

**INTERNATIONAL COMPARISON
CCEM.RF-K7b.F, (GT-RF 92-8):**

**RESULTS OF AN INTERCOMPARISON OF EMC ANTENNA
FACTORS IN THE FREQUENCY RANGE 30 MHZ –
1000 MHZ - NON-RESONANT DIPOLE ANTENNAS**

by

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Abstract

The inter comparison was piloted by NPL and took place between February 1996 and September 1999. Six antennas, of types typically used for EMC compliance testing within the frequency band 30 MHz to 1 GHz, were circulated to the six participating laboratories. The antenna factors of the antennas were measured at four or five mandatory frequencies and optionally two or three other frequencies. The reflection coefficients of each antenna were also measured. An agreement of antenna factors within ± 1 dB amongst the laboratories was broadly reached.

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Contents

1 Introduction.....	Page
1.1 Previous European inter-comparison	2
1.2 List of participating laboratories in order of measurements:	2
2 Antenna specifications	3
3 Scope of measurements.....	5
3.1 Horizontally Polarised antenna at a height of 2 m above a conducting ground plane at the following frequencies.....	5
3.2 Antenna at 80 MHz at the following heights above a conducting ground plane	5
3.3 Reflection coefficient.....	5
4. Uncertainties of Antenna Factor measurements	6
4.1 Uncertainties submitted by CSIRO	6
4.2 Uncertainties submitted by NPL.....	7
4.3 Uncertainties submitted by CRL	8
4.4 Uncertainties submitted by ETL.....	8
4.5 Uncertainties submitted by NIST	9
4.6 Uncertainties submitted by ETS	9
5 Site information and calibration methods used	9
6 Results	11
6.1 Measured Antenna Factors (dB/m)	11
6.2 Measured antenna factors minus arithmetic means (dB).....	13
6.3 Summary of deviation of antenna factor from the arithmetic mean	15
6.4 Error-bar charts showing deviation of antenna factors from mean values and showing measurement uncertainties.	16
7 References	19
Annex A: Reflection coefficients of the antennas	20

1.0 Introduction

The inter comparison was piloted by NPL and took place between February 1996 and September 1999. Six antennas, which are used for measuring electromagnetic field strength within the frequency band 30 MHz to 1 GHz, were circulated to the six participating laboratories. The antenna factors of the antennas, referred to as A, B, C, D, E and F, were measured at four or five mandatory frequencies and optionally two or three other frequencies. Most laboratories included the optional frequencies. The reflection coefficients of each antenna were also measured. There are a possible fifty-two antenna factor measurements, not all of which were done by all of the laboratories. An agreement of antenna factors within ± 1 dB amongst the laboratories was broadly reached.

1.1 Previous European inter-comparison

A comparison using the same set of antennas was conducted between January 1993 and May 1995. The organisation of that inter-comparison by NPL was funded by the European commission and involved 15 participating laboratories in 9 European countries¹. Each antenna was measured at an average of 6 frequencies. For this BIPM inter-comparison at least 2 new frequencies were introduced and the displaced frequencies became optional extras.

1.2 List of participating laboratories in order of measurements:

NPL (UK), Pilot laboratory, February 1996, September 1997, September 1999, Mr Martin J Alexander, National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK

ETL (Japan), April 1996, Dr Hiroyoshi Yajima, Electrotechnical Laboratory, 305: 1-1-4 Umezono, Tsukuba Ibaraki, Japan

CRL (Japan), May 1996, Dr Akira Sugiura, Kashima Space Research Centre, Communications Research Laboratory, Ministry of Posts & Telecoms, 893-1, Hirai, Kashima-machi, Kashima-gun, Ibaraki 314, Japan. ETL is a national standards institute for RF physical quantities in Japan, but its antenna calibration facilities were under construction. Hence the CRL participated in this inter-comparison.

NIST (USA), January 1997, Mr Dennis Camell, National Institute of Standards and Technology, Electromagnetic Fields Division, 325 Broadway, Boulder, Colorado 80303, USA

ETS (USA), January 1998, Mr Jim Psencik, EMC Test Systems, LP, 2205 Kramer Ln., Austin TX 78758.

The antennas were then sent to Liberty Labs, Iowa, Mr Michael Howard, who did some measurements but decided not to report the results because he had plans for a new ground plane.

CSIRO (Australia), March 1999, Dr John D Hunter, Division of Applied Physics, National Measurements Laboratory, PO Box 218, Lindfield NSW 2070, Australia

2 Antenna specifications

The manufacturer, type, model number and frequency range of each antenna follows:

A: Schwarzbeck, biconical, model VHBB9124, serial number 201, 30 MHz to 300 MHz.

B: Austrian Research Centre, biconical, model FZH-H1, serial number 93-05, 30 MHz to 300 MHz.

C: Chase EMC Ltd, log-periodic dipole array (LPDA) model UPA6108, serial number 1058, 300 MHz to 1 GHz.

D: Rohde & Schwarz, log-periodic dipole array (LPDA) model HL223, serial number 831465/007, 200 MHz to 1.3 GHz.

E: Schwarzbeck, tuneable dipole, model VHAP, serial number 646, 30 MHz to 300 MHz and Schwarzbeck, tuneable dipole model UHAP, serial number 609, 300 MHz to 1 GHz.

F: NPL short dipole antenna, serial number 02, 20 MHz to 100 MHz.

Some models of biconical antenna on the market suffer from balun imbalance which can cause large measurement uncertainties, especially in vertical polarisation. Some models of log antenna can suffer a breakdown in electrical contact of their dipole elements resulting in large resonances at some frequencies. For this inter-comparison antennas were chosen which were known to have neither of these problems and were expected to give reproducible results after much use. Antennas A and E have an excellent record for good balun design. Antenna B was chosen because it has a hybrid coupler balun and it has an internal 6 dB input attenuator which is not normal for biconical antennas, giving a high antenna factor than would usually be expected by the participants. Both antennas C and D are well designed log antennas with robust mechanical construction; antenna D has welded elements making an electrical breakdown impossible between the elements and the shaft.

The Schwarzbeck precision dipole antennas E, have built-in 10 dB attenuators which ensure that mismatch errors are minimised. Below approximately 55 MHz, antennas A, B and F act as short dipoles because their self impedances are high so the mutual impedance associated with the image antenna in the ground plane is relatively small. This means that the antenna factor below approximately 55 MHz is insensitive to variation of the height of the antenna above a ground plane. Antennas A and F were measured at 4 heights above the ground plane to demonstrate that the measurements could include the effects of mutual coupling.

The log-periodic dipole array antennas have gains of approximately 6 dB. Attention has to be paid to the methods used to calibrate LPDA antennas. If the antenna is measured over a ground plane account must be taken of the directivity to ensure that the ground reflected signal strength is significantly lower than the direct signal strength. Directivity errors can be reduced by reducing the angle between the boresight direction and the reflected ray. This can be done by reducing the antenna height and increasing the distance to the source antenna. Typically 3 dB beamwidths for LPDAs are E-plane 68°, compared with dipoles' E-plane 90° and bicones' E-plane 80°.

Another factor that must be considered for LPDAs is phase centre variation with frequency. The distance of the resonant element from the tip of the antenna varies with frequency so there will be errors if an LPDA is calibrated by substitution with a standard dipole antenna. This is especially the case over a ground plane because of the rate of variation of the resultant of the direct and reflected rays along the length of the LPDA.

Antennas A to E are proprietary designs for use in EMC test houses. Handling during the inter-comparison was not expected to have adverse effects on their performance. Antenna F was designed only for laboratory use and instructions accompanying the antenna requested care in handling.

Reflection coefficient was measured because it is needed to calculate the uncertainty of measurement. These are reported in Annex A.

3 Scope of measurements

The minimum set of measurements involves calibration of horizontally polarised antennas as defined below. The mandatory frequencies are given first, followed by optional frequencies.

3.1 Horizontally Polarised antenna at a height of 2 m above a conducting ground plane at the following frequencies

Biconical antenna **A**: 30 MHz, 70 MHz, 80 MHz, 250 MHz. Optional 60 MHz, 200 MHz and 300 MHz.

Biconical antenna **B**: 30 MHz, 70 MHz, 80 MHz, 250 MHz. Optional 60 MHz, 200 MHz and 300 MHz..

Log antenna **C**: 300 MHz, 400 MHz, 600 MHz, 1000 MHz. Optional 500 MHz, 700 MHz.

Log antenna **D**: 200 MHz, 300 MHz, 400 MHz, 600 MHz, 1000 MHz. Optional 500 MHz and 700 MHz.

Tuneable dipole antenna **E**: VHAP 60 MHz, 70 MHz, 200 MHz, 250 MHz. Optional 80 MHz, 300 MHz.

Tuneable dipole antenna **E**: UHAP 500 MHz, 600 MHz and 1000 MHz. Optional 700 MHz.

Short dipole antenna **F**: 30 MHz, 50 MHz, 60 MHz, 80 MHz and 90 MHz. Optional 45 MHz and 100 MHz.

3.2 Antenna at 80 MHz at the following heights above a conducting ground plane

Biconical antenna **A**: 1.0 m, 1.3 m, 1.9 m, 2.5 m.

Dipole antenna **F**: 1.0 m, 1.3 m, 1.9 m, 2.5 m.

3.3 Reflection coefficient

The complex (or vector) reflection coefficient of each horizontally polarised antenna was measured at a height of 2 m at the above frequencies.

4. Uncertainties of Antenna Factor measurements

This section contains uncertainties of measurement, $k = 2$, submitted by each laboratory.

4.1 Uncertainties submitted by CSIRO

The following expanded uncertainty values (U_C) are based on $k=2$ (95% confidence)

Table 4.1 *Uncertainties submitted by CSIRO*

	Frequency (MHz)	Height (m)	U_C ($\pm$ dB)
Biconical A	30.0	2.0	0.6
	70.1	2.0	0.5
	80.0	2.0	0.5
	250.0	2.0	0.5
	80.0	1.0	0.5
	80.0	1.3	0.5
	80.0	1.9	0.5
	80.0	2.5	0.5
Biconical B	30.0	2.0	0.6
	70.1	2.0	0.5
	80.0	2.0	0.5
	250.0	2.0	0.5
LPDA C	300.0	2.0	0.5
	400.0	2.0	0.5
	600.0	2.0	0.5
	1000.0	2.0	0.6
LPDA D	200.0	2.0	0.5
	300.0	2.0	0.5
	400.0	2.0	0.5
	600.0	2.0	0.5
	1000.0	2.0	0.6
Dipole E (VHAP) (UHAP)	60.0	2.0	0.6
	70.1	2.0	0.5
	80.0	2.0	0.5
	200.0	2.0	0.5
	250.0	2.0	0.5
	500.0	2.0	0.5
	600.0	2.0	0.5
	1000.0	2.0	0.6

4.2 Uncertainties submitted by NPL

4.2.1 *General uncertainty contributions*

This uncertainty treatment is based on the NPL procedure for the calibration of EMC antennas, Ref 4. The first table summarises the common uncertainty terms which are associated with voltage ratio type measurements made on the NPL open field site with an HP8753 model ANA. These terms are common to both the difference calculation made during a standard antenna method and also the site insertion loss calculation made during the three antenna method (although for the latter there is an additional factor of a half which arises from the calculation). Receiver noise and linearity errors, and also variations in cable attenuation contribute to the values included here in Table 4.2(i).

Table 4.2(i) *Uncertainty in voltage ratio measurement by an HP8753 type ANA.*

Frequency range (MHz)	Standard uncertainty (dB)
20 – 300	0.132
300 – 1000	0.142

4.2.2 *Bicones A and B*

The table below is a summary of the uncertainty budget for the standard antenna method employed for bicone calibrations at defined heights above the ground plane.

Table 4.2(ii) *Standard antenna method for biconical antennas.*

Source of uncertainty	Uncertainty contribution (dB)
Component from Table 4.2(i)	0.132
AF of standard	0.175
Unwanted site reflections	0.029
Errors caused by positioning	0.031
Mismatch	0.078 (x2)
Combined standard uncertainty	0.249
95% confidence limit (k=2)	0.5

4.2.3 *LPDAs C and D*

Table 4.2(iii) summarises the uncertainty in the three-antenna method calibration of LPDA antennas whose antenna factors rise sharply below 200 MHz

Table 4.2(iii) Three antenna method for LPDA antennas.

Source of uncertainty	Uncertainty contribution (dB)	
Component from Table 4.2(i)	0.071 (x3)	
Unwanted site reflections	0.119	(200 MHz to 249 MHz)
	0.058	(250 MHz to 1000 MHz)
Mutual coupling between antennas	0.129	(200 MHz to 249 MHz)
	0.065	(250 MHz to 1000 MHz)
Positioning error for each pair	0.109 (x3)	
Mismatch for each pair	0.053 (x3)	
Combined standard uncertainty	0.300	(200 MHz to 249 MHz)
	0.258	(250 MHz to 1000 MHz)
95% confidence limit (k=2)	0.6	(200 MHz to 249 MHz)
	0.5	(250 MHz to 1000 MHz)

4.2.4 Dipoles E and F

At NPL the antenna factor of the standard dipole is derived from the theoretical SIL values between two dipole elements calculated using NEC, Ref. 5, combined with actual S-parameter measurements of the dipole baluns. This produces antenna factors at any desired height or polarisation above a perfect ground plane. The uncertainties in the predicted SIL (when compared to measured SIL) are due to such things as imperfections in the real ground plane, the errors in the balun measurements, and droop of the longer dipole elements. When calibrating an unknown dipole there is the additional uncertainty due to the errors in the actual measurement of SIL during a standard antenna method on the open field site. These two terms are then combined to give an estimate of the total uncertainty.

Table 4.2 (iv) Uncertainty in dipole calibration at defined height over ground plane.

Uncertainties in dB	30 MHz - 500 MHz	501 MHz - 700 MHz	701 MHz - 1 GHz
Prediction of SIL	0.058	0.082	0.104
Measurement of SIL	0.164	0.190	0.230
Combined standard uncertainty	0.174	0.207	0.252
95% confidence limit (k=2)	0.35	0.4	0.5

4.3 Uncertainties submitted by CRL

Table 4.3 Uncertainties submitted by CRL

Frequency (MHz)	30-1000
U _C (± dB)	0.44

4.4 Uncertainties submitted by ETL

Table 4.4 Uncertainties submitted by ETL

Frequency (MHz)	30-1000
U _C (± dB)	0.42

4.5 Uncertainties submitted by NIST

Table 4.5(i) Uncertainties submitted by NIST (30 MHz - 1000 MHz)

Description of uncertainty	U_C ($\pm$ dB)	Typ
1 E-field magnitude	0.25	
2 Receiver measurement	0.20	
3 Cable measurement	0.20	
4 E-field uniformity	0.15	
5 RF source stability	0.15	
6 AUT alignment	0.10	
7 Maximum measured difference between repeated observations	0.25	
Combined standard uncertainty		
The expanded uncertainty (k=2) 95%		

Editor's note: NIST's expanded dB uncertainty is not equal to twice the standard dB uncertainty because NIST assumes a normal distribution of the linear quantities rather than the dB quantities.

4.6 Uncertainties submitted by ETS

Table 4.6 Uncertainties submitted by ETS

Frequency (MHz)	30-300	300-1000
U_C ($\pm$ dB)	0.90	1.00

5 Site information and calibration methods used

Table 5.1 Site information

Laboratory	Site
NPL	Open area welded sheet steel ground plane, flat to ± 5 mm over 96% of the area measuring 60 m x 30 m. Nearest structure is 45 m away from the centre.
CSIRO	Open area stainless steel mesh ground plane covering a concrete pad 20 m x 30 m set flush with the ground, flat to ± 4.5 mm R.M.S The nearest structure is approximately 40 metres away from the antenna locations in the direction of a dipole null. Steel mesh ground plane 40 m x 20 m with a welded sheet steel 40 m x 6 m in the centre. Obstruction free area 70 m x 40 m Fully Anechoic Chamber 15 m (l) x 10 m (w) x 8 m (h)
NIST	Open area steel mesh covering a concrete pad flat to ± 7 mm, 60 m x 30 m. Central region 20 m x 10 m is welded sheet metal conductively bonded to mesh. Nearest structure above ground plane level is over 30 m from any edge. Open area ground plane 26 m x 24 m, steel mesh around 18.37 m x 4.95 m sheet metal centre

All calibrations were performed with the antennas horizontally polarised at 2 m height above the ground plane except for measurements made at four heights (fh) at 80 MHz at these heights 1.0 m, 1.3 m, 1.9 m and 2.5 m. SAM = Standard Antenna Method, 3AM = Three Antenna Method. The range between antennas is given in metres below the method type, RAM = Radio frequency Absorbing Material (pyramidal absorber), - = no information available, n/m = antenna not measured.

Table 5.2 Calibration methods used

Laboratory	Antenna							
	A	A (fh)	B	C	D	E	F	F (fh)
NPL	SAM 10 m	SAM 10 m	SAM 10 m	3AM 2.5 m over RAM	3AM 2.5 m over RAM	SAM 10 m	SAM 10 m - 20 m	SAM 10 m
CSIRO	3AM 10 m	3AM 10 m	3AM 10 m	3AM 10 m	3AM 10 m	3AM 10 m	n/m	n/m
CRL*	SAM/3AM 8m to 20 m	SAM/3AM 10 m	SAM/3AM 8 m to 20 m	n/m	n/m	VHAP: SAM/3AM UHAP: 3AM 5.75 m - 10m	SAM/3AM 8 m to 20 m	3AM 10 m
ETL	SAM	SAM	SAM	SAM	SAM	SAM	SAM	SAM
NIST**	n/m	n/m	SAM2 10 m	n/m	SAM2 10 m	SAM2 10 m	SAM 2 10 m	n/m
ETS	ANSI C63.5 10 m	SAM -	ANSI C63.5 10 m	ANSI C63.5 10 m	ANSI C63.5 10 m	ANSI C63.5 10 m	ANSI C63.5 10 m	-

*All of the CRL measurements were made by the standard antenna method using a set of commercial dipole antennas, which were first calibrated with the fixed-height three-antenna method at the CRL site. This applies to Antennas A, B, E, and F in Table 5.2, which are labelled as "SAM/3AM". At the time they did not have a method of calibrating log antennas owing to their varying phase centres.

**NIST used the two-antenna method (SAM2) as described in Ref. 6

6 Results

6.1 Measured Antenna Factors (dB/m)

Results not submitted are represented by '~' in the table cells below. The arithmetic means are shown in the last column.

Any measured value exceeding ± 0.9 dB in difference from the arithmetic mean of the other five laboratory's antenna factors was excluded from contributing to the arithmetic mean. This prevents an unrepresentative offset of the arithmetic mean and this treatment is based on that used for the European inter comparison. Measurements that were excluded from the arithmetic mean antenna factor value calculation at each frequency are stated below each table.

Table 6.1(i) Antenna A at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
30	13.53	13.77	13.49	13.61	~	13.80	13.64
60	9.55	~	9.64	9.49	~	9.60	9.57
70	9.20	9.35	9.32	9.30	~	9.37	9.31
80	9.00	9.13	9.05	9.38	~	9.12	9.14
200	14.83	~	14.86	15.10	~	14.42	14.80
250	16.00	15.91	16.30	17.33	~	16.11	16.08
300	19.38	~	19.84	20.74	~	19.34	19.52

Table 6.1(ii) Antenna A four heights at 1.0 m, 1.3 m, 1.9 m, 2.5 m at 80 MHz.

height (m)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
1.0	9.20	9.48	9.31	9.05	~	9.72	9.35
1.3	9.50	9.73	9.61	8.94	~	9.95	9.55
1.9	9.00	9.26	9.17	8.98	~	9.44	9.17
2.5	8.80	8.95	8.85	9.66	~	9.24	9.10

Table 6.1(iii) Antenna B at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
30	22.48	22.71	22.31	22.55	23.32	22.57	22.66
60	14.65	~	14.87	14.45	15.72	14.67	14.66
70	13.40	13.50	13.45	13.13	14.29	13.43	13.53
80	12.55	12.71	12.5	12.8	13.33	12.72	12.77
200	21.15	~	21.05	21.13	21.55	20.97	21.17
250	21.40	21.55	21.94	22.78	21.83	21.70	21.68
300	23.90	~	24.35	24.94	~	23.63	23.96

NIST at 60 MHz, ETL at 250 MHz and 300 MHz

Table 6.1(iv) Antenna C at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
300	15.33	15.52	~	15.19	~	15.58	15.41
400	16.11	15.80	~	15.71	~	15.95	15.89
500	17.85	~	~	17.66	~	17.98	17.83
600	19.35	19.02	~	18.62	~	19.07	19.02
700	20.56	~	~	20.6	~	20.81	20.66
1000	24.60	24.66	~	24.78	~	24.69	24.68

Table 6.1(v) Antenna D at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
200	10.46	10.46	~	10.44	10.92	11.20	10.70
300	13.14	13.12	~	11.88	13.45	13.20	13.23
400	16.24	16.42	~	15.50	16.00	16.35	16.10
500	17.50	~	~	17.03	16.95	17.70	17.30
600	19.01	18.70	~	18.25	19.84	18.79	18.69
700	20.64	~	~	20.39	20.17	21.18	20.60
1000	23.51	22.96	~	23.81	23.08	23.27	23.33

ETL at 300 MHz, NIST at 600 MHz

Table 6.1(vi) Antenna E at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS	Average
60	14.55	14.73	14.70	14.11	15.52	14.51	14.52
70	15.00	15.15	15.15	15.05	15.99	15.33	15.14
80	15.31	15.46	15.3	16.22	15.75	15.60	15.61
200	24.50	24.55	24.35	24.27	24.63	24.17	24.41
250	25.88	25.69	25.90	26.2	26.16	25.73	25.93
300	27.52	~	27.94	27.83	27.22	27.50	27.60
500	32.13	32.19	32.13	31.68	31.20	31.85	31.86
600	33.20	33.56	33.65	33.50	32.85	33.23	33.33
700	34.97	~	34.63	35.20	34.73	34.49	34.80
1000	38.62	37.87	38.70	41.00	38.35	39.00	38.51

NIST at 60 MHz and 70 MHz, ETL at 1000 MHz.

Antenna F is a calculable dipole antenna. It has been shown that the calculated antenna factors have lower uncertainties than the measured antenna factors, see Refs. 2, 3 and 7. For this it is essential to have a high quality ground plane. It was demonstrated that the antenna factor is known to an uncertainty of ± 0.15 dB. The NEC calculated antenna factors are given in the following two Tables.

Table 6.1(vii) Antenna F at 2.0 m height (fa = faulty antenna)

Frequency (MHz)	NPL(NEC)	CSIRO	CRL	ETL	NIST	ETS	Average
30	25.62	fa	25.40	25.64	26.33	25.87	25.77
45	20.69	~	20.66	20.89	~	20.95	20.80
50	19.14	fa	19.27	19.59	20.38	19.27	19.32
60	15.93	fa	16.01	15.99	16.99	15.98	15.98
80	9.57	fa	9.69	10.28	10.16	9.84	9.91
90	11.60	fa	11.66	12.95	11.93	12.02	11.80
100	14.94	~	14.90	15.22	15.24	15.07	15.07

NIST at 50 MHz and 60 MHz, ETL at 90 MHz.

Table 6.1(viii) Antenna F four heights at 1.0 m, 1.3 m, 1.9 m, 2.5 m at 80 MHz.

height (m)	NPL(NEC)	CSIRO	CRL	ETL	NIST	ETS	Average
1.0	10.99	fa	10.99	10.04	~	11.19	11.06
1.3	11.29	fa	11.30	9.77	~	11.60	11.40
1.9	9.85	fa	9.88	9.74	~	10.24	9.99
2.5	9.49	fa	9.53	10.44	~	9.80	9.61

all ETL results as they measured in a fully anechoic room

NIST reported that the centre pin of antenna A was damaged while at NIST and therefore no data was produced for it. NPL subsequently returned it to Schwarzbeck for repair. ETS reported that dipole antenna F had an intermittent dipole element connection (weak solder joint) and made several measurements to obtain stable results. CSIRO also experienced a problem so their entries have been substituted by (fa) meaning faulty antenna. Antenna F was not working correctly when it was returned by CSIRO to NPL. It can be seen that the CRL four heights measurements agree to 0.04 dB of the NEC predicted measurements indicating that the antenna was working correctly. NIST reported repeatable results with this antenna. The ETL measurements are expected to deviate anyway as there is no ground plane in a fully anechoic chamber.

6.2 Measured antenna factors minus arithmetic means (dB)

The values given in the following tables represent the arithmetic mean antenna factor at each frequency subtracted from the measured value by each laboratory.

Table 6.2(i) Antenna A at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS
30	-0.11	0.13	-0.15	-0.03	~	0.16
60	-0.02	~	0.07	-0.08	~	0.03
70	-0.11	0.04	0.01	-0.01	~	0.06
80	-0.14	-0.01	-0.09	0.24	~	-0.02
200	0.02	~	0.06	0.30	~	-0.38
250	-0.08	-0.17	0.22	1.25	~	0.03
300	-0.14	~	0.32	1.22	~	-0.18

Table 6.2(ii) Antenna A four heights at 1.0 m, 1.3 m, 1.9 m, 2.5 m at 80 MHz.

height (m)	NPL	CSIRO	CRL	ETL	NIST	ETS
1.0	-0.15	0.13	-0.04	-0.30	~	0.37
1.3	-0.05	0.18	0.06	-0.61	~	0.41
1.9	-0.17	0.09	0.00	-0.19	~	0.27
2.5	-0.30	-0.15	-0.25	0.56	~	0.14

Table 6.2(iii) Antenna B at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS
30	-0.18	0.05	-0.35	-0.11	0.66	-0.08
60	-0.01	~	0.21	-0.21	1.06	0.02
70	-0.13	-0.03	-0.08	-0.40	0.76	-0.10
80	-0.22	-0.06	-0.27	0.03	0.56	-0.04
200	-0.02	~	-0.12	-0.04	0.38	-0.19
250	-0.28	-0.13	0.26	1.10	0.15	0.02
300	-0.06	~	0.39	0.98	~	-0.33

Table 6.2(iv) Antenna C at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS
300	-0.08	0.12	~	-0.21	~	0.18
400	0.22	-0.09	~	-0.18	~	0.06
500	0.02	~	~	-0.17	~	0.15
600	0.33	0.01	~	-0.39	~	0.06
700	-0.10	~	~	-0.06	~	0.16
1000	-0.08	-0.02	~	0.10	~	0.01

Table 6.2(v) Antenna D at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS
200	-0.24	-0.23	~	-0.25	0.23	0.50
300	-0.09	-0.11	~	-1.35	0.22	-0.03
400	0.13	0.32	~	-0.60	-0.10	0.25
500	0.20	~	~	-0.27	-0.35	0.41
600	0.32	0.01	~	-0.44	1.15	0.10
700	0.04	~	~	-0.20	-0.42	0.59
1000	0.19	-0.37	~	0.48	-0.25	-0.05

Table 6.2(vi) Antenna E at 2.0 m height

Frequency (MHz)	NPL	CSIRO	CRL	ETL	NIST	ETS
60	0.03	0.21	0.18	-0.41	1.00	-0.01
70	-0.14	0.02	0.02	-0.08	0.86	0.20
80	-0.30	-0.15	-0.31	0.61	0.14	-0.01
200	0.09	0.14	-0.06	-0.14	0.22	-0.24
250	-0.05	-0.24	-0.03	0.27	0.23	-0.20
300	-0.08	~	0.34	0.23	-0.38	-0.10
500	0.27	0.34	0.27	-0.18	-0.66	-0.01
600	-0.13	0.23	0.32	0.17	-0.48	-0.10
700	0.17	~	-0.17	0.40	-0.07	-0.31
1000	0.12	-0.64	0.19	2.49	-0.16	0.49

Table 6.2(vii) Antenna F at 2.0 m height (fa = faulty antenna)

Frequency (MHz)	NPL(NEC)	CSIRO	CRL	ETL	NIST	ETS
30	-0.15	fa	-0.37	-0.13	0.56	0.10
45	-0.11	~	-0.14	0.09	~	0.15
50	-0.18	fa	-0.05	0.27	1.06	-0.05
60	-0.05	fa	0.03	0.01	1.01	0.00
80	-0.34	fa	-0.22	0.37	0.25	-0.07
90	-0.20	fa	-0.14	1.15	0.13	0.22
100	-0.13	~	-0.17	0.15	0.17	0.00

Table 6.2(viii) Antenna F four heights at 1.0 m, 1.3 m, 1.9 m, 2.5 m at 80 MHz.

height (m)	NPL(NEC)	CSIRO	CRL	ETL	NIST	ETS
1.0	-0.07	fa	-0.07	~	~	0.13
1.3	-0.11	fa	-0.10	~	~	0.20
1.9	-0.14	fa	-0.11	~	~	0.25
2.5	-0.12	fa	-0.08	~	~	0.19

ETL measured but haven't been included as they measured in a fully anechoic room

6.3 Summary of deviation of antenna factor from the arithmetic mean.

Each cell contains comma-separated numbers. The first is the number of antenna factor values presented by the laboratory for that antenna. The second is the number of those discrete values that are $\leq \pm 1.0$ dB of the arithmetic mean (as detailed in section 6.2), the third is the number that are $\leq \pm 0.5$ dB, and the fourth is the number that are $\leq \pm 0.3$ dB of the arithmetic mean.

The ETL four heights results for Antenna F have been excluded as they made their measurements in a fully anechoic chamber. (fh) is fixed height antenna.

Table 6.3 Comparison of antenna factors to arithmetic means

Ant.	NPL	CSIRO	CRL	ETL	NIST	ETS
A	7, 7, 7, 7	4, 4, 4, 4	7, 7, 7, 6	7, 7, 5, 5	-	7, 7, 7, 6
A (fh)	4, 4, 4, 4	4, 4, 4, 4	4, 4, 4, 4	4, 4, 2, 2	-	4, 4, 4, 2
B	7, 7, 7, 7	4, 4, 4, 4	7, 7, 7, 5	7, 7, 5, 4	6, 5, 2, 1	7, 7, 7, 6
C	6, 6, 6, 4	4, 4, 4, 4	-	6, 6, 6, 5	-	6, 6, 6, 6
D	7, 7, 7, 6	5, 5, 5, 3	-	7, 6, 5, 3	7, 6, 6, 4	7, 7, 6, 4
E	10, 10, 10, 10	8, 8, 7, 6	10, 10, 10, 7	10, 9, 8, 6	10, 10, 7, 5	10, 10, 9, 8
F	7, 7, 7, 6	~	7, 7, 7, 6	7, 6, 6, 5	6, 4, 3, 3	7, 7, 7, 7
F (fh)	4, 4, 4, 4	~	4, 4, 4, 4	~	~	4, 4, 4, 4
Totals	52,52,52,49	29,29,28,25	39,39,39,32	48,45,37,30	29,25,18,13	52,52,50,43
% $\leq \pm$						
1.0 dB	100	100	100	94	86	100
0.5 dB	100	97	100	77	62	96
0.3 dB	94	86	82	63	45	83

(Table 6.3 is shown in histogram format in the following chart 6.3 in order of the total number of measurements made by each laboratory.)

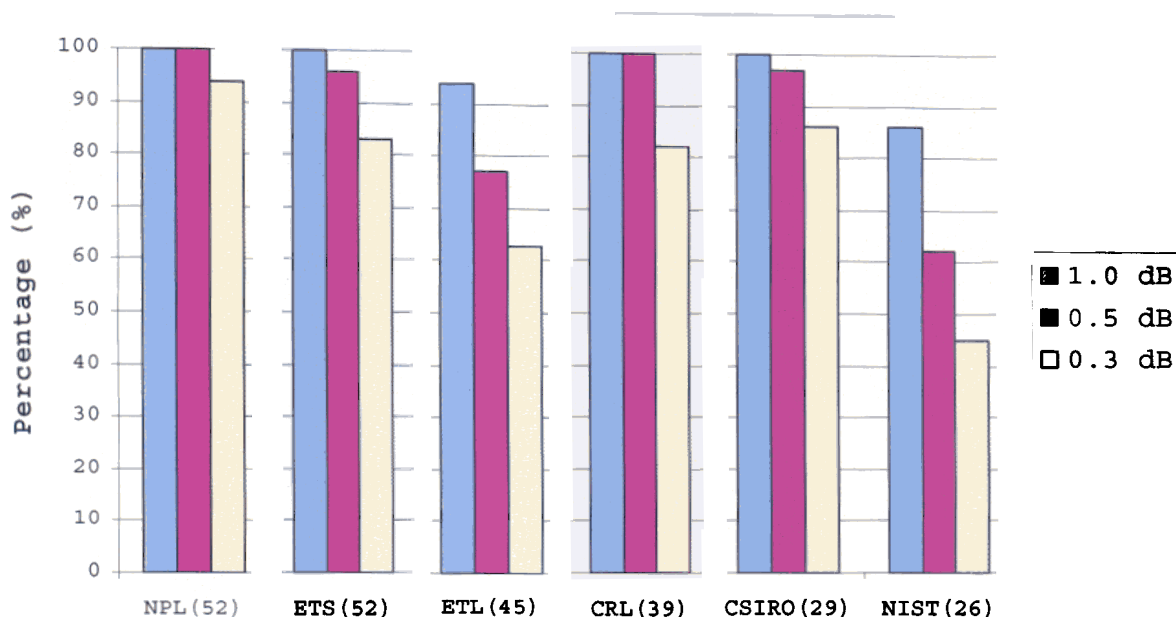


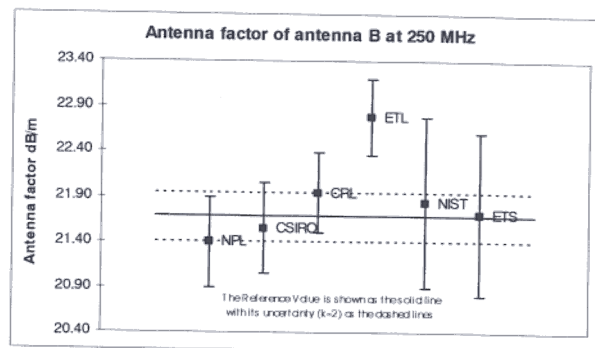
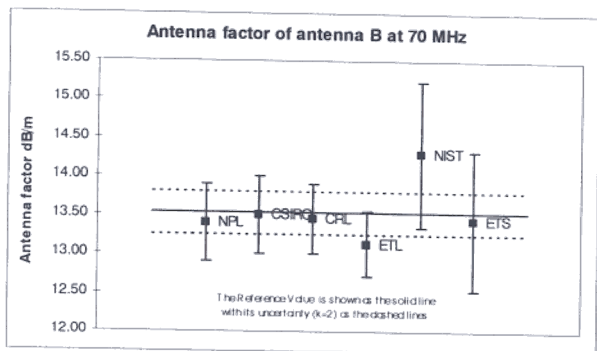
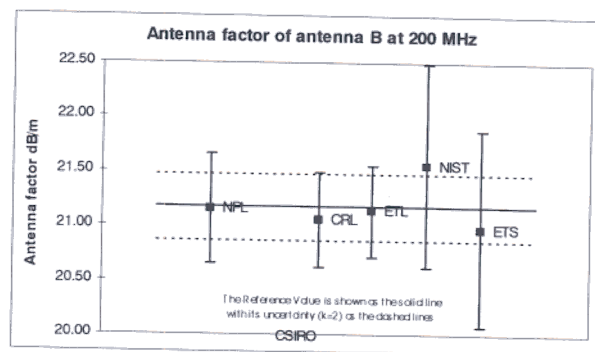
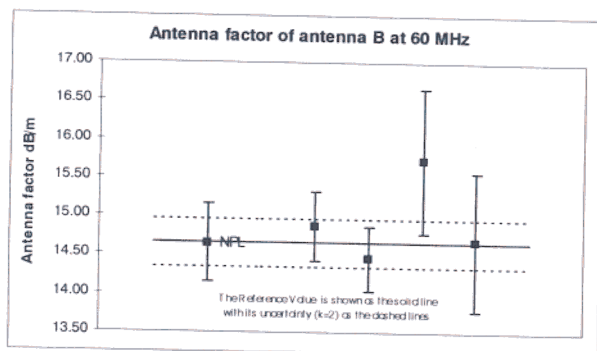
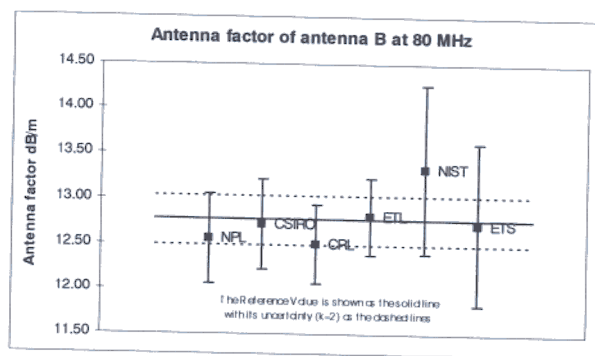
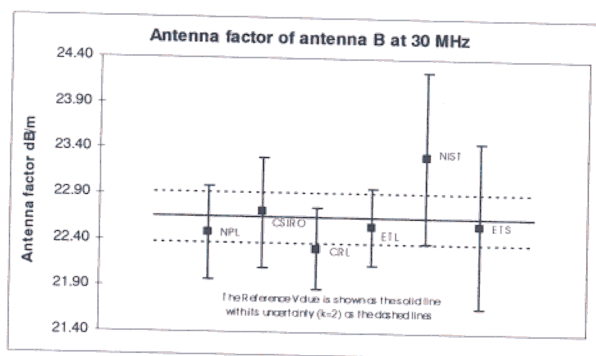
Chart 6.3 Percentage of each laboratory's antenna factor measurements falling within ± 1 dB, ± 0.5 dB and ± 0.3 dB of the arithmetic mean of the antenna factor measurements

6.4 Error-bar charts showing deviation of antenna factors from mean values and showing measurement uncertainties.

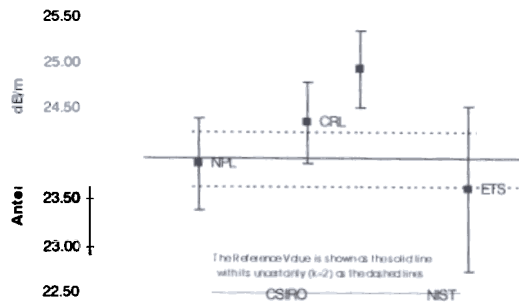
The number of results is too many to present as error-bar charts. There are two of each of three antenna types. The measurement uncertainties are the same for each antenna type, so error-bar charts are shown for one biconical antenna, B, one log-periodic antenna, D, and one dipole antenna, E, a total of 24 results. The charts show the deviation of the result of each laboratory from the mean value and error-bars giving the symmetrical uncertainties in decibels given by each laboratory. The combined uncertainty for $k=2$ is given by the following sum of the $k=2$ uncertainties of each laboratory.

$$u(\text{combined}) = ((u_{\text{NPL}}^2 + u_{\text{CSIRO}}^2 + u_{\text{CRL}}^2 + u_{\text{ETL}}^2 + u_{\text{NIST}}^2 + u_{\text{ETS}}^2)^{1/2})/N$$

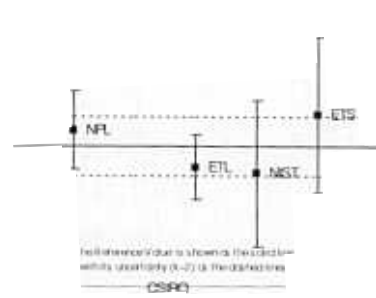
where N is the number of expanded uncertainty values being combined.



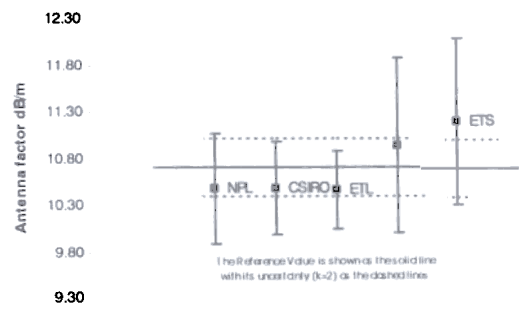
Antenna factor of antenna B at 300 MHz



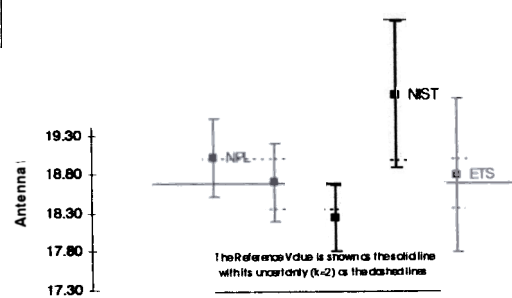
Antenna factor of antenna D at 500 MHz



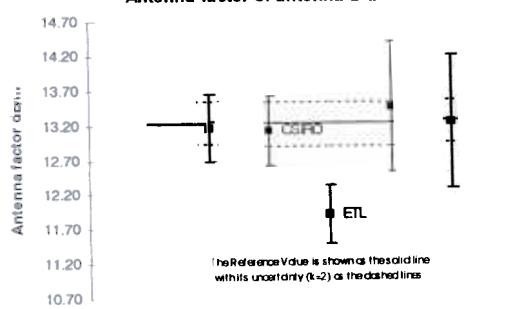
Antenna factor of antenna D at 200 MHz



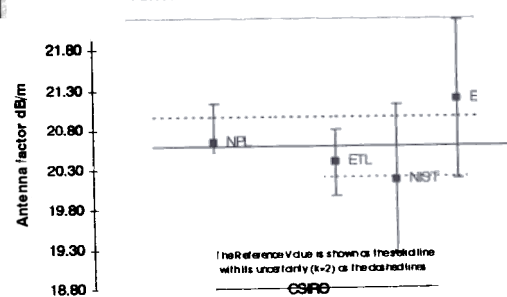
Antenna factor of antenna D at 600 MHz



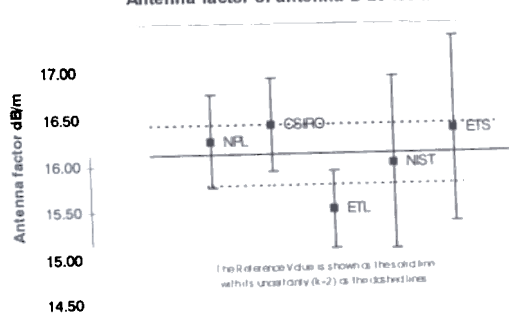
Antenna factor of antenna D at 300 MHz



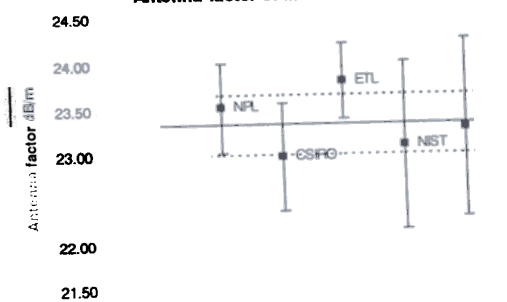
Antenna factor of antenna D at 700 MHz

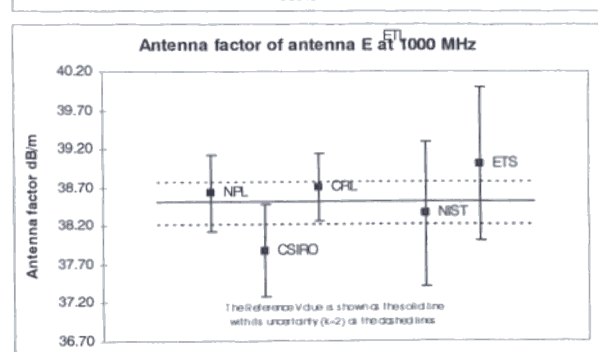
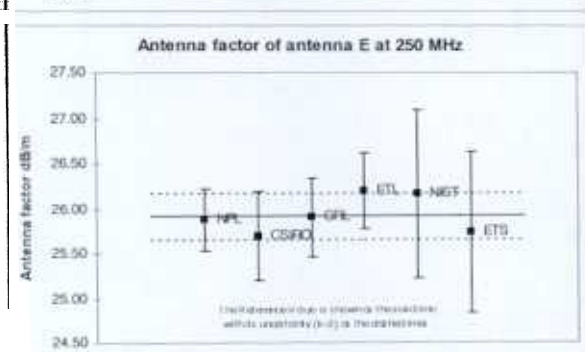
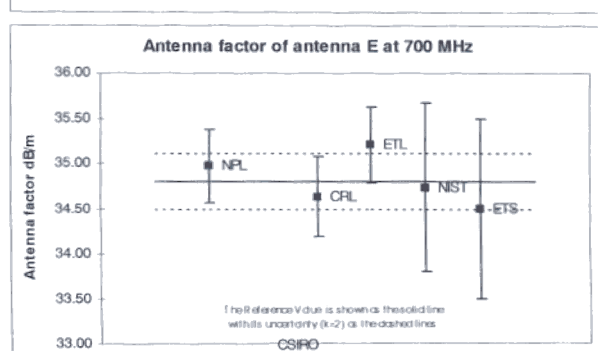
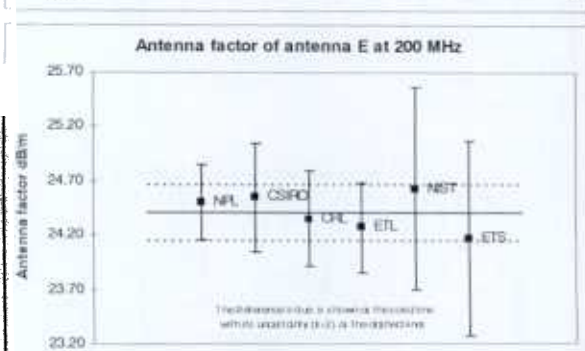
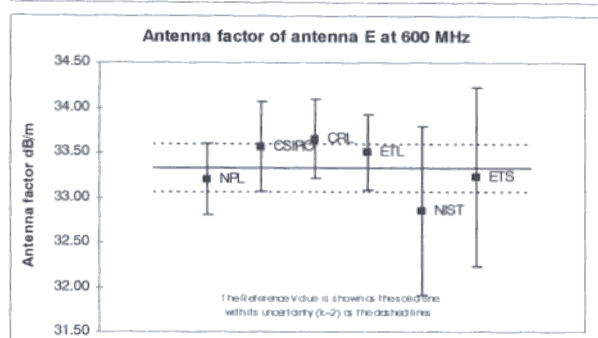
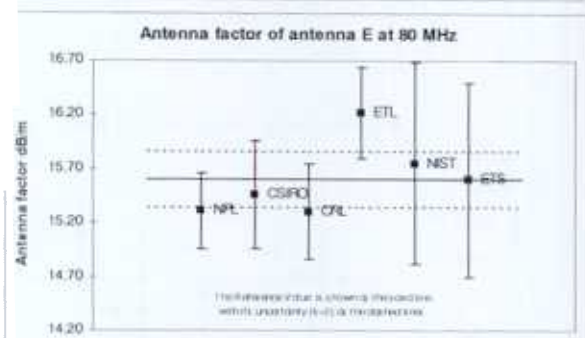
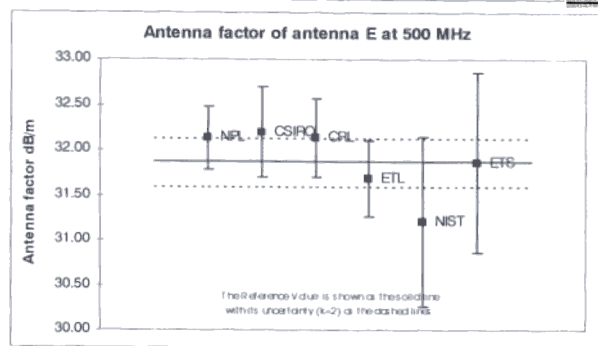
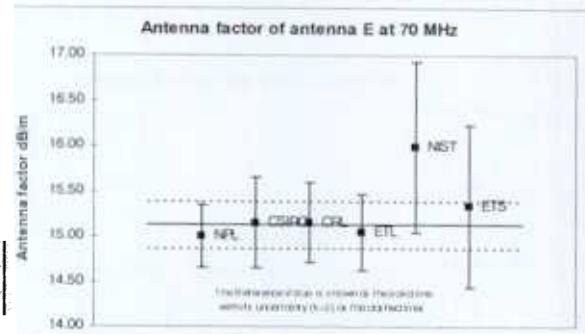
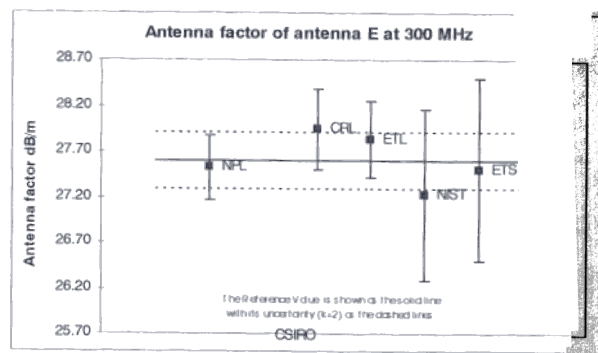
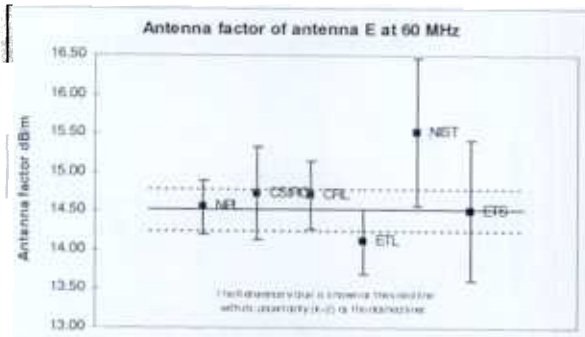


Antenna factor of antenna D at 400 MHz



Antenna factor of antenna D at 1000 MHz





7 References

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2. Alexander, M.J., Salter, M.J., Low measurement uncertainties in the frequency range 30 MHz to 1 GHz using a calculable standard dipole antenna and national reference ground plane, IEE Proc. Sci. Meas. Technol. Vol. 143 , No. 4 July 1996, 221 - 228.
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Annex A

Reflection coefficients of the antennas

Table A1(i) NPL Antenna A at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.6618	-0.6088	0.9224
60	0.4503	0.6758	1.8080
70	0.7369	0.1119	2.5525
80	0.5306	-0.3787	3.7173
200	-0.1225	0.2715	10.5205
250	0.3415	-0.1887	8.1753
300	-0.3385	0.0323	9.3711

Table A1(ii) CSIRO Antenna A at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.66	-0.62	0.9
70	0.69	0.16	3.0
80	0.55	-0.37	3.6
250	0.36	-0.10	8.5

Table A1(iii) CRL Antenna A at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.6946	-0.5817	0.86
60	+0.4333	+0.6276	2.35
70	+0.7201	+0.1020	2.77
80	+0.5245	-0.4385	3.30
200	-0.0011	+0.3442	9.27
250	+0.2925	-0.3262	7.17
300	-0.3544	+0.0856	8.76

Table A1(iv) ETL Antenna A at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.22	-0.91	0.63
60	-0.61	0.26	3.47
70	0.04	0.30	10.45
80	0.09	-0.24	11.70
200	0.03	-0.58	4.73
250	-0.43	0.27	6.02
300	0.33	0.26	7.33

Table A1(v) ETS Antenna A at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.66262	-0.62729	0.79586
60	0.373274	0.668306	2.321273
70	0.695719	0.176435	2.880629
80	0.573924	-0.36186	3.369301
200	-0.13156	0.270066	10.44579
250	0.356111	-0.17634	8.015897
300	-0.33808	-0.06769	9.248921

Table A3(i) NPL Antenna B at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	0.0841	-0.2672	11.0523
60	-0.2257	-0.0438	12.7700
70	-0.1409	0.1008	15.2290
80	0.0003	0.1020	19.8291
200	0.0143	0.1853	14.6191
250	0.1474	0.0610	15.9434
300	0.1104	-0.0338	18.7500

Table A3(ii) CSIRO Antenna B at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	0.08	-0.27	11.0
70	-0.15	0.09	15.4
80	-0.01	0.12	18.4
250	0.16	0.04	15.6

Table A3(iii) CRL Antenna B at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	+0. 0628	-0.2732	11. 05
60	-0.2244	-0.0283	12.91
70	-0.1394	+0. 1019	15. 26
80	+0. 0019	+0. 1317	17.61
200	+0. 0916	+0. 1666	14.42
250	+0.1620	-0.0092	15.79
300	+0.0787	-0.0846	18.75

Table A3(iv) ETL Antenna B at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	0.01	-0.89	0.9
60	-0.24	-0.08	11.8
70	-0.45	0.69	4.5
80	-0.03	0.11	18.8
200	-0.04	0.20	13.9
250	0.49	0.20	5.5
300	0.10	0.03	19.60

Table A3(v) ETS Antenna B at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	0.080713	-0.27016	10.99635
60	-0.21493	-0.04991	13.12594
70	-0.15440	0.079028	15.21656
80	-0.01874	0.12237	18.14586
200	0.021593	0.182471	14.71574
250	0.154166	0.064211	15.54549
300	0.115261	-0.03299	18.42430

Table A4(i) NPL Antenna C at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
300	0.3125	-0.0655	9.9175
400	-0.1476	0.1106	14.6831
500	0.1318	0.1156	15.1270
600	0.0400	-0.0795	21.0117
700	0.1250	-0.0405	17.6309
1000	0.1956	0.1228	12.7275

Table A4(ii) CSIRO Antenna C at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
300	0.36	-0.03	8.9
400	-0.13	0.06	16.8
600	0.02	-0.08	21.8
1000	0.23	-0.08	12.3

Table A4(iv) ETL Antenna C at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
300	0.33	0.05	9.5
400	-0.18	0.04	14.4
500	0.05	0.18	14.4
600	0.08	-0.04	21.0
700	0.14	0.05	16.4
1000	0.03	0.23	12.5

Table A4(v) ETS Antenna C at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
300	0.283298	-0.10247	10.42116
400	-0.15454	0.097074	14.77469
500	0.143991	0.102791	15.04464
600	0.033142	-0.05303	24.07718
700	0.133678	0.07329	16.33744
1000	0.211036	-0.099529	12.64065

Table A5(i) NPL Antenna D at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
200	-0.0743	0.1287	16.5596
300	0.0268	-0.1319	17.4229
400	0.1642	-0.2031	11.6606
500	-0.0950	0.0547	19.1992
600	-0.0024	-0.0124	37.9863
700	0.0759	0.1476	15.5991
1000	0.0145	0.2572	11.7803

Table A5(ii) CSIRO Antenna D at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
200	-0.01	0.11	18.8
300	0.05	-0.14	16.4
400	0.18	-0.20	11.5
600	-0.03	0.05	25.1
1000	0.05	0.19	14.0

Table A5(iv) ETL Antenna D at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
200	-0.02	0.12	15.4
300	0.06	-0.13	16.8
400	0.25	-0.12	11.2
500	-0.13	0.04	17.5
600	-0.06	0.02	24.1
700	-0.01	0.18	24.8
1000	-0.17	0.13	13.4

Table A5(v) ETS Antenna D at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
200	-0.06900	.134964	16.38713
300	0.01685	-0.13367	17.41106
400	0.204578	-0.19372	11.00293
500	-0.06978	0.08751	19.02145
600	-0.02422	0.065247	23.1481
700	0.080853	0.132267	16.19215
1000	0.012176	0.204641	13.76481

Table A6(i) NPL Antenna E at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
60	0.017	-0.014	33.3
70			
80	0.028	-0.020	29.3
200	-0.016	0.007	35.2
250			
300	0.036	-0.038	25.5
500	-0.013	0.042	27.1
600			
700	0.003	0.081	20.9
1000	-0.012	-0.039	27.9

Table A6(ii) CSIRO Antenna E at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
60.0	0.01	-0.01	34.3
70.1	0.02	-0.01	34.7
80.0	0.02	-0.02	31.5
200.0	-0.02	0.03	29.9
250.0	0.03	0.02	29.2
500.0	-0.03	0.04	26.1
600.0	0.03	-0.02	30.4
1000.0	0.00	-0.01	38.5

Table A6(iii) CRL Antenna E at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
60	+0.0121	-0.0127	35.12
70	+0.0302	-0.0050	30.29
80	+0.0235	-0.0211	30.01
200	-0.0100	+0.0095	37.21
250	+0.0282	+0.0263	28.28
300	+0.0468	-0.0411	24.10
500	-0.0265	+0.0476	25.27
600	+0.0136	-0.0180	32.94
700	-0.0002	+0.0785	22.10
1000	+0.0026	-0.0247	32.10

Table A6(iv) ETL Antenna E at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
60	0.03	-0.01	30.4
70	-0.05	-0.02	25.2
80	-0.07	0.01	22.2
200	-0.07	0.06	20.8
250	-0.07	0.06	20.8
300	-0.06	0.06	20.8
500	0.02	-0.12	12.8
600	0.02	-0.12	12.8
700	0.02	-0.12	12.8
1000	0.02	-0.12	12.8

Table A6(v) ETS Antenna E at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
60	0.0143097	-0.0156845	33.46044
70	0.017406	-0.009361	34.08268
80	0.022349	-0.019969	30.46615
200	-0.014043	0.0067485	36.14844
250	0.02041244	0.0210775	30.65033
300	0.030446	-0.03732	26.34553
500	-0.03723	0.036423	25.66549
600	0.022091	-0.012400	31.92598
700	-0.04456	0.090568	19.91919
1000	0.00692211	-0.0032133	42.34772

Table A7(i) NPL Antenna F at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.279	-0.218	9.0
45	-0.496	0.233	5.2
50			
60	-0.026	0.517	5.7
80	-0.0634	0.078	20.0
90			
100	0.317	0.158	9.0

Table A7(iii) CRL Antenna F at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.2853	-0.2073	9.05
45	-0.4664	+0.2956	5.16
50	-0.3535	+0.4417	4.95
60	+0.0015	+0.5160	5.75
80	-0.0527	+0.0813	20.28
90	+0.1079	+0.3577	8.55
100	+0.3356	+0.1305	8.87

Table A7(iv) ETL Antenna F at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	0.48	0.24	5.5
45	0.25	0.26	8.8
50	0.44	0.73	1.1
60	0.06	0.25	12.0
80	0.05	0.05	22.0
90	0.19	0.50	5.4
100	0.09	0.15	15.1

Table A7(v) ETS Antenna F at 2.0 m height

Frequency (MHz)	Real	Imaginary	Return loss (dB)
30	-0.257	-0.210	9.58
45	-0.455	0.241	5.77
50	-0.361	0.387	5.53
60	-0.041	0.482	6.30
80	-0.038	0.091	20.11
90	0.068	0.343	9.13
100	0.302	0.162	9.31

Return loss summary

The reflection coefficients (hence return losses) are in general good agreement between NPL, CSIRO, CRL and ETS. The results for ETL are in good agreement for antennas C and D but not so good for antennas A, B, E and F. NIST did not submit reflection coefficient or return loss results.