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Issues Concerning Radio Noise Floor Measurements using a Portable Measurement Set-up

Koos (T. W. H.) Fockens
University of Twente, Enschede 7522NB, The Netherlands,
EMC/EMF committee VERON, Arnhem 6801 BD, The Netherlands.
t.fockens@utwente.nl

Frank Leferink
University of Twente, Enschede 7522NB, The Netherlands,
Thales Netherlands, Hengelo 7554 RR, The Netherlands.
frank.leferink@utwente.nl

Abstract—An investigation is made into the selection of measurement antennas for man-made noise measurements. Although an ITU-R recommendation about noise measurements exists, the nature and goals of specific measurements campaigns prescribe additional requirements in the selection of antennas. Seen from points of sensitivity and calibration accuracy electric field rod antennas appeared to be suitable only for use on fixed locations in combination with a low impedance grounding. For portable measurement set-ups tuned magnetic field loop antennas are more applicable, but sensitivity and directivity of loop antennas require suitable measures.

Keywords—Natural and Man-made Radio Noise, EMC, EMI.

I. INTRODUCTION

From the early 30s of the twentieths century on radio background noise was investigated. In the 50s, 60s, and 70s systematic measurements were performed of radio noise from natural and from man-made origin. From those measurements worldwide noise level values were published, for example in Recommendation ITU-R P.372-13 [1]. Man-made noise (MMN) is of particular interest because its intensity and level are depending on human activity, what is variable in time. Furthermore, the MMN should be the basis of electromagnetic interference (EMI) requirements, such as is the case in the German VG standards. In early studies on MMN the focus was on Very High Frequency (VHF) and Ultra High Frequency (UHF) frequencies mainly. Up to the late 70s the most important sources of man-made radio noise were automotive, power transport and power generating facilities. Other sources were industrial equipment, consumer electrical appliances and lighting systems [2-12].

Current research on MMN is mainly directed towards radio noise inside industrial premises, the interference to short range devices [13], [14], and measurement methods [15]. The importance of MMN at frequencies below 30 MHz, generated by electronic equipment with an increasing number of switching devices, is addressed in reference [16]. This importance is not only set by the level of unintended radiation per device, but also by the increasing number of devices.

During the standardization processes of the EMC of networks, starting in 2000 in CEPT, later on continued in ETSI, CENELEC, and CISPR, the question of the existing levels of radio noise floor for frequencies lower than 30 MHz arose again. So did the question "How to measure radio noise", and under leadership of the Radio Agency of The Netherlands an expert group was formed to write a recommendation for measuring radio noise [17], [18]. The outcome of this work was submitted in ITU-R, what resulted in two ITU-R reports [19], [20], and finally in Recommendation ITU-R SM.1753-2, [21]. Although the recommendation gives a comprehensive overview of requirements for noise measurements in general, some more detailed aspects are depending on precise purpose and kind of the measurements. Other recent papers describe the study of indoor MMN in relation to digital broadcasting in the Medium Wave Band [22], [23], [24]. However, the measurement methods, as mentioned in these papers, use Electric(E)-field antennas without sufficient counterpoise and/ or grounding, resulting in large measurement uncertainties. This subject will be discussed in this paper in section III. The results fo this research activity has been applied in a MMN measurement campaign from which the results are published in [25]. The paper is organized as follows. First the requirements for man-made noise measurement are described in section II. Section III focus in on the choice of measurement antennas.

II. REQUIREMENTS FOR NOISE FLOOR MEASUREMENTS

This paper deals with outdoor measurements of the noise floor in habituated areas, where a statistical relation is sought between the level of the noise floor and density of habitations. The main sources of noise in these environments are Man-made, although under certain conditions natural sources may contribute too. So, the target is measuring MMN that may hamper or disturb residential radio reception in a wide variation of environments, from quiet rural to city areas. The frequency range is 0.5 to 50 MHz. The sensitivity has to be sufficient high to measure the lowest noise level that can be expected under the relevant measurement circumstances. Measurements had to be done at a large number of locations, divided over all kinds of environment, for a reliable statistical assessment. As a conseqence the measurement set-up has to be designed for portable use. This differs from reference [21], wherein the measurement locations were assumed to be fixed. The difference has consequences for the selection of antennas.

A. Determination of sensitivity requirements

To get a good understanding of the relationship between the density of habitation and the level of MMN it is necessary to measure in all kinds of environments, from Quiet Rural, where only natural kinds of noise are received, to the City environment, where high levels of MMN and Radio Frequency Interference (RFI) can be expected. Recommendation ITU-R P.372-13 [1] delivers data about relevant noise sources: atmospheric, galactic, and man-made noise. These data, given as noise power density numbers, measured with a vertical rod antenna, has been transferred to noise field strength levels in a bandwidth of 2700 Hz. The given atmospheric noise levels are depending on location, season, and time slot. Western Europe was chosen as regional location, and for the timing were selected the summer season, the time slot 08.00 - 12.00 hours local time for the frequencies 14 - 30 MHz, and 12.00 - 16.00 hours for 0.47 - 10 MHz. Figure 1 shows the expected noise levels of the noise sources separately, and the sum of all sources combined, depicted as Minimal Expected Noise Floor. The noise floor of the measurement system should be lower than this minimum, preferably 10 dB, so that the error caused by the system noise, is less than 0.5 dB. If the difference is smaller than 10 dB a correction should be made by subtracting the system noise power from the measured noise power. This requirement implicates that the system noise floor is a calibration parameter for each band separately, and should be determined in advance, after the antenna factor for each band and corresponding antenna has been measured.

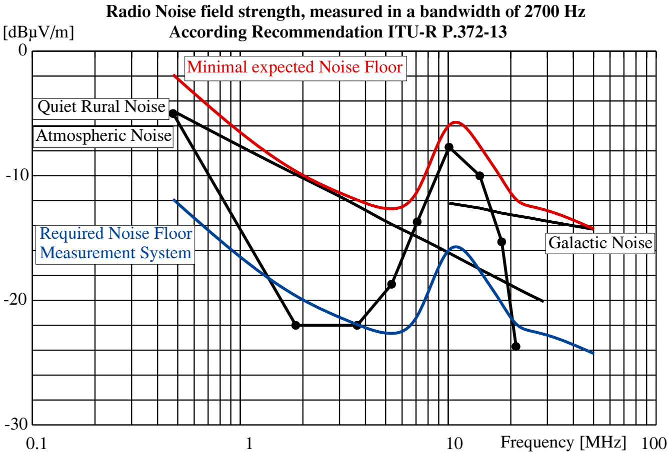

Figure 1.

III. SELECTION OF ANTENNAS

A. Field strength measurement using an E-field rod antenna.

The E-field rod antenna is a well-known antenna used for field strength measurements in many applications. For example, rod antennas were used for radio noise measurements in the frequency range 9 kHz to 30 MHz, for example in studies used in the ITU-R P.372-13 [1] for measuring atmospheric and man-made noise. In [26] we find a description for the antenna used in [1]. A vertical rod is used, which is matched to the receiver input impedance using a passive matching circuit. A high number of long radial rods form a ground plane. The constructing implies the installations to be fixed.

For the purpose of portable measurements setups several manufacturers developed active rod antennas. Figure 2 shows an example of such a rod antenna. The rod often has a length of 104 cm, resulting in an effective height of 0.5 m. The ground plane, which has limited dimensions too, may be formed by a set of radial rods, or by a metal plate. The antenna is matched to the characteristic impedance of the cable to the receiver and the receiver input impedance by an active circuit, often called an impedance convertor. Another example of a rod antenna is shown in [23]. The sensitivity of rod antennas is relative high with respect to broadband magnetic loop antennas, but the use of E-field rodantennas encounters a few problems as we will discuss below. Reference [27] already points out that there are accuracy problems. Reference [28] shows the influence of antenna cable, without a detailed analysis of the cause either.

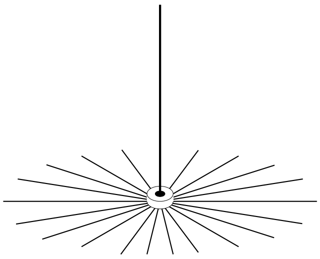

Figure 2. Example of an Active Rod Antenna for E-field measurements.

These problems are:
- calibration uncertainties;
- pollution of the antenna output by noise pick-up by the cable between antenna and receiver, thus parasitic behavior as antenna, resulting in extra calibration uncertainty and a disturbed directivity;
- pollution of the antenna output by noise originating from mains network and data processing equipment when the receiver is connected to the mains and eventually other equipment.

Reference [29] gives a solution for these problems, using optical fiber communication between antenna and measurement equipment, and grounding to ground plane of the measurement set-up. However, this solution is only useful for the EMI measurements mentioned therein, but not for noise floor measurements in general. Reference [30] shows a design for an active E-field rod antenna, which is tunable and narrow band, but meant to be used on the roof of a car, thus using the metal work of the car as counterpoise and reference plane. In reference [31] the grounding of the counterpoise is subject for investigation, and reveals large calibration uncertainties. Some solutions are shown, but only useful in the special cases of EMI measurements. Another problem with the rod antenna, the groundplane resonance, is shown in [32].

B. Calibration uncertainties

In Figure 3 we see a detailed schematic view of an electrical vertical rod antenna, as is commonly used for E-field measurements at non-fixed location. A vertical antenna rod is loaded by an impedance convertor, which has a high input impedance and a low, 50 ohms, output impedance, with a voltage gain of g. g may be 1 or higher.

The antenna rod is loaded by the following capacitances:
- The input capacitance of the impedance convertor, C_{in},
- the capacitance between the rod and the ground plane, C_{rg},
- the capacitance between the rod and earth, C_{re}, not coupled with the EM field,
- the capacitance between the rod and space, representing displacement currents, not direct resulting in earth return currents, but coupling with the EM field, C_{co}.

The ground plane, positioned close or at some distance above earth, shows a capacitance, C_{ge}, to earth. In case the ground plane is connected to earth, for example using a network of radials or a grounding rod, an additional grounding impedance, Z_{ge}, is connected parallel tot C_{ge}.

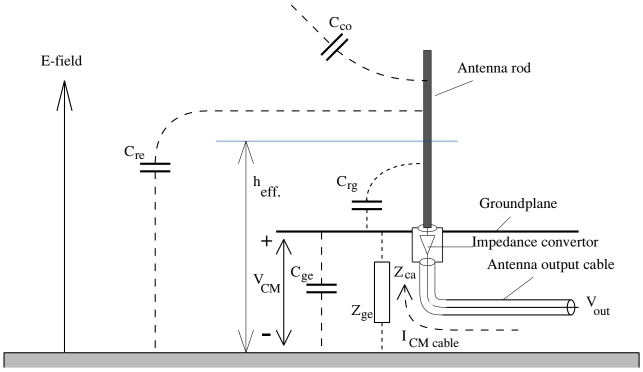

Figure 3.

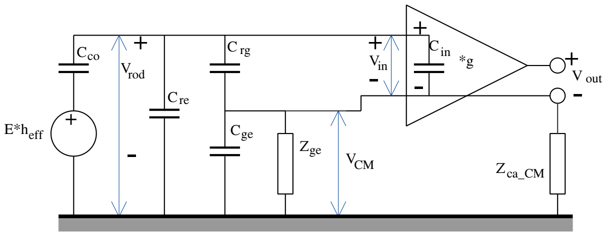

Figure 4.

The ground plane is also loaded by the common mode (CM) impedance Z_{ca_CM}, caused by CM currents $I_{CMcable}$ on the coaxial antenna cable. Z_{ca_CM} is strongly dependent on the length of the cable relative to the wavelength, and on the characteristics of the underground, suspending the cable. As the length is in the same order of the wave length the impedance at the end may strongly be influenced by resonance effects. These effects can be mitigated by applying lossy ferrite tubing over the cable.

Figure 4 shows the equivalent-circuit. To simplify the calculations we combine C_{ge}, Z_{ge}, and Z_{ca_CM} to one impedance from the ground plane to earth: Z_{gp}.

$$Z_{gp} = (1/j\omega C_{ge})//(Z_{ge})//(Z_{ca\_VM})$$

$$= \frac{Z_{ge}\cdot Z_{ca\_CM}}{j\omega C_{ge}\cdot Z_{ge}\cdot Z_{ca\_CM} + Z_{ge} + Z_{ca\_CM}} \qquad (1)$$

In a further simplification we assume that $C_{re} \ll C_{co}$ and $C_{re} \ll C_{rg}$, so C_{re} may be omitted. Also, we may add C_{in} to C_{rg} in $C_{base} = C_{in} + C_{rg}$. Now the schematic is simplified into Figure 5. The antenna rod is loaded by Z_{rod_load} consisting of the series circuit of C_{base} and Z_{gp}:

$$Z_{rod\_load} \approx \frac{j\omega C_{base} + Z_{gp}}{j\omega C_{re}\cdot(j\omega C_{base} + Z_{gp}) + 1} \qquad (2)$$

The loaded voltage on the antenna rod is now:

$$V_{rod} \approx \frac{C_{co} + j\omega C_{co}C_{base}Z_{gp}}{(C_{co} + C_{base}) + j\omega C_{co}C_{base}Z_{gp}}\cdot E\cdot h_{eff} \qquad (3)$$

$$V_{CM} = \frac{j\omega C_{base}Z_{gp}}{1 + j\omega C_{base}Z_{gp}}V_{rod} \qquad (4)$$

$$\approx \frac{j\omega C_{base}Z_{gp}}{1 + j\omega C_{base}Z_{gp}}\cdot\frac{C_{co} + j\omega C_{co}C_{base}Z_{gp}}{(C_{co} + C_{base}) + j\omega C_{co}C_{base}Z_{gp}}\cdot E\cdot h_{eff} \ (5)$$

When $Z_{gp} = 0$, then $V_{CM} = 0$.

$$V_{in} = V_{rod} - V_{CM}$$

$$V_{out} = V_{in}\cdot g$$

$$= \frac{C_{co} + j\omega C_{co}C_{base}Z_{gp}}{(C_{co} + C_{base}) + j\omega C_{co}C_{base}Z_{gp}} *$$

$$* \left(1 - \frac{j\omega C_{base}Z_{gp}}{1 + j\omega C_{base}Z_{gp}}\right)\cdot E\cdot h_{eff}\cdot g \qquad (6)$$

The antenna factor k, used as a calibration factor, is defined as:

$$k = \frac{E}{V_{out}}$$

$$= \frac{1}{\frac{C_{co} + j\omega C_{co}C_{base}Z_{gp}}{(C_{co} + C_{base}) + j\omega C_{co}C_{base}Z_{gp}}\cdot\left(1 - \frac{j\omega C_{base}Z_{gp}}{1 + j\omega C_{base}Z_{gp}}\right)\cdot h_{eff}\cdot g} \qquad (7)$$

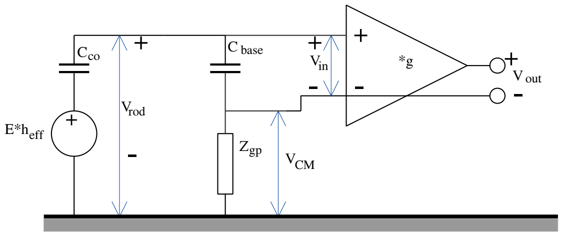

Figure 5.

We conclude that the calibration of the E-field rod antenna is depending on the impedance from the ground plane to earth, Z_{gp}, which consists of variable components like the capacitance between ground plane and earth, C_{ge}, the common mode impedance of the output cable at the output connector, Z_{ca_CM}, and the impedance of the earth connection of the antenna, Z_{ge}, if present. All three impedance values are more of less undefined, variable and frequency dependent, especially Z_{ca_CM}. They have a considerable influence on the calibration of the antenna. The only way to solve this problem is to make Z_{ge} very small, for example by using a low impedance grounding system like a wire mesh or radial network. This requirement can only be met in fixed installations and makes the E-field rod antenna unsuitable for portable measurement set-ups.

C. Pollution by noise pick-up by the cable between antenna and receiver

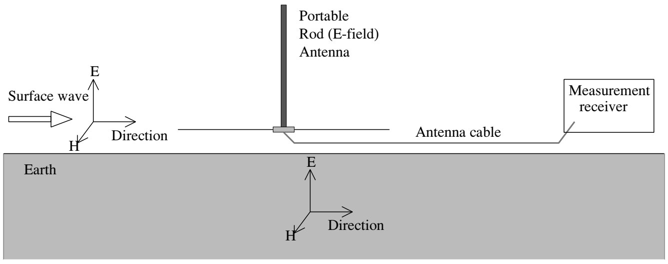

Figure 6.

So far we did not assume that noise or interference is arriving from the antenna cable into the antenna system, effectively the cable acting as a parasitic antenna. However, the antenna cable is a common mode conductor that lays over the ground between the antenna and the measuring receiver. This situation is pictured in Figure 6. Cable lengths of 4 to 10 meters are common. In the real world the soil is not a good conductor, but has certain values of permittivity and conductivity. Depending on the type of soil, the permittivity, ε_r, may vary between 3 and 40, and the conductivity, σ, between 0.1 and 30 mS/m. Not only this variance has an effect on Z_{ca_CM}, but more important the skindepth has a considerable depth in the relevant frequency range, 0.5 - 50 MHz. Table I gives an overview of the characteristics of various types of ground as defined by ITU-R PN.368-9 [33], [34] and the resulting skin-depth values.

TABLE I

Type of ground	σ [S/m]	ε_r	**Skindepth [m] @ frequency [MHz]**							
			0.1	1	5	10	20	30	50	100
Sea water, av. salinity	5	70	0.7	0.225	0.10	0.07	0.05	0,04	0.032	0.023
Sea water, low salinity	1	80	1.6	0.50	0.22	0.16	0.11	0.10	0.08	0.06
Fresh water	0.003	80	31.3	16.6	15.9	15.8	15.8	15.8	15.8	15.8
Wet land	0.030	40	9.22	3.02	1.52	1.30	1.17	1.15	1.13	1.12
Wet ground	0.010	30	16.0	5.47	3.25	3.03	2.97	2.92	2.91	2.91
Land	0.003	22	29.7	11.2	8.50	8.36	8.31	8.31	8.30	8.30
Medium dry ground	0.001	15	52.5	23.3	20.7	20.6	20.6	20.6	20.6	20.6
Dry ground	0.0003	7	98.0	49.8	46.9	46.9	46.8	46.8	46.8	46.8
Very dry ground	0.0001	3	173	95.7	92.1	92.0	92.0	92.0	92.0	92.0
Fresh water ice, -1 °C	0.00003	3	379	308	307	307	307	307	307	307
Fresh water ice, -10 °C	0.00001	3	957	920	920	920	920	920	920	920

For example, for a medium soil type as "Land", according to ITU-R definitions, with $\varepsilon_r = 22$, and $\sigma = 3$ mS/m, the skindepth varies from 30 m at 0.5 MHz to 8 m at 50 MHz. This means that an EM-wave, arriving from a high elevation, or propagating over the surface, is penetrating in the soil, and is surrounding the antenna cable. This EM field will induce a voltage in the cable in a common mode way.

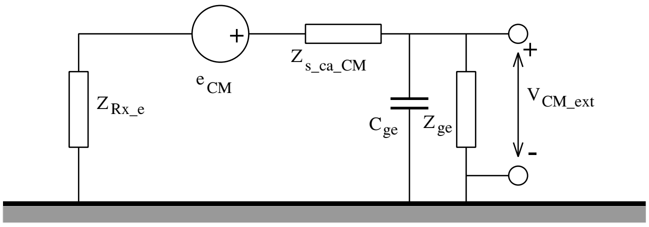

Figure 7.

Part of this voltage will arrive at the antenna connection and will be added to V_{CM}. As the length of the cable is considerable larger than the length of the antenna rod, this CM voltage, arriving from the cable, may be in the same order, or even stronger than de received voltage V_{rod}. Figure 7 shows an equivalent-circuit diagram for this situation. Source e_{CM} represents the common mode voltage induced in the antenna able over the full length, $Z_{s\_ca\_CM}$ the effective source impedance, frequency dependant, and Z_{Rx_e} the series impedance from the body of the receiver to earth. If the receivers is connected to the mains, Z_{Rx_e} also includes the conducting of the RF currents from the body of the Rx to the mains. A voltage V_{CM_ext} is developed over the common mode impedance of the antenna, the parallel combination of C_{ge} and Z_{ge}, see Figure 4.

Z_{ge} is only relevant when an earth connection is present. We can calculate V_{CM_ext} as:

$$V_{CM\_ext} = \frac{Z_{ge}(Z_{Rx\_e} + Z_{s\_ca\_CM} + Z_{ge}) - j\omega C_{ge}(Z_{Rx\_e} + Z_{s\_ca\_CM})Z_{ge}}{(Z_{Rx\_e} + Z_{s\_ca\_CM} + Z_{ge})^2 + \omega^2 C_{ge}^2 (Z_{Rx\_e} + Z_{s\_ca\_CM})^2} \cdot e_{CM} \quad (8)$$

Now we see the result of the pollution by e_{CM} on the output voltage V_{out}:

$$\begin{aligned} V_{out} &= g \cdot V_{in} \\ &= g \cdot \left(V_{rod} - (V_{CM} + V_{CM\_ext})\right) \end{aligned} \quad (9)$$

This added voltage in V_{out} causes loss of calibration and a serious deforming of the directivity of the antenna, as well as in the azimuth direction as in the elevation. It may be acceptable for EMI measurements, where the antenna cable is lying over a good conducting floor and can be routed optimal, but certainly not for noise floor measurements, without very large ground planes.

D. Pollution by noise originating from mains network

A second way of pollution is caused by noise that is arriving from the mains connection, when present. Figure 8 shows an equivalent-circuit diagram for this measurement set-up. Without an exact calculation, and referring to the foregoing calculation, we can conclude from Figure 8 that also noise from the mains network may arrive at the antenna ground plane and so pollute the output of the antenna. When Z_{Rx_e} is kept to a low value, for example by connecting the receiver case to a separate clean ground network, this mains-originated noise may be reduced. Also applying lossy ferrite chokes on the antenna cable, as on the cabling to the mains or other equipment may reduce external noise to a certain extend. But uncertainties still remain, and especially in noise floor measurement no certainty can by acquired about the origin of the measured noise floor.

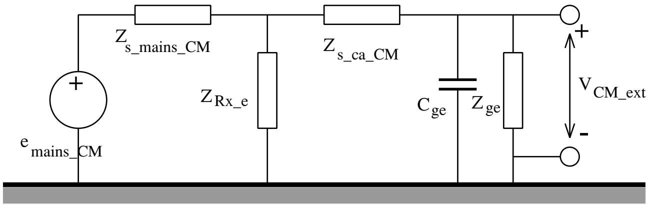

Figure 8.

For noise floor measurements we can conclude that an E-field rod antenna should only be used in a fixed installed antenna system, including a well-designed extensive ground network. For portable applications an E-field rod antenna should be avoided.

E. Loop antennas

With loop antennas we mean electrical small loop antennas with a circumference smaller than a quarter of a wavelength, that is designed to couple only with the magnetic field in the EM wave.

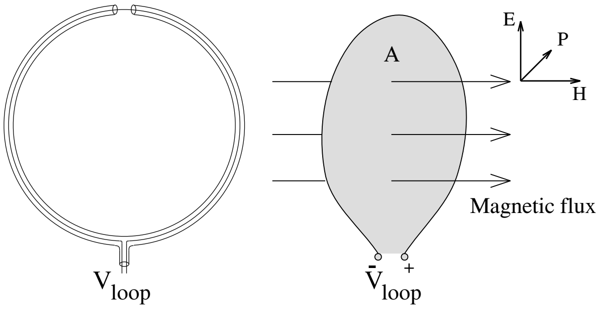

Figure 9. Screened realization of a loop antenna.

Figure 9 (left) shows a screened realization of a loop antenna, and Figure (right) the working principle. We can calculate the unloaded voltage of the loop for far field as:

$$V_{loop,max} = -j\omega\mu_0 A \frac{E}{120\pi} \qquad (10)$$

Herein is the constant $120\pi = 377$ ohm, often in dBs expressed as 51.5 dB, the correction factor for expressing the magnetic field strengths as an electric field strength in microvolts per meter. This is only valid for far field conditions. The sensitivity is only depending on the enclosed surface A and is linear with frequency. The loop is directly coupled to an active circuit. Often this is a circuit with a very low input impedance, which effectively short-circuits the loop. The short-circuit current is given by:

$$I_{short} = -\frac{\omega^2 L + j\omega R}{\omega^2 L^2 + \omega^2 R^2} \cdot \frac{\mu_0 A}{120\pi} \cdot E$$

$$\approx -\frac{\mu_0 A}{120\pi L} \cdot E \quad \text{for } |\omega L| \gg R \qquad (13)$$

wherein L is the self inductance of the antenna loop and R the sum of the loss resistance of the loop, R_{loss}, and the input resistance of the active circuit, R_{in}. The current is frequency independent and makes the antenna broadband. Relevant for the sensitivity of the antenna is the power inputted into the active circuit:

$$P_{in} = I_{short}^2 \cdot R_{in} \qquad (14)$$

for a low value of R_{in} the frequency range is large, but the sensitivity low, while for a higher value of R_{in} the sensitivity increases, but the useful broadband frequency range is limitted. Still, the sensitivity is relative low compared to a full size electric antenna, and not enough to match the requirements. By tuning the loop by a parallel capacitor, and loading that with high input impedance amplifier, the resonance effect of the resulting L/C circuit accumulates energy from the H-field at cost of a small bandwidth. The voltage over the loop connection and tuning capacitor is now:

$$V_{tuned,max} = V_{loop,max} \cdot Q = -j\omega\mu_0 \frac{QA}{120\pi} \cdot E \qquad (15)$$

wherein Q is the Quality factor, determined by the combination of the antenna loop, the tuning capacitor, and the loading of the high input impedance of the active circuit. Q may have values from 10 to 100 or higher. So a sensitive antenna can be constructed with limited dimensions. As common mode voltages on the antenna loop do not couple with the antenna output voltage, the problems with calibration and pollution, as described for the rod antenna, do not occur. These characteristics make the loop antenna very useful for portable measurement set-ups.

F. Directivity of loop antennas

An important difference with the rod antenna is the directivity. As the polarization just above ground is vertically directed, the vertical standing rod antenna is optimal coupled with the EM field. For vertical polarisation the loop antenna need to positioned with the plane of the loop vertical, as the magnetic field is horizontal. The azimuthal directivity of the loop antenna has a shape of a Figure 8, and is described by a spherical system with the axis on the axis of the loop as:

$$V_{loop} = V_{loop,max} \cdot \sin(\theta)$$

$$= V_{loop,max} \cdot \cos(\pi/2 - \theta) \qquad (11)$$

wherein $V_{loop,max}$ is the maximal value when the plane EM wave is arriving from any direction in the plane of the loop. θ is the deviation angle from the axis. In a transformed spherical system with the axis vertical directed with elevation angle E and azimuth A, see Figure 11, we can apply the relation $\cos(\alpha) = \cos(\beta) \cdot \cos(\gamma)$, valid for a rectangle triangle on a sphere, and arrive at:

$$\cos(\pi/2 - \theta) = \cos(\pi/2 - A) \cdot \cos(\pi/2 - E)$$

$$V_{loop} = V_{loop,max} \cdot \cos(\pi/2 - A) \cdot \cos(\pi/2 - E) \qquad (12)$$

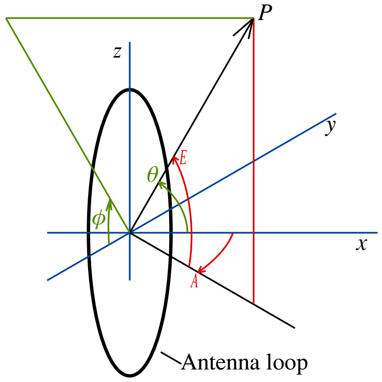

Figure 11. Transformation of spherical co-ordinates, θ, ϕ, of upright standing loop antenna (green) into azimuth, A / elevation co-ordinates, E (red).

We want to measure the noise floor omnidirectional, like the rod antenna does. To achieve that with a magnetic loop antenna, we may use two loops orthogonal to each other, or do two measurements with the same loop, but at the second measurement the loop turned in azimuth by 90 degrees. Both measurement results have to be vectoral added to get a final result that is directly comparable with noise measurement results used in [1], that came from measurements with vertical rod antennas. The vertical rod antenna has a horn toroidal shape for the directivity with a null in the vertical direction. This means that the rod antenna is not sensitive in high elevation directions, but is equal sensitive in all azimuth directions. However, high angle sky-wave signals and noise will not be received. In our investigations for man-made radio noise we expect to find the sources of man-made noise on the ground, and that the man-made noise floor, that we measure, is the result of accumulation of surface wave propagated man-made noise signals from a number of sources. So, the man-made noise to measure arrives at low elevation angles, and the difference between the rod antenna and the combination of loop antennas with respect to the high elevation sensitivity, is not relevant. Of course, we have to make sure that the level of atmospheric noise, arriving from high angles, is low. This can be achieved by choosing optimal time slots during the day wherein the D-layer absorption is maximal. It means we have to allocate the measurement periods around noon local time.

IV. CONCLUSION

An investigation into requirements for measuring the radio noise floor, using portable equipment, shows issues in the field of sensitivity, calibration accuracy, and directivity, besides the general requirements as described in Recommendation ITU-R SM.1753-2. A minimum sensitivity requirement for antennas is derived, and causes of uncertainty in the calibration of E-field rod antennas are analyzed. E-field rod antennas were found to be unsuitable for noise floor measurements when they are not grounded using a low impedance. H-field loop antennas do not show those accuracy problems, but require to be tuned in frequency for sufficient sensitivity, and there is a need to measure in two orthogonal directions with vectoral adding of both results to produce a radio noise floor that is direct comparable with the MMN levels as mentioned in Recommendation ITU-R P.372-13.

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