Supplementary comparison : CCEM.RF-S21.F

FINAL REPORT

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1 Introduction

This report describes the Supplementary comparison which was conducted between January 2002 and September 2004. This work was conducted in parallel with the Key comparison (CCEM.RF-K21.F). The five intercomparison artefacts were proprietary antennas which operate over different regions of a broad frequency range from 20 Hz to 2 GHz. In the range below 30 MHz there was one monopole antenna and two loop antennas; and above 30 MHz there was a Log Periodic Dipole Array (LPDA) and a broadband hybrid antenna (Schaffner-Chase CBL 6112B Bilog antenna).

These antennas represent the main groups of antennas which are used for EMC type measurements around the world. There are several well known methods for calibrating the antenna factor of these devices, and the aim of this work was to confirm the consistency of antenna measurements performed by the participating GT-RF laboratories.

For each measurement system used, the participants were asked to summarise how traceability to international standards is maintained. The objective was to ascertain whether there existed any significant correlation between participants in the way they achieved traceability. There is no formal treatment of correlation included in the calculation of Reference Value (RV), so this was for background information only.

2 Organisation of intercomparison

2.1 Participants

The Pilot Laboratory was the National Physical Laboratory (NPL) in the UK. The address is given below.

Division of Enabling Metrology
National Physical Laboratory
Teddington, Middlesex
TW11 0LW
UK

Table 2-1 lists the participants of the intercomparison along with the Regional Metrological Organisation (RMO) to which each laboratory belongs. The support group for the comparison were: Martin Alexander (NPL), Denis Camell (NIST), Vladimir Tischenko (VNIIFTRI), and Kurt Hilty (METAS).

Table 2-1 : Participating laboratories

Acronym	RMO	Responsible person(s)	Address
NPL	EUROMET	David Knight	DEM National Physical Laboratory Queens Road, Teddington Middlesex, TW11 0LW UK
AIST	APMP	Koji Komiyama	Radio-Frequency and Fields Section Electromagnetic Waves Division NMIJ / AIST Tsukuba Central 2 1-1-1, Umezono, Tukuba, Ibarai 305-8568 JAPAN
LNE	EUROMET	Djamel Allal	BNM-LNE/LAMA 33 avenue du Général 92260 Fontenay aux Roses FRANCE
ARCS	EUROMET	Wolfgang Müllner / Kriz Alexander	ARC SEIBERSDORF research GmbH EMC & RF Engineering A-2444 Seibersdorf AUSTRIA
NIST	NORAMET (part of SIM)	Dennis Camell	Radio-Frequency Fields Group Radio-Frequency Technology Division National Institute of Standards and Technology 325 Broadway, MS 813.02 Boulder, CO 80303 USA

KRISS	APMP	Jeong Hwan Kim	Electromagnetics Group Division of Electromagnetic Metrology Korea Research Institute of Standards and Science P.O. Box 102, Yusong, Taejon 305-600 KOREA
METAS	EUROMET	Frédéric Pythoud	Swiss Federal Office of Metrology and Accreditation (METAS) Lindenweg 50 CH- 3003 Bern-Wabern SWITZERLAND
SP	EUROMET	Ulrich Stein / Jan Welinder	Swedish National Testing and Research Institute Brinellgatan 4 Box 857 S-501 15 Borås SWEDEN
NMi-VSL	EUROMET	George Teunisse	NMi Van Swinden Laboratorium B.V. Thijsseweg 11 P.O. Box 654 NL-2600 AR Delft The NETHERLANDS

Note
ARCS took part in this intercomparison on behalf of the NMi in Austria, BEV (Bundesamt für Eich- und Vermessungswesen).

2.2 Measurement schedule

The antennas were sent to the participating laboratories in the following order. The dates are given for the completion of measurements in each case.

Antennas above 30 MHz (B and C)

NPL(1)	February 2002
ARCS	May 2002
NIST	August 2002
AIST	February 2003
NPL(2)	May 2003
LNE	June 2003
METAS	August 2003
SP	September 2003
KRISS	January 2004

Antennas below 30 MHz (D, E, and F)

NMi-VSL	October 2002
AIST	February 2003
NPL(1)	May 2003
KRISS	August 2003
NPL(2)	April 2004

Note 1: NMi-VSL were asked to re-measured Loop F because their first results for this antenna were not measured into a 50 ohm load. Re-measured data was received in September 2004.

Note 2: The two loop antennas (E and F) were measured by two independent techniques at NPL, and they are treated as separate measurements. NPL(1) was done by Helmholtz coil, and NPL(2) was done in a TEM cell.

On several journeys the consignment was hindered by problems encountered through customs, and often time and effort was required by everyone involved in order to overcome the hindrance. On some occasions participating laboratories were obliged to pay significant import duty and storage fees, and for this assistance NPL is very grateful. During the intercomparison the ATA carnet was separated from the consignment on three occasions, and overall the carnet proved to be of limited usefulness because covering for a lost carnet proved to be a larger problem than transporting the goods without a carnet.

3 Travelling standards and required measurement

3.1 Description of standards

The following list describes the travelling standards and gives the nominal operating range of each antenna. Each antenna was assigned a label to make future reference easier. Antenna A was a tuneable dipole which was circulated as the Key comparison artefact, (K21).

B Rohde & Schwarz log-periodic, model HL223: 200 MHz to 1.3 GHz.
s/n 834933/018

C Schaffner Chase bilog, model CBL 6112B: 30 MHz to 2 GHz.
s/n 2788

D Rohde & Schwarz active monopole HFH2-Z1: 9 kHz to 30 MHz.
s/n 881060/019

E EMCO active shielded loop, model 6507: 1 kHz to 30 MHz.
s/n 9004-1202

F EMCO passive shielded loop, model 7604: 20 Hz to 150 kHz.
s/n 9904-2465

3.2 Required measurement

The intercomparison required the antenna factor of antennas B and C to be measured in free-space conditions. Currently many international standards are evolving, and the use of free-space antenna factor is becoming more common (for example, CISPR 16-1:1999). Achieving perfect free-space conditions for broad beam-width antennas is not practicable but there are measurement methods which enable a good approximation to be achieved by techniques which reduce electromagnetic coupling with the surroundings.

NPL provided phase centre information for antennas B and C because they are both log periodic designs and the active region of the antenna will change with frequency. In order to define accurate antenna factor it is necessary to define the point along the antenna where the antenna factor applies. The approximate positions of the active regions on the antennas at each frequency was given in the technical protocol. The required measurement frequencies are given in the tables below, along with phase centre position measured from the tip.

Table 3-1: Required frequencies and phase centre positions for Antenna B

Required frequency (MHz)	Phase centre (m from tip)
200	0.54
280	0.38
900	0.09

Table 3-2: Required frequencies and phase centre positions for Antenna C

Required frequency (MHz)	Phase centre (m from tip)
30	see note below
80	see note below
200	0.82
1000	0.26
1500	0.16
2000	0.10

Note: At 30 MHz and 80 MHz the phase centre is assumed to be at the position of the triangular elements.

The calibration parameter 'antenna factor' describes the sensitivity of an antenna to E-field strength, and it is a common unit of calibration for antennas operating in the VHF and UHF frequency band. Antenna factor is used to determine measured E-field strength during EMC compliance tests. The unit is defined as the ratio of E-field strength (E) to received output voltage across a 50 Ω load (V), and it is most commonly expressed as a logarithm of voltage ratio.

$$AF(dB(m^{-1})) = 20 * Log_{10}\left(\frac{E}{V}\right)$$

Monopole antenna

The antenna factor of the monopole (antenna D) was required. The established methods of calibrating monopole antennas simulate the performance of the antenna when the zero potential reference is defined by an infinite ground plane. Therefore this condition is required for the intercomparison. The required frequencies are given below:

Monopole antenna (D): 10 kHz, 15 MHz, 30 MHz

Loop antenna

The magnetic antenna factor of the loop antennas was required. The most common measurement methods will give free-space antenna factor because the loop antennas are electrically small at these low frequencies, and there is relatively little coupling with nearby conductors. The unit of magnetic antenna factor is dB(siemens/m) which is defined by the ratio of H-field to output voltage across a 50 Ω load.

$$AF_{MAG}(dB(S.m^{-1})) = 20 * Log_{10}\left(\frac{H}{V}\right)$$

The required frequencies are given below:

Loop antenna (E): 10 kHz, 1 MHz, 30 MHz
Loop antenna (F) 20 Hz, 500 Hz, 100 kHz

3.3 Initial checks

It was recommended that each participant should check the pin depth of the N-type connector on antennas B and C and report the result in the confirmation of receipt. A brief visual inspection should be made and any defects noted.

For N-type connectors the ledge at the base of the male pin should be a minimum of 0.207 inches back from the mating reference plane, and for female connectors the top of the pin should be a maximum of 0.207 inches forward of the mating plane. Typically pin depth gauges have calibration blocks which set the zero at 0.207 inches, and they then measure the deviation from this. We asked participants to quote the pin depth as the deviation from nominal, using a negative sign to indicate recession of the pin into the body of the connector.

The following tables list the measurements taken by each participant. The results show that the centre pin on both antennas never protruded beyond the nominal position in such a way that other connectors may be damaged. It seems that the position of the pin in Antenna B was more variable than for Antenna C, however these reported variations may occur if the design of the N-type connector does not allow the pin measurement gauge to sit well on the connector, and therefore more variability is found.

Table 3-3: Measured recession of female pin on Antenna B

Laboratory	Recession of female pin (inches)
NPL(1)	-0.013
ARCS	[no data]
NIST	-0.023
AIST	-0.011
NPL(2)	-0.012
LNE	[no data]
METAS	-0.009
SP	-0.001
KRISS	[no data]

Table 3-4: Measured recession of female pin on Antenna C

Laboratory	Recession of female pin (inches)
NPL(1)	-0.008
ARCS	[no data]
NIST	-0.009
AIST	-0.009
NPL(2)	-0.011
LNE	[no data]
METAS	-0.011
SP	-0.009
KRISS	[no data]

The output connectors on antennas D, E, and F were of BNC type. These connectors are less stable than N-type connectors but they are primarily used for applications below 30 MHz, and therefore the dimensional tolerances can be more generous while still retaining reliable performance. BNC type connectors are not usually gauged and this intercomparison did not require any pin depth data to be supplied by each participant.

4 Methods of measurement for antennas B and C

4.1 NPL

Calibration method: Standard antenna method & Three antenna method

For frequencies of 200 MHz and above the antennas were calibrated by the three antenna method in a full anechoic chamber, using other similar log periodic antennas to complete the method, acting as the second and third antennas. The measurement separation was 2.5 m between reference points which were about half way along each antenna. The calculation of antenna factor takes into account the phase centre position of each antenna.

Below 200 MHz antenna C was calibrated by the standard antenna method against a calibrated biconical antenna on the NPL Open Field Site. The NPL open field site comprises a 60 m by 30 m metal ground plane, which is flat to within ± 6 mm over approximately 95% of its surface area. A uniform vertical field was generated by a linearly polarised transmitting antenna placed at 20 m separation, and the intercomparison antenna was mounted vertically at 2 m height. All antennas were supported by masts which were constructed of low reflectivity materials. The site attenuation was measured using a HP8753 network analyser and the antenna factor was determined by direct comparison with a calibrated biconical antenna.

System components	Traceability
HP8753 network analyser	Measured voltage ratio and internal generator frequency are both traceable to national standards at NPL.
Length & Separation	Tape measure, manufactured to EC class II.
Ground plane	Flatness is periodically verified using electronic laser surveying equipment.
Biconical antenna	AF calibrated against broadband NPL calculable dipole (SRD 6500).

4.2 ARCS

Antenna B

Calibration method: Three antenna method

A modified ANSI C63.5 three antenna method is used. The distance between the antenna tips is 3 m. The NSA value is calculated between the phase centers of the antenna. The auxiliary antennas are similar the AUT.

System components:

Device	Type
Free Space Test Site	ARCS
Network analyzer	HP 8753B, S/N 2824UO4168 HP 8753D, S/N 341OA04463
Calibration Kit	85054D, S/N 3101A00651 85032D, S/N 3217AO7109
Auxiliary antenna	ARCS LPV (200 MHz to 1 GHz) E0586 E0587
Attenuator	HP 8491B (10 dB) S/N 39641 S/N 39642
Cable	K 185/02 K 186/02

Antenna C

Calibration method: Three antenna method

A modified ANSI C63.5 three antenna method is used. The distance between the antenna tips is 3 m. The NSA value is calculated between the phase centers of the antenna. The auxiliary antennas are identical to the AUT.

System components:

Device	Type
Free Space Test Site	ARCS, 6 m height
Network analyzer	HP 8753B, S/N 2824UO4168 HP 8753D, S/N 341OA04463
Calibration Kit	85054D, S/N 3101A00651 85032D, S/N 3217AO7109
Auxiliary antenna	Chase Bilog CBL6112 s/n 2278 s/n 2280
Attenuator	HP 8491B (10 dB) S/N 39641 S/N 39642
Cable	K 185/02 K 186/02

4.3 NIST

Antenna B

Calibration method: Three antenna method

Test Site: full anechoic chamber (5m x 5m x 8m). Consisting of a shielded enclosure with a combination of 60cm and 90cm RF absorber on all interior surfaces. Test distance was 4.0 m.

System components:

Vector network analyzer, RF cables, half-wave tuned dipole antennas, 3dB attenuators, tripods, full anechoic chamber facility.

Power measurements traceable to NIST power references.
Frequency and length data is traceable through manufacturer's chain.

Note: NIST did not measure antenna C.

4.4 AIST

Antenna B

Calibration method used: Three-antenna method

Description of test site: Semi-anechoic chamber of which the inter-shielding space is 24 m(L)×15 m(W)×9 m(H)

System components: Vector network analyzer (HP8753E)
Additional antennas: Rhode & Schwarz HL223 (S/N: 50 & 51)

Traceability: Frequency was verified against a calibrated frequency counter.
Attenuation was verified against a calibrated stepped attenuator.
Length was verified against a calibrated steel measuring tape.

Calibration of the log-periodic dipole array antenna was carried out by the three-antenna method with two other HL223 antennas in the anechoic chamber. The interval between antenna tips was set to be 9.5 m for all of the measurements. Each pair of antennas was set at the same height and was measured in horizontal polarization. The pairs were vertically scanned together from 3.0 m to 6.0 m at all the frequencies for the purpose of correcting for free-space site-attenuation. The height was measured from the metal floor. The absorber walls in the anechoic chamber had some definite reflection coefficients and the measured raw site-attenuation was different from the ideal free-space one to some degree. The practical free-space site-attenuation between two antennas was estimated from the variation in the measured attenuation along the height changes for every different frequency, and the values were used for the calculation of antenna factors by using an electromagnetic reflection model of the absorber walls. A vector network analyzer (VNA) was used to measure the site-attenuation and the reflection coefficient of each antenna. The VNA was calibrated by a HP85032B calibration kit at the beginning of every measurement.

Antenna C

Calibration method used: Three-antenna method

Description of test site: Semi-anechoic chamber whose inter-shield size is 24 m(L)×15 m(W)×9 m(H)

System components: Vector network analyzer (HP8753E)
Additional antennas: Chase bilog antenna CBL6112 (S/N: 79 & 80)

Traceability: Frequency was verified against a calibrated frequency counter.
Attenuation was verified against a calibrated stepped attenuator.
Length was verified against a calibrated steel measuring tape.

Calibration of the bilog antenna was carried out by a three-antenna method with two other CBL6112 antennas in the anechoic chamber. The distance between antenna tips was set to be 8.5 m for all measurements. Each pair of the antennas was measured at the same height in horizontal polarization. The pairs were scanned together vertically from 3.0 m to 6.0 m at the frequencies 30, 80 and 200 MHz; and from 4.0 m to 5.0 m at the frequencies 1000, 1500 and 2000 MHz. In this way the measurement could be corrected to free-space site-attenuation. The estimated free-space site-attenuation between two antennas was also deductively calculated from the measured height-dependent attenuations using a reflection model of absorber walls for every measurement frequency. For the lowest two frequencies a different model, combining a dipole antenna and the reflection condition of absorber walls, was adopted because the CBL6112 antenna had a similar directivity as that of the dipole antenna. Thus the characteristics of the calculable dipole antennas were used to estimate free-space attenuation between antenna ports. A vector network analyzer (VNA) was used to measure the site-attenuation and the reflection coefficient of these antennas. The VNA was calibrated with HP85032B calibration kit in advance at every measurement.

4.5 LNE

Calibration method: Standard antenna method

Description of test site: Open-field site, (15 m ×10 m). The antennas were horizontally polarised, at a separation distance of 10 m and height of 4 m.

System components	Traceability
Calculable dipole antenna	Calculable
Spectrum analyser	Verified by manufacturer's calibration
HF synthesizer	Verified by manufacturer's calibration

4.6 METAS

Calibration method: Standard antenna method

The measurements of the antenna factors is traceable to power ratio (attenuation), frequency, and length (antenna separation). The method used is ANSI Reference Antenna Method. The antennas have been placed in horizontal polarisation at 3.6 m above ground. Measurements are performed in a fully anechoic room whose dimensions are 8 m x 6 m x 7 m (height).

System Components	Traceability
• Network Analyser Rohde and Schwarz 10Hz/9kHz - 4GHz ZVR	Power Ratio: manufacturer calibration Frequency: manufacturer calibration
• Leica Disto Classic (laser system for measuring distances)	Length: manufacturer calibration

The following tables give details of which reference antenna was used, and the effective separation between antennas.

Antenna B

Freq [MHz]	Reference Antenna	Tip-tip dist. [m]	Phase center [m]	Phase center 2	Eff. dist. [m]
200	PRD Seibersdorf 200 MHz	4.411	0.54		4.951
280	PRD Seibersdorf 250 MHz	4.301	0.38		4.681
280	PRD Seibersdorf 300 MHz	4.262	0.38		4.642
900	PRD Seibersdorf 900 MHz	4.45	0.09		4.540

Antenna C

Freq [MHz]	Reference Antenna	Tip-tip dist. [m]	Phase center [m]	Phase center 2	Eff. dist. [m]
30	PRD Seibersdorf 30 MHz	3.856	1.04	0.00	4.896
30	Schwarzbeck bilog VULB 9161				4.772
80	PRD Seibersdorf 80MHz	3.325	1.04	0.00	4.360
200	PRD Seibersdorf 200MHz	3.727	0.82	0.00	4.547
1000	PRD Seibersdorf 1000MHz	3.718	0.26	0.00	3.978
1500	Log Per Schwarzbeck VUSLP 9111 (182)	3.633	0.16	0.06	3.848
2000	Log Per Schwarzbeck VUSLP 9111 (182)	3.642	0.10	0.04	3.777

4.7 SP

Calibration method: Standard antenna method

Description of test site:
For frequencies up to 1000 MHz the measurements were done on an Open Area Test Site (OATS), with ground plane 20 m × 17 m. On the plane there is a permanently mounted wood and plastic shelter which protects the turntable and EUT during radiated emission measurements. During antenna calibration a diagonal measurement set-up is used to avoid interference by this shelter. Above 1000 MHz the measurements were done in an anechoic chamber (8m × 5m × 5m) at a separation of 4 m.

The antennas were calibrated by substitution, using a Schaffner precision dipole as the reference antenna.

Antenna B
A slightly modified ANSI Reference Antenna Method was used. Antenna 1 (Tx) was set at 2 m height above the ground plane, and antenna 2 (Rx, reference antenna & AUT) was set to the position of maximum field strength. The measurement distance was 10 m.

OATS measurement system

System components	Traceability
Schaffner reference antenna (broadband dipole)	Calibrated at NPL
Signal Generator R&S SMY 01	Physikalisch-Technische Bundesanstalt (PTB)
Test Receiver R&S ESVS 10	Physikalisch-Technische Bundesanstalt (PTB)
Power Meter Boonton 4200 RF	Nederlands Meetinstituut (NMi)

Antenna C

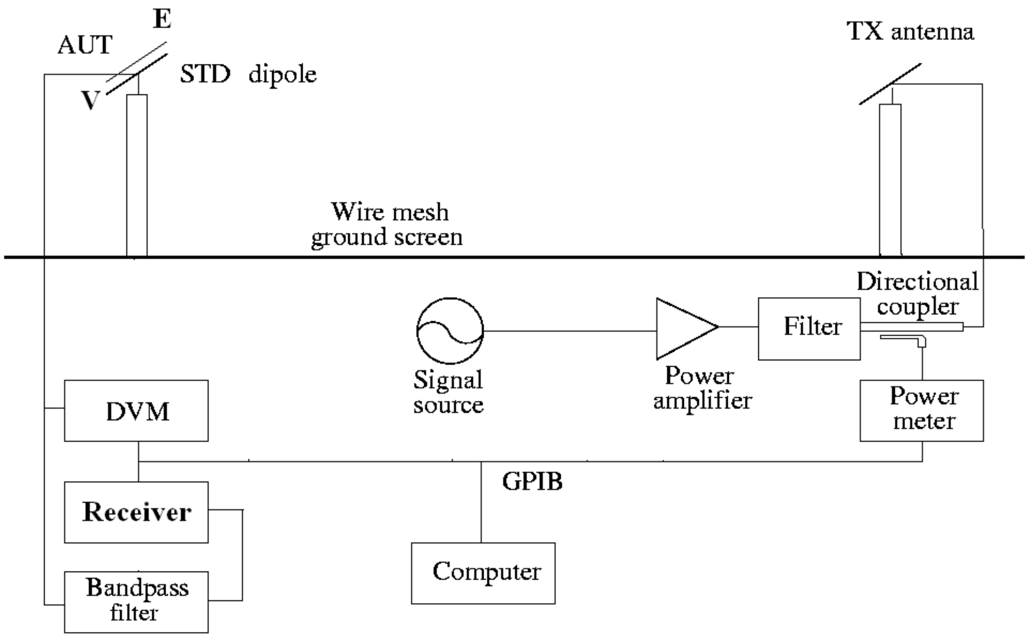
The same measurement system was used as for Antenna B, except for above 1000 MHz which was measured in a fully anechoic chamber.

Anechoic chamber measurement system

System components	Traceability
Standard gain horn	Gain calculated by theory using software
Signal Generator R&S SMR 40	Physikalisch-Technische Bundesanstalt (PTB)
Power Meter Boonton 4200 RF	Nederlands Meetinstituut (NMi)
Amplifier AR 100 S1G4	

4.8 KRISS

Description of test site:



Calibration of Antenna B

Measurements were done at the open area test site (OATS) of 30 m wide and 60 m long. An LPDA antenna is used as a transmitting (TX) antenna. The antenna under test (AUT) from NPL and a standard dipole (STD dipole) antenna from KRISS are used as receiving antennas. The transmitting antenna is positioned horizontally at 2 m above ground. The receiving antennas are positioned at 3.01 m, 4.03 m, and 3.95 m above ground for 200 MHz, 280 MHz, and 900 MHz measurements, respectively. The distance between the transmitting and the receiving antennas is 10.0 m.

At first, the STD dipole antenna is positioned at the height of measurement. Induced RF voltage on the STD dipole is detected by an antenna voltmeter, and the detected DC voltage is measured with a DVM (digital voltmeter). The incident field strength (E) is calculated from the RF open circuit voltage induced and the effective length of the STD dipole antenna calculated by a numerical method. The open circuit voltage is obtained using the RF-DC conversion factor of the antenna voltmeter.

The AUT is then substituted at the same position as the STD dipole. Received RF signal is measured with an RF receiver through 50 ohm coaxial cable. To measure the RF voltage (V) onto 50 ohm at the output terminal of the AUT, the RF signal power should be measured. For this purpose, after detaching the AUT, RF signal (calibrated with a standard power sensor) is applied directly through the receiving coaxial cable and the power level of the signal is adjusted with a step attenuator until the receiver reads the same value as that when the AUT is connected to the receiver.

Due to ground reflection and radiation pattern of the AUT, antenna factor calculated from the measured E and V is height dependent. To compensate for this radiation pattern effect, we obtained the radiation patterns of the AUT and the TX antenna by measuring the height patterns of the antennas with a dipole antenna. Then the antenna factor in the direction of bore-sight is determined from a simple geometrical calculation.

Measurement system below 1000 MHz

System components	Traceability
Antenna voltmeter (KRISS)	Standard thermistor mount, network analyzer (calibration kit)
Step attenuator	Attenuation calibration system
Power sensor and power meter	Standard thermistor mount
DVM	DC voltage

Calibration of Antenna C

For frequencies 30 MHz, 80 MHz, and 200 MHz, the Standard antenna method was used. The system was the same as for Antenna B except that a biconical antenna was used as a transmitter.

For the high frequencies (1000 MHz, 1500 MHz, and 2000 MHz), the three antenna method was used. The measurement method used two other antennas, either two standard dipole antennas or two LPDA wideband antennas which operate in this frequency range. An automatic vector network analyser is used to measure the attenuation between the transmitting and the receiving antennas. The TX antenna is positioned horizontally at 3.72 m above ground, and the separation to the RX antenna is 2.28m. The receive (RX) antenna is height-scanned from 3.5 m to 4.0 m. Ground reflections are separated from direct waves by using a numerical modelling of the antenna radiation pattern and measurement geometry. AF is then calculated using only the direct wave components between the transmitting and the receiving antenna.

Measurement system for 1000 MHz and above

System components	Traceability
Network analyser	Network analyser (calibration kit)
Step attenuator	Attenuation calibration system
Power sensor and power meter	Standard thermistor mount

5 Methods of measurement for antennas D, E, and F

5.1 NMi-VSL

Antenna D

The Rod antenna was measured using a Scalar Network Analyser (SNA) and a dummy antenna, as described in SAE ARP958 and CISPR 16-1 amendment 1.

System components	Traceability All devices are part of the yearly routine maintenance of the Dutch national standards. In this measurement the traceability claim is only valid on the insertion loss measurement.
Dummy antenna 10 pF; NMi-VSL made	Capacitance NMi-VSL calibrated
Lock-in analyser SR 830	NMi-VSL calibrated
50 ohm terminations	NMi-VSL calibrated
SNA HP 8711B +Calibration kit	Calibration kit NMi-VSL calibrated

The rod of the monopole antenna was not installed, but instead a VSL dummy antenna (approximately 10 pF, but actual = 13 pF), designed for this purpose and configured according to the ARP and CISPR standards mentioned, was mounted on the device. Insertion loss measurements were performed using the SNA for the higher frequencies and the lock-in analyser for the lower frequency range. A 10 dB BNC attenuator was used at the source side (input of the device) and a 9 dB BNC attenuator (consisting of the combination of a 6 and a 3 dB BNC attenuator) at the detecting side.

Since NMi-VSL does not have an outdoor site adequate for calibration of monopole antennas the dummy antenna method described in the ARP and CISPR standards has to be used. These standards employ on mathematical basis a dummy of 10 pF to substitute the capacitance of the 1 m Rod antenna. However when taking into account the actual diameter of the rod (30 mm) and using the formulas from the standard the capacitance will have a value of 17 pF. The actual measurements were performed using a 13 pF dummy. Since the input impedance of the antenna electronics is about a 8 pF over a >100 kΩ resistance at 1 MHz, the influence of this deviation cannot be neglected. This problem is not currently considered in the standards, however recent work at NPL has clarified the situation (see Conclusion).

Antenna E

The active loop antenna measurements were performed using two different facilities (TEM cell and Helmholtz coil), in combination with a Scalar Network Analyser (SNA) at the higher frequency range or a lock-in analyser at the lower frequency range. Measurements were performed at field levels from 20 dBµA/m up to 60 dBµA/m. From 20 Hz up to 20 kHz measurements were performed in a set of Helmholtz coils. Measurements from 10 kHz up to 40 MHz were performed in a TEM cell (75 cm septum height).

System components	Traceability All devices are part of the yearly routine maintenance of the Dutch national standards
Helmholtz coils; NMi-VSL made	NMi-VSL calibrated
TEM cell; NMi-VSL made	NMi-VSL calibrated
Lock-in analyser SR 830	NMi- VSL calibrated
50 ohm terninations	NMi-VSL calibrated
SNA HP 8711B +Calibration kit	Calibration kit NMi-VSL calibrated
BNC Attenuators 3; 6 and 10 B	NMi-VSL calibrated
N type 30 dB attenuator	NMi-VSL calibrated

Antenna F

Measurements from 20 Hz up to 20 kHz at levels from 120 dBµA/m up to 140 dBµA/m were performed in a set of Helmholtz coils. Measurements from 1 kHz up to 100 kHz at the level of 60 dBµA/m were performed in a TEM cell. The passive antenna measurements were performed using the lock-in analyser.

System components	Traceability All devices are part of the yearly routine maintenance of the Dutch national standards
Helmholtz coils; NMi-VSL made	NMi-VSL calibrated
TEM cell; NMi-VSL made	NMi-VSL calibrated
Lock-in analyser SR 830	NMi- VSL calibrated
50 ohm terninations	NMi-VSL calibrated
BNC Attenuators 3; 6 and 10 B	NMi-VSL calibrated
N type 30 dB attenuator	NMi-VSL calibrated

5.2 AIST

Antenna D

Calibration method : Three antenna method

Description of test site: OATS which has welded steel ground plane of 30m by 50m.

Calibration of the monopole antenna was carried out at the OATS by a three antenna method with two additional passive monopole antennas. The transmitting and receiving antennas were set vertically on the ground plane. Horizontal separation between the centre points of these two antenna elements was set to the distance of 1.5 m. The vector network analyzer (VNA) was calibrated by the Agilent 85032B calibration kit before every measurement. In spite of the short range of the measurement, since the sensitivity of the passive monopole antenna was not sufficient at 10 kHz no data was provided at this frequency.

System components	Traceability
Combination Analyzer (Agilent 4395A, used as Vector Network Analyzer) Test Set (Agilent 87512A) Two additional Passive monopole antennas: A.H. System MODEL SAS-551 (S/N: 194, & 195)	Frequency is verified against a calibrated frequency counter. Attenuation is verified against a calibrated stepped attenuator. Length is verified against a calibrated steel measure.

Antenna E

Calibration method used: Three antenna method

Description of test site: Anechoic chamber whose size is 15m(L) × 10m(W) × 8m(H)

Calibration of this active loop antenna was carried out by a three antenna method with two additional passive loop antennas on a long, thin wooden table. The table was set at the effective floor level in the anechoic chamber, which was at the top of pyramidal absorbers placed on the bottom shield material (lined with ferrites). The distance between the top of the table and the bottom shielding material was 1.8 m. A pair of loop antennas was set parallel with each other on the wooden table. In order to set the centres of the loops to the same level, a polystyrene foam block was used for trimming in height. The separation between centre points of the transmitting and receiving loop antenna elements was 0.5 m. The vector network analyzer (VNA) was used to measure the transmission S-parameter between two antennas. The VNA was calibrated by Agilent85032B calibration kit in advance before every measurement.

System components	Traceability
Combination Analyzer (Agilent 4395A, used as Vector Network Analyzer) Test Set (Agilent 87512A) Two additional Passive loop antennas: EMCO MODEL6512 (S/N: 9309-1142, & 9309-1143)	Frequency is verified against a calibrated frequency counter. Attenuation is verified against a calibrated stepped attenuator. Length is verified against a calibrated steel measure.

Antenna F

Calibration method used: Three antenna method

Description of test site: Anechoic chamber whose size is 15m(L) × 10m(W) × 8m(H)

Calibration of this passive loop antenna was carried out by a three antenna method with two additional passive loop antennas of the same model on the wooden table set in the anechoic chamber. A pair of loop antennas was set parallel on the wooden table. This table was located at the centre of the anechoic chamber. The separation between centre points of transmitting and receiving loop antenna elements was 0.1 m. The height of the top of the table is 1.8 m from the floor shielding surface (ferrite). There was some absorber and a foam polystyrene board between this table and the ferrites. The vector network analyzer (VNA) was used to measure transmission S-parameter between the two antennas. The VNA was calibrated by Agilent85032B calibration kit before every measurement.

System components	Traceability
Combination Analyzer (Agilent 4395A, used as Vector Network Analyzer) Test Set (Agilent 87512A) Two additional passive loop antennas: EMCO MODEL7604 (S/N: 2590, 2593)	Frequency is verified against a calibrated frequency counter. Attenuation is verified against a calibrated stepped attenuator. Length is verified against a calibrated steel measure.

5.3 NPL

Antenna D

Calibration method used: Standard antenna method

The monopole was calibrated in a GTEM cell against a passive reference monopole antenna. The antenna factor of the reference monopole has been calculated using numerical code, and verified by site insertion loss measurements on the 60 m × 30 m ground plane at NPL. The intercomparison antenna was placed on the floor of the GTEM and its response measured by a scalar network analyser. The antenna is then substituted by a passive standard of the same height. The GTEM measurement system has been developed in such a way that it emulates the performance of the antenna under test when placed on a large ground plane. Below 30 MHz the antenna impedance is very high so there is relatively little coupling with the side walls of the GTEM cell.

System components	Traceability
HP3589A Scalar Network Analyser	NPL attenuation and frequency standards.
GTEM cell (MEB 1750)	Septum height checked against a traceable steel rule.
Passive standard monopole	Calculable AF, verified by measurements on the NPL ground plane.

Loop E and F

These loops were measured by two independent methods. The measurement using a Helmholtz coil system is labelled NPL(1), and the measurement in a Crawford TEM cell is labelled NPL(2).

NPL(1) Calibration method: Helmholtz coil

The antennas were individually mounted at the centre of a calibrated Helmholtz coil. The voltage induced in the antenna was measured for a 50 Ω load at a series of frequencies in the range 20 Hz to 100 kHz.

The calibration of the Helmholtz coil at DC for coil constant (ratio of magnetic field strength to current) was made using a proton resonance magnetometer ELSEC 820 (S/N 002612) to measure the magnetic flux density. The current was measured using a calibrated resistor and calibrated DVM. For this calibration the ambient magnetic field strength was reduced to less than 1 nT using a three axis cancellation system. The AC calibration of the Helmholtz coil used a single turn search coil to establish the frequency response normalised to the DC value. For the AC calibration and the generation of known magnetic flux densities, shunts with calibrated DC and AC/DC difference values were used.

NPL(2) Calibration method: Standard field method

The loop was positioned at the centre of a Crawford Type TEM Cell with the plane of the loop perpendicular to the magnetic field and parallel to the direction of propagation. The output from the loop was connected to a calibrated 50 Ω receiver. A tracking generator and amplifier were used to set up a calculable, linearly polarised, electromagnetic field in the TEM cell, approximating to a plane wave. Below 500 Hz a correction was made to account for the change in TEM cell wave impedance at low frequency.

At each frequency, the ratio of the TEM cell voltage to the terminated loop output voltage was measured and used to calculate the antenna factor according to the following definition.

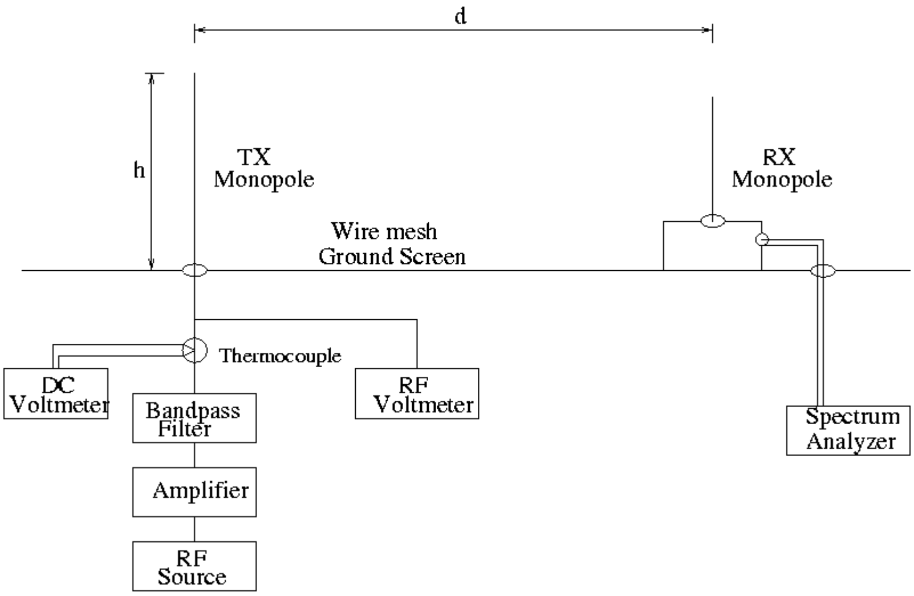
$$H\ [\mathrm{dB}(\mu\mathrm{A/m})] = V\ [\mathrm{dB}(\mu\mathrm{V})] + K\ [\mathrm{dB}(\mathrm{S/m})]$$

where: H is the magnetic field strength in dB referenced to 1 μA/m
V is the correctly terminated output voltage from the loop
K is the magnetic antenna factor

5.4 KRISS

Antenna D

Calibration method used: Standard field method



The antenna factor measurements were done on an OATS (Open Area Test Site) 30 m wide and 60 m long. The distance between the transmitting and receiving antenna is 10.53 m. At frequencies below 30 MHz, the transmitting monopole base current is calculated from the base voltage measured with an RF voltmeter and the input impedance. At frequencies above 30 MHz, the base current is measured with an antenna voltmeter consisting of a thermo-element. The electric field strength is calculated in terms of the monopole base current and the geometry of the transmitting and the receiving monopole. The output voltage of the receiving monopole is measured with a spectrum analyzer (receiver).

System components	Traceability
- Signal source	Standard thermistor mount, attenuation calibration system
- RF voltmeter	Standard thermal voltage converter
- Thermo-element	DC current, standard thermistor mount
- Spectrum analyzer (receiver)	Standard thermistor mount, attenuation calibration system
- Step attenuator	Attenuation calibration system
- Power sensor and power meter	Standard thermistor mount
- DVM	DC voltage

Antenna E (Active Loop) and Antenna F (Passive Loop)

Calibration method used: Standard field method

Standard magnetic field is generated using a standard transmitting loop antenna, which is a shielded loop with TE (thermo-element) connected at its feed gap. The loop current is determined by measuring the TE output voltage with a DVM. The antenna under test (AUT) is aligned coaxially with the standard antenna at the distance of 25 cm to 75 cm. The average magnetic field is calculated from the measured diameters of the standard loop and the AUT, the distance between them, and the loop current. The antenna factor is obtained from the average magnetic field and the measured voltage at a receiver. As receiver, a spectrum analyzer and a signal analyzer are used and the measured values are corrected using a calibrated step attenuator and a calibrated power sensor. To minimize the mismatch effect, a 6 dB pad is used at the receiver input.

System components	Traceability
- Signal source	Standard thermistor mount, attenuation calibration system
- Thermo element	dc current, standard thermistor mount
- Receiver	Standard thermistor mount, attenuation calibration system
- Step attenuator	Attenuation calibration system,
- Power sensor and power meter	Standard thermistor mount
- DVM	dc voltage

6 Stability of standard

Participants were requested to measure the complex S11 for antennas B and C when they were placed in the measurement configuration. This provides some feedback on the stability of the antennas during the period of the intercomparison work, and also the relative difference between measured S11 values gives an approximate indication of the quality of the environment in the measurement facility of each participant. For example, a significant variation may indicate that one laboratory had some unwanted coupling with a nearby conductor.

Figure 6-1 : S11 of Antenna B at 200 MHz

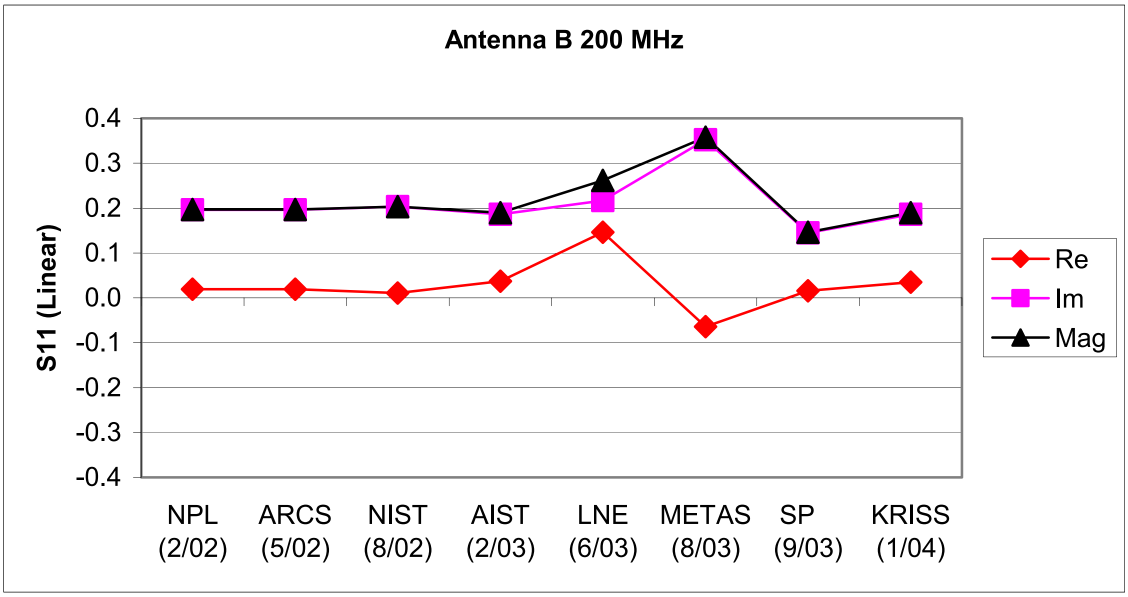


Figure 6-2 : S11 of Antenna B at 280 MHz

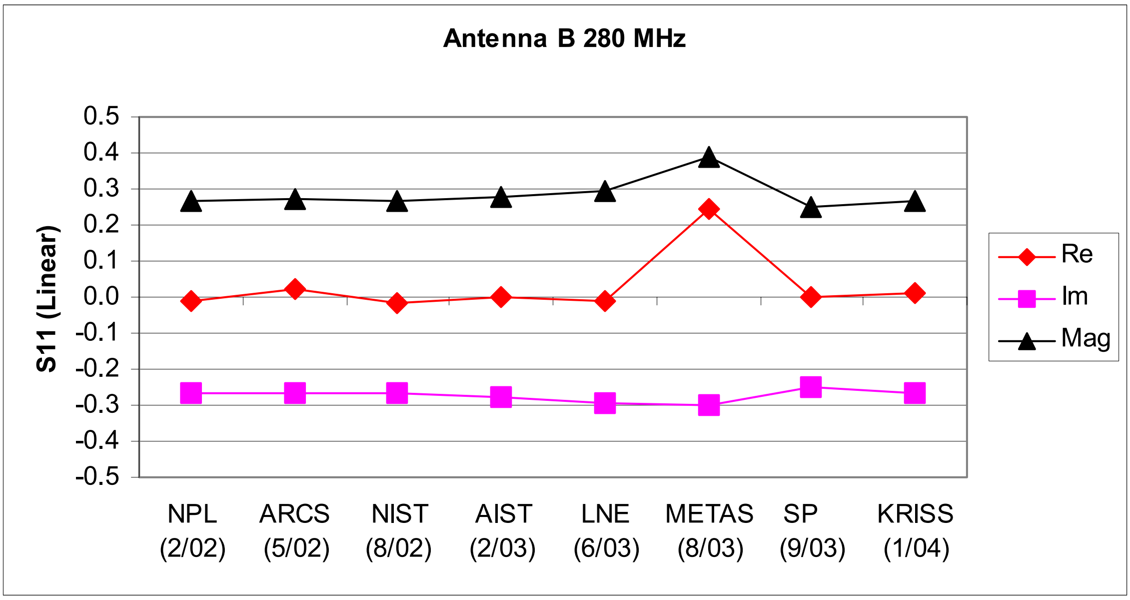


Figure 6-3 : S11 of Antenna B at 900 MHz

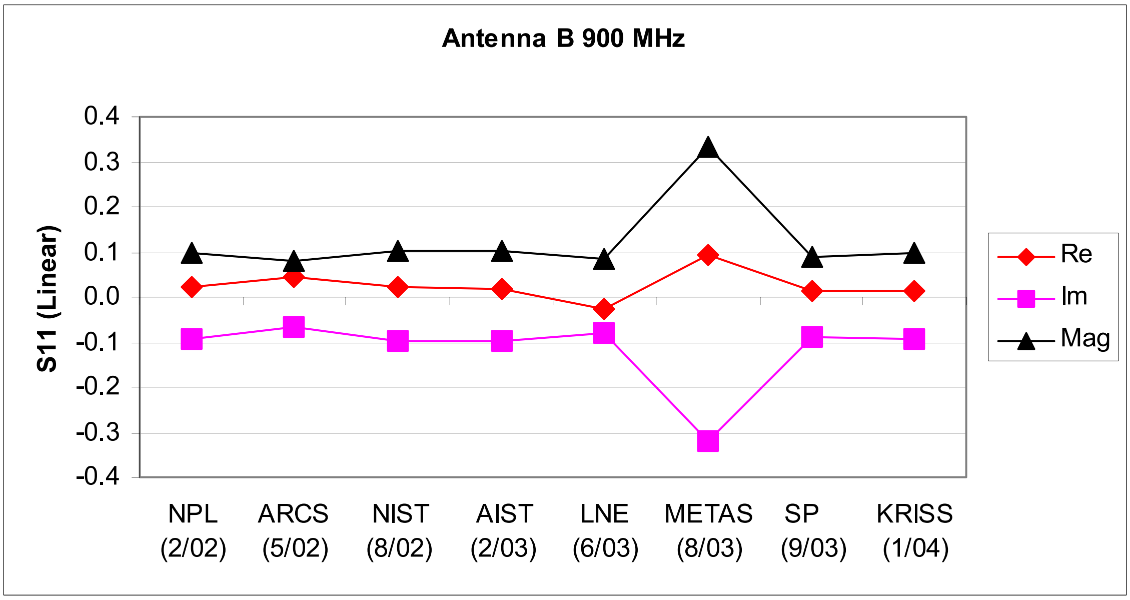


Figure 6-4 : S11 of Antenna C at 30 MHz

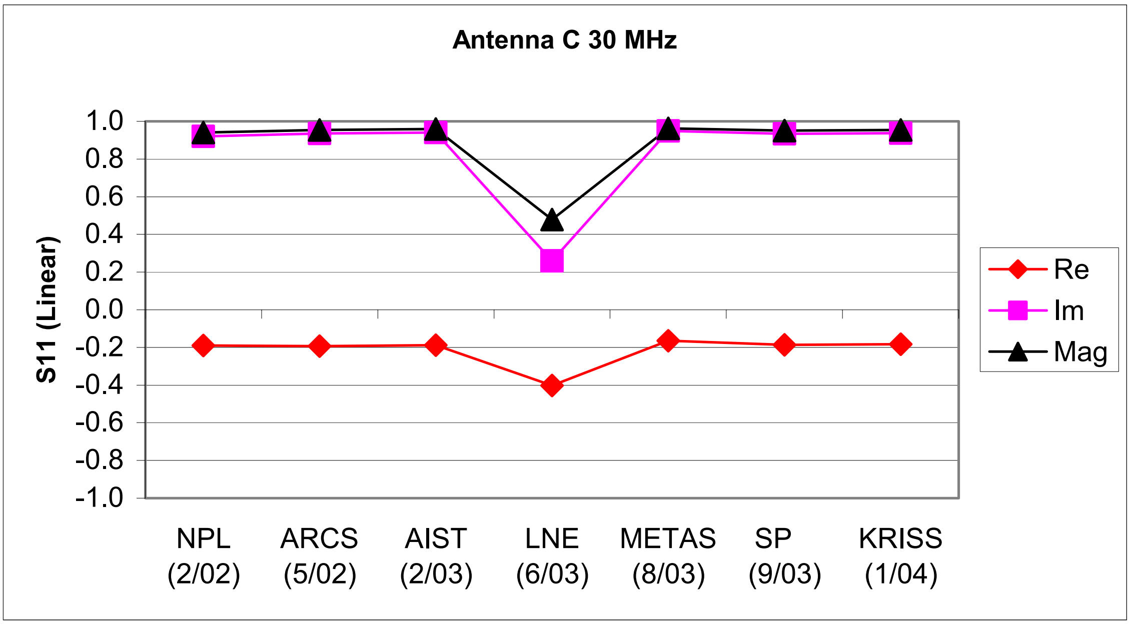


Figure 6-5 : S11 of Antenna C at 80 MHz

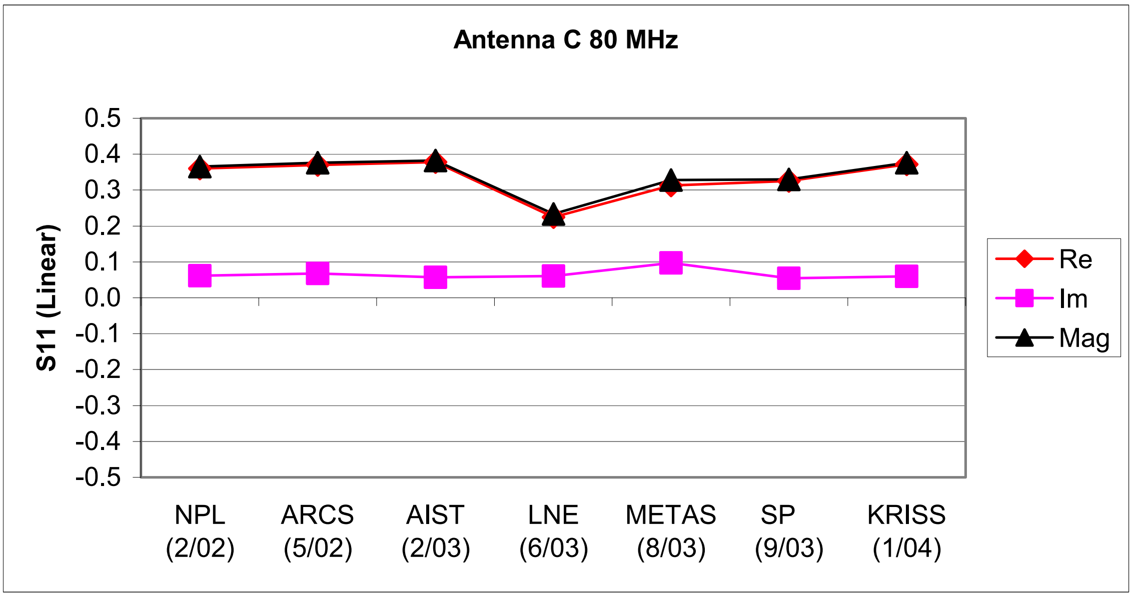


Figure 6-6 : S11 of Antenna C at 200 MHz

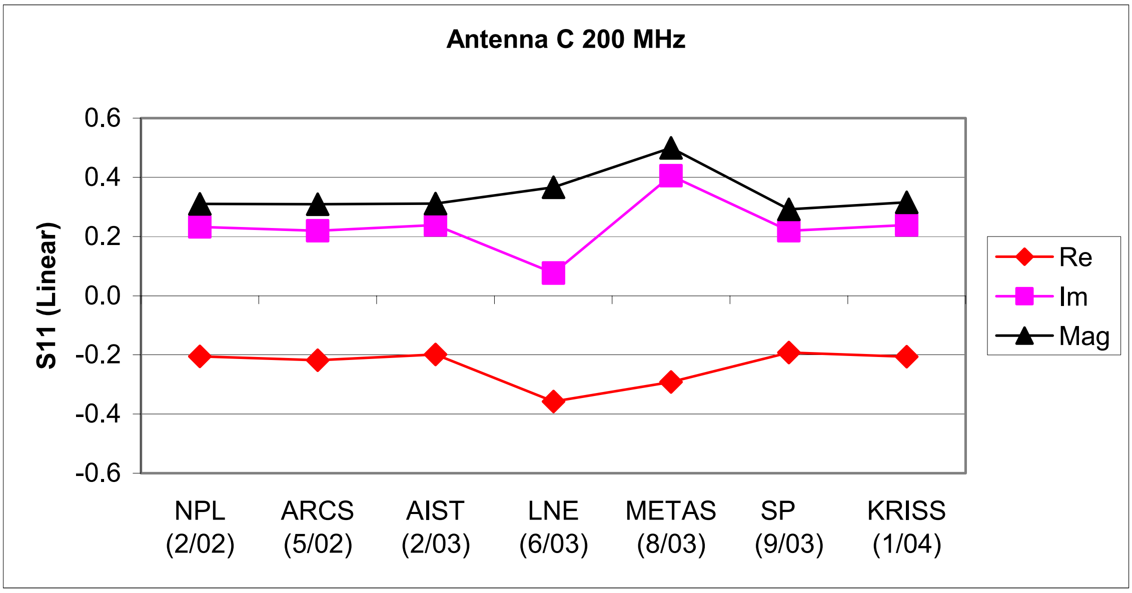


Figure 6-7 : S11 of Antenna C at 1000 MHz

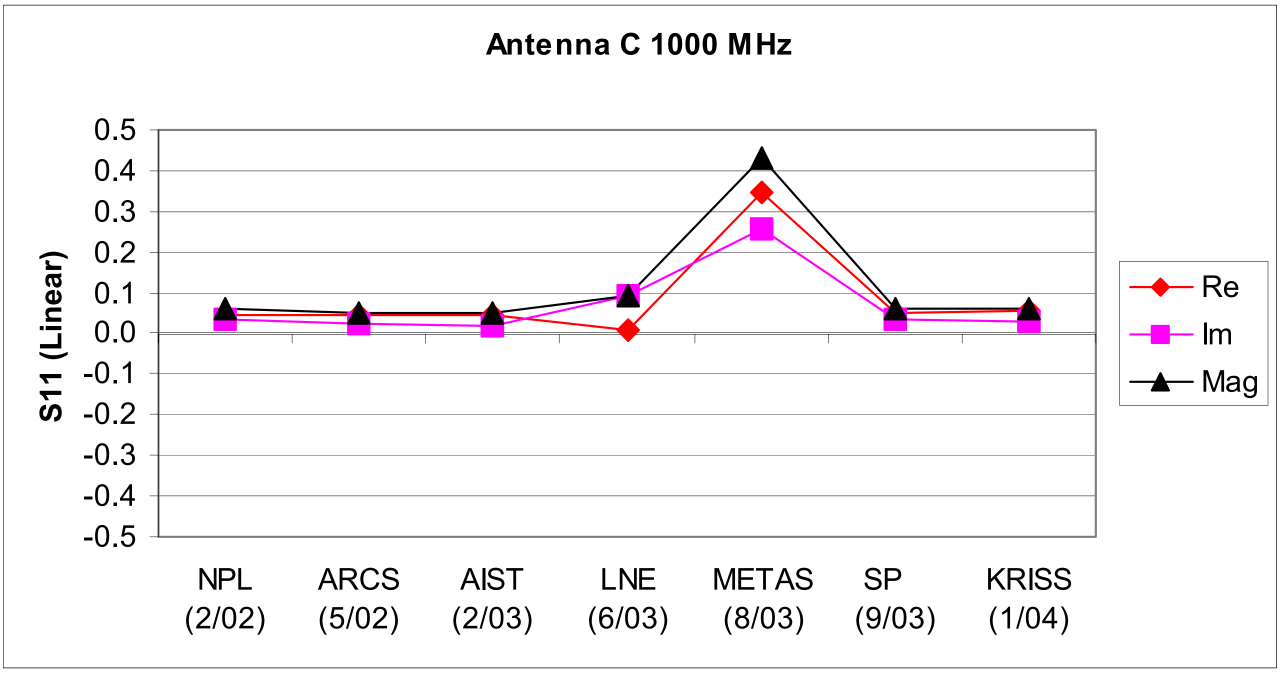


Figure 6-8 : S11 of Antenna C at 1500 MHz

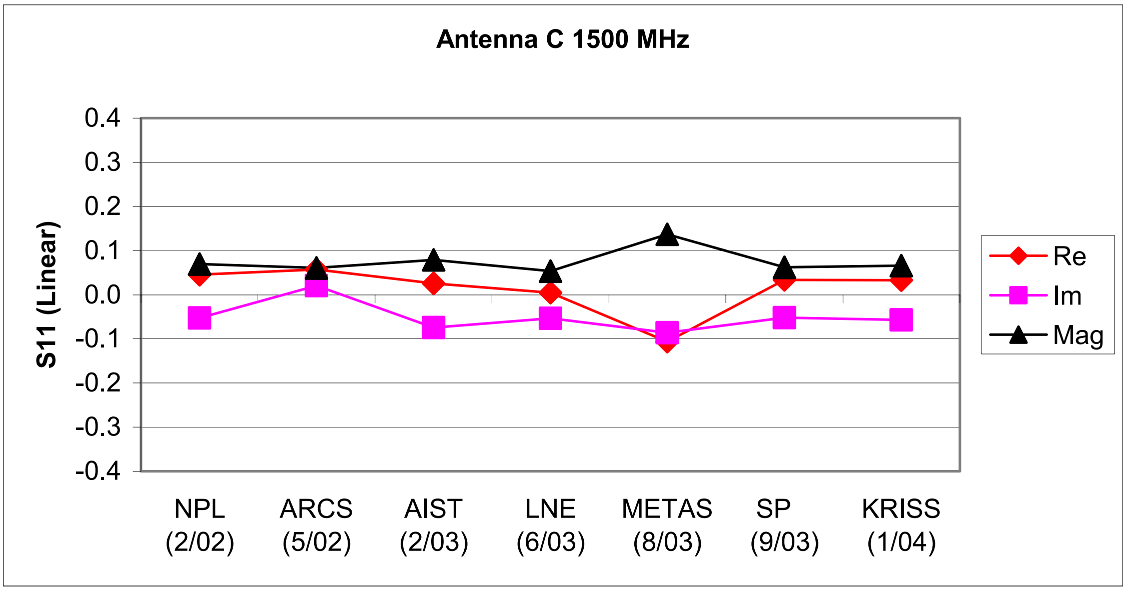
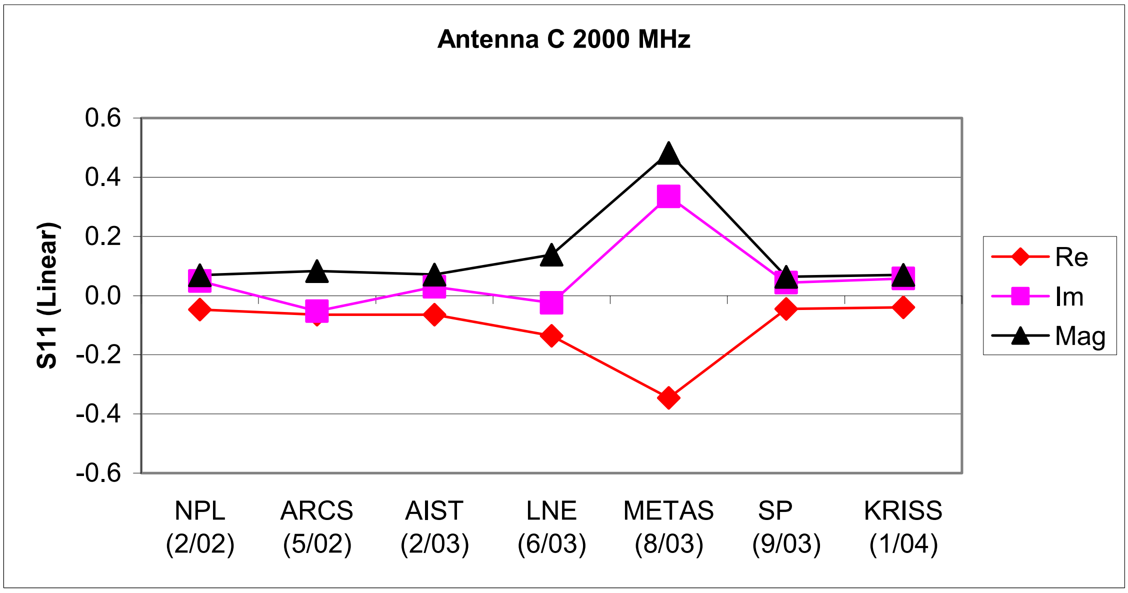


Figure 6-9 : S11 of Antenna C at 2000 MHz



7 Intercomparison results

7.1 Evaluating Reference Value

The Reference Value (RV) and the associated uncertainties have been calculated using the guidance given by Reference [1]. In order to avoid systematic bias when calculating Median of Absolute Deviations, S(MAD), the two NPL values for each of the antennas B, C, and D were averaged together and treated as a single measurement. The two NPL measurements of antennas E and F (loops) were independent so they are treated as separate results and they are not averaged.

Once the median value and S(MAD) were evaluated, each NPL result was compared separately to the specified limit, together with the results from the other participants, and those which exceeded the limit were excluded from the RV calculation. The excluded results are reported in the note attached to the relevant table of Degree of Equivalence.

In the technical protocol for this intercomparison it was stated that the un-weighted mean would be used for the RV, which is just the average of all those results which pass the test against the S(MAD) described above. For antennas B, C, and D, where both NPL results passed the test against S(MAD) their average value was used in the calculation of RV, which effectively assigns a weighting of half to each NPL result. There are two possible methods we can use to determine the variance in the un-weighted mean, and these are described in parts (b) and (c) of Reference[2]. The method used here is effectively the expression given for the weighted case but with equal weights applied to the data, which is described in part (b). J Randa in Reference [1] labels this same approach as the 'un-weighted case', but mathematically it is identical because when the weights are equal we may use the standard expression for sample variance to calculate the variance in the RV.

Therefore the RV is given by:

$$X_{RV} = \frac{1}{N}\sum_{j=1}^{N} X_j$$ (N = number of results which pass the S(MAD) test)

The uncertainty in RV is given by:

$$u_{RV}^2 = \frac{\sum_{j=1}^{N}(X_j - X_{KCRV})^2}{N(N-1)}$$

The Degree of equivalence for each laboratory is simply:

$$D_i = (X_i - X_{RV})$$

The variance in the Degree of Equivalence is given by the following expression.

$$VAR(X_i - X_{RV}) = VAR(X_i) + VAR(X_{RV}) - 2 \cdot COVAR(X_i, X_{RV})$$

In the case where there is no correlation between laboratories, the covariance term is equal to $VAR(X_i)/N$ for those data points which were included in the RV, and the term is zero for excluded results. From the above expression the uncertainty in D_i (at 95% confidence) is given by:

$$U(D_i) = 2 \cdot \sqrt{u_{RV}^2 + u_i^2} \qquad \text{(for excluded results)}$$

$$U(D_i) = 2 \cdot \sqrt{u_{RV}^2 + \left(1 - 2/N\right) \cdot u_i^2} \qquad \text{(for all other results)}$$

Where u_i is the uncertainty of each laboratory, and N is the number of data points included in the calculation of RV.

For the matrix of equivalence between laboratories we use the following expressions:

$$D_{ij} = (X_i - X_j)$$

$$U(D_{ij}) = 2 \cdot \sqrt{u_i^2 + u_j^2}$$

All the expressions used here assume there is no correlation between laboratories.

7.2 Calculated Degree of Equivalence for antennas B and C.

The calculated Degrees of Equivalence are shown in Table 7-1 to Table 7-9. All the uncertainties in the tables are presented at the 95% confidence level.

The Degrees of Equivalence are illustrated in Figure 7-1 to Figure 7-9. The limit bars show the calculated $U(D_i)$ at each point.

The unit of the intercomparison is antenna factor which is described in Section 3.2. It is standard practice to quote this unit as a dB quantity, so consequently the measurement uncertainty is also given in dB. The degree of equivalence is given as the difference in dB between the Reference Value and each measured value.

Table 7-1 : Degree of Equivalence for Antenna B (Rohde & Schwarz HL223 LPDA) at 200 MHz. RV = 10.25 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.063 dB.

Degree of Equivalence with RV			Lab(j)																	
			ARCS		NIST		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	-0.001	0.441			0.25	2.02	0.05	1.51	-0.85	1.49	-0.08	0.99	0.13	1.10	-0.26	1.12	-0.11	0.86	-0.09	0.86
NIST	-0.251	1.661	-0.25	2.02			-0.20	2.42	-1.10	2.41	-0.33	2.14	-0.12	2.19	-0.51	2.20	-0.36	2.08	-0.34	2.08
AIST	-0.051	1.207	-0.05	1.51	0.20	2.42			-0.90	1.99	-0.13	1.66	0.08	1.73	-0.31	1.74	-0.16	1.58	-0.14	1.58
LNE	0.849	1.406	0.85	1.49	1.10	2.41	0.90	1.99			0.77	1.64	0.98	1.71	0.59	1.72	0.74	1.57	0.76	1.57
METAS	0.079	0.738	0.08	0.99	0.33	2.14	0.13	1.66	-0.77	1.64			0.21	1.30	-0.18	1.32	-0.03	1.11	-0.01	1.11
SP	-0.131	0.838	-0.13	1.10	0.12	2.19	-0.08	1.73	-0.98	1.71	-0.21	1.30			-0.39	1.40	-0.24	1.20	-0.22	1.20
KRISS	0.259	0.854	0.26	1.12	0.51	2.20	0.31	1.74	-0.59	1.72	0.18	1.32	0.39	1.40			0.15	1.22	0.17	1.22
NPL(1)	0.109	0.605	0.11	0.86	0.36	2.08	0.16	1.58	-0.74	1.57	0.03	1.11	0.24	1.20	-0.15	1.22			0.02	0.99
NPL(2)	0.089	0.605	0.09	0.86	0.34	2.08	0.14	1.58	-0.76	1.57	0.01	1.11	0.22	1.20	-0.17	1.22	-0.02	0.99		

Note

After testing against the Median of Absolute Deviation LNE were excluded from the calculation of Reference Value (RV).

Table 7-2 : Degree of Equivalence for Antenna B (Rohde & Schwarz HL223 LPDA) at 280 MHz. RV = 12.77 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.057 dB.

Degree of Equivalence with RV			Lab(j)																	
			ARCS		NIST		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	-0.194	0.448			-0.12	2.02	-0.26	1.15	-0.02	1.49	-0.44	0.80	-0.38	1.10	-0.11	1.12	-0.21	0.71	-0.24	0.71
NIST	-0.074	1.701	0.12	2.02			-0.14	2.22	0.10	2.41	-0.32	2.06	-0.26	2.19	0.01	2.20	-0.09	2.02	-0.12	2.02
AIST	0.066	0.908	0.26	1.15	0.14	2.22			0.24	1.74	-0.18	1.21	-0.12	1.43	0.15	1.44	0.05	1.15	0.02	1.15
LNE	-0.174	1.218	0.02	1.49	-0.10	2.41	-0.24	1.74			-0.42	1.53	-0.36	1.71	-0.09	1.72	-0.19	1.49	-0.22	1.49
METAS	0.246	0.549	0.44	0.80	0.32	2.06	0.18	1.21	0.42	1.53			0.06	1.16	0.33	1.18	0.23	0.80	0.20	0.80
SP	0.186	0.856	0.38	1.10	0.26	2.19	0.12	1.43	0.36	1.71	-0.06	1.16			0.27	1.40	0.17	1.10	0.14	1.10
KRISS	-0.084	0.873	0.11	1.12	-0.01	2.20	-0.15	1.44	0.09	1.72	-0.33	1.18	-0.27	1.40			-0.10	1.12	-0.13	1.12
NPL(1)	0.016	0.448	0.21	0.71	0.09	2.02	-0.05	1.15	0.19	1.49	-0.23	0.80	-0.17	1.10	0.10	1.12			-0.03	0.71
NPL(2)	0.046	0.448	0.24	0.71	0.12	2.02	-0.02	1.15	0.22	1.49	-0.20	0.80	-0.14	1.10	0.13	1.12	0.03	0.71		

Table 7-3 : Degree of Equivalence for Antenna B (Rohde & Schwarz HL223 LPDA) at 900 MHz. RV = 22.68 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.156 dB.

Degree of Equivalence with RV			Lab(j)																	
			ARCS		NIST		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	0.070	0.534			-0.45	2.02	0.21	1.21	-0.65	1.87	0.66	0.65	0.47	1.10	0.29	1.12	0.04	0.71	0.02	0.71
NIST	0.520	1.726	0.45	2.02			0.66	2.25	-0.20	2.66	1.11	2.00	0.92	2.19	0.74	2.20	0.49	2.02	0.47	2.02
AIST	-0.140	1.003	-0.21	1.21	-0.66	2.25			-0.86	2.11	0.45	1.18	0.26	1.47	0.08	1.49	-0.17	1.21	-0.19	1.21
LNE	0.720	1.590	0.65	1.87	0.20	2.66	0.86	2.11			1.31	1.85	1.12	2.05	0.94	2.06	0.69	1.87	0.67	1.87
METAS	-0.590	0.480	-0.66	0.65	-1.11	2.00	-0.45	1.18	-1.31	1.85			-0.19	1.07	-0.37	1.08	-0.62	0.65	-0.64	0.65
SP	-0.400	0.905	-0.47	1.10	-0.92	2.19	-0.26	1.47	-1.12	2.05	0.19	1.07			-0.18	1.40	-0.43	1.10	-0.45	1.10
KRISS	-0.220	0.921	-0.29	1.12	-0.74	2.20	-0.08	1.49	-0.94	2.06	0.37	1.08	0.18	1.40			-0.25	1.12	-0.27	1.12
NPL(1)	0.030	0.534	-0.04	0.71	-0.49	2.02	0.17	1.21	-0.69	1.87	0.62	0.65	0.43	1.10	0.25	1.12			-0.02	0.71
NPL(2)	0.050	0.534	-0.02	0.71	-0.47	2.02	0.19	1.21	-0.67	1.87	0.64	0.65	0.45	1.10	0.27	1.12	0.02	0.71		

Table 7-4 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 30 MHz. RV = 18.11 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.137 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	0.565	0.652			0.52	2.14	1.17	1.57	0.72	3.47	0.39	1.20	0.43	1.22	0.74	0.99	0.71	0.99
AIST	0.045	1.729	-0.52	2.14			0.65	2.46	0.20	3.95	-0.13	2.25	-0.09	2.25	0.22	2.14	0.19	2.14
LNE	-0.605	1.214	-1.17	1.57	-0.65	2.46			-0.45	3.68	-0.78	1.71	-0.74	1.72	-0.43	1.57	-0.46	1.57
METAS	-0.155	2.887	-0.72	3.47	-0.20	3.95	0.45	3.68			-0.33	3.54	-0.29	3.54	0.02	3.47	-0.01	3.47
SP	0.175	0.872	-0.39	1.20	0.13	2.25	0.78	1.71	0.33	3.54			0.04	1.40	0.35	1.20	0.32	1.20
KRISS	0.135	0.888	-0.43	1.22	0.09	2.25	0.74	1.72	0.29	3.54	-0.04	1.40			0.31	1.22	0.28	1.22
NPL(1)	-0.175	0.652	-0.74	0.99	-0.22	2.14	0.43	1.57	-0.02	3.47	-0.35	1.20	-0.31	1.22			-0.03	0.99
NPL(2)	-0.145	0.652	-0.71	0.99	-0.19	2.14	0.46	1.57	0.01	3.47	-0.32	1.20	-0.28	1.22	0.03	0.99		

Table 7-5 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 80 MHz. RV = 6.96 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.125 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	0.044	0.642			0.40	2.14	-0.40	1.57	-0.34	1.58	0.36	1.20	-0.04	1.22	0.35	0.99	0.30	0.99
AIST	-0.356	1.725	-0.40	2.14			-0.80	2.46	-0.74	2.47	-0.04	2.25	-0.44	2.25	-0.05	2.14	-0.10	2.14
LNE	0.444	1.209	0.40	1.57	0.80	2.46			0.06	1.99	0.76	1.71	0.36	1.72	0.75	1.57	0.70	1.57
METAS	0.384	1.226	0.34	1.58	0.74	2.47	-0.06	1.99			0.70	1.73	0.30	1.74	0.69	1.58	0.64	1.58
SP	-0.316	0.865	-0.36	1.20	0.04	2.25	-0.76	1.71	-0.70	1.73			-0.40	1.40	-0.01	1.20	-0.06	1.20
KRISS	0.084	0.882	0.04	1.22	0.44	2.25	-0.36	1.72	-0.30	1.74	0.40	1.40			0.39	1.22	0.34	1.22
NPL(1)	-0.306	0.642	-0.35	0.99	0.05	2.14	-0.75	1.57	-0.69	1.58	0.01	1.20	-0.39	1.22			-0.05	0.99
NPL(2)	-0.256	0.642	-0.30	0.99	0.10	2.14	-0.70	1.57	-0.64	1.58	0.06	1.20	-0.34	1.22	0.05	0.99		

Table 7-6 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 200 MHz. RV = 8.84 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.046 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	-0.104	0.550			-0.22	1.58	0.74	1.57	-0.20	1.11	-0.09	1.20	-0.52	1.22	0.04	0.99	-0.06	0.99
AIST	0.116	1.104	0.22	1.58			0.96	1.99	0.02	1.66	0.13	1.73	-0.30	1.74	0.26	1.58	0.16	1.58
LNE	-0.844	1.403	-0.74	1.57	-0.96	1.99			-0.94	1.64	-0.83	1.71	-1.26	1.72	-0.70	1.57	-0.80	1.57
METAS	0.096	0.673	0.20	1.11	-0.02	1.66	0.94	1.64			0.11	1.30	-0.32	1.32	0.24	1.11	0.14	1.11
SP	-0.014	0.765	0.09	1.20	-0.13	1.73	0.83	1.71	-0.11	1.30			-0.43	1.40	0.13	1.20	0.03	1.20
KRISS	0.416	1.004	0.52	1.22	0.30	1.74	1.26	1.72	0.32	1.32	0.43	1.40			0.56	1.22	0.46	1.22
NPL(1)	-0.144	0.550	-0.04	0.99	-0.26	1.58	0.70	1.57	-0.24	1.11	-0.13	1.20	-0.56	1.22			-0.10	0.99
NPL(2)	-0.044	0.550	0.06	0.99	-0.16	1.58	0.80	1.57	-0.14	1.11	-0.03	1.20	-0.46	1.22	0.10	0.99		

Note

After testing against the Median of Absolute Deviation LNE and KRISS were excluded from the calculation of Reference Value (RV).

Table 7-7 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 1000 MHz. RV = 21.28 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.017 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	-0.019	0.573			-0.08	1.46	-0.04	1.93	0.01	0.82	-0.41	1.20	-0.04	1.22	0.05	0.99	0.02	0.99
AIST	0.061	1.046	0.08	1.46			0.04	2.21	0.09	1.35	-0.33	1.61	0.04	1.62	0.13	1.46	0.10	1.46
LNE	0.021	1.470	0.04	1.93	-0.04	2.21			0.05	1.85	-0.37	2.05	0.00	2.06	0.09	1.93	0.06	1.93
METAS	-0.029	0.345	-0.01	0.82	-0.09	1.35	-0.05	1.85			-0.42	1.07	-0.05	1.08	0.04	0.82	0.01	0.82
SP	0.391	0.981	0.41	1.20	0.33	1.61	0.37	2.05	0.42	1.07			0.37	1.40	0.46	1.20	0.43	1.20
KRISS	0.021	0.817	0.04	1.22	-0.04	1.62	0.00	2.06	0.05	1.08	-0.37	1.40			0.09	1.22	0.06	1.22
NPL(1)	-0.069	0.573	-0.05	0.99	-0.13	1.46	-0.09	1.93	-0.04	0.82	-0.46	1.20	-0.09	1.22			-0.03	0.99
NPL(2)	-0.039	0.573	-0.02	0.99	-0.10	1.46	-0.06	1.93	-0.01	0.82	-0.43	1.20	-0.06	1.22	0.03	0.99		

Note

After testing against the Median of Absolute Deviation SP were excluded from the calculation of Reference Value (RV).

Table 7-8 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 1500 MHz. RV = 24.90 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.055 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	-0.039	0.602			-0.09	1.35	0.06	2.31	-0.24	1.60	-0.10	1.20	0.21	1.22	-0.02	0.99	-0.21	0.99
AIST	0.051	0.986	0.09	1.35			0.15	2.49	-0.15	1.85	-0.01	1.52	0.30	1.53	0.07	1.35	-0.12	1.35
LNE	-0.099	1.863	-0.06	2.31	-0.15	2.49			-0.30	2.63	-0.16	2.41	0.15	2.42	-0.08	2.31	-0.27	2.31
METAS	0.201	1.222	0.24	1.60	0.15	1.85	0.30	2.63			0.14	1.74	0.45	1.75	0.22	1.60	0.03	1.60
SP	0.061	0.835	0.10	1.20	0.01	1.52	0.16	2.41	-0.14	1.74			0.31	1.40	0.08	1.20	-0.11	1.20
KRISS	-0.249	0.852	-0.21	1.22	-0.30	1.53	-0.15	2.42	-0.45	1.75	-0.31	1.40			-0.23	1.22	-0.42	1.22
NPL(1)	-0.019	0.602	0.02	0.99	-0.07	1.35	0.08	2.31	-0.22	1.60	-0.08	1.20	0.23	1.22			-0.19	0.99
NPL(2)	0.171	0.602	0.21	0.99	0.12	1.35	0.27	2.31	-0.03	1.60	0.11	1.20	0.42	1.22	0.19	0.99		

Table 7-9 : Degree of Equivalence for Antenna C (Schaffner Chase CBL6112B Bilog) at 2000 MHz. RV = 27.27 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.018 dB.

Degree of Equivalence with RV			Lab(j)															
			ARCS		AIST		LNE		METAS		SP		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
ARCS	0.270	0.701			0.23	1.41	-1.26	2.69	0.63	1.60	0.31	1.20	0.29	1.22	0.40	0.99	0.10	0.99
AIST	0.040	0.863	-0.23	1.41			-1.49	2.87	0.40	1.89	0.08	1.56	0.06	1.58	0.17	1.41	-0.13	1.41
LNE	1.530	2.600	1.26	2.69	1.49	2.87			1.89	2.97	1.57	2.78	1.55	2.79	1.66	2.69	1.36	2.69
METAS	-0.360	1.440	-0.63	1.60	-0.40	1.89	-1.89	2.97			-0.32	1.74	-0.34	1.75	-0.23	1.60	-0.53	1.60
SP	-0.040	0.694	-0.31	1.20	-0.08	1.56	-1.57	2.78	0.32	1.74			-0.02	1.40	0.09	1.20	-0.21	1.20
KRISS	-0.020	0.708	-0.29	1.22	-0.06	1.58	-1.55	2.79	0.34	1.75	0.02	1.40			0.11	1.22	-0.19	1.22
NPL(1)	-0.130	0.496	-0.40	0.99	-0.17	1.41	-1.66	2.69	0.23	1.60	-0.09	1.20	-0.11	1.22			-0.30	0.99
NPL(2)	0.170	0.496	-0.10	0.99	0.13	1.41	-1.36	2.69	0.53	1.60	0.21	1.20	0.19	1.22	0.30	0.99		

Note

After testing against the Median of Absolute Deviation ARCS, LNE, and METAS were excluded from the calculation of Reference Value (RV).

Figure 7-1 : Degrees of equivalence for LPDA at 200 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

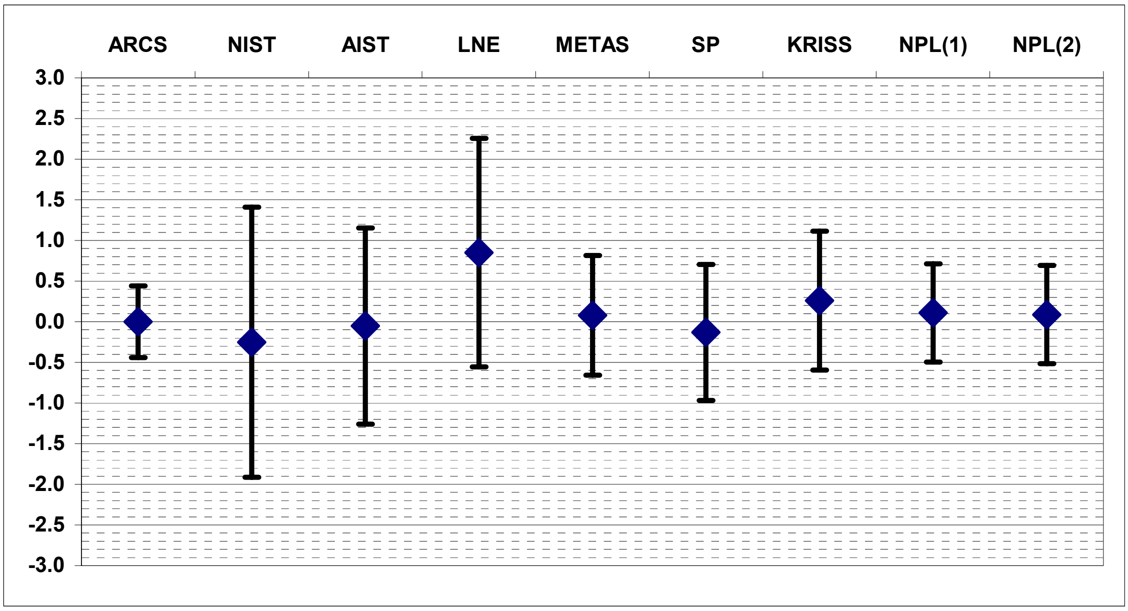


Figure 7-2 : Degrees of equivalence for LPDA at 280 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

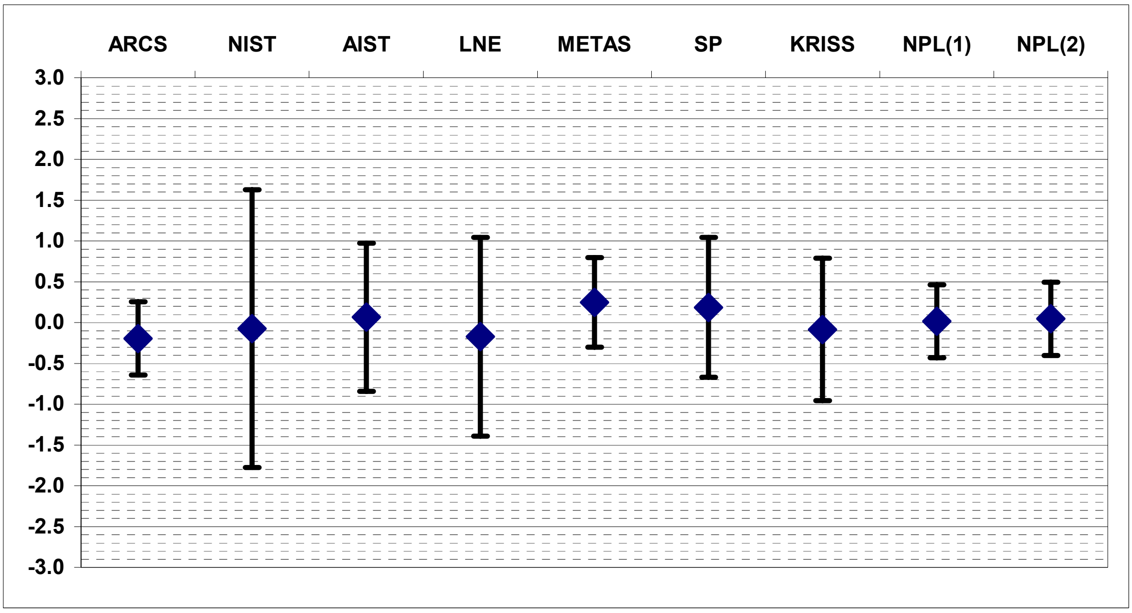


Figure 7-3 : Degrees of equivalence for LPDA at 900 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

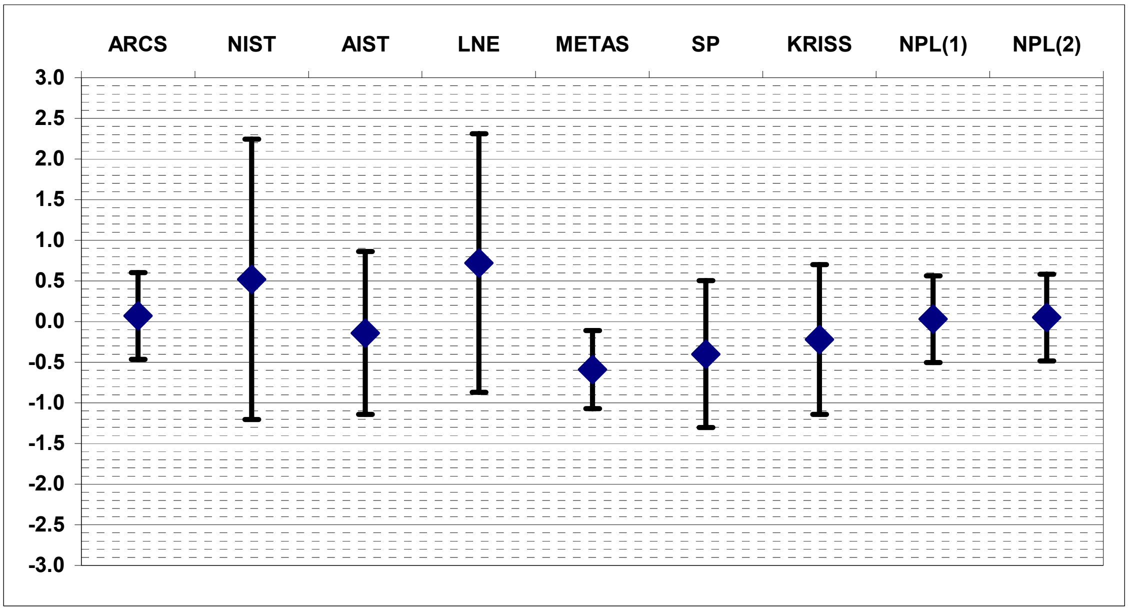


Figure 7-4 : Degrees of equivalence for Bilog at 30 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

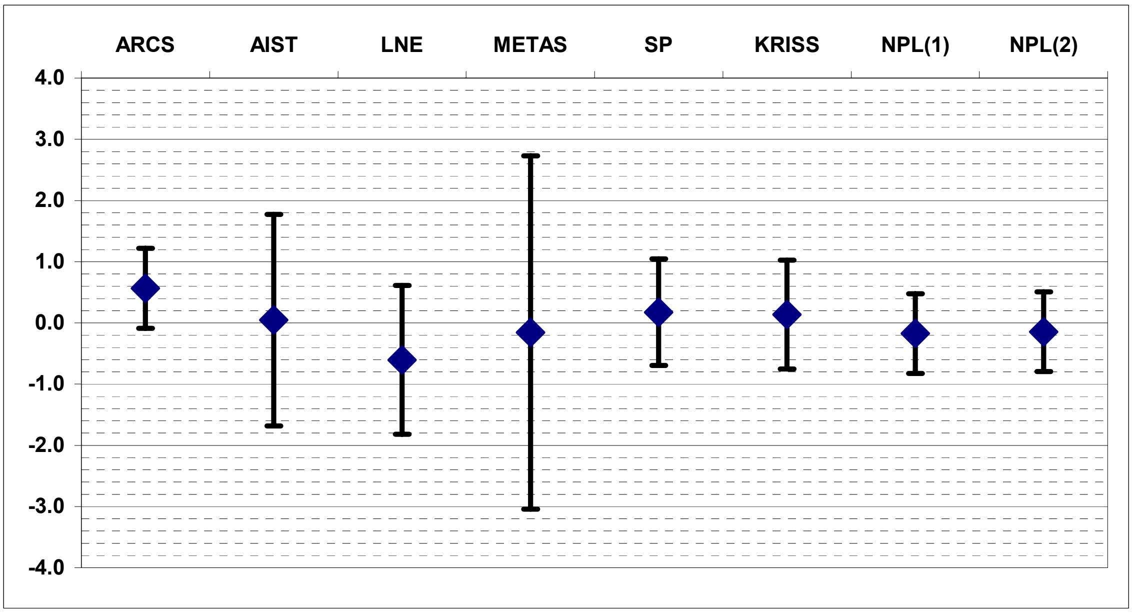


Figure 7-5 : Degrees of equivalence for Bilog at 80 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

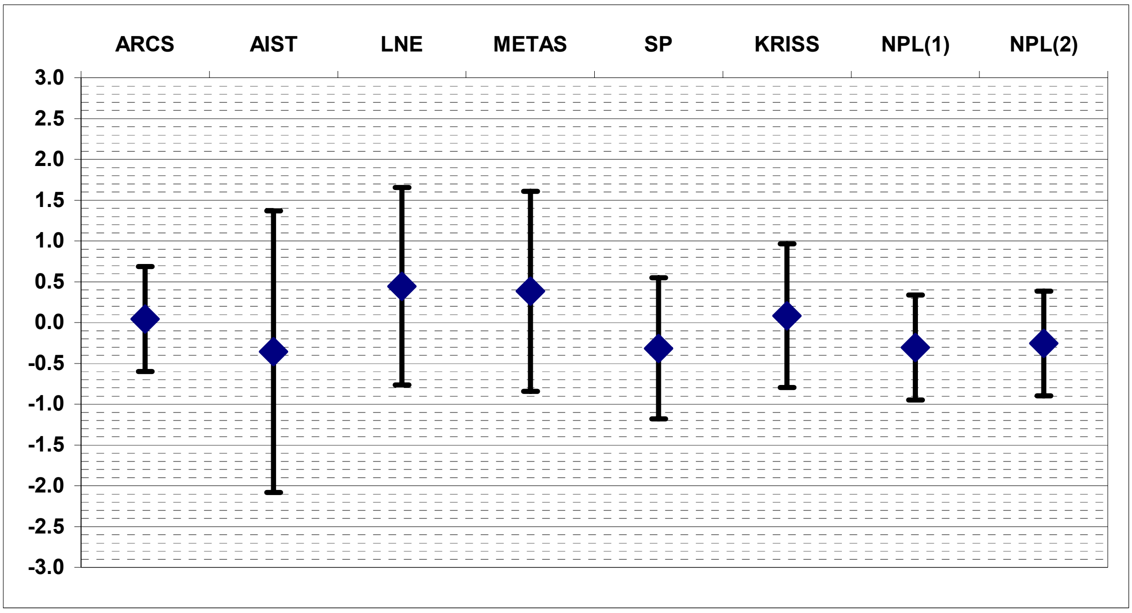


Figure 7-6 : Degrees of equivalence for Bilog at 200 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

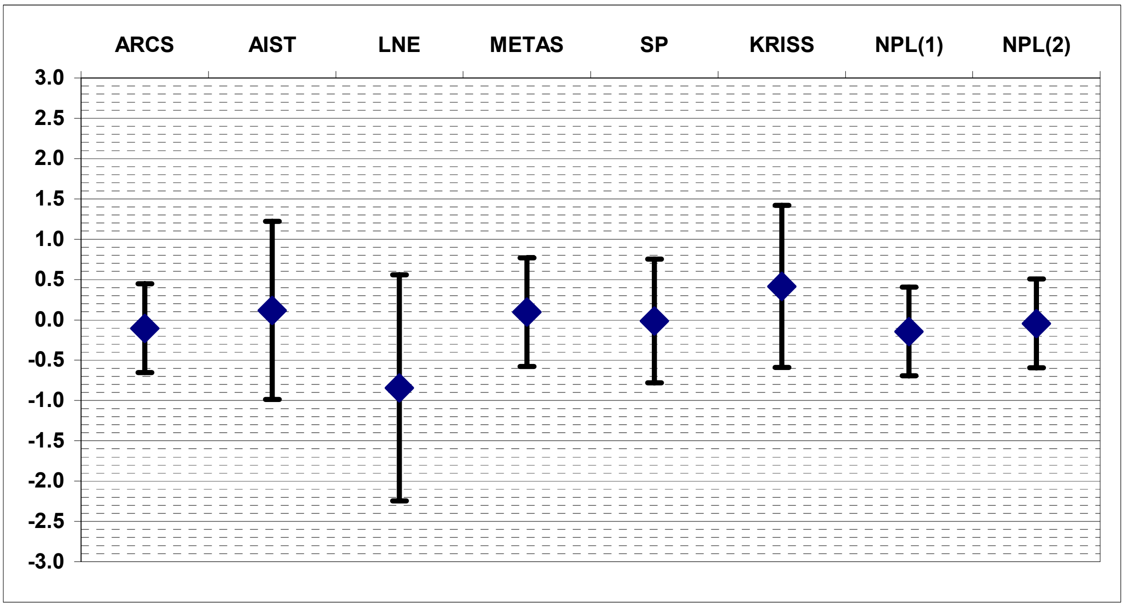


Figure 7-7 : Degrees of equivalence for Bilog at 1000 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

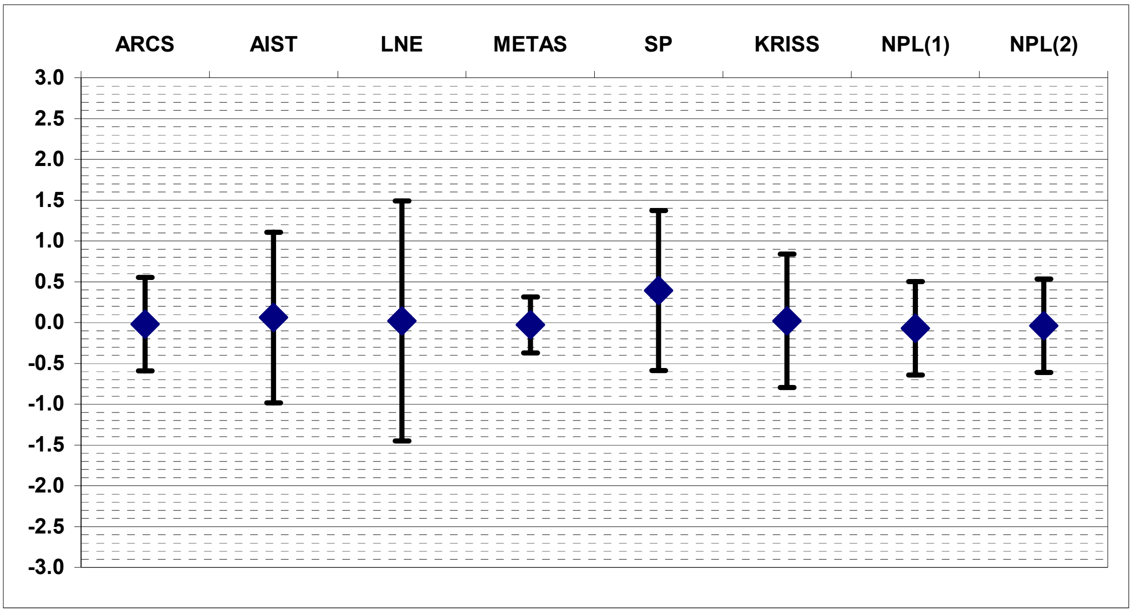


Figure 7-8 : Degrees of equivalence for Bilog at 1500 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

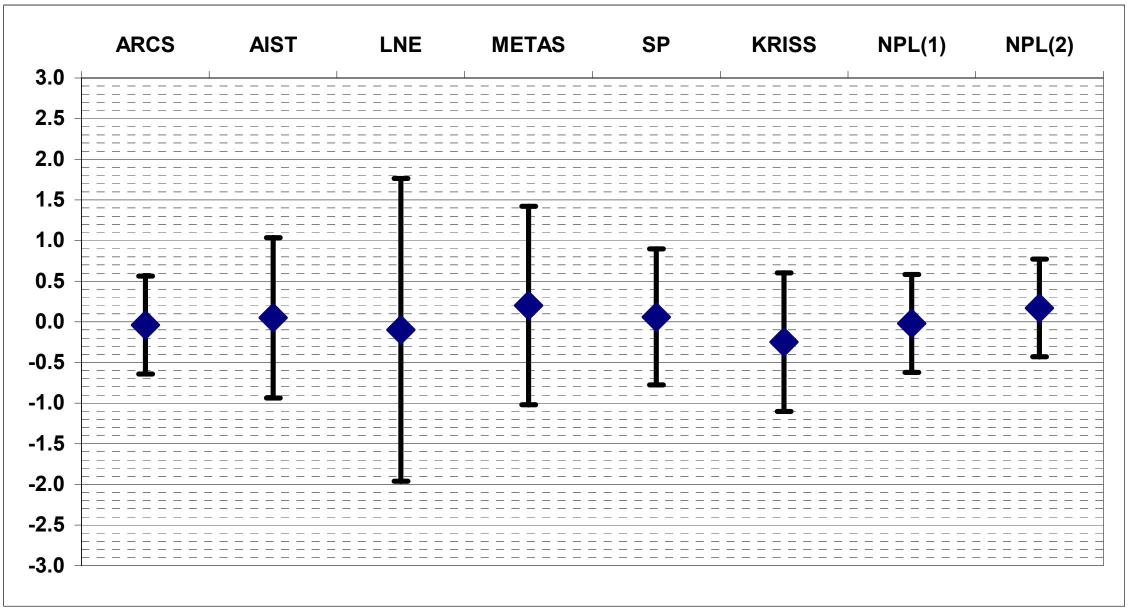
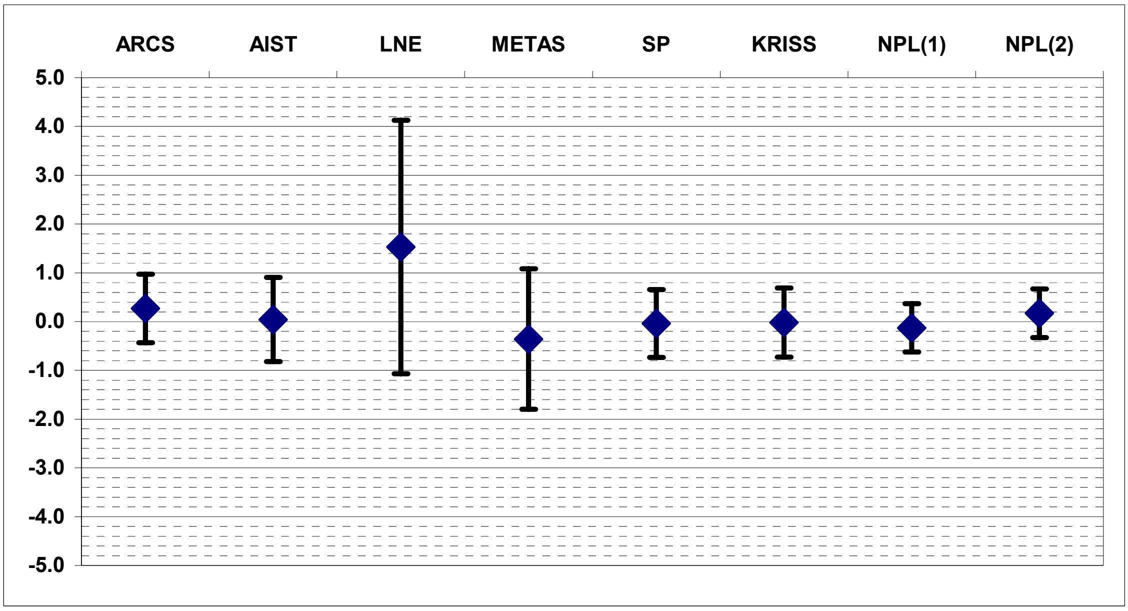


Figure 7-9 : Degrees of equivalence for Bilog at 2000 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).



7.3 Calculated Degree of Equivalence for antennas D, E, and F.

The calculated Degrees of Equivalence are reported in Table 7-10 to Table 7-17. All the uncertainties in the tables are presented at the 95% confidence level. The Degrees of Equivalence are illustrated in Figure 7-10 to Figure 7-17. The limit bars show the calculated $U(D_i)$ at each point.

The unit of the intercomparison is antenna factor which is described in Section 3.2. It is standard practice to quote this unit as a dB quantity, so consequently the measurement uncertainty is also given in dB. The degree of equivalence is given as the difference in dB between the Reference Value and each measured value.

During the NPL measurement in a TEM cell Loop E (active) seemed to have some oscillation on its output at 10kHz. It is possible that the loop was radiating a low level signal which gets amplified inside the TEM cell due to the loop picking up its own signal. Investigation showed that this was only a problem when the loop was inside the TEM cell with the door closed. Because of this instability the result for Loop E at 10 kHz is not formally reported, but it is briefly summarised in Appendix F for information only. The data at the higher frequencies seemed to be stable so they are included in this section.

Table 7-10 : Degree of Equivalence for Antenna D (Rohde & Schwarz HFH2-Z1 monopole) at 10 kHz. RV = 8.18 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.125 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	1.925	1.031			n/a	n/a	2.05	1.26	1.80	1.80	1.80	1.80
AIST	n/a	n/a	n/a	n/a			n/a	n/a	n/a	n/a	n/a	n/a
KRISS	-0.125	0.250	-2.05	1.26	n/a	n/a			-0.25	1.68	-0.25	1.68
NPL(1)	0.125	0.250	-1.80	1.80	n/a	n/a	0.25	1.68			0.00	2.12
NPL(2)	0.125	0.250	-1.80	1.80	n/a	n/a	0.25	1.68	0.00	2.12		

Notes

After testing against the Median of Absolute Deviation NMi-VSL were excluded from the calculation of Reference Value (RV).

(See further comment about the Equivalent Capacitance method in Conclusion).

No data was submitted by AIST at this frequency.

Table 7-11 : Degree of Equivalence for Antenna D (Rohde & Schwarz HFH2-Z1 monopole) at 15 MHz. RV = 8.36 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.183 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	1.943	1.065			1.90	1.72	2.28	1.20	1.80	1.80	1.50	1.80
AIST	0.043	0.887	-1.90	1.72			0.38	1.55	-0.10	2.05	-0.40	2.05
KRISS	-0.337	0.529	-2.28	1.20	-0.38	1.55			-0.48	1.64	-0.78	1.64
NPL(1)	0.143	0.940	-1.80	1.80	0.10	2.05	0.48	1.64			-0.30	2.12
NPL(2)	0.443	0.940	-1.50	1.80	0.40	2.05	0.78	1.64	0.30	2.12		

Notes

After testing against the Median of Absolute Deviation NMi-VSL were excluded from the calculation of Reference Value (RV).

(See further comment about the Equivalent Capacitance method in Conclusion).

Table 7-12 : Degree of Equivalence for Antenna D (Rohde & Schwarz HFH2-Z1 monopole) at 30 MHz. RV = 6.84 dB(m^{-1}). The calculated u_{RV} of the reference value was 0.205 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	3.357	1.081			3.60	1.17	3.52	1.20	3.20	1.80	2.70	1.80
AIST	-0.243	0.536	-3.60	1.17			-0.08	0.89	-0.40	1.62	-0.90	1.62
KRISS	-0.163	0.559	-3.52	1.20	0.08	0.89			-0.32	1.64	-0.82	1.64
NPL(1)	0.157	0.958	-3.20	1.80	0.40	1.62	0.32	1.64			-0.50	2.12
NPL(2)	0.657	0.958	-2.70	1.80	0.90	1.62	0.82	1.64	0.50	2.12		

Notes

After testing against the Median of Absolute Deviation NMi-VSL were excluded from the calculation of Reference Value (RV).
(See further comment about the Equivalent Capacitance method in Conclusion).

Table 7-13 : Degree of Equivalence for Antenna E (EMCO 6507 loop) at 1 MHz. RV = –35.73 dB(S.m^{-1}). The calculated u_{RV} of the reference value was 0.033 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	0.033	0.581			0.10	1.17	0.00	1.22	n/a	n/a	0.30	1.41
AIST	-0.067	0.353	-0.10	1.17			-0.10	0.92	n/a	n/a	0.20	1.17
KRISS	0.033	0.410	0.00	1.22	0.10	0.92			n/a	n/a	0.30	1.22
NPL(1)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a			n/a	n/a
NPL(2)	-0.267	1.002	-0.30	1.41	-0.20	1.17	-0.30	1.22	n/a	n/a		

Notes

After testing against the Median of Absolute Deviation NPL(2) were excluded from the calculation of Reference Value (RV).

There was no NPL(1) data at this frequency (Helmholtz coil).

Table 7-14 : Degree of Equivalence for Antenna E (EMCO 6507 loop) at 30 MHz. RV = –36.88 dB(S.m^{-1}). The calculated u_{RV} of the reference value was 0.020 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	-0.620	1.600			-0.60	1.61	-0.66	1.79	n/a	n/a	-0.60	1.89
AIST	-0.020	0.122	0.60	1.61			-0.06	0.82	n/a	n/a	0.00	1.02
KRISS	0.040	0.464	0.66	1.79	0.06	0.82			n/a	n/a	0.06	1.28
NPL(1)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a			n/a	n/a
NPL(2)	-0.020	0.579	0.60	1.89	0.00	1.02	-0.06	1.28	n/a	n/a		

Notes

After testing against the Median of Absolute Deviation NMi-VSL were excluded from the calculation of Reference Value (RV).

There was no NPL(1) data at this frequency (Helmholtz coil).

Table 7-15 : Degree of Equivalence for Antenna F (EMCO 7604 loop) at 20 Hz. RV = 83.29 dB(S.m^{-1}). The calculated u_{RV} of the reference value was 0.104 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	0.336	0.440			0.23	3.24	0.57	0.94	0.35	0.50	0.53	1.58
AIST	0.106	2.487	-0.23	3.24			0.34	3.30	0.12	3.20	0.30	3.53
KRISS	-0.234	0.654	-0.57	0.94	-0.34	3.30			-0.22	0.80	-0.04	1.70
NPL(1)	-0.014	0.209	-0.35	0.50	-0.12	3.20	0.22	0.80			0.18	1.50
NPL(2)	-0.194	1.180	-0.53	1.58	-0.30	3.53	0.04	1.70	-0.18	1.50		

Table 7-16 : Degree of Equivalence for Antenna F (EMCO 7604 loop) at 500 Hz. RV = 55.54 dB(S.m^{-1}). The calculated u_{RV} of the reference value was 0.103 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	0.364	0.439			0.40	0.78	0.51	0.94	0.31	0.50	0.60	1.12
AIST	-0.036	0.509	-0.40	0.78			0.11	1.00	-0.09	0.60	0.20	1.17
KRISS	-0.146	0.653	-0.51	0.94	-0.11	1.00			-0.20	0.80	0.09	1.28
NPL(1)	0.054	0.208	-0.31	0.50	0.09	0.60	0.20	0.80			0.29	1.00
NPL(2)	-0.236	0.802	-0.60	1.12	-0.20	1.17	-0.09	1.28	-0.29	1.00		

Table 7-17 : Degree of Equivalence for Antenna F (EMCO 7604 loop) at 100 kHz. RV = 21.06 dB(S.m^{-1}). The calculated u_{RV} of the reference value was 0.048 dB.

Degree of Equivalence with RV			Lab(j)									
			NMi-VSL		AIST		KRISS		NPL(1)		NPL(2)	
Lab(i)	Di	U(Di)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)	Dij	U(Dij)
NMi-VSL	0.042	0.627			0.10	1.00	-0.03	1.06	-0.06	0.80	0.20	1.28
AIST	-0.058	0.474	-0.10	1.00			-0.13	0.92	-0.16	0.61	0.10	1.17
KRISS	0.072	0.551	0.03	1.06	0.13	0.92			-0.03	0.70	0.23	1.22
NPL(1)	0.102	0.114	0.06	0.80	0.16	0.61	0.03	0.70			0.26	1.00
NPL(2)	-0.158	0.780	-0.20	1.28	-0.10	1.17	-0.23	1.22	-0.26	1.00		

Figure 7-10 : Degrees of equivalence for Monopole at 10 kHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

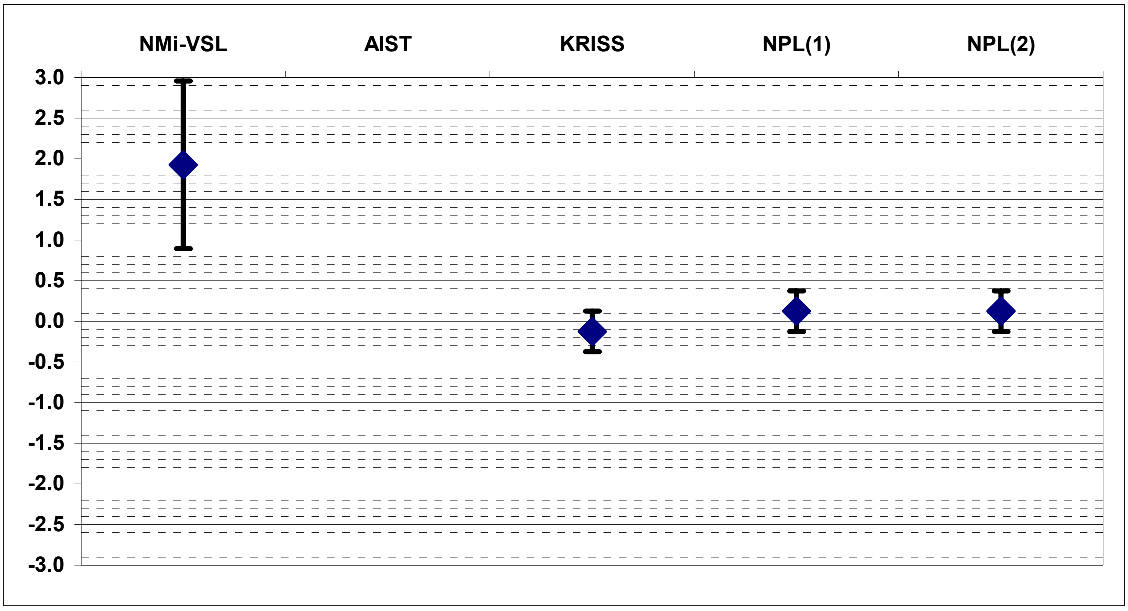


Figure 7-11 : Degrees of equivalence for Monopole at 15 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

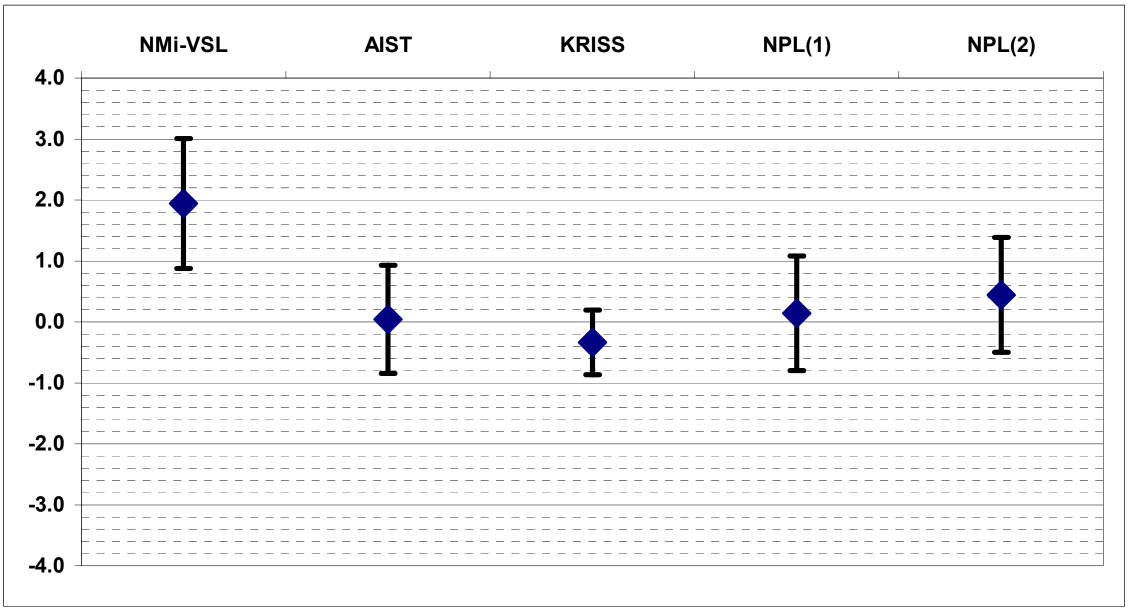


Figure 7-12 : Degrees of equivalence for Monopole at 30 MHz. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

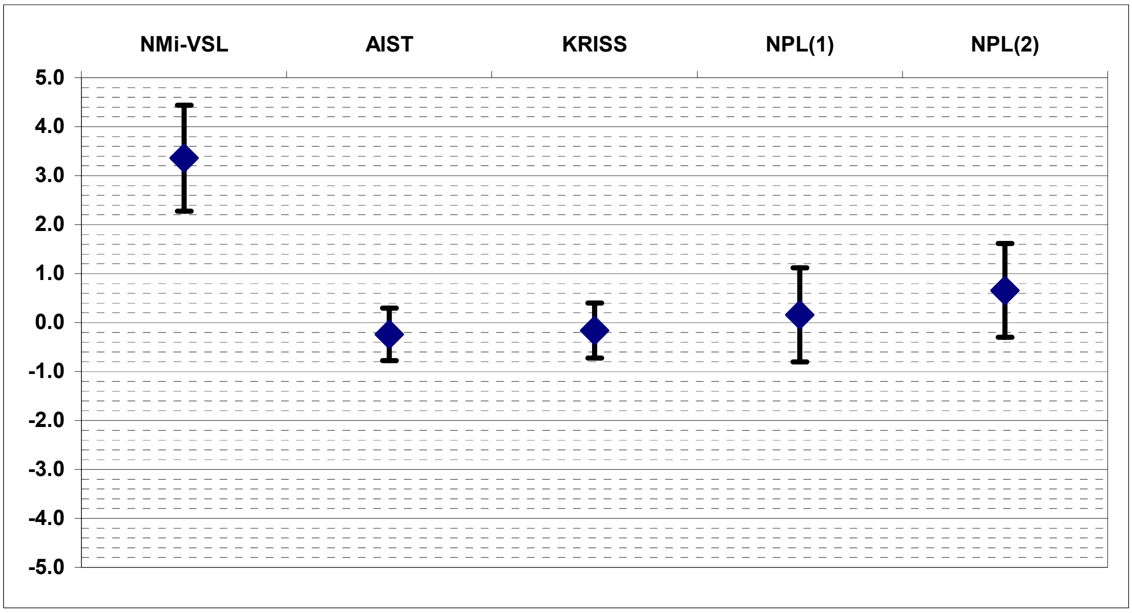


Figure 7-13 : Degrees of equivalence for Loop E at 1 MHz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

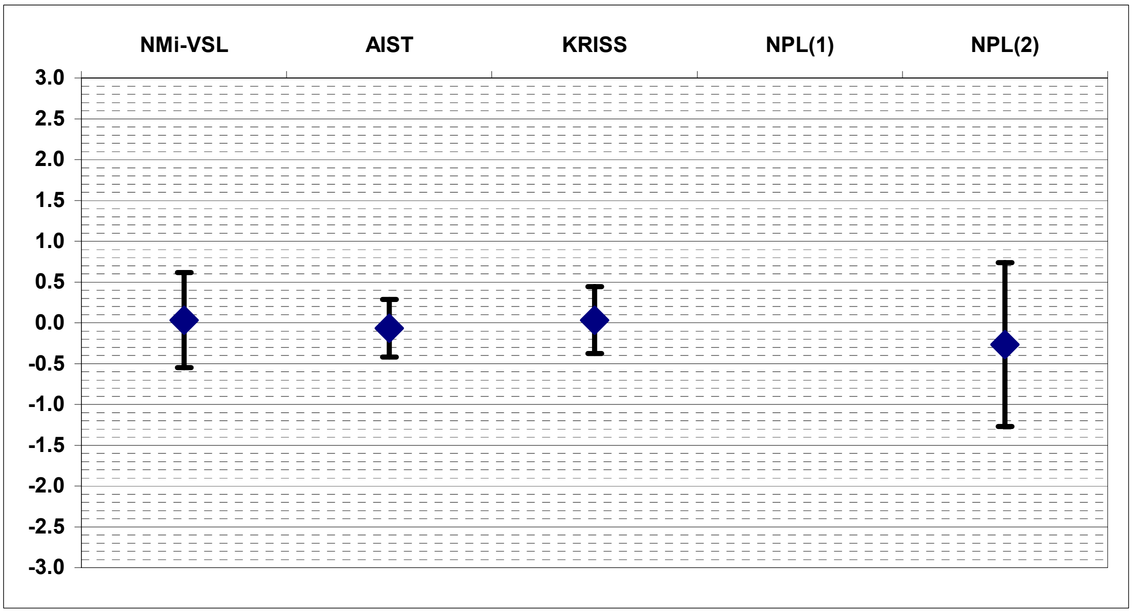


Figure 7-14 : Degrees of equivalence for Loop E at 30 MHz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

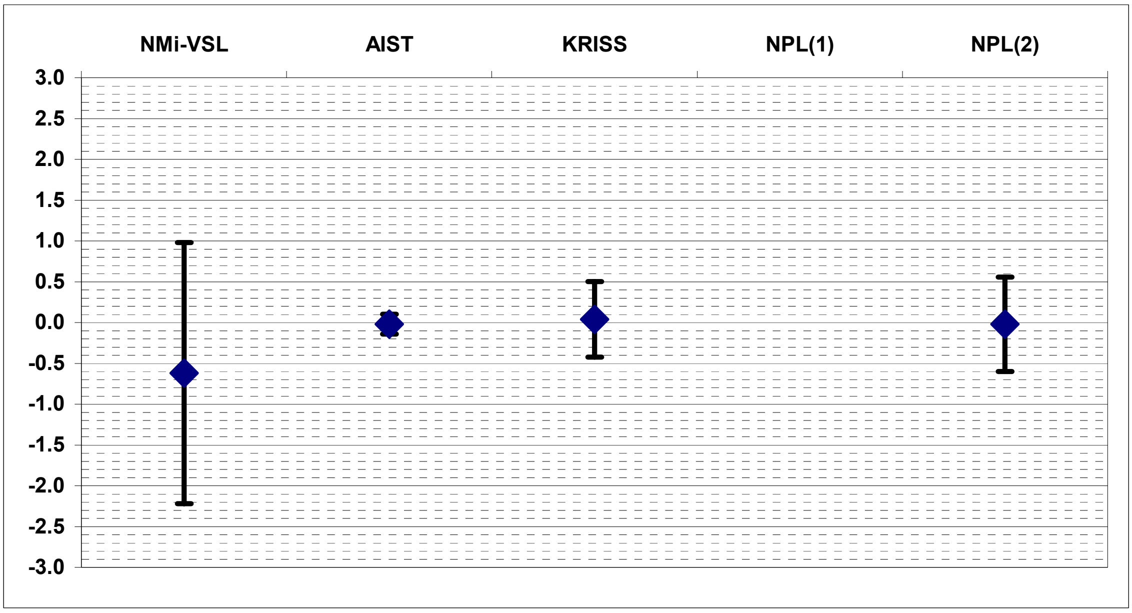


Figure 7-15 : Degrees of equivalence for Loop F at 20 Hz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

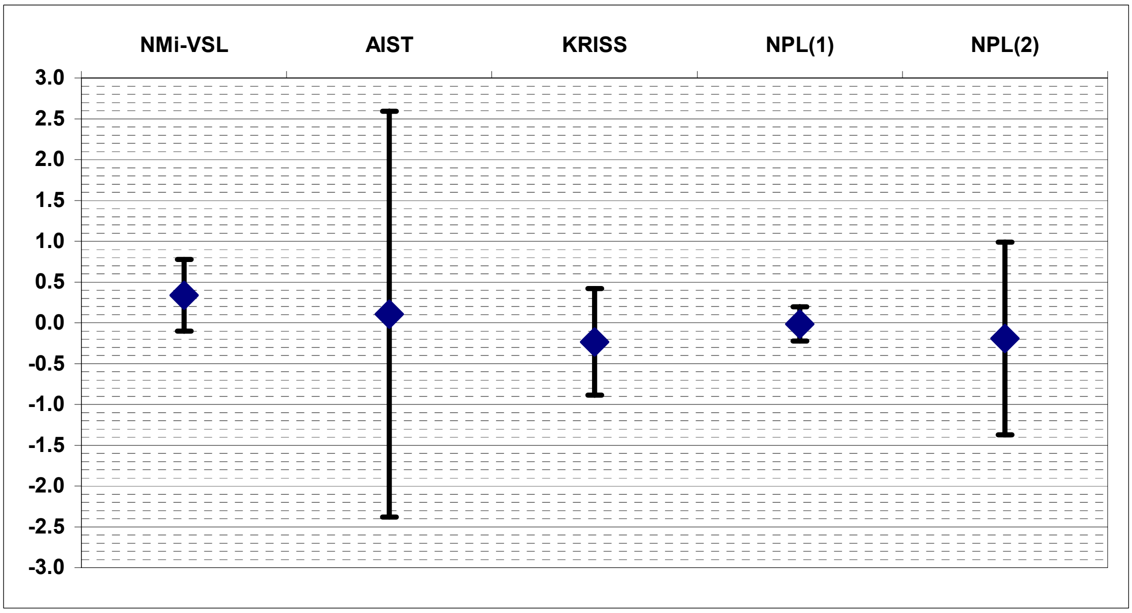


Figure 7-16 : Degrees of equivalence for Loop F at 500 Hz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).

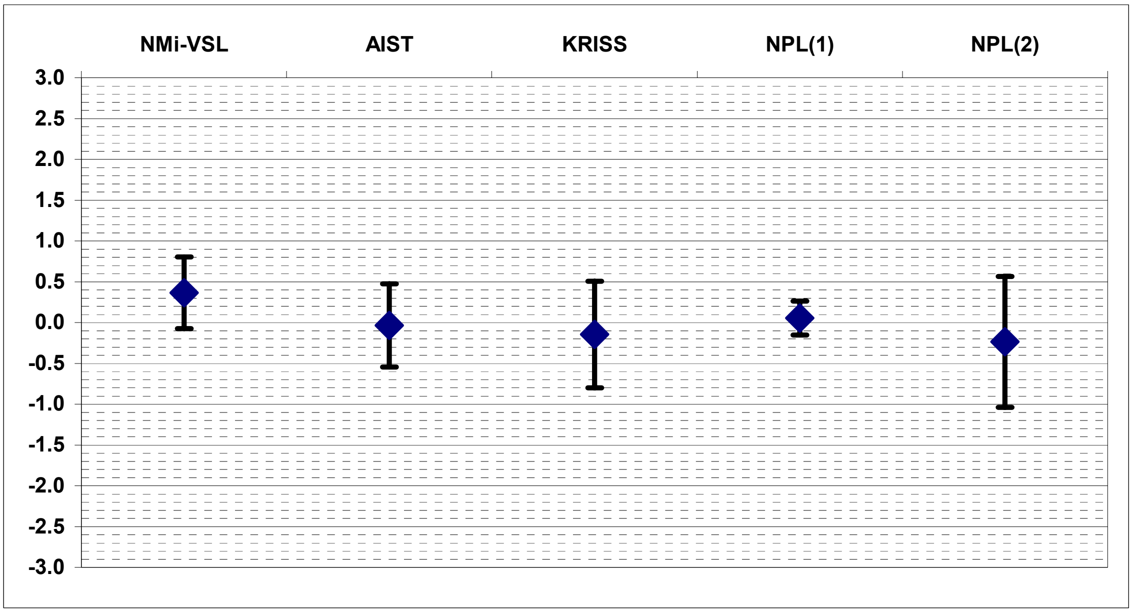
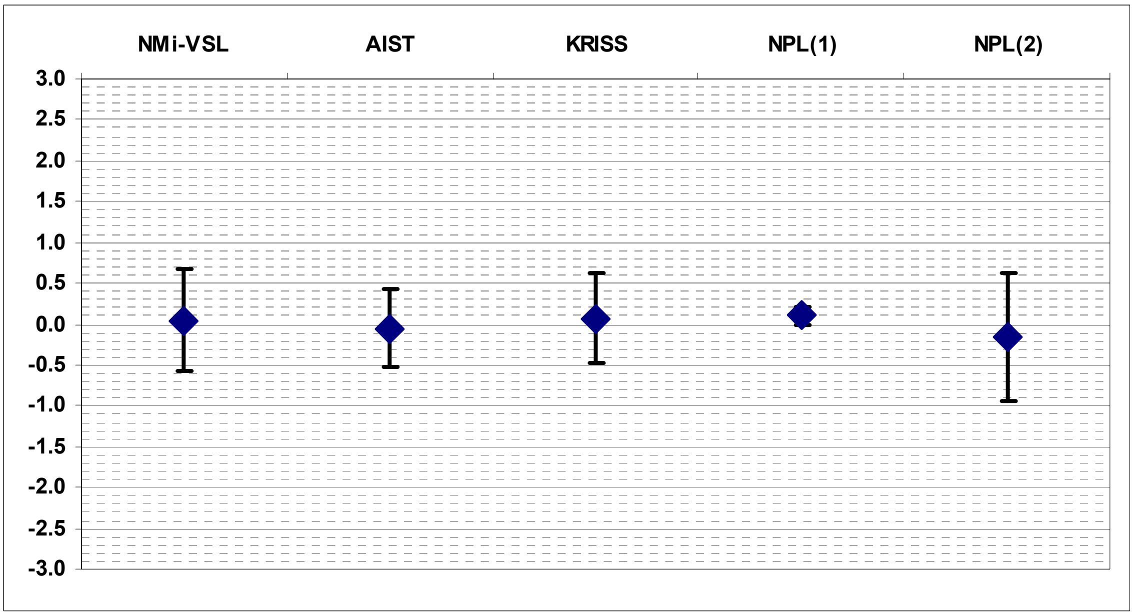


Figure 7-17 : Degrees of equivalence for Loop F at 100 kHz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).



8 Full listing of submitted results for intercomparison

Table 8-1 : Results submitted for Antenna B (LPDA).

Laboratory	Frequency MHz	Antenna factor dB(m^{-1})	Uncertainty (1 SD)
ARCS	200	10.25	0.25
	280	12.58	0.25
	900	22.75	0.25
METAS	200	10.33	0.43
	280	13.02	0.31
	900	22.09	0.21
NIST	200	10.00	0.98
	280	12.70	0.98
	900	23.20	0.98
AIST	200	10.20	0.71
	280	12.84	0.52
	900	22.54	0.55
LNE	200	11.1	0.7
	280	12.6	0.7
	900	23.4	0.9
KRISS	200	10.51	0.5
	280	12.69	0.5
	900	22.46	0.5
SP	200	10.12	0.49
	280	12.96	0.49
	900	22.28	0.49
NPL(1)	200	10.36	0.35
	280	12.79	0.25
	900	22.71	0.25
NPL(2)	200	10.34	0.35
	280	12.82	0.25
	900	22.73	0.25

Table 8-2 : Results submitted for Antenna C (Bilog).

Laboratory	Frequency MHz	Antenna factor dB(m^{-1})	Uncertainty (1 SD)
ARCS	30	18.67	0.35
	80	7.00	0.35
	200	8.74	0.35
	1000	21.26	0.35
	1500	24.86	0.35
	2000	27.54	0.35
METAS	30	17.95	1.7
	80	7.34	0.71
	200	8.94	0.43
	1000	21.25	0.21
	1500	25.1	0.72
	2000	26.91	0.72
AIST	30	18.15	1.01
	80	6.60	1.01
	200	8.96	0.71
	1000	21.34	0.64
	1500	24.95	0.58
	2000	27.31	0.61
LNE	30	17.5	0.7
	80	7.4	0.7
	200	8.0	0.7
	1000	21.3	0.9
	1500	24.8	1.1
	2000	28.8	1.3
KRISS	30	18.24	0.5
	80	7.04	0.5
	200	9.26	0.5
	1000	21.3	0.5
	1500	24.65	0.5
	2000	27.25	0.5

Table 8-2 (continued)

Laboratory	Frequency MHz	Antenna factor dB(m^{-1})	Uncertainty (1 SD)
SP	30	18.28	0.49
	80	6.64	0.49
	200	8.83	0.49
	1000	21.67	0.49
	1500	24.96	0.49
	2000	27.23	0.49
NPL(1)	30	17.93	0.35
	80	6.65	0.35
	200	8.70	0.35
	1000	21.21	0.35
	1500	24.88	0.35
	2000	27.14	0.35
NPL(2)	30	17.96	0.35
	80	6.70	0.35
	200	8.80	0.35
	1000	21.24	0.35
	1500	25.07	0.35
	2000	27.44	0.35

Table 8-3 : Results submitted for Antenna D (Monopole).

Laboratory	**Frequency MHz**	**Antenna factor dB(m^{-1})**	**Uncertainty (1 SD)**
AIST	0.01	No data	No data
	15	8.4	0.7
	30	6.6	0.3
KRISS	0.01	8.05	0.38
	15	8.02	0.33
	30	6.68	0.33
NMi-VSL	0.01	10.1	0.5
	15	10.3	0.5
	30	10.2	0.5
NPL(1)	0.01	8.3	0.75
	15	8.5	0.75
	30	7.0	0.75
NPL(2)	0.01	8.3	0.75
	15	8.8	0.75
	30	7.5	0.75

Table 8-4 : Results submitted for Antenna E (Loop).

Laboratory	Frequency MHz	Antenna factor db(S.m^{-1})	Uncertainty (1 SD)
AIST	0.01	-21.5	0.2
	1	-35.8	0.3
	30	-36.9	0.1
KRISS	0.01	-21.24	0.35
	1	-35.7	0.35
	30	-36.84	0.4
NMi-VSL	0.01	-20.5	0.3
	1	-35.7	0.5
	30	-37.5	0.8
NPL(1) (Helmholtz coil)	0.01	-21.26	0.05
	1	no data	no data
	30	no data	no data
NPL(2) (TEM cell)	0.01	no data	no data
	1	-36.0	0.5
	30	-36.9	0.5

Table 8-5 : Results submitted for Antenna F (Loop).

Laboratory	Frequency MHz	Antenna factor dB(S.m^{-1})	Uncertainty (1 SD)
AIST	0.00002	83.40	1.6
	0.0005	55.50	0.3
	0.1	21.00	0.3
KRISS	0.00002	83.06	0.4
	0.0005	55.39	0.4
	0.1	21.13	0.4
NMi-VSL	0.00002	83.63	0.25
	0.0005	55.9	0.25
	0.1	21.1	0.40
NPL(1) (Helmholtz coil)	0.00002	83.28	0.015
	0.0005	55.59	0.015
	0.1	21.16	0.040
NPL(2) (TEM cell)	0.00002	83.1	0.75
	0.0005	55.3	0.50
	0.1	20.9	0.50

9 Withdrawals

No results were supplied by NIMC (China) for the supplementary comparison, therefore they are not included in this report.

10 Summary and conclusions

The stated aim of the first half of the supplementary intercomparison was to compare free-space antenna factor for the two log periodic type antennas. The various measurement systems for Antennas B and C employed by each participant used either the standard antenna method or the three-antenna method. The facilities ranged from fully anechoic and semi-anechoic ranges to OATS ground planes. Some participants who used a semi-anechoic range used a theoretical correction to achieve free-space antenna factor. It is pleasing to see such good agreement between all these methods.

The plane wave measurements of the monopole (antenna D) agreed well. NMi-VSL was the only participant who used the Equivalent Capacitance Substitution Method (ECSM), and there was a consistent offset between their results and the Reference Value. The description of the measurement submitted by NMi-VSL acknowledges that the information in the current standards is inadequate, so it is hard for laboratories to perform consistent ECSM calibrations. Recent work on this topic (Reference [3]) has investigated the ECSM and it has been shown that there are physical reasons which explain why antenna factor measured by the ECSM will usually be larger than plane wave antenna factor.

The calibration systems used for the loop antennas employed TEM cells, Helmholtz coils, and free-space (three antenna) techniques. The agreement was very good in all cases. An instability was discovered when measuring Loop E at 10 kHz, so this data is not reported as part of the intercomparison.

Despite the limitations of the algorithm which we used to derive the Reference Value in each case, particularly for small samples, the actual calculated Reference Values seemed to be reasonable. Occasionally, when the results from a few laboratories agreed very closely the uncertainty in the RV was small, and this resulted in the exclusion of some data points which were only a little bit away from the RV. In general these exclusions do not reflect badly on those participants concerned because the exclusions are mostly due to the limitations of the algorithm.

11 References

[1] Proposal for KCRV & Degree of Equivalence for GTRF key comparisons. J Randa (NIST), GT-RF 2000/12, Sept 2000.

[2] Some statistical formulas used in the analysis of key comparisons. T J Witt (BIPM), CCEM WGKC/2001-25 (ver 1.0), July 2001.

[3] Comparison of calibration methods for monopole antennas, with some analysis of the capacitance substitution method. D A Knight, A Nothofer, M J Alexander, NPL report DEM-EM-005, October 2004.

Appendix A : NIST uncertainty budget

Calibration of Antenna B by three-antenna method in an anechoic chamber.

Source of uncertainty	Type	Value x_i	Probability distribution	Probability factor, p_i	Sensitivity factor, s_i	Resultant value, dB u_i
Source drift in Frequency	B	10ppm x F	Rectangular	1/√3	4.34/F	0.000
Receiver linearity	B	0.25 dB	Rectangular	1/√3	0.5	0.072 0.072 0.072
Cable variation	B	0.20 dB	Rectangular	1/√3	0.5	0.058 0.058 0.058
Mismatch error	B	0.33 dB	U-shaped	1/√2	1	0.232 0.232 0.232
Site environment	B	1.0 dB	Rectangular	1/√3	1	0.577
Connector repeatability	A	0.15 dB	Gaussian	1	0.5	0.075 0.075 0.075
Positioning errors	B	0.075 m	Rectangular	1/√3	4.34/D	0.042 0.042 0.042
Combined uncertainty (one std dev)						0.98

Where: $u_i = p_i \cdot s_i \cdot x_i$

D = 4.5m

F= 200 MHz.

Appendix B : AIST uncertainty budget

The antenna factor A_f for both antenna B and C was derived using the following equation.

$$A_f = \sqrt{\frac{\pi}{125}}\sqrt{\frac{F_{M1}F_{M2}}{F_{M3}}}\sqrt{\frac{r_3}{r_1 r_2}}\sqrt{\frac{A_1 A_2}{A_3}}$$

where
F_{Mi}: frequency(MHz)
r_i: distance of direct propagation, (i=1,2,3)
A_i: site-attenuation between antenna pairs among three antennas

The uncertainty of the antenna factor was primarily derived from the frequency, distances, site attenuation and their sensitivity factors calculated as their partial derivatives. The resultant standard uncertainty is calculated along the propagation principle of the uncertainty shown in the GUM.

Note
AIST provided detailed analysis of their uncertainties, however for brevity just the summary tables are included here. The mark of (-) in the tables indicates that the component is dimensionless.

Table B-1: Uncertainty for antenna B at 200 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.0944 × AF	($1/m^2$)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	2021	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 50 & 51			0.0447 × AF	(1/m)	1.0990	(-)	Combined (See text)
Attenuation measurement 50 & AUT			0.0450 × AF	(1/m)	1.0919	(-)	Combined (See text)
Attenuation measurement 51 & AUT			0.0450 × AF	(1/m)	1.0912	(-)	Combined (See text)
Total uncertainty					0.0875× AF	(1/m)	
					0.71	(dB/m)	

Table B-2: Uncertainty for antenna B at 280 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.0974 × AF	(1/m^2)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	2829	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 50 & 51			0.0361 × AF	(1/m)	0.9799	(-)	Combined (See text)
Attenuation measurement 50 & AUT			0.0357 × AF	(1/m)	0.9933	(-)	Combined (See text)
Attenuation measurement 51 & AUT			0.0360 × AF	(1/m)	0.9819	(-)	Combined (See text)
Total uncertainty					0.0622 × AF	(1/m)	
					0.52	(dB/m)	

Table B-3: Uncertainty for antenna B at 900 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.1032 × AF	($1/m^2$)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	9093	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 50 & 51			0.0129 × AF	(1/m)	2.8888	(-)	Combined (See text)
Attenuation measurement 50 & AUT			0.0129 × AF	(1/m)	2.8983	(-)	Combined (See text)
Attenuation measurement 51 & AUT			0.0131 × AF	(1/m)	2.8626	(-)	Combined (See text)
Total uncertainty					0.0656 × AF	(1/m)	
					0.55	(dB/m)	

Table B-4: Uncertainty for antenna C at 30 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.0974 × AF	($1/m^2$)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	303	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0011 × AF	(1/m)	66.6620	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0011 × AF	(1/m)	65.9070	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0011 × AF	(1/m)	65.9691	(-)	Combined (See text)
Total uncertainty					0.1237 × AF	(1/m)	
					1.01	(dB/m)	

Table B-5: Uncertainty for antenna C at 80 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.0947 × AF	(1/m^2)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	808	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0412 × AF	(1/m)	1.7137	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0414 × AF	(1/m)	1.7073	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0415 × AF	(1/m)	1.7025	(-)	Combined (See text)
Total uncertainty					0.1228 × AF	(1/m)	
					1.01	(dB/m)	

Table B-6: Uncertainty for antenna C at 200 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.0986 × AF	(1/m^2)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	2021	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0635 × AF	(1/m)	0.7694	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0632 × AF	(1/m)	0.7736	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0633 × AF	(1/m)	0.7720	(-)	Combined (See text)
Total uncertainty					0.0853 × AF	(1/m)	
					0.71	(dB/m)	

Table B-7: Uncertainty for antenna C at 1000 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.1107 × AF	($1/m^2$)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	10104	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0206 × AF	(1/m)	1.7709	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0207 × AF	(1/m)	1.7618	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0203 × AF	(1/m)	2.7120	(-)	Combined (See text)
Total uncertainty					0.0765 × AF	(1/m)	
					0.64	(dB/m)	

Table B-8: Uncertainty for antenna C at 1500 MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.1132 × AF	($1/m^2$)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	15155	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0134 × AF	(1/m)	2.8090	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0134 × AF	(1/m)	2.8070	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0136 × AF	(1/m)	3.1456	(-)	Combined (See text)
Total uncertainty					0.0695 × AF	(1/m)	
					0.58	(dB/m)	

Table B-9: Uncertainty for antenna C at 2000MHz

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Distance	B	Rectangular	0.1148 × AF	(1/m^2)	0.06351	(m)	Setting uncertainty ±0.01 m Phase center ±0.1 m
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	20207	(Hz)	Accuracy ±10 ppm Stability ±7.5 ppm
Attenuation measurement 79 & 80			0.0109 × AF	(1/m)	3.6250	(-)	Combined (See text)
Attenuation measurement 79 & AUT			0.0107 × AF	(1/m)	3.6750	(-)	Combined (See text)
Attenuation measurement 80 & AUT			0.0109 × AF	(1/m)	4.0715	(-)	Combined (See text)
Total uncertainty					0.0726 × AF	(1/m)	
					0.61	(dB/m)	

Appendix C : METAS uncertainty budget

The expression for antenna factor is:

$$AF = SIL[dB] - (32dB + 20\log_{10}(dist[m]) - 20\log_{10}(f[MHz])) - AF_{reference}[dB(1/m)]$$

The following table gives the general uncertainty budget, with the parameters X and Y defined in the tables below. Tuned dipole elements were used at 30, 80, 200, 900, and 1000MHz. At 280 MHz the PRD dipole was used in a broadband mode. Where two measurements were taken at one frequency a weighted mean was used to determine the final result.

Source of uncertainty	Type	Value	Probability Distribution	Uncertainty (one SD) (ui)	Sensitivity Factor (Ci)	(Ci x ui)
Mismatch errors	B	0.02 dB	U-Shape	0.014	1	0.014
Connector + cable repeatability	A	0.05 dB	Gaussian	0.050	1	0.050
Linearity of receiver over the range of measured signal	B	0.20 dB	Rectangular	0.115	1	0.115
Variation of cable attenuation due to temperature	B	0.05 dB	Rectangular	0.028	1	0.028
Error in unexpected reflections of the walls, including near field effects	B	X	Rectangular	X/1.73	1	X/1.73
Positioning errors	B	0.05 m	Rectangular	0.028 m	8.68/dist[m]	0.25/dist[m]
Frequency error of source	B	10ppm x f0	Rectangular	5.8ppm x f0	8.68/f0	0.000
Reference Antenna	B	Y	Gaussian	Y	1	Y

Site reflections

	30-70 MHz	70-150 MHz	150-500 MHz	0.5-1GHz	> 1 GHz
X	4.0 dB	1.2 dB	0.7 dB	0.25 dB	0.15 dB

Reference antenna

	Tuned dipole	Broadband dipole	Bilog	Log periodic
Y	0.05 dB	0.1 dB	1 dB	0.7 dB

Appendix D : SP uncertainty budget

Uncertainty budget for standard antenna method (30 - 2000 MHz)

Source of uncertainty	Value	Probability distribution	Sensitivity coefficient	Contribution to standard uncertainty
Reference antenna	0.0647	Gaussian	1	0.0647
Power meter	0.0277	Gaussian	1	0.0277
Test receiver	0.0478	Gaussian	2	0.0956
Positioning error	0.0080	Rectangular	2	0.0092
Combined uncertainty (1 SD, power ratio)				0.1191
Combined uncertainty (dB)				0.49

Appendix E : NMi-VSL uncertainty analysis

Magnetic field strength calculation in TEM cell

The transverse magnetic field H is given by the formula:

$$H = \frac{1}{d \cdot Z_c} \sqrt{P \cdot Z_L} \cdot (1 + \Delta_{SW}) \cdot f(x, y)$$

H	=	electric field strength at position (x,y), in A/m
d	=	inner distance between septum and upper wall of TEM cell, in m
P	=	actual power in TEM cell, in watts
Z_L	=	50 Ω characteristic impedance of the system
Z_c	=	120 π Ω characteristic far field impedance
Δ_{SW}	=	correction term for standing waves in the TEM cell, scalar

f(x,y)= Form factor for the field strength as a function of the position in the TEM cell, scalar
x is the horizontal transversal position, *y* is the vertical position

A detailed uncertainty budget can be delivered for the generation of the field.
The information can be provided from the VSL report S-EL-GT-01.01

A number of contributions can be eliminated as a consequence of insertion loss measurements performed on part of the system during the calibration. The following insertion loss measurements were performed:

- probe cabling loss including attenuators
- Tem cell cabling loss including attenuators and excluding TEM cell
- Tem cell cabling loss including attenuators and including TEM cell

In this manner the main portion of the systematic uncertainty in attenuation was eliminated from the circuits mentioned.

From the report mentioned the typical (k=1) uncertainty using the TEM cell for generating a E-field is 0.3 dB. Main contribution in this case is the reflection coefficient of the cell ports within the cell. When transforming to H-field generation there will be extra uncertainty contributions from the in-homogeneity of the surface covered by the loop and the loading of the cell by the device under calibration. The estimated contribution for this in-homogeneity is 0.3 dB, which is based on the known in-homogeneity of the E-field value.

A shift of the results for the measurements at 30 MHz of 0.7 dB was noticed when turning the coil over 180 degrees around the axis. The main part of this deviation is expected to be the result of the difference in lay out of the cabling and their interactions with the field. At 1 MHz this shift was less than 0.2 dB.

Magnetic field strength calculation in Helmholtz coil

The magnetic field H generated in a pair of Helmholtz coils is given by the formula:

$$H = \left(\frac{4}{5}\right)^{\frac{3}{2}} \cdot \frac{I}{R} \cdot f(x, y)$$

H	=	electric field strength at position (x,y), in A/m
R	=	radius of coils = distance between coils, in m
I	=	current though the coils, in ampere
f(x,y)	=	Form factor for the field strength as a function of the position in the coil set. *x* is the horizontal transversal position, *y* is the vertical position

As the loop antennas cover an area in the Helmholtz pair a correction to the value at f (0,0) had to be made. This correction was calculated using the integral over the surface exposed.

Appendix F : Results for Loop E at 10 kHz - excluded because of instability.

During NPL's TEM cell measurements on Loop E, i.e. NPL(2), some oscillatory behaviour was found at 10 kHz. Therefore no stable data could be measured and it was felt that the artefact (at this frequency) was not suitable to be included in the formal results, so this frequency was excluded from the intercomparison. The results are briefly reported here for information only.

The Reference Value was: –21.33 dB(S.m^{-1})

After testing against the Median of Absolute Deviation the result from NMi-VSL was excluded from the calculation of Reference Value (RV). It is likely that this laboratory suffered the same instability because they used a TEM cell system similar to NPL.

Degrees of equivalence for Loop E at 10 kHz. The unit of measurement is antenna factor (dB(S.m^{-1})), and the difference between the RV and each measured result is presented here as a logarithmic ratio (dB).