

**NPL REPORT
DEM-EM 011**

**Comparison of Electric Field
Strength Standards at NPL,
20 MHz to 2.6 GHz**

October 2006



The DTI drives our ambition of 'prosperity for all' by working to create the best environment for business success in the UK. We help people and companies become more productive by promoting enterprise, innovation and creativity.

We champion UK business at home and abroad. We invest heavily in world-class science and technology. We protect the rights of working people and consumers. And we stand up for fair and open markets in the UK, Europe and the world.

The National Physical Laboratory is operated on behalf of the DTI by NPL Management Limited, a wholly owned subsidiary of Serco Group plc

Comparison of Electric Field Strength Standards at NPL, 20 MHz to 2.6 GHz

Authors: Benjamin Loader, Tian Hong Loh, Edward Goodall, David
Knight Daniel Bownds, David Gentle, Martin Alexander.

Enabling Metrology Division

ABSTRACT

This report presents the results of a comparison of electric field strength standards at NPL. The calibration factors of three optical electric field sensors were measured in the different free-space and guided-wave electric field standards facilities at NPL and the results compared. The excellent agreement between the calibration factors obtained in the different facilities gives confidence in the basis of four distinct methods that provide traceability for E-field strength, namely: the calculable dipole, the TEM cell, the standard gain horn antenna and matched waveguide systems.

© Crown copyright 2006
Reproduced with the permission of the Controller of HMSO
and Queen's Printer for Scotland

ISSN 1744-0483

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

This document has been produced for the Department of Trade and Industry's National
Measurement System Policy Unit under contract number GBBK/C/02/45.

Approved on behalf of the Managing Director, NPL
by R N Clarke, Knowledge Leader for the Electromagnetics Team

CONTENTS	Page
1. INTRODUCTION	1
2. MEASUREMENTS	2
2.1 Opto-electric field sensor system.....	2
2.2 Measurements on the OATS.....	4
2.3 Measurements in the TEM cells	6
2.4 Measurements in the PFD range	7
2.5 Measurements in Waveguides	7
3. RESULTS OF THE COMPARISON	8
4. CONCLUSIONS	12
5. REFERENCES	13
APPENDIX 1. TABULATED RESULTS	14

1. INTRODUCTION

There are a number of different facilities that provide standards for electric field strength at NPL. Table 1 shows the different facilities, frequency range and the best measurement uncertainty quoted in the UKAS schedule for NPL calibration services. Whilst many comparisons have been made between free-field standards and between different guided-wave standards for electric field strength, few have been made between free-field and guided-wave devices. Such a comparison requires a sensor that is minimally perturbing to the electric field, but has sufficient sensitivity for calibration on the open area test site, where only low field strengths are permitted to be generated by the radio regulators.

Table 1. Standards for electric field strength at NPL

Facility	Frequency range	Measurement uncertainty at a coverage factor of $k = 2$ ($\pm$ dB)
<i>Free space standards</i>		
Calculable dipole antenna on Open Area Test Site (OATS) (described in [1])	30 MHz to 500 MHz 501 MHz to 700 MHz 701 MHz to 1 GHz	0.43 ^a 0.56 ^a 0.74 ^a
Calculable dipole antenna in Fully Anechoic Room	60 MHz to 500 MHz 501 MHz to 700 MHz 701 MHz to 1 GHz	0.43 ^a 0.56 ^a 0.74 ^a
Large power flux density range	Horn 1: 250 MHz to 500 MHz Horn 2: 450 MHz to 1.2 GHz Horn 3: 1.1 GHz to 2.6 GHz	0.65 0.62 0.47
Small power flux density range	2.4 GHz to 18 GHz 18.1 GHz to 45.5 GHz	0.40 0.35
<i>Guided wave standards</i>		
EMCO TEM cell model 5106 (described in [2])	20 Hz to 60 MHz	0.68
IFI TEM cell model CC-102	20 Hz to 180 MHz	0.68
Narda TEM cell model 8801	20 Hz to 300 MHz	0.68
NPL Tapered cell	180 MHz to 2.5 GHz	0.80
<i>Additional guided wave facilities^b</i>		
IEC-R 9 (UK WG4) system	0.75 to 1.12 GHz	0.50
IEC-R 14 (UK WG6) system	1.12 to 1.70 GHz	0.50
IEC-R 22 (UK WG8) system	1.70 to 2.60 GHz	0.50
IFI TEM cell model CC110	100 kHz to 1 GHz	0.68
GTEM 1750 cell ^c	100 kHz to 3 GHz	3.00

Notes:

^a The uncertainty associated with measuring the output voltage from the device (into 50 Ω) was added to the uncertainty for antenna factor, quoted in NPL's UKAS schedule valid at October 2006, to give the uncertainty for electric field strength.

^b These standards do not form part of the UKAS accredited calibration service.

^c The GTEM cell is used as a calibration standard for rod antennas over the frequency range 100 Hz to 30 MHz for which an uncertainty of ± 1 dB is quoted.

Three different sizes of optical electrical field sensor were used for the comparison between these electric field standards. The sensors were developed through collaboration between NPL and Seikoh-Giken (SG), formerly NEC-Tokin Corporation, Japan. The signal is transferred from the sensor to the receiver by a fibre optic cable, and this provides a full analogue link for the RF signal. The main characteristics of the sensors are shown in Table 2. The performance of the Robust Sensor is described in [3].

Table 2. Sensors used for the comparison measurements

	Small Sensor	Medium Sensor	Robust Sensor
Model number	OEFS-S1	OEFS-NS	ROEFS
S/N	OEFS-H-S1-0003	OEFS-H-NS-0006	ROEFS-000002
Type	Michelson interferometer on LiNo ₃ substrate	Michelson interferometer on LiNo ₃ substrate	Mach-Zehnder Interferometer on LiNo ₃ substrate
Dimensions	Cylindrical diameter: 10 mm length: 60 mm	Cylindrical diameter: 30 mm length: 90 mm	Dipole length 133 mm
Number of sensor channels	3 (orthogonal)	3 (orthogonal)	1
Frequency range	100 kHz to 9.8 GHz	100 kHz to 2.5 GHz	100 kHz to 1 GHz
Field strength range ^a	0.1 to 10,000V/m	0.01 to 10 V/m	0.00005 to 3 V/m

Note: ^a With 9.8 Hz resolution bandwidth.

2. MEASUREMENTS

2.1 Opto-electric field sensor system

Two classes of sensor were used, that are based on the technology described in [3]. The first is a Robust single axis sensor with a dipole element 133 mm long in order to be sensitive to the very low field levels permitted outdoors, of the order of 1 mV/m. The second is a 3-axis sensor whose dipole elements are of the order of 4 mm long and intended to measure field levels greater than 1 V/m, and where the polarisation may be unspecified.

The field sensor system and the RF receiver were calibrated together, the calibration factor being:

$$CF = \frac{V}{E} \quad (1)$$

where V is the voltage reading from the RF receiver, in μV measured into $50\ \Omega$, and E is the applied field strength in V/m . The voltage reading (into $50\ \text{Ohms}$) from the field sensor system was measured using an Agilent PSA spectrum analyser, model E4440A. To minimise the uncertainty for the comparison, a fixed length cable and 10 dB attenuator were used to connect the sensor system to the spectrum analyser. The small and medium sensors contain three orthogonal sensors, and were calibrated for total field strength; in this case the output voltage for the sensor was:

$$V = \sqrt{V_1^2 + V_2^2 + V_3^2} \quad (2)$$

where V_1 , V_2 and V_3 are the voltage readings for each of the three axes. The orientation of the sensor to the field propagation and polarisation was the same for each facility to prevent additional uncertainty due to the probe isotropy. The Robust sensor has a single dipole element, and this was aligned to the polarisation of the field in each facility. Again the orientation of the sensor relative to the field propagation direction was the same for each facility.

Table 3 shows which field standards were used to calibrate each of the sensors for the comparison. The choice of sensor used was governed by the field levels that can be generated, and also by the size of the sensor. In the FAR, the robust sensor was not calibrated below 100 MHz because the size difference between the sensor elements and the standard dipole elements would give rise to significant additional uncertainties for the calibration.

Table 3. Facilities used to calibrate each sensor

Facility	Small sensor	Medium sensor	Robust sensor
<i>Free-space standards</i>			
Calculable dipole antenna on Open Area Test Site.			X
Calculable dipole antenna in Fully Anechoic Room			X
Large power flux density range	X	X	X
<i>Guided-wave standards</i>			
EMCO TEM cell model 5106	X	X	X
IFI TEM cell model CC-102	X	X	X
Narda TEM cell model 8801	X	X	
NPL Tapered cell		X	X
<i>Additional guided-wave facilities</i>			
Waveguide 4 system	X		
Waveguide 6 system	X		
Waveguide 8 system	X		
IFI TEM cell model CC110	X		
GTEM 1750 cell		X	

The field levels used for the calibration of the sensors against each standard are shown in Table 4, and these were chosen to limit the sensor linearity error to ± 0.1 dB. Figure 1 shows the linearity performance of the three sensors measured against a calibrated step attenuator. There is an additional uncertainty of ± 0.1 dB for the stability of the field sensor system, which includes a temperature correction as described in [3]; the sensitivity of the system is dependent on the temperature of the sensor head. Temperatures between 0 °C and 30 °C can be experienced on the OATS, as this is an outdoor facility. For the measurements reported, the temperature of the sensor on the OATS was within 5 °C of the laboratory temperature, so this correction was small.

Table 4. Field levels used for calibration in each facility

Facilities	Small sensor (V/m)	Medium sensor (V/m)	Robust sensor (V/m)
Open area test site	-	-	0.0006 to 0.015
FAR	-	-	0.07
TEM cells	100	3	0.1
PFD ranges	100	3	0.1
GTEM	-	3	-
Waveguide cells	100		-

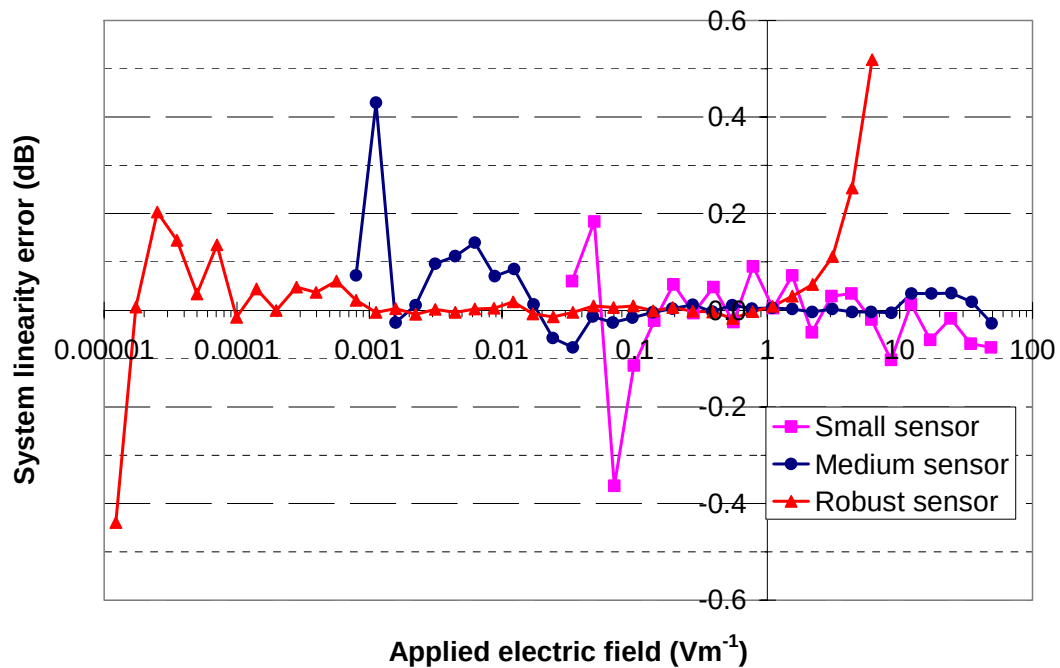


Figure 1. Sensor linearity error

2.2 Measurements on the OATS

An NPL calculable dipole antenna [1] was used to set up a known field level on the NPL open area test site as shown in Fig. 2. The ground plane is flat to within ± 5 mm over 95% of its area of 60 m x 30 m. The antenna was supported horizontally polarised at a height of 2 m above the ground plane. The robust sensor was substituted for the calculable dipole to measure this same field level. These antennas were approximately 45 m distance from the measuring equipment, which was housed in a temperature-controlled hut. The OEFS equipment is shown in Fig. 3. The robust sensor is equipped with a temperature sensor, which recorded a temperature between 22 °C and 24 °C across the measurements cited in this report. This is the temperature of the modulator chip within the sensor head. The outdoor temperature was measured with a separate thermometer and was 19 °C.

Resonant elements were used on the calculable dipole antenna at 60, 70, 80 & 90 MHz. At 20, 30, 40 & 50 MHz the dipole length resonant at 60 MHz was used. This was

because the robust sensor and the standard dipole will not sample the same field if the size of their measuring elements is very different, and this would reduce the accuracy of the calibration using the standard antenna method. Note that there is a slight increase in uncertainty for the antenna factor of the standard dipole when it is used off-resonance compared to resonance.

Two sets of measurements were made on the OATS, on different days. The separation distance between the transmit and receive antennas was 10 m, except for the first set of measurements where it was 20 m for the frequency range 20-50 MHz.



Figure 2. The NPL ground plane viewed from the measurement hut. There is approximately 50 m of low loss heliax cable underground, accessed by bulkhead connectors, one end shown in Fig. 3. The calculable dipole is connected to a further 15 m of coaxial cable. A 6 dB pad was used to reduce mismatch effects. The insertion loss of the cable run was measured using an additional 50 m of cable and the network analyser shown in Fig. 3. A biconical antenna was used, at a height of up to 5 m, to transmit the field.

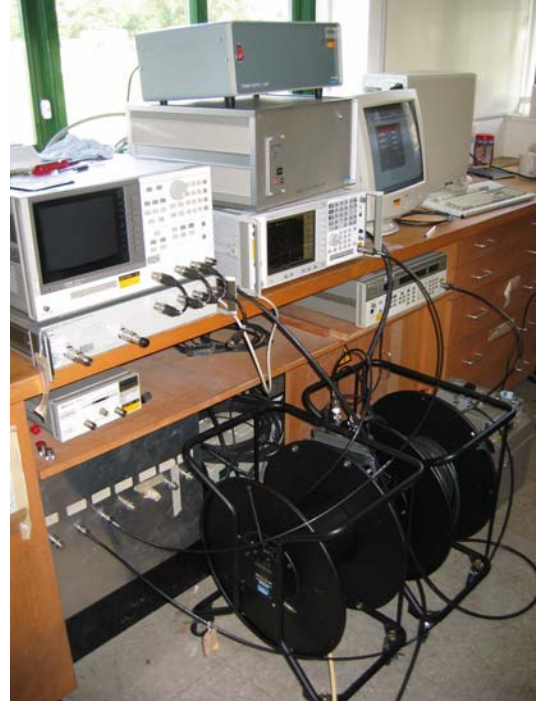


Figure 3. The optical sensor system in the hut on the OATS, showing the two drums for 60 m of sensor fibre and temperature fibre, and the optical controller above the PSA.

The E-field at the location of the calculable dipole antenna is obtained from its antenna factor, AF , and its output voltage into 50Ω , V , as measured by the PSA.

$$E = AF \cdot V \quad (3)$$

AF is obtained by modelling the dipole elements using a method of moments calculation, and combining this with the measured S-parameters of the antenna balun. The calculated antenna factor is verified by measuring the insertion loss between two dipole antennas at a known separation and heights above a large metal ground plane on an open area test site.

The robust sensor was placed in this field, E , and its output voltage, V' , was measured by the PSA. The uncertainty in measuring V' is added to the uncertainty for AF to

obtain the uncertainty in CF (given in Table 1). For the Agilent PSA, the additional uncertainty was ± 0.25 dB.

2.3 Measurements in the TEM cells

The outputs from the small, medium and robust sensors were measured in five NPL TEM cells:

Cell model	Lowest frequency	Highest frequency	Plate separation
EMCO 5106	20 Hz	60 MHz	0.910 m
IFI CC-102	20 Hz	180 MHz	0.298 m
Narda 8801	20 Hz	300 MHz	0.145 m
NPL Tapered	150 MHz	2.5 GHz	0.15 m to 0.3 m
GTEM MEB 1750	10 Hz	18 GHz	0.1 m to 1.75 m

The outside of the IFI cell is shown in Fig. 4 where the optical fibres for the robust sensor can be seen entering the cell. Fig. 5 shows the medium sized sensor in the GTEM cell. Fig. 6 shows the robust sensor, with dipole extensions in the EMCO cell. The dipole without extensions is 133 mm long and is the same dimension as the balsawood mount. The data using the longer dipole is not included in this report because it had limited use due to its size. The uncertainties for the TEM cells quoted in Table 1 account for the effect that the sensor has on the field within the device. This uncertainty term is based on a range of commercially available field probes, and it is assumed that the perturbation caused by the optical electric field sensors will be similar.



Figure 4. The IFI TEM cell

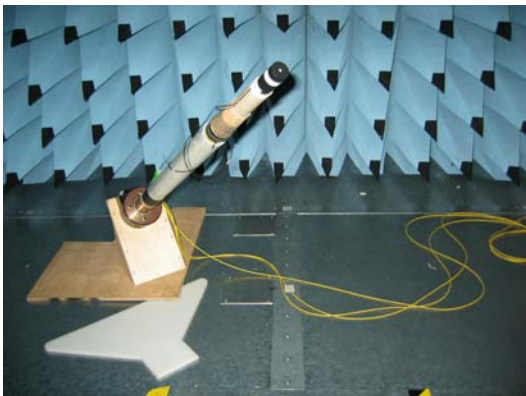


Figure 5. Medium sensor in GTEM cell



Figure 6. The robust sensor mid-way between the plates of the EMCO TEM cell. NPL uses this cell to calibrate field probes and loop antennas up to 60 MHz.

The E-field in the TEM cell is traceable to power measurement, impedance (which can be calculated from the cell dimensions) and length. The E-field magnitude is given by Eqn. (4):

$$E = \frac{\sqrt{P_{in} Z_0}}{d} \quad (4)$$

where:

P_{in} is the RF power into the cell

Z_0 is the cell's characteristic impedance

d is the plate separation in metres.

2.4 Measurements in the PFD range

An NPL PFD range is a facility for calibrating field probes at frequencies above 250 MHz. It is a rectangular enclosure with pyramidal absorbing material on all surfaces, Fig. 7, apart from one end, which has a trolley supporting a horn antenna that transmits the required field strength at the probe location. Traceability for this field is to the calibrated gain of the horn antenna, input power and length. The power flux density is given by Eqn. 5 and the E-field by Eqn. 6:

$$PFD = \frac{P_{in} \times G}{4\pi d^2} \quad (5)$$

$$E = \sqrt{PFD \times \eta} \quad (6)$$

where:

P_{in} is the RF power into the horn antenna

G is the gain of the horn antenna

d is the distance from the horn to the location of the field probe, in metres.

η is the characteristic impedance of free space

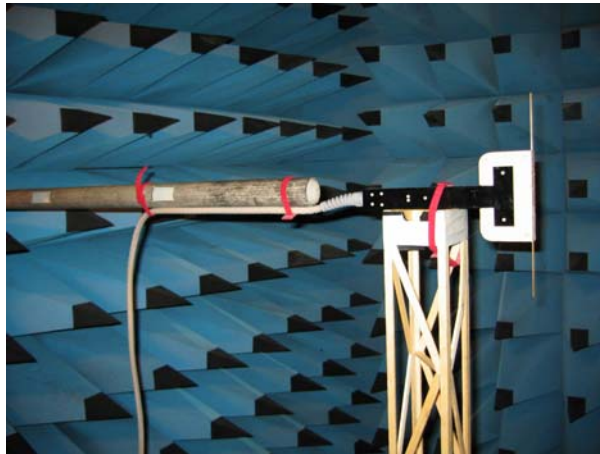


Figure 7. NPL PFD chamber with robust sensor on balsawood tower.

2.5 Measurements in Waveguides

Measurements were made with the small sensor in waveguide sizes 4, 6 and 8, whose frequency ranges are given in Table 1. The E-field magnitude is traceable to input

power, insertion loss and waveguide dimensions. The E-field for the TE_{01} mode is given by Eqn. 7:

$$E^2 = \frac{4P_{in} \cdot Z_{TE}}{a \cdot b} \quad (7)$$

where:

P_{in} is the RF power into the waveguide

Z_{TE} is the characteristic impedance of the waveguide for the TE_{01} mode, which can be calculated from the waveguide height, wavelength and free-space impedance.

a and b are internal height and width of the waveguide in metres.



Figure 8. Small three-axis sensor, suitable for insertion into waveguide

3. RESULTS OF THE COMPARISON

In order to measure the low field levels on the OATS, the noise floor of the PSA was reduced to lower than -110 dBm by setting the resolution bandwidth to 9.8 Hz for the measurements in all the facilities. At 60 MHz the PSA readings for the calculable dipole and robust sensor were approximately -30 dBm and -50 dBm respectively. At 20 MHz the field strength was much lower because a) the antenna factor for the transmitting biconical antenna was high, b) there was destructive interference between the direct and ground reflected signals because the transmit antenna could not be set high enough to achieve in-phase signals, and c) the antenna factor of the calculable dipole was high because a dipole length resonant at 60 MHz was being used: the PSA readings for the calculable dipole and robust sensor were approximately -78 dBm and -86 dBm respectively for a 20 m range. However, the field values were within the region of ± 0.1 dB linearity shown in Fig. 1. An aim of this project was to make a fundamental comparison between the field strengths measured by calculable dipoles and by TEM cells, therefore it is not good practice just to make a single measurement. In view of the fact that the ambient temperature on the OATS could not be controlled, the measurements were repeated on another day.

The results of the measurements are cross-referenced to the Figure numbers in Table 5. The error bars show the measurement uncertainty for calibration factor of the sensor in each facility (at a coverage factor of $k = 2$). For the comparison there is an additional uncertainty of ± 0.2 dB to account for the stability and linearity of the field sensor. Tabulated results are given in Appendix 1.

Ideally the TEM cell power and the calculable dipole and optical sensor measurements should be made with the same instrument in order to reduce the uncertainties. But traditionally TEM cell power is measured with a thermocouple power sensor. The PSA was calibrated against the NRV-Z51 power sensor and the correction factor was applied to the difference between the TEM cell and OATS results in the last column of Table 7.

The results show agreement that is well within the stated measurement uncertainties. Agreement between the OATS and TEM cell at 100 MHz is not as good as for the other frequencies measured, and this is probably due to a higher ambient signal level on the OATS at this frequency which is used by a nearby commercial radio station. Note that the ambient RF levels were not measured during the OATS calibration. It was pleasing that the results were very reproducible, as shown by the OATS1 and OATS2 columns in Table 7 and their comparison in decibels in column 6. The biggest discrepancy of 0.34 dB was at 20 MHz and there are three main reasons for this: (a) the PSA readings were lower than at all other frequencies, (b) the calculable dipole is most accurate at its resonant frequency, but 20 MHz is the furthest away from the resonant frequency of 60 MHz, and (c) the hybrid coupler in the calculable dipole is outside its specified frequency range of 30 MHz to 1 GHz. In spite of these, the average of the two readings agreed very well with the TEM cell reading.

Fig. 10 raises an issue with the accuracy of the EMCO cell above 60 MHz (above which it is not used by the calibration services), but this points to further research to examine the uncertainties of TEM cells as the frequency approaches the first resonance.

Table 5. Measurement results

Figure number	Frequency range	Sensor
9	20 MHz to 300 MHz.	Small sensor
10 ^{a b c}	20 MHz to 90 MHz	Robust sensor
11 ^b	20 MHz to 1 GHz	Robust sensor
12	400 MHz to 2.5 GHz.	Medium sensor
13	1.05 GHz to 2.6 GHz	Small sensor

Notes:

^a The absolute calibration values shown in Figure 10 may be different to those in Figure 11, because the sensor was repaired between these measurements.

^b The EMCO TEM cell is only used for calibrations up to 60 MHz, and the results above this frequency have been included for information only.

^c The calculable dipole balun is specified from 30 MHz to 1 GHz and the result at 20 MHz has included for information only.

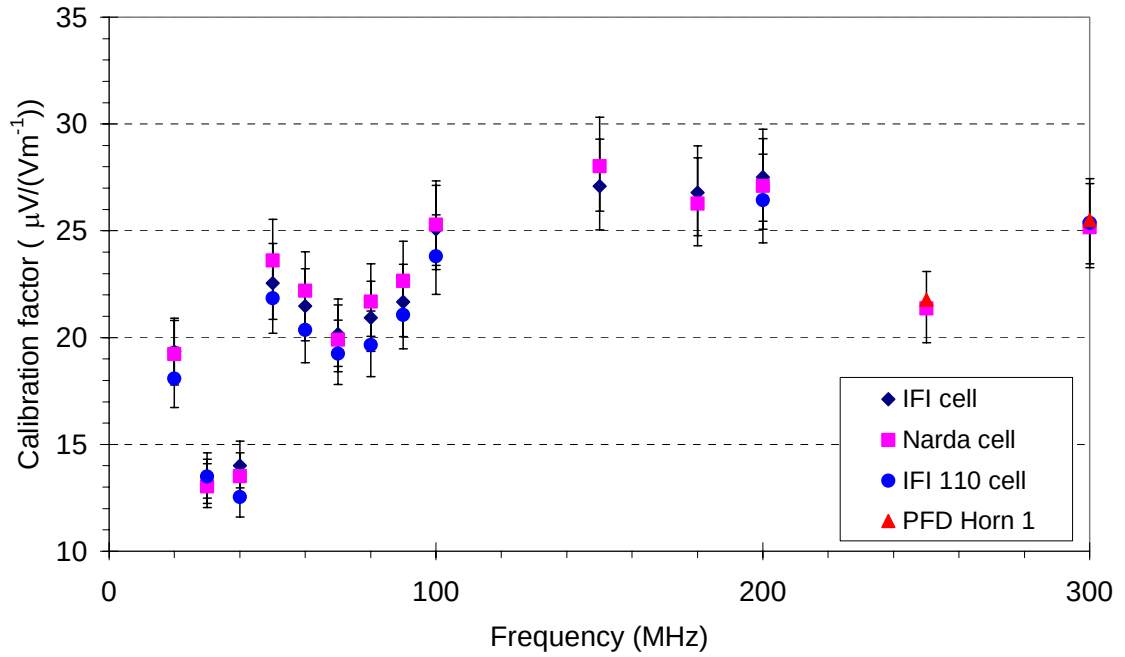


Figure 9. Calibration factor of small sensor measured in different facilities 20 MHz to 300 MHz

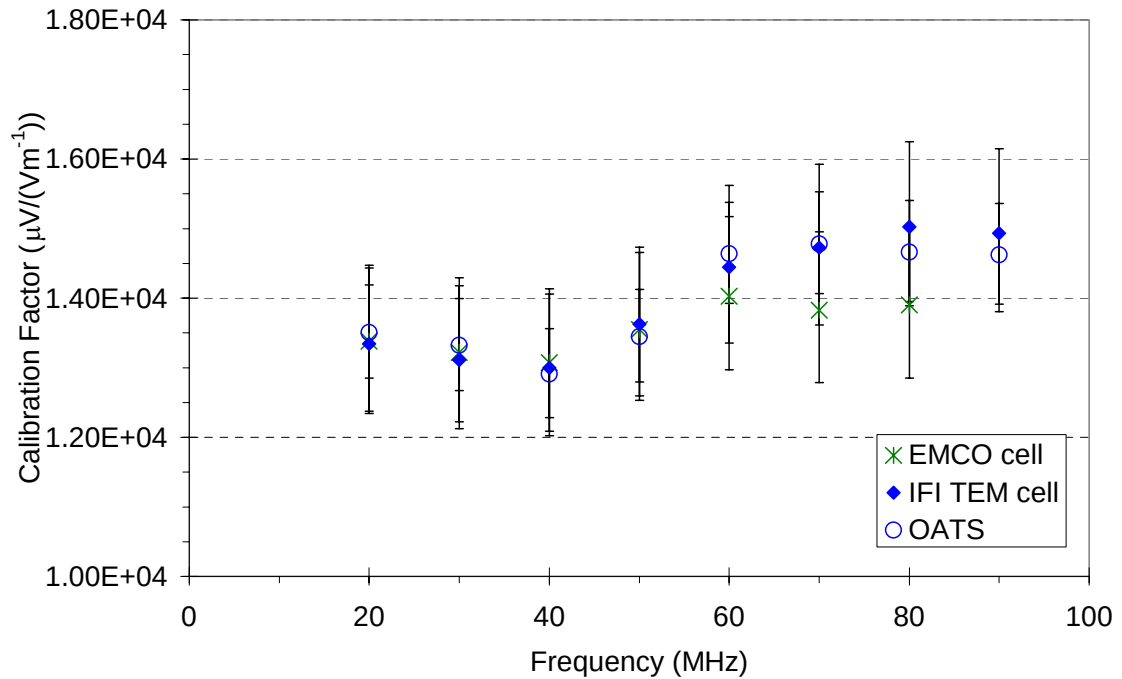


Figure 10. Calibration factor of robust sensor measured in different facilities, 20 MHz to 90 MHz

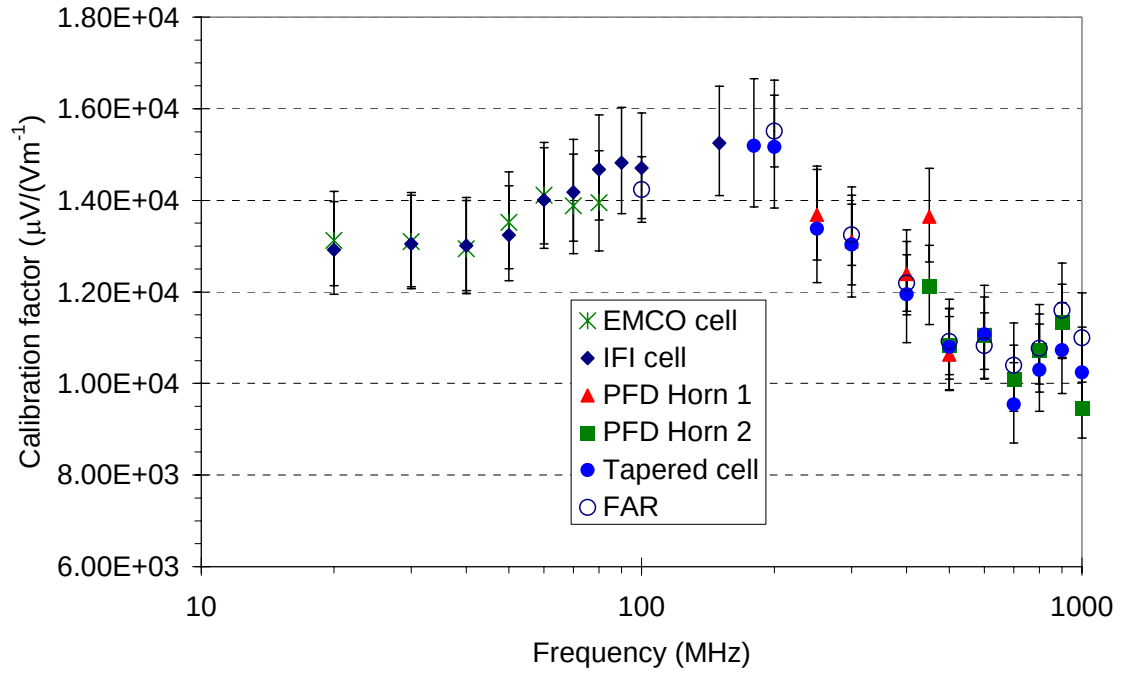


Figure 11. Calibration factors for robust sensor measured in different facilities, 20 MHz to 1 GHz

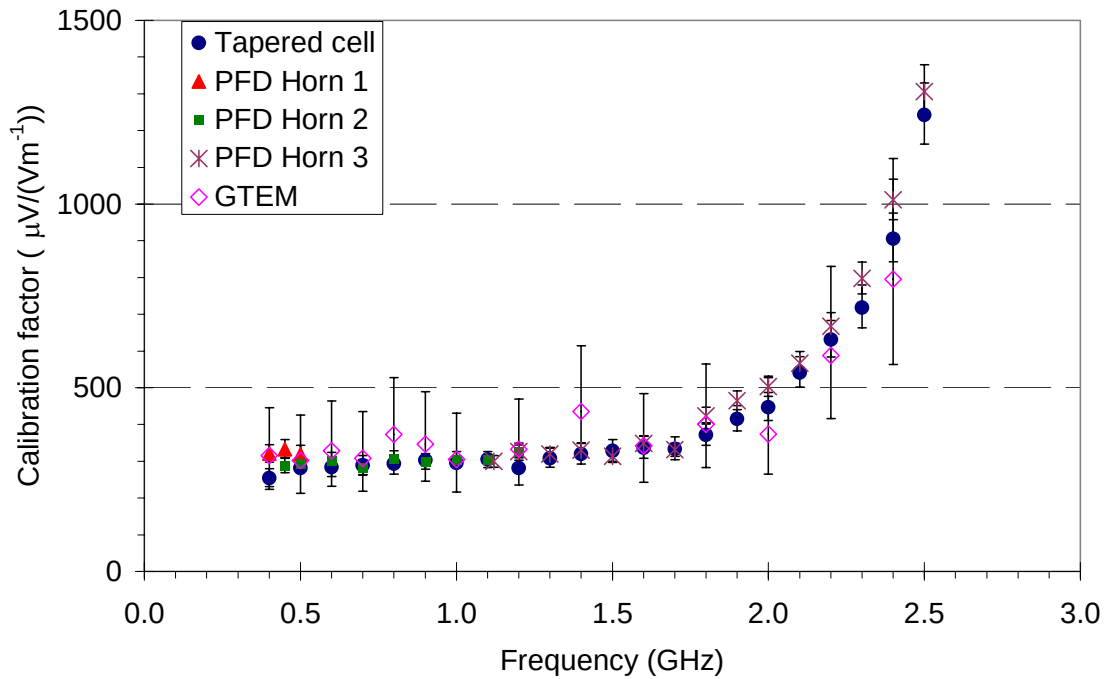


Figure 12. Calibration factor of medium sensor measured in different facilities, 400 MHz to 2.5 GHz

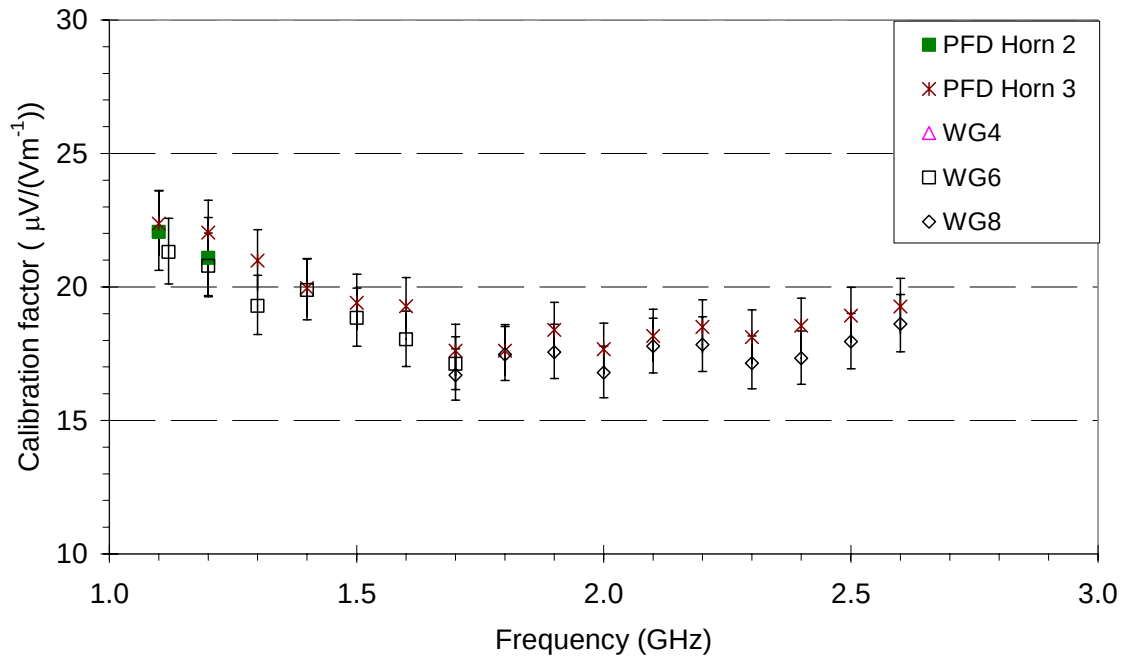


Figure 13. Calibration factor of small sensor measured in different facilities, 1.05 GHz to 2.6 GHz

4. CONCLUSIONS

Three optical electric field sensors were calibrated in the different standard facilities for electric field strength maintained at NPL over the frequency range 20 MHz to 2.6 GHz. These sensors are minimally perturbing to the fields being measured. This enabled a comparison between the free-space and guided-wave facilities. Results of the calibrations in the different facilities agree significantly better than the combined measurement uncertainties quoted for these facilities. The average calibration factors measured on the OATS agreed to within ± 0.1 dB of those obtained in the TEM cells for the frequencies below 80 MHz.

Best measurement uncertainties that are quoted in the UKAS schedule for NPL calibration services were used to determine the accuracy for the comparison of electric field strength reported, and these uncertainties cover the calibration of a wide range of devices. The results of this report indicate that lower uncertainties may be applicable for the calibration of sensors that do not perturb the fields significantly.

The results for the large EMCO TEM cell show that the field starts to deviate from the calculated values above 60 MHz, above which it is not used for commercial calibration services. This is well below the frequency of the first resonance calculated from the dimensions of this cell, and indicates that further research is needed on uncertainties in field strength within TEM cells at the upper end of their specified frequency range of operation.

5. REFERENCES

- [1] M.Alexander, M.Salter, B.Loader, and D.Knight, "Broadband Calculable Dipole Reference Antennas", *IEEE Trans. on EMC*, Feb 2002, Vol 44, No 1, pp. 45 – 59.
- [2] Crawford, ML, "Generation of standard fields using TEM transmission cells", *IEEE Trans on EMC*, 1974, Vol. 16, No. 4, pp 189 – 195.
- [3] Loader, B.G, M Alexander, A Gregory, W Liang, "An optically modulated field sensor to make TEM cells traceable to the NPL calculable standard dipole antenna", *Conference on Precision Electromagnetic Measurement*, Sydney, 14-19 May 2000, pp.495-496.

Note: The field in TEM cells is not traceable to calculable dipole antennas at present, as these standards have similar measurement uncertainties

APPENDIX 1. TABULATED RESULTS

Table 6. Calibration factor of small sensor
20 MHz to 300 MHz

Frequency (MHz)	Calibration factor in different facilities [$\mu\text{V}/(\text{Vm}^{-1})$]			
	IFI cell	Narda cell	IFI 110 cell	PFD Horn 1
20	19.34	19.23	18.08	-
30	13.23	13.04	13.50	-
40	14.01	13.51	12.54	-
50	22.56	23.61	21.85	-
60	21.47	22.21	20.36	-
70	20.16	19.91	19.26	-
80	20.93	21.69	19.65	-
90	21.67	22.66	21.07	-
100	25.09	25.28	23.81	-
150	27.09	28.03	-	-
180	26.80	26.28	-	-
200	27.51	27.11	26.44	-
250	-	21.37	-	21.78
300	-	25.17	25.37	25.51

Table 7. Calibration factor of robust sensor
20 MHz to 90 MHz.

Frequency (MHz)	Calibration factor in different facilities [$10^4 \mu\text{V}/(\text{Vm}^{-1})$]				Differences [dB]		
	OATS1	OATS2	IFI cell	EMCO cell	OATS 1 v. 2	Av. OATS v. IFI	Av. OATS* v. IFI
20	1.30	1.40	1.33	1.34	-0.34	0.11	0.06
30	1.32	1.34	1.31	1.32	-0.07	0.14	0.10
40	1.28	1.31	1.30	1.31	-0.11	-0.06	-0.06
50	1.32	1.37	1.36	1.36	-0.15	-0.11	-0.08
60	1.47	1.45	1.44	1.40	0.06	0.12	0.10
70	1.49	1.47	1.47	1.38	0.05	0.03	-0.02
80	1.47	1.46	1.50	1.39	0.02	-0.21	-0.30
90	1.47	1.45	1.49	-	0.07	-0.18	-0.10

*corrected PSA reading

Table 8. Calibration factors for robust sensor
20 MHz to 1 GHz

Frequency (MHz)	Calibration factor in different facilities [$10^4 \mu\text{V}/(\text{Vm}^{-1})$]					
	FAR	Tapered cell	IFI cell	EMCO cell	PFD Horn 1	PFD Horn 2
20	-	-	1.29	1.31	-	-
30	-	-	1.31	1.31	-	-
40	-	-	1.30	1.29	-	-
50	-	-	1.32	1.35	-	-
60	-	-	1.40	1.41	-	-
70	-	-	1.42	1.39	-	-
80	-	-	1.47	1.39	-	-
90	-	-	1.48	-	-	-
100	1.42	-	1.47	-	-	-
150	-	-	1.53	-	-	-
180	-	1.52	-	-	-	-
200	1.55	1.52	-	-	-	-
250	-	1.34	-	-	1.37	-
300	1.32	1.30	-	-	1.31	-
400	1.22	1.19	-	-	1.24	-
450	-	-	-	-	1.36	1.21
500	1.09	1.08	-	-	1.06	1.08
600	1.08	1.11	-	-	-	1.11
700	1.04	0.95	-	-	-	1.01
800	1.08	1.03	-	-	-	1.07
900	1.16	1.07	-	-	-	1.13
1000	1.10	1.02	-	-	-	0.95

Table 9. Calibration factor of medium sensor
400 MHz to 2.5 GHz

Frequency GHz	Calibration factor in different facilities [$\mu\text{V}/(\text{Vm}^{-1})$]				
	Tapered cell	PFD Horn 1	PFD Horn 2	PFD Horn 3	GTEM
0.40	254	321	-	-	316
0.45	-	333	289	-	-
0.50	282	319	292	-	301
0.60	284	-	302	-	328
0.70	289	-	283	-	308
0.75	-	-	-	-	-
0.80	293	-	306	-	373
0.85	-	-	-	-	-
0.90	303	-	299	-	347
0.95	-	-	-	-	-
1.00	296	-	304	-	305
1.05	-	-	-	-	-
1.10	305	-	304	-	-
1.12	-	-	-	299	-
1.20	282	-	325	326	332
1.30	309	-	-	320	-
1.40	320	-	-	330	435
1.50	328	-	-	314	-
1.60	337	-	-	349	342
1.70	334	-	-	331	-
1.80	372	-	-	424	400
1.90	415	-	-	465	-
2.00	448	-	-	504	374
2.10	542	-	-	567	-
2.20	631	-	-	668	588
2.30	719	-	-	797	-
2.40	906	-	-	1011	796
2.50	1243	-	-	1306	-

Table 10. Calibration factor of small sensor
1.05 GHz to 2.6 GHz

Frequency GHz	Calibration factor in different facilities [$\mu\text{V}/(\text{Vm}^{-1})$]					
	Tapered cell	PFD Horn 2	PFD Horn 3	WG4	WG6	WG8
1.05			-	21.54	-	-
1.10	20.50	22.06	22.37	21.04	-	-
1.12	-	-	-	20.73	21.31	-
1.20	23.72	21.08	22.03	-	20.79	-
1.30	19.53	-	20.98	-	19.30	-
1.40	20.29	-	19.95	-	19.88	-
1.50	17.33	-	19.41	-	18.84	-
1.60	18.20	-	19.28	-	18.03	-
1.70	17.61	-	17.62	-	17.12	16.70
1.80	18.46	-	17.61	-	-	17.47
1.90	24.13	-	18.39	-	-	17.55
2.00	15.25	-	17.67	-	-	16.79
2.10	15.56	-	18.16	-	-	17.78
2.20	20.12	-	18.50	-	-	17.83
2.30	19.58	-	18.13	-	-	17.15
2.40	17.25	-	18.55	-	-	17.33
2.50	20.87	-	18.93	-	-	17.95
2.60	18.34	-	19.26	-	-	18.61