Key comparison : CCEM.RF-K21.F
Intercomparison of tuned dipole antenna factor at 300 MHz and 900 MHz.

FINAL REPORT

AUTHORS
D A Knight, M J Alexander

CONTENTS

1 Introduction

This report describes the key comparison which was conducted between January 2002 and September 2004. The intercomparison was originally planned for the Euromet Regional Metrology Organisations (RMO) as Euromet 458, then the scope was expanded to form a worldwide GT-RF intercomparison. The chosen intercomparison artefact was a commercially produced tuneable dipole antenna which was to be measured at 300 MHz and 900 MHz. In recent years it has become more common for calculable dipole antennas to be used for evaluating antenna range performance. At the same time, many international standards laboratories have adopted the calculable dipole antenna as a primary reference. It is therefore hoped that this intercomparison will contain a mixture of measurement techniques, and that the comparison between these will 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 KCRV, so this was for background information only.

A supplementary comparison (S21.F) was conducted in parallel with this key comparison. The supplementary work involved the calibration of broadband EMC antennas, with the aim of comparing measurements of common proprietary antenna designs, operating over a broad frequency range. This work is summarised in another document.

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 technical referees 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	CETM 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	Kriz Alexander Wolfgang Müllner **(See note after table)**	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
NIMC	APMP	Fan Wu	RF & Microwave Division National Institute of Metrology No.18 Bei San Huan Dong Lu Beijing 100013 P.R. CHINA
VNIIFTRI	COOMET	Vladimir Tischenko	Department of electromagnetic field measurements VNIIFTRI All-Russian Institute for Physical-Technical and Radiotechnical Measurement Mendeleevo RU - 141570 Moscow region RUSSIA
SP	EUROMET	Ulrich Stein / Jan Welinder	Swedish National Testing and Research Institute Brinellgatan 4 Box 857 S-501 15 Borås SWEDEN

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 comparison standard was sent to the participating laboratories in the following order. The dates are given for the completion of measurements in each case.

NPL(1)	October 2001
ARCS	May 2002
NIST	August 2002
AIST	February 2003
NPL(2)	May 2003
LNE	June 2003
SP	September 2003
KRISS	January 2004
NIMC	May 2004
VNIIFTRI	August 2004

On several legs the consignment was hindered by problems encountered through customs, and often a fair amount of 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 standard and required measurement

3.1 Description of standard

The antenna used for the key comparison was a Schwarzbeck tuneable dipole, model UHAP (s/n 610). This antenna has tuneable elements which may be set to achieve resonant length anywhere in the frequency range 300 MHz to 1 GHz.

3.2 Required measurement

The intercomparison required the antenna factor of the dipole to be measured when placed horizontally at 2 m above a large ground plane. The required frequencies are 300 MHz and 900 MHz. It is expected that, at 2 m height, the 900 MHz dipole should only couple weakly with the ground plane, however the 300 MHz dipole will couple more strongly because the wavelength is a significant fraction of the height.

In order to achieve resonance the elements were set to the following lengths, which are given as tip-tip measurements:

300 MHz	470 mm
900 MHz	158 mm

Antenna factor describes the sensitivity of an antenna to E-field strength, and it is the standard unit of calibration for antennas operating in the VHF and UHF frequency band. Throughout industry 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.

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

3.3 Initial checks

It was recommended that each participant should check the pin depth of the N-type connector 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 table lists the measurements taken by each participant. The data suggests that the dipole connector remained stable throughout the intercomparison period.

Table 3-1: Measured recession of female pin on KC dipole

Laboratory	Recession of female pin (inches)
NPL(1)	-0.004
ARCS	[no data]
NIST	-0.004
AIST	-0.003
NPL(2)	-0.005
LNE	[no data]
SP	-0.004
KRISS	[no data]
NIMC	[no data]
VNIIFTRI	-0.003

4 Methods of measurement

4.1 NPL

Calibration method: Standard antenna method

The dipole was calibrated by substitution against the NPL calculable standard dipole 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 horizontal field was generated by a linearly polarised transmitting dipole type antenna, and the intercomparison dipole was mounted as a receive antenna placed at 2 m height, horizontally polarised over the ground. All antennas were supported by masts which were constructed of low reflectivity materials. At 300 MHz a 10 m antenna separation was used, and at 900 MHz a 2 m separation was used.

The height of the transmit antenna was chosen to generate a maximum field strength at the receive antenna, and the site attenuation was measured using a HP8753 model network analyser. The antenna factor was determined by direct comparison with the NPL calculable dipole. The following table details the system traceability:

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.
NPL calculable dipole (SRD 6500)	AF verified by measurement of site attenuation over the ground plane, and comparison with numerical modelling.

4.2 ARCS

Calibration method: Standard antenna method

The Antenna under Test (AUT) is mounted on a tripod at a height of 2 m. The receive antenna is a log periodic antenna positioned at the theoretical maximum of the field strength (114 cm for 300 MHz and 124 cm for 900 MHz). The distance between the antennas is 10 m. After measuring the site attenuation the AUT is replaced by the Precision Reference Dipole (PRD). The difference of the site attenuations is the difference of the antenna factors.

System components

Device	Type
Open Area Test Site	Built by ARCS
Network analyzer	HP 8753B S/N 2824U04168 HP 8753D S/N 3410A04463
Calibration Kit	85054D S/N 3101A00651 85032D S/N 3217A07109
Auxiliary antenna	Chase Bilog CBL6112 S/N 2280
Attenuator	HP 8491B 6 dB S/N 24058, S/N 24063

The Precision Reference Dipole is calculable and provides traceability to primary standards for antenna factor.

4.3 NIST

Calibration method: Three antenna method

Test site was the NIST OATS (30m x 60m). Consisting of 6.4mm galvanized mesh with solid galvanized sheet metal in central 10m x 20m section. Test distance was 10.0 m.

System components:

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

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

4.4 AIST

Calibration method: Three antenna method

Description of test site: OATS with a 30 m by 50 m welded steel ground-plane

System components: Vector network analyzer (HP8753E)
Two additional dipoles :
Shaffner-Chase SRD6500s (S/N: 6010 & 6021) for 300 MHz
Shaffner-Chase SRD6500s (S/N: 6021 & 6022) for 900 MHz

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.

The dipole antenna was measured by a three-antenna method using two additional antennas of model type SRD6500 at the AIST OATS which has a welded steel ground plane with the dimension of 30 m by 50 m. The transmitting and receiving antennas were set up in horizontal polarization at the height of 2.0 m above the ground plane. The distances between the transmitting and receiving antennas were 4.3 m at 300 MHz and 3.4 m at 900 MHz. A vector network analyzer (VNA) was used to measure the propagation attenuation S21 between these antenna terminals and also their reflection coefficients S11 and S22. The VNA was calibrated using a HP85032B calibration kit for each antenna measurement.

4.5 LNE

Calibration method: Standard antenna method

Description of test site: Open-field site, (15 m ×10 m). Horizontal polarisation, separation distance of 10 m, dipole height of 2 m.

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

4.6 SP

Calibration method: Standard antenna method

The dipole was calibrated by substitution, using a Schaffner precision dipole as the reference antenna. Antenna 1 (Tx) was set at 2 m height above the ground plane, and antenna 2 (Rx, reference antenna & AUT) was set to 2 m height as required. The measurement distance was 10 m.

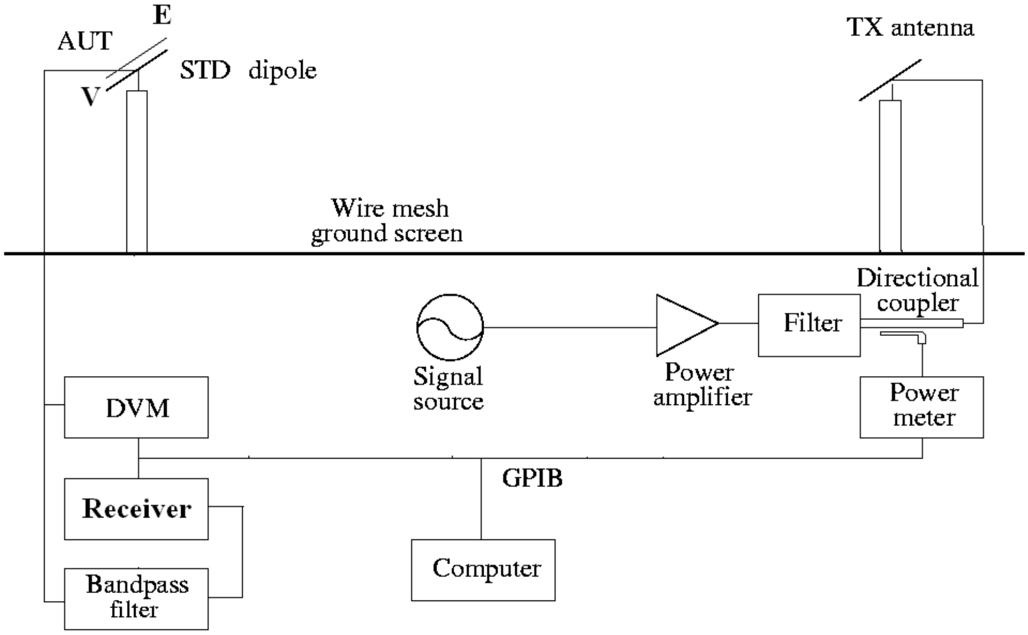
Description of test site:
Open are test site (OATS), with ground plane 20 m × 17 m. On the plane there is a permanently mounted wood and plastic shelter which protects the turntable and EUT during radiated emission measurements. During antenna calibration a diagonal measurement set-up is used to avoid interference by this shelter.

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)

4.7 KRISS

Calibration method: Standard antenna method

Description of test site:



Measurements were done at the open area test site (OATS) which is 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 and the receiving antennas are positioned horizontally at 2 m above ground plane using a tripod/styrofoam box. The distance between the antennas is 4.58 m.

At first, the STD dipole antenna is positioned at the required height for this measurement, which is 2 m above the ground plane. Induced RF voltage on the STD dipole is detected by an antenna voltmeter, and the DC voltage from the voltmeter 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 which is 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 derive the RF voltage (V) into 50 Ohm at the output terminal of the AUT, the RF signal power should be measured at the output. 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. The antenna factor of the AUT is calculated from the ratio of E and V.

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

4.8 NIMC

Calibration method: Three antenna method

The dipole was calibrated on an open area test site, placed at 2 m horizontally polarised.

System components	Traceability
Spectrum analyzer	NIMC
Attenuator	NIMC
Signal generator	NIMC
Network analyzer	NIMC

4.9 VNIIFTRI

Calibration method: Standard antenna method

The dipole antenna factor was measured at the frequencies 300 MHz and 900 MHz. The distance between the transmitting and standard biconical antennas was 3 m and the height above the ground was 2 m. All the antennas were horizontally polarised. The dipole antenna was placed at the same point of free-space as the standard biconical antenna. The field intensity created by the transmit antenna was constant during the measurement period. The dipole antenna factor was measured 10 times, then the arithmetic mean was calculated. The ambient conditions were: temperature 22°C, and humidity 65 %.

A power meter was used to measure the output signal from the dipole, and therefore the antenna factor is given by the following expression:

$$AF = \gamma \frac{E_{ST}}{\sqrt{Z_0 P}} \qquad \gamma = \frac{\sqrt{1 - |\Gamma_P|^2}}{|1 - \Gamma_A \Gamma_P|}$$

Where:
E_{ST} = The electrical field, defining the National Primary Standard in free-space (V/m).
P = The power measured at the mating reference plane of the dipole antenna (W).
Z_0 = 50 Ω
Γ_A = Reflection coefficient of antenna.
Γ_P = Reflection coefficient of power meter.

With the assumption of $\Gamma_P << 1$, the coefficient $\gamma \approx 1$, and the mismatch error is derived from the maximum limits of the coefficient gamma:

$$Error = \pm\left(\tfrac{1}{2}\left|\Gamma_P\right|^2 + \left|\Gamma_A\right| \cdot \left|\Gamma_P\right|\right)$$

System components:
The National Primary Standard for the Unit of Electrical Field Strength is traceable through the set of standard biconical antennas UEPE-BA (30 - 1000 MHz).
Type A evaluation of standard uncertainty = 0.50 % (nominal limit value)
Type B evaluation of standard uncertainty = 0.62 %.

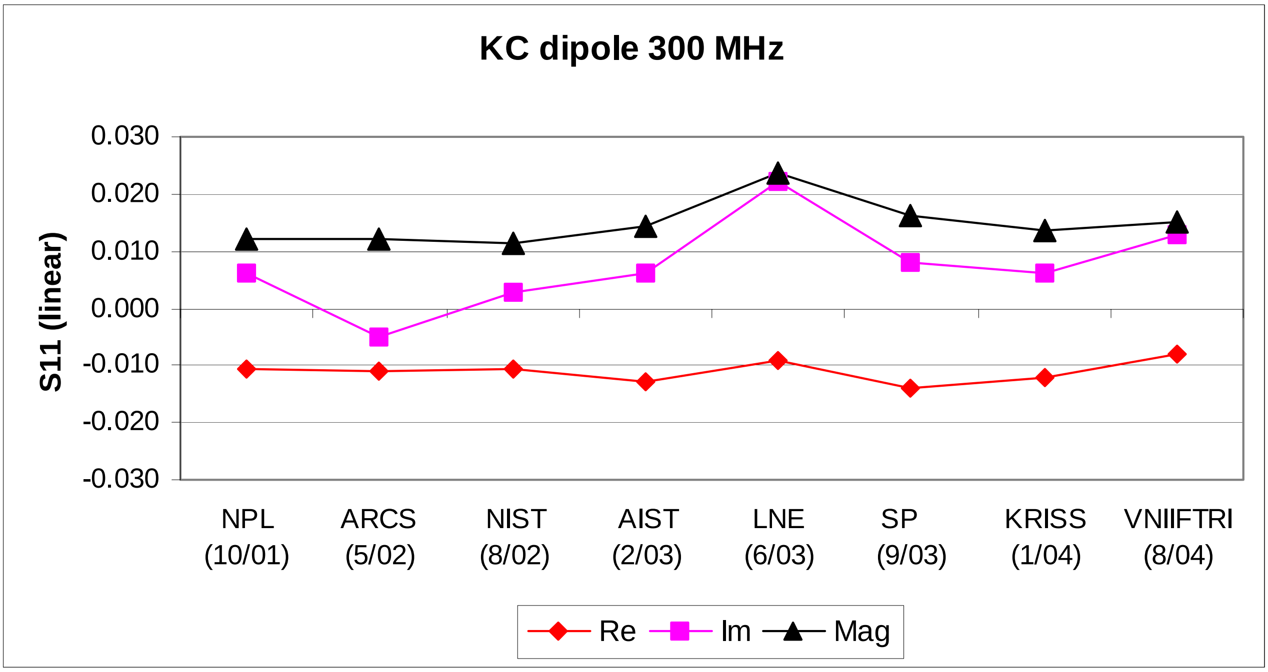
The characteristics of the power meter are:
Frequency range = 0.009 - 1000 MHz
The power range = 10^{-5} - 10^{-2} W
The power meter impedance = 50Ω
Reflection coefficient of power meter < 0.05
The limits of permissible error of the power meter = ±2.0 %.

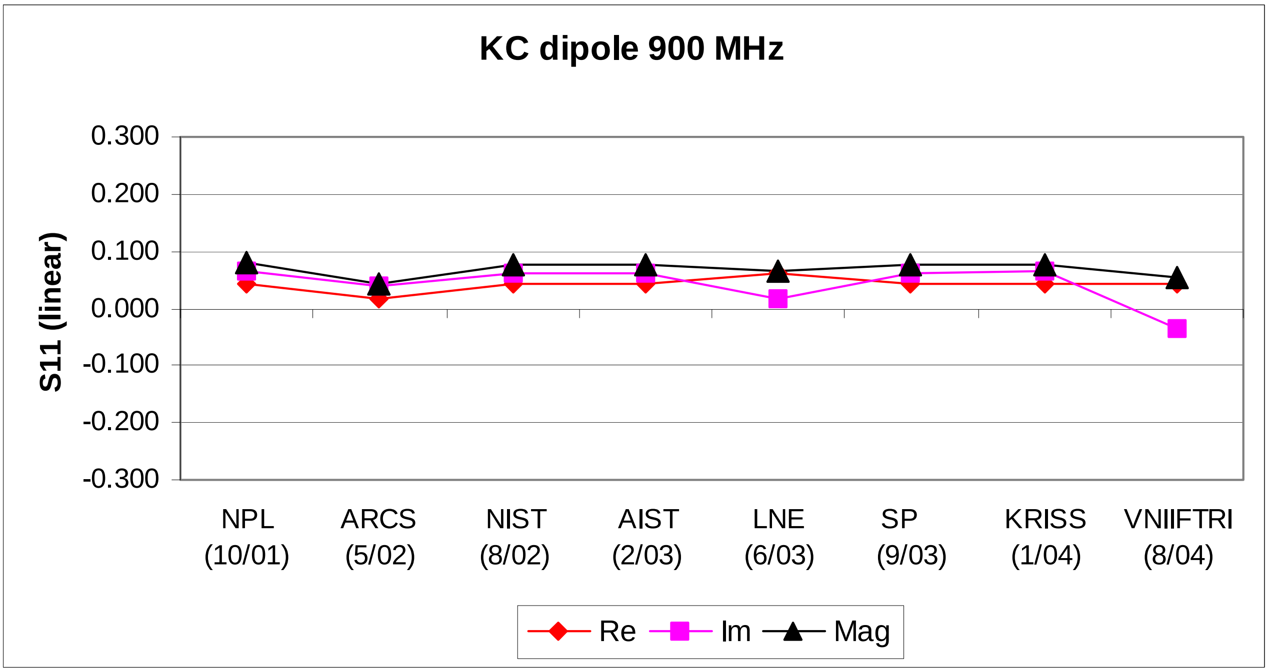
5 Stability of standard

Participants were required to measure the complex S11 for the dipole when placed in the measurement configuration. This provides some feedback on the stability of the dipole 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 in addition to the ground plane coupling.

Figure 5-1 shows the real and imaginary parts of the dipole S11, and the resultant magnitude of the complex vector is presented in the same plot. The graphs indicate that the input to the travelling standard was stable during the period of the intercomparison. The minor differences between each measurement of complex S11 are probably due to phase errors in the calibration of each particular network analyser used.

Figure 5-1 : S11 of Key Comparison dipole placed at 2 m horizontal polarization above ground plane.





6 Intercomparison results

6.1 Evaluating Key Comparison Reference Value (KCRV)

Table 6-1 and Table 6-2 give the calculated Degree of Equivalence at the two frequencies used for the key comparison. All the uncertainties in the tables are presented at the 95% confidence level. The KCRV 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 NPL values were averaged together and treated as a single measurement. 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 KCRV 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 KCRV, which is just the average of all those results which pass the test against the S(MAD) described above. In the situation where both NPL results passed the test against S(MAD) their average value was used in the calculation of KCRV, 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 KCRV.

Therefore the KCRV is given by:

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

The uncertainty in KCRV is given by:

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

The Degree of equivalence for each laboratory is simply:

$$D_i = \left(X_i - X_{KCRV}\right)$$

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

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

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 KCRV, and the term is zero for excluded results. From the above expression the uncertainty in D_i (at 95% confidence) is given by:

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

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

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

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

$$D_{ij} = \left(X_i - X_j\right)$$

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

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

6.2 Calculated Degree of Equivalence with KCRV and inter-laboratory matrix.

Table 6-1 : Degree of Equivalence for 300 MHz Schwarzbeck UHAP tuned dipole (470 mm tip to tip). KCRV = 27.51 dB(m^{-1}). The calculated u_{KCRV} of the reference value was 0.054 dB.

Degree of Equivalence with KCRV			Lab(j)																			
			ARCS		NIST		AIST		LNE		SP		KRISS		NIMC		VNIIFTRI		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)	Dij	U(Dij)
ARCS	-0.004	0.253			-0.19	1.00	0.02	0.36	-0.19	1.04	-0.07	1.02	0.07	0.50	-0.35	0.77	0.21	0.59	0.00	0.43	0.10	0.43
NIST	0.186	0.819	0.19	1.00			0.21	0.99	0.00	1.39	0.12	1.37	0.26	1.05	-0.16	1.20	0.40	1.09	0.19	1.02	0.29	1.02
AIST	-0.024	0.230	-0.02	0.36	-0.21	0.99			-0.21	1.03	-0.09	1.01	0.05	0.48	-0.37	0.76	0.19	0.57	-0.02	0.42	0.08	0.42
LNE	0.186	0.852	0.19	1.04	0.00	1.39	0.21	1.03			0.12	1.40	0.26	1.08	-0.16	1.23	0.40	1.13	0.19	1.06	0.29	1.06
SP	0.066	0.835	0.07	1.02	-0.12	1.37	0.09	1.01	-0.12	1.40			0.14	1.07	-0.28	1.22	0.28	1.11	0.07	1.04	0.17	1.04
KRISS	-0.074	0.371	-0.07	0.50	-0.26	1.05	-0.05	0.48	-0.26	1.08	-0.14	1.07			-0.42	0.83	0.14	0.67	-0.07	0.54	0.03	0.54
NIMC	0.346	0.728	0.35	0.77	0.16	1.20	0.37	0.76	0.16	1.23	0.28	1.22	0.42	0.83			0.56	0.89	0.35	0.80	0.45	0.80
VNIIFTRI	-0.214	0.453	-0.21	0.59	-0.40	1.09	-0.19	0.57	-0.40	1.13	-0.28	1.11	-0.14	0.67	-0.56	0.89			-0.21	0.62	-0.11	0.62
NPL(1)	-0.004	0.307	0.00	0.43	-0.19	1.02	0.02	0.42	-0.19	1.06	-0.07	1.04	0.07	0.54	-0.35	0.80	0.21	0.62			0.10	0.48
NPL(2)	-0.104	0.307	-0.10	0.43	-0.29	1.02	-0.08	0.42	-0.29	1.06	-0.17	1.04	-0.03	0.54	-0.45	0.80	0.11	0.62	-0.10	0.48		

Note

After testing against the Median of Absolute Deviation NIMC was excluded from the calculation of KCRV.

After review by the GT-RF committee The Swedish National Testing and Research Institute (SP) result was excluded from the calculation of KCRV because there was significant correlation between the traceability of SP and NPL.

Table 6-2 : Degree of Equivalence for 900 MHz Schwarzbeck UHAP tuned dipole (158 mm tip to tip). KCRV = 37.69 dB(m^{-1}). The calculated u_{KCRV} of the reference value was 0.040 dB.

Degree of Equivalence with KCRV			Lab(j)																			
			ARCS		NIST		AIST		LNE		SP		KRISS		NIMC		VNIIFTRI		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)	Dij	U(Dij)
ARCS	0.004	0.234			-0.01	1.00	-0.08	0.48	-0.41	1.62	0.03	1.02	-0.10	0.64	0.04	0.90	0.59	0.59	0.15	0.55	0.19	0.55
NIST	0.014	0.788	0.01	1.00			-0.07	1.04	-0.40	1.87	0.04	1.37	-0.09	1.12	0.05	1.29	0.60	1.09	0.16	1.07	0.20	1.07
AIST	0.084	0.336	0.08	0.48	0.07	1.04			-0.33	1.65	0.11	1.06	-0.02	0.70	0.12	0.95	0.67	0.66	0.23	0.62	0.27	0.62
LNE	0.414	1.602	0.41	1.62	0.40	1.87	0.33	1.65			0.44	1.88	0.31	1.70	0.45	1.82	1.00	1.68	0.56	1.67	0.60	1.67
SP	-0.026	0.804	-0.03	1.02	-0.04	1.37	-0.11	1.06	-0.44	1.88			-0.13	1.14	0.01	1.30	0.56	1.11	0.12	1.09	0.16	1.09
KRISS	0.104	0.480	0.10	0.64	0.09	1.12	0.02	0.70	-0.31	1.70	0.13	1.14			0.14	1.04	0.69	0.78	0.25	0.75	0.29	0.75
NIMC	-0.036	0.707	-0.04	0.90	-0.05	1.29	-0.12	0.95	-0.45	1.82	-0.01	1.30	-0.14	1.04			0.55	1.00	0.11	0.98	0.15	0.98
VNIIFTRI	-0.586	0.526	-0.59	0.59	-0.60	1.09	-0.67	0.66	-1.00	1.68	-0.56	1.11	-0.69	0.78	-0.55	1.00			-0.44	0.71	-0.40	0.71
NPL(1)	-0.146	0.400	-0.15	0.55	-0.16	1.07	-0.23	0.62	-0.56	1.67	-0.12	1.09	-0.25	0.75	-0.11	0.98	0.44	0.71			0.04	0.68
NPL(2)	-0.189	0.400	-0.19	0.55	-0.20	1.07	-0.27	0.62	-0.60	1.67	-0.16	1.09	-0.29	0.75	-0.15	0.98	0.40	0.71	-0.04	0.68		

Note

After testing against the Median of Absolute Deviation VNIIFTRI and LNE were excluded from the calculation of KCRV.

After review by the GT-RF committee The Swedish National Testing and Research Institute (SP) result was excluded from the calculation of KCRV because there was significant correlation between the traceability of SP and NPL.

Figure 6-1 and Figure 6-2 illustrate the degrees of equivalence for all the participants. The limit bars show $U(D_i)$ 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 KCRV and each measured value.

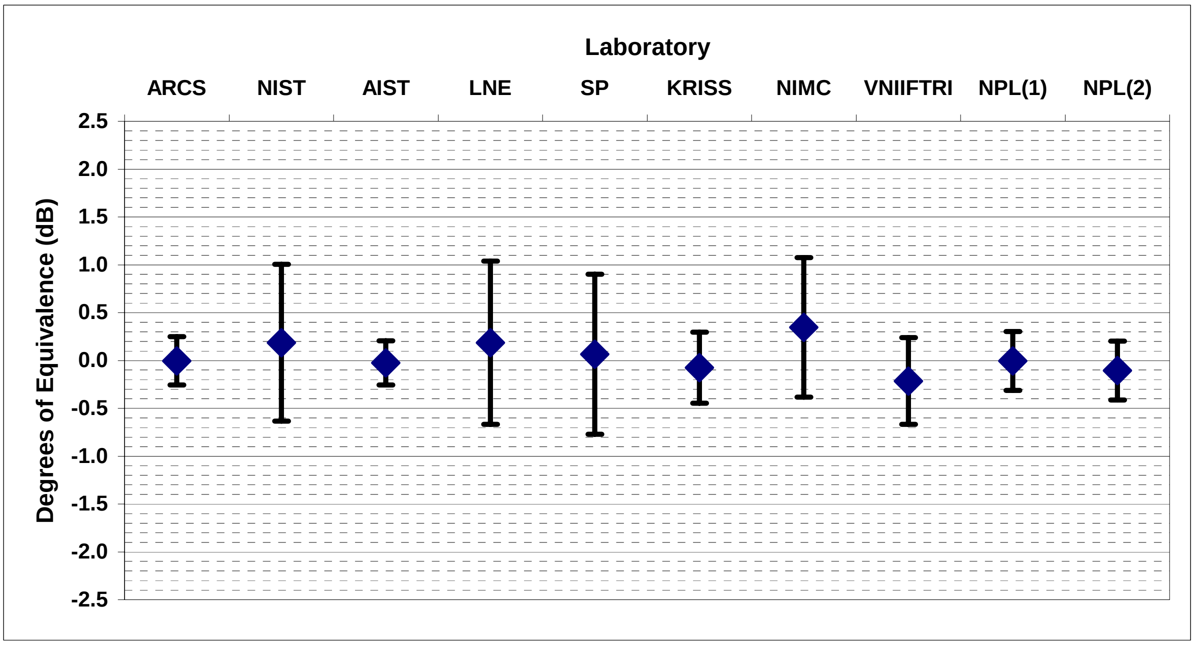


Figure 6-1: Degrees of equivalence for 300 MHz dipole. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the KCRV and each measured result is presented here as a logarithmic ratio (dB).

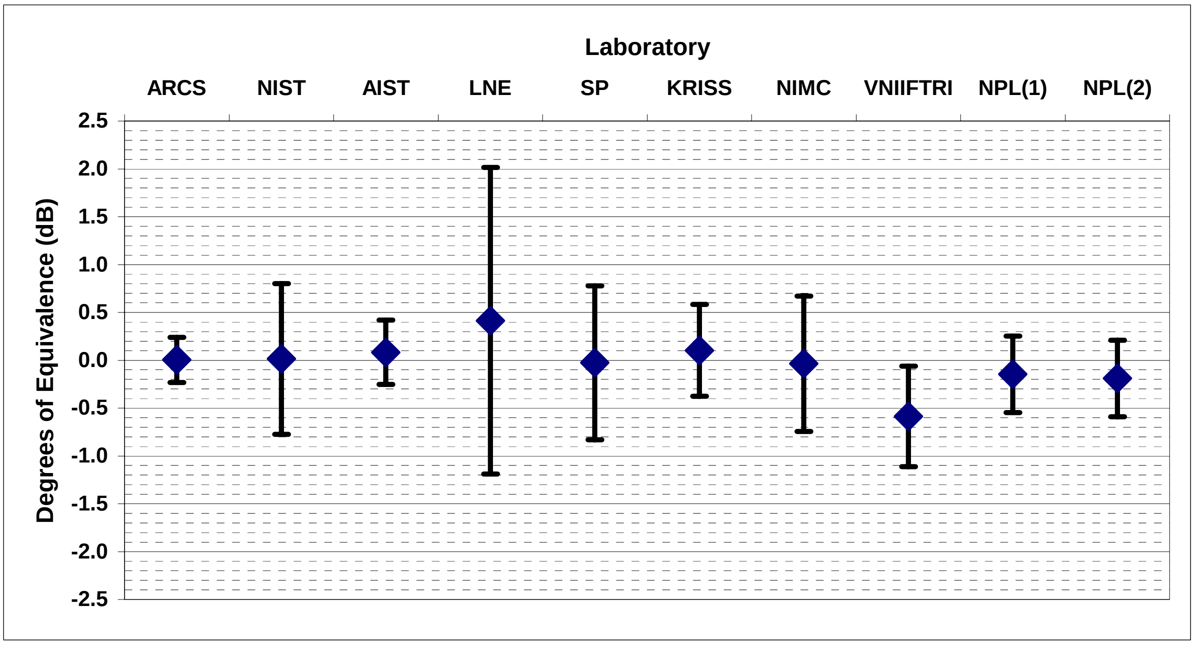


Figure 6-2: Degrees of equivalence for 900 MHz dipole. The unit of measurement is antenna factor (dB(m^{-1})), and the difference between the KCRV and each measured result is presented here as a logarithmic ratio (dB).

7 Submitted results for KC dipole

Table 7-1 and Table 7-2 list the individual results submitted by each participant for the key comparison dipole.

Laboratory	Antenna factor dB(m^{-1})	Uncertainty (1 SD)
ARCS	27.51	0.135
NIST	27.70	0.48
AIST	27.49	0.12
LNE	27.70	0.5
SP	27.58	0.49
KRISS	27.44	0.21
NIMC	27.86	0.36
VNIIFTRI	27.30	0.26
NPL(1)	27.51	0.17
NPL(2)	27.41	0.17

Table 7-1: Results submitted for the KC dipole at 300 MHz

Laboratory	Antenna factor dB(m^{-1})	Uncertainty (1 SD)
ARCS	37.69	0.135
NIST	37.70	0.48
AIST	37.77	0.2
LNE	38.10	0.8
SP	37.66	0.49
KRISS	37.79	0.29
NIMC	37.65	0.43
VNIIFTRI	37.10	0.26
NPL(1)	37.54	0.24
NPL(2)	37.497	0.24

Table 7-2: Results submitted for the KC dipole at 900 MHz

8 Withdrawals

Because of technical problems METAS (Switzerland) were unable to measure the key comparison dipole.

9 Summary and conclusions

The submitted descriptions of each measurement facility show that 6 laboratories used the standard antenna method, and 3 used the three antenna method. The detail in the application of these measurement techniques varied considerably between laboratories, so it is pleasing to find close agreement between the final results. For those participants who used the standard antenna method the traceability was achieved through a reference antenna, which was often a calculable dipole. The submitted ($k = 1$) measurement uncertainties varied between 0.12 dB and 0.49 dB.

The comparison of each D_{ij} to its corresponding $U(D_{ij})$ presented in the inter-laboratory matrix shown in Table 6-1 and Table 6-2 allows us to state that the results support the mutual equivalence between the national standards laboratories for realization of the tuned dipole antenna factor at 300 and 900 MHz.

In the inter-laboratory matrix the worst case D_{ij} is larger than $U(D_{ij})$ by 0.01 dB. This is not significant because by a crude analysis we see that this value of D_{ij} is only 1.5% above $U(D_{ij})$, at k = 2.

One aim of this intercomparison was to obtain a measure of the performance of conducting ground planes at each laboratory. This was the reason why the dipole was required to be measured at 2 m above a ground plane. However, after analysing the configuration, we concluded that the dipole performance, at both 300 MHz and 900 MHz, when placed at 2 m horizontally polarised over a perfect ground plane, will be actually quite close to the free-space value (see Table 4 in Reference [3]). The coupling between a dipole and the ground is a function of height (expressed in wavelength), and just by chance the antenna factor of the dipole at 2 m horizontal is within approximately 0.1 dB of the free-space value. This intercomparison was not perhaps a direct comparison of ground plane performance, but many of the measurement techniques described in this report require a well characterised E-field to be generated, and this will be a combination of the reflected signal and direct signal path. Therefore we may still conclude that the overall level of agreement achieved in this intercomparison provides good evidence of the quality of facilities at each participating laboratory.

10 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 compaisons. T J Witt (BIPM), CCEM WGKC/2001-25 (ver 1.0), July 2001.

[3] Corrections to antenna factors of resonant dipole antennas used over a ground plane. M J Salter and M J Alexander (NPL), NPL Report DES 131, Nov 1993.

Appendix A : NPL uncertainty budget

These budgets refer to a SAM measurement which requires two dipole SILs to be measured. Some components, such as mismatch, apply to both SILs so they appear twice in the summation, whereas others are most easily treated as an error in the measured difference in SILs, so they only appear once.

The uncertainty in standard dipole AF is derived from accurate SIL measurements on the NPL ground plane. The difference between theoretical and measured SIL can be as much as ±0.27 dB at 300 MHz, and ±0.35 dB at 900 MHz. This agreement between theory and measurement has been demonstrated for many antenna heights and separations, therefore we have confidence that any systematic uncertainties in the theory are relatively small and consequently we can derive an estimate of Gaussian uncertainty in dipole AF for any height above a ground plane. In practice the majority of dipole SIL measurements have smaller differences than these quoted maximum values, so we say that these limits represent a *measured* (k=2) uncertainty in SIL. This *measured* uncertainty (U_{MEAS}) is made up from the *actual* uncertainty in (theoretical) AF of both dipoles combined with the random uncertainty in measurement of SIL.

$$U_{MEAS} = 2 \cdot \sqrt{u_{AF1}^2 + u_{AF2}^2 + u_{SIL}^2}$$

If we assume that the uncertainty in AF is equally shared between the two dipoles then $u_{AF1} = u_{AF2} = u_{AF}$ and we may rearrange the expression:

$$u_{AF} = \sqrt{\frac{\left(U_{MEAS}/2\right)^2 - u_{SIL}^2}{2}}$$

An estimate of u_{SIL} is 0.084 dB at 300 MHz, and 0.105 dB at 900 MHz. Thus we arrive at the following (k=1) uncertainties in the AF of the NPL standard dipole.

300 MHz 0.075 dB
900 MHz 0.099 dB

300 MHz SAM AF (2m HP) at 10 m distance

Source of uncertainty	Value (± dB)	Distribution	Divisor	Sensitivity coefficient	Standard deviation
Measurement repeatability	0.1	Normal (type A)	1	1	0.1
Cable attenuation change with temperature	0.05	Rectangular	1.73	1	0.029
Ambient signals (40dB S/N, coherent)	0.086	Rectangular	1.73	1	0.050 0.050
Mismatch (Std & AUT)	0.06	U-shaped	1.41	1	0.042 0.042
Unwanted reflections (masts & cables)	0.05	Rectangular	1.73	1	0.029
Positioning error (height & separation)	0.03	Rectangular	1.73	1	0.017
Receiver linearity (typical for HP8753)	0.08	Rectangular	1.73	1	0.046
AF of std dipole	0.15	Normal (k = 2)	2	1	0.075
Combined uncertainty		Normal			0.168
Expanded uncertainty		Normal (k = 2)			0.34

900 MHz SAM AF (2m HP) at 2 m distance

Source of uncertainty	Value (± dB)	Distribution	Divisor	Sensitivity coefficient	Standard deviation
Measurement repeatability	0.15	Normal (type A)	1	1	0.15
Cable attenuation change with temperature	0.1	Rectangular	1.73	1	0.058
Ambient signals (40dB S/N, coherent)	0.086	Rectangular	1.73	1	0.050 0.050
Mismatch (Std & AUT)	0.06	U-shaped	1.41	1	0.042 0.042
Unwanted reflections (masts & cables)	0.15	Rectangular	1.73	1	0.087
Positioning error (height & separation)	0.07	Rectangular	1.73	1	0.040
Receiver linearity (typical for HP8753)	0.08	Rectangular	1.73	1	0.046
AF of std dipole	0.2	Normal (k = 2)	2	1	0.1
Combined uncertainty		Normal			0.236
Expanded uncertainty		Normal (k = 2)			0.47

Appendix B : ARCS uncertainty budget

Here the notation 'neg' indicates that the component is negligibly small and may be ignored.

Source of uncertainty	Type	Value (± dB)	Probability distribution	Uncertainty 1 SD (u_i)	Sensitivity (C_i)	($C_i \times u_i$)
Mismatch error AUT	B	0.01	U-shaped	0.007	1	0.007
Mismatch error PRD	B	0.01	U-shaped	0.007	1	0.007
Receiver linearity (VNA)	B	0.08	Gaussian	0.04	2	0.08
Influence of test site	B	neg	Rectangular	neg	1	0
AF of PRD	B	0.15	Gaussian	0.075	1	0.075
Balun loss	B	0.08	Gaussian	0.04	1	0.04
Connector repeatability	A	0.03	Rectangular	0.017	2	0.035
Temperature drift	A	0.02	Gaussian	0.01	1	0.01
Positioning	A	0.05	Rectangular	0.029	2	0.058
Frequency error	B	neg	Rectangular	neg	1	0
Combined uncertainty			Normal			0.137
Expanded uncertainty			Normal (k = 2)			0.27

Appendix C : NIST uncertainty budget

Source of uncertainty	Type	Value x_i	Probability distribution	Probability factor p_i	Sensitivity factor s_i	Resultant value, dB u_i
Source drift 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	0.25 dB	Rectangular	1/√3	1	0.144
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	0.019 0.019 0.019
Combined uncertainty (one std dev)						**0.48**

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

D = 10 m

F= 1000 MHz.

Appendix D : AIST uncertainty budget

The antenna factor was derived by using the following equation:

$$A_f = \sqrt{\frac{1}{279.1}}\sqrt{\frac{F_{M1}F_{M2}}{F_{M3}}}\sqrt{\frac{E_{H1}E_{H2}}{E_{H3}}}\sqrt{\frac{A_1A_2}{A_3}}$$

$$E_{Hi} = \frac{\sqrt{30P_tG_i}\sqrt{d_{di}^2 + d_{ri}^2 + 2d_{di}d_{ri}Cos(\pi - \beta\{d_{ri} - d_{di}\})}}{d_{di}d_{ri}}, \quad i = 1,2,3$$

where:

F_{Mi}: frequency(MHz)

E_{Hi}: Electric field generated by input power of 1 pW into the transmitting antenna

G_i: antenna gain

d_{di}: distance of direct propagation

d_{ri}: distance with a bounce of reflection on the ground plane

A_i: site attenuation between each antenna pair

The uncertainty of the antenna factor was primarily derived from the frequency, electric field strength, site attenuation and their sensitivity factors (calculated as their partial derivatives). The uncertainty for 300 MHz is shown in Table D-1, and the uncertainty for 900 MHz is shown in Table D-5. The resultant standard uncertainty is calculated along the propagation principle which is described in the GUM. The mark of (-) in the tables indicates that the component is dimensionless.

Table D-1: Resultant uncertainty budget for the antenna factor of UHAP at 300 MHz, obtained by three-antenna method above the ground plane

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	5250 5250 5250	(Hz)	Include once for each measurement
Attenuation measurement 6010 & 6021	combined		0.0096 × AF	(1/m)	0.6485	(-)	See table D-2
Attenuation measurement 6010 & UHAP	combined		0.0050 × AF	(1/m)	0.7998	(-)	See table D-3
Attenuation measurement 6021 & UHAP	combined		0.0051 × AF	(1/m)	0.7261	(-)	See table D-4
Electric field strength	combined **See Note**	Gaussian	0.1816 × AF	(1/μV)	0.03513 0.03513 0.03513	(μV/m)	Include once for each measurement
Total uncertainty					0.0138 × AF	(1/m)	
					0.12	(dB/m)	

Note: Derivation of this electric field uncertainty component was provided by AIST, but for brevity it is not reproduced here.

Table D-2: Uncertainty budget for the attenuation measurement with 6010 and 6021 at 300 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	0.2052	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.1073	(-)	
VNA resolution	B	Rectangular	1	(-)	0.0374	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	0.1864	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.0183	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.0000	(-)	Fixed element is used
Connector repeatability	B	Rectangular	1	(-)	0.0564	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	0.5721	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					0.6485	(-)	

Table D-3: Uncertainty budget for the attenuation measurement with 6010 and UHAP at 300 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	0.3627	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.1073	(-)	
VNA resolution	B	Rectangular	1	(-)	0.0664	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	0.3314	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.0577	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.2003	(-)	
Connector repeatability	B	Rectangular	1	(-)	0.1079	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	0.5721	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					0.7998	(-)	

Table D-4: Uncertainty budget for the attenuation measurement with 6021 and UHAP at 300 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	0.2323	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.1073	(-)	
VNA resolution	B	Rectangular	1	(-)	0.0664	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	0.3314	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.0577	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.0731	(-)	
Connector repeatability	B	Rectangular	1	(-)	0.1074	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	0.5721	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					0.7261	(-)	

Table D-5: Resultant uncertainty budget for the antenna factor of UHAP at 900 MHz, obtained by three-antenna method above the ground plane

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Frequency	B	Rectangular	0.0000 × AF	(1/Hz.m)	15750 15750 15750	(Hz)	Included once for each measurement
Attenuation measurement 6010 & 6021	combined		0.0033 × AF	(1/m)	3.0442	(-)	See table D-6
Attenuation measurement 6010 & UHAP	combined		0.0017 × AF	(1/m)	3.5133	(-)	See table D-7
Attenuation measurement 6021 & UHAP	combined		0.0017 × AF	(1/m)	3.8301	(-)	See table D-8
Electric field strength	combined **See Note**	Gaussian	0.1488 × AF	(1/μV)	0.07462 0.07462 0.07462	(μV/m)	Included once for each measurement
Total uncertainty					0.0234 × AF	(1/m)	
					0.20	(dB/m)	

Note: Derivation of this electric field uncertainty component was provided by AIST, but for brevity it is not reproduced here.

Table D-6: Uncertainty budget for the attenuation measurement with 6010 and 6021 at 900 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	0.6723	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.5301	(-)	
VNA resolution	B	Rectangular	1	(-)	0.1053	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	0.5252	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.1450	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.0000	(-)	Fixed element is used
Connector repeatability	B	Rectangular	1	(-)	0.1628	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	2.8635	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					3.0442	(-)	

Table D-7: Uncertainty budget for attenuation measurement with 6010 and UHAP at 900 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	1.4600	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.5301	(-)	
VNA resolution	B	Rectangular	1	(-)	0.2101	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	1.0480	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.5774	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.3980	(-)	
Connector repeatability	B	Rectangular	1	(-)	0.3117	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	2.8635	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					3.5133	(-)	

Table D-8: Uncertainty budget for the attenuation measurement with 6021 and UHAP at 900 MHz.

Source of uncertainty	Type	Probability distribution	Sensitivity coefficient		Uncertainty		Note
Measurement repeatability	A	Normal	1	(-)	2.0807	(-)	10 measurements
Attenuation calibration of VNA	B	Rectangular	1	(-)	0.5301	(-)	
VNA resolution	B	Rectangular	1	(-)	0.2101	(-)	Resolution of 0.01 dB is assumed
VNA non-linearity	B	Rectangular	1	(-)	1.0480	(-)	Linearity of 0.05 dB is assumed
Signal to noise ratio	B	Rectangular	1	(-)	0.5774	(-)	Noise floor of –100 dBm is assumed
Element length adjustment	A	Normal	1	(-)	0.5346	(-)	
Connector repeatability	B	Rectangular	1	(-)	0.3130	(-)	0.02 dB boundary limit
Attenuation drift of cables	B	Rectangular	1	(-)	2.8635	(-)	Maximum temperature drift of 25 degrees is assumed
Combined uncertainty					3.8301	(-)	

Appendix E : LNE uncertainty budget

Uncertainty budget for standard antenna method, 300 MHz dipole

Source of uncertainty	Type	Value (±)	Probability distribution	Uncertainty u_i	Sensitivity factor C_i	$C_i \times u_i$
Mismatch error	B	0.2 dB	Rectangular	0.115	1	0.115
Connector repeatability	A	0.2 dB	Gaussian	0.2	1	0.2
Receiver linearity	B	0.2 dB	Rectangular	0.115	1	0.115
Combined positioning error	B	0.05 m	Rectangular	0.03	10	0.3
AF of standard	B	0.25 dB	Rectangular	0.144	1	0.144
Combined uncertainty						**0.44**

Uncertainty budget for standard antenna method, 900 MHz dipole

Source of uncertainty	Type	Value (±)	Probability distribution	Uncertainty u_i	Sensitivity factor C_i	$C_i \times u_i$
Mismatch error	B	0.6 dB	Rectangular	0.35	1	0.35
Connector repeatability	A	0.2 dB	Gaussian	0.2	1	0.2
Receiver linearity	B	0.2 dB	Rectangular	0.115	1	0.115
Combined positioning error	B	0.05 m	Rectangular	0.03	6	0.18
AF of standard	B	0.9 dB	Rectangular	0.55	1	0.55
Combined uncertainty						**0.72**

Appendix F : 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 G : KRISS uncertainty budget

Uncertainty budget at 300 MHz (All values in dB except sensitivity factor)

Sources of uncertainty	Type	Value (±)	Probability distribution	Uncertainty (1 sd) (u_i)	Sensitivity factor (C_i)	$u_i \times C_i$
Effective length	B	0.050	Rectangular	0.029	1.0	0.029
Antenna voltmeter RF-DC conversion factor	B	0.200	Rectangular	0.115	1.0	0.115
Antenna voltmeter impedance loading	B	0.140	Rectangular	0.081	1.0	0.081
Mismatch	B	0.150	Rectangular	0.087	1.0	0.087
Source stability	B	0.100	Rectangular	0.058	1.0	0.058
Connector repeatability	A	0.030	Gaussian	0.030	1.0	0.030
Variation of cable loss	B	0.060	Rectangular	0.035	1.0	0.035
Error in AF due to test environment and positioning	B	0.150	Rectangular	0.087	1.0	0.087
Power sensor	B	0.060	Rectangular	0.035	1.0	0.035
Step attenuator	B	0.020	Rectangular	0.012	1.0	0.012
DC voltage	B	0.001	Rectangular	0.001	1.0	0.001
Combined uncertainty (1 standard deviation)						0.21

Uncertainty budget at 900 MHz (All values in dB except sensitivity factor)

Sources of uncertainty	Type	Value (±)	Probability distribution	Uncertainty (1 sd) (u_i)	Sensitivity factor (C_i)	$u_i \times C_i$
Effective length	B	0.125	Rectangular	0.072	1.0	0.072
Antenna voltmeter RF-DC conversion factor	B	0.400	Rectangular	0.231	1.0	0.231
Antenna voltmeter impedance loading	B	0.140	Rectangular	0.081	1.0	0.081
Mismatch	B	0.150	Rectangular	0.087	1.0	0.087
Source stability	B	0.100	Rectangular	0.058	1.0	0.058
Connector repeatability	A	0.030	Gaussian	0.030	1.0	0.030
Variation of cable loss	B	0.060	Rectangular	0.035	1.0	0.035
Error in AF due to test environment and positioning	B	0.150	Rectangular	0.087	1.0	0.087
Power sensor	B	0.060	Rectangular	0.035	1.0	0.035
Step attenuator	B	0.020	Rectangular	0.012	1.0	0.012
DC voltage	B	0.001	Rectangular	0.001	1.0	0.001
Combined uncertainty (1 standard deviation)						0.29

Appendix H : NIMC uncertainty budget

300 MHz KC dipole uncertainty budget for three antenna method at 10m

Source of uncertainty	**Type**	**Value**	**Probability Distribution**	**Uncertainty (one SD) (u_i)**	**Sensitivity Factor (C_i)**	**Resultant Value ($C_i \times u_i$)**
Mismatch error(s)	B	0.038dB	Rectangular	0.027	1/2	0.013 0.013 0.013
Measurement repeatability(n=10)	A	0.1 dB	Gaussian	0.1	1/2	0.05 0.05 0.05
Linearity of Spectrum analyzer measured signal	B	0.36 dB	Rectangular	0.207	1/2	0.104 0.104 0.104
Variation of cable attenuation due to temperature	B	0.1 dB	Rectangular	0.057	1/2	0.028 0.028 0.028
Test site environment	B	0.51 dB	Rectangular	0.294	1	0.294
Combined positioning error for each pair, including uncertainty in phase centres	B	0.09 m (r = 10m)	Rectangular	0.051 m (r = 10m)	4.34/r	0.022 0.022 0.022
Frequency error of source	B	10 ppm×F_M	Rectangular	1732 Hz	4.34/F_M	0.000
Combined uncertainty						**0.36**

900 MHz KC dipole uncertainty budget for three antenna method at 10m

Source of uncertainty	**Type**	**Value**	**Probability Distribution**	**Uncertainty (one SD) (u_i)**	**Sensitivity Factor (C_i)**	**Resultant Value ($C_i \times u_i$)**
Mismatch error(s)	B	0.083dB	Rectangular	0.048	1/2	0.024 0.024 0.024
Measurement repeatability(n=10)	A	0.120 dB	Gaussian	0.120	1/2	0.060 0.060 0.060
Linearity of Spectrum analyzer measured signal	B	0.540 dB	Rectangular	0.311	1/2	0.155 0.155 0.155
Variation of cable attenuation due to temperature	B	0.220 dB	Rectangular	0.127	1/2	0.063 0.063 0.063
Test site environment	B	0.510 dB	Rectangular	0.294	1	0.294
Combined positioning error for each pair, including uncertainty in phase centres	B	0.090 m (r = 10m)	Rectangular	0.051 m (r = 10m)	4.34/r	0.022 0.022 0.022
Frequency error of source	B	10 ppm×F_M	Rectangular	5196 Hz	4.34/F_M	0.000
Combined uncertainty						**0.43**

Appendix I : VNIIFTRI uncertainty budget

Uncertainty budget at 300 MHz

Source of uncertainty	**Type**	**Value (±) %**	**Probability Distribution**	**Uncertainty (one SD) (u_i) %**	**Sensitivity Factor (C_i)**	**($C_i \times u_i$) %**
The standard electric field strength	B	-	-	0.62	1	0.62
Power measurement	B	2.0	Rectangular	1.16	0.5	0.58
Power meter mismatch	B	0.1	Rectangular	0.06	0.5	0.03
Error in free-space AF assumption, due to test environment	B	5.0	Rectangular	2.89	1	2.89
The KC dipole AF measurement repeatability	A	0.33	Gaussian	0.33	1	0.33
Combined uncertainty (one SD)						3.03 % (0.26 dB)

Uncertainty budget at 900 MHz.

Source of uncertainty	**Type**	**Value (±) %**	**Probability Distribution**	**Uncertainty (one SD) (u_i) %**	**Sensitivity Factor (C_i)**	**($C_i \times u_i$) %**
The standard electric field strength	B	-	-	0.62	1	0.62
Power measurement	B	2.0	Rectangular	1.16	0.5	0.58
Power meter mismatch	B	0.5	Rectangular	0.29	0.5	0.15
Error in free-space AF assumption, due to test environment	B	5.0	Rectangular	2.89	1	2.89
The dipole measurement repeatability	A	0.48	Gaussian	0.48	1	0.48
Combined uncertainty (one SD)						3.05 % (0.26 dB)