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Calibration of Vertical Monopole Antennas (9kHz - 30MHz)

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1. Introduction

Vertical Monopole Antennas are used for the measurement of the electric component of EM fields, especially in the frequency range 9 kHz - 30 MHz. In spite of the fact that field-strength measurements in this range are by far more accurate by using loop antennas for the magnetic field component (less influence of near-by objects and ground influence), this method is only recommended for the far-field zone where the ratio of the electric field-strength (V/m) to the magnetic component (A/m) is $120\pi\Omega = 377\ \Omega$, the "characteristic impedance of free space".

As practically all measurements in the EMC field are in the *near-field zone,* the results of a loop measuring system may only be expressed as *"fictitious" E field-strength".* The actual result, however, is the magnetic field-strength, expressed in units of V/m under the assumption of far-field free-space situation.

In the near-field, the electric field-strength depends on the size of the monopole used. There is general agreement to use 1 metre rods. Calculations will be shown in the next sections.

For decades, disputes about the correct method of calibration existed. The standard way of calibration for E-field antennas is the use of strip-line or TEM cells. According to generally accepted rules, the cell height should be five times the monopole height. For a fully screened Crawford cell, the total height should be 10 m for 1 m monopole length. This is rarely available in test laboratories. For this reason a dummy antenna calibration was generally used, but due to differences in the data of impedance converters, amplifiers and rod capacity and concept errors, the spread of results often exceeded 6 dB.

2. Calibration Methods

A committee draft has been developed for CISPR 16-1 with the title *Use of monopole (rod) antennas* in a document CISPR / A / 270 / CD and a revised version CISPR / A / 296 / CDV which is still under consideration. It provides calculations for the electrical length and capacity of the 1m rod, and the measurement of the voltage ratios with a dummy antenna, using network analyzers or EMI receivers.

For a first rough check, the rod capacity can be calculated or measured. With an 8 mm ϕ rod and 1 m length, the capacity is 10 pF and the *effective length* is 0.5 m. This is 50% of an effective electrical length of 1 m and accounts for - 6 dB. If the amplifier FET input capacity is also 10 pF, the unloaded voltage of the rod is reduced to 50 % by capacitive voltage division. This results in twice - 6 dB = - 12 dB. To obtain the antenna factor of 0 dB (1:1) which facilitates practical work, the amplifier gain should be 12 dB. In this case the voltage level shown by the receiver in dBµV is the electric field-strength in dBµV/m. If the input capacity of the amplifier is lower, the antenna factor becomes negative and the amount must be subtracted from the level display. Under real conditions, the capacity ratio contains uncertainties, especially if the rod uses a solid construction for connecting to the FET input. *This is one of the reasons why vertical monopole antennas should be checked or adjusted by a practical calibration in a well-defined plain EM field as shown in chapter 4.*

3. CISPR Calibration with calculated rod data

The calculation for the effective height of the vertical monopole h_e uses the physical length of the rod h and the wavelength λ **.** In the practical application of monopole antennas for the hf range with 1 m rods the wavelength of the 1st and 2nd term cancel each other and the final result is very close to **$h_e = 0.5\ h$** (formula 1).
At 30 MHz (λ = 10 m) the rod is far from the quarter-wave resonance ($\lambda / 4$).

$$h_e = \frac{\lambda}{2\pi} \tan\frac{\pi h}{\lambda}$$

$$C_a = \frac{55.6h}{\ln(\frac{2h}{a}) - 1} \frac{\tan\frac{2\pi h}{\lambda}}{\frac{2\pi h}{\lambda}}$$

$$C_h = 20 \lg h_e$$

The capacitance of the rod is one of the significant values for the antenna factor**.** It is calculated using formula (2) which requires the actual length of the rod **h** (m) and the radius **a**, also expressed in metres. The terms containing the wavelength are nearly identical for the 1 m monopole and cancel each other. An alternative formula (2.1) does not consider the wavelength, only the actual height of the monopole **h** and the diameter **D** are required in the same units:

$C_a = 0.24\ h /\ \log (h/D)$ [cm], [pF]

Both formulas result in the same self-capacitance. In case of a 1m rod with 8 mm Φ the capacitance is 10 pF ± 1 pF. The correction factor for the **effective height h_e** is expressed as a dB-value for the antenna factor AF calculation. **$C_h = 20 \log h$** which in practical applications results in a correction of **- 6 dB(m).** (formula 3)

The effective electric monopole height **h_e** has been calculated with equ. (1) and the self-capacitance of the rod with equ. (2). If all measurements refer to voltage levels in dB(µV), the height correction is expressed in dB, using equ.(3)**.** The vertical rod is for further measurements replaced by a ***dummy antenna,*** a capacitor with the same capacitance as the rod, in most cases near 10 pF. This capacitor is regarded as a part of the FET amplifier. The voltage ratio at the "input" of this dummy antenna and the output of the FET amplifier is required for the final calibration. It may be measured with a ***network analyzer, EMI receiver calibrated in dB(µV) or with an r.-f- voltmeter.***

Fig. 1 shows the CISPR set-up with a traditional network analyzer, providing a generator signal output, a reference input and a test channel input. Modern network analyzers often use built-in impedance testing sections, but may still be used for voltage ratio measurement after a normalisation. The set-up can be arranged as shown in ***Fig.2*** where a network analyzer or a signal generator and EMI test receiver are used.

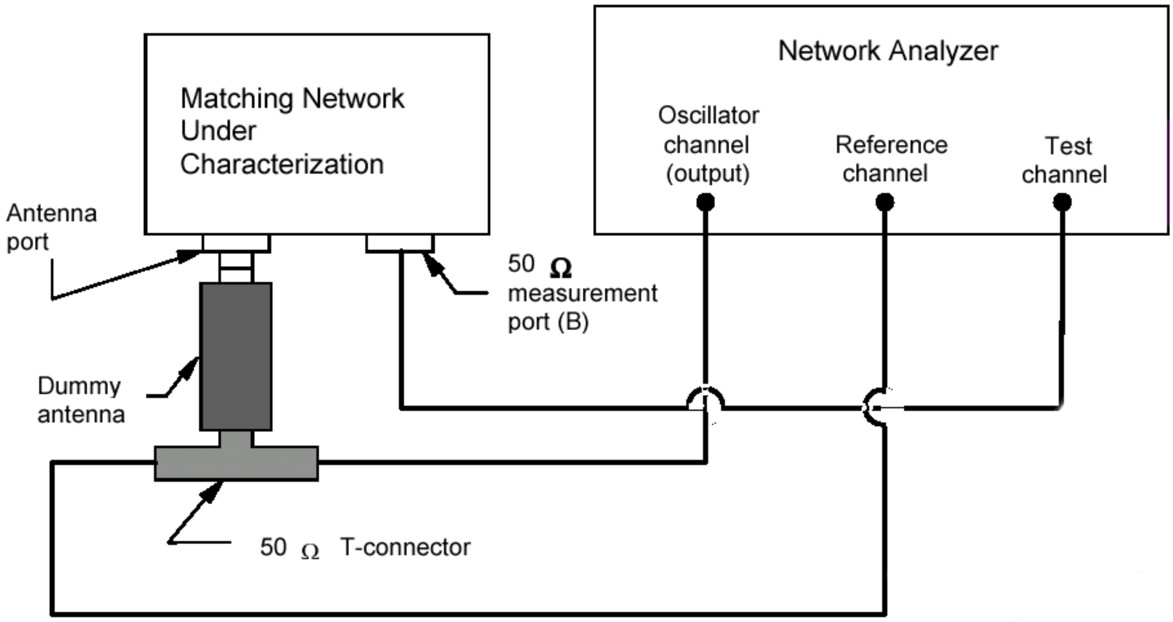

Fig. 1: Test Setup using a Network Analyzer

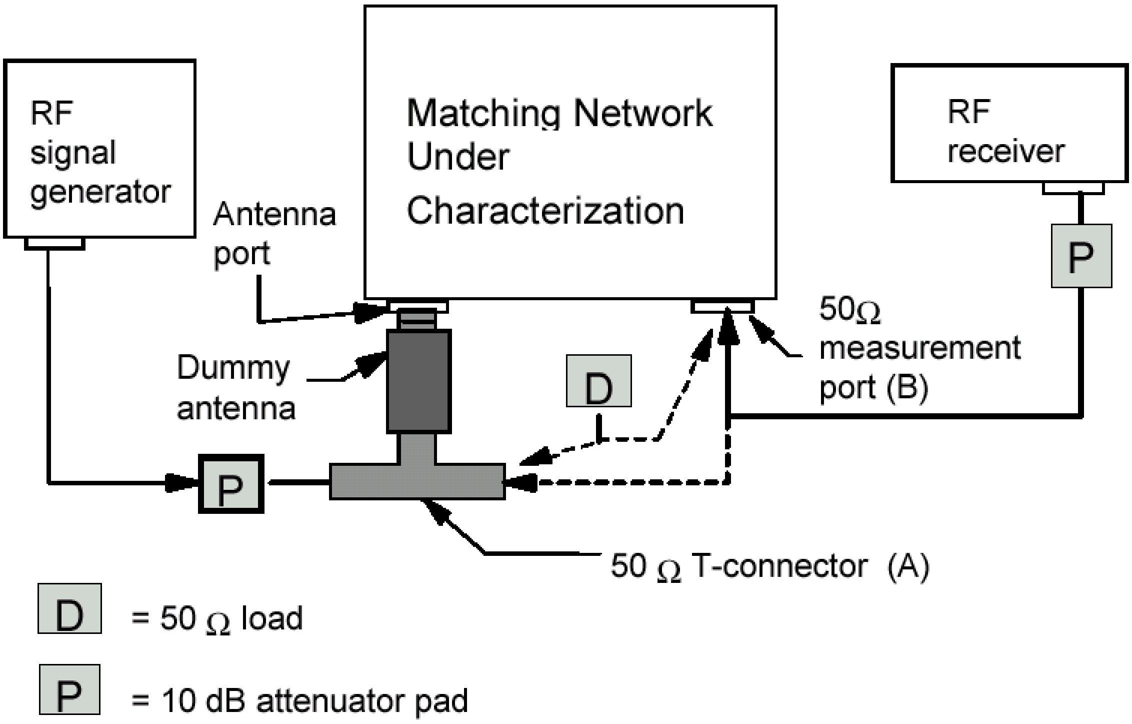

Fig. 2: Test Setup using a RF-Signal Generator and a Receiver

The calculation of the (log) antenna factor according to the CISPR method requires the measurement of the output of the signal generator, expressed as the level in dB(µV) across 50 Ω **(V_D)** that is fed into the Dummy Antenna**.** The output of the FET amplifier, also expressed as a level in dB(µV) across 50 Ω of the receiver or network analyzer input **(V_L)** is the second term of the antenna factor equation. The 3rd term **(C_h)** introduces the reduced effective height of the monopole compared to the actual height (length) of the rod.

$$AF = V_D - \mathbf{V_L} - \mathbf{C_h} \quad [\mathrm{dB}(1/\mathrm{m})]$$

This log. **Antenna Factor** is added to the dBµV reading of the EMI test receiver to find the electric field-strength level in dB(µV)/m. As the height correction factor of any monopole rod shorter than 2 m, expressed in dB(m), is always negative (- 6 dB for 50% effective height in case of the common 1 m rod), the magnitude $|C_h|$ actually ***adds*** to the antenna factor. A higher AF represents a less sensitive active antenna.

Another method to find the antenna factor is the measurement of the capaci-tances of the monopole rod and the FET amplifier input and to calculate the capacitive voltage division ratio. It leads to similar results compared to eq.(4). These capacitances are in the low pico-farad range. As with the dummy antenna capacitor of the CISPR method, these components are sensitive to the position regarding the housing and con-ductor length. Calibration uncertainties are expected to be 2dB to 3 dB.

In manuals of active vertical monopole antennas, different antenna factors may be found, ranging from 1 dB(1/m) to 4 dB(1/m). For this reason, comparisons of the mostly calculated antenna factors to actual measurement results in homogeneous EM fields have been established. As mentioned before, it seems quite difficult to provide a constant field-strength in a large volume.

In the course of CISPR agreement, the British national committee asked to include a note of caution in the text "to alert the reader of potential problems when applying the ***equivalent capacitance substitution method".***

The substitution of a capacitor is satisfactory up to about 15 MHz, depending on the actual model of rod antenna. However at 30 MHz the error can amount to several dB. Some rod antennas are used as high as 100 MHz when the method becomes unacceptable. The British *National Physical Laboratory NPL* uses a large ground plane (20 m x 20 m) and the source antenna placed about 20 m away. The customer´s rod antenna is substituted by a calculable rod antenna with bases in electrical contact with the ground plane.

In the following chapter (4) a practical calibration method is described, using H field and E field calibrated antennas to check the quality of an EM field from AM broadcast radio stations in the vlf and hf range with vertical polarisation. When used with several medium- and long-wave stations with identical results, a dependable direct calibration is possible. A moving-coil meter could well be calculated if the magnetic data and the spring constants are known, but in all cases the direct calibration by comparison with a standard meter would be preferred.

4. Practical Monopole calibration at an open-area test range

The generation of a homogeneous EM field of sufficient size is a severe problem. Small antennas can be calibrated with good accuracy in *TEM cells* for E field and in *Helmholtz-Coil* sets for H fields. Especially H field calibration can be very accurate and dependable as enviromental influences can be kept low. An alternative check-test is possible with a defined coil at a calculated separation.

Two circular coils with 1+1 turns in series of a radius and separation R [m] generate a magnetic field-strength of H [A/m] with a current of **I** [A]

$$\mathbf{H = 0.7155\ I\ n / R} \quad [A/m]$$

For higher levels of H field at lower frequencies, the coils may have more than 1 turn each (**n** turns for each coil). With fixed R for radius and separation, any magnetic calibration field-strength may be generated in the centre of the two coils by adjusting the current **I .** A magnetic field probe of about half the diameter can be accurately calibrated with these Helmholtz Coils. An absolute check of H field can be performed with a test coil of **n** turns and the area **F** [qm] at a frequeny **f** [kHz] by measuring the open-loop (unloaded) voltage **U** [mV]**.** This measurement must be made far off the parallel resonance of the coil and the input capacitance of the high-/Z/ r.f. voltmeter.

A cross-check of H field calibration is possible with a circular test coil (1 turn), a radius **R ,** a current **I** and an axial distance **x** which should be **>** 2x the sum of the coil diameters of the test coil and the H field loop.

The H field test loop for the practical measurement provides a frequency-independent constant magnetic antenna factor if the short-circuit current is measured, either by using a current-sensing toroid core transformer or with an emitter-input amplifier with feedback and near-zero input resistance. The loop calibration is primarily in magnetic units (A/m, dBµA/m) or in the classical way in "fictitious E field-strength" (V/m, dBµV/m) for far-field measurement. If the true magnetic units are used, **51.5dB** must be added to get the far-field electric (fictitious) E field-strength (20 log 377).

With this calibrated loop antenna, magetic field-strengths can be measured with an uncertainty of less than ± 1 dB.

Active Dipole E-field antennas can be calibrated in TEM cells with a measurement uncertainty of < ± 1.5 dB if all rules of DIN VDE 0847 part 26 / IEC 1000-4-26 are followed. For the convenient sizes of TEM cells, relatively small Active Dipoles can be calibrated and used as transfer standards for larger antennas. An often ignored problem with small active antennas is the influence of unwanted common-mode E-field components that are not present in the TEM cell, but do exist in an open area test site. High symmetry models with built-in rechargeable batteries (to avoid feed line currents) and isolating broad-band transformers are used for precise E field measurements.

To compare the calculated antenna factors with the behaviour of a vertical monopole antenna on a groundplane, a large volume of constant field-strength is required. This can be found at a distance of 20 km to 30 km from broadcast and data transmission radio stations if an unobstructed path exists (line of sight) to a flat hilltop without trees or buildings. The qualification can be checked with calibrated H field and E field antennas. As the surface will be normal soil, the E-field component will suffer from damping at an operation height of less than 1m. All measurements or comparisons should be made at this or similar height (1m ... 3 m). The requirements for a suitable area for calibrations of monopole antennas are:

A) The place is suitable for the comparisons if the field-strength is nearly constant (±2 dB) over the volume of operation.

B) The magnetic field-strength, expressed as far-field fictitious E field-strength, should be identical (± 1.5 dB) with the true electric field-strength. [51.5 dB difference between H field in dB(µA/m) and E field in db(µV/m)]. This confirms that the EM-wave does not suffer from local reflections and is within the theoretical relations.

C) These conditions should remain nearly constant when changing the location 1 m up / down and 2 m in the horizontal plane.

D) The H field measuring result is considered as the true field-strength at this location and is used to adjust the amplification of the vertical monopole FET amplifier. These comparisons should be repeated at different locations both with the H field loop (the loop plane for maximum reading directed to the radio station) and with the E field active antenna in vertical position (all radio stations below 2 MHz use vertical polarisation) and finally with the vertical monopole antenna with the 0.6 m x 0.6m "vestigial" ground-plane.

All radio stations fulfilling requirement (A) on different frequencies from long-wave (150 kHz) to 1.6 MHz medium wave should be used. The typical monopole amplifiers show a flat constant amplification in this range. Shortwave signals are not qualified because of horizontal polarisation at the transmitter site and polariation changes by ionospheric influence, not to mention the fading. The results of the hf range calibrations may be extended to at least 15 MHz with the dummy antenna (10 pF capacitor) and a level-controlled generator. Field generation with a transmit antenna (loaded vertical dipole) at 20 m distance and measuring the E field strength with the small transfer standard, calibrated in the TEM Cell, will provide results up to 30 MHz with an estimated ± 3 dB uncertainty when comparing to the vertical monopole with the 600mm x 600mm groundplane.

Practical results, depending on monopole height from ground

These comparisons and calibrations have been repeated at several locations that fulfill requirement (A). The AM radio stations provide a constant fieldstrength during daytime. The EMI receiver was used with the ***average detector*** which indicates the carrier level, not responding to the modulation, in case of standard AM**.** Most broadcast stations use additional carrier-control. In this case the readings must be made in voice pauses. Comparisons of the calibrated to the calculated antenna factors have shown an important fact: Vertical active monopole antennas - in contrast to vertical active **Dipoles** - show a "height-gain". As information in literature concerning this phenomenon is scarce, an explanation may be found in **fig.3** where active monopoles are shown.

A monopole is sometimes supplemented by a second identical monopole to complete a *dipole.* The symmetry plane between them represents the "zero-potential ground plane". If the two monopoles are separated, a larger volume of the field is included and the output voltage rises with the separation (the dipole length is increased). This happens with an active monopole when mounted on a conductive mast or an insulated mast if the feed and signal coaxial cable is routed down to the receiver. Such an elevated active monopole has restrictions in bandwidth, so calibrations must be limited to vlf and long-/medium waves up to 2 MHz.

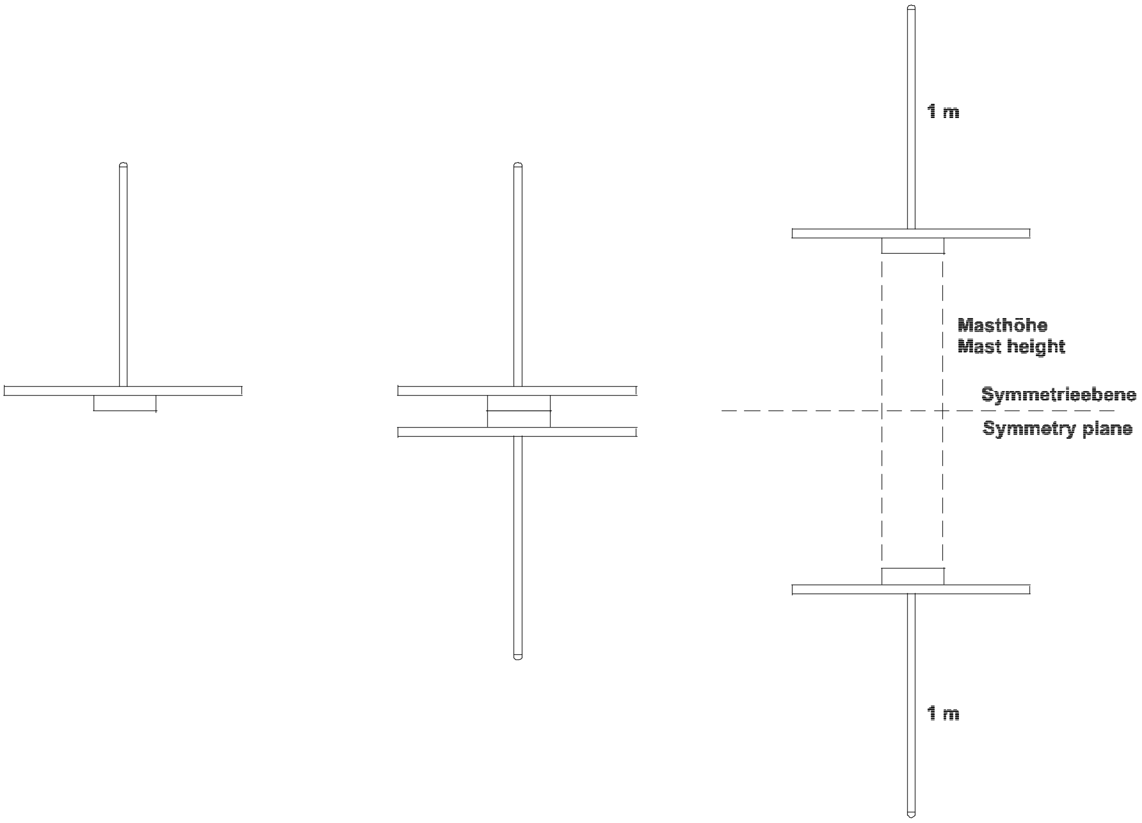

Fig. 3: Rod antenna and elevated rod antenna with symmetry plane

For normal E field-strength measurement, an elevation to a table height or a low tripod is a standard, as a monopole height of zero is impracticable because of the environment and the influence of ground conductivity. The antenna factors found with the MIL-CISPR method are valid for the rare case of a very large metal groundplane with the zero-level monopole with no surrounding obstacles. **In the case of SAE / CISPR 25**

measurements where in a screened room the 0.6m x 0.6m "vestigial ground-plane" is directly connected to the metal table, the calculated antenna factor according to the MIL-CISPR method is correct. For outdoor E field measurement of EMC sources, PLC (power-line communication) or ground-waves of radio stations, the calibration method of comparison to active dipole antennas and magnetic loop antennas provides the best accuracy. With these applications, a height-dependent reduction of the antenna factor as shown in fig. 5 applies.

Fig.4 shows the elevated active monopole and a loop antenna and an active dipole or bicone antenna in a zone of constant field-strength deriving from radio stations at a distance of 20 km to 30 km under "line-of-sight" conditions on a flat-top hill. In this case the field strength will be nearly constant, independent of height over ground. Similar conditions can be provided in a strip-line cell of 3 m to 5 m height over a metal ground plane. While the output of the symmetrical antennas will be almost independent of height, the vertical active monopole antenna with the "height-gain" will provide output voltages depending on the height over ground.

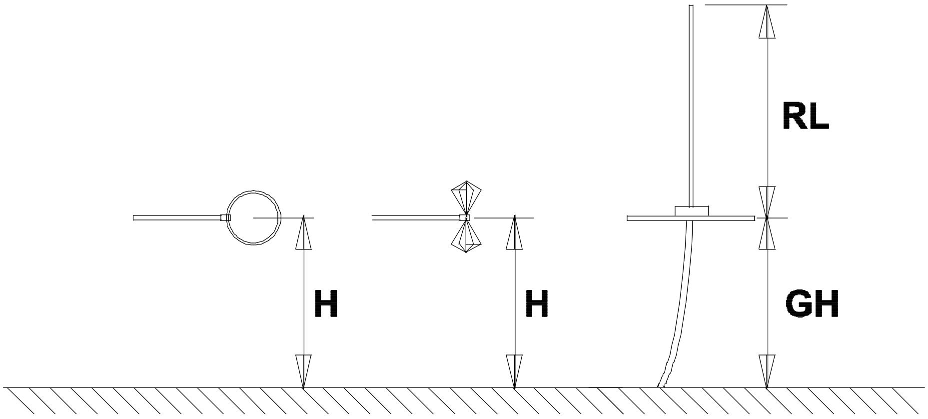

Fig. 4: Calibration setup consisting of an active biconical, a loop antenna and an elevated monopole antenna

Fig. 5 indicates the reduction of the antenna factor due to the height gain. In the normal case of **1.2** m elevation from ground, the output rises by 6 dB. If an active vertical monopole is adjusted to 0 dB antenna factor at this height, it will be **+6 dB at zero height as used in SAE / CISPR 25.**

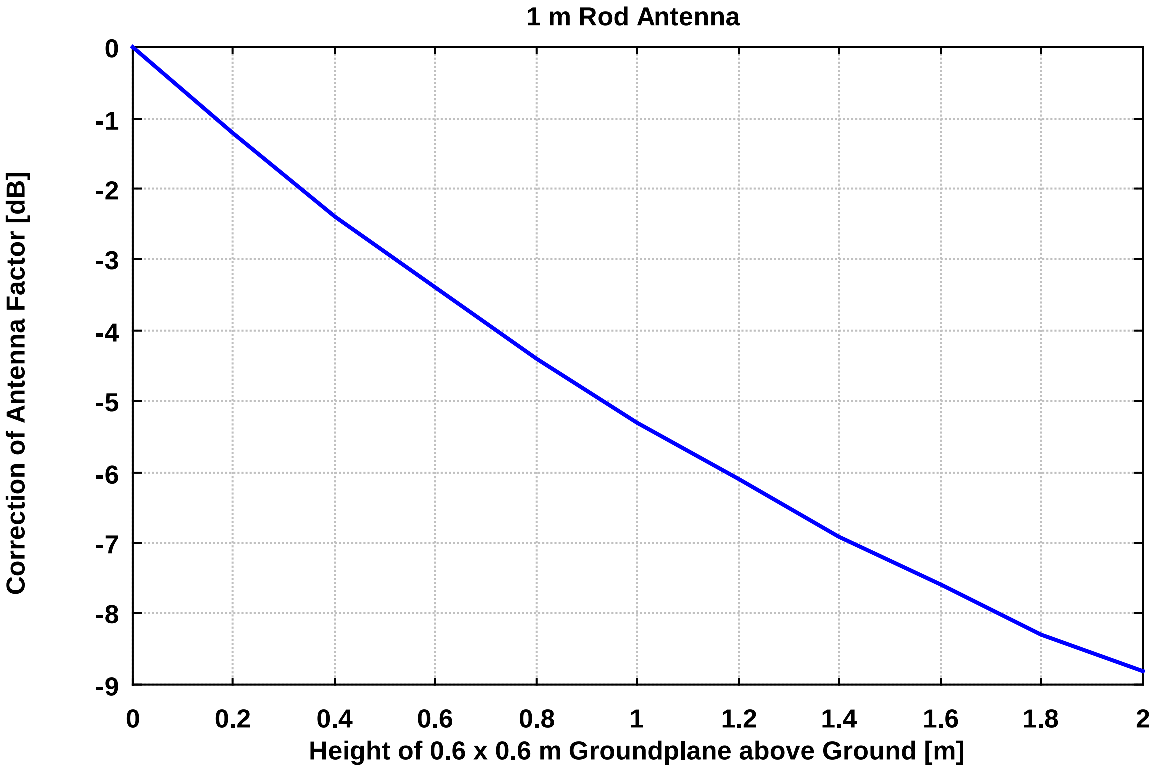

Fig. 5: Height dependent antenna factor correction of elevated monopole antennas

If another model of an active vertical monopole is adjusted for an antenna factor of +10 dB/m at zero-height (*calculated* as shown above), it will change to 10 dB - 6 dB =4 dB/m at **1.2** m height of the "vestigial groundplane" when used for outdoor E field-measurements.

If such an antenna is operated with a dc source fastened to the base and if an optical link is used to the receiver, the height-gain will disappear and it will act like a symmetrical vertical dipole with a height-independent antenna factor. Ferrite common-mode absorbers will not replace the non-metallic high-impedance optical link.