Lightning Data Observed With Lightning Location System in Portugal

R. B. Rodrigues, V. M. F. Mendes, and J. P. S. Catalão, *Member, IEEE*

***Abstract*—This paper presents an investigation into cloud-to-ground lightning activity over the continental territory of Portugal with data collected by the national Lightning Location System. The Lightning Location System in Portugal is first presented. Analyses about geographical, seasonal, and polarity distribution of cloud-to-ground lightning activity and cumulative probability of peak current are carried out. An overall ground flash density map is constructed from the database, which contains the information of more than five years and almost four million records. This map is compared with the thunderstorm days map, produced by the Portuguese Institute of Meteorology, and with the orographic map of Portugal. Finally, conclusions are duly drawn.**

***Index Terms*—Ground flash density, lightning location system, lightning protection, thunderstorm days.**

I. Introduction

Effective risk analysis of faults in power systems is of the utmost importance in the design of adequate protection measures. One of the main causes of damage for power systems is certainly constituted by lightning [1].

Due to the enormous amount of data that can be gathered by means of lightning location systems (LLS), these systems represent a promising source of experimental data to be used for the development of standards related to the protection of power systems against lightning [2], [3].

LLS have been installed worldwide to monitor lightning activity. The LLS are being operated in many countries, including the U.S. [4]; U.K. [5]; Japan [6], [7]; Canada [8]; Austria [9]; Italy [10]; Guang-Dong Province, China [11], [12]; and Saudi Arabia [13]. The U.S. National Lightning Detection Network is the largest LLS in the world, recording more than 216 million cloud-to-ground (CG) lightning flashes during the first decade (1989–1998). Information about CG lightning is of primary interest for lightning protection applications [14]. These LLS collect information on lightning location, peak value of discharge current, number of lightning strokes per flash, polarity, and other useful information.

The lightning data observed with the LLS in Portugal is reported in this paper. Preliminary results were shown in [15] and [16]. About four million flashes were investigated to find out how many flashes occurred in the continental territory of Portugal. Ground flash density (GFD) maps are possible to be drawn with the data recorded by the LLS. When GFD maps are not available, the fault rate is derived from the so-called iso-keraunic level map or thunderstorm days (Td) map.

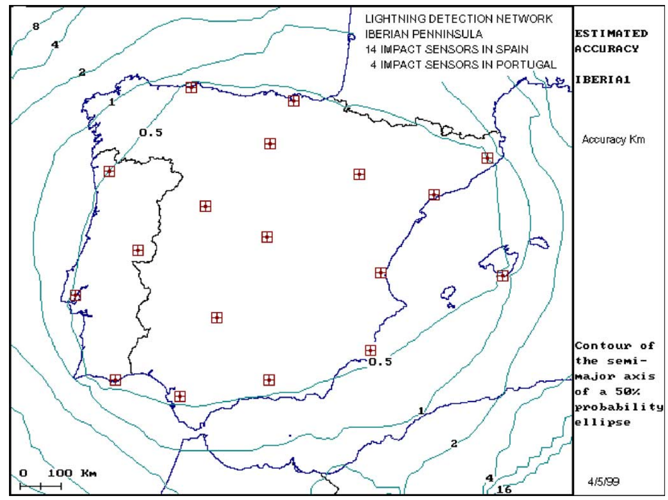

Fig. 1. Location and accuracy of the LLS.

The LLS in Portugal is first presented. Analyses about geographical, seasonal, and polarity distribution of CG lightning activity, and cumulative probability of peak current, are carried out. An overall GFD map is constructed from the database, which contains the information of more than five years and almost four million records. This map is compared with the Td map, produced by the Portuguese Institute of Meteorology (IM) and with the orographic map of Portugal.

This paper is structured as follows. Section II describes the LLS in Portugal. Section III presents the Td map available. Section IV describes the methodology considered. Section V illustrates the results obtained. Finally, in Section VI conclusions are duly drawn.

II. Lightning Location System in Portugal

The LLS in Portugal was put into operation in June 2002 by the IM. The system in the Iberian Peninsula consists of 18 combined magnetic direction and time-of-arrival finders (DTFs), four in Portugal, and 14 in Spain. In addition, Portugal receives information from the closest five DTFs placed in Spain, since December 2002. Fig. 1 shows the location of DTFs and contour lines of accuracy [17].

DTFs are designed to respond to magnetic fields emitted from return strokes in lightning flashes. Three methods are used by DTFs to find the geographical location of lightning in latitude

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R. B. Rodrigues and V. M. F. Mendes are with the Instituto Superior de Engenharia de Lisboa, Lisbon 1950-062, Portugal.

J. P. S. Catalão is with the University of Beira Interior, Covilha 6201-001, Portugal (e-mail: catalao@ubi.pt).

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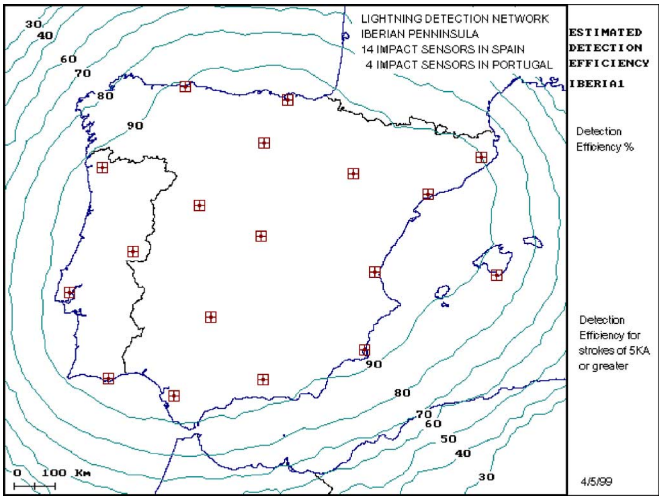

Fig. 2. Estimated detection efficiency of the LLS.

and longitude: magnetic direction, time of arrival, and a combination of the two. More comprehensive discussions, including other detection methods and frequency ranges, can be found in [18] and [19]. Furthermore, the system allows to indirectly infer the peak current from the remote field measurements and identifies the order of the return stroke measured in each flash detected.

The software manufacturer announces an error in spatial location, over the continental territory of Portugal, which is less than 500 m for the semimajor axis of a 50% probability ellipse. This manufacturer also announces efficiency in the order of 90% for flashes with first-stroke peak current higher than 5 kA, and for the same area (see Fig. 2) [17].

When a magnetic pulse is detected by two or more DTFs, each DTF will determine the direction and time of arrival. Usually, an algorithm of waveform discrimination will be applied to distinguish the signal of CG return strokes from others (e.g., signals of intercloud lightning strokes, local noises, etc.). This is accomplished by comparing the waveform to a set of preset criteria regarding rise time, pulse width, etc.

As long as the signal of CG strokes is recognized as good, information of the direction, time of arrival, and signal strength will then be processed to determine the flash location and is recorded in the database.

The database includes about four million records, until the end of 2007. However, the number of DTFs involved in the detection, the error associated, and the quality of the correlation on data recorded by each DTF involved is analyzed by an algorithm. Due to this procedure, only about 700 000 records were considered for this paper.

III. Thunderstorm Days Map

In most areas of the world, an indication of lightning activity may be obtained from the isokeraunic level map or Td map. The Td map of Portugal, shown in Fig. 3, is a 30–years average map [17]. The Td maps show the average of thunderstorm days over many years. However, the thunderstorm days may vary with the year in a range of one order of magnitude. Hence, the Td map by itself does not show the variation of lightning activity with time in an area.

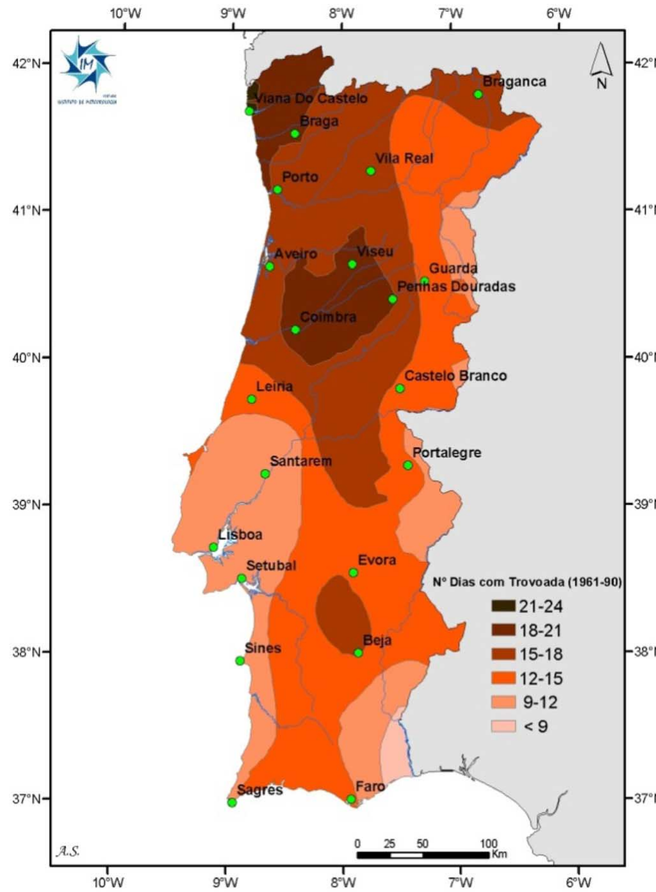

Fig. 3. Thunderstorm days map of Portugal, from 1961 to 1990.

Some empirical formulas, establishing a relation between parameters Td and GFD, are available. Equation (1) was originally published by Anderson *et al.* in 1984 and is now recommended by IEC and CENELEC (ENV 61024, 1995) in risk evaluations for lightning protection systems if there are no LLS data available

$$\mathrm{GFD} = a \cdot \mathrm{Td}^{b} \tag{1}$$

where GFD is the ground flash density in fl/km^2/year; Td is the thunderstorm days in days with thunderstorm per year; $\mathrm{a} = 0.04$, and $\mathrm{b} = 1.25$ are empirical constants.

IV. Methodology

The area under investigation is shown in Fig. 4. A rectangle, named B, fully covers the continental territory of Portugal, limited in longitude by $-9.6^\circ \leq \mathrm{long.} \leq -6.1^\circ$ and in latitude by $36.9^\circ \leq \mathrm{lat.} \leq 42.2^\circ$, was established. Two more rectangles with the same limits of latitude: rectangle A, covering an area on the Atlantic Ocean $(13.1^\circ \leq \mathrm{long.} \leq -9.6^\circ)$, and rectangle C, covering a part of Spain near to Portugal $(6.1^\circ \leq \mathrm{long.} \leq -2.6^\circ)$, were established. Since Portugal is in the boundary between the European continent and the Atlantic Ocean, it is interesting to compare data of these three different regions.

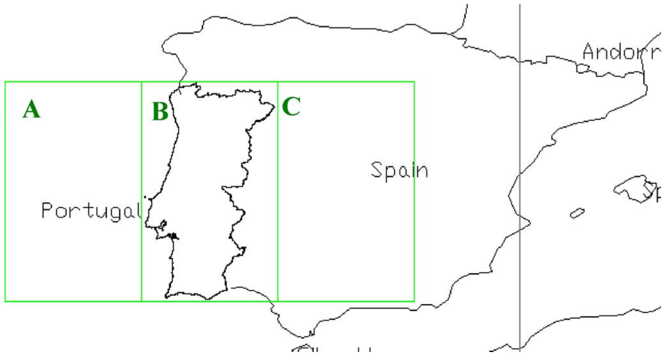

Fig. 4. Areas considered in this paper.

TABLE I
ABSOLUTE AND RELATIVE NUMBER OF FLASHES

Year	A			B			C		
	+	-	Total	+	-	Total	+	-	Total
2002	1415	962	**2377**	3195	7154	**10349**	231	1042	**1273**
	59,53%	40,47%		30,87%	69,13%		18,15%	81,85%	
2003	4900	10437	**15337**	10053	36000	**46053**	4880	36085	**40965**
	31,95%	68,05%		21,83%	78,17%		11,91%	88,09%	
2004	3579	4833	**8412**	7114	37704	**44818**	3778	36529	**40307**
	42,55%	57,45%		15,87%	84,13%		9,37%	90,63%	
2005	3813	8211	**12024**	6400	24496	**30896**	3727	36179	**39906**
	31,71%	68,29%		20,71%	79,29%		9,34%	90,66%	
2006	8652	16551	**25203**	20677	62950	**83627**	8558	62378	**70936**
	34,33%	65,67%		24,73%	75,27%		12,06%	87,94%	
2007	7050	15956	**23006**	30490	84445	**114935**	10692	78926	**89618**
	30,64%	69,36%		26,53%	73,47%		11,93%	88,07%	
Total	**29409**	**56950**	**86359**	**77929**	**252749**	**330678**	**31866**	**251139**	**283005**

Note from Figs. 1 and 2 that inside rectangles B and C, the system has the highest accuracy and efficiency. Although the accuracy and efficiency of the LLS is lower in rectangle A, the decision was made to also present these data, which must be taken with reserve.

The Portuguese boundary of Fig. 4 is provided by [20], corresponding to official limits, rather than the Spanish boundary, which is a rough illustration.

Finally, text files with raw data are converted to database software files, filtering data by date, geographical location, polarity, and strength of signal.

V. RESULTS AND DISCUSSION

The results presented are related to data from July 2002, when the system became operational, until December 2007, which is the last month of data considered in this paper. However, the data of 2002 should be taken with reserve, since the system was still under testing.

Table I shows the absolute and relative number of flashes, inside rectangles A, B, and C, from 2002 until the end of 2007. The average incidence over rectangle B is the highest, 380% more than A, and 17% more than C. Furthermore, the incidence of positive flashes in B is 265% higher than A and 244% higher than C. Positive CG strokes represent 34% over rectangle A, 22% over rectangle B, and 11% over rectangle C.

International standards, such as IEC 62305-1, assume a polarity ratio of 10% for positive flashes and 90% for negative flashes, if no local information is available. However, Portugal has an average percentage of 23.5% for positive flashes. This may be due to Portugal boundary condition, between the European continent, and the Atlantic Ocean, but also may be due to misclassification by the LLS of small positive cloud pulses as CG flashes [21]. In [22], an analysis made to the Austrian LLS shows an increase of positive flashes after an upgrade to the sensors and the software package, which is similar to the Portuguese LLS.

TABLE II
GFD AND TD VALUES

Year	A		B		C	
	GFD	Td	GFD	Td	GFD	Td
2002	0,01	0,4	0,06	1,4	0,01	0,3
2003	0,09	1,9	0,26	4,5	0,23	4,1
2004	0,05	1,1	0,25	4,4	0,23	4,0
2005	0,07	1,5	0,17	3,3	0,23	4,0
2006	0,14	2,8	0,47	7,2	0,40	6,3
2007	0,13	2,6	0,65	9,3	0,51	7,6

TABLE III
FLASHES BY LATTTUDE

Latitude		37	37,5	38	38,5	39	39,5	40	40,5	41	41,5	42
2002	+	**47**	**69**	**61**	**112**	**397**	**347**	**75**	**1508**	**813**	**429**	**308**
		41,6%	26,5%	20,2%	21,5%	30,3%	32,1%	6,3%	46,9%	38,6%	25,5%	19,9%
	-	**66**	**191**	**241**	**409**	**914**	**735**	**1111**	**1707**	**1291**	**1255**	**1238**
		58,4%	73,5%	79,8%	78,5%	69,7%	67,9%	93,7%	53,1%	61,4%	74,5%	80,1%
2003	+	**1453**	**1812**	**2004**	**2151**	**2393**	**223**	**2181**	**1683**	**1479**	**1163**	**1286**
		26,7%	73,2%	19,8%	16,8%	22,6%	2,9%	25,4%	21,7%	17,1%	12,9%	11,3%
	-	**3993**	**664**	**8127**	**10637**	**8186**	**7369**	**6407**	**6083**	**7166**	**7853**	**10064**
		73,3%	26,8%	80,2%	83,2%	77,4%	97,1%	74,6%	78,3%	82,9%	87,1%	88,7%
2004	+	**739**	**1100**	**1261**	**1518**	**1407**	**1590**	**1907**	**1695**	**1244**	**1099**	**911**
		20,3%	18,6%	19,2%	20,1%	20,2%	17,5%	17,3%	18,1%	13,4%	9,4%	7,4%
	-	**2905**	**4824**	**5322**	**6039**	**5563**	**7514**	**9087**	**7695**	**8059**	**10612**	**11457**
		79,7%	81,4%	80,8%	79,9%	79,8%	82,5%	82,7%	81,9%	86,6%	90,6%	92,6%
2005	+	**1094**	**1436**	**1953**	**1707**	**1325**	**1055**	**923**	**1330**	**1302**	**903**	**912**
		22,8%	21,5%	20,7%	14,1%	17,0%	15,8%	16,6%	17,0%	19,4%	13,4%	10,7%
	-	**3711**	**5236**	**7466**	**10380**	**6482**	**5609**	**4623**	**6515**	**5400**	**5823**	**7643**
		77,2%	78,5%	79,3%	85,9%	83,0%	84,2%	83,4%	83,0%	80,6%	86,6%	89,3%
2006	+	**1658**	**3199**	**4001**	**4143**	**3874**	**4057**	**4401**	**5066**	**3428**	**2346**	**1714**
		24,5%	23,5%	19,8%	17,5%	21,7%	25,6%	27,6%	27,0%	20,9%	14,8%	11,5%
	-	**5097**	**10440**	**16187**	**19504**	**13956**	**11816**	**11546**	**13715**	**12972**	**13496**	**13151**
		75,5%	76,5%	80,2%	82,5%	78,3%	74,4%	72,4%	73,0%	79,1%	85,2%	88,5%
2007	+	**2782**	**8843**	**7772**	**6892**	**8827**	**3720**	**2942**	**2775**	**1540**	**1234**	**905**
		25,4%	32,0%	27,2%	21,5%	26,9%	16,1%	14,3%	15,3%	14,2%	11,7%	8,9%
	-	**8158**	**18791**	**20848**	**25095**	**24016**	**19451**	**17660**	**15352**	**9308**	**9329**	**9320**
		74,6%	68,0%	72,8%	78,5%	73,1%	83,9%	85,7%	84,7%	85,8%	88,3%	91,1%

Table II shows GFD and computed Td values. Using (1), the average Td is computed, as shown in Table II. Considering data from 2003 to 2007, this table clearly reveals the great variation of GFD values along the years studied. The max/min GFD ratio is 3.0 for area A, 3.7 for area B, and 2.2 for area C. The variation observed in area B from 2005 to 2007 could be caused by a malfunction of the LLS observed in 2005, affecting its efficiency.

Tables III and IV show the absolute and relative flash count distribution by latitude and longitude and by year. In these tables, a decrease of positive flashes with the increase of latitude and the decrease of longitude may be observed. Portugal has the highest number of positive flashes, compared with the other two regions.

In order to avoid overloading the paper with diagrams, the year 2007, the most recent one, is chosen as an illustrative example. Fig. 5 shows the absolute flash distribution by month over A, B, and C. Fig. 6 shows the relative flash distribution by month over A, B, and C. The trend observed for 2007 is followed by data collected from 2003 to 2006.

A significant variation is observed (Fig. 5) in the absolute flash count distribution in all areas considered. It is not possible to say which month has the highest GFD because it varies significantly with no apparent rule.

However, relative flash count distribution has a more steady behavior. It can be seen (Fig. 6) that positive flashes are more

TABLE IV
FLASHES BY LONGITUDE

Longitude		-12,5	-11,5	-10,5	-9,5	-8,5	-7,5	-6,5	-5,5	-4,5	-3,5	-2,5
2002	+	202	291	715	758	1498	764	399	105	68	38	3
		69,7%	58,1%	61,0%	41,0%	34,9%	23,9%	25,8%	14,4%	20,2%	45,8%	25,0%
	-	88	210	458	1089	2790	2427	1148	625	269	45	9
		30,3%	41,9%	39,0%	59,0%	65,1%	76,1%	74,2%	85,6%	79,8%	54,2%	75,0%
2003	+	801	1470	1803	2306	2593	3034	3208	1824	1165	1090	541
		42,4%	27,9%	33,3%	29,6%	28,3%	19,3%	18,2%	16,0%	11,9%	8,5%	10,2%
	-	1088	3793	3616	5492	6575	12704	14433	9608	8646	11805	4765
		57,6%	72,1%	66,7%	70,4%	71,7%	80,7%	81,8%	84,0%	88,1%	91,5%	89,8%
2004	+	1118	888	1055	1164	2223	2255	2140	1361	1005	912	350
		58,6%	39,9%	35,2%	32,2%	17,3%	15,5%	13,1%	10,0%	9,1%	9,2%	7,9%
	-	790	1340	1939	2446	10640	12282	14217	12304	10074	8984	4061
		41,4%	60,1%	64,8%	67,8%	82,7%	84,5%	86,9%	90,0%	90,9%	90,8%	92,1%
2005	+	682	888	1596	1284	1243	2943	1747	1135	1260	781	381
		31,7%	33,3%	31,8%	29,6%	24,7%	22,3%	14,8%	12,0%	13,0%	6,3%	5,4%
	-	1469	1775	3429	3048	3784	10232	10095	8322	8419	11622	6693
		68,3%	66,7%	68,2%	70,4%	75,3%	77,7%	85,2%	88,0%	87,0%	93,7%	94,6%
2006	+	764	1245	3942	6217	5935	6095	5645	3074	2348	1870	752
		43,1%	32,8%	35,9%	30,9%	31,3%	25,8%	17,3%	13,3%	14,8%	9,9%	7,4%
	-	1009	2550	7034	13874	12997	17499	26960	20085	13516	16975	9381
		56,9%	67,2%	64,1%	69,1%	68,7%	74,2%	82,7%	86,7%	85,2%	90,1%	92,6%
2007	+	320	1162	4262	5142	8960	10574	7718	4397	3338	1792	567
		41,2%	27,7%	30,1%	40,3%	30,1%	26,2%	19,7%	15,4%	13,6%	7,7%	7,0%
	-	456	3037	9902	7625	20805	29750	31453	24237	21145	21368	7550
		58,8%	72,3%	69,9%	59,7%	69,9%	73,8%	80,3%	84,6%	86,4%	92,3%	93,0%

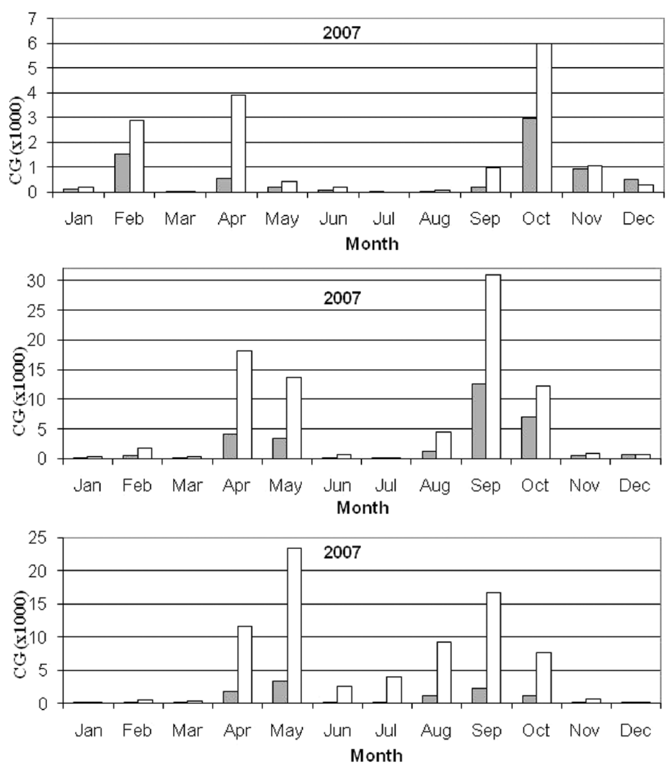

Fig. 5. Absolute flash distribution by month over A (above), B (middle), and C (bottom). Gray is for positive and white is for negative.

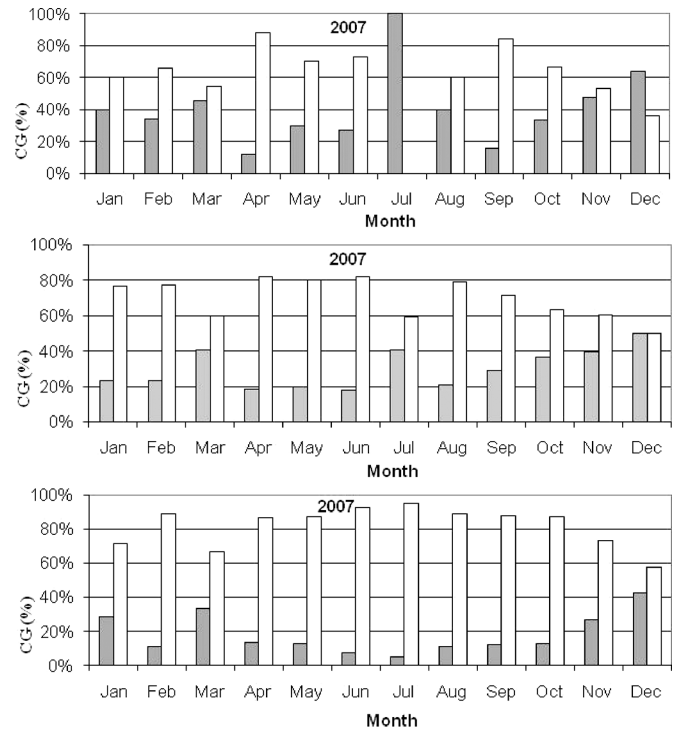

Fig. 6. Relative flash distribution by month over A (above), B (middle), and C (bottom). Gray is for positive and white is for negative.

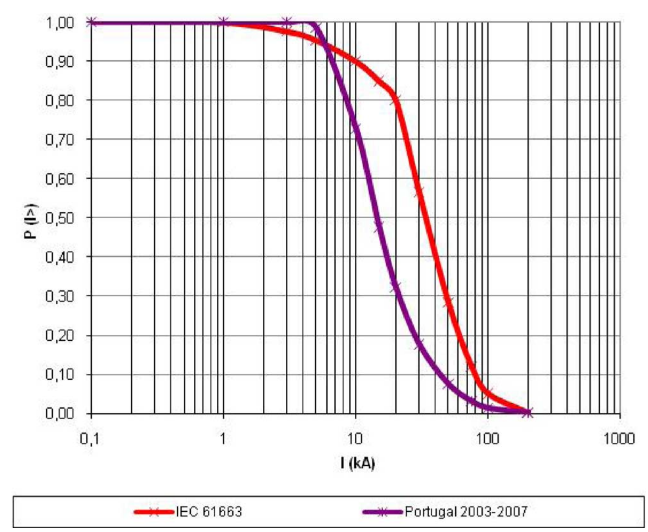

Fig. 7. Cumulative probability of the peak current from 2003 to 2007 over area B (Portugal).

frequent in winter months (October to March), reaching 40%, while negative flashes are more frequent (90%) in the summer months (April to September).

The cumulative probability of the peak current over area B (Portugal) is computed and compared with the curve given by IEC standards [23] (Fig. 7). All present values of the peak current are related to the first stroke. Peak current values were not corrected from possible errors introduced by detection efficiency or propagation models [22].

Along the five years under study, all curves overlap quite well, but they do not match the IEC curve so well . According to the IEC curve, only 20% of first CG strokes have a peak current of lower than 20 kA. However, for the Portuguese situation, 20% of first CG strokes have a peak current that is lower than about 8–10 kA. We note that the preliminary results presented in [15] match those presented here quite well.

The comparison between the cumulative distribution of peak current inferred by LLS and the one given by IEC standards should be taken with reserve. Note that the LLS provides current amplitude reports that may be affected by several uncertainties. These uncertainties are related mainly to the following issues: 1) LLS infers current amplitude starting from the measurement of magnetic fields and using an empirical formula that relates the measured peak fields with peak currents. Two strokes with the same peak value but different return stroke velocities

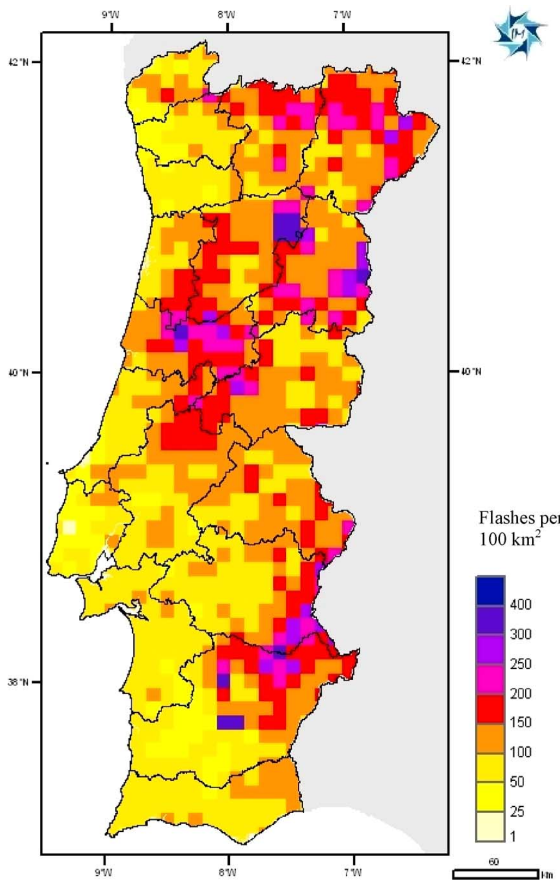

Fig. 8. Overall ground flash density map between 2003 and 2006 (IM).

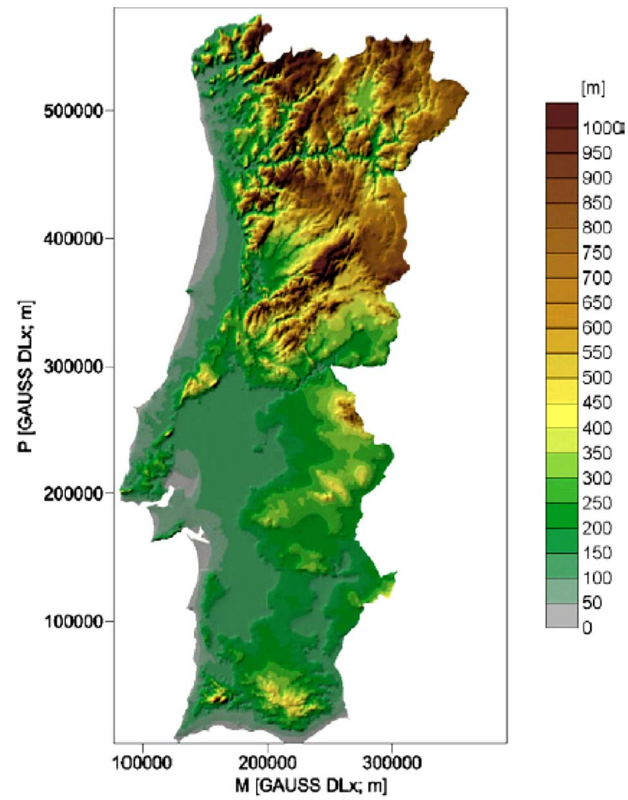

Fig. 9. Orographic map of Portugal.

would result in the same inferred current amplitude, while it is known that, for two different return stroke velocities, two different current amplitudes are needed to get the same field; however, and despite of the above, the statistical estimation (e.g., in terms of mean values and standard deviations) should be less affected by the variability of the return stroke speed, as shown in [2]; 2) the cumulative distribution depends on the lowest value that the LLS are able to detect; 3) ground propagation effects and calibration errors may also have a great influence; 4) IEC distributions are based on current measurements of the lightning striking instrumented towers; it is known that this causes the so-called “tower effect,” namely, the presence of the tower tends to bias toward higher values of the lightning current amplitudes [24], [25], while LLS refers to lightning striking the soil at ground level and, therefore, the relevant statistics do not suffer this bias. An excellent background that allows to better interpret and validate LLS-based findings is given in [3].

The overall GFD map is shown in Fig. 8. In this map, the country was divided into 10-km-long squares. GFD is calculated by counting lightning flashes during all of the years and dividing this number by the area of incidence and the number of years.

Please note that Fig. 8 was drawn taking into account only validated data from 2003 to 2006.

The GFD map characterizes the overall lightning threat to a power system, allowing to estimate how often the electrical installations are exposed to direct and indirect strokes. Hence, the GFD map has a very important role in evaluating the risk level associated with the potential location of any structure.

From Table II, the average GFD between 2003 and 2007 in the B region is $0.17 \leq \text{GFD} \leq 0.65$. These values are low enough to classify Portugal as a low-risk country. This is also in agreement with the damage due to lightning associated with human beings, services, and material goods [1]. However, in some mountains areas, the GFD value could reach 1 fl/km^2/year or higher.

A comparison between the GFD map in Fig. 8 and the Td map in Fig. 3 is discussed as follows. According to the Td map in Fig. 3, North Portugal, and especially the Viana do Castelo region, is particularly affected by lightning. However, the GFD map drawn in Fig. 8 shows that the Viana do Castelo region is among the regions with lower risk. Looking at Fig. 3, the region of Viana do Castelo is characterized by $18 < \text{Td} < 21$ which corresponds, using (1), to $1.5 < \text{GFD} < 1.8$. For the same region with 2200 km^2, we find 1869 flashes over four years which gives an average $\text{GFD} = 0.2$. This value is 9 times lower than that presented in the Td map of Fig. 3.

Fig. 9 shows the orographic map of Portugal. The overall GFD map of Fig. 8 matches the orographic map of Portugal quite well. As expected, a higher density of CG strokes in mountain regions can be observed, rather than in flat regions.

Comparing our results with those of a country with some geographical similarities, such as Japan [15], we can say that the GFD is lower in Portugal than in Japan which varies from 0.5 to 5.0; as in Japan, the average ratio of positive flashes to negative is 20% in summer, and it is 33% in winter; the 50% current peak in Japan is higher and varies from 20 to 35 kA, while in Portugal, it is about 15 kA.

VI. Conclusion

This paper presents lightning data observed with LLS in Portugal. The contributions of this paper are threefold. First, it is shown that Portugal has a percentage of positive flashes which is at least twice than that which was expected by IEC standards. Second, it is shown that positive flashes are more frequent in winter months, reaching 40%, while negative flashes are more frequent in summer months, reaching 90%. Finally, an overall GFD map is presented. This GFD map is compared with the Td map produced by the IM, and a weak correlation is noted. However, the GFD map matches the orographic map of Portugal quite well, showing a higher density of flashes in mountain regions rather than in flat ones and suggesting a strong influence of terrain with lightning activity. Hence, this paper greatly improves the knowledge of the lightning activity in Portugal. As a future work, a report on the precision and efficiency evaluation of the LLS through actual measurements is being carried out with IM. Also, since a large variation of the GFD parameter could be observed along these five years, especially in area B, a meteorological explanation is being investigated with IM.

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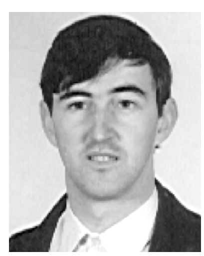

R. B. Rodrigues received the M.Sc. degree from the Instituto Superior Técnico, Lisbon, Portugal, in 2005 and is currently pursuing the Ph.D. degree at the University of Beira Interior, Covilha, Portugal, in collaboration with the Instituto Superior de Engenharia de Lisboa, Lisbon.

V. M. F. Mendes received the M.Sc. and Ph.D. degrees from the Instituto Superior Técnico, Lisbon, Portugal, in 1987 and 1994, respectively.

Currently, he is a Coordinator Professor with Aggregation at the Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal. He is the author or co-author of many scientific papers presented at international conferences or published in reviewed journals.

J. P. S. Catalão (M'04) received the M.Sc. degree from the Instituto Superior Técnico, Lisbon, Portugal, in 2003 and the Ph.D. degree from the University of Beira Interior, Covilha, Portugal, in 2007.

Currently, he is an Assistant Professor at the University of Beira Interior. He is the author or co-author of many scientific papers presented at international conferences or published in reviewed journals. He is an Associate Editor for the *International Journal of Power and Energy Systems*.

Dr. Catalão is a member of the Editorial Board of *Electric Power Components & Systems*. He is a reviewer for the IEEE Transactions on Power Delivery and other IEEE and international journals.