Statistical Distribution of Parameters of Lightning Impulses in Antennas and Radar Towers - Practical Application Examples

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Abstract: The paper presents practical application examples of the method described in [1]. For some typical geometries of antennas and radar towers, the number of lightning strokes per year (in statistical sense, and in connection with the lightning density in flat ground, or with keraunic level), the statistical distribution of lightning impulses current amplitude, and examples of maximum current amplitude to consider with a risk criteria, are presented. Some results are given in parametric form, e. g. in function of height of antennas and towers. The results show the important influence of geometry in the statistical distribution of parameters of lightning discharges incident in towers, and the need of specific evaluation, in order to consider, in correct way, lightning effects and risks in people and equipment, and in design of equipment, cabling, shielding and grounding.

INTRODUCTION

In [1], we have presented a computational method to evaluate the statistical distribution of parameters of lightning impulses in antennas, towers, structures and buildings. Such method is based on an electrogeometric lightning model (EGLM).

In this paper, we will present practical examples related mainly to antennas and telecommunication towers, but that cover, also, tall buildings and structures. Some aspects of the influence of tower or structure geometry, in lightning incidence and in statistical distribution of lightning parameters, are shown. Such statistical distributions are strongly influenced by tower geometry, that must be considered with reasonable accurate modeling, for correct evaluation of lightning impact in equipment and installation design.

Some results are given in parametric form, e. g. in connection with height of tower, **H** , and lightning to ground density, **D** , for some typical radar and telecommunication tower geometries.

STRUCTURE SHAPE

In Figure 1 we represent, in 3D , the basic shape type of examples, designated by Type 1 , Type 2 , Type 3 , Type 4 . Dimensions in Figure 1 (in meter) are only examples. In all cases, **H** is the maximum height to ground surface, assuming a flat soil. In Type 1 , **R** is the radius of cylinder and upper half-sphere. For small **R** value, Type 1 represents a mast, with height **H**. In Type 2 , $\mathbf{R}_s$ is the radius of upper sphere and $\mathbf{R}_c$ is the cylinder radius. In Type 3 , β is the angle of upper guys with a vertical line. In Type 4 , β is half the opening angle of the cone. In Types 3 and 4 , **R** is the radius of upper sphere. For the examples of this paper, the distributions of atmospheric discharges in Types 3 and 4 are quite similar, and, so, the parametric computation was done for Type 4 , but also applies, with a small numeric difference, to Type 3 .

LIGHTNING CURRENT AMPLITUDE DISTRIBUTION

For a general interpretation of the influence of structure shape in lightning discharge incidence, in Figures 2 to 9 , several structure types and parameter values are considered. For each figure, several **H** values are compared (in most cases **H** = 20 m , 40 m , 80 m , 160 m), the other parameters being equal, in each Figure.

In each of Figures 2 to 9, two graphics are presented. The first one shows the average "shadow" area, **A** , of the "object", in function of the lightning current amplitude, **I** (in logarithmic scales). The second one represents the average number of lightning discharges per year, **M** , in the "object", of amplitude higher than **I** , for a reference average discharge density, **D** , in flat soil, 20 discharges per square kilometer per year, corresponding to an average keraunic level, **N** , of 100 thunderstorm days per year. Logarithmic scales are also used. Figure 9 refers to lightning striking the guys and not the upper part of "object", for a guyed structure. Total number of discharges in such structure is dealt with in Figure 8 .

In order to allow an easy comparison of different shapes and parameter value, we present, in Table 1 , the **M** values, for a few **I** values, for the conditions defined for figures 2 to 9 . Each condition is identified in the second column of the Table by the corresponding Figure number.

For a **D** value not equal to 20 (km^{-2} $year^{-1}$), **M** is equal to the **M** value of graphics or Table 1 multiplied by $\mathbf{D}/20$.

For the geometric shapes of presented examples, or similar, and **H** within the range of examples, effect of **H** value in **M** , for the same **I** , can be obtained, in a first approximation, interpolating logarithmicaly (considering, in interpolation interval, $\mathbf{M} = k\,\mathbf{H}^{\nu}$, with **k** , ν constant).

For striking currents of "very high amplitude", in the range of presented examples, the dominant parameter of structure shape is maximum height to ground, **H** . For "lower" current amplitude, however, other parameters of "object" geometry also affect lightning incidence. This behavior is associated to the fact that, for very high current amplitude, "almost all" strokes occur near the top part of structure. However, for lower currents, strokes also occur in lower regions of structure. By example, for conditions of Figure 8 :

- Considering "all discharges" in the object: for **H** = 160 m , about 37 % of the discharges in "object" strike the guys; for **H** = 80 m , about 7 % ; for **H** ≤ 40 m , lightning discharges directly in guys are exceptional.
- Considering only discharges for **I** ≥ 100 kA : for **H** = 160 m , only about 3 % of the discharges strike the guys; for **H** = 80 m , lightning discharges directly in guys are exceptional.

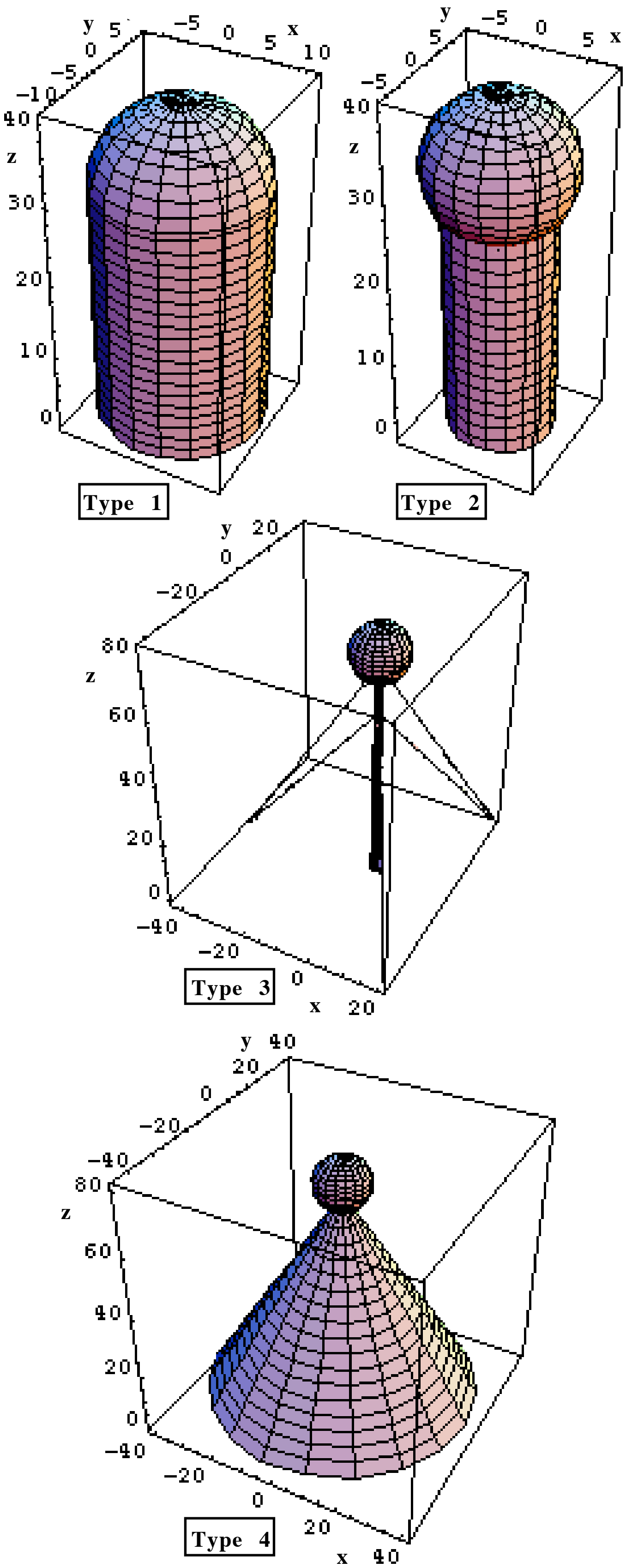

Figure 1. Structure shapes of examples.

Table 1. Comparison of M , for some I values, and different structure types and geometric parameters

I [kA]	Fig.	**M** (in year^{-1} , for **D** = 20 km^{-2} year^{-1}) **H** = 20 m	**H** = 40 m	**H** = 80 m	**H** = 160 m
1	2	0.298	0.657	1.488	3.431
	3	0.323	0.711	1.617	3.729
	4	0.351	0.772	1.759	4.060
	5		0.891	2.037	4.718
	6	0.318	0.699	1.587	3.635
	7	0.318	0.699	1.605	4.356
	8	0.318	0.700	1.698	5.438
	9		0.0000795	0.115	2.037
10	2	0.295	0.650	1.475	3.399
	3	0.320	0.704	1.600	3.690
	4	0.347	0.762	1.739	4.012
	5		0.878	2.008	4.654
	6	0.314	0.692	1.571	3.599
	7	0.314	0.692	1.586	4.288
	8	0.314	0.693	1.674	5.337
	9		0	0.105	1.954
50	2	0.101	0.220	0.503	1.174
	3	0.106	0.230	0.527	1.232
	4	0.111	0.242	0.553	1.297
	5		0.265	0.605	1.425
	6	0.104	0.228	0.522	1.218
	7	0.104	0.228	0.520	1.271
	8	0.104	0.229	0.521	1.424
	9		0	0.00317	0.193
100	2	0.0166	0.0358	0.0811	0.192
	3	0.0171	0.0369	0.0833	0.197
	4	0.0176	0.0380	0.0858	0.203
	5		0.0403	0.0909	0.215
	6	0.0170	0.0366	0.0828	0.196
	7	0.0170	0.0366	0.0830	0.195
	8	0.0170	0.0366	0.0827	0.201
	9		0	0	0.00658
150	2	0.00336	0.00720	0.0161	0.0380
	3	0.00343	0.00735	0.0164	0.0388
	4	0.00352	0.00752	0.0168	0.0396
	5		0.00785	0.0175	0.0413
	6	0.00342	0.00732	0.0164	0.0386
	7	0.00342	0.00732	0.0164	0.0384
	8	0.00342	0.00729	0.0164	0.0384
	9		0	0	0.000205
200	2	0.000833	0.00177	0.00393	0.00921
	3	0.000848	0.00180	0.00400	0.00936
	4	0.000864	0.00183	0.00407	0.00951
	5		0.00190	0.00421	0.00982
	6	0.000845	0.00180	0.00398	0.00932
	7	0.000845	0.00180	0.00398	0.00932
	8	0.000845	0.00180	0.00399	0.00928
	9		0	0	0.0000217
250	2	0.000242	0.000512	0.00113	0.00262
	3	0.000246	0.000519	0.00114	0.00266
	4	0.000250	0.000527	0.00116	0.00269
	5		0.000543	0.00119	0.00277
	6	0.000245	0.000518	0.00114	0.00265
	7	0.000245	0.000518	0.00114	0.00265
	8	0.000245	0.000519	0.00114	0.00265
	9		0	0	0

LIGHTNING CURRENT AMPLITUDE ACCORDING RISK CRITERIA

In Table 2 , it is indicated the lightning impulse amplitude, **I** , that has an expectation of being exceeded 0.03 times per year (once in 33 years), for the objects to which refer Figures 2 to 9 , and defined in such Figures, for three levels (10 , 20 , 40) of lightning discharge density **D** (expressed in discharges to ground per square

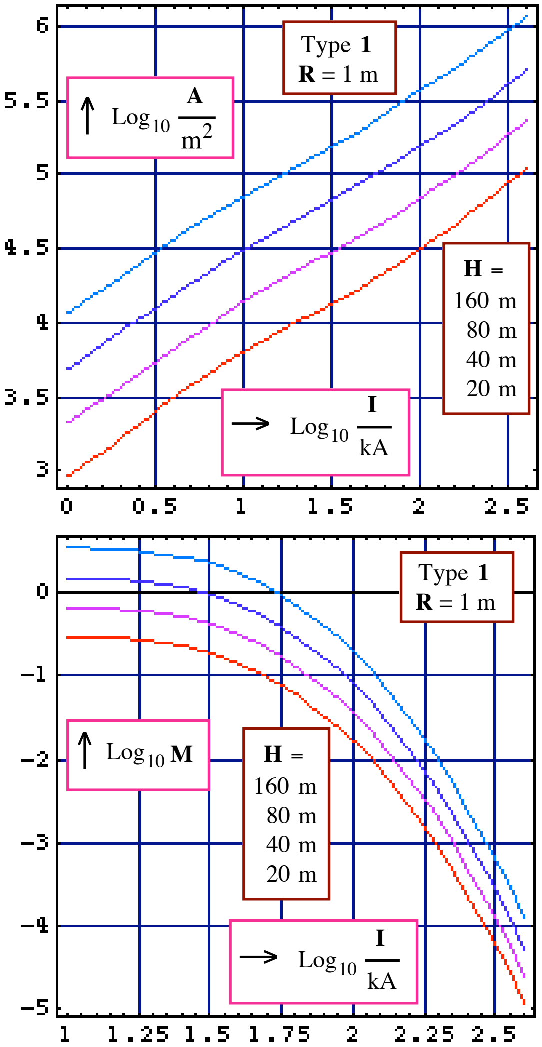

Figure 2. Structure of Type 1, for R = 1 m .

kilometer per year). The **I** values of this table are rounded, by excess, to multiples of 10 kA .

In the range of examples included in Table 2 , and for strokes in objects including their upper part, with the assumed risk criteria, current amplitude to consider for design purposes varies from 70 to 190 kA. Example defined in Fig. 9, related to strokes in guys, shows that, for tall structures, strokes in object above their upper part must be considered, although with current amplitude lower than strokes near the top (conditions including discharges near the top correspond to line Table identified by Fig. 8, instead by Fig. 9).

Previous example results apply directly to conditions such that severity of lightning discharge, for withstand purposes, can be assumed to depend on current amplitude, **I** , or on a parameter with an high correlation factor with **I** . When this assumption is not enough accurate, risk analysis must consider other important parameters ahead of **I** . For several typical withstand conditions, and some human safety criteria, severity can be assumed to depend on **I** and on lightning impulse time front, $\mathbf{T}_f$, for relative shape of front of wave typical of such impulses [2-3]. In fact, induced voltages, grounding and related voltages, and withstand limits, are quite sensitive to $\mathbf{T}_f$, for small values of $\mathbf{T}_f$.

We present now an example related to conditions in which, for

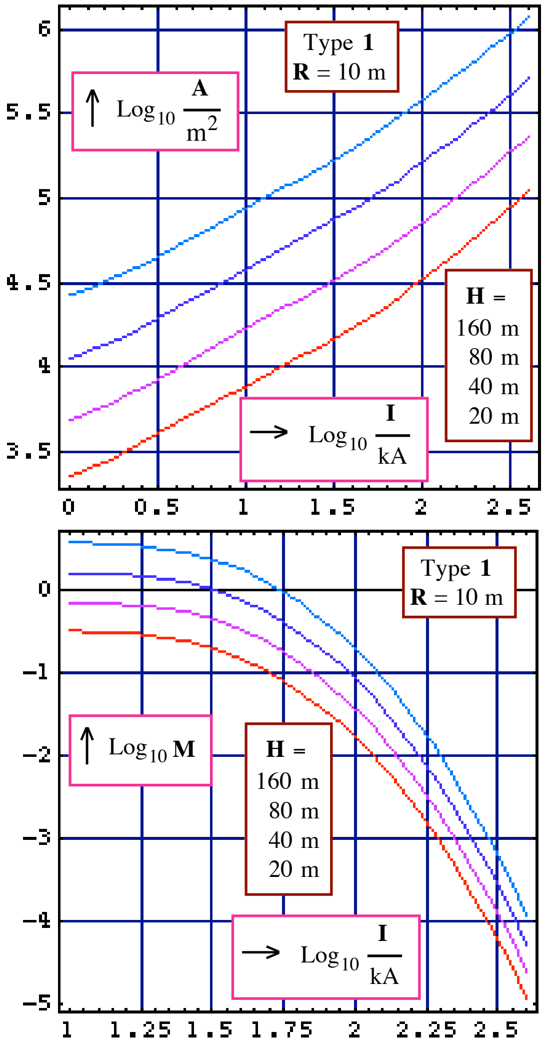

Figure 3. Structure of Type 1, for R = 10 m .

equipment and design characteristics, severity of a lightning impulse can be assumed proportional to the product **I . S** , being **S** a severity factor depending on $\mathbf{T}_f$, as represented by curve identified by $\mathbf{S}_{Tf}$ in Figure 10a . Curve identified by $\mathbf{S}_0$, in the

Table 2. Amplitude, I , of lightning discharge with an expectation of being exceeded 0.03 per year (rounded, by excess, to a multiple of 10 kA)

H [m] ⇒	20			40			80			160		
D (*) ⇒	10	20	40	10	20	40	10	20	40	10	20	40
Fig. ⇓	I [kA] ⇓											
2	70	90	110	90	110	130	110	130	160	140	160	190
3	70	90	110	90	110	130	110	140	160	140	160	190
4	70	90	110	90	110	130	120	140	160	140	160	190
5				90	110	130	120	140	160	140	170	190
6	70	90	110	90	110	130	110	140	160	140	160	190
7	70	90	110	90	110	130	110	140	160	140	160	190
8	70	90	110	90	110	130	110	140	160	140	160	190
9				10	10	10	20	30	40	70	80	90

(*) Average lightning density, in discharges to ground per square kilometer, per year.

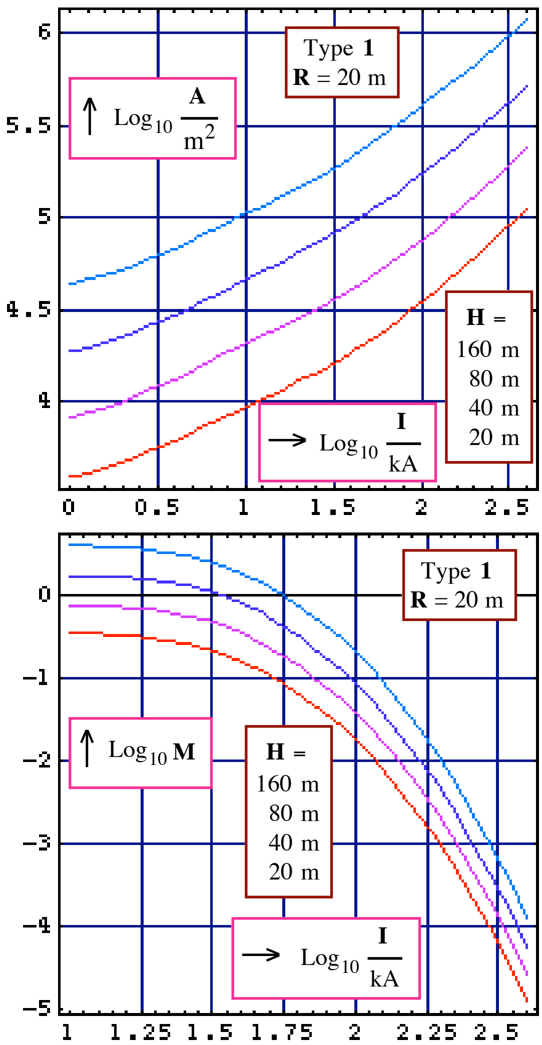

Figure 4. Structure of Type 1, for R = 20 m .

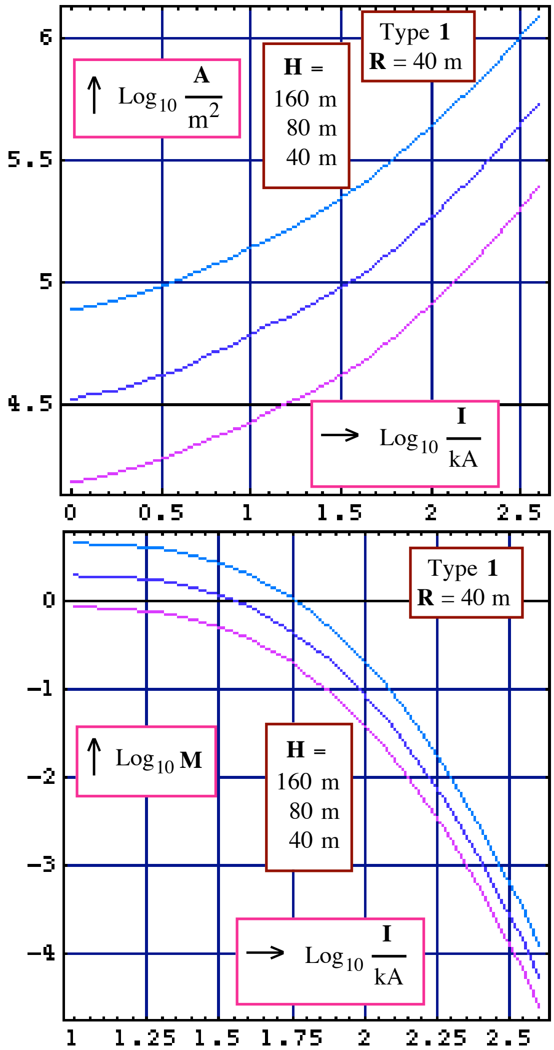

Figure 5. Structure of Type 1, for R = 40 m .

same figure, being $\mathbf{S}_0 = 1$, would correspond to a severity depending only on **I** . Severity factor $\mathbf{S}_{Tf}$ is chosen such that, for $\mathbf{T}_f = 1.5$ μs , it is $\mathbf{S}_{Tf} = 1$. This choice is in some sense arbitrary, and is based in the fact that, for several conditions, the severity for $\mathbf{T}_f = 1.5$ μs can be assumed, in a first approximation or simplified analysis, representative of an weighted average severity.

The time front and current amplitude have different statistical distributions, for first negative impulses, for subsequent negative impulses and for positive impulses. Otherwise, there is a positive correlation factor between amplitude of first negative impulse and of subsequent impulses. In Figure 10b we present an weighted equivalent statistical distribution, for some specific conditions, and with reference to “equivalent” independent statistical distributions of **I** and $\mathbf{T}_f$. This equivalent distribution is obtained from simulations of typical shape impulses, varying $\mathbf{T}_f$, and with some assumptions about statistical distributions. Some simplifications have been done, due to the fact that there are limited information about the statistical distributions of several parameters, what implies some limitations to confidence in parameters of a more elaborate and detailed model. Apart limitation of statistical information, it is easy to establish a more detailed model. The distribution presented in this example is a bimodal one, what is adequate to consider the more important statistical effects. In Figure 10c it is represented **M** in function of **I** , for this example conditions.

Apart influence of $\mathbf{T}_f$ in severity, we consider conditions identical to those of example of Figure 8 , for **H** = 160 m and **D** = 20 lightning discharges per square kilometer per year, in flat ground. The lightning current amplitude, **I** , for design purposes with a risk criteria associated to a severity factor $\mathbf{S}_0 = 1$, in previous examples, for this case, was 158.2 kA , that was rounded, in Table 2 , to 160 kA .

Assuming a severity factor according curve $\mathbf{S}_{Tf}$ of Figure 10a , instead of $\mathbf{S}_0$, the withstand condition is defined by curve $\mathbf{I}_1$ of Figure 10d . For a discharge defined by a pair [$\mathbf{T}_f$, **I**] , the withstand assumptions are fulfilled if, and only if, the point with abscissa $\mathbf{T}_f$ and ordinate **I** is below curve marked $\mathbf{I}_1$. So, the probability that such assumptions are not respected is the probability that the pair [$\mathbf{T}_f$, **I**] is above curve marked $\mathbf{I}_1$.

So, the average number of lightning discharges for which withstand assumptions are not fulfilled, per year, is

$$\overline{\mathbf{M}} = \int_0^\infty \mathbf{M}(\mathbf{I}(\mathbf{T}_f))\ p_{Tf}(\mathbf{T}_f)\ d\,\mathbf{T}_f \qquad (1)$$

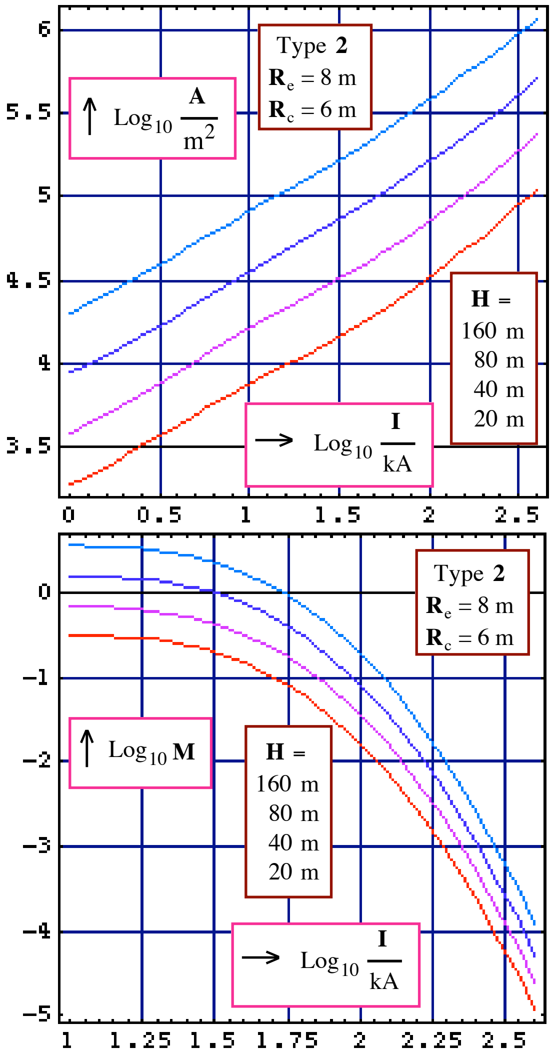

Figure 6. Structure of Type 2, for R_c = 6 m , R_e = 8 m .

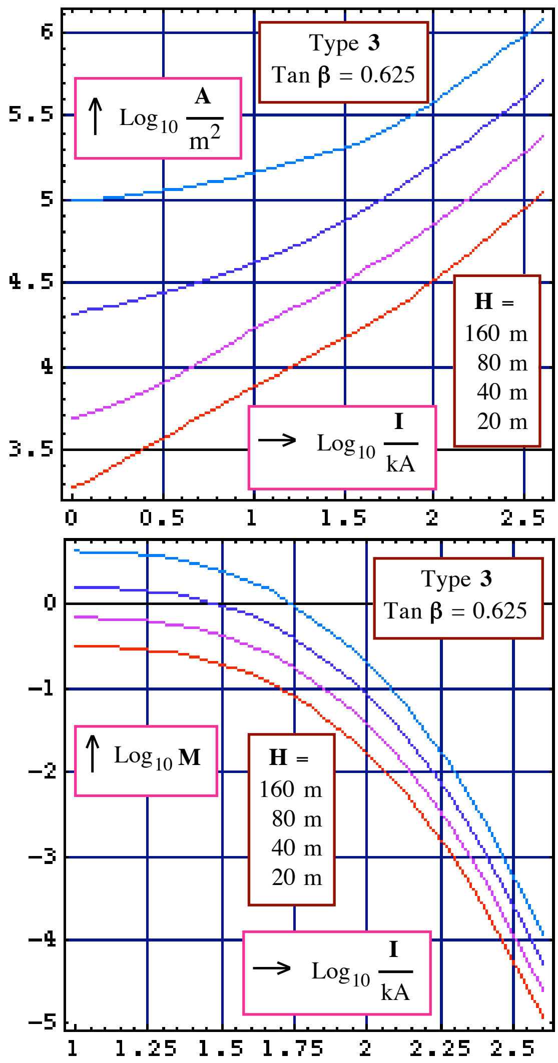

Figure 7. Structure of Type 3 or Type 4, Tan β = 0.625.

being **M** = **M(I)** the average number of discharges per year with amplitude higher than **I** , being **I**($\mathbf{T}_f$) the limit withstand current, related to $\mathbf{T}_f$ by curve marked $\mathbf{I}_1$ in Figure 10d, and being $\mathbf{p}_{Tf}$ = $\mathbf{p}_{Tf}(\mathbf{T}_f)$ the probability density of equivalent time front statistical distribution (that corresponds to minus the derivative of function represented in Figure 10b).

In conditions of this example, the average number of discharges "above" curve $\mathbf{I}_1$ is 0.0255 per year . So, in this example conditions, to consider a severity factor depending on $\mathbf{T}_f$, acording $\mathbf{T}_f$ influence in relative withstand conditions, evaluated by amplitude limit **I**($\mathbf{T}_f$) of lightning impulse for which withstand occurs, is more favorable (average of 0.0255 $year^{-1}$ instead of 0.03 $year^{-1}$) than to consider a constant severity factor equivalent to severity conditions for $\mathbf{T}_f$ = 1.5 µs .

The amplitude **I** , referred to $\mathbf{T}_f$ = 1.5 µs, such that, considering the severity function depending on $\mathbf{T}_f$, the average number of discharges violating withstand assumed condition, in hypothesis of this example, is 152.8 kA (instead of 158.2 kA) . Withstand conditions would be fulfilled for pairs [$\mathbf{T}_f$, **I**] below curve marked $\mathbf{I}_2$ in Figure 10d .

For this example, the simplifying assumption of considering severity conditions for $\mathbf{T}_f$ = 1.5 µs, and "assumed" independent of $\mathbf{T}_f$, for statistical purposes, would lead to results near the "more accurate" estimated value. However, the approximate validity of such simplifying assumption depends on specific conditions, and should not be adopted without careful examination.

It is convenient to notice that a front of wave with an assumed shape as described in [2-3] , and with a time front $\mathbf{T}_f$ = 1.5 µs , is, in general, more severe than than a double exponential impulse 1.2 µs / 50 µs , as defined and forseen in several standards.

CONCLUSION

The examples presented show that the EGLM, as described in [1] , allows to consider statistical aspects of lightning discharges, considering specific characteristics of antennas, towers, structures, and buildings, specific lightning density, and risk criteria for design, taking into account human and equipment safety. Presented examples also show important aspects of lightning effects, namely dominant parameters and its influence, including parametric basic information for risk analysis, covering some typical shapes of antennas and radar towers.

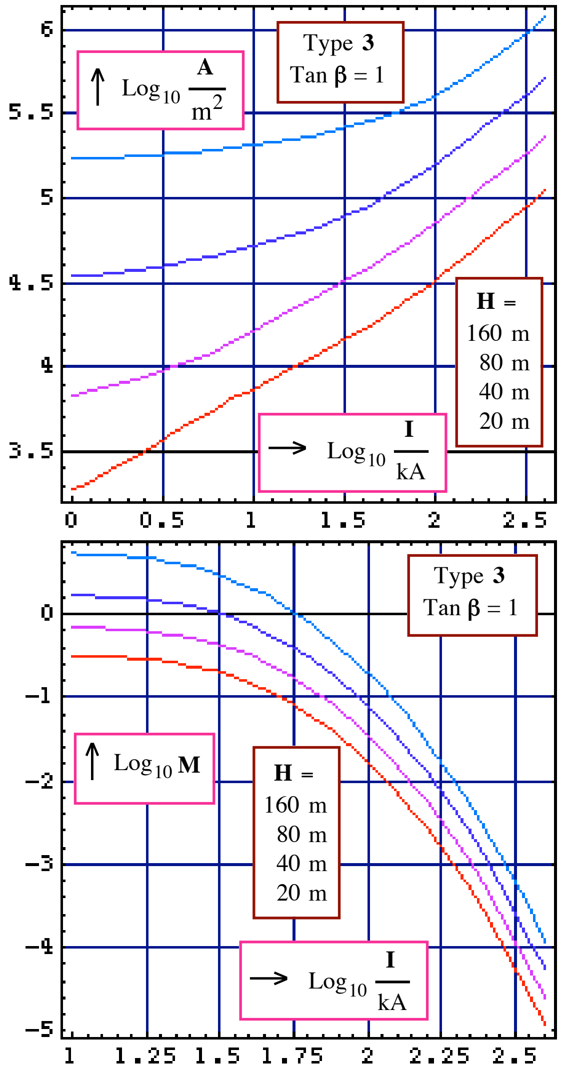

Figure 8. Structure of Type 3 or Type 4 , Tan β = 1 .

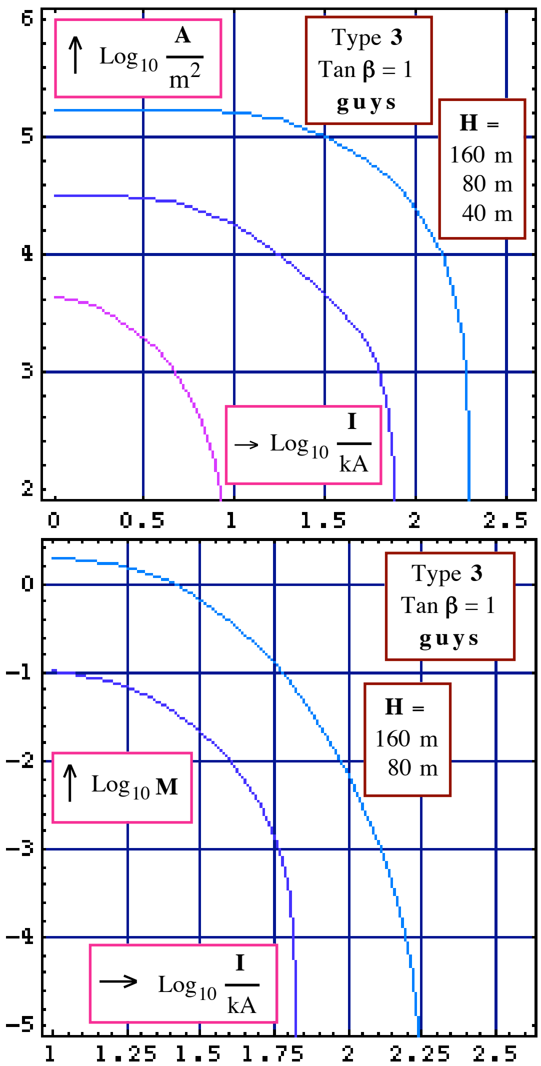

Figure 9. Structure of Type 3 , Tan β = 1 . Lightning discharges in guys.

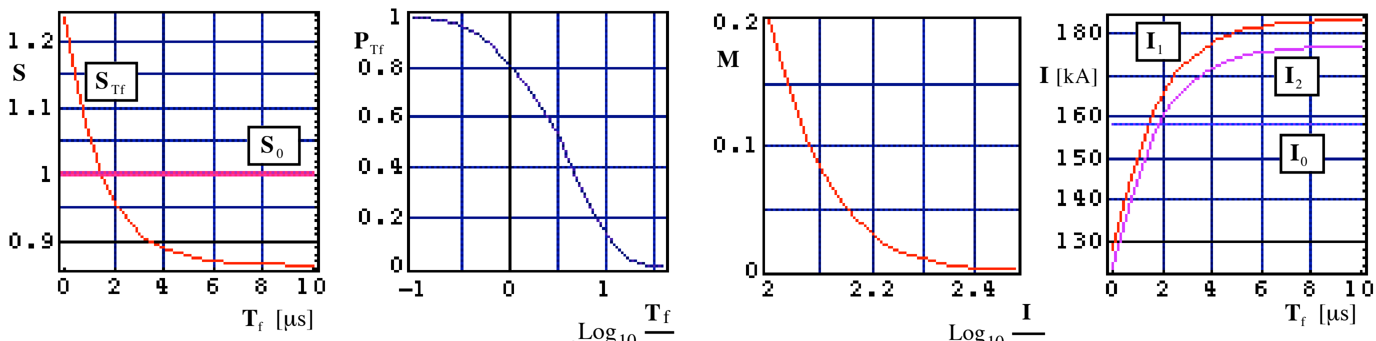

Figure 10a Figure 10b Figure 10c Figure 10d

Figure 10. Functions considered in example described in text, with severity of lightning impulse depending on **I** and $\mathbf{T}_f$.

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