A case study on electromagnetic field assessment and uncertainty evaluation

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Abstract. This paper presents a radiofrequency electromagnetic field exposure assessment carried out in an observatory open for general public, where there are multiple radio and television transmitters in the surrounding area. An uncertainty evaluation is presented, considering that the main broadcast stations reduced their transmitted power to comply with the regulatory limits throughout the observatory area. A discussion is done about uncertainty of measurement result and its use or not in both precautionary measure and sanctioning process applied by regulatory authority.

1. Introduction
The growing number of radiofrequency emitters due to the popularization of radiocommunication services has increased the population’s concern about radiofrequency electromagnetic fields (RF-EMF) human exposure.

Thus, the National Telecommunications Agency (ANATEL), as well as regulatory authorities of various countries have been adopting the exposure limits set by ICNIRP [1], which are recognized by the World Health Organization (WHO).

Considering that the recommended and normative limits use quantities (usually electric and magnetic fields) measured through instruments used in practice, the RF-EMF exposure evaluation results have an expected real value, with measurement uncertainties associated to it.

In this context, this article presents in section 2 a case study of assessment made by ANATEL with the measurements results. The field increase effect occurred in the vicinity of the metal parapet occurred due to the radiation are also presented. An assessment of measurement uncertainty is presented in section 3. Finally, in section 4, using the case study as an example, some aspects of the uncertainty impact and the actions that could be taken by the regulatory authority for both corrective measures and sanctioning process are presented.

2. Case study
In the present work, the EMF exposure in a complex and realistic environment is assessed. The site is an observatory, located at Boa Vista Hill, in Joinville, Brazil. The observatory gazebo is surrounded by ungrounded metallic parapets and a massive concrete floor, where the general
public can visit at any time. At Boa Vista Hill, there are several sources of broadcasting and telecommunication services including VHF, UHF and several microwave bands. The distances from the main antennas to gazebo are between 19 to 32 meters. Figure 1 shows this scenario.

![Figure 1. Observatory in the city of Joinville.](image)

### 2.1. Procedure and equipment

On site measurements were performed using time-averaging, with 6 min averaging for the E and H fields in the frequency range 100 kHz to 1 GHz (up to 3 GHz for the E field), according to international recommendations [1, 2].

Evaluations were performed following international standards [2, 3, 4]. These recommendations provide guidance on measurement methods that can be used to achieve a compliance assessment. They also provide guidance on the selection of numerical methods suitable for exposure prediction in various situations. The instruments\(^1\) that were used are:

- Sensors: NBM- 520 Broadband Field Meter with electric field probe EF 0691 (100 kHz - 3 GHz) and
- EMR-300 Broadband Field Meter with magnetic field probe Type 10C (27 MHz - 1 GHz).

Sensor positions during measurement ranged from 90 mm to 1080 mm from the parapet located in the worst affected region (with higher field strength).

The use of broadband equipment was the most appropriate, since it was identified the presence of a re-radiator and so therefore a near field region. In addition, since the electric field was relatively high, the use of narrow band instruments - the spectrum analyzer (which can be used in conjunction with a laptop) could present an electromagnetic compatibility problem. The broadband instruments measure the sum of power density contributions from all the sources operating within the frequency range of the field probe.

Several measurements were taken and repeated and some discarded or eliminated, for example, when people were circulating in the test space. Most of the measurements were carried out at dawn without visitors at the observatory.

As stated before, there are several sources of broadcasting and telecommunication services in the VHF, UHF and microwave bands near the observatory. However, it was verified that more than 90% of the total power density contribution came from only 5 sources, all in the VHF band: one analog TV and four FM radios. There are no medium wave AM sources near the observatory.

\(^1\) Instruments calibrated at Centro de Pesquisa e Desenvolvimento em Telecomunicações – CPQD on 11. Sept. 2019. The calibration is valid for one year.
The instrument used for electric field evaluation measures all sources in the range from 100 kHz to 3 GHz. When there are multiple sources (as in this case), the error may increase as anticipated by the equipment’s manufacturer [5]. However, it was not observed a significant error in the instrument related to the multiple carriers, as evidenced in tests done by selectively switching off transmitters.

To analyze the near-to-far-field transition zone, a broadband electric field meter was gradually moved away from the metallic parapet, as shown in the Figure 2. According to [2], measurements should be made at a distance no closer than three probe-diameters between the center of the probe and any object. Thus, the measurements were carried out from 90 mm, since the size of the probe used is 30 mm. Based on these measurements, it was obtained evidence of near-field existence in the proximity of the parapets, due to re-radiation from the metallic structure.

![Near-field measurement at the observatory.](image)

Figure 2. Near-field measurement at the observatory.

### 2.2. Results

Even with the reduction of the main sources to 25% of the authorized power, it was observed some hot spots, although the spatial averaging of the fields was kept below the ICNIRP limit of 28 V/m [1]. Figure 3 illustrates a view of the spatial averaging method. For the generation of this map, more than one hundred measurements were made at points of a 250 by 250 mm mesh, and at the points not measured linear interpolations were applied. The probe was kept positioned at 1.5 m above the gazebo ground. This height was chosen since the highest levels, on average, were observed at that level.

Figure 4 shows that some points are above the ICNIRP limit. In addition, those points are not only in the vicinity of the parapet. Figure 5 compares all principal source measurements.

Through both electric and magnetic field measurement, it was confirmed the existence of a near-field, since the ratio between electric and magnetic magnitude was shown to be different than 377 ohms. Table 1 summarizes the wave impedance as a function of distance from the parapet.

| Dist. [cm] | 27 | 54 | 81 | 108 | 135 | 162 | 189 | 216 |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| $|E/H| [Ω]$ | 423 | 432 | 472 | 462 | 455 | 417 | 394 | 380 |

Table 1. $|E/H|$ as a function of distance from parapet.
Figure 3. Electric Field measurement map with main sources operating with 25% of the licensed power.

Figure 4. Comparison between exposure measurement (total and sum of power density contributions) considering the most restrictive ICNIRP limits.

3. Uncertainty evaluation

The uncertainty of a measurement result should always be stated to assure metrological traceability. Uncertainty also serves as a measure for the quality of the results. Furthermore, for the measurement task discussed in this paper, it is essential to take the uncertainty of the results into account when judging whether population exposure is exceeding legally established limits.

Uncertainty estimation according to the “Guide to the Expression of Uncertainty in Measurement (GUM)” [6] is a well-established practice among the metrology community. Nonetheless, the identification and quantification of the main contributions to the uncertainty demands deep knowledge and experience on the specific measurement process. Some effort has been done by the academia to systematize knowledge on sources of uncertainty in electromagnetic field measurement [7, 8, 9]. We adopted the recommendations formulated by Stratakis et al. [7] as primary reference to estimate the uncertainty of our measurement results. Table 2 summarizes the sources of uncertainty that we considered in our analysis. Conversion from dB-values to %-values was done according to Equation 1.

\[ x_\% = \left(10^{\frac{db}{20}} - 1\right) \times 100\% \quad (1) \]
The parapet was separated from the transmitting antenna by 3100 mm. The system was horizontal polarization using a log periodic antenna. The ambient measurements were performed using vertical and horizontal polarization at some frequencies the measured field is higher than the ICNIRP limit. This result confirms the on-site measurements.

**Figure 5.** Measurements at Observatory 1.

**Table 2.** Sources of uncertainty.

| Source of uncertainty                        | Value        | Value $\alpha_i$ [%] | Prob. Distr. | Reference for quantification        |
|---------------------------------------------|--------------|----------------------|--------------|-------------------------------------|
| Uncertainty of calibration                  | 2.1 dB       | 27.35                | Normal (k=2) | Calibration certificate.            |
| Probe isotropy                              | 0.91 dB      | 11.05                | Normal (k=2) | Calibration certificate. Maximum anisotropy of the field sensor. |
| Frequency response                          | -            | 17                   | Normal (k=2) | Calibration certificate. Maximum error. |
| Linearity                                   | 0.7 dB       | 8.39                 | Normal (k=2) | Calibration certificate. Maximum error. |
| Isotropy of probe and field meter into the field | 0.5 dB     | 5.93                 | Rectangular  | Data sheet.                        |
| Temperature                                 | 0.2 dB       | 2.33                 | Rectangular  | Data sheet.                        |
| Resolution                                  | 0.01 V/m     | 0.00                 | Rectangular  | Data sheet. Converted to relative value for $x=24.1$ V/m (average indication on repeatability test). |
| Repeatability                               | 1.07 V/m     | 4.42                 | Normal (k=1) | Standard deviation of 20 repeated observations in the field. Converted to relative value for $x=24.1$ V/m (average indication on repeatability test). |

Table 3 presents the measurement uncertainty budget. Standard uncertainty $u_i$, combined uncertainty $u_c$, effective degrees of freedom $\nu_{eff}$, expanded uncertainty $U$ and percentage of contribution $%c$ are calculated according to equations 2, 3, 4, 5 and 6, respectively. Coverage factor $k$ is the Student’s t-distribution coefficient for $\nu_{eff}$ degrees of freedom and 0.9545 probability (two-tailed).

The main source of uncertainty is the uncertainty of calibration, which has a percentage of contribution $%c = 55\%$ (according to equation 6). Thus, improvements in the calibration process may significantly reduce the overall uncertainty of measurements performed with this specific broadband meter.
Table 3. Measurement uncertainty budget.

| i | Source of uncertainty                     | $a_i$ [%] | Divisor | $u_i$ [%] | $\nu_i$ | %c |
|---|------------------------------------------|-----------|---------|-----------|--------|-----|
| 1 | Uncertainty of calibration               | 27.35     | 2       | 13.68     | $\infty$ | 55  |
| 2 | Probe isotropy                           | 11.05     | 2       | 5.52      | $\infty$ | 9   |
| 3 | Frequency response                       | 17        | 2       | 8.50      | $\infty$ | 21  |
| 4 | Linearity                                | 8.39      | 2       | 4.20      | $\infty$ | 5   |
| 5 | Isotropy of probe and field meter into the field | 5.93 | $\sqrt{3}$ | 3.42 | $\infty$ | 3   |
| 6 | Temperature                              | 2.33      | $\sqrt{3}$ | 1.34 | $\infty$ | 1   |
| 7 | Resolution                               | 0.00      | $\sqrt{3}$ | 0.00 | $\infty$ | 0   |
| 8 | Repeatability                            | 4.42      | 1       | 4.42      | 19     | 6   |

Combined uncertainty $u_c$ 18.45  $\nu_{eff} = 5749$

Expanded uncertainty $U$ (95.45% coverage probability) 37  $k = 2$

\[
    u_i = \frac{a_i}{\text{divisor}} \quad (2) \quad u_c = \sqrt{\sum u_i^2} \quad (3) \quad \nu_{eff} = \frac{u_c^4}{\sum \frac{u_i^4}{\nu_i}} \quad (4)
\]

\[
    U = k \cdot u_c \quad (5) \quad \% c_i = \frac{u_i^2}{u_c^2} \cdot 100\% \quad (6)
\]

4. Discussion and conclusions

Regulatory authorities should ensure that players are operating within pre-established rules. When violations of rules are detected, precautionary and / or corrective measures could or should be applied to eliminate or correct as soon as possible the conduct that may affect the regulated object. Additionally, a sanctioning process is opened, when applicable.

Although each source was individually compliant with the exposure to EMF limits, it was found that the combined exposure to multiple RF sources was exceeding the general public exposure limit of 28 V/m (applicable for VHF). Thus, as a precautionary measure, the regulatory authority notified those responsible for the main sources to reduce their transmitted power proportionally up to the population limit, regardless of the sanctioning process. In this case, the uncertainties were not added from the measured value because the general public exposure limit already considers a reduction factor of 50 times of the whole-body specific absorption rate (SAR), that could cause short-term (tissue warm) adversely health effect, so that any measurement uncertainty is within this range. On the other hand, immediate measure to reduce power should not consider uncertainty in favor of the transmitter, since the population safety should be ensured considering the health protection principles.

Therefore, the regulatory authority did not use the uncertainty (neither to add nor subtract) under the measured value. However, knowledge of uncertainty is paramount to make the regulatory body’s acts transparent and to ensure that the measured values are within the safety factors recommended by international organizations, guaranteeing reproducibility and repeatability of the in-situ evaluation.

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