Electromagnetic Compatibility (EMC) Antenna Gain and Factor

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***Abstract*—A method for calculating and measuring antenna gain and factor over perfect ground is presented. The electromagnetic compatibility antenna factor is used to determine the spurious electric field of the device under evaluation. The radio link employed to calibrate the receiving antenna gain and factor will produce completely different values for the transmitting and receiving antennas, and the principle of reciprocity does not hold true, in this particular case, even if both antennas are identical.**

***Index Terms*—Antennas, antenna radiation patterns, dipole antennas, electromagnetic fields, electromagnetic coupling, electromagnetic reflection, electromagnetic radiation, far-field, line-of-sight propagation, near-field, radio propagation.**

I. Introduction

ELECTRIC field strength and power density in space produced by a transmitting antenna is given by

$$E = \frac{(30 \cdot W_T \cdot G_T)^{1/2}}{r} \cdot e^{-j\beta r} \ (\mathrm{V\,/\,m}) \qquad (1)$$

where

E is the electric field strength (V/m);
W_T is the transmitted power (w);
G_T is the transmitting antenna gain;
r is the distance (m);
β is the space phase constant (rad/m) or (degree/m);
λ is the wavelength (m).

Power density in free space can be calculated as

$$P_i = \frac{W_T G_T}{4\pi r^2} \ (\mathrm{W\,/\,m^2}) \qquad (2)$$

where

P_i is the power density $\mathrm{W/m^2}$;
G_T is the transmitting antenna gain;
r is the distance (m).

The electric field strength in space for a half-wave dipole antenna whose gain is $G = 1.64$ and for a transmitted power $W_T = 1$(w), is as follows [1]:

$$E = \frac{(30 \cdot 1.64)^{1/2}}{r} = \frac{7.0143}{r} \ (\mathrm{V\,/\,m}). \qquad (3)$$

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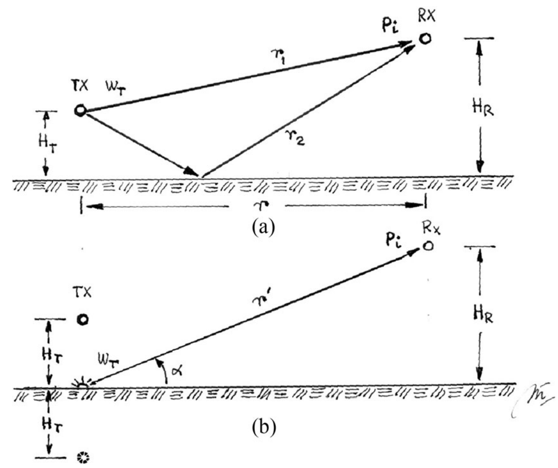

Fig. 1. Radio link over perfect ground.

Smith [2] used this simple equation and included in it the transmitting antenna factor (AF_T).

In order to calibrate the receiving antenna gain (G_R) and factor (AF_R) a controlled radio link over perfect ground is used where conductivity σ is practically infinite ($\sigma = \infty$).

Fig. 1 shows the geometry of the radio link or antenna range.

In this radio link, from its geometry, following equations apply:

$$r_1 = [(H_R - H_T)^2 + r^2]^{1/2} \ (\mathrm{m}) \qquad (4)$$

$$r_2 = [(H_R + H_T)^2 + r^2]^{1/2} \ (\mathrm{m}) \qquad (5)$$

$$\alpha = \tan^{-1}\left(\frac{H_R}{r}\right) \ (^\circ) \qquad (6)$$

$$r' = [(H_R)^2 + r^2]^{1/2} \ (\mathrm{m}). \qquad (7)$$

Traditionally, the electric field strength for horizontal polarization can be calculated taking into account the reflexion coefficient of the perfect ground for horizontal polarization whose value is

$$\Gamma_H = |1|\angle 180^\circ. \qquad (8)$$

And the total electric field E_i arriving at the receiving antenna is

$$E_i = \frac{7.0143 \cdot \left(r_1^2 + \Gamma_H^2 \cdot r_2^2 + 2 \cdot r_1 \cdot r_2 \cdot \Gamma_H \cdot \cos(\phi_H - \delta)\right)^{1/2}}{r_1 \cdot r_2} \qquad (9)$$

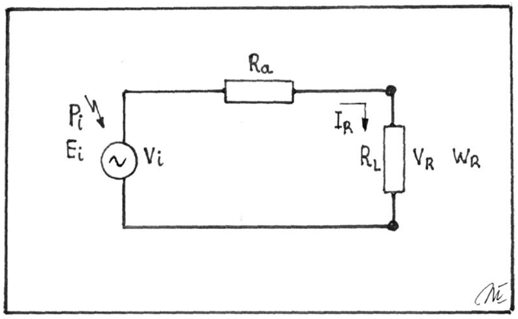

Fig. 2. Receiving antenna Thevenin equivalent circuit.

where

$\Gamma_H = 1$;
$\phi_H = 180°$;
$\delta = \beta \cdot (r_2 - r_1)$;
$\beta = \frac{2\cdot\pi}{\lambda} = \frac{360}{\lambda}$.

In this geometry, the transmitting antenna (half-wave dipole antenna) is in reality an array of two elements, the actual antenna and its image. Due to the perfect reflexion ($|\Gamma_H| = 1$) both sources deliver the power density on the receiving antenna (half-wave dipole antenna) and the total power density is

$$P_i = \frac{E_i^2}{Z_{oo}} \text{ (w/m}^2\text{)} \quad (10)$$

where

E_i is the total electric field (effective value) (V/m);
Z_{oo} is the free space characteristic impedance $(120\pi) = 377\ \Omega$.

The receiving antenna equivalent circuit, for a perfect matched and resonant antenna $R_L = R_a = R_{\text{rad}}$ and $X_a = 0$ can be a Thevenin circuit as indicated in Fig. 2 [3].

In this condition, the receiving antenna delivers the power (W_R) on its resistive load (R_L) and an equal amount on its radiation resistance ($R_a = R_{\text{rad}}$) that it is scattered into the surrounding space. The power density on the receiving antenna is calculated in a simpler form taking into account that the transmitting antenna is an array of two elements whose gain is obtained by its radiating pattern calculated by the traditional equation or by a standard antenna software. The equation for horizontal polarization is

$$G_T = 10 \cdot \log(4 \cdot (\sin(\beta H_T \cdot \sin(\alpha)))^2) + 2.15 \text{ (dBi)} \quad (11)$$

where βH_T is the transmitting antenna height in radian or degree. The power density on the receiving antenna is

$$P_i = \frac{W_T \cdot G_T(\alpha)}{4 \cdot \pi \cdot (r')^2} \text{ (W / m}^2\text{)} \quad (12)$$

where P_i is the power density on the receiving antenna at the distance r' and at the elevation angle α. $G_T(\alpha)$ is the transmitting antenna gain at the elevation angle α. r' is the distance between the radiating wave center phase and the center of the receiving antenna, according to Fig. 1.

Both methods give exactly the same result for the power density on the receiving antenna but this last one is simpler to be used. This same procedure can be used also for vertical polarization, using the proper equation. To show the same result in calculating the power density over the receiving antenna, two calculations were performed in a radio link at a frequency $f = 300$ MHz and for a distance $r = 100$ m, $H_T = 2$ m for both polarizations. Figs. 3 and 4 show the power density for a frequency $f = 300$ MHz and at the distance of $r = 100$ m as a function of receiving antenna height for the traditional procedure and the new one where no differences are noted showing the exact numerical result for both polarizations. The receiving antenna effective length is calculated by the traditional equation

$$L_e = \frac{1}{I_o} \cdot \int_{-H}^{H} I(z) \cdot dz \text{ (m)}. \quad (13)$$

For a half-wave dipole antenna performing the indicated integration, the effective length L_e is

$$L_e = \frac{\lambda}{\pi} \text{ (m)}. \quad (14)$$

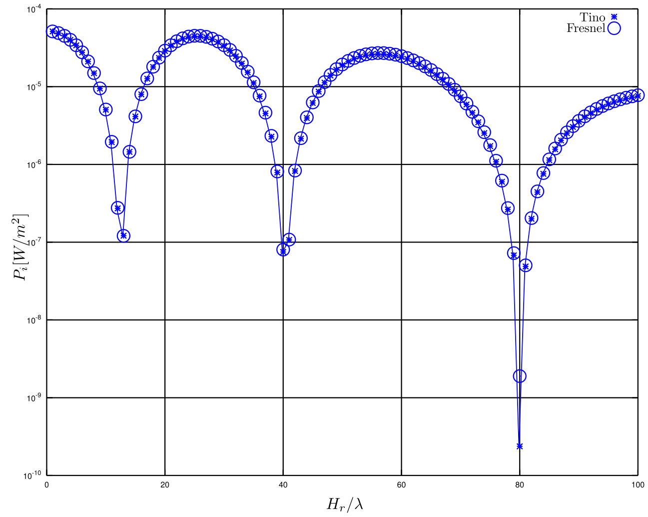

Fig. 3. Power density for vertical polarization, f= 300 MHz, r= 100 m, $H_T = 2$ m.

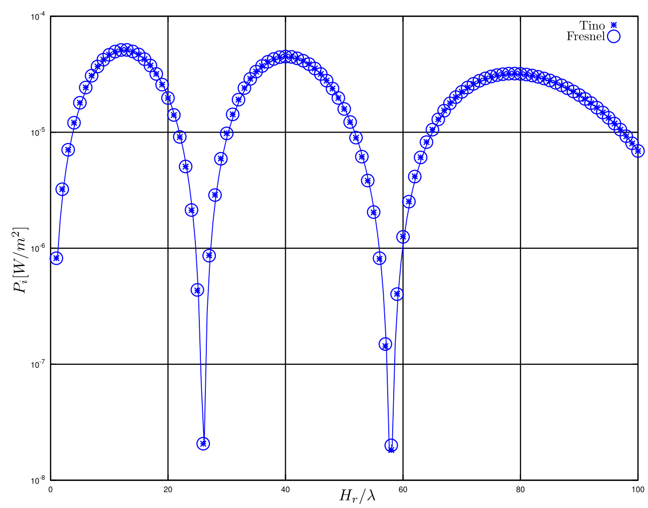

Fig. 4. Power density for horizontal polarization, f= 300 MHz, r= 100 m, $H_T = 2$ m.

Knowing the power density and the electric field strength, the induced voltage (V_i) can be calculated, as [4]

$$L_e = \frac{V_i}{E_i}\ (\mathrm{m}). \tag{15}$$

And immediately the Thevenin equivalent circuit current is available and the power delivered on the resistive load R_L can be calculated, as

$$I_R = \frac{V_i}{R_a + R_L}\ (A). \tag{16}$$

For a perfectly matched and resonant antenna

$$I_R = \frac{V_i}{2\ R_a} = \frac{V_i}{2\ R_L}\ (A) \tag{17}$$

$$W_R = I_R^2 \cdot R_L\ (w). \tag{18}$$

The receiving antenna effective area A_{eR} is calculated by the relationship between the delivered power (W_R) and the power density (P_i), or

$$A_{eR} = \frac{W_R}{P_i}\ (\mathrm{m}^2). \tag{19}$$

The receiving antenna gain is calculated by

$$G_R = \frac{4 \cdot \pi \cdot A_{eR}}{\lambda^2}. \tag{20}$$

For a perfect matched and resonant antenna, the effective area (A_{eR}) will be the maximum value or (A_{eRM}). In this case, the antenna must be oriented for the maximum signal and perfectly adapted in polarization [3]. The effective scattered area (A_{sR}) is obtained as

$$A_{sR} = \frac{W_s}{P_i}\ (\mathrm{m}^2) \tag{21}$$

where W_s is the scattered power delivered on the radiation resistance ($R_a = R_{\mathrm{rad}}$), or

$$W_s = I_R^2 \cdot R_a\ (w). \tag{22}$$

The maximum effective scattered area (A_{sRM}) is obtained when the receiving antenna resistive load is $R_L = 0$, so the power delivered on the receiving antenna is totally scattered in the surrounding space. In this case

$$A_{sRM} = 4 \cdot A_{eRM}\ (\mathrm{m}^2) \tag{23}$$

or the maximum scattered area is four time the maximum effective area (relationship is 6 dB). As an example at a frequency $f = 100$ MHz for a half-wave receiving dipole antenna perfectly matched and resonant, results in

$R_L = 73\ \Omega$;
$A_{eRM} = 1.18\ \ (\mathrm{m}^2)$;
$A_{sR} = 1.18\ \ (\mathrm{m}^2)$;
$G_{RM} = G_s = 1.64$ (2.16 dBi);
$R_L = 0\ \Omega$;
$A_{eR} = 0\ (\mathrm{m}^2)$;
$A_{sRM} = 4.72\ \ (\mathrm{m}^2)$;
$G_{sM} = 6.56$ (8.17 dBi).

The receiving antenna is more efficient in scattering the received electromagnetic waves, or its scattered gain (G_s) is 6 db larger than the maximum effective receiving antenna gain (G_{RM})[3]. As the receiving antenna work without the presence of its image, the receiving antenna gain and antenna factor is practically constant as a function of antenna height over perfect ground, when heights are larger than one wavelength and the ground mutual effect is negligible. It is clear that the receiving antenna image receive no power from the incoming wave and it has no effect at the received power on R_L.

This becomes a very good reference antenna, called the free space antenna factor (FSAF).

The receiving antenna factor (AF) is similar to the effective antenna length (L_e) but the relationship is between the incident electric field (E_i) and the voltage (V_R) developed on the receiving resistance (R_L). As an example at a frequency $(f = 100\ \mathrm{MHz})$, resulting effective length is

$$L_e = \frac{V_i}{E_i} = \frac{\lambda}{\pi} = 0.9549\ (\mathrm{m}). \tag{24}$$

For a perfect matched and resonant antenna, the antenna factor is

$$\mathrm{AF} = \frac{E_i}{V_R} = \frac{2E_i}{V_i} = \frac{2}{L_e}\ (1/\mathrm{m}). \tag{25}$$

Also

$$\mathrm{AF}_R = \frac{E_i}{V_R} = \frac{1.303}{6.22E - 1} = 2.0948\ (1/\mathrm{m}) \tag{26}$$

$(\mathrm{AF}_R)_{73} = 6.42$ (dB/m);
$(\mathrm{AF}_R)_{50} = 8.06$ (dB/m).

This value was obtained by a radio link geometry. It can be obtained by the federal ccomunication commission (FCC) expression knowing the frequency and the antenna gain and for $Z_o = 50\ (\Omega)$, or

$$\mathrm{AF}_R(\mathrm{FCC}) = -29.78 + 20\log f_{\mathrm{MHz}} - 10\log G_R \tag{27}$$

$$\mathrm{AF}_R(\mathrm{FCC}) = 8.07\ (\mathrm{dB/m}). \tag{28}$$

Also, through the expression

$$\mathrm{AF}_R = \frac{\pi}{\lambda} \cdot \left(\frac{480}{R_a \cdot G_R}\right)^{1/2}\ (1/\mathrm{m}) \tag{29}$$

$$\mathrm{AF}_R = 2.097\ (1/\mathrm{m}) \tag{30}$$

$(AF_R)_{73} = 6.43$ (dB/m);
$(AF_R)_{50} = 8.07$ (dB/m).

All mathematical expression are derived from the original definition

$$\mathrm{AF} = \frac{E_i}{V_R}\ (1/\mathrm{m}). \tag{31}$$

The transmitting antenna is an array of two half-wave dipole elements, and of course, its value will be different from that of the receiving antenna. In this case, the principle of reciprocity is invalid even when the antennas are similar or identical. They seem identical but they operate in a very different way. The simplest way is using the same equation as the receiving antenna to calculate the transmitting antenna factor when the antenna gain and its radiation resistance can be known as

$$\mathrm{AF}_T = \frac{\pi}{\lambda} \cdot \left(\frac{480}{R_a G_T}\right)^{1/2} \ (1/\mathrm{m}). \tag{32}$$

Generally, this value must be calculated according to the data and the radio link geometry. Also, by the well-known radiation pattern equations for horizontal or vertical polarization, it is possible to know the transmitting antenna gain, or by means of a lot of antenna specialized software programs, the antenna height over perfect ground can be known. Other form is the transmitting antenna gain calculation by the Friis equation during measurements [5]. If the ground is not perfect, the transmission antenna gain can suffer some deterioration decreasing its maximum gain value obtained over perfect ground but this does not modify the receiving antenna gain and factor because it works in free space if its height is larger than one wavelength. The other problem is knowing at what elevation angle (α) is necessary to know the antenna gain $((G_T(\alpha))$. This angle (α) is generally the elevation angle indicated in the radio link geometry between the radiated phase center and the center of the receiving antenna according to Fig. 1. The array radiation phase center is exactly in the center of the two radiating elements (the actual antenna and its image) for perfect ground $(\sigma = \infty)$. As an example at a frequency $f = 100$ MHz, $\lambda = 3$ m for transmitting antenna height $H_T = 1$ m and radio link distance $r = 10$ m, the calculated transmitting antenna factor AF_T results $(\mathrm{AF}_T)_{50} = 5.13$ (dB/m) when the receiving antenna is located at a height of $H_R = 4$ m or when the received power on the resistive load is a maximum for the available receiving antenna scanned height. If the transmitting antenna height is $H_T = 2$ m for the same radio link distance of $r = 10$ m, the calculated transmitting antenna factor $(\mathrm{AF}_T)_{50} = 2.05$ (dB/m) the receiving antenna factor is almost constant and $(\mathrm{AF}_R)_{50} = 8.06$ (dB/m), so the receiving antenna is operating like in free space and almost independent of the height over the ground.

The normalized site attenuation (NSA) is defined as

$$\mathrm{NSA} = A_w(\mathrm{dB}) - \mathrm{AF}_T(\mathrm{dB/m}) - \mathrm{AF}_R(\mathrm{dB/m}) \ (\mathrm{dB}) \tag{33}$$

where

A_w is the power relationship in dB;
$(\mathrm{AF}_T)_{50}$ is the transmitting antenna factor (dB/m);
$(\mathrm{AF}_R)_{50}$ is the receiving antenna factor (dB/m).

In this example, results are:

$$\mathrm{NSA} = 25.83 - 5.13 - 8.06 = 12.64 \ (\mathrm{dB}) \tag{34}$$

$$\mathrm{NSA} = 22.76 - 2.05 - 8.06 = 12.65 \ (\mathrm{dB}). \tag{35}$$

The NSA is almost the same for two different transmitting antenna heights and the antenna range is supposed to be exactly the same. Is it really important to know the NSA value?

For EMC evaluation, the most important value is the receiving antenna factor $\mathrm{AF}_R(\mathrm{dB}/m)$ that must be as accurate as possible. In order to know the amount of error generated when considering that the transmitting and receiving antenna fulfill or not the reciprocity theorem, an example can be given as an illustration

At a frequency $f = 100$ MHz, $\lambda = 3$ m, a radio link has the following data:

$H_T = 2$ (m); $1 \leq H_R \leq 4$ (m); $W_T = 1$ (w); $r = 10$ (m); $L_e = 0.9549$ (m).

Results are as follows:

$A_w = -22.70$ (dB); $A_{\mathrm{FS}} = -33.09$ (dB); $P_i = 4.5E-3$ (w/m^2); $E_i = 1.24$ (V/m); $I_R = 8.52E-3$ (A); $W_R = 5.3E-3$ (w); $A_{eR} = 1.177$ (m^2); $G_R = 2.16$ (dBi); $K = A_w - A_{\mathrm{FS}} = 10.33$ (dB); $V_R = 6.22E-1$ (V); and $\mathrm{AF}_R = 8.06$ (dB/m).

Using the transmission equation or Friis equation

$$G_T(\mathrm{dBi}) + G_R(\mathrm{dBi}) = A_w(\mathrm{dB}) - A_{FS}(\mathrm{dB}) = K \ (\mathrm{dB}) \tag{36}$$

$$G_T(\mathrm{dBi}) + G_R(\mathrm{dBi}) = K(\mathrm{dB}) = 10.33 \ (\mathrm{dB}). \tag{37}$$

If the antennas are "supposed" to have the same behavior, i.e., gain and factor, the results of the Friis equation will be divided by 2, resulting in:

$G_T = 5.17$ (dBi) (3.28);
$G_R = 5.17$ (dBi) (3.28);
and $(AF_T)_{50} = 5.06$ (dB/m)
$(\mathrm{AF}_R)_{50} = 5.06$ (dB/m).
In this case, the NSA is

$$\mathrm{NSA} = 22.70 - 5.06 - 5.06 = 12.58 \ (\mathrm{dB}). \tag{38}$$

Nevertheless, the receiving antenna gain calculation for this radio link gives $G_R = 2.16$ (dBi). Applying the Friis equation [5]

$$G_T(\mathrm{dBi}) = K(\mathrm{dB}) - G_R(\mathrm{dBi}) = 10.33 - 2.16 = 8.17 \ (\mathrm{dBi}). \tag{39}$$

In this condition, the antenna factors will be
$(\mathrm{AF}_T)_{50} = 2.05$ (dB/m);
$(\mathrm{AF}_R)_{50} = 8.07$ (dB/m).
And the NSA produces

$$\mathrm{NSA} = 22.70 - 2.05 - 8.07 = 12.58 \ (\mathrm{dB}). \tag{40}$$

The NSA gives the same result, but, the antenna gains and factors are completely different as calculations indicate. If the receiving antenna factor $(\mathrm{AF}_R)_{50} = 8.07$ (dB/m) is used for certification or evaluation of electric field radiated by any kind of devices, the result will be also correct.

If the receiving antenna factor $(\mathrm{AF}_R)_{50} = 5.06$ (dB/m) is used, the error will be around 3 dB in any measurements.

Of course, if the standards tolerate +/− 4 dB errors in any measurements or calculations, the result of a wrong antenna factor could fits the task.

Good engineering practices always advocate reducing errors analyzing perfectly well the physics involved in this kind of operations and the best receiving antenna calibration is of paramount importance.

II. Antennas at Short Elevations Over Ground

This was a typical installation in the past and with radio links in high-frequency bands (HF) through the ionosphere. In HF, generally the transmitting and receiving antenna height was

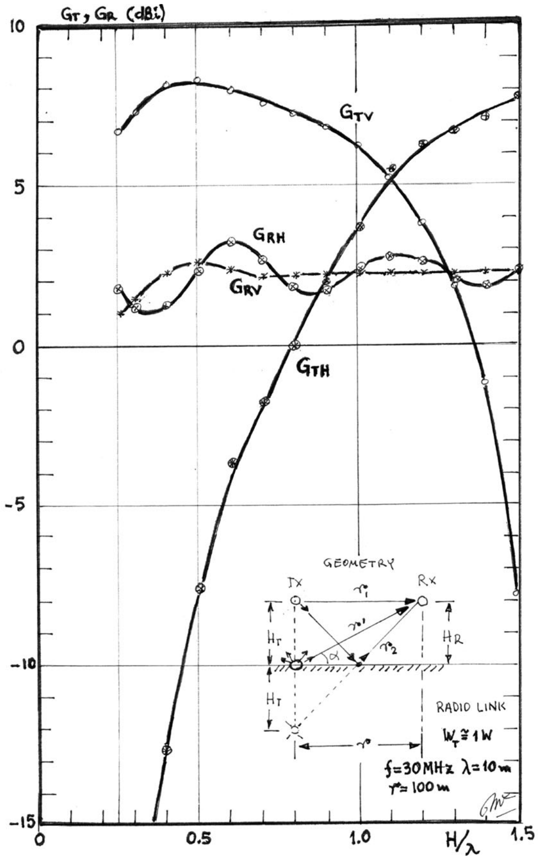

Fig. 5. Resonant dipole gain over perfect ground, $f = 30$ MHz, $r = 100$ m.

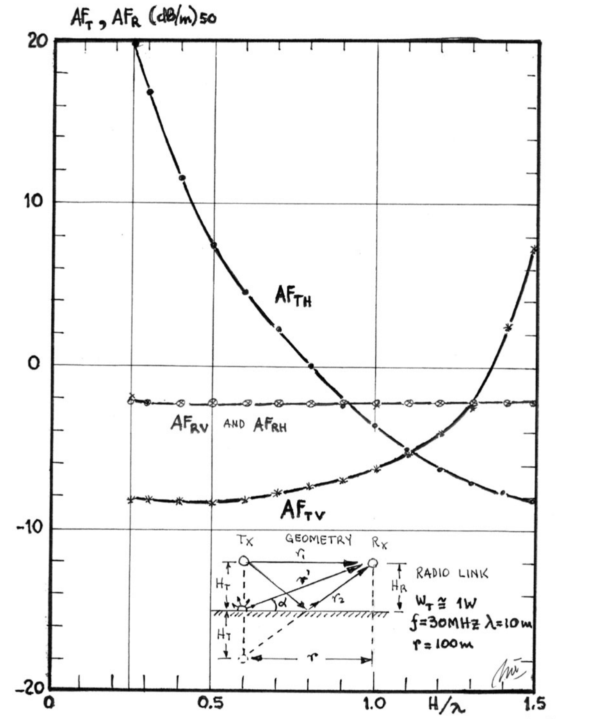

Fig. 6. Resonant dipole factor over perfect fround, $f = 30$ MHz, $r = 100$ m.

quite low due to the long wavelengths involved (λ ≅ 100–10 m) and most of them operated between 0.1 and 1.5 wavelength in height [3], [6]. It was well known that the transmitting antenna was an array of two elements and its radiation pattern was calculated in order to get the maximum radiation at a specific elevation angle α to fulfill the ionosphere radio link requirements [3]. This problem for EMC operation occurs in the lower part of the radio spectrum below 100 MHz ($\lambda = 3$ (m)). Both antennas in the radio link are installed at low heights, and for this reason, the antenna interacts with ground. Maximum interaction occurs for horizontal polarization and more moderate effect is for vertical polarization. According to Fig. 1, several examples were performed for a frequency of 30 MHz, $r = 100$ (m) and for both vertical and horizontal polarization. Fig. 5 shows the result of the gain of a half-wave dipole for both polarizations in the transmitting and receiving role. Clearly the transmitting and receiving antenna gain is completely different as a function of the antenna height. In this case, both antennas were moved simultaneously at the same height. In Fig. 5, the receiving antenna gain oscillations around the free space gain as a function of height are very close to 2.15 dBi. Vertically polarized half-wave dipole acquires faster this position and with lower oscillation around the free space value. Transmitting and receiving antenna factors are shown in Fig. 6. Here, receiving antenna factor value are very close to the free space value and almost constant as a function of height for both polarizations. On the contrary, the transmitting antenna factors show large variations as a function of the transmitting antenna height.

Fig. 7 shows the half-wave dipole resistance $R_a = R_{\text{rad}}$ at resonance $X_a = 0$ calculated at the frequency $f = 30$ MHz, $\lambda = 10$ (m), as a function of antenna height over λ. They can be valid at any frequency for H/λ. It can be seen clearly the tendency at the free space resistance value as receiving antenna height is increased. Vertical polarized dipole acquires this free space value at lower heights. Nevertheless, for horizontal polarized dipoles, the resistance values for heights larger than one wavelength are producing very low mismatches. These mismatches produce standing wave ratio lower than 1.1, so the efficiency of the receiving system is larger than 99% in this matter when $R_L \cong R_a$, $X_a = 0$. The half-wave dipole resistance at resonance depends, also, on the H/a relationship in free space decreasing a little bit the theoretical value of very thin dipoles with higher value of H/a. Simulations with H/a values at different antenna heights show practically the same resistance value for a resonant dipole for any H/a value. The resonance resistance is oscillating around the free space value of 73 Ω for H/a value between 1000 and 50 where most antennas are to be used. At low frequencies and horizontal polarization, the transmitting antenna is located at very low elevations over ground and for this reason its radiation pattern has a maximum radiation near the zenith ($\alpha \cong 90°$). At the same time, very low elevations means very low radiation resistance. For this reason, minimum height of a fixed transmitting antenna for both polarizations in a radio link could be 0.25–0.3 wavelength. In Fig. 8, the dipole radiation pattern can be seen for a frequency of $f = 30$ MHz where the maximum radiation is pointing to the zenith $\alpha = 90°$. In Fig. 9, the transmitting and receiving

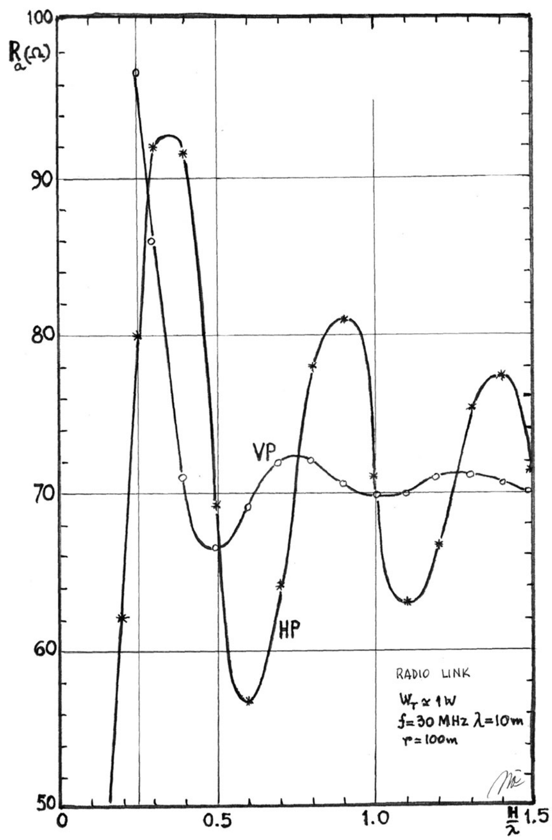

Fig. 7. Resonant dipole resistance over the perfect ground, $f = 30$ MHz, $r = 100$ m.

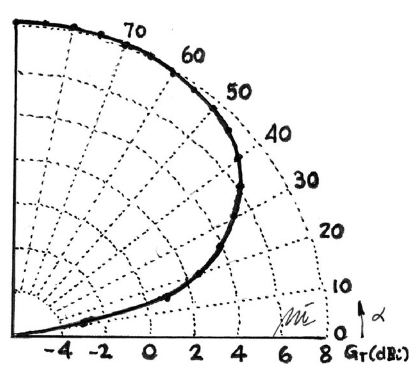

Fig. 8. Dipole radiation pattern $f = 30$ MHz, $H_T = 2.5$ m, $r = 10$ m.

antenna gains can be seen as a function of the antenna height at a frequency $f = 30$ MHz, and Fig. 10 shows the transmitting and receiving antenna factors for the same frequency and H/λ. As frequency is increased, the transmitting antenna radiation pattern has a maximum at lower elevation angles α as seen in Fig. 11 at a frequency $f = 60$ MHz, $\lambda = 5$ m. At this frequency, the transmitting antenna maximum radiation for a height of 2.5 m is located at an angle $\alpha = 30°$.

In Fig. 12, the transmitting and receiving antenna gain are plotted as a function of receiving antenna height, and in Fig. 13, the antenna factors are presented for a frequency $f = 60$ MHz and the transmitting antenna height $H_T = 2.5$ m. If frequency

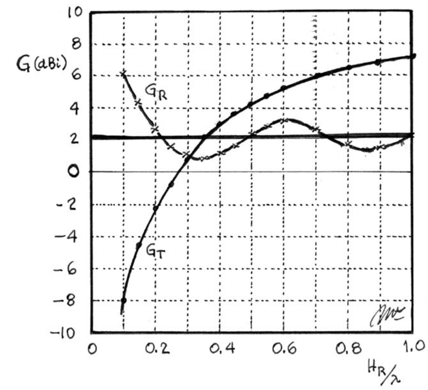

Fig. 9. Dipole gain $f = 30$ MHz, $H_T = 2.5$ m, $r = 10$ m.

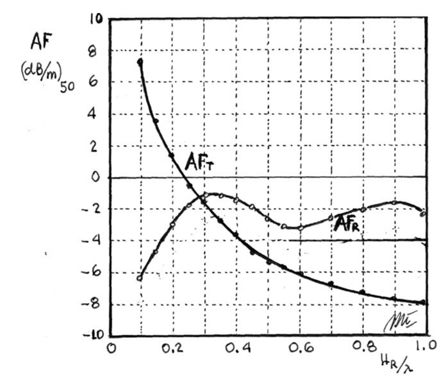

Fig. 10. Dipole factor $f = 30$ MHz, $H_T = 2.5$ m, $r = 10$ m.

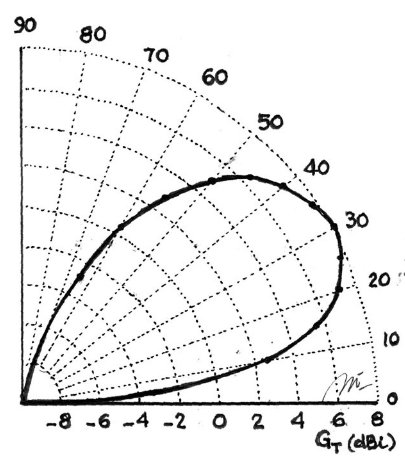

Fig. 11. Dipole radiation pattern $f = 60$ MHz, $H_T = 2.5$ m, $r = 10$ m.

is further increased, the radiation pattern is split in several lobes each one with a maximum gain at different elevation angles α. Fig. 14 represents the radiation pattern at a frequency $f = 150$ MHz as well its lobular structure with maximum gain at elevation angles $\alpha = 12°$, $\alpha = 37°$, and $\alpha = 90°$. The transmitting and receiving antenna gain are represented in Fig. 15 where the receiving antenna gain is practically constant as a function of the receiving antenna height. At the same time, the transmitting antenna gain variation is noticed due to its lobular

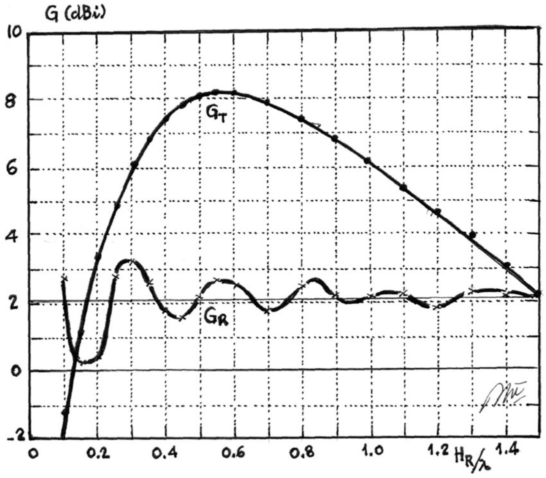

Fig. 12. Dipole gain $f = 60$ MHz, $H_T = 2.5$ m, $r = 10$ m.

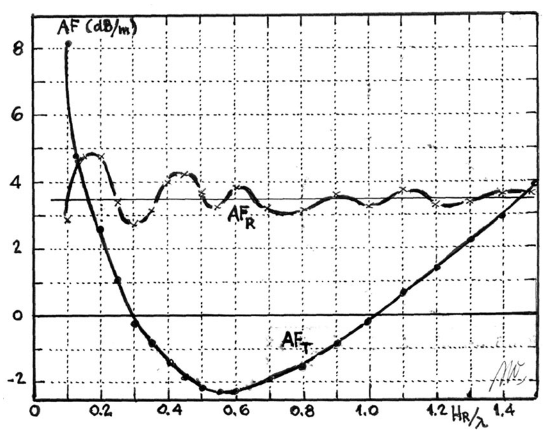

Fig. 13. Dipole factor $f = 60$ MHz, $H_T = 2.5$ m, $r = 10$ m.

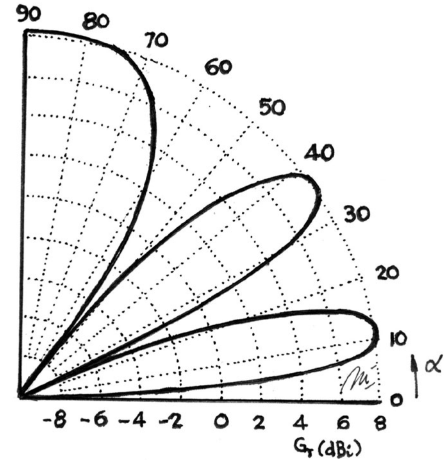

Fig. 14. Dipole radiation pattern $f = 150$ MHz, $H_T = 2.5$ m, $r = 10$ m.

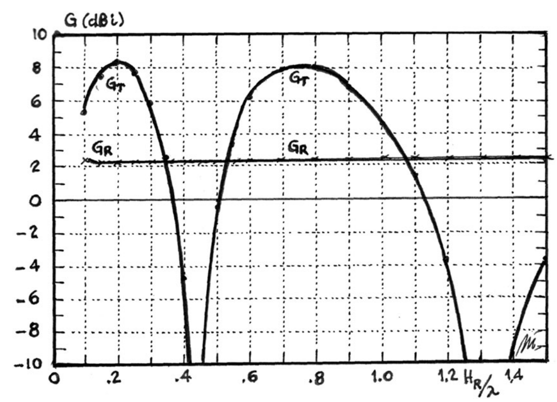

Fig. 15. Dipole gain $f = 150$ MHz, $H_T = 2.5$ m, $r = 10$ m.

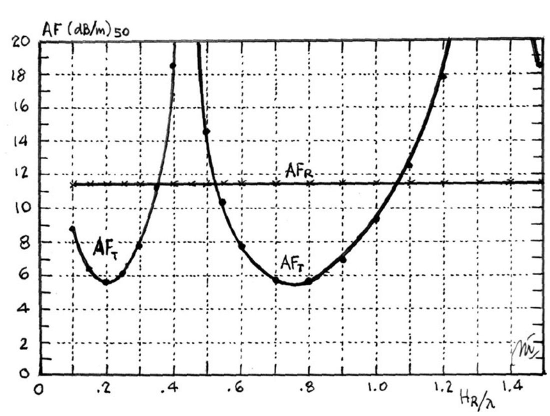

Fig. 16. Dipole factor $f = 150$ MHz, $H_T = 2.5$ m, $r = 10$ m.

structure as a function of the elevation angle α. The receiving antenna is scanning in height the power density in space produced by the transmitting antenna as a function of height, but its gain is practically constant no matter the larger variation of the the transmitting antenna gain. This is a good demonstration of the receiving antenna behavior when the receiving antenna height is larger than one wavelength working as in free space. Similar behavior for the transmitting and the receiving antenna factors are represented in Fig. 16.

III. Radio Link Site Evaluation

Receiving antenna gain and factor calculations are determined in a radio link installed over an almost perfect conductive ground plane. This can be achieved with a smooth area covered by metallic plates in an open test site and without nearby obstacles like walls or fences, in order to avoid any possible spurious reflexions. Metallic plates have a very high conductivity in the order of $\sigma = 10^7$ (S/m). This conductivity value corresponds to most metals from iron to copper. In case of security or defense, this metallic surface can be installed in an anechoic chamber in order to create a quasi-free space environment over a perfect ground. Distance *r* between antennas in this radio link must be sufficient to have a far-field conditions and almost no mutual effects between antennas. For this reason, a minimum distance *r* must be in the order of 10 m or a wavelength at the minimum frequency.

Site attenuation can be calculated by the Friis Equation [5], and written as

$$G_T(\text{dBi}) + G_R(\text{dBi}) = A_w(\text{dB}) - A_{FS}(\text{dB}) = K(\text{dB}) \quad (41)$$

where

G_T is the transmitting antenna gain (dBi);
G_R is the receiving antenna gain (dBi);
A_w is the link power relationship (dB);
A_{FS} is the free space attenuation (dB).

The Friis equation can be used also in a link over the perfect ground. In this case, the antenna gains must be determined in working conditions and the distance *r*' corresponds at the line of sight between the transmitting antenna radiation phase center and the center of the receiving antenna. This line of sight must be free of any obstacles and the transmitting antenna gain is that at the elevation angle α, as indicated in Fig. 1.

Power relationship A_w is calculated in dB as

$$A_w(\text{dB}) = W_R(\text{dBW}) - W_T(\text{dBW}). \quad (42)$$

And the free space attenuation A_{FS} in dB, as

$$A_{\text{FS}} = 20 \cdot \log \frac{\lambda}{4\pi r'}. \quad (43)$$

Site attenuation can be calculated also by a similar equation by FCC obtained from the Friis equation, as

$$\begin{aligned} A_w &= 20 \cdot \log r + 20 \cdot \log f(\text{MHz}) - G_T(\text{dBi}) \\ &\quad - G_R(\text{dBi}) - 27.6 - R. \end{aligned} \quad (44)$$

This equation can be simplified over perfect ground if G_T and G_R are the real gain in working conditions and distance *r* is that *r*' indicated in Fig. 1. In this case, the term *R* will be $R = 1$ or 0 dB. Factor 27.6 is simply

$$20 \cdot \log \frac{300}{4\pi} = 27.6 \text{ (dB)} \quad (45)$$

and corresponds using frequency instead of wavelength in the free space attenuation (A_{FS}). The transmitting antenna gain is that radiated at the elevation angle α and the receiving antenna gain is that calculated by the standard procedure. The transmitting antenna is installed at a fixed height with a minimum of 0.2 or 0.3 λ at the minimum frequency (*f* = 30 MHz). Receiving antenna height must be scanned in height in order to obtain the maximum power on the receiving antenna resistive load. Generally, in the lower frequencies, this maximum power is not obtained due to the transmitting antenna radiation pattern whose maximum is pointing at the zenith ($\alpha \cong 90°$). Receiving antenna height scanning depends on the measurement site possibilities but generally is performed between a minimum of 1 or 2 m and a maximum of 4 or 6 m. At each frequency withing, the spectrum the maximum power delivered (W_{RM}) on the receiving antenna load (R_L) must be recorded as well as the receiving antenna gain (G_R) and factor (AF_R). The transmitting antenna gain (G_T) and factor (AF_T) can be calculated by means of its radiation pattern. In the case the transmitting power (W_T) and the received power (W_R) are known, the procedure is determining the receiving antenna current (I_R) in the equivalent Thevenin circuit and in it calculating the induced voltage (V_i). For a resonant and well-matched half-wave dipole, its effective length (L_e) is known as [4]

$$L_e = \frac{V_i}{E_i} \ (m). \quad (46)$$

And the electric field strength (E_i) and power density (P_i) can be determined, as

$$E_i = \frac{V_i}{L_e} \ (\text{V/m}) \quad (47)$$

$$P_i = \frac{E_i^2}{Z_{oo}} \ (\text{w/m}^2) \quad (48)$$

where Z_{oo} is the free space characteristic impedance ($120\pi = 377\ \Omega$).

The receiving antenna effective area is

$$A_{eR} = \frac{W_R}{P_i} \ (\text{m}^2). \quad (49)$$

And the receiving antenna gain is

$$G_R = \frac{4 \cdot \pi \cdot A_{eR}}{\lambda^2}. \quad (50)$$

Receiving antenna factor is the relationship between the electric field (E_i) and the voltage developed in the resistive load, or

$$\text{AF}_R = \frac{E_i}{V_R} = \frac{E_i}{I_R R_L} \ (1/\text{m}) \quad (51)$$

$$(\text{AF}_R)_{73} = 20 \cdot \log \text{AF}_R \quad (52)$$

$$(\text{AF}_R)_{50} = (\text{AF}_R)_{73}(\text{dB/m}) + 1.64(\text{dB}) \ (\text{dB/m}). \quad (53)$$

By means of the Friis equation, the transmitting antenna gain (G_T) can be calculated and corresponds to the power density (P_i) injected over the receiving antenna at the elevation angle α. The transmitting antenna gain is obtained by the Friis equation as

$$G_T(\text{dBi}) = A_w(\text{dB}) - A_{\text{FS}} - G_R(\text{dBi}) \quad (54)$$

$$G_T(\text{dBi}) = K(\text{dB}) - G_R(\text{dBi}). \quad (55)$$

If the transmitting antenna gain is known previously, the Friis equation permits to check the performance of the radio link because it must produce the same answer.

The transmitting antenna factor can be calculated by

$$\text{AF}_T = \frac{\pi}{\lambda}\left(\frac{480}{G_T R_a}\right) \ (1/\text{m}) \quad (56)$$

$$(\text{AF}_T)_{73} = 20 \cdot \log \text{AF}_T \quad (57)$$

$$(\text{AF}_T)_{50} = (\text{AF}_T)_{73}(\text{dB/m}) + 1.64(\text{dB}) \ (\text{dB/m}). \quad (58)$$

The transmitting antenna factor can also be calculated by the FCC equation, or

$$\text{AF}_T = -29.78 + 20 \cdot \log f(\text{MHz}) - 10 \cdot \log G_T \ \ (\text{dB/m})_{50}. \quad (59)$$

The answer to both equations are identical and given by

$$\text{AF} = \frac{E_i}{V_R} \ \ (1/\text{m}) \quad (60)$$

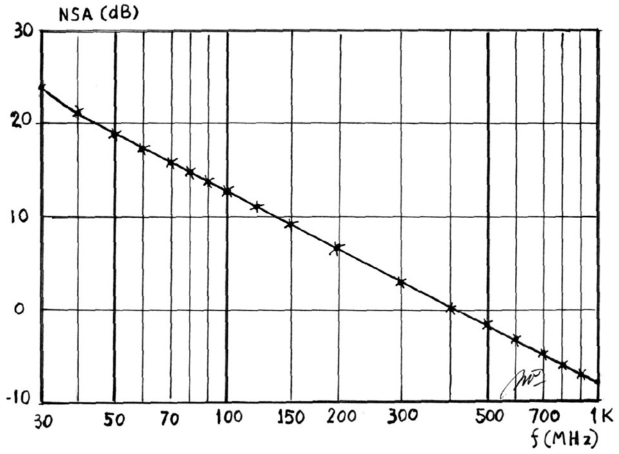

Fig. 17. Normalized site attenuation $r = 10$ m, $H_T = 1$ m or $H_T = 2$ m.

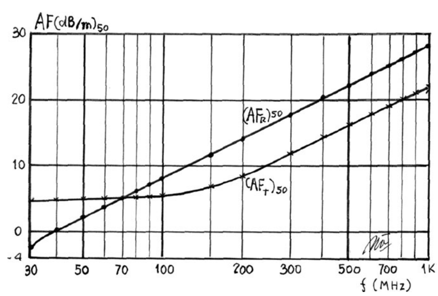

Fig. 18. Radio link antenna factors for $H_T = 1$ m.

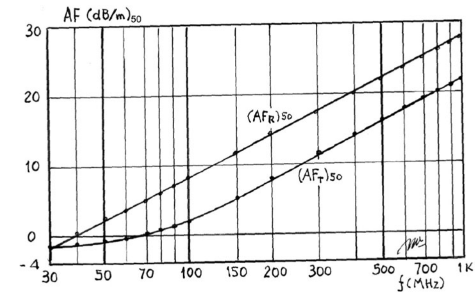

Fig. 19. Radio link antenna factors for $H_T = 2$ m.

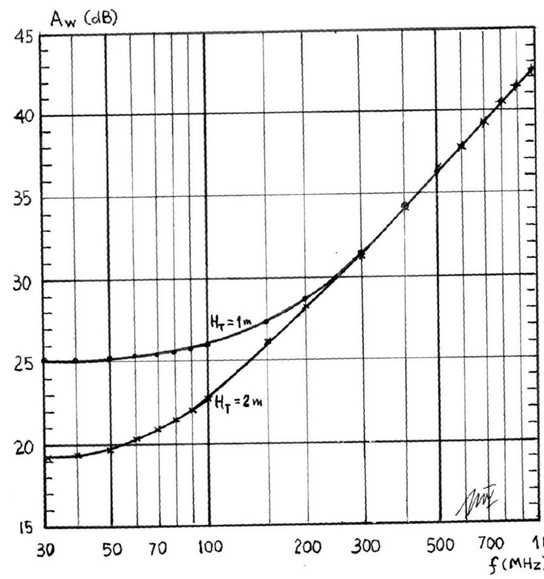

Fig. 20. Radio link power relationship for $H_T = 1$ m and $H_T = 2$ m.

where

E_i is the induced electric field effective value (V/m);

V_R is the voltage on the receiving antenna resistive load R_L;

$V_R = I_R \cdot R_L$.

Calculation of the power relationship, antenna gains, and factors as well as the NSA have been calculated for a radio link of a distance $r = 10$ m and for the transmitting antenna height fixed at 1 and 2 m. Half-wave dipole in horizontal polarization was used in this task ($H/a \cong 1000$). Fig. 17 shows the NSA obtained for the radio link with a distance $r = 10$ m and with a transmitting antenna height fixed at $H_T = 1$ m and $H_T = 2$ m, while the receiving antenna was scanned from 1 to 4 m in height in order to acquire the maximum received power W_{RM} on the resistive load R_L. The NSA value representation corresponds at both cases for the transmitting antenna height of $H_T = 1$ m and $H_T = 2$ m with an error less than 0.5 dB within the frequency spectrum from 30 to 1000 MHz where horizontal polarization was used. Fig. 18 shows the transmitting and receiving antenna factors for the transmitting fixed at $H_T = 1$ m and Fig. 19 the same result at $H_T = 2$ m. It can be noted in both cases the different values of the transmitting and receiving antenna factors and their 6-dB difference. The power relationship A_w as shown seen in Fig. 20 for both transmitting antenna height of $H_T = 1$ m and $H_T = 2$ m where more attenuation below 200 MHz for $H_T = 1$ m than $H_T = 2$ m can be appreciated, and practically, the same attenuation of both cases above it. In the case of $H_T = 2$ m and $r = 10$ m, the power relationship is practically the same as obtained by Bennett [7], [8] and Fitzgerrell [9] obtained by calculations and measurements. At the same time in an INTI measurement with two half-wave dipole, the power relationship measured was $A_w = 26.79$ (dB) and the calculated here was $A_w = 26.25$ (dB) very close to 0.5 dB at the frequency of $f = 150$ MHz in a semianechoic chamber.

IV. Conclusion

This step-by-step analysis proves the difference between the transmitting and receiving antenna behavior; and also that the principle of reciprocity does not apply to these antennas in a radio link over perfect ground. Additionally, the 6-dB difference in the antenna factor should allow for the reduction of the +/− 4 dB in the measurement standard. The receiving antenna gain and factor is practically constant as a function of the height for both polarization if the antenna height is higher than one wavelength. This makes up a good reference as an FSAF. It can be useful for measurements of spurious field strengths by any device and it permits calibration of other antenna types to be used in wide band operations.

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