24. IMPROVED TECHNIQUE FOR SIMPLIFYING STANDARDS-COMPLIANT TESTS OF NON-IONIZING ELECTROMAGNETIC RADIATION

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Summary

Typically the compliance with Standards for personal safety in electromagnetic fields under complex exposure situations was measured by experts with specific equipment. Recently, measuring instruments became more sophisticated. This enables also less educated staff to carry out the measurements. Inexperienced workers can be fitted with personal monitors.

Ease of use was improved in three points. The frequency response shaping according to the Standards was integrated before the detector inside the probes. Electric and magnetic fields in the range 1 MHz up to 40 GHz (and up to 1 GHz, respectively) can be measured with the radiation monitor ESM-20 simultaneously for the first time. It has been established, that significant under-estimation can be avoided, even when this monitor is carried close to the body. True r.m.s. measurement could practically be achieved employing diode detectors. Even direct evaluation of operating radars has become possible by using fast signal processing.

1 Personal safety standards for high-frequency electromagnetic radiation

The relevant protection guides for personal safety in RF and microwave electromagnetic fields all sets reference levels as limits for electric and magnetic fields derived from the basic limits. These reference levels are frequency dependent. The possibility of a higher specific absorption in the region of the body resonance is thus taken into account by defining lower limit values for the electric and magnetic fields in this frequency range. All relevant standards dictate to measure the electric and magnetic field components in the absence of persons. [7 - 10]

The electric field and the magnetic field can be measured one after the other, for example by changing the appropriate field probes. In order to reduce interference in the electromagnetic field to a minimum and to get reproducible results, it is a common way to mount the field strength sensor on a wooden tripod at the measuring site and either store the measured values in an integrated data logger or transmit them via optical fibers. Often, however, the electromagnetic field needs to be monitored using measuring devices or personal monitors carried close to the body, particularly to protect unexperienced persons adequately. Simultaneous measurements of the electric field strength and the magnetic field strength in the frequency range from 1 MHz to 40 GHz (or 1 GHz) has became possible for the first time with the integration of two isotropic sensors in the ESM-20 radiation monitor.

2 Shaped probes

It is only possible to measure field strength in order to monitor the derived personal protection limits if the frequency of the radiation source is already known. The frequency information is not necessary if a frequency response shaping is integrated in front of the signal detection. This filter network must have a frequency response inverse to the limit curve. Multiple-frequency signals can also be evaluated correctly in this way.

The basic principle of the sensors for electric and magnetic fields have already been described elsewhere. [1, 2] Sensors for the electric RF field consist of short, resistively damped dipoles with detector diodes at the center. These sensors are usually optimized for a flat frequency response and the maximum possible bandwidth. A compensation network consisting of discrete components utilizes to fit the magnitude frequency response to the limit curve in the low-frequency range. In the high-frequency range however, the frequency response can be adjusted to the limit curve by optimizing the resistive coating of the dipole arms. Since an analytical solution previously only existed for flat frequency responses [5], a new approach had to be adopted here. Wandel & Goltermann has developed a straightforward functional model, for approximately determining the dimensions and the damping of the dipole without numerical calculations. The frequency responses have been optimized for various personal safety standards using the FEKO software package [4] and verified by means of measurements. Fig. 1 shows this for the FCC 96-326 standard [8] in the frequency range from 300 kHz to 40 GHz. The limit curves in the currently valid standards all have sharp edges. By real equalizer networks consisting of decoupled single order circuit elements however only a soft curve shaping can be realized. The measurement reflects a good fitting to the limit curve. The deviations at higher frequencies are due to parasitics and to the reduced calibration accuracy. A similar approach for optimizing the dipole damping numerically is described in [6].

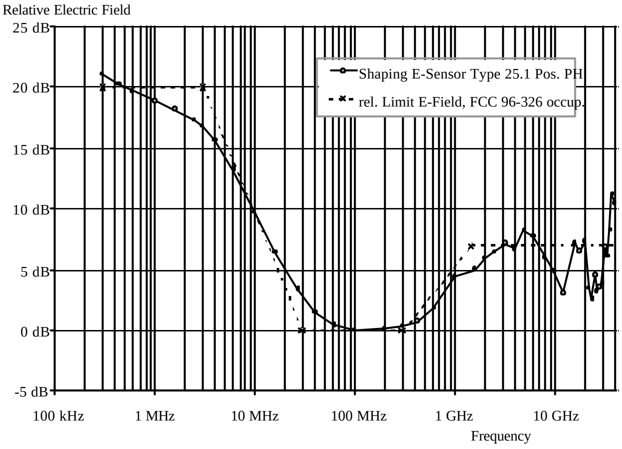

Fig. 1: Typical frequency response of EMR measurement system with a shaped E-field probe (type 25) for the standard FCC 96-326 occupational in position PH

Shaped E-sensors are available for the EMR system as interchangeable, isotropic probes and have also been integrated in the ESM-20 radiation monitor. Both variants are available for various standards.

Magnetic field sensors consist of small loops, loaded by a shunt resistor and detector diodes. [2] Once again, the magnitude frequency response can be shaped to fit the standards by connecting suitably dimensioned equalizer networks. Moreover, in the case of H-sensors it is beneficial to insert multi-stage low-pass filters in front of the detector in order to suppress loop resonances, as well as the hypersensitivity to electric fields at the higher frequencies. As an example, fig. 2 shows the frequency response shaping of the H-sensor integrated in the ESM-20 radiation monitor.

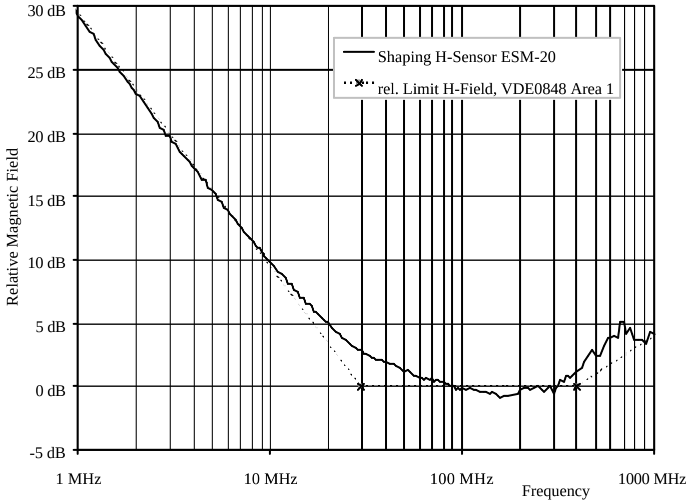

Fig. 2: Frequency response shaping of H-sensor in ESM-20 radiation monitor (DIN VDE 0848, Area 1)

3 The influence of the human body

Extensive studies have been carried out to determine the to what extent the presence of a human body influences the individual electric and magnetic field components. The numerical computations were done using the FEKO program utilizing the surface-current method. FEKO is based on an extended method of moments and was developed at the Institute für Hochfrequenztechnik at the University of Stuttgart. [4]

Various scenarios were examined using a dielectric model of an upright human body (170 cm tall) and the results compared with a simplified model with a conductive surface. This enabled the memory and CPU-time requirements to remain within a tolerable limit, while producing more or less the same results. The metallic model slightly overestimates the influence of the human body is slightly overestimated. This represents the worst case, though the principle information is still retained.

Five different incident directions of a planar wave in the front hemisphere of the body model were analyzed in the frequency range from 100 kHz to 3 GHz. . For each direction both horizontal and vertical polarization was examined, i.e. a total of 10 different situations were covered. The field components were evaluated close to the chest at 3 cm in front of the body surface, since this is the preferred position, where radiation monitors are usually carried. The most important results of this work are summarized below [3]. The various graphs show the normalized field strength curves close to the body. All values are normalized to the resultant field strength, that would be present without the body model. The 0 dB line means "no influence of the body". Positive and negative values imply that the field is either increased or attenuated by the body. All three spatial components of the electric and magnetic fields were evaluated in each case and a combination presented on a graph. The E and H components without an index represent the effective electric and magnetic field strength. In other words, these curves show the response of an ideal isotropic E- or H-field sensor carried on the body. The normal component E_n corresponds to the part of the electric field which is perpendicular to the bodies surface. H_t represents a combination of the two tangential components of the magnetic field on the body. In accordance with the boundary conditions the field components E_n and H_t do not disappear on the surface of the model.

Fig. 3 illustrates the exposition from the front with vertical polarization. There is clear evidence of the body resonance around 70 MHz. It is striking to note that this resonance occurs in both the electric field and the magnetic field. This increase in the electromagnetic field is unavoidable when a radiation monitor is carried. As a result the measured field strength is considerably overestimated. Further measurements revealed, however, that in practice the increase due to body resonance is always less than 10 dB.

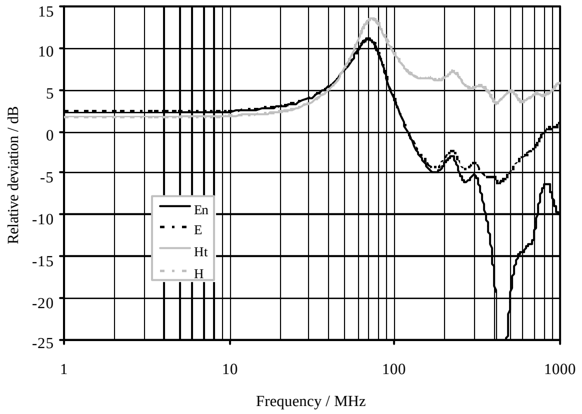

Fig. 3: Influence of the body when exposed from the front with vertical polarization

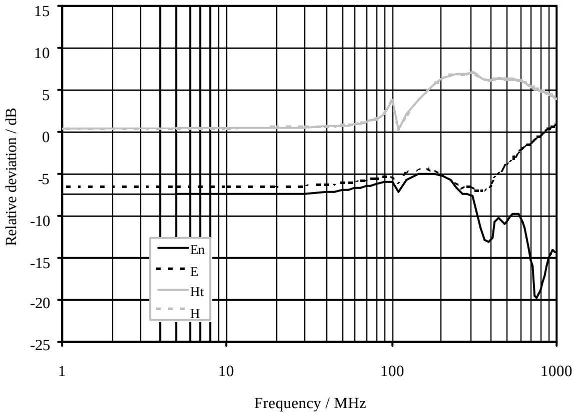

Fig. 4: Influence of the body when exposed from the front with horizontal polarization

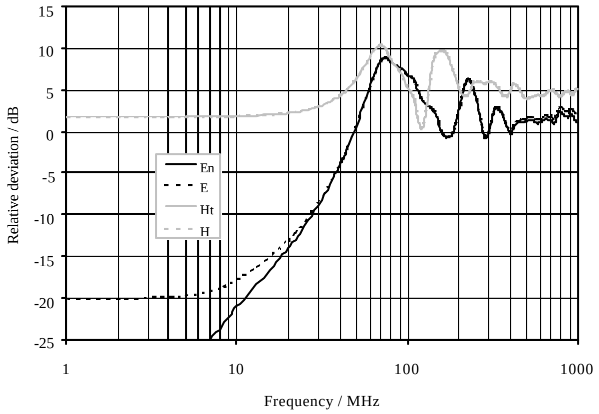

Fig. 5: Influence of the body when exposed diagonally from above with vertical polarization

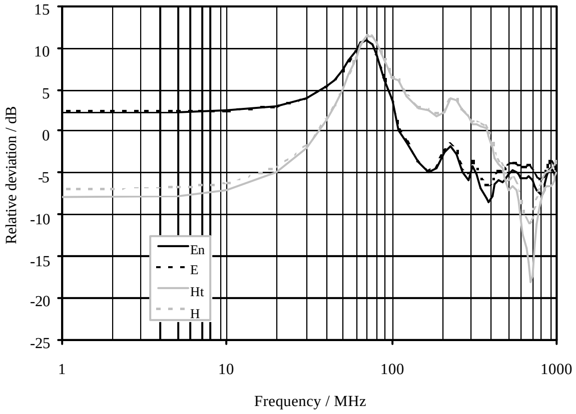

Fig. 6: Influence of the body when exposed from the side with vertical polarization

From the point of view of personal safety, the scenario with incidence of a horizontally polarized wave from the front is far more critical (see fig. 4). Measuring the electric field alone for such a exposition results in a significant underestimation by approximately 6.5 dB over a wide frequency range.

The third example shows an even more extreme case of underestimating the electric field, with exposition from the front spatial diagonal (i.e. incident angle 45 degrees to the top) with vertical polarization (see fig. 5). Other scenarios, such as a vertically polarized wave incident laterally from the side of the body model, also results in a significant underestimation of the magnetic field in various frequency ranges (see fig. 6).

If these results are summarized, the conclusion to be drawn is that it is not sufficient to measure only the electric field or only the magnetic field on the body when monitoring the maximum exposure level of electromagnetic radiation. The electric field is in some cases completely suppressed if only the normal component E_n is measured, and the tangential magnetic field components H_t may also be suppressed by up to 17 dB. Even if isotropic sensors are used close to the body, underestimation of the electric field strength by more than 20 dB and of the magnetic field strength by more than 10 dB must still be considered. It is however unlikely that both the electric field and the magnetic field will be suppressed at the same time. If, therefore, the resulting electric and magnetic fields on the body are measured simultaneously and the maximum value determined for each, the risk of underestimation can in all probability be avoided in the event of exposition from the front hemisphere.

Overestimation cannot be entirely prevented, however, if field strength measurements are used to monitor exposure in the immediate vicinity of the human body.

Fig. 7 summarizes the ten different scenarios: The top curve (max.) is the maximum reading of an ideal personal safety monitor, that works according to this principle above, for all ten exposure situations. The broken line (min.) shows the minimum reading of an ideal monitor for seven out of the ten situations, while the remaining three curves represent the minimum readings for the other three situations. The results were confirmed by practical measurements under near-field conditions, whereby other incident directions were examined additionally. These experiments did not reveal any shadowing in the frequency range up to 300 MHz, even with exposition from the rear hemisphere. The theoretical extreme cases of over- and underestimation did not occur in practice. Only if a pure electric field exists below 30 MHz, this may be underestimated when the ideal personal safety monitor is carried on the body.

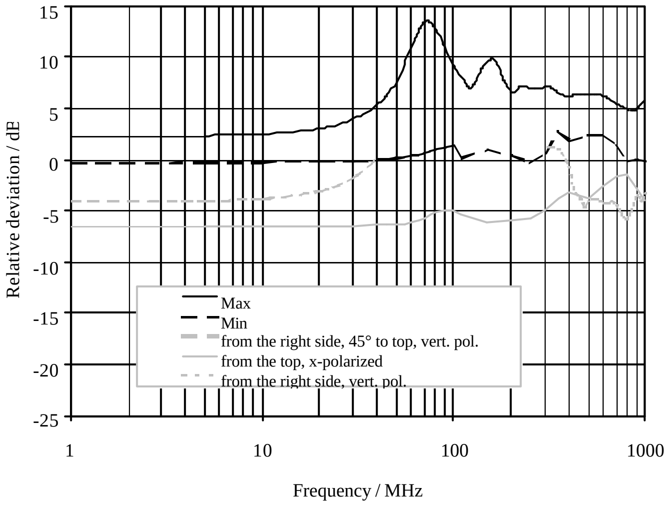

Fig. 7: Influence of the body in ten different exposure situations (summary)

Above 1 GHz, it is only necessary to measure the electric field. The influence of the standing waves that form in front of a person when the monitor is carried close to the body can be diminished by positioning an absorber between the electric field sensor and the reflective body surface. The shadowing effect of the human body at high frequencies can be avoided - if it is of any concern at all - by using two monitors.

The overall influence of the body can be significantly moderated if the radiation monitor is held with the hand stretched out. Furthermore, a dielectric extension rod is recommended to obtain a closer approximation of the result when no persons are present.

4 Measurements of moderately modulated signals

The waveform of the field source may lead to further measurement problems, because a diode detector leaves the square-law region when driven at higher signal levels and no longer operates as a true r.m.s. rectifier. This issue has been featured prominently in several earlier publications. A novel sensor design keeps the signal level at the diode low in the relevant dynamic range. In this way the influence of non ideal r.m.s. detection will be minimal with moderately modulated signals, such as those that occur in radio broadcast and communication systems.

Wandel & Goltermann defines the effective dynamic range for true r.m.s. measurements as follows: the waveform dependent deviation of the display value from the true r.m.s. value should remain less than 0.5 dB for a 2-tone signal and less than 1 dB for an 8-tone signal. The term '*h*-tone signal" indicates *n* sine carrier frequencies, spaced in *Df* = 10 MHz, each of representing the same exposure level.

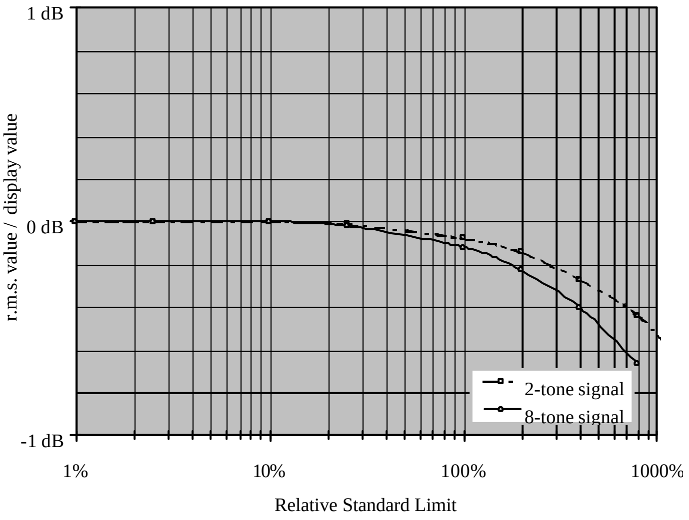

Fig. 8: r.m.s. deviation with n-tone signals (Df = 10 MHz) for shaped E-field probe (type 25)

The 8-tone signal shown here is an extreme example. A smaller number of carriers or moderately modulated signals (e.g. AM) will produce smaller r.m.s. deviations. Fig. 8 shows the measured result as a true r.m.s. deviation for a shaped E-field probe. On the whole a slight overestimation occurs below the limit values (100%). The true r.m.s. range defined above covers up to 600% of the standard in this case.

The ESM-20 monitor has an integrated E-sensor with an identical design. Measurement evaluation applies here only up to the limit value for exposure area 1 in accordance with VDE 0848 (100 % vertical line in fig. 8). As a result, the r.m.s. deviation is negligible in practice (< 0.15 dB) and the standard-compliant estimation of the r.m.s. value is almost ideal for communication signals.

5 Characteristics with radar signals

While the innovative design of the E-sensors ensures that the true r.m.s. value is detected sufficiently accurately for moderately modulated signals, a relevant r.m.s. deviation is likely for pulsed radar signals with their signigicantly higher crest factors. Extensive measurements with numerous radar signal parameters were carried out to qualify the various sensors. The net of parameters, consisting of the pulse width, the pulse repetition frequency and the duty cycle, was chosen to cover all practically relevant radar applications.

Fig. 9 to 11 illlustrate the r.m.s. characteristics of the ESM-20 radiation monitor for three different duty cycles and pulse repetition frequencies. Only if a pulse repetition frequency of 316 Hz occurs in combination with a duty cycle of 1:316 a slight underestimation is likely. This signal is underestimated at the limit value by a mere 3 dB.

The behavior of the shaped E-probes for the EMR system is similar. Results in detail are published in detail in an application note.

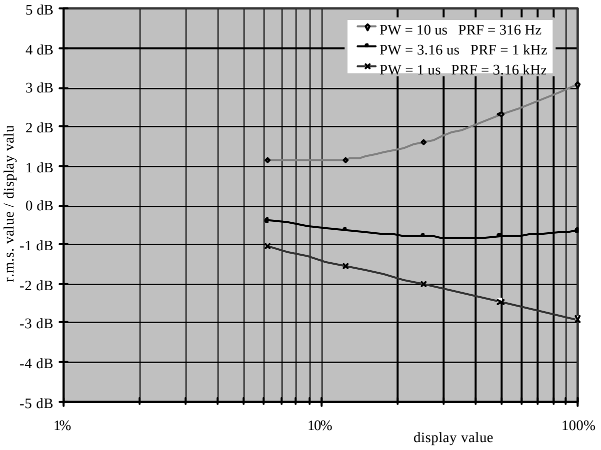

Fig. 9: r.m.s. deviation with a duty cycle of 1:316 for the EMS-20 radiation monitor (DIN VDE 0848, Area 1)

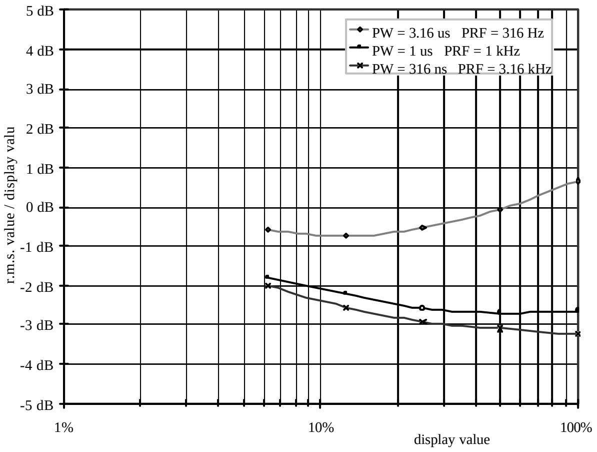

Fig. 10: r.m.s. deviation with a duty cycle of 1:1000 for the EMS-20 radiation monitor (DIN VDE 0848, Area 1)

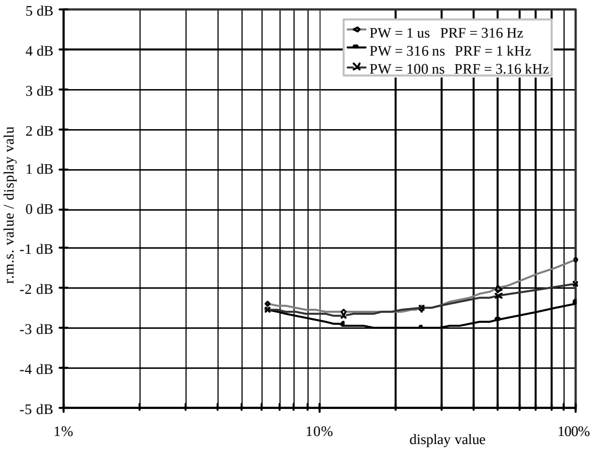

Fig. 11: r.m.s. deviation with a duty cycle of 1:3162 for the EMS-20 radiation monitor (DIN VDE 0848, Area 1)

6 Standards-compliant measurements on radars

Knowledge about r.m.s. characteristics is directly useful for the evaluation of MPE in many radar applications. Controlling standing radars or searching for radiation leakage in the waveguide based high-power RF or microwave systems are typical applications.

For pulsed signals with duty cycles up to 1:1000 the r.m.s. limit value is relevant in all RF protection guide standards. ICNIRP [7] and DIN VDE 0848 Part 2 [9] set additional peak limit values for pulsed signals. In addition to the r.m.s. value averaged over six minutes, the peak power density is not allowed to exceed 1000 times the power density limit value. In other words, the peak value of the field strength divided by 32 is not allowed to exceed the derived field strength limit. These peak limits become relevant if the duty cycle is less than 1:1000. This means for a duty cycle of 1:3162 that the set of curves in fig. 11 must be shifted upwards by 5 dB, in order to refer the display deviation to the permissible limit value, i.e. signals with a duty cycle of 1:3162 are slightly underestimated. The underestimation of the analyzed signals does not exceed 3.8 dB at the limit value.

When measurements are carried out on scanning radars, the illumination from the pulsed signals is only present for a fraction of the time. According to the standards, the peak value is also relevant here if the duty cycle is greater than 1:1000. In order to evaluate the exposure, the set of curves for a duty cycle of 1:316 (see fig. 9) must be shifted downwards by 5 dB. In other words, these signals may be overestimated by up to 8 dB. For a duty cycle of 1:1000 fig. 10 is still valid, while for a duty cycle of 1:3162 the curves shown in fig. 11 must again be shifted upwards by 5 dB.

In practice, moreover, the illumination time (time on target) of the signal has to be considered. If the time on target is significantly longer than the integration time of the measuring device, no additional deviation occurs. If, on the other hand, the time on target is much shorter than the system integration time, this will lead to a further underestimation, caused by the inertia of the measuring device. In this case, an additional display correction factor for the power density can be derived from the ratio of equivalent integration time to equivalent time on target. The time on target of a typical radar signal (rotation time 5 s, angle of radiation 1.8°) is 25 ms, which in conjunction with the equivalent integration time of the ESM-20 monitor (30 ms) yields a correction value of 1.9 dB.

The exposure at all operating radars that are relevant in practice can be estimated with the ESM-20 radiation monitor correctly within the range -3.8 dB to +8 dB, even if the measurement deviation is not compensated. The measurement deviation can also be corrected if the signal parameters are known or approximated. Radars can thus now be measured more precisely, particularly when employing the shaped E-field probe.

Conclusion

This paper has demonstrated how standards-compliant tests of non-ionizing electromagnetic radiation can be carried out both simply and reliably with improved measurement technique.

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