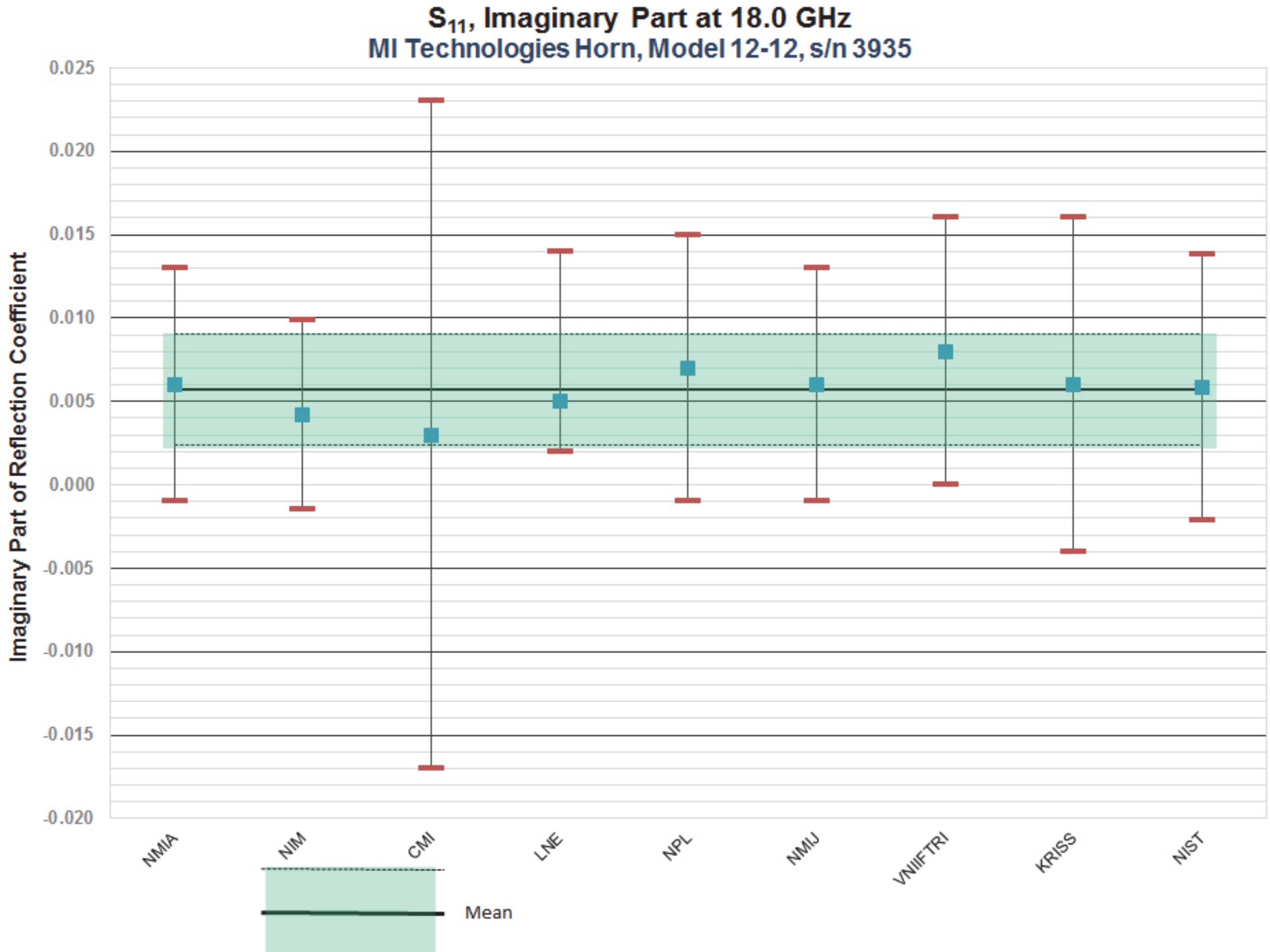

Figure 24. Imaginary part of the measured reflection coefficient at 18.0 GHz, for S/N 3935.

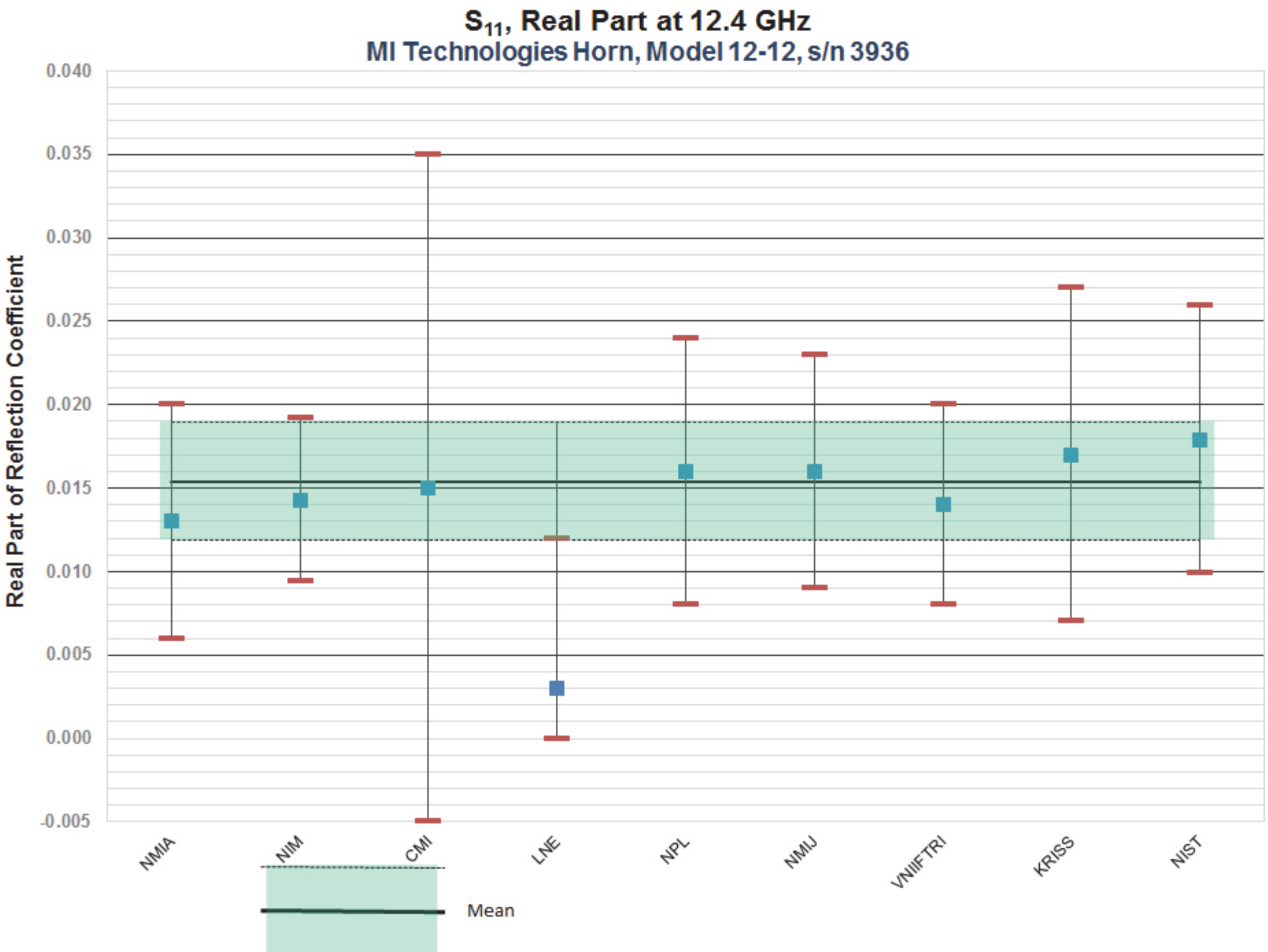

Figure 25. Real part of the measured reflection coefficient at 12.4 GHz, for S/N 3936.

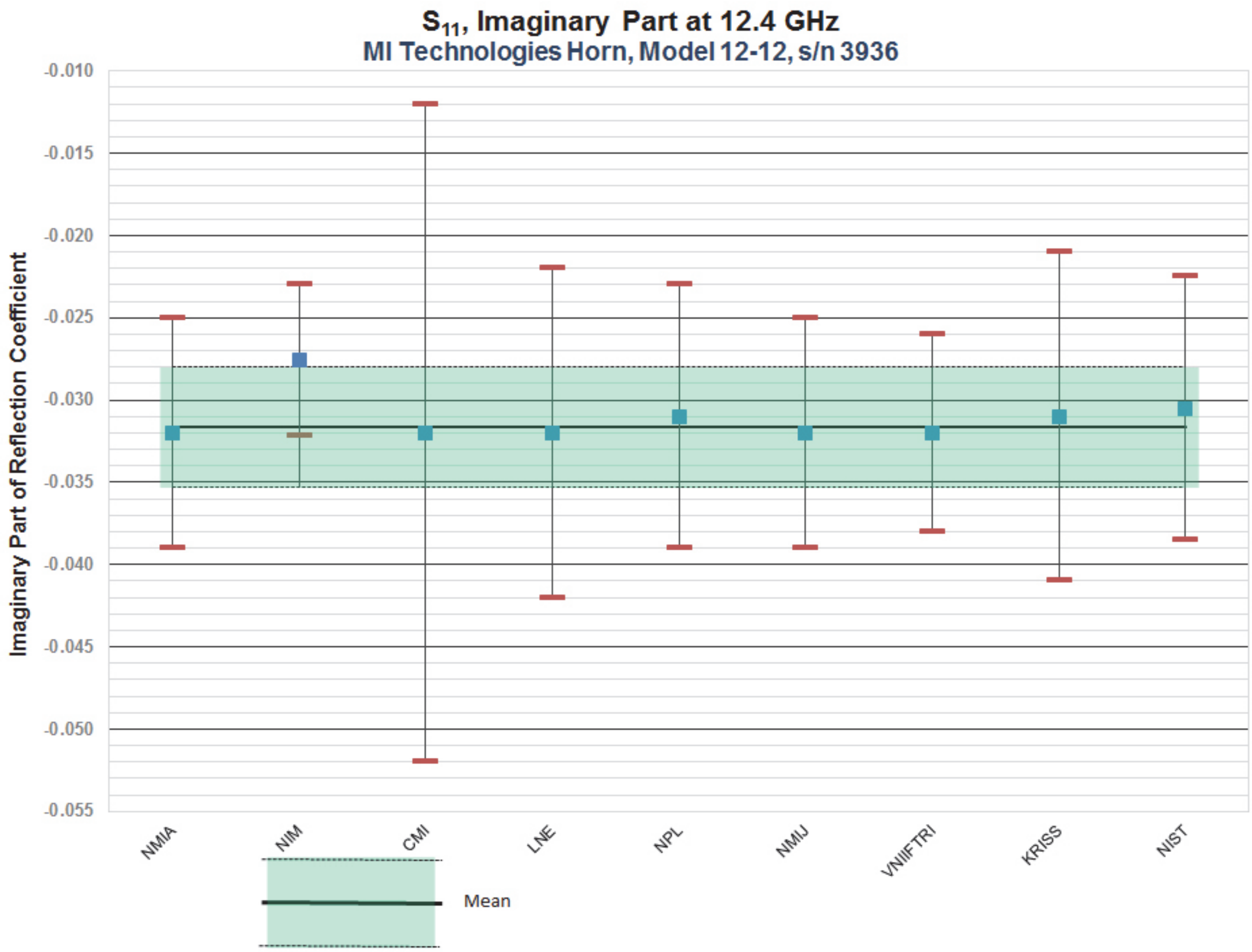

Figure 26. Imaginary part of the measured reflection coefficient at 12.4 GHz, for S/N 3936.

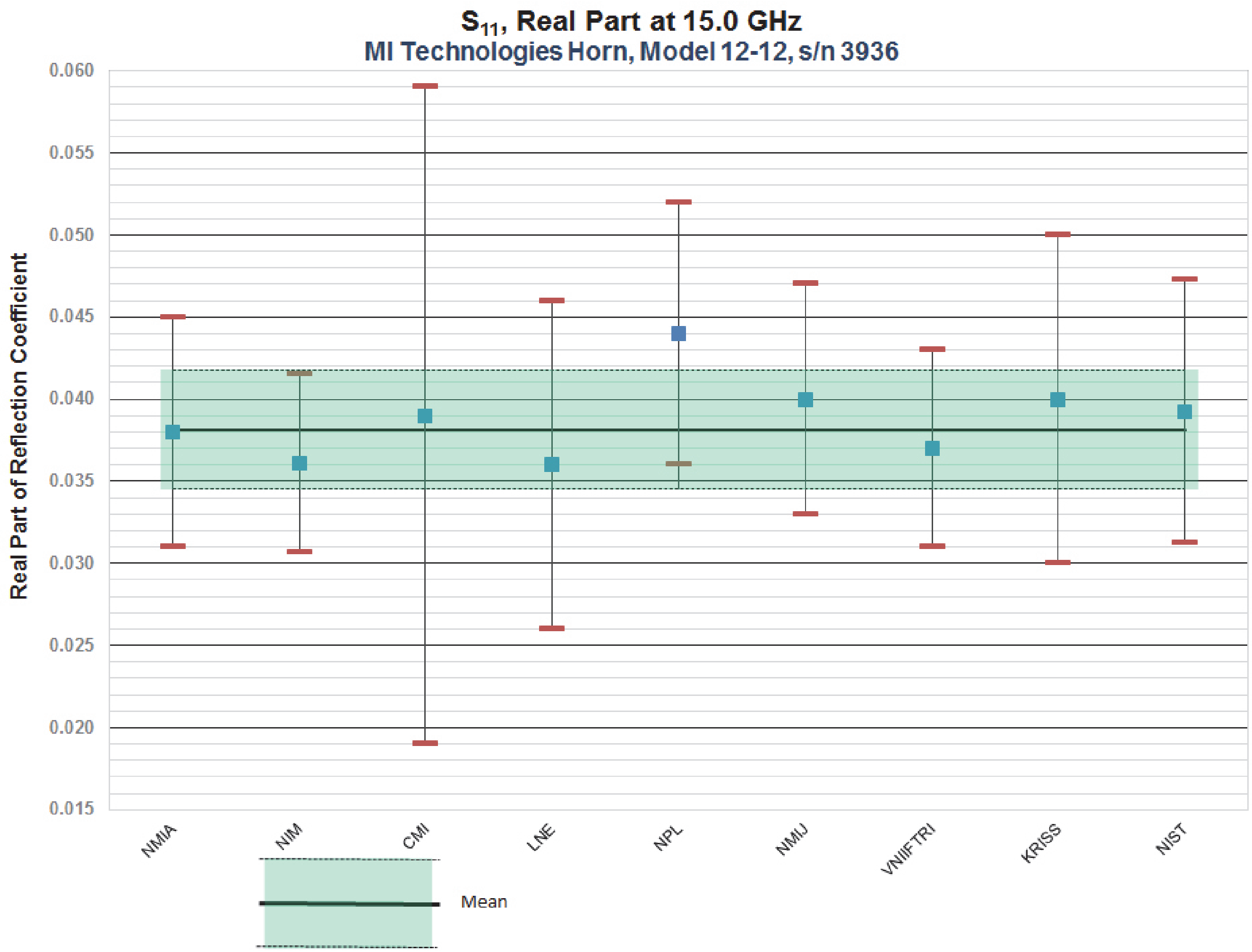

Figure 27. Real part of the measured reflection coefficient at 15.0 GHz, for S/N 3936.

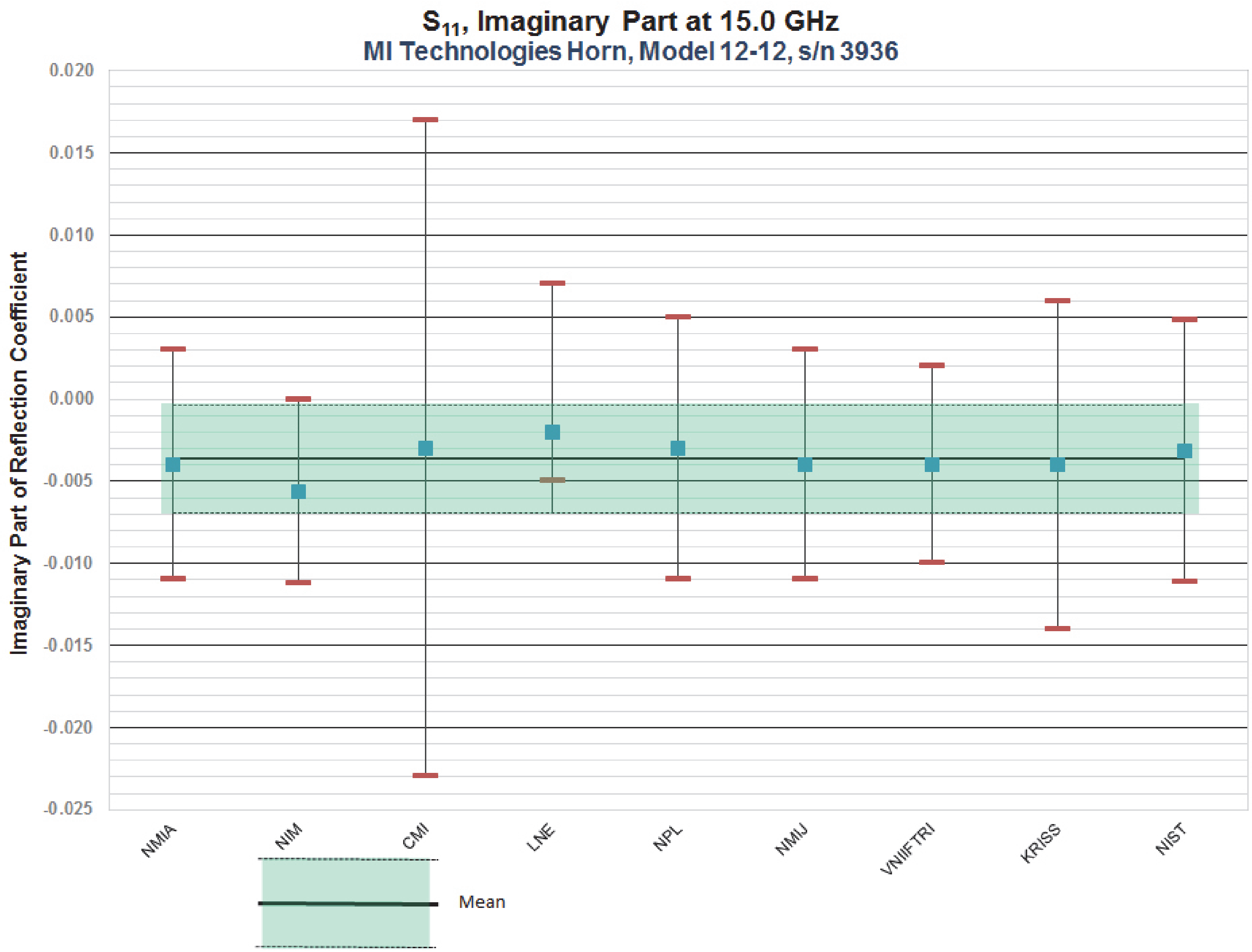

Figure 28. Imaginary part of the measured reflection coefficient at 15.0 GHz, for S/N 3936.

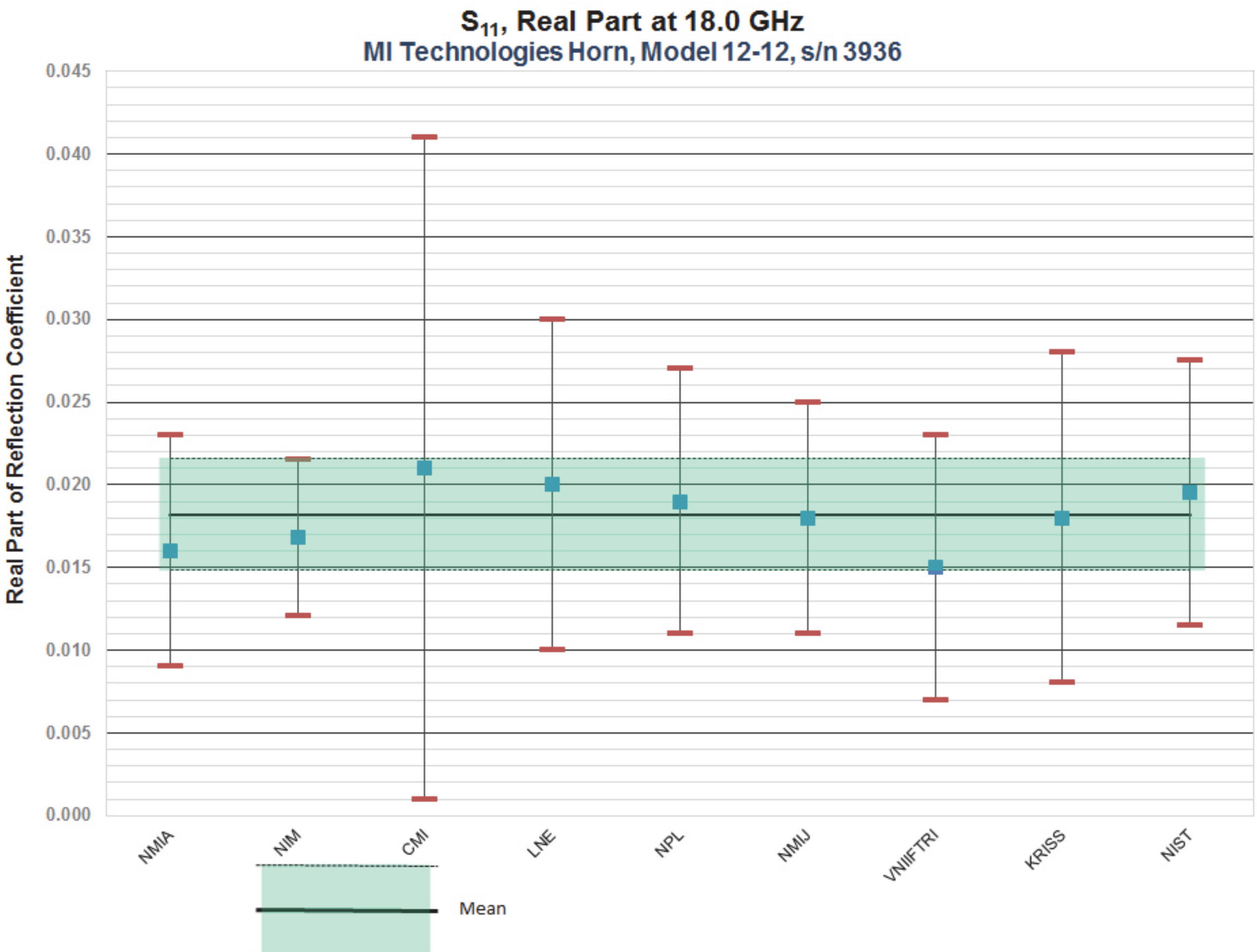

Figure 29. Real part of the measured reflection coefficient at 18.0 GHz, for S/N 3936.

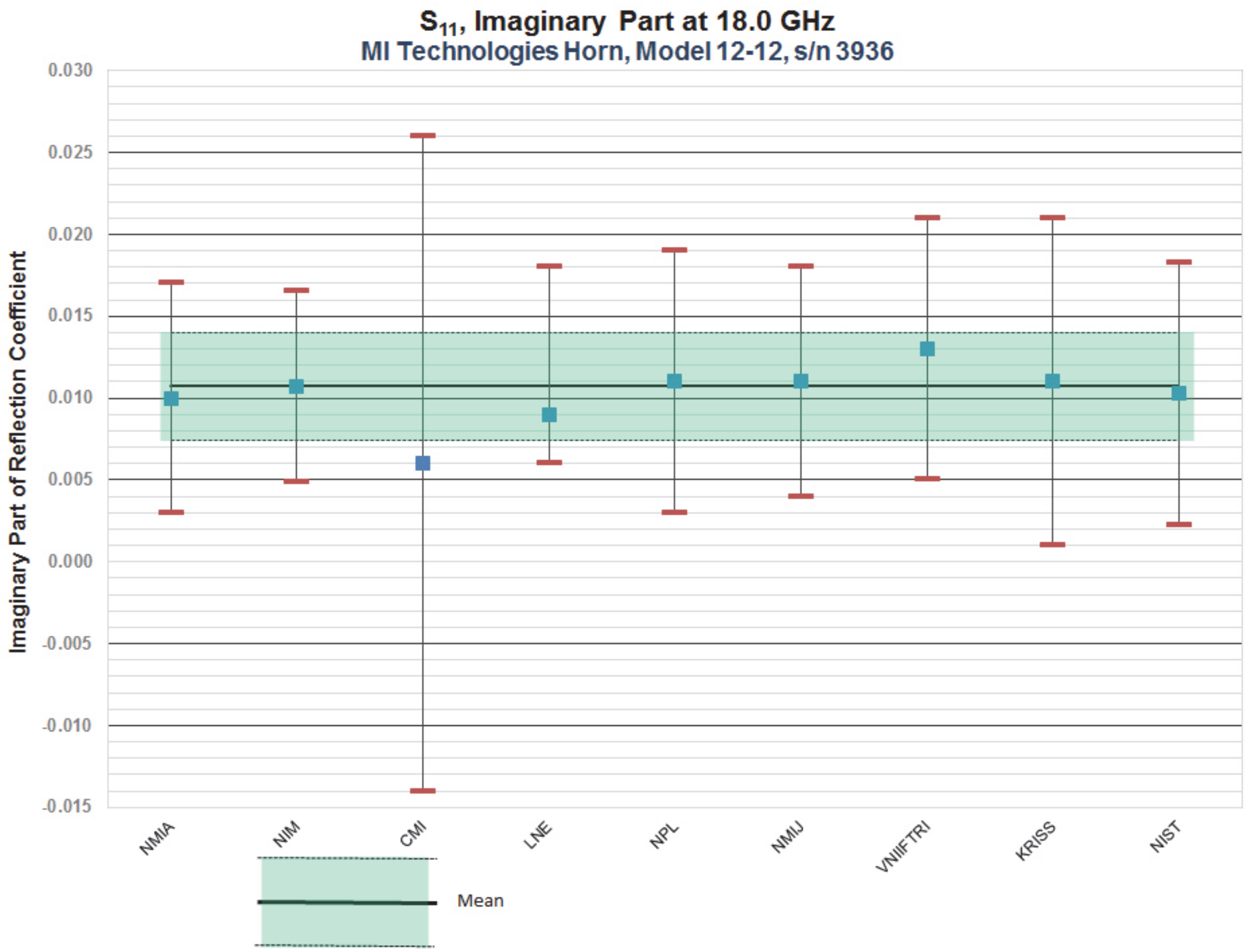

Figure 30. Imaginary part of the measured reflection coefficient at 18.0 GHz, for S/N 3936.

Stepped Frequency Gain

Stepped frequency gain measurements were submitted by the NMIs, from Australia, Sweden, Switzerland, United Kingdom and United States. The two NIST measurements were averaged and entered as one measurement for the comparison. The NMI stepped frequency measurement results for S/N 3935 and S/N 3936 are displayed graphically in **Figure 31** and **Figure 32**.

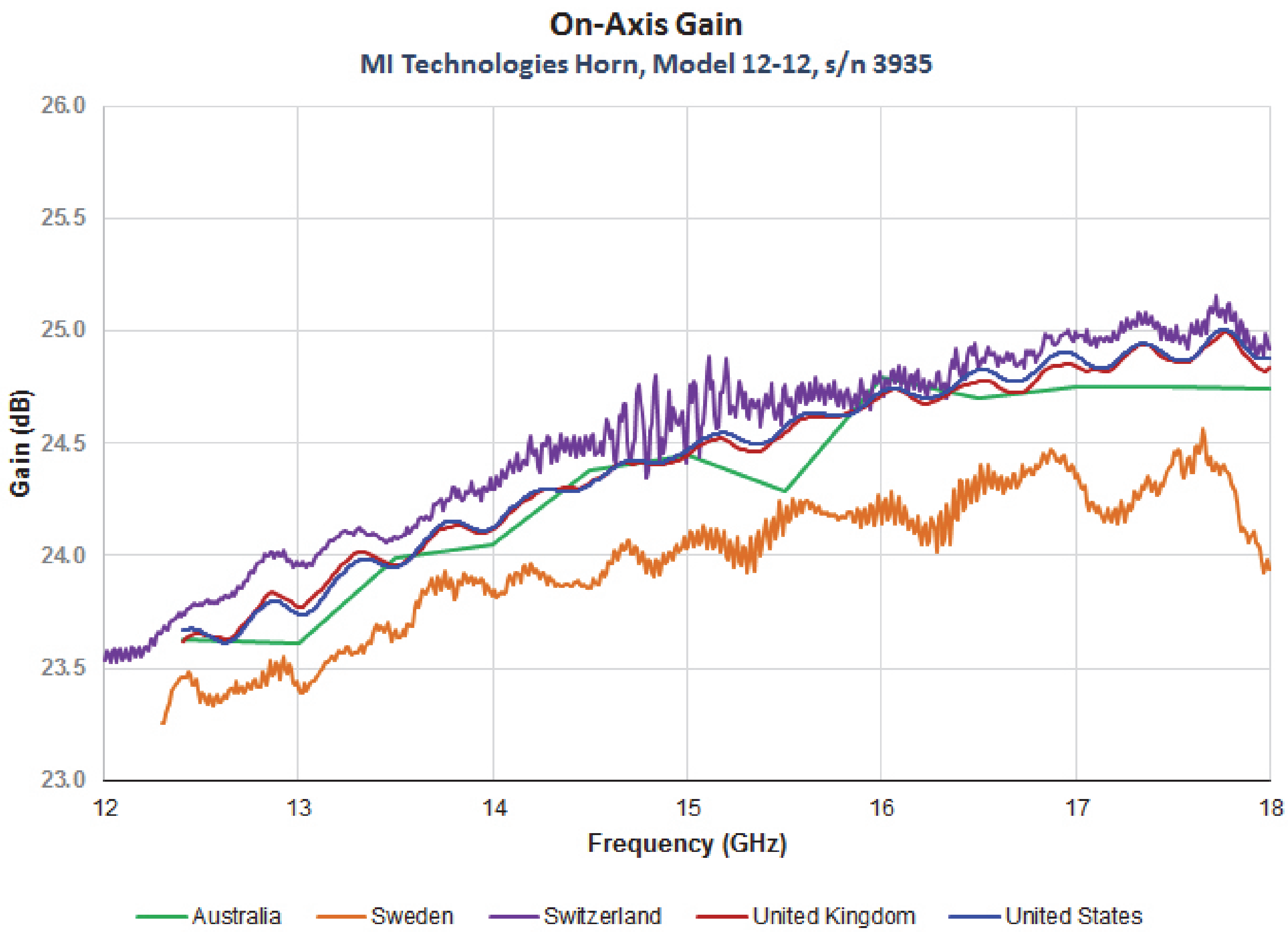

Figure 31. Stepped Frequency on axis gain measurement results for S/N 3935.

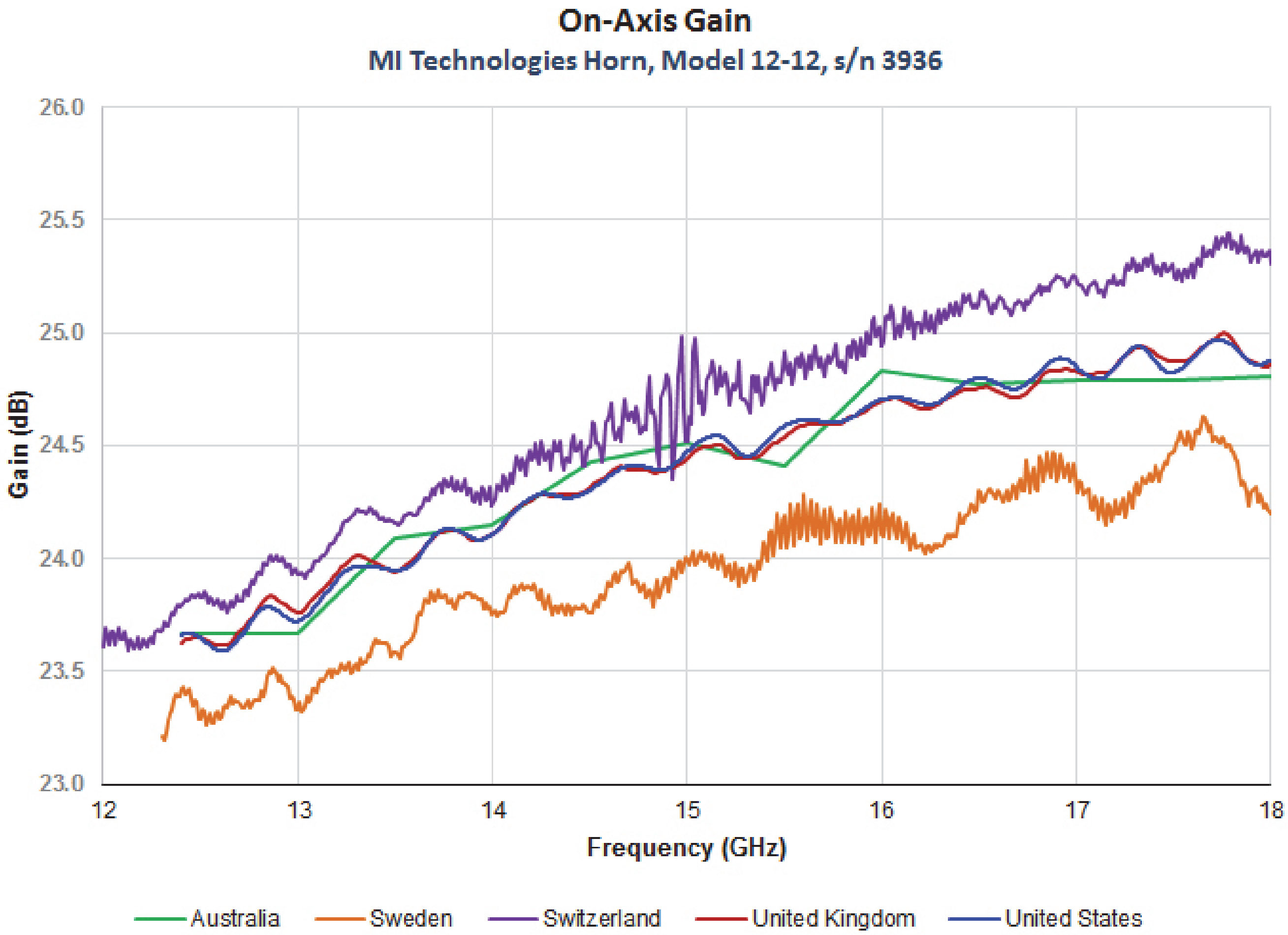

Figure 32. Stepped Frequency on axis gain measurement results for S/N 3936.

8. Mean Values and Key Comparison Reference Values

The BIPM Key Comparison, **CCEM.RF-K23.F**, Comparison Protocol required the Key Comparison Reference Value (KCRV) be reported for the BIPM database at the three mandatory frequencies and a non-weighted mean. Treatment of outlier measurement values were determined in accordance with "Proposal for KCRV & Degree of Equivalence for GTRF Key Intercomparisons" GT_RF/2000-12 [2]. Outlier does not necessarily mean bad, or wrong, or out of compliance. It just means that the point in question was not used in computing the mean. It may still be in agreement with the KCRV, depending on the uncertainties in each. For purposes of judging whether a lab's results are "good," one should refer to the degrees of equivalence, or to the plots that include uncertainties.

To test for the presence of outliers, we estimated the standard deviation σ of the underlying distribution. The most common such estimate is just the standard deviation of the sample. However, the sample standard deviation is itself quite sensitive to outliers, so a more robust estimate [9] was obtained by using the Median of Absolute Deviations (*MAD*), defined by

$$\sigma \approx S(MAD) \equiv 1.596 median_j\{|Y_i - Y_{med}|\}.$$

Where, Y_{med} is the median of the sample $\{Y_i\}$, and the factor of 1.596 is a normalization factor that produces the correct estimate of σ for Gaussian error distributions (i.e., in the absence of outliers)[10]. A value of Y_i which differs from the median by more than 2.5 times *S(MAD)* is commonly considered an outlier [11], so we use this criterion to test each point.

If

$$|Y_i - Y_{med}| > 2.5 \times S(MAD),$$

The sample Y_i was identified as an outlier.

<u>Key Comparison Reference Value and Uncertainty Calculation</u>

The non-weighted mean, *KCRV*, was defined as

$$KCVR = \frac{1}{N}\sum_{j=1}^{N} Y_j ,$$

where Y_j were the remaining samples and *N* is the number of remaining samples after removing the outliers.

The *KCRV* uncertainty, *u(y)* was defined as

$$u(y) = \sqrt{\frac{1}{N^2}\sum_{j=1}^{N} u^2(y_j)} ,$$

where $u^2(y_j)$were the uncertainties of the remaining samples and N is the number of remaining samples after removing the outliers.

Degree of Equivalence Calculation

The Mutual Recognition Arrangement (MRA) defines the degree of equivalence to be the "deviation from the key comparison reference value and the uncertainty of this deviation (at a 95% level of confidence)" [12].

The deviation Δ_i for laboratory i is,

$$\Delta_i = KCRV - Y_i \, .$$

If Y_i is an outlier, the uncertainty in Δ_i is defined as,

$$U_{\Delta_i} = 2\sqrt{u_{Y_i}^2 + u(y)^2} \, .$$

If Yi is not an outlier the non-weighted uncertainty is defined as,

$$U_{\Delta_i} = 2\sqrt{u(y)^2 + (1 - \frac{2}{N})u_{Y_i}^2} \, .$$

Table 9 through **Table 14** list the *KCRV* and Degree of Equivalence information for the fixed frequency on-axis gain measurements for traveling standard S/N 3935 at frequencies 12.4, 15.0 and 18.0 GHz and S/N 3936 at frequencies 12.4, 15.0 and 18.0 GHz, respectively. Sub-tables; (a) defines the NMI outliers and *KCRV* calculation, (b) defines the uncertainty *u(y),* and (c) lists the Degree of Equivalence values (Δ_i , $U_{\Delta i}$) for each NMI.

Table 15 through **Table 20** list the KCRV and Degree of Equivalence information for the fixed frequency reflection coefficient measurements for traveling standard S/N 3935 at frequencies 12.4, 15.0 and 18.0 GHz and S/N 3936 at frequencies 12.4, 15.0 and 18.0 GHz, respectively. Sub-tables; (a) defines the NMI outliers and KCRV calculation, (b) defines the uncertainty *u(y),* and (c) lists the Degree of Equivalence values (Δ_i , $U_{\Delta i}$) for each NMI.

Table 9. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 On-axis Gain Measurements at 12.4 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 12.4 GHz

(a) Outliers and KCRV

NMI	(Y_i) *Gain* (dB)	(Y_i) *Gain* (linear)	Difference From Median	ok or OUTLIER
NMIA	23.63	230.67	0.00	ok
NIM	23.63	230.67	0.00	ok
CMI	23.652	231.85	1.17	ok
LNE	23.67	232.81	2.13	ok
NPL	23.619	230.09	0.58	ok
NMIJ	23.56	226.99	3.69	ok
VNIIFTRI	23.612	229.72	0.95	ok
KRISS	23.692	233.99	3.32	ok
SP	23.5	223.87	6.80	ok
METAS	23.75	237.14	6.46	ok
UME	23.59	228.56	2.11	ok
NIST	23.67	232.55	1.87	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		230.67	**1.99**	**7.96**
			KCRV (linear)	**230.74**
			KCRV (dB)	**23.63**

(b) Uncertainty

NMI	$u(y_i)$ (dB)	$u(y_i)$ (fractional)	$u^2(y_i)$
NMIA	0.05	-0.012	0.0001
NIM	0.20	-0.047	0.0022
CMI	0.208	-0.049	0.0024
LNE	0.24	-0.057	0.0032
NPL	0.027	-0.006	0.0000
NMIJ	0.16	-0.038	0.0014
VNIIFTRI	0.094	-0.022	0.0005
KRISS	0.110	-0.026	0.0007
SP	0.43	-0.104	0.0108
METAS	0.35	-0.084	0.0070
UME	0.84	-0.213	0.0455
NIST	0.07	-0.016	0.0003
		$(1/N^2)\sum u^2(y_i)$	0.0005
		$u(y)$ (fractional)	**0.023**
		$u(y)$ (dB)	**0.10**

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.00	0.22
NIM	0.00	0.44
CMI	0.02	0.46
LNE	0.04	0.52
NPL	0.01	0.21
NMIJ	0.07	0.37
VNIIFTRI	0.02	0.27
KRISS	0.06	0.29
SP	0.13	0.94
METAS	0.12	0.76
UME	0.04	2.16
NIST	0.03	0.24

Table 10. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 On-axis Gain Measurements at 15.0 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 15.0 GHz

(a) Outliers and KCRV

NMI	(Y_i) *Gain* (dB)	(Y_i) *Gain* (linear)	Difference From Median	ok or OUTLIER
NMIA	24.44	277.97	0.61	ok
NIM	24.46	279.25	0.67	ok
CMI	24.410	276.06	2.52	ok
LNE	24.45	278.61	0.03	ok
NPL	24.449	278.55	0.03	ok
NMIJ	24.47	279.90	1.32	ok
VNIIFTRI	24.374	273.78	4.80	ok
KRISS	24.474	280.16	1.58	ok
SP	24.0	251.19	27.39	OUTLIER
METAS	24.62	289.73	11.15	OUTLIER
UME	24.13	258.82	19.76	OUTLIER
NIST	24.48	280.23	1.65	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		278.58	1.61	6.44
			KCRV (linear)	278.28
			KCRV (dB)	24.44

(b) Uncertainty

NMI	$u(y_i)$ (dB)	$u(y_i)$ (fractional)	$u^2(y_i)$
NMIA	0.05	-0.012	0.0001
NIM	0.20	-0.047	0.0022
CMI	0.230	-0.054	0.0030
LNE	0.24	-0.057	0.0032
NPL	0.027	-0.006	0.0000
NMIJ	0.20	-0.047	0.0022
VNIIFTRI	0.140	-0.033	0.0011
KRISS	0.110	-0.026	0.0007
SP	0.5	-0.122	0.0149
METAS	0.53	-0.130	0.0168
UME	0.84	-0.213	0.0455
NIST	0.07	-0.016	0.0003
		$(1 / N^2) \sum u^2(y_i)$	0.0002
		$u(y)$ (fractional)	0.013
		$u(y)$ (dB)	0.05

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.00	0.14
NIM	0.02	0.39
CMI	0.03	0.45
LNE	0.01	0.47
NPL	0.00	0.12
NMIJ	0.03	0.39
VNIIFTRI	0.07	0.28
KRISS	0.03	0.23
SP	0.44	1.22
METAS	0.18	1.31
UME	0.31	2.42
NIST	0.03	0.17

Table 11. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 On-axis Gain Measurements at 18.0 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 18.0 GHz

(a) Outliers and KCRV

NMI	(Y_i) *Gain* (dB)	(linear)	Difference From Median	ok or OUTLIER
NMIA	24.82	303.39	1.12	ok
NIM	24.84	304.79	0.28	ok
CMI	24.779	300.54	3.97	ok
LNE	24.96	313.33	8.82	ok
NPL	24.832	304.23	0.28	ok
NMIJ	25.09	322.85	18.34	OUTLIER
VNIIFTRI	24.800	302.00	2.51	ok
KRISS	24.879	307.54	3.03	ok
SP	23.9	245.47	59.04	OUTLIER
METAS	24.92	310.46	5.95	ok
UME	24.49	281.19	23.32	OUTLIER
NIST	24.88	307.64	3.13	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		304.51	3.55	14.17
			KCRV (linear)	305.99
			KCRV (dB)	24.86

(b) Uncertainty

NMI	$u(y_i)$ (dB)	(fractional)	$u^2(y_i)$
NMIA	0.05	-0.012	0.0001
NIM	0.20	-0.047	0.0022
CMI	0.245	-0.058	0.0034
LNE	0.24	-0.057	0.0032
NPL	0.027	-0.006	0.0000
NMIJ	0.26	-0.062	0.0038
VNIIFTRI	0.150	-0.035	0.0012
KRISS	0.110	-0.026	0.0007
SP	0.5	-0.122	0.0149
METAS	0.56	-0.138	0.0189
UME	0.84	-0.213	0.0455
NIST	0.07	-0.016	0.0003
		$(1 / N^2) \sum u^2(y_i)$	0.0004
		u(y) (fractional)	0.019
		u(y) (dB)	0.08

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.04	0.19
NIM	0.02	0.42
CMI	0.08	0.50
LNE	0.10	0.49
NPL	0.03	0.18
NMIJ	0.23	0.60
VNIIFTRI	0.06	0.33
KRISS	0.02	0.27
SP	0.96	1.23
METAS	0.06	1.23
UME	0.37	2.43
NIST	0.02	0.21

Table 12. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 On-axis Gain Measurements at 12.4 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 12.4 GHz

(a) Outliers and KCRV

NMI	(Y_i) *Gain* (dB)	(linear)	Difference From Median	ok or OUTLIER
NMIA	23.63	230.67	0.00	ok
NIM	23.63	230.67	0.00	ok
CMI	23.645	231.47	0.80	ok
LNE	23.63	230.67	0.00	ok
NPL	23.624	230.36	0.32	ok
NMIJ	23.56	226.99	3.69	ok
VNIIFTRI	23.608	229.51	1.17	ok
KRISS	23.695	234.15	3.48	ok
SP	23.4	218.78	11.90	OUTLIER
METAS	23.79	239.33	8.66	OUTLIER
UME	23.61	229.61	1.06	ok
NIST	23.66	232.28	1.60	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		230.67	**1.11**	**4.44**
			KCRV (linear)	**230.64**
			KCRV (dB)	**23.63**

(b) Uncertainty

NMI	$u(y_i)$ (dB)	(fractional)	$u^2(y_i)$
NMIA	0.05	-0.012	0.0001
NIM	0.20	-0.047	0.0022
CMI	0.208	-0.049	0.0024
LNE	0.24	-0.057	0.0032
NPL	0.027	-0.006	0.0000
NMIJ	0.16	-0.038	0.0014
VNIIFTRI	0.094	-0.022	0.0005
KRISS	0.110	-0.026	0.0007
SP	0.43	-0.104	0.0108
METAS	0.35	-0.084	0.0070
UME	0.84	-0.213	0.0455
NIST	0.07	-0.016	0.0003
		$(1 / N^2) \sum u^2(y_i)$	0.0006
		$u(y)$ (fractional)	**0.024**
		$u(y)$ (dB)	**0.10**

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.00	0.23
NIM	0.00	0.44
CMI	0.02	0.46
LNE	0.00	0.52
NPL	0.01	0.22
NMIJ	0.07	0.37
VNIIFTRI	0.02	0.28
KRISS	0.07	0.30
SP	0.23	1.04
METAS	0.16	0.83
UME	0.02	2.11
NIST	0.03	0.25

Table 13. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 On-axis Gain Measurements at 15.0 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 15.0 GHz

(a) Outliers and KCRV

	(Y_i) *Gain*		Difference From	ok or
NMI	(dB)	(linear)	Median	OUTLIER
NMIA	24.43	277.33	0.77	ok
NIM	24.47	279.90	1.80	ok
CMI	24.410	276.06	2.04	ok
LNE	24.45	278.61	0.51	ok
NPL	24.444	278.23	0.13	ok
NMIJ	24.44	277.97	0.13	ok
VNIIFTRI	24.387	274.60	3.50	ok
KRISS	24.473	280.09	1.99	ok
SP	24.0	251.19	26.91	OUTLIER
METAS	24.52	283.14	5.04	ok
UME	24.14	259.42	18.68	OUTLIER
NIST	24.48	280.23	2.13	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		278.10	**2.02**	**8.05**
			KCRV (linear)	**278.62**
			KCRV (dB)	**24.45**

(b) Uncertainty

	$u(y_i)$		
NMI	(dB)	(fractional)	$u^2(y_i)$
NMIA	0.05	-0.01	0.0001
NIM	0.20	-0.05	0.0022
CMI	0.230	-0.05	0.0030
LNE	0.24	-0.06	0.0032
NPL	0.027	-0.01	0.0000
NMIJ	0.20	-0.05	0.0022
VNIIFTRI	0.140	-0.03	0.0011
KRISS	0.110	-0.03	0.0007
SP	0.5	-0.12	0.0149
METAS	0.53	-0.13	0.0168
UME	0.84	-0.21	0.0455
NIST	0.07	-0.02	0.0003
		$(1/N^2)\sum u^2(y_i)$	0.0003
		$u(y)$ (fractional)	**0.017**
		$u(y)$ (dB)	**0.08**

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.02	0.18
NIM	0.02	0.41
CMI	0.04	0.47
LNE	0.00	0.49
NPL	0.01	0.16
NMIJ	0.01	0.41
VNIIFTRI	0.06	0.31
KRISS	0.02	0.26
SP	0.45	1.23
METAS	0.07	1.16
UME	0.31	2.43
NIST	0.03	0.20

Table 14. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 On-axis Gain Measurements at 18.0 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 18.0 GHz

(a) Outliers and KCRV

NMI	(Y_i) *Gain* (dB)	(Y_i) *Gain* (linear)	Difference From Median	ok or OUTLIER
NMIA	24.83	304.09	1.51	ok
NIM	24.83	304.09	1.51	ok
CMI	24.788	301.16	4.44	ok
LNE	24.89	308.32	2.72	ok
NPL	24.863	306.41	0.81	ok
NMIJ	24.99	315.50	9.90	OUTLIER
VNIIFTRI	24.840	304.79	0.81	ok
KRISS	24.881	307.68	2.08	ok
SP	24.2	263.03	42.57	OUTLIER
METAS	25.30	338.84	33.25	OUTLIER
UME	24.51	282.49	23.11	OUTLIER
NIST	24.88	307.28	1.68	ok
		Median of Gains	Median of Differences	2.5 times S(MAD)
		305.60	2.40	9.58
			KCRV (linear)	305.48
			KCRV (dB)	24.85

(b) Uncertainty

NMI	$u(y_i)$ (dB)	$u(y_i)$ (fractional)	$u^2(y_i)$
NMIA	0.05	-0.01	0.0001
NIM	0.2	-0.05	0.0022
CMI	0.245	-0.06	0.0034
LNE	0.24	-0.06	0.0032
NPL	0.027	-0.01	0.0000
NMIJ	0.26	-0.06	0.0038
VNIIFTRI	0.15	-0.04	0.0012
KRISS	0.11	-0.03	0.0007
SP	0.5	-0.12	0.0149
METAS	0.56	-0.14	0.0189
UME	0.84	-0.21	0.0455
NIST	0.07	-0.02	0.0003
		$(1 / N^2) \sum u^2(y_i)$	0.0002
		$u(y)$ (fractional)	0.013
		$u(y)$ (dB)	0.06

(c) Degree of Equivalence

NMI	Δ_i	$U_{\Delta i}$
NMIA	0.02	0.15
NIM	0.02	0.39
CMI	0.06	0.48
LNE	0.04	0.47
NPL	0.01	0.13
NMIJ	0.14	0.59
VNIIFTRI	0.01	0.30
KRISS	0.03	0.23
SP	0.65	1.22
METAS	0.45	1.41
UME	0.34	2.42
NIST	0.03	0.17

Table 15. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 Reflection Measurements at 12.4 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 12.4 GHz

(a) Outliers and KCRV

	Real			Imaginary		
NMI	(Y_i)	Difference From Median	ok or OUTLIER	(Y_i)	Difference From Median	ok or OUTLIER
NMIA	0.007	0.0030	ok	-0.034	0.0010	ok
NIM	0.0067	0.0033	ok	-0.0334	0.0016	ok
CMI	0.008	0.0020	ok	-0.036	0.0010	ok
LNE	0.01	0.0000	ok	-0.035	0.0000	ok
NPL	0.01	0.0000	ok	-0.033	0.0020	ok
NMIJ	0.01	0.0000	ok	-0.036	0.0010	ok
VNIIFTRI	0.009	0.0010	ok	-0.035	0.0000	ok
KRISS	0.011	0.0010	ok	-0.035	0.0000	ok
NIST	0.013	0.0030	ok	-0.034	0.0010	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.01	0.0010	**0.0041**	-0.035	0.0010	**0.0041**
		KCRV	**0.009**		KCRV	**-0.035**

(b) Uncertainty

	Real		Imaginary	
NMI	$u(y_i)$	$u^2(y_i)$	$u(y_i)$	$u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0055	0.00003	0.0042	0.00002
CMI	0.02	0.00040	0.02	0.00040
LNE	0.01	0.00010	0.01	0.00010
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.006	0.00004	0.006	0.00004
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1/N^2)\sum u^2(y_i)$	0.00001	$(1/N^2)\sum u^2(y_i)$	0.00001
	$u(y)$	**0.003**	$u(y)$	**0.003**

(c) Degree of Equivalence

	Real		Imaginary	
NMI	Δ_i	$U_{\Delta i}$	Δ_i	$U_{\Delta i}$
NMIA	0.002	0.014	-0.001	0.014
NIM	0.003	0.012	-0.001	0.010
CMI	0.001	0.036	0.001	0.036
LNE	-0.001	0.019	0.000	0.019
NPL	-0.001	0.016	-0.002	0.016
NMIJ	-0.001	0.014	0.001	0.014
VNIIFTRI	0.000	0.012	0.000	0.012
KRISS	-0.002	0.019	0.000	0.019
NIST	-0.004	0.016	-0.001	0.016

Table 16. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 Reflection Measurements at 15.0 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 15.0 GHz

(a) Outliers and KCRV

	Real			Imaginary		
NMI	(Y_i)	Difference From Median	ok or OUTLIER	(Y_i)	Difference From Median	ok or OUTLIER
NMIA	0.028	0.0010	ok	-0.009	0.0020	ok
NIM	0.0268	0.0022	ok	-0.015	0.0040	ok
CMI	0.028	0.0010	ok	-0.013	0.0020	ok
LNE	0.031	0.0020	ok	-0.011	0.0000	ok
NPL	0.033	0.0040	ok	-0.01	0.0010	ok
NMIJ	0.029	0.0000	ok	-0.012	0.0010	ok
VNIIFTRI	0.028	0.0010	ok	-0.011	0.0000	ok
KRISS	0.029	0.0000	ok	-0.01	0.0010	ok
NIST	0.029	0.0000	ok	-0.011	0.0000	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.029	0.0010	**0.0041**	-0.011	0.0010	**0.0041**
		KCRV	**0.029**		KCRV	**-0.011**

(b) Uncertainty

	Real		Imaginary	
NMI	$u(y_i)$	$u^2(y_i)$	$u(y_i)$	$u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0046	0.00002	0.0062	0.00004
CMI	0.02	0.00040	0.02	0.00040
LNE	0.01	0.00010	0.01	0.00010
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.006	0.00004	0.006	0.00004
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1 / N^2) \sum u^2(y_i)$	0.00001	$(1 / N^2) \sum u^2(y_i)$	0.00001
	$u(y)$	**0.003**	$u(y)$	**0.003**

(c) Degree of Equivalence

	Real		Imaginary	
NMI	Δ_i	$U_{\Delta i}$	Δ_i	$U_{\Delta i}$
NMIA	0.001	0.014	-0.002	0.014
NIM	0.002	0.010	0.004	0.013
CMI	0.001	0.036	0.002	0.036
LNE	-0.002	0.019	0.000	0.019
NPL	-0.004	0.016	-0.001	0.016
NMIJ	0.000	0.014	0.001	0.014
VNIIFTRI	0.001	0.012	0.000	0.013
KRISS	0.000	0.019	-0.001	0.019
NIST	0.000	0.016	0.000	0.016

Table 17. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3935 Reflection Measurements at 18.0 GHz

MI Technologies Horn, Model 12-12, s/n 3935 at 18.0 GHz

(a) Outliers and KCRV

	Real			Imaginary		
NMI	(Y_i)	Difference From Median	ok or OUTLIER	(Y_i)	Difference From Median	ok or OUTLIER
NMIA	0.011	0.0022	ok	0.006	0.0000	ok
NIM	0.0132	0.0000	ok	0.0042	0.0018	ok
CMI	0.016	0.0028	ok	0.003	0.0030	ok
LNE	0.013	0.0002	ok	0.005	0.0010	ok
NPL	0.015	0.0018	ok	0.007	0.0010	ok
NMIJ	0.014	0.0008	ok	0.006	0.0000	ok
VNIIFTRI	0.011	0.0022	ok	0.008	0.0020	ok
KRISS	0.013	0.0002	ok	0.006	0.0000	ok
NIST	0.015	0.0018	ok	0.006	0.0000	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.0132	0.0018	**0.0073**	0.006	0.0010	**0.0041**
		KCRV	**0.013**		KCRV	**0.006**

(b) Uncertainty

	Real		Imaginary	
NMI	$u(y_i)$	$u^2(y_i)$	$u(y_i)$	$u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0045	0.00002	0.0057	0.00003
CMI	0.02	0.00040	0.02	0.00040
LNE	0.01	0.00010	0.009	0.00008
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.008	0.00006	0.008	0.00006
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1 / N^2) \sum u^2(y_i)$	0.00001	$(1 / N^2) \sum u^2(y_i)$	0.00001
	$u(y)$	**0.003**	$u(y)$	**0.003**

(c) Degree of Equivalence

	Real		Imaginary	
NMI	Δ_i	$U_{\Delta i}$	Δ_i	$U_{\Delta i}$
NMIA	0.002	0.014	0.000	0.014
NIM	0.000	0.010	0.001	0.012
CMI	-0.003	0.036	0.003	0.036
LNE	0.000	0.019	0.001	0.017
NPL	-0.002	0.016	-0.001	0.016
NMIJ	-0.001	0.014	0.000	0.014
VNIIFTRI	0.002	0.016	-0.002	0.016
KRISS	0.000	0.019	0.000	0.019
NIST	-0.002	0.016	0.000	0.016

Table 18. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 Reflection Measurements at 12.4 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 12.4 GHz

(a) Outliers and KCRV

NMI	Real (Y_i)	Real Difference From Median	Real ok or OUTLIER	Imaginary (Y_i)	Imaginary Difference From Median	Imaginary ok or OUTLIER
NMIA	0.013	0.0020	ok	-0.032	0.0000	ok
NIM	0.0143	0.0007	ok	-0.0276	0.0044	OUTLIER
CMI	0.015	0.0000	ok	-0.032	0.0000	ok
LNE	0.003	0.0120	OUTLIER	-0.032	0.0000	ok
NPL	0.016	0.0010	ok	-0.031	0.0010	ok
NMIJ	0.016	0.0010	ok	-0.032	0.0000	ok
VNIIFTRI	0.014	0.0010	ok	-0.032	0.0000	ok
KRISS	0.017	0.0020	ok	-0.031	0.0010	ok
NIST	0.018	0.0030	ok	-0.031	0.0010	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.015	0.0010	**0.0041**	-0.032	0.0005	**0.0020**
		KCRV	**0.015**		KCRV	**-0.032**

(b) Uncertainty

NMI	Real $u(y_i)$	Real $u^2(y_i)$	Imaginary $u(y_i)$	Imaginary $u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0049	0.00002	0.0046	0.00002
CMI	0.02	0.00040	0.02	0.00040
LNE	0.009	0.00008	0.01	0.00010
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.006	0.00004	0.006	0.00004
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1 / N^2) \sum u^2(y_i)$	0.00001	$(1 / N^2) \sum u^2(y_i)$	0.00001
	$u(y)$	**0.004**	$u(y)$	**0.004**

(c) Degree of Equivalence

NMI	Real Δ_i	Real $U_{\Delta i}$	Imaginary Δ_i	Imaginary $U_{\Delta i}$
NMIA	0.002	0.014	0.000	0.014
NIM	0.001	0.011	-0.004	0.012
CMI	0.000	0.035	0.000	0.035
LNE	0.012	0.019	0.000	0.019
NPL	-0.001	0.016	-0.001	0.016
NMIJ	-0.001	0.014	0.000	0.014
VNIIFTRI	0.001	0.013	0.000	0.013
KRISS	-0.002	0.019	-0.001	0.019
NIST	-0.003	0.016	-0.001	0.016

Table 19. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 Reflection Measurements at 15.0 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 15.0 GHz

(a) Outliers and KCRV

	Real			Imaginary		
NMI	(Y_i)	Difference From Median	ok or OUTLIER	(Y_i)	Difference From Median	ok or OUTLIER
NMIA	0.038	0.0010	ok	-0.004	0.0000	ok
NIM	0.0361	0.0029	ok	-0.0056	0.0016	ok
CMI	0.039	0.0000	ok	-0.003	0.0010	ok
LNE	0.036	0.0030	ok	-0.002	0.0020	ok
NPL	0.044	0.0050	OUTLIER	-0.003	0.0010	ok
NMIJ	0.04	0.0010	ok	-0.004	0.0000	ok
VNIIFTRI	0.037	0.0020	ok	-0.004	0.0000	ok
KRISS	0.04	0.0010	ok	-0.004	0.0000	ok
NIST	0.039	0.0000	ok	-0.003	0.0010	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.039	0.0010	**0.0041**	-0.004	0.0010	**0.0041**
		KCRV	**0.038**		KCRV	**-0.004**

(b) Uncertainty

	Real		Imaginary	
NMI	$u(y_i)$	$u^2(y_i)$	$u(y_i)$	$u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0054	0.00003	0.0056	0.00003
CMI	0.02	0.00040	0.02	0.00040
LNE	0.01	0.00010	0.009	0.00008
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.006	0.00004	0.006	0.00004
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1 / N^2) \sum u^2(y_i)$	0.00001	$(1 / N^2) \sum u^2(y_i)$	0.00001
	$u(y)$	**0.004**	$u(y)$	**0.003**

(c) Degree of Equivalence

	Real		Imaginary	
NMI	Δ_i	$U_{\Delta i}$	Δ_i	$U_{\Delta i}$
NMIA	0.000	0.014	0.000	0.014
NIM	0.002	0.012	0.002	0.012
CMI	-0.001	0.035	-0.001	0.036
LNE	0.002	0.019	-0.002	0.017
NPL	-0.006	0.018	-0.001	0.016
NMIJ	-0.002	0.014	0.000	0.014
VNIIFTRI	0.001	0.013	0.000	0.012
KRISS	-0.002	0.019	0.000	0.019
NIST	-0.001	0.016	-0.001	0.016

Table 20. (a.) Computation of Outliers and KCRV, (b.) Computation of Uncertainty, (c.) Degree of Equivalences, for S/N 3936 Reflection Measurements at 18.0 GHz

MI Technologies Horn, Model 12-12, s/n 3936 at 18.0 GHz

(a) Outliers and KCRV

NMI	Real (Y_i)	Real Difference From Median	Real ok or OUTLIER	Imaginary (Y_i)	Imaginary Difference From Median	Imaginary ok or OUTLIER
NMIA	0.016	0.0020	ok	0.01	0.0007	ok
NIM	0.0168	0.0012	ok	0.0107	0.0000	ok
CMI	0.021	0.0030	ok	0.006	0.0047	OUTLIER
LNE	0.02	0.0020	ok	0.009	0.0017	ok
NPL	0.019	0.0010	ok	0.011	0.0003	ok
NMIJ	0.018	0.0000	ok	0.011	0.0003	ok
VNIIFTRI	0.015	0.0030	ok	0.013	0.0023	ok
KRISS	0.018	0.0000	ok	0.011	0.0003	ok
NIST	0.020	0.0020	ok	0.010	0.0007	ok
	Median of Real	Median of Differences	2.5 times S(MAD)	Median of Imaginary	Median of Differences	2.5 times S(MAD)
	0.018	0.0020	**0.0082**	0.0107	0.0007	**0.0029**
		KCRV	**0.018**		KCRV	**0.011**

(b) Uncertainty

NMI	Real $u(y_i)$	Real $u^2(y_i)$	Imaginary $u(y_i)$	Imaginary $u^2(y_i)$
NMIA	0.007	0.00005	0.007	0.00005
NIM	0.0047	0.00002	0.0058	0.00003
CMI	0.02	0.00040	0.02	0.00040
LNE	0.01	0.00010	0.009	0.00008
NPL	0.008	0.00006	0.008	0.00006
NMIJ	0.007	0.00005	0.007	0.00005
VNIIFTRI	0.008	0.00006	0.008	0.00006
KRISS	0.01	0.00010	0.01	0.00010
NIST	0.008	0.00006	0.008	0.00006
	$(1 / N^2) \sum u^2(y_i)$	0.00001	$(1 / N^2) \sum u^2(y_i)$	0.00001
	$u(y)$	**0.003**	$u(y)$	**0.003**

(c) Degree of Equivalence

NMI	Real $\lvert\Delta_i\rvert$	Real $U_{\Delta i}$	Imaginary $\lvert\Delta_i\rvert$	Imaginary $U_{\Delta i}$
NMIA	0.002	0.014	0.001	0.013
NIM	0.001	0.011	0.000	0.012
CMI	-0.003	0.036	0.005	0.040
LNE	-0.002	0.019	0.002	0.017
NPL	-0.001	0.016	0.000	0.015
NMIJ	0.000	0.014	0.000	0.013
VNIIFTRI	0.003	0.016	-0.002	0.015
KRISS	0.000	0.019	0.000	0.018
NIST	-0.002	0.016	0.001	0.015

9. Conclusions

The on axis comparison measurements at the three fixed frequencies, 12.4, 15.0, 18.0 GHz, was successfully completed using different measurement approaches by the 12 participating NMI's. The determination and handling of outliers was performed and the non-weighted mean values and uncertainties were calculated according to [2]. Outlier does not necessarily mean bad, or wrong, or out of compliance. It just means that the point in question was not used in computing the mean. It may still be in agreement with the KCRV, depending on the uncertainties in each. For purposes of judging whether a lab's results are "good," one should refer to the degrees of equivalence, or to the plots that include uncertainties. The agreement of the fixed frequency on axis measurement results were good with the exception of a few outliers mainly at the two higher frequencies.

Reflection coefficient measurement results were reported by 9 of the participating NMI's. Again, the determination and handling of outliers was performed and the non-weighted mean values and uncertainties were calculated according to [2]. The agreement between participants for the reflection coefficient measurements was very good.

On axis stepped frequency measurements were reported by 5 of the participating NMI's.

10. References

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11. Uncertainty Budgets

It was required that values for uncertainty of the gain measurements be reported. Additionally, the principal contributions to the gain uncertainty should be reported. Uncertainty estimates should be carried out in accordance with the recommendations of the ISO publication "Guide to the Expression of Uncertainty in Measurement" ISBN 92-67-10188-9. Uncertainties should be evaluated for a coverage factor $k = 2$ and an estimate of the number of effective degrees of freedom made. Typically lower case u is used for standard uncertainty, whereas upper case U is used for expanded uncertainty. This section lists the uncertainty processes as described by each NMI. The uncertainty budgets provided by the NMIs are shown from **Table 21** through **Table 49**.

a. **NMIA** - *National Measurement Institute of Australia* - Australia

Table 21. NMIA Uncertainty Budget for Discrete Frequency Gain Measurements

Source of Uncertainty	Value (+/-)	Distribution	Divisor	u_i	unit	DoF	c_i	unit	$c_i * u_i$	unit
Category *a* uncertainty contributions										
Yaw (trolley horn)	0.0080	Rect	1.732	0.0046	dB	50	1	d'less	0.0046	dB
Pitch (trolley horn)	0.006	Rect	1.732	0.0035	dB	50	1	d'less	0.0035	dB
Noise in power	0.001	Norm	1.000	0.0010	dB	30	1	d'less	0.0010	dB
Horn-horn reflections	0.0060	Norm	1	0.0060	dB	5	1	d'less	0.0060	dB
Chamber wall random reflections	0.0100	Rect	1.732	0.0058	dB	50	1	d'less	0.0058	dB
Separation	0.5	Rect	1.732	0.2887	mm	50	0.01	dB/mm	0.0017	dB
Horn pitching	1	Rect	1.732	0.5774	mm	50	0.01	dB/mm	0.0033	dB
Freq stability/freq	1E-07	Rect	1.732	5.8E-08	d'less	50	8.6	dB	0.0000	dB
Combined Cat *a* u(a)									**0.0108**	dB
Category *b* uncertainty contributions										
Yaw (fixed horn)	0.01	Rect	1.732	0.0058	dB	50	1	d'less	0.0058	dB
Yaw (trolley horn)	0.0070	Rect	1.732	0.0040	dB	50	1	d'less	0.0040	dB
Pitch (fixed horn)	0.006	Rect	1.732	0.0035	dB	50	1	d'less	0.0035	dB
Pitch (trolley horn)	0.007	Rect	1.732	0.0040	dB	50	1	d'less	0.0040	dB
Roll	0.001	Rect	1.732	0.0006	dB	50	1	d'less	0.0006	dB
Drift in power meter	0.0050	Rect	1.732	0.0029	dB	50	1	d'less	0.0029	dB
Tx Connector scatter	0.0050	Rect	1.732	0.0029	dB	50	1	d'less	0.0029	dB
Rx Connector scatter	0.0050	Rect	1.732	0.0029	dB	50	1	d'less	0.0029	dB
Source Drift	0.006	Rect	1.732	0.0035	dB	50	1	d'less	0.0035	dB
Antenna connector scatter	0.0050	Rect	1.732	0.0029	dB	50	1	d'less	0.0029	dB
Tx antenna reflection coefficient	0.007	Norm	1.000	0.0070	d'less	10	0.52	dB	0.0037	dB
Rx antenna reflection coefficient	0.007	Norm	1.000	0.0070	d'less	10	0.52	dB	0.0037	dB
Tx Mismatch	0.0052	U	1.414	0.0037	dB	50	1	d'less	0.0037	dB
Rx Mismatch	0.0052	U	1.414	0.0037	dB	50	1	d'less	0.0037	dB
Mismatch in direct connection	0.00009	U	1.414	0.0001	dB	50	1	d'less	0.0001	dB
Separation initialisation	2	Rect	1.732	1.1547	mm	50	0.01	dB/mm	0.0066	dB
Near-field correction	0.02	Rect	1.732	0.0087	dB	50	1	d'less	0.0087	dB
Combined Cat *b* u(b)									**0.0172**	dB
Category *c* uncertainty contributions										
Power meter linearity	0.0020	Rect	1.732	0.0012	dB	50	1	d'less	0.0012	dB
Chamber reflections	0.02	Rect	1.732	0.0115	dB	3	1	d'less	0.0115	dB
Near-field correction offset	0.05	Rect	1.732	0.0289	dB	8	1	d'less	0.0289	dB
Combined Cat *c* u(c)									**0.0311**	dB
						Combined Standard u			**0.022**	dB
						Expanded U (k=2)			**0.043**	dB

Uncertainty of horn antenna calibration was estimated by using the following equation:

$$u(G)=\sqrt{\frac{3}{4}\left[\frac{1}{Q}u^2(a)+u^2(b)\right]+\frac{u^2(c)}{4}}$$

where Q is the number of half-wavelengths over which measurements were made.

Category *a* uncertainty *u(a)* represents uncertainty components that vary with separation distance. An example of the latter is the chamber reflections at different separation distances.

Category *b* uncertainty *u(b)* represents uncertainty components that do not vary with separation distance. An example is the separation initializing error.

Category *c* uncertainty *u(c)* represents uncertainty components that do not vary with separation distance and are independent of the antenna pairs. An example is the power meter linearity.

Minor uncertainty components are not shown in the above table.

The unit ‘d'less’ means dimension-less.

Notes

1. The uncertainties have been calculated in accordance with principles in the ISO Guide to the Expression of Uncertainty in Measurement, and give an interval estimated to have a level of confidence of 95%. The uncertainty applies at the time of measurement only and takes no account of any drift or other effects that may apply afterwards. When estimating the uncertainty at any later time, other relevant information should also be considered, including, where possible, the history of the performance of the instrument and the manufacturer's specification.
2. The calibration was performed using Test Methods RFM-Proc_Hard-0030-1, RFM-Proc_Hard-0031-1, RFM-Proc_Hard-0032-1 and RFM-Proc_Hard-0039-1 of the RF and Microwave project operations manual.
3. The calibration was conducted at NMI Physical metrology, RF and Microwave project, Bradfield Road, West Lindfield NSW 2070, Australia.

b. **NIM** - *National Institute of Measurement* – China

Table 22. NIM uncertainty budget for the antenna gain at 12.4 GHz

Site insertion loss measurement							
Source of uncertainty	Value±(dB)	*k*	Probability distribution	Standard Deviation (dB)	ci	Standard uncertainty (dB)	Degrees Of Freedom
System Stability	0.1200	1.73	Rectangular	0.0694	0.8650	0.0600	∞
network-S21-accurancy	0.0772	2.00	Normal	0.0386	0.8650	0.0334	∞
horn antenna mutual coupling	0.0906	1.73	Rectangular	0.0523	0.8650	0.0453	∞
Mismatch error	0.0134	1.41	U-shape	0.0095	0.8650	0.0082	∞
Chamber reflection	0.0889	1.73	Rectangular	0.0514	0.8650	0.0445	∞
Antenna misalignment	0.0297	1.73	Rectangular	0.0172	0.8650	0.0149	∞
Antenna polarization Mismatch	0.0090	1.00	Normal	0.0090	0.8650	0.0078	∞
Repeatability	0.0341	1.00	Normal	0.0341	0.8650	0.0295	9.0000
Frequency	0.0000	1.73	Rectangular	0	7.6120	0.0000	∞
Distance error	0.0100	1.73	Rectangular	0.0058	1.0899	0.0063	∞
Combined standard uncertainty on Gain, u_c , for horn						0.1000	6889
Expanded uncertainty (*k*=2), U_G , for horn						0.20	

Table 23. NIM uncertainty budget for the antenna gain at 15.0 GHz

Site insertion loss measurement							
Source of uncertainty	Value±(dB)	*k*	Probability distribution	Standard deviation (dB)	ci	Standard uncertainty (dB)	Degrees Of Freedom
System Stability	0.1400	1.73	Rectangular	0.0808	0.8650	0.0699	∞
network-S21-accurancy	0.0772	2.00	Normal	0.0386	0.8650	0.0334	∞
horn antenna mutual	0.0550	1.73	Rectangular	0.0318	0.8650	0.0275	∞
Mismatch error	0.0155	1.41	U-shape	0.0110	0.8650	0.0095	∞
Chamber reflection	0.0599	1.73	Rectangular	0.0346	0.8650	0.0300	∞
Antenna misalignment	0.0415	1.73	Rectangular	0.0240	0.8650	0.0208	∞
Antenna polarization mismatch	0.0090	1.00	Normal	0.0090	0.8650	0.0078	∞
Repeatability	0.0484	1.00	Normal	0.0484	0.8650	0.0418	9.0
Frequency	0.0000	1.73	Rectangular	0	7.6120	0.0000	∞
Distance error	0.0100	1.73	Rectangular	0.0058	1.0899	0.0063	∞
Combined standard uncertainty on Gain, u_c , for horn						0.1001	2660
Expanded uncertainty (*k*=2), U_G , for horn						0.20	

Table 24. NIM uncertainty budget for the antenna gain at 18.0 GHz

Site insertion loss measurement							
Source of uncertainty	Value± (dB)	k	Probability distribution	Standard deviation (dB)	ci	Standard uncertainty (dB)	Degrees Of Freedom
System Stability	0.14	1.732	Rectangular	0.0808	0.8650	0.0699	∞
network-S21-accurancy	0.0789	2.00	Normal	0.0395	0.8650	0.0341	∞
horn antenna mutual coupling	0.0576	1.73	Rectangular	0.0333	0.8650	0.0288	∞
Mismatch error	0.0134	1.41	U-shape	0.0095	0.8650	0.0082	∞
Chamber reflection	0.06	1.73	Rectangular	0.0347	0.8650	0.0300	∞
Antenna misalignment	0.0524	1.73	Rectangular	0.0303	0.8650	0.0262	∞
Antenna polarization mismatch	0.0090	1.00	Normal	0.0090	0.8650	0.0078	∞
Repeatability	0.0378	1.00	Normal	0.0378	0.8650	0.0327	9.0
Frequency	0.0000	1.73	Rectangular	0.0000	7.6120	0.0000	∞
Distance error	0.0100	1.73	Rectangular	0.0058	1.0899	0.0063	∞
Combined standard uncertainty on Gain, u_c , for horn						0.0985	6595
Expanded uncertainty (k=2), U_G , for horn						0.20	

Uncertainty analysis for Ku-band standard gain horn antenna

Mathematics model for gain calibration

The combined uncertainty for the antenna gain is written as

$$u_G^2 = c_{12}^2 u^2(P_{12}) + c_{13}^2 u^2(P_{13}) + c_{23}^2 u^2(P_{23}) + c_{K_{12}}^2 u^2(K_{12}) + c_{K_{13}}^2 u^2(K_{13}) + c_{K_{23}}^2 u^2(K_{23})$$

Where $u(P_{12})$, $u(P_{13})$ and $u(P_{23})$ are uncertainty components associated with measured power P_{12}, P_{13} and P_{23}.

Considering that the conditions are almost the same for the three sets of power measurements, the difference, among $u(P_{12})$, $u(P_{13})$ and $u(P_{23})$ can be neglected, therefore,

$u(P_{12}) = u(P_{13}) = u(P_{23})$

$u(K_{12})$, $u(K_{13})$ and $u(K_{23})$ are the uncertainty components associated with the signal frequency and the distance between the two antenna, similarly, we have,

$u(K_{12}) = u(K_{13}) = u(K_{23})$. $c_{12} = c_{13} = c_{23} = c_{K_{12}} = c_{K_{13}} = c_{K_{23}} = \frac{1}{2}$

Therfore,

$$u_G = \frac{1}{2}\sqrt{3u^2(P) + 3u^2(K)} = \frac{\sqrt{3}}{2} u_c$$

and u_c(G) has the following components,

$$u_c = \sqrt{u_{sys}^2 + u_{s21}^2 + u_{amc}^2 + u_{ma}^2 + u_{cr}^2 + u_{am}^2 + u_{apm}^2 + u_{rm}^2 + u_f^2 + u_D^2}$$

Each item was be analyzed.

Table 25. Uncertainty component of u_c(G)

u_{sys}	System Stability
u_{s21}	That introduced by VNA when measuring S_{21}
u_{amc}	That introduced by mutual coupling between the antennas
u_{ma}	That introduced by mismatch error at the antenna port
u_{cr}	That introduced by chamber reflection
u_{am}	That introduced by antenna misalignment error
u_{apm}	That introduced by polarization mismatch error of the two linearly polarized antennas
u_{rm}	That introduced by repeatability
u_f	Frequency error
u_D	Distance error

c. CMI – *Czech Metrology Institute* – Czech Republic

Table 26. Uncertainty budget for on axis gain measurements at 12.4 GHz.

Type of Uncertainty	Source of Uncertainty	Value +/-	Unit	Probability Distribution	Divisor	Sensitivity Ci	Ui (CF) +/- dB	Degs of Freedom Vi or Veff
B	Power meter 1 accuracy	0.080	dB	Normal	2.00	0.50	0.020	Inf.
B	Power meter 2 accuracy	0.130	dB	Normal	2.00	0.50	0.033	Inf.
B	Mismatch sensor - coupler	0.023	dB	U-shaped	1.41	1.00	0.016	Inf.
B	Mismatch antenna - coupler	0.003	dB	U-shaped	1.41	1.00	0.002	Inf.
B	Mismatch antenna - sensor	0.034	dB	U-shaped	1.41	1.00	0.024	Inf.
B	Coupler power ratio	0.141	dB	Normal	2.00	0.50	0.035	Inf.
B	WG to coax transition atten.	0.100	dB	Normal	2.00	0.50	0.025	Inf.
B	Near field correction	0.100	dB	Rectangular	1.73	1.00	0.058	Inf.
B	Antenna distance	0.010	dB	Rectangular	1.73	1.00	0.006	Inf.
B	Antenna alignment	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
B	Reflections in chamber	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
A	Experimental standard uncertainty	0.003	dB	Normal	1.00	1.00	0.003	3
Uc(CF)	Combined uncertainty			normal			0.104	>10000
U	Expanded uncertainty			normal (k=2)			**0.208**	

Table 27. Uncertainty budget for on axis gain measurements at 15.0 GHz.

Type of Uncertainty	Source of Uncertainty	Value +/-	Unit	Probability Distribution	Divisor	Sensitivity Ci	Ui (CF) +/- dB	Degs of Freedom Vi or Veff
B	Power meter 1 accuracy	0.090	dB	Normal	2.00	0.50	0.023	Inf.
B	Power meter 2 accuracy	0.133	dB	Normal	2.00	0.50	0.033	Inf.
B	Mismatch sensor - coupler	0.019	dB	U-shaped	1.41	1.00	0.014	Inf.
B	Mismatch antenna - coupler	0.003	dB	U-shaped	1.41	1.00	0.002	Inf.
B	Mismatch antenna - sensor	0.059	dB	U-shaped	1.41	1.00	0.042	Inf.
B	Coupler power ratio	0.141	dB	Normal	2.00	0.50	0.035	Inf.
B	WG to coax transition atten.	0.100	dB	Normal	2.00	0.50	0.025	Inf.
B	Near field correction	0.115	dB	Rectangular	1.73	1.00	0.066	Inf.
B	Antenna distance	0.010	dB	Rectangular	1.73	1.00	0.006	Inf.
B	Antenna alignment	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
B	Reflections in chamber	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
A	Experimental standard uncertainty	0.008	dB	Normal	1.00	1.00	0.008	3
Uc(CF)	Combined uncertainty			normal			0.115	>10000
U	Expanded uncertainty			normal (k=2)			**0.230**	

Table 28. Uncertainty budget for on axis gain measurements at 18.0 GHz

Type of Uncertainty	Source of Uncertainty	Value +/-	Unit	Probability Distribution	Divisor	Sensitivity Ci	Ui (CF) +/- dB	Degs of Freedom Vi or Veff
B	Power meter 1 accuracy	0.120	dB	Normal	2.00	0.50	0.030	Inf.
B	Power meter 2 accuracy	0.133	dB	Normal	2.00	0.50	0.033	Inf.
B	Mismatch sensor - coupler	0.051	%	U-shaped	1.41	1.00	0.036	Inf.
B	Mismatch antenna - coupler	0.001	%	U-shaped	1.41	1.00	0.001	Inf.
B	Mismatch antenna - sensor	0.036	%	U-shaped	1.41	1.00	0.026	Inf.
B	Coupler power ratio	0.141	dB	Normal	2.00	0.50	0.035	Inf.
B	WG to coax transition atten.	0.100	dB	Normal	2.00	0.50	0.025	Inf.
B	Near field correction	0.133	dB	Rectangular	1.73	1.00	0.077	Inf.
B	Antenna distance	0.010	dB	Rectangular	1.73	1.00	0.006	Inf.
B	Antenna alignment	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
B	Reflections in chamber	0.070	dB	Rectangular	1.73	1.00	0.040	Inf.
A	Experimental standard uncertainty	0.002	dB	Normal	1.00	1.00	0.002	3
Uc(CF)	Combined uncertainty			normal			0.123	>10000
U	Expanded uncertainty			normal (*k*=2)			**0.245**	

d. **LNE** – *Laboratoire national de metrologie et d'essais* - France

Table 29. Uncertainty budget for on axis gain measurements.

Uncertainties				
Sources of Uncertainty	**Value**	**Probability Distribution**		**Ui (kx)**
Repeatability	0.001	-	1	0.001
ruler calibration	0.004	-	2	0.002
Reflection Coefficients calibration	0.006	-	2	0.003
wattmeter calibration	0.048	Rectangular	2	0.024
ruler drift	0.024	Rectangular	3.46	0.007
ruler resolution	0.002	Rectangular	3.46	0.001
wattmeter drift	0.002	Rectangular	3.46	0.001
anechoic chamber imperfection	0.017	Rectangular	3.46	0.005
Connector Repeatability	0.014		1.41	0.010
Combined Uncertainty		Normal (k=1)		0.028
Combined Uncertainty		Normal (k=1)	dB	0.12
Expanded Uncertainty		Normal (k=2)		0.055
Expanded Uncertainty		Normal (k=2)	dB	0.24

e. **NMIJ** – *National Metrology Institute of Japan* – Japan

Table 30. Gain uncertainty budget for MI 12-12, S/N 3935, at 12.4 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.267 dB	Normal	3	0.089	0.5	0.044	145
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.263 dB	Normal	3	0.088	0.5	0.044	142
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.262 dB	Normal	3	0.087	0.5	0.044	141
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.08	519
	Expanded Uncertainty		Normal				0.16	

Table 31. Gain uncertainty budget for MI 12-12, S/N 3935, at 15.0 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.348 dB	Normal	3	0.116	0.5	0.058	207
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.346 dB	Normal	3	0.115	0.5	0.058	208
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.343 dB	Normal	3	0.114	0.5	0.057	209
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlges	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlges	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlges	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.10	630
	Expanded Uncertainty		Normal				0.20	

Table 32. Gain uncertainty budget for MI 12-12, S/N 3935, at 18.0 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.43 dB	Normal	3	0.143	0.5	0.072	13
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.434 dB	Normal	3	0.145	0.5	0.072	14
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.437 dB	Normal	3	0.146	0.5	0.073	14
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlges	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.13	47
	Expanded Uncertainty		Normal				0.26	

Table 33. Gain uncertainty budget for MI 12-12, S/N 3936, at 12.4 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.266 dB	Normal	3	0.089	0.5	0.044	144
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.261 dB	Normal	3	0.087	0.5	0.044	139
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.262 dB	Normal	3	0.087	0.5	0.044	141
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.005 dB	Normal	3	0.0016	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.08	520
	Expanded Uncertainty		Normal				0.16	

Table 34. Gain uncertainty budget for MI 12-12, S/N 3936, at 15.0 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.342 dB	Normal	3	0.114	0.5	0.057	207
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.343 dB	Normal	3	0.114	0.5	0.057	207
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.343 dB	Normal	3	0.114	0.5	0.057	209
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.10	651
	Expanded Uncertainty		Normal				0.20	

Table 35. Gain uncertainty budget for MI 12-12, S/N 3936, at 18.0 GHz.

Standard Uncertainty Component $u(x_i)$	Source of Uncertainty	Value (±)	Probability Distribution	Divisor	Value of standard uncertainty $u(x_i)$ [dB]	c_i	$c_i\ u(x_i)$ [dB]	Degrees of Freedom
$u(R_{12})$	Normalized trasmission coefficient between the antennas 1 and 2	0.43 dB	Normal	3	0.143	0.5	0.072	13
$u(R_{13})$	Normalized trasmission coefficient between the antennas 1 and 3	0.434 dB	Normal	3	0.145	0.5	0.072	14
$u(R_{23})$	Normalized trasmission coefficient between the antennas 2 and 3	0.437 dB	Normal	3	0.146	0.5	0.073	14
$u(p_{12})$	Polarization-mismatch factor between the antennas 1 and 2	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{13})$	Polarization-mismatch factor between the antennas 1 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(p_{23})$	Polarization-mismatch factor between the antennas 2 and 3	1 deg.	Rectangular in anlge	2500	0.0004	0.5	0.0002	Inf.
$u(N_{12})$	Mismatch correction factor for the antennas 1 and 2	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{13})$	Mismatch correction factor for the antennas 1 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
$u(N_{23})$	Mismatch correction factor for the antennas 2 and 3	0.004 dB	Normal	3	0.0014	0.5	0.001	Inf.
	Combined Uncertainty		Normal				0.13	47
	Expanded Uncertainty		Normal				0.26	

The gain uncertainty budget for each antenna is estimated at each frequency and the subdivided components of the uncertainty consist of three kinds of the components for each antenna pair (*i,j*) as listed in **Table 30** through **Table 35**.

The uncertainty components subdivided are explained in detail below and its uncertainty budget at a frequency for each antenna are shown in Table 2a.1 to Table 3c.2 (Appendix A and B of the NMIJ report).

1. 1 Normalized transmission coefficient between the antennas *i* and *j* $u(R_{ij})$

The uncertainty of $u(R_{ij})$ consists of the uncertainties of S_{ji}, the antenna distance *r*, and the wavelength. The standard uncertainties of the distance and the wavelength are smaller than 0.001 dB because the distance is measured by a laser interferometer (Agilent Technologies 5529A) and the wavelength (that is, frequency) is determined by the VNA whose frequencies is calibrated by a frequency counter. Therefore the contributions from these uncertainties were neglected. The uncertainty of S_{ji} consists of 12 factors as explained below.

1.1.1 VNA TRL calibration

As shown in **Figure 4**, the reference planes of both ports are defined at the waveguide ports of the antennas whereas the ports of the VNA are connected through coaxial cables. Therefore, coaxial to waveguide adapters are used and these *S*-parameters were determined by unterminating using the TRL calibration [13]. Agilent P11644A mechanical calibration kit was used for the TRL calibration. Therefore, the uncertainty by the TRL calibration was calculated using Agilent Technologies uncertainty calculator (UncertTest.xls revision 2.6.1).

1.1.2 VNA TRL calibration repeatability

The unterminating is repeated 5 times to obtain the uncertainty due to the repeatability of the TRL calibration.

1.1.3 VNA SOLR calibration

The VNA and the coaxial to waveguide adapters are connected through two coaxial cables whose lengths are approximately 6 m. In the SOLR calibration (Agilent Technologies 85052C 3.5 mm calibration kits), the error terms including the VNA and the coaxial cables are determined by Short-Open-Load calibration of each port [14]. Therefore the uncertainty is obtained from the uncertainties of the standards for Short-Open-Load calibration that were determined by the impedance metrology group in NMIJ.

1.1.4 VNA SOLR calibration repeatability

The SOL calibration for each terminal of the coaxial cable was repeated 5 times at the coaxial to waveguide adapter side in order to decide the uncertainty due to the repeatability of the SOLR calibration.

1.1.5 Antenna connection repeatability at Port 1

At the Port 1, the antenna and the adapter connection were repeated 5 times to obtain the uncertainty of the S-parameters due to the repeatability of the connection.

1.1.6 Antenna connection repeatability at Port 2

At Port 2, the antenna - adapter connections were repeated 5 times to obtain the uncertainty of the S-parameters due to the repeatability of the connection.

1.1.7 System drift

The time drift of S_{21} and S_{12} by the VNA was measured during 5 hours that corresponds to the measurement time interval for each antenna pair. The number of the sampling points is 151. Since the drift in dB scale was almost linearly changed during the period, the probability distribution function was approximated to be rectangular.

1.1.8 VNA linearity

The linearity of S_{21} and S_{12} of the VNA was measured using an Agilent Technologies 84905M programmable step attenuator that was calibrated by the attenuation metrology group in NMIJ. The uncertainty was combined with the measured uncertainty of the VNA and the given uncertainty of the attenuator.

1.1.9 Extrapolation

The uncertainty due to the extrapolation was calculated by the 2nd order polynomial regression model [15] to R_{ij} where the variable is the inverse of the distance r.

1.1.10 Antenna alignment

The alignment of two antennas set on the holders was measured using a laser autocollimator and the mirrors attached to the flanges of antennas. The laser beam from the autocollimator was used as the reference straight line of the measurement system. Therefore the center position and the normal direction of the waveguide flange of each antenna were adjusted to be coincident with the laser beam. The center position and the inclination of the fixed antenna relative to the laser beam were adjusted and were within 1 mm shift and 0.1 degrees respectively. Those of the moving antenna were adjusted during the movement and were within 1 mm shift and 0.1 degrees respectively. The center position shifts and the inclinations are equivalent to the inclination between the antennas within 0.2 degrees during the movement. Therefore, the uncertainty due to the alignment is calculated from the antenna pattern inferred by the simulation model, assuming that the inclination is uniformly distributed within 0.2 degrees.

1.1.11 Cable movement during antenna movement

The SOLR calibration of the measurement system for each pair among three antennas was done only when the antenna separation distance was about 1.5 m, that is, the end position of the measurement. Therefore the characteristics of the cable connected to the moving antenna might be changed due to the movement. The change was estimated using the time gating in the time domain data for S_{ij} during the movement. After the time gating for the effect of the cable movement, it was converted back into the data in the frequency domain. The data around 12.4 GHz, 15 GHz, 18 GHz were used to estimate the uncertainties.

1.1.12 Reflection from RAM

The reflection from RAM around the measurement system was estimated using the time domain data as explained in 1.1.11. It is considered that the reflected waves include the reflected waves from the floor, the ceiling, the walls, and other objects that were covered by various kinds of RAMs. It was estimated to be smaller than -60 dB relatively to the main wave component and the uncertainty was estimated assuming the U-shape distribution with the amplitude being 0.009 dB.

1. 2 Polarization-mismatch factor between the antennas *i* and *j* $u(p_{ij})$

The uncertainty of the polarization mismatch factor was estimated on the assumption that the antennas are linearly polarized. Therefore the polarization mismatch factor is calculated as

$$p_{ij} = \cos^2 \theta_{ij}$$

where θ_{ij} is the angle between the two antenna polarizations. The E-plane line of the antenna was defined along the line through the notches on the +Y side and the opposite side of the antenna flare. The E-plane line of each antenna was adjusted to be parallel to the vertical line within 1 degree. Therefore, the uncertainty is estimated as θ_{ij} is distributed uniformly within 1 degree around 0 degree. In the estimation, the polarization mismatch factor is approximated as

$$p_{ij} \approx 1 - \theta_{ij}{}^2,$$

where θ_{ij} is in radians.

1.3 Mismatch-correction factor for the antennas *i* and *j* $u(N_{ij})$

The mismatch-correction factor is calculated using the reflection coefficients of the antennas *i* and *j* measured at the reflection coefficient measurements. The uncertainty is estimated as explained in the section 3 of the NMIJ report.

f. **VNIIFTRI** – *Russian Scientific Research Institute of Physico-Technical Measurements - Russia*

Table 36. Uncertainty budget for on axis gain measurements at 12.4 GHz.

	Value+-dB	Probability Distribution		Ui(kx) +_dB
Receiver Nonlinearity	0.02	Rectangular Type B	1.73	0.0116
Drift of Transmission Factor	0.03	Rectangular Type B	1.73	0.0173
Impedance Mismatch	0.002	U-Shape Type B	1.41	0.0014
Extrapolation	0.05	Rectangular Type B	1.73	0.0289
Multiple reflections between antennas	0.03	Normal Type B	3	0.0100
Antenna positioning and displacement	0.03	Rectangular Type B	1.73	0.0173
Connector Repeatability	0.02	Normal Type A	3	0.0067
Free space area and absorbing material	0.03	U-Shape Type B	1.41	0.0213
Random Uncertainty	0.023	Normal Type B	3	0.0077
Combined Uncertanty		Normal		0.0472
Expanded Uncertainty		Normal (*k*=2)		**0.094**

Table 37. Uncertainty budget for on axis gain measurements at 15.0 GHz.

	Value+-dB	Probability Distribution		Ui(kx) +_dB
Receiver Nonlinearity	0.02	Rectangular Type B	1.73	0.0116
Drift of Transmission Factor	0.03	Rectangular Type B	1.73	0.0173
Impedance Mismatch	0.003	U-Shape Type B	1.41	0.0021
Extrapolation	0.09	Rectangular Type B	1.73	0.0520
Multiple reflections between antennas	0.05	Normal Type B	3	0.0167
Antenna positioning and displacement	0.05	Rectangular Type B	1.73	0.0289
Connector Repeatability	0.02	Normal Type A	3	0.0067
Free space area and absorbing material	0.03	U-Shape Type B	1.41	0.0213
Random Uncertainty	0.032	Normal Type B	3	0.0107
Combined Uncertanty		Normal		0.0698
Expanded Uncertainty		Normal (*k*=2)		**0.14**

Table 38. Uncertainty budget for on axis gain measurements at 18.0 GHz.

	Value+-dB	Probability Distribution		Ui(kx) +_dB
Receiver Nonlinearity	0.02	Rectangular Type B	1.73	0.0116
Drift of Transmission Factor	0.03	Rectangular Type B	1.73	0.0173
Impedance Mismatch	0.004	U-Shape Type B	1.41	0.0028
Extrapolation	0.12	Rectangular Type B	1.73	0.0694
Multiple reflections between antennas	0.03	Normal Type B	3	0.0100
Antenna positioning and displacement	0.04	Rectangular Type B	1.73	0.0231
Connector Repeatability	0.02	Normal Type A	3	0.0067
Free space area and absorbing material	0.01	U-Shape Type B	1.41	0.0071
Random Uncertainty	0.045	Normal Type B	3	0.0150
Combined Uncertanty		Normal		0.0788
Expanded Uncertainty		Normal (*k*=2)		**0.15**

g. **KRISS** – *Korea Research Institute of Standards and Science* – Korea

Table 39. Uncertainty budget for on axis gain measurements

Source of uncertainty		u(xi), dB	Probability distribution	Divider	ci	|ci|u(xi), dB	Degrees of Freedom
Square root of Gain product for antenna pair 1 & 2						0.031	16,209
Direct connection measurement		0.005	Normal	1	1	0.005	11
System Drift		0.010	Rectangular	1.732	1	0.006	∞
Curve fitting		0.007	Normal	1	1	0.007	∞
Antenna alignment		0.020	Normal	1	1	0.020	∞
Multiple reflection between antennas		0.012	Normal	1	1	0.012	∞
Reflection from RAM		0.010	Normal	1	1	0.010	∞
Receiver nonlinearity		0.025	Rectangular	1.732	1	0.014	∞
Square root of Gain product for antenna pair 2 & 3						0.031	16,209
Square root of Gain product for antenna pair 1 & 3						0.031	16,209
Mismatch correction factor		0.012	U-shaped	1.414	1	0.008	∞
Measurement repeatability		0.007	Normal	1	1	0.007	3
Combined uncertainty (*k*=1)						0.055	9,271
Expanded uncertainty (*k*=2)						0.110	

h. **SP** – *Technical Research Institute of Sweden* – Sweden

Uncertainty Budget

The uncertainty budget is based on the following relation,

$$(G_T)_{dB} = (G_S)_{dB} + 20log\left(\frac{R_T}{R_S}\right) + 10log\left(\frac{P_{MS} \cdot P_T}{P_{MT} \cdot P_S}\right)$$

where:

$(G_T)_{dB}$ = Test object antenna – gain

$(G_S)_{dB}$ = Standard gain horn antenna – gain

R_T = Distance between reference antenna and test antenna.

R_s = Distance between reference antenna and standard gain horn.

P_{MT} = Power into transmitting test object antenna.

P_{MS} = Power into transmitting standard gain horn.

P_T = Received power when the test object is transmitting.

P_S = Received power when the standard gain horn is transmitting.

The uncertainty budget equation gives the following for a calibration using horn antennas:

(In **Table 40** the σ_{Eff} power meters frequency dependent uncertainty, and the uncertainty δ(G) of the positioning, in height and sideways, is frequency dependent, see **Table 41**.)

Table 40. Total uncertainty for the calibration.

Factor	Estimated value	Standard uncertainty	Distribution	Sensitivity coefficient	Contribution to standard uncertainty
$G_{S,1}$	12.62	0.21	normal	3	0.021
$G_{S,2}$	12.62	0.26	normal	1	0.026
$\Delta P_{S/T}$	0.49	σ_{Eff1}	normal	2	σ_{Eff1}
$\Delta P_{MT/MS}$	1.00	σ_{Eff2}	normal	2	σ_{Eff2}
N-*contact*	0.0	σ_{Eff3}	normal	1	σ_{Eff3}
ΔR	1.00	0.00625 (App. A2)	rectangular	4	0.0075
G_T	6.1838 (7.91dBi)				**$(0.002224 + 2\sigma^2_{Eff1} + 2\sigma^2_{Eff1})^{1/2}$**

The uncertainty contribution of the gain of the standard gain horn $G_{S,1}$ with its three factors:

Table 41. Error contributions for the gain from a standard gain horn

Factor	Contribution
Angular offset 1.5°	0.020
Skewness 3 mm	0.0029
Strain 1 mm	0.0058
$\Delta G_{S,1}$	**0.0210**

The uncertainty contribution of $G_{S,2}$, the error from the gain value of the standard gain horn antenna:

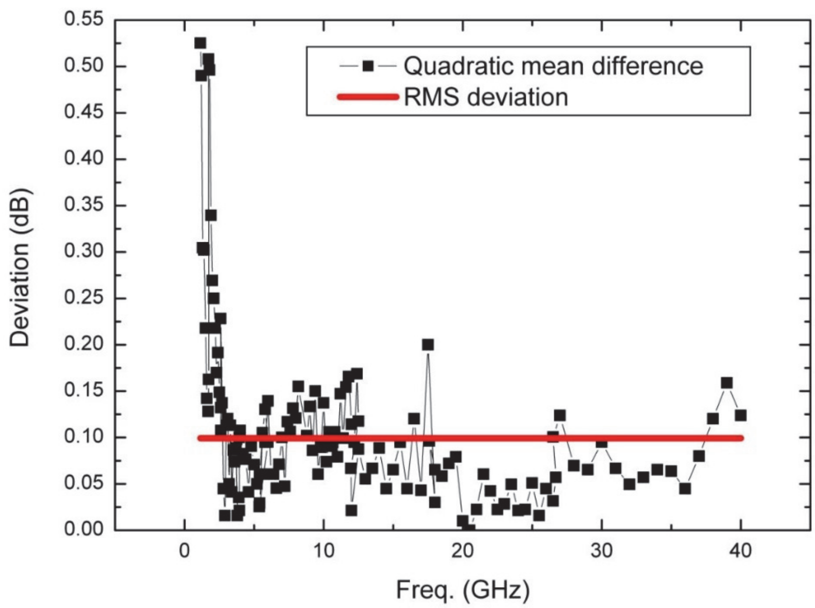

Figure 33. The error contribution from the standard gain horn ($G_{S,2}$) is presented as the RMS deviation.

In **Figure 33** we present the quadratic mean difference of the contributions from two numerical calculations (CST model of the standard gain horn antennas and a "PyrHorn" model of the same antenna) and the provided data of the manufacturer (Flann). The Quadratic mean difference is defined in the equation below:

$$(\textit{Quadratic mean difference})^2 = (CST - PyrHorn)^2 + (Flann - Pyrhorn)^2$$

The output from a "PyrHorn" calculation is used as input for the reference antenna and is a part of the software "HF kalibrering". The quadratic mean difference is a frequency dependent quantity; however its RMS value is defined as a frequency independent measure of the error contribution ($G_{S,2}$) coming from the calculated value of the gain of a standard gain horn.

The frequency dependent uncertainties of the diode sensor of the power meter are:

Table 42. Frequency dependent uncertainty diode sensor

Frequency (GHz)	σ_{Eff1}
0-6	0.0067
6-13	0.0075
13-18	0.0114

The frequency dependent uncertainties of the thermal sensor of the power meter are:

Table 43. Frequency dependent uncertainty thermal sensor

Frequency (GHz)	σ_{Eff2}
0-6	0.0075
6-13	0.0088
13-18	0.0099

The disconnection and connection of the antenna gives an error contribution:

Table 44. Frequency dependent N-contact

Frequency (GHz)	σ_{Eff3}
0-5	0.0024
5-8	0.0024
8-13	0.0157
13-18	0.0322

The total uncertainties, e.g. (2σ), for the gain transfer method are:

Table 45. Total uncertainty for the different frequencies

Frequency (GHz)	Total uncertainty [%]	Total uncertainty [dB]
0-5	10	0.41
5-8	10	0.41
8-13	11	0.43
13-18	13	0.50

i. **METAS** – *Federal Institute of Metrology* – Switzerland

Table 46. Uncertainty budget

Source of uncertainty	Estimation source	Distribution Type	Information	value (dB)	k_value ()	standard uncertainty (dB)	sensitivity factor ()	uncertainty (dB)
VNA nonlinearity	Verification of tolerance	B – normal	0.1 dB @ 10 GHz 0.3 dB @ 18.0 GHz	0.16 @ 12.4 GHz 0.23 @ 15.0 GHz 0.3 @ 18.0 GHz	$\sqrt{3}$	0.10 @ 12.4 GHz 0.14 @ 15.0 GHz 0.18 @ 18.0 GHz	$\sqrt{3}/2$	0.08 @ 12.4 GHz 0.12 @ 15.0 GHz 0.15 @ 18.0 GHz
Reference Attenuators	Calibration Certificate	B - normal	0.09 dB	0.09	2	0.045	$\sqrt{3}/2$	0.04
Residual multipath	Fit quality	A - normal	0.15 dB @ 12.4 GHz 0.25 dB @ 15.0 GHz 0.25 dB @ 18.0 GHz	0.15 @ 12.4 GHz 0.25 @ 15.0 GHz 0.25 @ 18.0 GHz	1	0.15 @ 12.4 GHz 0.25 @ 15.0 GHz 0.25 @ 18.0 GHz	$\sqrt{3}/2$	0.130 @ 12.4 GHz 0.217 @ 15.0 GHz 0.217 @ 18.0 GHz
Mismatch uncertainty	Calculation	B – U-shape	0.1 (cable)' 0.1 (horn)	0.086	$\sqrt{2}$	0.061	$\sqrt{3}/2$	0.053
Connector Repeatability	Estimation	B - normal	0.05 dB	0.05	2.0	0.025	$\sqrt{3}/2$	0.022
Adaption N-connector - Waveguide	Estimation	B-rectangular	0.10 dB	0.10	$\sqrt{3}$	0.057	$\sqrt{3}/2$	0.050
Distance uncertainty	Estimation	B- rectangular	3 mm @ 2m	0.013	$\sqrt{3}$	0.008	$\sqrt{3}/2$	0.007
Combined standard uncertainty (k=1)								0.175 @ 12.4 GHz 0.263 @ 15.0 GHz 0.277 @ 18.0 GHz

j. **TÜBİTAK-UME** – *The Scientific and Technological Research Council of Turkey* – Turkey

Table 47. Uncertainty budget by using ANSI C63.5:2006

Source of Uncertainty	Value ± (dB)	Probability distribution	Divisor	U_i (kx) ± (dB)
EMI test receiver relative amplitude accuracy	0.23	Rectangular	1.732	0.1328
Discrete Frequency Method without pre-scan, frequency accuracy	0.05	Rectangular	1.732	0.0289
Signal source amplitude stability	0.08	Rectangular	1.732	0.0462
Signal source frequency accuracy	0.19	Rectangular	1.732	0.1097
Cable attenuation variations	0.13	Rectangular	1.732	0.0751
Transmit side mismatch	0.09	U-Shaped	1.414	0.0636
Receive side mismatch	0.08	U-Shaped	1.414	0.0566
Free space area and absorbing material (site imperfections)	0.32	Triangle	1	0.3200
Variations in antenna phase center	0	Rectangular	1.732	0.0000
Antenna directivity	0.09	Rectangular	1.732	0.0520
Transmit pattern variations from dipole	0.1	Rectangular	1.732	0.0577
Antenna Height	0.1	Rectangular	1.732	0.0577
Antenna Distance	0.1	Rectangular	1.732	0.0577
Measurement repeatability	0.12	Normal 1	1	0.1200
Combined uncertainty		Normal		0.4184
Expanded uncertainty		Normal (*k*=2)		0.84

k. **NPL** – *National Physical Laboratory* – United Kingdom

Table 48. Uncertainty contributions for the extrapolation gain results

Symbol	Source of Uncertainty	Value +/- dB	Probability Distribution	Divisor	Ci	Ui (Kx) +/- dB	Vi or Veff
K(f) U1.1	Measurement of Transmission factor	0.0019	Normal	1	0.5000	0.0009	9
K(f) U1.2	Drift of Transmission factor	0.0024	Rectangular	1.73	0.8660	0.0012	Inf
U2	Repeatability of antenna connections	0.0019	Normal	1	1.2247	0.0023	9
U3.1	Random error in fitting of curve	0.0005	Normal	1	0.8660	0.0004	2142
U3.2	Truncation of higher order terms	0.0068	Normal	1	1.1180	0.0076	Inf
U3.3	Systematic fitting error	0.0020	Rectangular	1.73	1.1180	0.0013	Inf
U4	Mismatch correction	0.0104	Normal	1.00	1.0000	0.0104	Inf
U5	Cross polarisation	0.0004	Normal	2	1.0000	0.0002	Inf
U6	Antenna alignment	0.0040	Normal	2	1.2247	0.0024	Inf
U7	Absorber reflections	0.0026	U-shaped	1.41	1.0000	0.0018	Inf
Uc(Kx)	Combined uncertainty		normal			0.0136	11359
U	Expanded uncertainty		normal (k=2)			**0.027**	

For each of the parameters measured, the reported expanded uncertainties are based on a standard uncertainty multiplied by a coverage factor *k=2*, provided a coverage probability of approximately 95%. These uncertainties apply only to the measured values and give no indication of the long-term stability of the antenna.

l. **NIST** – *National Institute of Standards and Technology* – United States

Table 49. Uncertainties in Fixed Frequency On-Axis Gain Measurements

Sources of Uncertainty	Value ± dB	Probability Distribution	Probability Divisor	Ui (Kx) ±dB
Receiver Nonlinearity	0.02	Rectangular	1.73	0.0116
Impedance Mismatch	0.02	Rectangular	1.73	0.0116
Antenna Alignment	0.03	Normal	3	0.0100
Data Curve Fit	0.04	Rectangular	1.73	0.0231
Connector Repeatability	0.03	Normal Type A	3	0.0100
Residual Multipath	0.03	Rectangular	1.73	0.0173
Random Uncertainties	0.03	Normal	3	0.0100
Combined Uncertainty		Normal		0.0374
Expanded Uncertainty		**Normal (*k*=2)**		**0.0748**

The components are all of Type B, unless noted Type A, and are assumed independent of other uncertainties [16]. The expanded uncertainties use a coverage factor of *k*=2.

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