CONDENSED CATALOGUE OF ELECTROMAGNETIC ENVIRONMENT
MEASUREMENTS, 30-300 HZ

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Abstract: The IEEE Electromagnetic Compatibility Society's Technical Committee on Electromagnetic Environments (TC-3) has undertaken a long-term project to compile an inventory or catalogue of published measurements of electromagnetic environments. The frequency spectrum has been divided into tractable bands which will be considered one at a time. We have now completed the 30-300 Hz band. We present here an abridged version of the resulting bibliography, along with a brief summary of what has been measured.

Introduction

The IEEE Electromagnetic Compatibility Society's Technical Committee on Electromagnetic Environments (TC-3) has undertaken a long-term project to compile an inventory or catalogue of published measurements of electromagnetic (EM) environments. We have completed the first frequency band (30-300 Hz), and we present here an abbreviated version of the resulting bibliography. The full bibliography comprises over 100 papers at present and is therefore too long for a conference paper; it will be published elsewhere.

The focus of the project is on published measurement results for electric and magnetic fields or for exposure. (By exposure we mean the time integral or average of the amplitude of the electric or magnetic field. We do not include measures such as the specific absorption rate SAR.) Our primary aim is to collect information on what has been measured on EM environments and to make available a bibliography for anyone interested in pursuing the matter further. Our principal interest in this project is what quantities have been measured in what environments, rather than in the actual results. In general we do not include calculations, effects, or unpublished results. There

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are some exceptions, but we have not attempted to be complete in our coverage of anything except published measurements. A few review articles have been included because we thought that they provide good overviews or useful sets of references. Also, some papers prescribing standard measurement methods have been included. In reducing the full bibliography to the shorter version presented here, we considered breadth and depth of measurements reported in each paper, as well as the availability of the paper. Most of the review papers from the full bibliography are included in the present shortened version since they contain condensed information and provide extensive lists of references. The papers are divided into the following categories: natural noise measurements, power-line fields, residential fields (including those from appliances), and workplace environments (including VDT's). In discussing the results, we will use the term "magnetic field" to refer generically to both the magnetic field (H) and the magnetic flux density (B); since all the measurements considered were performed in air, the distinction between H and B is largely semantic for this paper. Results for magnetic field measurements will be given in terms of B in teslas (T, μ T, fT, etc.) rather than the other common units, B in gauss ($1 \text{ G} = 10^{-4} \text{ T}$) or H in amperes per meter (where $H = 1 \text{ A/m}$ corresponds to $B = 4\pi \times 10^{-4} \text{ T}$).

Natural Noise

References [1-12] deal with natural ambient levels in the ELF range. For frequencies between 30 and 300 Hz, the natural ambient noise arises primarily from lightning, the major part of which occurs in storms in the tropics. In general, the magnitude of the natural noise will exhibit diurnal, seasonal, and geographic variations, but between 30 and 300 Hz the variations are relatively small. The naturally

occurring noise fields are broadband, and they have been studied almost exclusively in connection with communications applications. The results are typically given in terms of the noise factor f_a or quantities derived from it. To define f_a , one introduces the concept of the noise power p_n available at the terminals of an antenna which is lossless but equivalent in other respects to the antenna of the system used in the measurements [1,2]. The noise factor is then defined by

$$f_a = \frac{p_n}{k_B t_0 b}, \quad (1)$$

where k_B is Boltzmann's constant, t_0 is the reference temperature (288 K), and b is the bandwidth of the system in hertz. While the noise factor is useful for communications applications, its relationship to the actual electromagnetic fields or power density depends on the antenna and the bandwidth of the system used in the measurement.

An early survey [3,4] measured both vertical and horizontal components of the magnetic field, as well as the ratio of the vertical electric field to the horizontal magnetic field, at several locations worldwide. Reference [4] reports results for the vertical electric field, including average and rms values and amplitude probability distributions. Other early measurements are referenced in [5], which contains an exhaustive bibliography of surveys of ELF noise up to 1981. Other reviews with extensive references are [6,7]. Results of measurements made before 1978 were summarized in [1,2]. The ELF portion of the spectrum is shown in fig. 1. The quantity F_a

is the noise factor expressed in dB: $F_a = 10 \log_{10} f_a$. The two curves represent the maximum and minimum of all measurements worldwide. The spread between maximum and minimum is not very great, especially below 100 Hz, reflecting the small temporal and geographical variations noted above.

The most recent major survey is the Stanford University ELF/VLF Radiometer Project [8-10]. The measurement system and the general program are described in [8]. There are eight sites worldwide, each of which monitors two components of the magnetic field. The systems can record temporal variations of the field and can determine both rms and average values, as well as amplitude probability distributions. Reference [9] contains results for the average field at several sites, primarily at high latitudes. It also reports one site's results for the voltage deviation V_d the ratio of rms to average signal. This is a measure of the impulsive content of the noise. Reference [10] concentrates on the average magnetic field noise amplitude at the two common power frequencies, 50 and 60 Hz, and their harmonics. It also contains the information needed to convert between the average field results and the noise factor. The average field amplitude is found to decrease with frequency roughly as $1/f$ ($1/f^2$ for the noise factor). The value at 60 Hz typically lies between 150 and 600 fT/ $\sqrt{\text{Hz}}$, depending on location and season. A model and program for detailed prediction of natural noise over a range of frequencies including ELF is described in [11,12].

Power-Line Fields

Fields from power lines are treated extensively in the EPRI handbook [13], but its availability is rather limited. Measurement results for the electric field, obtained with three different meters under and near high-voltage transmission lines, are presented and compared to calculated results by Bracken [14]. (Regarding the title of [14], in the power engineering community the term "electrostatic" has, or at least had, a broader interpretation than in some other segments of society.) Deno [15] presents results of measurements of both electric and magnetic fields under transmission lines, also comparing them with calculated results. A good, accessible review of power-line magnetic fields is that of Olsen *et al.* [16]. Besides a prescription for calculating the magnetic fields, [16] also discusses the various factors affecting the amplitude of the fields around

Fig. 1 Minimum and maximum natural noise levels, from [1,2]. A refers to micropulsations, B to lightning, and C and D to expected, rather than measured levels.

transmission and distribution lines and compares calculational results to measurements. It also contains information on harmonics and notes the usefulness of a statistical treatment of magnetic fields from power lines. A statistical treatment is appropriate because the magnetic field is determined by the currents on the lines, and (unlike the voltage) the currents on power lines are not constant and well controlled. Generally power-line electric and magnetic fields are understood quite well, provided the currents in the lines are known [13-16]. Agreement between measurement and prediction is typically within 10% or better (in the absence of nearby structures or irregular terrain). The amplitudes of the fields depend on the voltage, the currents, the geometrical configuration of the wires, and the location at which the measurement is made. For the particular transmission lines measured in [14-16], maximum amplitudes for the fields under transmission lines were in the range 2-10 kV/m for electric fields and 1-40 μ T for magnetic fields for lines in normal use. Magnetic fields near distribution lines can be comparable to those of transmission lines, due to the greater (locally) unbalanced currents in distribution lines.

A statistical study of electric and magnetic fields from a distribution network was performed in Quebec Province and is reported by Héroux [17]. A mobile unit was driven through various representative human environments. Typical values of electric and magnetic fields encountered were 32 V/m and 0.16 μ T, respectively. The review by Miller [18] touches on several areas, including power-line, residential, and workplace environments. Measurements of fields in residences or workplaces near power lines are included in the residential or workplace discussions below.

Both ANSI/IEEE [19] and IEC [20] have standards for measurements of power-frequency fields. The ANSI/IEEE standard covers both electric and magnetic fields, whereas the IEC standard is restricted to electric fields. There are also recommendations for measurement of power-frequency magnetic fields away from power lines [21]. There are several reasons for using different measurement methods away from power lines than those used in their proximity. Away from power lines, the fields have a much greater dynamic range, and the harmonic content is more important. Also, power lines provide a well defined, relatively simple geometry, which is not the case in other environments.

Residential Fields

There has been a great deal of recent activity in measuring residential EM environments. Results of several substantial surveys of residential fields and exposure [22-25] have now been published, and other surveys are in progress. References [22-24] all performed measurements of all components of the magnetic field at several locations in each of numerous residences. Kaune *et al.* [22] and Silva *et al.* [23] performed periodic measurements over continuous 24-hour periods as well as single-time spot measurements, whereas Barnes *et al.* [24] did only single-time measurements. Barnes and Kaune both also measured the vertical component of the electric field, though the location chosen in the Kaune study was not representative of human occupation. All three studies investigated the correlation between field level and wiring configuration. Other factors considered were harmonic content and temporal variation in [22,23] and power use in [24]. Reference [23] also investigated correlation of field level with power line proximity, population density, grounding, age of the home, and location in the room. The mean values of the magnetic field found in these studies fall in the range 0.05-0.3 μ T, with significant (a factor of 2) temporal variations. For the electric field, [24] found that the mean ranged from about 8 V/m to 12 V/m for different classes of wiring configurations.

An exposure study by Kavet *et al.* [25] measured the average magnetic field to which participants were exposed during the day both at home and away from home. Participants were grouped according to whether they lived near overhead transmission lines. Average magnetic fields fell in the range 0.1-0.3 μ T at home and 0.18-0.6 μ T away. A good review of residential fields, with many additional references, is [26].

Magnetic fields from many common household appliances have been measured, with the most extensive studies being those by Gauger [27] and Silva *et al.* [23]. Gauger measured the maximum magnetic field as a function of distance from the appliance, using at least three different models for each type of appliance. Silva *et al.* measured the magnetic field in typical use for a number of appliances using sample sizes ranging from 1 to 59. Delpizzo [28] measured and averaged the magnetic field over a grid corresponding to the human body in order to estimate the exposure from various appliances. Other measurement results for appliances can be found in

Miller's review [18] and in the paper of Stuchly *et al.* [29], which also contains measurements of harmonic content. The measured fields fall off rapidly with distance. For distances corresponding to typical use the field is usually a few microteslas for most appliances, but several have fields exceeding 20 μ T and fields above 100 μ T were found. Appliances with the largest fields tended to be relatively small devices -- such as shavers, can openers, or hair dryers -- which lack the shielding of large devices like dishwashers, refrigerators, or clothes dryers.

Workplace Environments

The ELF EM fields have been measured for a variety of work environments. As might be expected, electrical utility workers have been the subject of several studies, including [30-32]. The Bonneville Power Administration (BPA) study [30] reports average daily accumulated electric field exposure, whereas the Canadian study [31,32] reports the geometric mean of the fields to which the workers were exposed, for both electric and magnetic fields. Both studies use exposure of office workers for comparison, which provides data on the office environment also. The office exposures indicate field levels comparable to residential levels, of order 1-10 V/m for electric fields and 0.1-0.2 μ T for magnetic fields. In the BPA study electric-field exposures of "exposed" occupations (lineman, electrician, splicer, etc.) were all much (100-1000 times) higher than those of the office workers. In the Canadian study, some of the exposed occupations experienced elevated electric-field exposure (a few hundred V/m) and all experienced higher magnetic-field exposure (1-4 μ T) compared to office workers. An interesting extension of the Canadian study was to compare a number of different statistical indices which can be used to characterize exposure. Armstrong *et al.* [33] present a comparison and correlations between indices such as mean, median, peak, 90th percentile level, etc.

Measurements of both electric and magnetic fields in an office building near a transmission line have been reported by Nielsen [34]. The building provides some shielding for the electric fields, although fields inside are still somewhat high. For magnetic fields the building provides little or no shielding. The specific question of VDT emissions has been addressed in [29,35,36]. Typical values measured 30 cm from the screen are 0.2-0.5 μ T. (Note, however, that these measurements may not reflect the behavior

of newer model VDT's.) Magnetic fields near various welders and steel furnaces are reported in [37]. They fall in the range of 0.1-10 mT.

Summary

We have presented an overview of measurements of electromagnetic environments in the 30-300 Hz frequency range. Not all such measurements have been included; a more complete bibliography and discussion will be published elsewhere. In discussing measurement results and characteristics of specific environments, we have indicated only general, approximate features to provide some perspective in comparing different environments. Results we quote should be regarded as representative, not definitive. Anyone needing a quantitative characterization of particular electromagnetic environments should consult the original papers for exact, detailed results and for discussion of measurement methods and limitations.

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