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Isotropic Irradiation Model from Atmospheric Discharges Using Local Atmospheric Electric Field Data

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HIGHLIGHTS

- Free-space communication theory using an antenna located on the Earth's surface.
- VLF spectrum represents about 59% of correlation with the free space electric field.
- The EIRP has a result of ~26% for the value between 1000-2000 W.

Abstract: Using a local atmospheric electric field sensor network (Field Mill), an electromagnetic link model was proposed considering a free space electric field and a theoretical electric field calculated from an atmospheric discharge. With this, it was possible to compare the theoretical value of this electric field with the experimental value of the local atmospheric electric field (estimated by the Field Mill sensor network). The results are initially analyzed considering wavelengths in the EHF spectrum ($\lambda \sim 10^{-5} m$) and the VLF spectrum ($\lambda \sim 10^{4} m$). As assumed before, admitting that the lightning channel acts as an isotropic irradiator and a Field Mill sensor acts as a receiving antenna for the spectrum emitted by the lightning, a irradiated power model of the electromagnetic waves reaching the Field Mill sensor, according to the ITU-R P.873.4 standard, was calculated, thus allowing a correlation with a satellite radio link, in which the Field Mill sensor acts as a ground receiving antenna and the main channel of the lightning strikes acts as a transmitting antenna. Also, a model of the power irradiated by each lightning discharge, recorded by the Field Mill sensor network, was proposed, and the Equivalent Isotropically Radiated Power - EIRP was calculated for different values of effective electric field (Eef) and then compared with the model of the power irradiated by the antenna (lightning). This makes it possible to do an analysis and determine if the lightning discharge can be approximated to an isotropically irradiated antenna model.

Keywords: satellital link; atmospheric electric field; field mil; lightning.

INTRODUCTION

All lightning discharges irradiate electromagnetic waves throughout the frequency spectrum [11,13]. For certain frequencies, there are power spectra with higher intensity [4,6]. Sensors such as the Field Mill are capable of registering variations of the local atmospheric electric field at a certain frequency (depending on the frequency of registration of the local atmospheric electric field intensities), measuring and estimating the value of this local atmospheric electric field (CEAL) by an aperture device with capacitor plates and whose detection range of this type of sensor, reaches 10-15 km of distance [6,15].

The Meteorological System of Paraná - SIMEPAR operates a network of Field Mill sensors, called REMCEA - Metropolitan Network for Atmospheric Electric Field Monitoring, which monitors storms with a CEAL sampling every 1 second (1Hz frequency). This equipment estimates the electric field profile during a storm in an atmospheric column, and provides an expectation of the electrostatic conditions of electrically active storms, but does not account for the relation of this recorded electric field with the distance to the lightning. For this, it is necessary to estimate a relation between the measured electric field and the effective distance to lightning.

The electric field sensor considered is an equipment developed by Campbell, composed of a data logger, CR1000, with an interface connected to a database and a GPS antenna, which receives the local atmospheric electric field records and stores them in a database to be used in the risk management of approaching or retreating storms over a certain region. The input data related to the lightning distances to the Field Mill sensor was obtained from the Integrated Network for Atmospheric Discharge Detection - RINDAT. The data analysis interval was from a Field Mill station, synchronized with the timestamp of the RINDAT network, for the period 23/12/2015 to 17/02/2016. The reasons for choosing this period are: (a) availability and access to the data, (b) period with high lightning incidence on this Field Mill sensor, and (c) sufficient sampling for the study at hand.

These sensors are installed around a region of interest, for monitoring the electrostatic profile of the atmosphere. Data from the REMCEA network indicate that for the same lightning event, at the same instant of time, different electric field values are recorded by the Field Mill sensors. These data have no similarity in intensity or polarity, which configures a surprise in the measurements, since the lightning discharge should behave as an isotropic irradiator, because it is an event that can be recorded by electromagnetic waves, both in the shortwave and longwave spectrum [4,6,9].

Considering a radio link (electromagnetic wave propagation link established between an antenna on a satellite and an antenna on the ground) between an antenna on a satellite in Earth orbit, operating as a transmitter (T_x) and emitting electromagnetic waves to a ground antenna (R_x), which acts in this model as a receiver. In this case, an electromagnetic signal is sent from a point far above the Earth's surface and propagates through the atmosphere until it reaches the receiving antenna on the ground. To fit this radio link model, we will consider that the power irradiated by the main channel of lightning has a center of maximum intensity, previously located in the storm cloud, coincident with the center of charge of the cloud (thus we define that the center of charge in a storm cloud will act as an antenna that irradiates electromagnetic waves, just as the transmitting antenna on board an artificial satellite would do). This point will act as an isotropic irradiator, that is, a transmitting antenna (T_x), and whose quasi-static electric field variation can be registered by a Field Mill sensor, which in this concept will be defined as a receiving antenna (R_x). With this model of electromagnetic signal transmission (radio link, or satellite link), defined here as an "electromagnetic link", we intend to establish a response regarding the different measurements of the atmospheric electric field made by the Field Mill sensors for the same lightning event.

The following steps contemplate extracting expressions for the free space electric field as a function of the quasi-static electric field measured by a Field Mill sensor network (equation 3), considering mathematical relations in the high-frequency range. Next, to estimate a model of the irradiating power of the point where lightning originates as a function of distance assuming some considerations of the ITU-R P.873.4 standard, admitting a similarity with a satellite radio link (equation 12), and to estimate an effective electric field (E_{ef}), considering the lightning discharge as an isotropic irradiator (equation 15).

From this analysis, the following objectives will be possible: (a) Analyze the interference zone between the quasi-static electric field and the free space electric field, and make a clustering of the values of both electric fields for the frequencies at EHF and VLF. Then make an estimate of the distance from the Field Mill sensor to the lightning, which in this case corresponds to the monitoring range, as to the distance between the Field Mill and the effective detection distance of atmospheric discharges, data obtained from the National Network for Atmospheric Discharge Detection - RINDAT. (b) with the model of the power irradiated by each lightning discharge, it will be possible to find the EIRP (Equivalent Isotropically Radiated Power) for different values of effective electric field (E_{ef}) and compare it with the model of the power irradiated by the antenna (lightning). With these results, it will be possible to analyze the behavior of the electric fields and determine whether a lightning discharge can (or cannot) be approximated to an antenna model with isotropically irradiated power. The approximation of the main channel of a lightning discharge, and the success in formulating an isotropic irradiation model allows further studies that analyze the behavior of the electric current intensity that passes through the main channel of a lightning, alternative ways to quantify and qualify the waveform pattern of the electric current peaks in this channel.

Free Space Communication Theory

With the free space communication theory considering an antenna located on the Earth's surface (Field Mill) and a point located at a certain height from the surface (~2 m from the ground), it is possible to make a comparison of this point, with another point located at the center of charges of a storm, which here represents the point where the lightning discharges originate. The free space communication theory is also used in the radio link between an antenna located on the surface and another attached to a geostationary satellite [7]. This type of satellite has a constant distance to the antenna on the ground (geostationary orbit) and rotates with the same angular velocity as the Earth (geostationary satellites). As the point located in the storm is at a certain height from the ground (more than 2 m from the ground) we approximate this model to the satellite antenna system and thus treat a first consideration that the lightning channel will always be visible by the Field Mill sensor, assuming that the monitoring (or recording) range of this type of sensor, will be between 10-15km, with a response efficiency in the electric field gradient (E) [V/m], decreasing with distance (Figure 1).

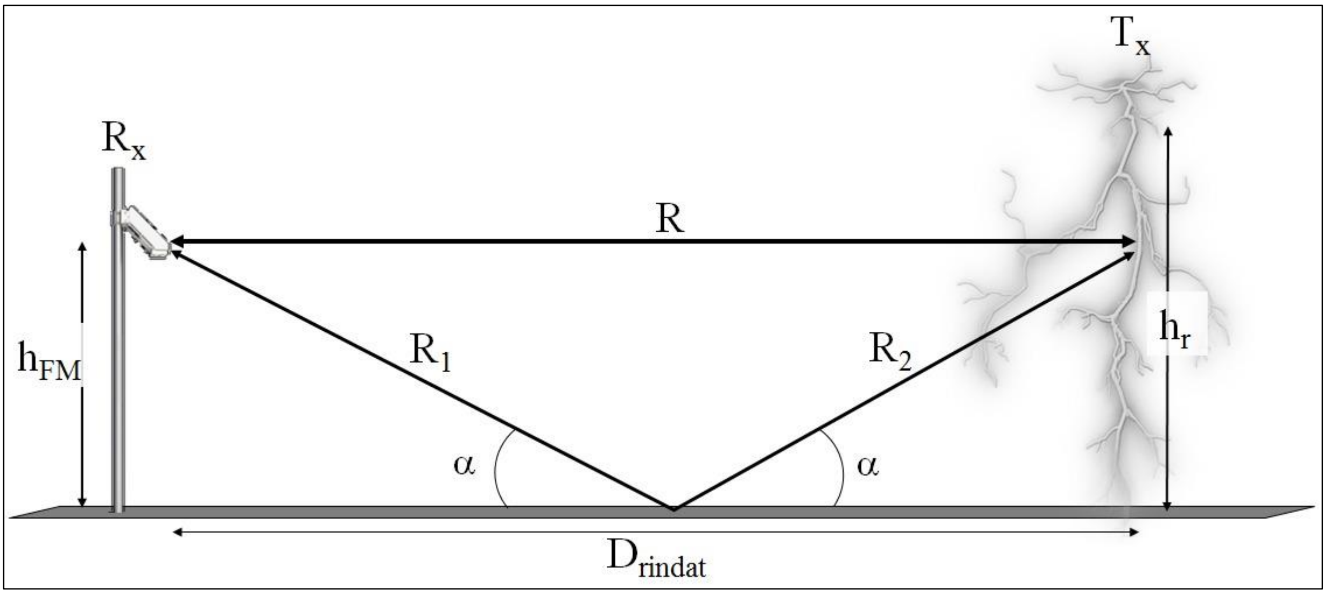


Figure 1. Concept of a transmitting (lightning - T_x) and receiving (Field Mill - R_x) antenna, where R is the distance between T_x and R_x, D_{rindat} is the distance [m], predicted by the lightning discharge detection system (RINDAT). Source: The authors (2022).

Therefore, the Field Mill sensor starts operating, by the free space communication theory, as a receiving antenna (R_x) [m], and the point at the center of charge that originates the lightning as a representative region of the electric field emission, at a certain height from the ground and registered by the Field Mill sensor, as it would occur in a satellite radio link system, and therefore subject to the geometric projections necessary to calculate the distance between the lightning (transmitting antenna - T_x) and the Field Mill (receiving antenna - R_x) (Figure 1).

Although the loss in free space is highly significant in the link calculation, and in practice we must take into account the reduced distance between the Field Mill sensor (R_x) [m] and the electric field signal propagating channel (E) [V/m] of the lightning (T_x) [m], it is admitted the consideration that the losses may be negligible as to the order of magnitude involved in the model in question [1,2,4,13]. The electric field at the reception point, recorded by the Field Mill (E) [V/m] is given by the expression:

$$E = E_o \left| \left[1 + R_r e^{\psi} \right] \right|, \quad (1)$$

where

$$\psi = -j \frac{2\pi}{\lambda} \left(\frac{2\pi h_r h_{FM}}{\lambda \, D_{rindat}} \right),$$

with R_r being the complex Fresnel reflection coefficient for plane waves [7,14]. E_o in [V/m], free space electric field term.

Between the electromagnetic link that is established between a lightning and a Field Mill sensor, interference zones can occur, which can produce oscillations in the electric field intensity around its value in free space [5,6,13].

This region of free space is known as the diffraction zone and is characterized by the fact that the local electric field strength E [V/m] is always below its free space value, in which case: $\alpha \approx 0$ and $R_r \approx 1$.

Thus equation (1) can be rewritten as a function in the domain of the reals, so that:

$$E = 2E_o \sin \left(\frac{2\pi h_r h_{FM}}{\lambda \ D_{rindat}} \right) \quad (2)$$

Isolating the free space electric field term E_o [V/m] (theoretical/recalculated), we have (in modulus):

$$E_o = \frac{E}{2} \frac{1}{\left| \sin \frac{2\pi h_r h_{FM}}{\lambda D_{rindat}} \right|} , \quad (3)$$

where E is the quasi-static (experimental) electric field recorded by the Field Mill sensor [V/m], h_r the average height of the lightning channel, from which the emission of the electric field signal starts [m], h_{FM} the height of the Field Mill sensor relative to the height of the lightning channel [m], D_{rindat} the distance between the lightning and the Field Mill sensor, obtained by RINDAT [m], and λ is the wavelength of the electromagnetic signal [m].

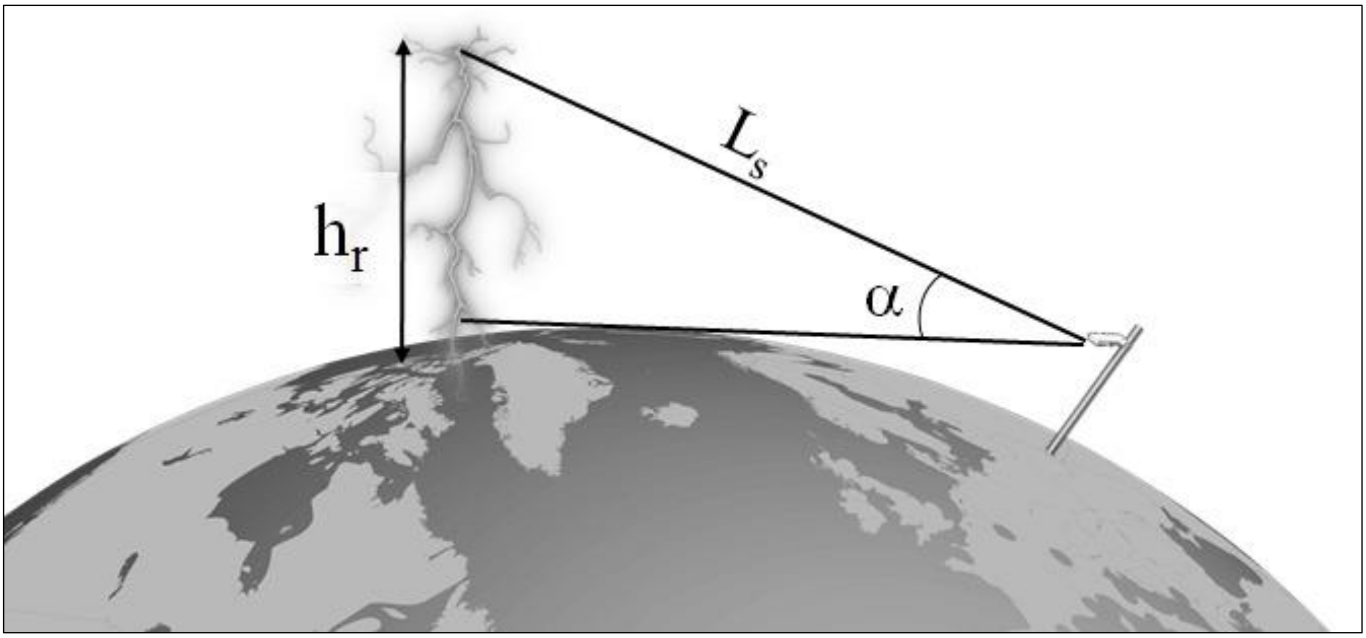


Figure 2. Model of a satellite radio link adapted to the case of an atmospheric electric field sensor and a lightning discharge. Graphic representation is not to scale. Source: The authors (2022).

The total electromagnetic irradiation power by a lightning [W] is described as a spatial relation (Figure 2), (Equation 4) [8,11,14,15]:

$$P = \left(\frac{4\pi R^2}{3} \right) \left(\frac{E_{pk}^2}{\mu c} \right) \quad (4)$$

where μ is the magnetic permeability ($4\pi \times 10^{-7}\ N/A^2$) and c is the speed of light ($3 \times 10^8\ m/s$). Important here is the dimensional analysis of equation (4). For the total irradiation power to be given in Watt, it is necessary that the term $(1/\mu c)$ has a dimension of [Ω^{-1}]. Doing literally the dimensional analysis on the basis of the International System of Units, we conclude that, in fact, $(1/\mu c) = [[A^2][s]/[N][m]] = [A].[[A][s]/[N][m]] = [A].[[C]/[N][m]]$. It should be noted that by definition, the electric force has dimension of $[[C][V]/[m]]$, so, $(1/\mu c) = [A].[[C][m]/[C][V][m]]$ which results in the dimension $[A/V]$, or [Ω^{-1}]. Taking this dimensional analysis into equation (4) and concluding the dimensional analysis for the electric field and the term R^2, we arrive at the unit of total electromagnetic irradiation power, in Watt. Assuming that the n-th peak of the electric field irradiation (E_{pk}) [V/m] is equal to the value of the electric field recorded by a Field Mill sensor (E) [V/m], corresponding to few losses in free space, then we have the power irradiated by a lightning discharge in [W]:

$$P = \frac{4\pi R^2}{3}\frac{2\left|E_o{}^2\right|}{\mu c}\left|\sin\left(\frac{2\pi h_r h_{FM}}{\lambda D_{rindat}}\right)\right| \quad (5)$$

Considering $R^2 \approx L_s{}^2$ (Figures 1 and 2) as the distance from the Field Mill sensor to a midpoint in the lightning channel, located at a certain height from the ground (L_s) [km], and which is estimated as being the region of highest irradiation power of that lightning, (Figure 2). It is possible to make these substitutions in equation (4) so that:

$$P = \frac{4\pi L_s{}^2}{3}\frac{2\left|E_o{}^2\right|}{\mu c}\left|\sin\left(\frac{2\pi h_r h_{FM}}{\lambda D_{rindat}}\right)\right| \quad (6)$$

Equation (6) represents the power irradiated by a lightning discharge as a function of the distance separating the location (latitude and longitude) of a lightning impact, measured by the RINDAT, point of location of the local atmospheric electric field sensor - Field Mill, and wavelength of the frequency of maximum power spectrum, in this case for high frequencies (EHF).

Elevation Angle Calculation

Taking as a reference the calculation of rain attenuation in the satellite link in the ITU-R standard, it was possible to establish a correlation for the analysis of the free space electric field path (E_o) at a point in the lightning channel with height (h_r), and then estimate an elevation angle from the Field Mill sensor (Figure 3).

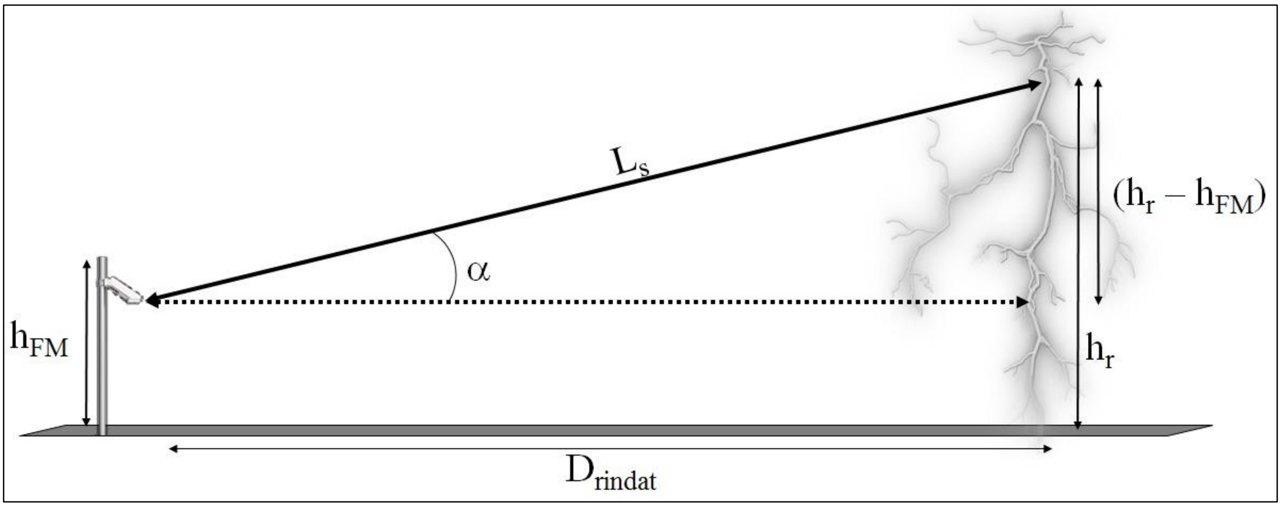


Figure 3. Relation between the system's heights R_x (Field Mill) and T_x (lightning) and minimum elevation angle.

The equation that estimates the rainfall height will be approximated to the calculation of the height that corresponds to the beginning of the lightning discharge in a storm cloud (it is a good approximation since it was considered the center of charges of the storm cloud, place in the origin of a lightning, to be the very base of the cloud, from where precipitation (rain) begins), therefore (h_r) will be estimated relative to sea level, and calculated according to the recommendation of ITU-R P. 839-3, in which:

$$h_r = 3{,}8\ \left|1 + exp^{(-0{,}1R_{(0{,}01)})}\right| \quad (7)$$

where $R_{(0,01)}$ is the rainfall in $[mm/h]$ and corresponds to $0{,}01\%$ of the recorded annual average rainfall intensity in the region where intends to establish the distance relation between a lightning strike and the Field Mill sensor. According to ITU-R P. 837-4, tropical and equatorial regions have a $R_{(0,01)}$ range between $95 - 145\,mm/h$, and temperate climate regions have a $R_{(0,01)}$ range between $19 - 42\,mm/h$. Therefore, we consider the average value of $R_{(0,01)}$ for temperate climate regions, so there is one more parameter that will be included in equation (6).

Figure 3 is following ITU-R P.618-8 for which the distance L_s can be calculated considering a minimum elevation angle of $\alpha \approx 5°$ under the argument that the distance $D_{(rindat)}$ is always estimated considering a visible lightning within the perimeter of the Field Mill sensor's monitoring range (Figure 3), so that:

$$L_s = \frac{h_r - h_{FM}}{\sin\alpha}. \tag{8}$$

The projection of L_s will be similar to the distance $D_{(rindat)}$ by the following argument:

$$D_{(rindat)} = L_s \cos\alpha. \tag{9}$$

Replacing equation (9) into (8):

$$\alpha = \tan^{-1}\left(\frac{(h_r - h_{FM})}{\sin\alpha}\right). \tag{10}$$

Now substituting equation (8) into (6) and also equation (7) into (8), it is possible to rewrite the expression for the power irradiated by a lightning discharge (equation 6) in the form:

$$P = \frac{4\pi}{3}\left(\frac{(h_r - h_{FM})^2}{\sin\left[arctan\left(\frac{(h_r - h_{FM})}{D_{(rindat)}}\right)\right]}\right)\frac{2\left|E_o{}^2\right|}{\mu c}\left|\sin\left(\frac{2h_{FM}h_r}{\lambda D_{(rindat)}}\right)\right| \tag{11}$$

Taking equation (2), isolating the quasi-static electric field (E_o) and substitute it into equation (11), where:

$$P = \frac{4\pi}{3}\left(\frac{(h_r - h_{FM})^2}{\sin\left[arctan\left(\frac{(h_r - h_{FM})}{D_{(rindat)}}\right)\right]}\right)\frac{E^2}{\mu c}. \tag{12}$$

This is the equation that estimates the power irradiated by an isotropic antenna, with $h_r = 3{,}8\left[1 + exp^{\left(-0{,}1R_{(0{,}01)}\right)}\right]$ as a function of the lightning location distance (between the Field Mill sensor and the point of impact of the discharge) $[m]$, and rain height for different regions according to the ITU-RP. 873,4 standard. The variable E is the quasi-static electric field, recorded by the Field Mill sensor [V/m].

The power density irradiated by the antenna at a certain distance (r), measured in $[W/m^2]$, will be:

$$S_o = \frac{P}{4\pi r^2}. \tag{13}$$

This expression shows that in an unobstructed environment, for high frequencies and no losses, the power density (P) is inversely proportional to the square of the distance. According to electromagnetic theory, this quantity is related to the intensity of the electromagnetic field generated at the point in space where the power density is being measured, so it can be calculated from:

$$S_o = \frac{E^2}{2\eta}, \tag{14}$$

Where η is the intrinsic impedance of the medium $= 377\,\Omega$. Combining (13) and (14) gives a relation of the electric field from an atmospheric discharge acting as an isotropic irradiator, (equation 15).

$$E_{ef} \approx \sqrt{\frac{30P}{D_{rindat}}}, \tag{15}$$

With the estimation of the effective electric field E_{ef} by the previous equation, we find the equivalent irradiating power when considering an atmospheric discharge as an antenna irradiating at a certain altitude from the Earth's surface, such as the model of an antenna attached to an orbiting satellite and which, irradiating isotropically, corresponds to the power density associated with the amount of energy emitted by the atmospheric discharge (equation 16).

Assuming that the atmospheric discharge irradiating a power (P), produces the same maximum power density irradiated by an isotropic antenna, it is possible to determine an Isotropically Irradiated Equivalent Power (EIRP), in the form:

$$\mathrm{EIRP} = \frac{D_{rindat}^{2} E_{ef}^{2}}{30} \quad (16)$$

Where $EIRP \approx P$, given in $[W]$ indicates that expressions (15) and (16) are equivalent.

MATERIAL AND METHODS

The lightning data correspond to the period January - December 2015 and have the quasi-static electric field information (the one measured by the Field Mill sensor) and information regarding the instant of cloud-to-ground lightning occurrence, geographic location, current peak and polarity.

A flash from a lightning discharge is said to exist if at least one stroke is detected, while not all strokes of the same flash are detected. This is how the RINDAT detection system considers the detection of strokes in its operational design.

The data was prepared using the *DbVisualize*r tool (Database Management Software Tools), to access and organize the data from the database.

From the atmospheric electric field records, average values were taken, intermediate to 2 minutes before and after the occurrence of lightning. The instant considered was calculated from the instant of time recorded by the RINDAT network, and synchronized with the GPS of the Field Mill sensors, using the following relationship (equation 17),

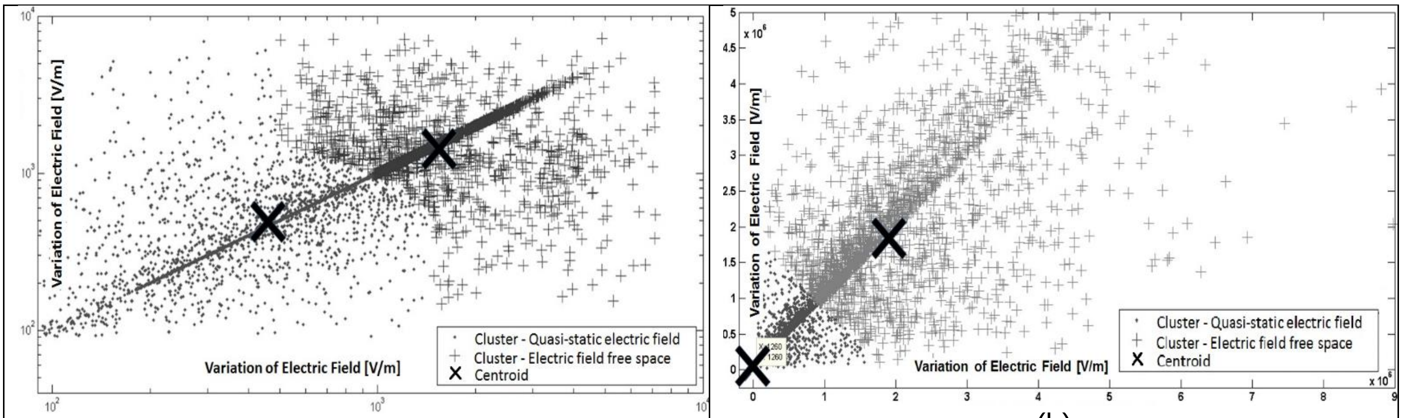
$$E_m = \sum_{i=1}^{240} \frac{E_i}{N_{strokes}} \quad (17)$$

where E_m is the average quasi-static electric field at $[V/m]$, E_i are the quasi-static electric field values recorded by the Field Mill sensor in the 240-second interval, which corresponds to 2 minutes before and after the central instant, when lightning strikes, and $N_{strokes}$ corresponds to the number of strokes recorded by the RINDAT network in the 4 minutes interval.

Each lightning discharge registered by the RINDAT network is correlated with the time window of registration of the atmospheric electric field value. When the *DbVisualizer* tool identifies the correlation, it returns, as a result, the average intensity of the quasi-static atmospheric electric field, the distance of this lightning to the Field Mill sensor, the polarity, and the geographic coordinates of that lightning discharge, for a time instant identical to the moment of lightning detection by the RINDAT.

RESULTS

The k-means function in Matlab uses the average measures of a group of measures and creates a classification (clusters) to represent a centroid for each of the parameters (E_o and E). This distance between the centroids of different data goes through iterations so that each centroid is refined by averaging the values of each element of each occurrence that belongs to this centroid.



(a) (b)

Figure 4. (a) Clustering of the measured and calculated electric field values for the EHF range; (b) Clustering of the measured and calculated electric field values for the VLF range.

Figure 4 shows the clustering of the quasi-static electric field and free space values for the frequency spectra at the EHF and VLF.

An analysis of the free space electric field was performed, considering a wavelength λ of the order of $10^{-5}\, m$ (for millimeter waves near the EHF range), that is for high frequencies and, another considering a wavelength of the order of λ of the order of $10^{4} m$ (for long-distance waves in the VLF range).

Figure 4(a) has a log-log scale because the distance between the centroids is much larger than the distance between the centroids in Figure 4(b), which used a normal scale for its coordinates. This means that the frequency range in the VLF spectrum, that is, for wavelengths on the order of $10^{3} - 10^{4}\, m$ results in a sample correlation of data between the quasi-static electric field and that of free space, much closer than that considering millimeter wavelengths, indicating that the consideration of low frequencies is better characterized by equation (3) compared to the quasi-static electric field records made by the Field Mill sensor.

Using equation (3) and considering a λ for EHF and VLF, we have that if $E_o < E$, the distance between the lightning discharge (D_{rindat}) may be greater than that estimated by the RINDAT system. If $E_o > E$, D_{rindat} is overestimated, and if $E_o \approx E$ then D_{rindat} represents an adequate distance between the point of impact of the lightning discharge and the Field Mill sensor.

Figure 5 shows the measurements of both free-space and quasi-static electric fields. E_o (theoretical) and quasi-static E (experimental)). All input data from the quasi-static electric field records (E) consider a monitoring range less than or equal to 15 km.

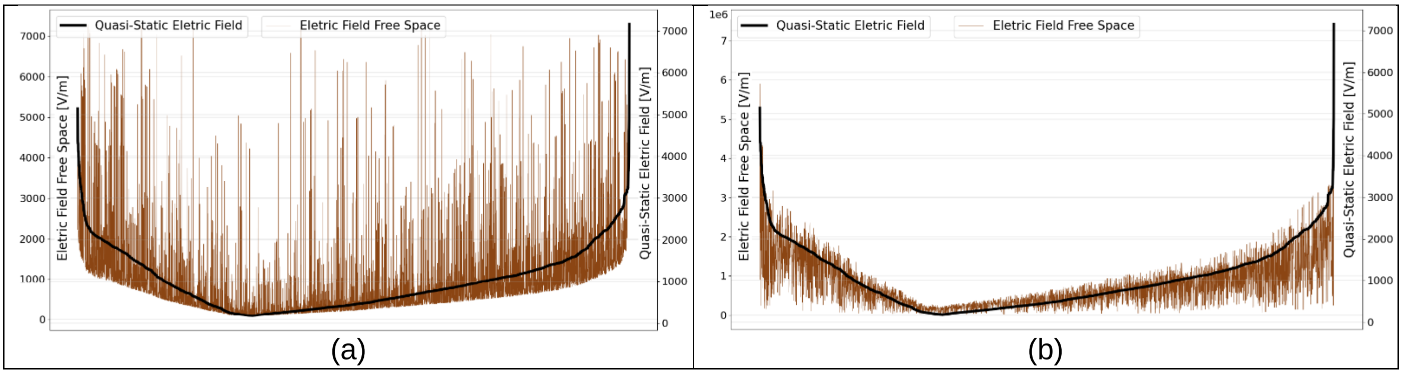


Figure 5. (a) Absolute values of the quasi-static and free space electric fields, considering waves in the EHF rage. (b) Absolute values of the quasi-static and free space electric fields, considering waves in the VLF range.

The results shown in Figure 5, indicate that the quasi-static electric field, considering an atmospheric discharge as an isotropic irradiator in the EHF frequency range is approximate of the same order of magnitude as the free space electric field. This means that D_{rindat} is an adequate distance estimate between the impact point of the lightning discharge and the Field Mill sensor. However, the largest power spectrum of a lightning is in the VLF spectrum, around $15\ kHz$, which represents a λ of the order of $10^{4} m$. For this case (Figure 5(a)) indicates that the free space electric field is about $10^{4} m$ times larger than the quasi-static electric field values (in absolute values).

The polynomial trend correlation on the calculated values of the free space electric field in Figure (5(a)), shows that the coefficient of determination is a measure of the fit of a statistical model to the calculated values. For a wavelength in the EHF range, the free space electric field that is calculated by equation (3), R^4 is equal to 0.2363, while considering a wavelength in the VLF range R^4 is equal to 0.5922. The R^4 is how well the model can explain the calculated values of the free space electric field.

This means that a model of the electromagnetic link in the VLF spectrum represents about 59% of correlation with the dependent variable in the model used to calculate the free space electric field. Therefore, equation (3) follows the representation of the occurrence of interference zones, or diffraction zones, characterized by the fact that the quasi-static electric field intensity is always below the free space electric field value. Thus, according to the results, the distance between the lightning discharge (D_{rindat}) and a Field Mill sensor is overestimated by the RINDAT system.

Figure 6 show the superposition of the plots of the effective electric field E_{ef} and the quasi-static electric field E (experimental), with both polynomial regressions of degree 4.

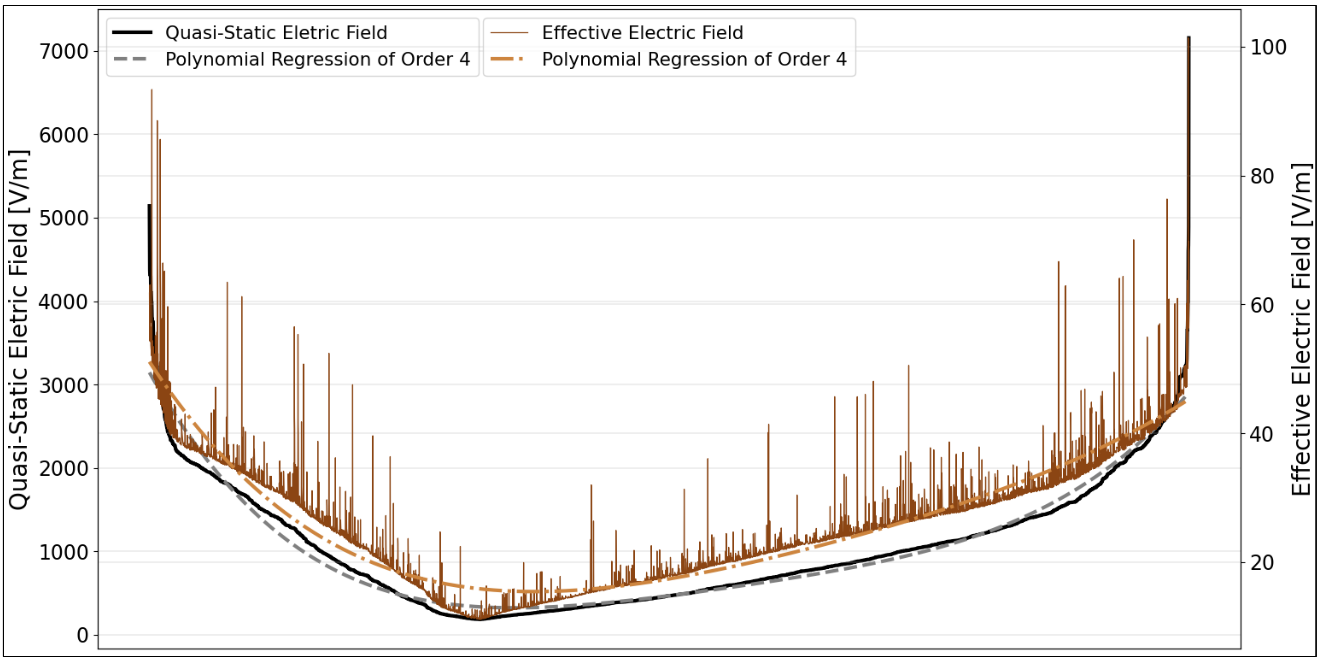


Figure 6. Absolute values of the quasi-static and effective electric fields.

The polynomial regressions shown in Figure 6 are of degree 4 because the independent variables are raised to the fourth power. This manipulation in place of a higher order of magnitude, even if performing the best curve fit, is due to less consideration of the data as noise.

One of the factors that contribute to the regressions not aligning is the use of wavelengths in the VLF range, which, even with its use representing the best correlation with the dependent variables, does not exactly represent the values of the wavelengths of an atmospheric discharge, as it irradiates waves in all frequency spectrums and not just in VLF spectrum.

From a table with the values of E_{ef}, E, E_o and the calculated values of EIRP (equation 16), we calculate for each of the lightning monitored by the RINDAT system and simultaneously registered by the Field Mill sensor, the cumulative frequency of EIRP and irradiation power $[W]$ and also the probability values of the EIRP and the irradiated power of a lightning (Figure 7).

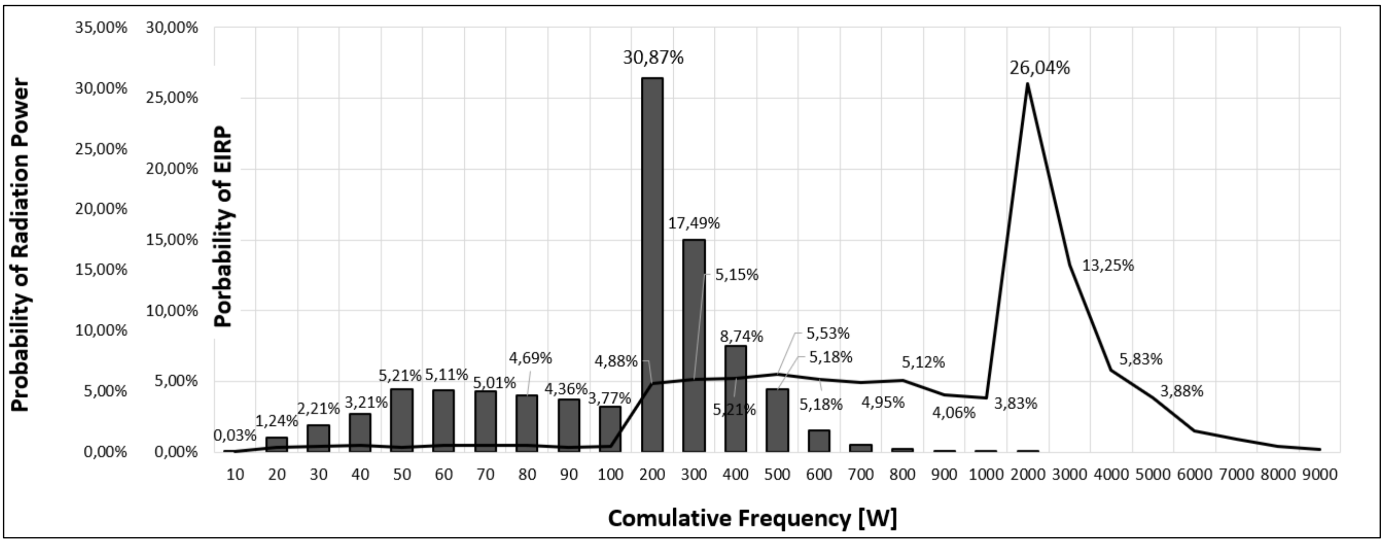


Figure 7. Cumulative frequency of EIRP values (line) and irradiated power (bar), both in [Watt], and the respective probability values.

Figure 7 indicates that the cumulative frequency of the irradiation power calculated according to the proposed model has a value between $100 - 200\ W$ for a probability of $\approx 30.87\%$. For the EIRP a result of $\approx 26\%$ for the value between $1000 - 2000\ W$. Therefore, the discrepancy between the calculated values of irradiated power and EIRP is 10^3 orders of magnitude. The probabilities shown in Figure 7, indicate that a larger variation occurs, between 10 − 200 W for the values of the power irradiated by a lightning discharge and between $300 - 3000\ W$ for EIRP values. This range is quite distributed for both parameters.

Although the largest power spectrum of a lightning discharge is in the VLF spectrum near $15\ kHz$, when considering a lightning discharge as an isotropically irradiating antenna, it also irradiates isotropically in several other frequency spectra (LF, ELF, VHF), and the Field Mill sensor, being a device that does not discriminate the electromagnetic signal, also does not have the property to recognize the different types of frequency spectrum irradiated by a lightning discharge.

Having the EIRP (which is associated with the energy density emitted by the lightning discharge), presented a cumulative frequency of intensities greater than the values of power isotropically irradiated by a lightning, this indicates that the electromagnetic link model, that is an atmospheric discharge acting as an antenna that irradiates isotropically, is consistent above all by the results that show an EIRP greater than the irradiated power, because between equations (12) and (16) the estimated distance of the location of the discharges by the system RINDAT, as discussed above, is overestimated, since the model considers a direct proportion between EIRP and the loads location distance.

Although the lightning irradiation power is associated with the lightning location distance (D_{rindat} between the Field Mill sensor and the point of discharge impact), this parameter does not consider only this information, being necessary to admit also the rain height for different regions according to the ITU-RP. 873.4 and the quasi-static electric field, measured and recorded by the Field Mill sensors.

It is unlikely that the recorded values of quasi-static electric field present inconsistencies, because the data considered for this model, admit values related to the occurrence of lightning discharges, correlated with the instant of time (GPS) of the RINDAT system and with accuracy in the time scale of 1 millisecond. However, the lightning location record is made by sensors that are hundreds of kilometers away from the point of impact of lightning, and this can imply the inaccuracy of the location, unless the condition ensures efficiency in the detection of atmospheric discharges.

Another factor that may contribute to an EIRP of 10^3 orders of magnitude higher than the irradiated power predicted by the model, may be the amount of data selected and used in the previous calculations. An average quasi-static electric field (equation 17) was considered, 2 minutes before and after the occurrence of a lightning. This sample gradient of the electric field data recorded by the Field Mill may also contribute to the difference in the order of magnitude. It is speculation whether to consider an average quasi-static electric field, 1 or 2 seconds before and after a lightning strike, as an input parameter for performing the calculations of this model.

DISCUSSION

Taking the lightning discharge data for the period January - December 2015, the free space electric field model as a function of the quasi-static electric field gives mathematical sustainability, consistent with the analysis of a local electric field intensity below its free space value. The clustering of the simulated electric field data in the EHF and VLF spectrum indicates that, as an antenna model with isotropic irradiation, it behaves more appropriately when considering a spectrum with high wavelengths, which is in agreement with measurements in this range of the electromagnetic spectrum (VLF), and also indicates a larger spectrum of lightning discharge irradiation power.

The variations in the calculated values of the irradiated power by lightning, showed that a lightning discharge irradiates isotropically in other frequency spectra. The EIRP calculations for lightning discharges showed a cumulative frequency intensity on the order of 10^3 higher than the calculated values of the power irradiated isotropically by a discharge. This is because the estimated distance of discharge location by the RINDAT system is overestimated, as the model considers a direct relation between EIRP and the distance of discharge location.

The large variation in the EIRP probability and irradiated power values showed that, although the quasi-static electric field measurements were performed at one point in space, the lightning discharges irradiate isotropically in all directions, irradiating power in all frequency spectra, predominantly in the spectrum for wavelengths closer to low frequencies. Therefore, the electromagnetic link model, making the lightning discharge act as a transmitting antenna and an electric field sensor as a receiving antenna, can be represented by a model that considers that lightning discharges exhibit an antenna behavior with isotropic irradiation.

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