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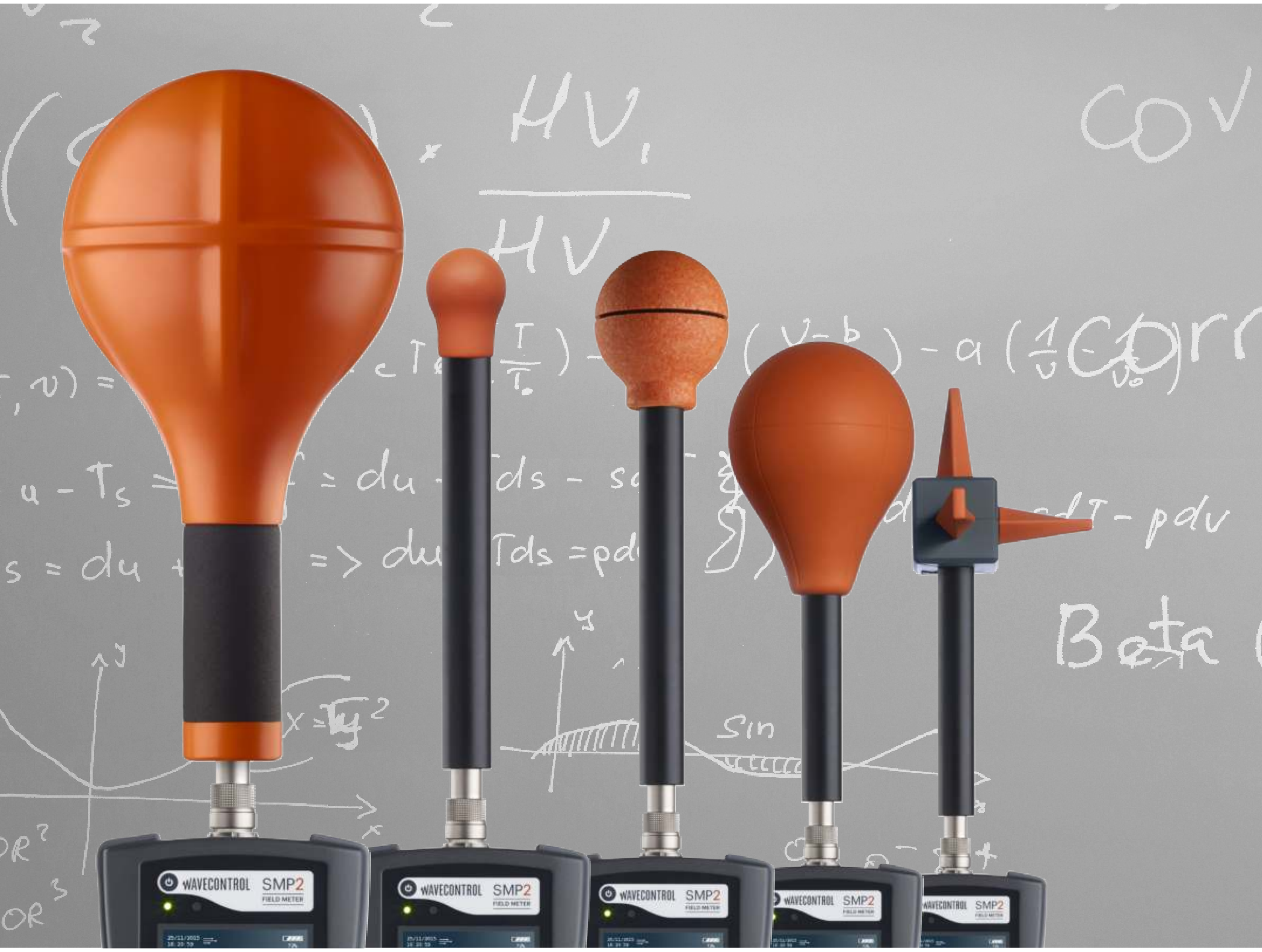
Calculation of the total measurement uncertainty of a field strength meter

APPLICATION NOTE



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Application Note

Calculation of the total measurement uncertainty of a field strength meter

1. MEASUREMENT UNCERTAINTY

The expression of the results of a measurement will be complete only if it states both the measured value and the associated measurement uncertainty.

Measurement uncertainty is a parameter associated with the results of a measurement that defines the spread of the values that may reasonably be assigned to the measured magnitude. Therefore, when any measurement device is used, it is important to know the uncertainty that the device will produce so that it can be included in the results.

This document explains how to calculate the total measurement uncertainty introduced by an electromagnetic field measurement device. It is important to note that the total measurement uncertainty will depend not only on the uncertainty of the measurement equipment, but also on the uncertainty due to the measurement method. That last type of uncertainty lies outside the scope of this document and how it is calculated will depend on the measurement method used.

2. SOURCES OF UNCERTAINTY

The result given by an electromagnetic field measurement device is a value for intensity of the electric or magnetic field or a value for power density. That value is an “estimated” value of the magnitude. In order for the expression of the result to be complete, it must include the measurement uncertainty. Thus, the result is expressed as follows:

- **Electric field intensity:**

$$E = E_{measured}\ (\frac{V}{m}) \pm U\ (dB)$$

- **Magnetic field intensity:**

$$H = H_{measured}\ (T) \pm U\ (dB)$$

- **Power density:**

$$S = S_{measured}\ (\frac{\mu W}{cm^2}) \pm U\ (dB)$$

where U is the uncertainty, expressed in decibels.

In the case of the type of measurement devices and the magnitudes that we are concerned with here, the uncertainty is normally stated in decibels (dB), a logarithmic unit. This sort of unit defines an error that is not constant, but instead proportional to the value of measured magnitude.

To calculate the uncertainty introduced by a measurement device, we need to take into account all the possible sources of uncertainty associated with the device. The degree of uncertainty introduced from each of those sources must be stated by the manufacturer in the specification sheet for the device, or, preferably, in the calibration certificate supplied with each device. If the degree of uncertainty is not specified as such, it must at least be possible to calculate based on the information provided by the manufacturer.

As a rule, electromagnetic field measurement devices have the following sources of uncertainty:

a. **Frequency deviation:** this uncertainty is due to the fact that the response of the field probe is not completely flat over the full range of frequencies, i.e. certain frequencies are measured with higher gain than others. If this uncertainty is not shown as a discrete figure in the manufacturer’s specifications, it can be obtained from the device’s calibration certificate, based on the correction factors.

b. **Linearity error:** this is the uncertainty caused by the lack of linearity in the device’s response. This lack of linearity can mean that the lowest or highest values may be measured with a degree of error. If this uncertainty is not shown as a discrete figure in the manufacturer’s specifications, it can be obtained from the device’s calibration certificate, based on the correction factors.

c. **Anisotropy:** this is the uncertainty caused by the measurement device's lack of isotropy. The device does not measure equally in all spatial directions and certain directions are measured with higher gain than others. This value is stated on the specification sheet.

d. **Calibration uncertainty:** this is the uncertainty of the process through which the device has been adjusted and calibrated. This value is shown on the device's calibration certificate and it may also appear on the specification sheet.

e. **Resolution:** this is the uncertainty caused by the measurement device's resolution. Resolution is the smallest difference in magnitude that the device can detect. It must be stated on the device's specification sheet.

f. **Repeatability:** this is the uncertainty caused by the repeatability of the measurement. Repeatability refers to the variation observed on repetition of the measurement under the same conditions. It is calculated, when a measurement is taken, by carrying out successive measurements under the same conditions.

g. **Temperature deviation:** this uncertainty is caused by the effect of temperature on the technology of the measurement device. This value should be stated on the specification sheet.

3. CALCULATION OF THE TOTAL MEASUREMENT UNCERTAINTY

The method for calculating measurement uncertainty is explained in the document GUM (Guide to the Expression of the Uncertainty in Measurement).

In our case, the mathematical model defining the measurement process is simple, since it is a direct measurement:

$$E_m = E_{act} + \sum \partial_j$$

Where

E_{act} = *Actual electric field strengh*

E_m = *Measured electric field strengh*

∂_j = *Contribution of source of uncertainty j*

To find the Total expanded uncertainty of the measurement (U), we need to calculate the combined standard uncertainty (U_c) based on the standard uncertainties associated with each source of uncertainty (U_j).

$U = k\,U_c$ *(k = 2 for a normal distribution and a confidence interval of 95%)*

$$U_c = \sqrt{\left(\sum c_j^2\, U_j^2\right)} = \sqrt{\left(\sum U_j^2\right)}$$

In our case, all the sensitivity (c_j) are equal to 1.

Note: *each sensitivity coefficient corresponds to the partial derivative of the contribution of the corresponding source of uncertainty in the mathematical model of the measurement process. In our case, since it is a direct measurement, the contributions of the sources of uncertainty are added together, and so their partial derivatives are equal to 1.*

The process for calculating the total expanded uncertainty is as follows:

1. Obtain or calculate the values associated with the different sources of uncertainty. As a rule, those values are stated as expanded uncertainty values in dB.
2. Convert the uncertainties in dB into uncertainties in linear units (%).
3. Calculate the standard uncertainties based on the expanded uncertainties (U_j).
4. Calculate the standard combined uncertainty (U_c).
5. Calculate the total expanded uncertainty (U).
6. Convert the total expanded uncertainty into logarithmic units (dB).

3.1 Calculation of the uncertainty values associated with the different sources

3.1.1 Frequency deviation

There are two ways to obtain this value:

- We can use the limit value for frequency deviation stated by the manufacturer on the probe specification sheet under frequency response or frequency deviation. This is a maximum value, given in **dB**.

  For example for the WPF18 field probe from Wavecontrol the frequency response is given as:

Frequency response	± 2 dB (1 MHz – 5 GHz) + 0 / - 6 dB (5 GHz - 18 GHz)

- We can use the device's calibration certificate to obtain its exact frequency deviation. To do so, we take the highest correction factor (CF_{max}) and the lowest correction factor (CF_{min}) given in the frequency calibration section, and calculate the frequency deviation as follows:

  $$\text{Frequency response} = \pm \text{Max}\,[20 \log (CF_{max}); 20 \log (CF_{min})]\ dB$$

  In both cases, the probability distribution of this source is rectangular.

3.1.2 Linearity

There are two ways to obtain this value:

- We can use the limit value for linearity error stated by the manufacturer on the probe specification sheet under linearity. This is a maximum value, given in **dB**.

  For example for the **WPF18** field probe from Wavecontrol the linearity is given as:

Linearity	± 0.5 dB (1 V/m - 150 V/m)

- We can use the device's calibration certificate to obtain its exact linearity error. To do so, we take the highest correction factor (CF_{max}) and the lowest correction factor (CF_{min}) given in the frequency calibration section, and calculate the frequency deviation as follows:

  $$\text{Linearity error} = \pm 10 \log \left(\frac{CF_{max}}{CF_{min}} \right) dB$$

  In both cases, the probability distribution of this source is rectangular.

3.1.3 Anisotropy

We obtain this uncertainty value from the device's specification sheet or calibration certificate, in the axial isotropy section. It is a maximum value, given in dB. The probability distribution is rectangular. For example for the **WPF18** field probe from Wavecontrol the anisotropy is given as:

Isotropic deviation	± 1.2 dB (up to 10 GHz) ± 3 dB (10 GHz - 18 GHz)

3.1.4 Resolution

This value is obtained from the device's specification sheet in the Resolution section. It may be given in **dB** or linear units. The value for uncertainty due to resolution is half the value for resolution and it has a rectangular distribution. For example for the **WPF18** field probe from Wavecontrol the resolution is given as:

Resolution	< 5 %

3.1.5 Calibration

This value is obtained from the device's calibration certificate, although it may also appear on its specification sheet. Different values may be given, depending on the frequency range, since the calibration method varies for different frequencies. This uncertainty has a normal probability distribution and it is usually stated in **dB**, although it may also be given in linear units. Next example presents the uncertainty of calibration for a **WPF18** field probe from **Wavecontrol**:

Uncertainties:

The uncertainty of calibration for this device is a follows:

300 kHz - 10 MHz:	±	1.19 dB
10 MHz - 300 MHz:	±	1.33 dB
300 MHz - 500 MHz:	±	1.09 dB
500 MHz - 800 MHz:	±	1.46 dB
800 MHz - 1 GHz:	±	1.03 dB
1 GHz - 2.5 GHz:	±	0.96 dB
2.5 GHz - 8 GHz:	±	0.93 dB
8 GHz - 18 GHz:	±	0.91 dB

3.1.6 Repeatability

The uncertainty due to device repeatability is based upon a number *"n"* of measurements taken under the same conditions. Those samples are used to obtain the average value, and the average value is used to obtain the standard deviation and the standard deviation of the average, which gives the standard uncertainty associated with repeatability:

Mean value: $\ddot{x} = \frac{\sum_{i=1}^{i=n} x_i}{n}$

Standard deviation: $\sigma = \sqrt{\frac{\sum_{i=1}^{i=n} (x_i - \ddot{x})^2}{n-1}}$

Standard deviation of the mean value: $u = \frac{\sigma}{\sqrt{n}}$

This uncertainty has a normal distribution and the coverage factor for a confidence interval of 95% is k=2.

3.1.7 Temperature deviation

This value is given in **dB** and its probability distribution is rectangular. For example, for the **WPF18** field probe from Wavecontrol the temperature response is given as::

Temperature response	+ 0.1/ - 1 dB (related to 20 ºC)

3.2 Conversion of logarithmic units (dB) to linear units (%)

All uncertainty values must be converted to linear units (% uncertainty) for calculation of the total uncertainty. The calculation is as follows:

In the case of a field strength value:

$$u_i(\%) = 100 * (10^{\frac{u_i(dB)}{20}} - 1)$$

In the case of a power density value:

$$u_i(\%) = 100 * (10^{\frac{u_i(dB)}{10}} - 1)$$

3.3 Calculation of standard uncertainties from expanded uncertainties

Once we have the uncertainties in linear units, the next step is to calculate the standard uncertainties, since all the sources of uncertainty are characterized by their expanded uncertainties. To do so, we divide the expanded uncertainty value by the divisor corresponding to the type of probability distribution for the source of uncertainty:

- Rectangular distribution: divisor = √3 = 1.732
- Normal distribution: divisor = 2 (for a confidence interval of 95%)

3.4 Calculation of the combined standard uncertainty u_c

The standard combined uncertainty is calculated from the standard uncertainties associated with the different sources of uncertainty by means of a quadratic sum of those standard uncertainties. As mentioned earlier, the sensitivity coefficients c_j are equal to 1 in our case.

$$u_c = \sqrt{(\sum c_j^2 u_j^2)} = \sqrt{(\sum u_j^2)}$$

3.5 Calculation of the total expanded uncertainty U

Lastly, the total expanded uncertainty is calculated by applying a coverage factor of k=2, giving a confidence interval of 95%. This means that by multiplying the combined standard uncertainty by the factor k=2, we ensure that the real value will fall within the interval [measured value ± U] with a confidence of 95%.

$$U = 2.u_c$$

Lastly, this linear value is converted to logarithmic units:

$$U\,(dB) = 20\,.log\left(1 + \frac{U}{100}\right)$$

4. Uncertainty calculation: examples

Below are three examples of uncertainty calculation for an **SMP2** measurement device with a **WPF18** field probe (E-field), a **WP400** field probe (E-field) and a **WP400** field probe (H-field), all from **Wavecontrol**. At **Wavecontrol** we always calibrate the field probe and the measurement device together following the **ISO 17025** standard so that the calibration will give an exact description of the combined performance of the probe and measurement device.

4.1 Calculation of the measurement uncertainty of an SMP2 + WPF18 probe

(based on datasheet and calibration certificate)

The values for the different sources of uncertainty are taken from the probe's specification sheet and the calibration certificate:

- **Frequency response:**
  ± 2 dB (1 MHz - 5 GHz)
  + 0 / - 6 dB (5 GHz - 18 GHz)
- **Linearity:** ± 0.5 dB
- **Anisotropy:**
  ± 1.2 dB (up to 10 GHz)
  ± 3 dB (10 GHz – 18 GHz)
- **Calibration uncertainty**
  (example from a calibration report):
  300 kHz - 10 MHz: ± 1.19 dB
  10 MHz - 300 MHz: ± 1.33 dB
  300 MHz - 500 MHz: ± 1.09 dB
  500 MHz - 800 MHz: ± 1.46 dB
  800 MHz - 1 GHz: ± 1.03 dB
  1 GHz - 2.5 GHz: ± 0.96 dB
  2.5 GHz - 8 GHz: ± 0.93 dB
  8 GHz - 18 GHz: ± 0.91 dB
- **Resolution:**
  < 5% (Resolution uncertainty= $\frac{5\%}{2}$ =2.5 %)
- **Repeatability:** ± 0.1 dB
- **Temperature deviation:**

+0.1/ -1 dB @ 20 ºC (- 0.035 dB/ºC @ -20ºC to 50ºC)

For 1 GHz – 2.5 GHz frequency range:

Source of uncertainty	Unit	Expanded uncertainty (dB)	Expanded uncertainty (%)	Distribution	Divisor	Standard uncertainty (%)
Frequency response	dBV/m	2	25.9	Rectangular	1.732	14.9
Linear error	dBV/m	0.5	5.9	Rectangular	1.732	3.4
Anisotropy	dBV/m	1.2	14.81	Rectangular	1.732	8.55
Calibration	dB	0.96	11.68	Normal	2	5.84
Resolution	%		2.5	Rectangular	1.732	1.4
Repeatability	dBV/m	0.1	1.2	Normal	2	0.6
Temperature deviation (@ 26°C)	dBV/m	0.21	2.44	Rectangular	1.732	1.41
Standard combined uncertainty (U_c)	%					18.57
Expanded uncertainty (U)	%			Normal	2	37.15
Expanded uncertainty (U)	**dB**					**2.74**

Thus, the results obtained for the SMP2 + WPF18 probe may be expressed, within a confidence interval of 95%, as:

$E_{act} = E_m \pm 2.74$ dB *(for the 1 GHz – 2.5 GHz range)*

4.2 Calculation of the measurement uncertainty for the electric field of an SMP2 + WP400 probe

(based on datasheet and calibration certificate)

The values for the different sources of uncertainty are taken from the probe's specification sheet and the calibration certificate:

- **Frequency response (25 Hz – 100 kHz):** ± 4%
- **Linearity (datasheet):** ± 1% (typ.)
- **Isotropy (datasheet):** ± 5%
- **Calibration uncertainty (example from a calibration report):**
  10 Hz - 10 kHz: ± 2.60%
  10 kHz - 400 kHz: ± 3.33%
- **Resolution:** 0.02 %
- **Repeatability:** ± 0.01 dB
- **Temperature deviation:** - 0.005 dB/°C @25°C

For 10 Hz – 10 kHz frequency range:

Source of uncertainty	Unit	Expanded uncertainty (dB)	Expanded uncertainty (%)	Distribution	Divisor	Standard uncertainty (%)
Frequency response	dB V/m		4	Rectangular	1.732	2.31
Linear error	dB V/m		1	Rectangular	1.732	0.58
Isotropy	dB V/m		5	Rectangular	1.732	2.89
Calibration uncertainty	dB		2.6	Normal	2	1.3
Resolution	%		0.02	Rectangular	1.732	0.01
Repeatability	dB V/m	0.01	0.12	Normal	2	0.06
Temperature deviation (@25 °C)	dB V/m	0.005	0.05	Rectangular	1.732	0.03
Standard combined uncertainty (U_c)	%					3.96
Expanded uncertainty (U)	%			Normal	2	7.92
Expanded uncertainty (U)	**dB**					**0.66**

Thus, the electric field results obtained for the SMP2 + WP400 probe may be expressed, within a confidence interval of 95%, as:

$E_{act} = E_m \pm 0.66$ dB *(for the 10 Hz – 10 kHz range)*

4.3 Calculation of the measurement uncertainty for the magnetic field of an SMP2 + WP400 probe

(based on datasheet and calibration certificate)

The values for the different sources of uncertainty are taken from the probe's specification sheet and the calibration certificate:

- **Frequency response (25 Hz – 100 kHz):** ± 4%
- **Linearity (datasheet):** ± 1%
- **Isotropy (datasheet):** ± 4%
- **Calibration uncertainty (example from a calibration report):**
  10 Hz - 10 kHz: ± 2.77%
  10 kHz - 400 kHz: ± 2.87%
- **Resolution:** 0.01%
- **Repeatability:** ± 0.01 dB
- **Temperature deviation:** - 0.003 dB/°C @25°C

For 10 Hz – 10 kHz frequency range:

Source of uncertainty	Unit	Expanded uncertainty (dB)	Expanded uncertainty (%)	Distribution	Divisor	Standard uncertainty (%)
Frequency response	dB V/m		4	Rectangular	1.732	2.31
Linear error	dB V/m		1	Rectangular	1.732	0.58
Isotropy	dB V/m		4	Rectangular	1.732	2.3
Calibration uncertainty	dB		2.77	Normal	2	1.38
Resolution	%		0.01	Rectangular	1.732	0.005
Repeatability	dB V/m	0.01	0.12	Normal	2	0.06
Temperature deviation (@25ºC)	dB V/m	0.003	0.034	Rectangular	1.732	0.02
Standard combined uncertainty (U_c)	%					3.58
Expanded uncertainty (U)	%			Normal	2	7.17
Expanded uncertainty (U)	**dB**					**0.60**

Thus, the magnetic field results obtained for the SMP2 + WP400 probe may be expressed, within a confidence interval of 95%, as:

$E_{act} = H_m \pm 0.60$ dB *(for the 10 Hz – 10 kHz range)*

5. REDUCING MEASUREMENT UNCERTAINTY: CORRECTION FACTORS

The calculations of uncertainty set out above were made for specific measurement ranges, i.e. where the frequency or other parameters are unknown.

If any of those parameters are known, correction factors from the calibration certificate can be applied to reduce the corresponding source of uncertainty (for example the frequency response or linearity error).

Thus, if the measurements are made within a temperature range (±5ºC) close to the calibration temperature, which is 20 – 26ºC in the case of Wavecontrol, the uncertainty due to temperature deviation is negligible.

This allows us to reduce measurement uncertainty substantially.

6. Annex I: WPF18 Field Probe Datasheet

7. Annex II: WP400 Field Probe Datasheet

WPF18 Field Probe
300 kHz - 18 GHz

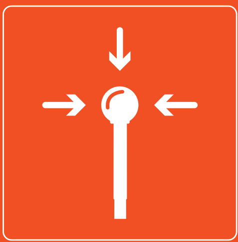
- **High sensitivity** from 0.5 V/m
- **Isotropic and RMS** measurement
- **Excellent attenuation** at 50/60 Hz
- **Meets international standards**

300 kHz - 18 GHz

E

RMS

ISOTROPIC



Telecommunications: certification and audit of telecommunication services (GSM, 3G, LTE, TDT, AM, FM, WiFi, etc.).

Industry: assessment of industrial processes for worker's exposure protection.

Defence: assessment of military sites and personnel exposure protection.

Labs/R&D: RF exposure protection of R&D and labs personnel.

ISO17025 ·Accredited calibration lab

Technical Specifications

	WPF18	WPF18-HP High Power version
Frequency range	300 kHz - 18 GHz	
Sensor type	Isotropic RMS diode technology	
Type of frequency response	Flat	
Measurement range	0.5 - 250 V/m (CW) 0.5 - 30 V/m (RMS)	0.5 – 1000 V/m (CW)
Dynamic range	54 dB	66 dB
Sensitivity	0.5 V/m	
Resolution	< 5 %	
Frequency response	± 2 dB (1 MHz – 5 GHz) + 0 / - 6 dB (5 GHz - 18 GHz)	
Linearity	± 0.5 dB (1 V/m - 150 V/m)	
Isotropic deviation	± 1.2 dB (up to 10 GHz) ± 3 dB (10 GHz - 18 GHz)	
Calibration	ISO 17025 accredited calibration (ILAC)	
Calibration period	24 months (recommended)	
Temperature range	- 20 ºC to 50 ºC	
Temperature response	+ 0.1/ - 1 dB (related to 20 ºC)	
Dimensions	28.4 cm x 6 cm Ø	
Weight	95 g	
Attenuation at 50/60 Hz	> 80 dB	

(*) The frequency response can be corrected with the SMP2 by using the correction factors stored in the probe (ISO 17025 accredited calibration).

Compatible with **SMP2**, **MonitEM**, **MapEM**

Product specifications and descriptions in this document subject to change without notice

WPF18_EN_1703_v1.1

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WP400 Probe
1 Hz - 400 kHz

- Electric & Magnetic field measurement
- Isotropic & True RMS measurement
- Spectrum analysis probe
- Measurements in accordance with International Standards

1 Hz - 400 KHz

E & H

RMS

ISOTROPIC

Power grid
Measurement of the exposure to EM fields at transformer stations and high-voltage lines.

Railway
Measurement of EM fields in trains and in the railway environment with respect to human exposure.

Industry
Assessment of workers' exposure to EM fields in all kind of manufacturing facilities.

Technical Specifications

	Electric Field	Magnetic Field
Sensor type	Isotropic patented electrodes	
Frequency range	1 Hz – 400 kHz	1 Hz – 400 kHz
Field Strength Mode		
Measurement range	1 V/m to 100 kV/m	50 nT - 10 mT (100 Hz - 10 kHz) · Upper range increases linearly with decreasing frequency below 100 Hz. · Upper range decreases linearly with increasing frequency above 10 kHz.
Graphical display	RMS, Axis Values, AVG, MAX, MIN, PEAK, RMS time graph	
Peak value	digital realtime	digital realtime
Resolution	< 0.4 mV/m above 8 Hz	< 0.1 nT (at 50 Hz) and < 0.05 nT above 100 Hz
Noise level	< 1 V/m (10 Hz - 400 kHz)	< 50 nT (10 Hz – 400 kHz)
Typical Uncertainty (1)	0.67 dB	0.60 dB
Weigthed Peak Method mode		
Measurement range	200 % (min)	200 % (min)
Graphical display	PEAK (%), AXIS VALUES (%), AVG (%), MAX (%), MIN (%), RMS (%), Time graph	
Standards/Limits	EU Directive 2013/35/EU, FCC/IEEE, Safety Code 6, ICNIRP, BGV B11, Chinese Standard. Easy software update to future modifications and to other limits.	
Typical Uncertainty (1)	0.67 dB	0.60 dB

WP400_EN_1709_v2.0

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WP400 Probe
1 Hz - 400 kHz

Technical Specifications

	Electric Field	Magnetic Field
FFT Mode		
Measurement range	4 mV/m – 100 kV/m	0.5 nT - 10 mT (100 Hz - 10 kHz) · Upper range increases linearly with decreasing frequency below 100 Hz. · Upper range decreases linearly with increasing frequency above 10 kHz.
Graphical display	Frequency analysis, total field and axis	
SPAN (Resolution)	400 Hz (1 Hz) - 4 kHz (10 Hz) - 40 kHz (100 Hz) - 400 kHz (1 kHz)	
Noise level	< 4 mV/m	< 0.5 nT
FFT	1024 point FFT	
General Specifications		
Isotropy	± 5 %	± 4 %
Temperature deviation [typ. at 60 Hz] (referred to 25 °C, 50 % relative humidity)	- 0.005 dB/°C (- 15 °C to 40 °C)	- 0.003 dB/°C (- 15 °C to 25 °C) + 0.003 dB/°C (25 °C to 40 °C)
Damage level	> 200 kV/m	> 2000 mT up to 60 Hz Damage level decreases linearly with increasing frequency above 60 Hz
Linearity	± 1 % (typ.) ± 2 % (max.)	
Weight	220 g	
Probe size	280 mm x 120 mm Ø	

(1) Total, counting isotropy, temperature deviation, resolution, frequency response, linearity, repetability.

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