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SPATIAL DISTRIBUTION OF ELECTRIC FIELD STRENGTH AT A TEACHING HOSPITAL PREMISES DUE TO TRANSMISSIONS BETWEEN 87.5 MHz AND 2.6 GHz

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A radiofrequency (RF) electromagnetic radiation safety assessment had been carried out at public access points within the compound of a teaching hospital. The frequency band investigated ranged from 87.5 MHz to 2.6 GHz. Eighty-eight measurements were made using a spectrum analyser coupled with a log-periodic antenna. The objective was to determine the level and nature of RF fields within the immediate premise of the facility where patients of health conditions are kept and treated. Results complied with the International Commission of Non-Ionising Radiation (ICNIRP) guidelines. The values of the resolved electric field at four spatial heights ranged from 1.00 ± 0.144 mV/m to 1.174 ± 0.169 V/m. Power densities varied from 2.65 ± 0.38 nWm^{-2} to 3.66 ± 0.528 mWm^{-2}. There were relatively high contributions from frequencies above 900 MHz compared with contributions from lower frequency bands.

INTRODUCTION

All life on earth is now exposed to radiations of different frequencies and intensity. Majority of persons exposed are not even aware of the existence of these energies in motion. They equally are unaware of the possible effects that might arise from being exposed to radiations. While most of these radiations arise from natural phenomena which have relatively small intensities compared with man-made fields[1, 2], a lot more is generated by human activities either intentionally or as a by-product of essential usages. Globally, Radiofrequency applications have gained prominence and continue to evolve daily. The ever increasing evolution in radiofrequency (RF) application has consequences both for the environment and life; humans and animals alike. RF finds its varied applications in telecommunications, food processing, defence and industry, etc. While exposures from most of the RF gadgets, e.g. microwave ovens, dielectric heating system, induction heating equipment and smart meters are localised to a few meters around such equipment, those employed in providing telecommunication (TV, AM and FM radio, Radar and mobile telephony) radiate into the vast environment. It is expected that these fields have significantly increased since its massive usage in the World War II which lasted from 1939 to 1945 when radars were extensively used. Several studies have investigated the contributions of fields from telecommunications base stations to ambient levels in localities and countries. There are varied researches that reported possible biological effects due to exposure to RF fields[3–7].

In this study, the researchers set out to determine the level of environmental RF fields produced by antennas that intentionally generate and propagate RF fields into the immediate environment of a teaching hospital where patients of varying health conditions are kept and treated. This study was motivated by public concern for the indiscriminate sighting of masts in neighborhoods especially near health facilities and the levels of radiation emanating from the antennas hoisted on such masts. In response to the loud disquiet of members of the general public towards the siting of the traditional masts, the operators of telecommunication services in Ghana are gradually shifting to esthetic masts in the form of Palm trees, sign posts, lamp posts, etc. These masts blend beautifully with the natural environment. However, they may be hiding potential dangers in plain sight. This work investigated such potential dangers by determining the exposures of members of the general public on the hospital ground premises, compliance with the ICNIRP standards and possible implications to patients who might be susceptible due to their health conditions.

MATRIAL AND METHODS

An Anritsu Spectrum Master (MS2722T), a spectrum analyser for RF and microwave handheld instruments, was coupled to an Anritsu log-periodic antenna model MP666A with serial number 6200849238 via an RF cable of fixed balun load impedance of 50 Ω. The Spectrum Master with serial number 1338067 and

App version V5.98 is sensitive to RF within the range 9 kHz–7.1 GHz. The log-periodic antenna is sensitive and effective within the frequency range of 80 MHz–2.690 GHz. A space-based satellite navigation system (GPS) provided information on the coordinates of the location as well as the elevation of the measurement point. The methodology used incorporated many of the measurement methods and procedures outlined in Electronic Communications Committee (ECC) Recommendation (02)04[8]

Three steps were involved in the measurement process: an initial desktop assessment using aerial photographs and street view from Google map software to determine likely measurement locations, a quick broadband measurement of all possible signals within the compound of the hospital and final measurements at the locations of the highest field levels. Measurements were taken at four spatial heights of 1.0 m, 1.5 m, 1.7 m and 2.0 m. The frequency span under investigation was divided into bands as shown in Table 1. Two measurements were taken at each spatial height. A total of 88 measurements were logged into the spectrum master at each location. The measurements were performed between 10:00 am and 1:00 pm, since data available at the offices of the telecommunication companies indicates that there is heavy traffic within the said period[9]. The schematic RF diagram of the frequency selective measurement of RF field is as shown in Figure 1.

The highest peak corresponding to the frequency of interest is marked using Master Software Tools. The equivalent amplitude in units of dBμV was converted to dBmV by changing the scales on the Spectrum master. For the determination of the field strength, the measured voltage across 50 Ω, the cable loss, and the logarithmic antenna factor, K, were used to do the calculations. Equation 1 shows how these quantities are related and was used to convert the received voltage V_{rx} into electric field strength, F, corresponding to the signal.

Table 1. Frequency bands investigated.

S/n	Frequency bands	No. of measurements
1	87.8 MHz–2.6 GHz	8
2	87.5 MHz–109 MHz	8
3	109 MHz–400 MHz	8
4	400 MHz–600 MHz	8
5	600 MHz–800 MHz	8
6	800 MHz–900 MHz	8
7	900 MHz–1 GHz	8
8	1 GHz–1.2 GHz	8
9	1.2 GHz–1.7 GHz	8
10	1.7 GHz–1.9 GHz	8
11	1.9 GHz–2.6 GHz	8

$$F = V_{rx} + A_F + A_k \tag{1}$$

where F is the field strength level in (dBmV/m), V_{rx} is the receiver input voltage across 50 Ω in units of (dBmV), A_F is the antenna factor in (dB/m) and A_k is the cable loss in (dB). The field strength level F (dBmV/m) is converted to E_i (V/m) for each measurement using the relation in Equation (2)

$$E_i = (10^{-6})10^{F(dBmV/m)/20} \tag{2}$$

Since most signals employed in radio communication demonstrate, a variation with time due to modulation of mobile telecommunication system or due to traffic, time-averaged rms values of the electric field strength, E_t, averaged over 6 min, were obtained by using Equation 3.

$$E_t = \left[\frac{1}{6}\sum_{i=1}^{n} E_i^2 \Delta t_i\right]^{0.5} \tag{3}$$

where Δt_i is the time duration, in minutes, of the i^{th} time period and n is the number of time periods within 6 min. The spatial average electric field strength E_{av} for each location was determined using Relation 4;

$$E_{av} = \left[\frac{1}{n}\sum_{i=1}^{n} E_i^2\right]^{0.5} \tag{4}$$

Assuming a far-field condition, the power density $\boldsymbol{S}$ (W/m^2), at the location was calculated employing Equation 5[10]

$$S = \frac{E_{av^2}}{376.7303} \tag{5}$$

where E_{av} = spatial averaged electric field strength (V/m) measured and 376 7303 Ω is characteristic impedance of free space (Z_o).

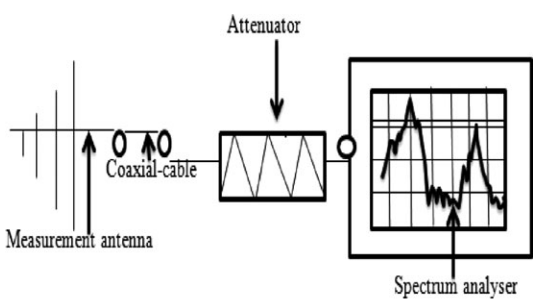

Figure 1. Schematic diagram of a frequency selective measurement of RF field.

For thermal considerations, relevant above 100 kHz, the following requirement should be applied to the field levels in order to remain within compliance:

$$\sum_{i-100\,\mathrm{kHz}}^{1\,\mathrm{MHz}} \left(\frac{E_i}{c}\right)^2 + \sum_{i>1\,\mathrm{MHz}}^{300\,\mathrm{GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1 \qquad (6)$$

where E_i = the electric field strength at frequency i; $E_{L,i}$ = the electric field reference levels[1]; c = is a constant which is frequency dependent and is $87/f^{1/2}$ Vm^{-1} for general public exposure.

Since frequencies investigated in this work are far above 1 MHz, the second part of equation (6) was applied to the fields as

$$\sum_{i>1\,\mathrm{MHz}}^{300\,\mathrm{GHz}} \left(\frac{E_i}{E_{L,i}}\right)^2 \leq 1 \qquad (7)$$

In comparing the results with ICNIRP, compliance was evaluated using Equation 8[1]

$$\sum_{1}^{N} \frac{S_i^{\mathrm{meas}}}{S_i^{\mathrm{guid}}} = \frac{S_1^{\mathrm{meas}}}{S_1^{\mathrm{guid}}} + \frac{S_2^{\mathrm{meas}}}{S_2^{\mathrm{guid}}} + \ldots \frac{S_N^{\mathrm{meas}}}{S_N^{\mathrm{guid}}} \leq 1 \qquad (8)$$

where S^{meas} is the measured (calculated) power density and S^{guid} is the guidance or reference power density. The combined spatial average uncertainty $U_c(E)$ was obtained from a large number of partial uncertainty values. The larger the number of measurements, the more closely the distribution approaches the Gaussian normal distribution. The combined spatial average uncertainty associated with ith spatial point assumed a normal probability distribution as shown in Table 2. In estimating the total uncertainty,

- ❖ Estimation of the arithmetic mean values of the field strength at each spatial point was made.
- ❖ Estimation of the spatial average field value was carried out by employing Equation (4).
- ❖ The mean value of the square of the deviations of the individual measurements from the mean called Variance was calculated. The normal statistical method of finding out the standard deviation which is equal to the standard uncertainty of that particular quantity was employed.
- ❖ The standard deviation was calculated. This was done by normal statistical method of finding out the measure of dispersion of the physical quantity by taking the square root of the variance.
- ❖ The partial derivatives c_i (sensitivity coefficients) of the mean values were calculated according to equation (4).
- ❖ The effective degrees of freedom were calculated, level of confidence (95.45%) was chosen and the coverage factor k (the probability that the set of true quantity values of a measurand is contained within specified coverage interval.) was determined from the Students t factor table.

Table 2. Calculation of expanded uncertainty for measurement of electric field strength.

Uncertainty sources	Type	Value	Probability distribution	Divisor	c_i	$u(x_i)$%	V_i
Spectrum Analyzer							
1 Amplitude accuracy	B	–	Rectangular	1.73	1	–	∞
2 Resolution Bandwidth	B	–	Normal	1.00	1	–	∞
Device-Under-Test							∞
3 Mismatch (Analyzer and Antenna)	B	–	U-shape	1.41	1	–	∞
4 Antenna calibration factors	B	–	Normal	2.00	1	–	∞
5 Cable correction factor	B	–	Rectangular	1.73	1	–	∞
6 Measurement Repeatability	A	–	Normal	1.00	1	–	$n-1$
N Measurement uncertainty		–					
Combined uncertainty (%)			$u_c(E) = \sqrt{\sum_{i=1}^{n} (C_i * u(x_i))^2}$				
Effective degrees of freedom			$V_{eff} = \frac{(u_c(E))^4}{\sum_{i=1}^{n} (u(x_i))^4 / V_i}$				
Desired coverage probability			P				
Respective coverage factor			k				
Expanded uncertainty (%)			$U = \pm k_* u_c(E)$				

Table 3. Uncertainty associated with the electric field measurement.

Uncertainty sources	Type	Estimate (%)	Probability distribution	Divisor	Standard uncertainty (%)
Spectrum analyzer					
Amplitude accuracy	B	5.94	Rectangular	2.00	2.97
Resolution Bandwidth(200 kHz)	B	10.00	Normal	2.00	5.00
Device-under-test					
Mismatch (Analyzer and Antenna)	B	3.64	U-shape	1.41	2.58
Antenna calibration factors	B	5.95	Normal	2.00	2.98
Cable correction factor	B	1.45	Rectangular	1.73	0.84
Measurement Repeatability	A	0.10	Normal	2.00	0.05
Measurement uncertainty					
Combined uncertainty (%)			Coverage factor		7.21
Expanded uncertainty (%)			2		14.42

The combined standard uncertainty estimation of each frequency sample involves the evaluation of root mean square value of all the partial standard uncertainties that affect the displayed value according to the method of the International Bureau of Weight and Measures (BIPM)[11] using the following equation:

$$u_i = \sqrt{\sum_j u_{TA,j}^2 + \sum_m u_{TB,m}^2} \tag{9}$$

where $u_{\mathrm{TA,j}}$ refers to the standard uncertainty accounting for the jth type-A uncertainty contributor (estimated by statistical method), and $u_{\mathrm{TB,m}}$ refers to the standard uncertainty accounting for the mth type-B uncertainty contributor (estimated using non-statistical analysis of a series of observation).

When a large number of measurements is averaged to obtain the best estimate, the uncertainty due to repeatability of measurement can be neglected, i.e. $u_{TA,j} = 0$. The combined standard uncertainty $u(\mathrm{E_{av}})$ of E_{av} becomes

$$u_i = \sqrt{\sum_{m=1}^{uc} u_{TB,m}^2} = \sqrt{\sum_{m=1}^{uc} (c_{m,i} * u(x_{m,i}))^2} \tag{10}$$

where $c_{m,i}$ is the sensitivity coefficient of the type-B uncertainty contributor x_{m} at a frequency i, and u $(x_{\mathrm{m,i}})$ is the standard uncertainty due to the contributor x_{m} at the same frequency (Table 3).

The sensitivity coefficient c_i of E_{av} with respect to the resultant field strength component at spatial point i, $E_{\mathrm{R,i}}$ (taking into account the partial uncertainties)[12] was evaluated using the same principles as follows:

$$c_i = \frac{\partial E_{\mathrm{av}}}{\partial E_{B,i}} = \frac{E_{R,i}}{\sqrt{\sum_{i=1}^{m} E_{R,i}^2}} = \frac{E_{R,i}}{E_{\mathrm{av}}} \tag{11}$$

The combine standard uncertainty for the average value is as follows:

$$u_c(E_{\mathrm{av}}) = \sqrt{\sum_{i=1}^{m} (c_i * u_c(E_{R,i}))^2}$$
$$= \frac{1}{E_{\mathrm{av}}} * \sqrt{\sum_{i=1}^{m} E_{R,i}^2 (u_c(E_{R,i}))^2} \tag{12}$$

In examining the uncertainty of the exposure quotient, E_{EQ}, in absolute values, the sensitivity coefficient of E_{EQ} with respect to $E_{\mathrm{R,i}}$ has to be calculated as;

$$C_R = \frac{\partial E_{EQ}}{\partial E_R} = \frac{2E_R}{E_{L,i}^2} \tag{13}$$

Given that $u_A(E_{R,i})$ is the uncertainty of $E_{R,i}$ in absolute values (V/m), then the absolute combined standard uncertainty $\mathrm{u_A}(E_{\mathrm{EQ}})$ of E_{EQ} will be given as;

$$u_A(E_{EQ}) = \sqrt{\sum_i \left(\frac{\partial E_{EQ}}{\partial E_{R,i}}\right)^2 u_A(E_{R,i})^2}$$
$$= \sqrt{\sum_i \left(\frac{2E_{R,i}}{E_{L,i}^2}\right)^2 u_A(E_{R,i})^2} \tag{14}$$

The uncertainties associated with the electric field measurements are stated in Table 3. The uncertainty associated with power density was estimated assuming far-field conditions using the following equations:

$$u(S) = 2u(E_{av}) \tag{15}$$

The reference values used are stated in Table 4.

Table 4. Variation of plane-wave electric field strength with height.

Band	Frequency (MHz)	Reference level (V/m)	Height (m)	Measured value (mV/m)	Exposure quotient	Power density/ nWm^{-2}
FM broadcast	87.5–108	28	1.0	0.837 ± 0.121	$8.93 \times 10^{-10} \pm 1.25 \times 10^{-10}$	1.86 ± 0.26
			1.5	0.961 ± 0.139	$1.18 \times 10^{-9} \pm 1.65 \times 10^{-10}$	2.45 ± 0.35
			1.7	0.545 ± 0.079	$3.78 \times 10^{-10} \pm 5.29 \times 10^{-11}$	0.78 ± 0.11
			2.0	0.432 ± 0.062	$2.38 \times 10^{-10} \pm 3.33 \times 10^{-11}$	0.50 ± 7.13
				Average	$\mathbf{6.72 \times 10^{-10} \pm 9.41 \times 10^{-11}}$	**1.40 ± 0.03**
VHF TV	174–230	28	1.0	2.415 ± 0.348	$7.44 \times 10^{-9} \pm 1.04 \times 10^{-9}$	15.52 ± 2.23
			1.5	2.476 ± 0.357	$7.82E \times 10^{-9} \pm 1.09 \times 10^{-9}$	16.33 ± 2.35
			1.7	2.540 ± 0.366	$8.23 \times 10^{-9} \pm 1.15 \times 10^{-9}$	17.14 ± 2.47
			2.0	1.832 ± 0.264	$4.28 \times 10^{-9} \pm 5.99 \times 10^{-10}$	8.91 ± 1.28
				Average	$\mathbf{6.94 \times 10^{-9} \pm 9.72 \times 10^{-10}}$	**14.42 ± 2.08**
UHF TV	470–862	30	1.0	9.656 ± 1.392	$1.04 \times 10^{-7} \pm 2.11 \times 10^{-8}$	247.32 ± 35.62
			1.5	11.709 ± 1.688	$1.52 \times 10^{-7} \pm 2.03 \times 10^{-8}$	363.66 ± 52.35
			1.7	18.565 ± 2.677	$3.83 \times 10^{-7} \pm 5.36 \times 10^{-8}$	914.22 ± 127.99
			2.0	11.797 ± 1.701	$1.55 \times 10^{-7} \pm 2.17 \times 10^{-8}$	369.15 ± 53.23
				Average	$\mathbf{1.99 \times 10^{-7} \pm 2.79 \times 10^{-8}}$	**473.59 ± 68.41**
GSM 900	925–960	42	1.0	63.178 ± 9.110	$2.26 \times 10^{-6} \pm 3.16 \times 10^{-7}$	10 587.43 ± 1482.24
			1.5	95.628 ± 13.790	$5.18 \times 10^{-6} \pm 7.25 \times 10^{-7}$	24 256.54 ± 3395.92
			1.7	56.789 ± 8.189	$1.83 \times 10^{-6} \pm 2.56 \times 10^{-7}$	8554.35 ± 1197.60
			2.0	50.606 ± 7.297	$1.45 \times 10^{-6} \pm 2.03 \times 10^{-7}$	6793.02 ± 951.02
				Average	$\mathbf{2.68 \times 10^{-6} \pm 3.75 \times 10^{-7}}$	**12 547.84 ± 1856.70**
GSM 1800	1805–1910	58	1.0	63.104 ± 9.100	$1.18 \times 10^{-6} \pm 1.65 \times 10^{-7}$	10 562.64 ± 1478.77
			1.5	62.410 ± 9.000	$1.16 \times 10^{-6} \pm 1.62 \times 10^{-7}$	10 331.59 ± 1446.42
			1.7	48.831 ± 7.041	$7.09 \times 10^{-7} \pm 9.93 \times 10^{-8}$	6324.84 ± 885.48
			2.0	63.319 ± 9.131	$1.19 \times 10^{-6} \pm 1.67 \times 10^{-7}$	10 634.74 ± 1488.86
				Average	$\mathbf{1.06 \times 10^{-6} \pm 1.48 \times 10^{-7}}$	**9463.45 ± 1324.88**
UMTS (WCDMA/3 G)	2110–70	61	1.0	33.059 ± 4.767	$2.94 \times 10^{-7} \pm 4.12 \times 10^{-8}$	2898.93 ± 405.85
			1.5	31.114 ± 4.487	$2.60 \times 10^{-7} \pm 3.64 \times 10^{-8}$	2567.85 ± 359.50
			1.7	33.172 ± 4.783	$2.96 \times 10^{-7} \pm 4.14 \times 10^{-8}$	2918.78 ± 408.63
			2.0	35.240 ± 5.081	$3.34 \times 10^{-7} \pm 4.68 \times 10^{-8}$	3294.05 ± 461.17
				Average	$\mathbf{2.96 \times 10^{-7} \pm 4.14 \times 10^{-8}}$	**2919.91 ± 408.79**

Note: The bold values are spatial average values for each frequency band.

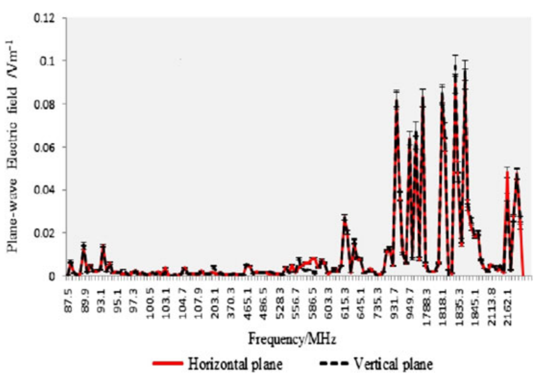

Figure 2. Plot of electric field against frequency for horizontal and vertical orientation of antenna elements at 1.0 m.

RESULTS

Results indicate that electric field distribution at measurement points varied with both height and

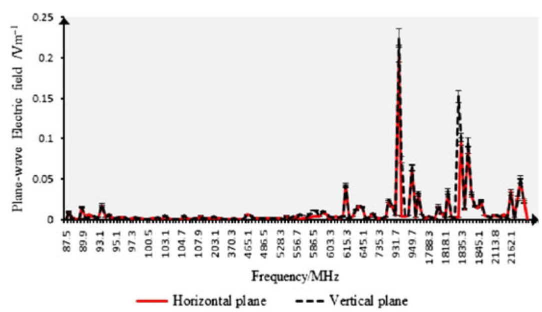

Figure 3. Plot of electric field against frequency for horizontal and vertical orientation of antenna elements at 1.5 m.

antenna orientation. Higher values were obtained for antenna orientations that aligned the antenna's log-periodic elements with the vertical plane (*Y*-axis) than when the antenna elements were polarized in the horizontal in almost all instances. For all the spatial heights investigated, the variations was

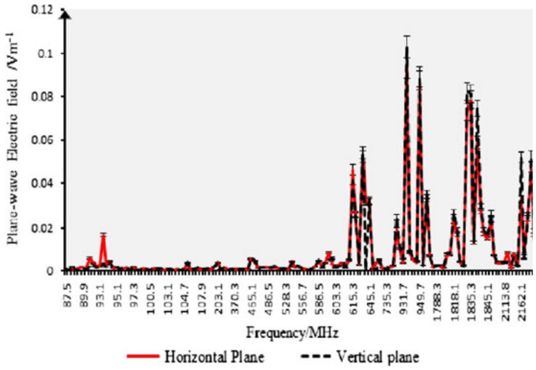

Figure 4. Plot of electric field against frequency for horizontal and vertical orientation of antenna elements at 1.7 m.

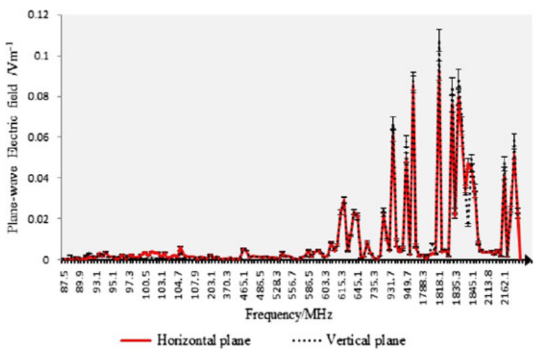

Figure 5. Plot of electric field against frequency for horizontal and vertical orientation of antenna elements at 2.0 m.

consistent and Figures 2–5 show how the electric field strengths vary with both horizontal and vertical orientations of antenna elements.

The electric field strengths were highest at Ultra High Frequencies above 600 MHz. Fields due to FM broadcast were very low. The highest electric field strength obtained at the hospital's premises due to FM radio broadcast was $0.0162 \pm 0.002\ \mathrm{Vm^{-1}}$ at a spatial height of 1.7 m above ground level with the antenna elements aligned with the vertical plane. This field strength has an associated power density of $0.697 \pm 0.101\ \mu\mathrm{Wm^{-2}}$. The highest electric field for this location was $0.3648 \pm 0.019\ \mathrm{Vm^{-1}}$ giving rise to the highest power density of $0.35 \pm 0.05\ \mathrm{m\ Wm^{-2}}$. These values are of similar magnitude as those reported by Mann *et al.*[13]

The spatial average values of the electric fields from the various orientations of the antenna elements, i.e. *X*-

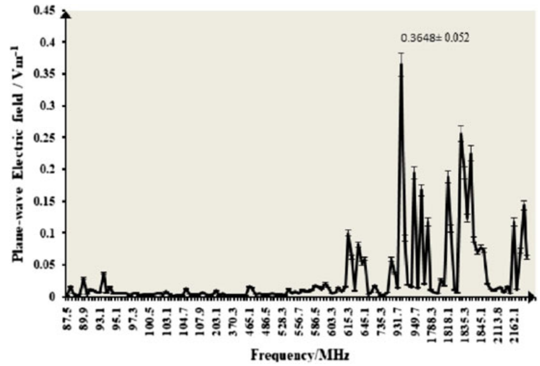

Figure 6. Plot of *E* (spatial average).

axis and *Y*-axis are plotted against their corresponding frequencies in Figure 6. The values of the resolved electric field at the four spatial heights ranged from 1.00 ± 0.144 m V/m to 1.174 ± 0.169 V/m. In Table 2, a summary of the numeral results of the assessment were displayed for each frequency band.

DISCUSSION

Results obtained showed a general compliance with ICNIRP reference levels and agreed to some extent with other results from similar works conducted in the Ghana[8, 14]. The field levels were greatest while the stacked log-periodic antenna elements were aligned with the vertical plane in more than 90% of the measurements. This shows that absorption of the fields by a body being exposed depends on the orientation of the body in the field and the coupling between the body and the electric field is maximized in this orientation. In this case, upright bodies in the far-field have a higher exposure than other postures. The variations in the electric field levels at the various spatial heights can be attributed to ground reflections. The highest values were measured at a height of 1 m above the ground in most cases. With the stacked antenna elements aligned vertically, the highest electric field levels were detected. This might be so due to the fact that at far-field distances, the components of the electric field are planar.

The human body is known to resonate at FM frequencies. Fields due to FM frequencies at the hospitals ground premise are the lowest and are well below the ICNIRP levels. Comparing results reported here to wide-band assessment of two major TV stations in Ghana by Osei *et al.* in 2015[15], our plane-wave field strengths levels were much lower in value. This is so because Osei *et al.* made a work-place (occupational exposure) assessment and most of their measurements were done in close proximity to transmitters.

CONCLUSION

The results obtained from this comprehensive survey on the ground premises of a teaching hospital in Ghana are clear indications of the ambient RF field levels within the premises of most hospitals in Ghana. Within 87.5 MHz and 2.6 GHz, results show that upright bodies are likely to be more exposed to RF fields. Even though the results were well within the ICNIRP limit, it was higher when compared with work conducted in schools within the same period by this research team. There is the need to duplicate this study within the wards, corridors and balcony of this hospital and at higher heights above the ground since the wards are several floors above ground. This will go a long way to help provide a definitive description of the exposure situations of patients admitted to or visiting the facility.

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