doi: 10.5028/jatm.2011. 03032511

Marco Antonio da Silva Ferro*
Institute of Aeronautics and Space
São José dos Campos/SP – Brazil
marcomasf@iae.cta.br

Jorge Yamasaki
Institute of Aeronautics and Space
São José dos Campos/SP – Brazil
yamasakijy@iae.cta.br

Douglas Roberto M. Pimentel
Institute of Aeronautics and Space
São José dos Campos/SP – Brazil
douglas.roberto.fis@gmail.com

Kleber Pinheiro Naccarato
National Institute for Space Research
São José dos Campos/SP – Brazil
kleberp@dge.inpe.br

Marcelo Magalhães Fares Saba
National Institute for Space Research
São José dos Campos/SP – Brazil
msaba@dge.inpe.br

*author for correspondence

Lightning risk warnings based on atmospheric electric field measurements in Brazil

***Abstract**: This paper presents a methodology that employs the electrostatic field variations caused by thundercloud formation or displacement to generate lightning warnings over a region of interest in Southeastern Brazil. These warnings can be used to prevent accidents during hazardous operations, such as the manufacturing, loading, and test of motor-rockets. In these cases, certain equipment may be moved into covered facilities and personnel are required to take shelter. It is also possible to avoid the threat of natural and triggered lightning to launches. The atmospheric electric field database, including the summer seasons of 2007/2008 and 2008/2009 (from November to February), and, for the same period and region, the cloud-to-ground lightning data provided by the Brazilian lightning detection network – BrasilDAT – were used in order to perform a comparative analysis between the lightning warnings and the cloud-to-ground lightning strikes that effectively occurred inside the area of concern. The analysis was done for three areas surrounding the sensor installation defined as circles with 5, 10 and 15 km of radius to determine the most effective detection range. For each area it was done using several critical electric field thresholds: +/- 0.5; +/- 0.8; +/- 0.9; +/- 1.0; +/- 1.2; and +/- 1.5 kV/m. As a result of the reduction of atmospheric electric field data provided by the sensor installed in area of concern and lightning provided by BrasilDAT, it was possible, for each of the areas of alert proposals, to obtain the following parameters: the number of effective alarms; the number of false alarms; and the number of failure to warning. From the analysis of these parameters, it was possible to conclude that, apparently, the most interesting critical electric field threshold to be used is the level of 0.9 kV/m in association with a distance range of 10 km around the point where the sensor is installed.*
***Keywords**: Atmospheric electric field, Electric field-mill, Lightning.*

INTRODUCTION

A recent study showed that more than half of lightning casualties resulted from the first or one of the first few cloud-to-ground (CG) flashes in a storm, and significant numbers of casualties resulted from returning to outdoor activities just before lightning had actually ceased (Lengyel, 2004). Between these times, when the threat of lightning is obvious, there are fewer casualties. Thus, it can be concluded that the initiation and cessation of lightning activity are critically important periods for both patrimonial and human safety. Therefore, great effort has been made to develop methods for accurate lightning occurrence forecast both to make secure the development of critical activities and to protect human life in several outdoor activities.

Received: 06/06/11
Accepted: 20/09/11

Several papers have dealt with lightning warning methods developed from CG lightning location systems (LLS) (Murphy and Cummins, 2000; Murphy *et al*., 2002; Holle *et al*., 2003). Furthermore, other particular researches combine total lightning with weather radar information in an effort to improve the accuracy of lightning threat alarms (Murphy and Holle, 2005; 2006). Finally, some recent studies presented automated lightning warning systems as a combination of lightning detection information and data from one or more electric field mills (EFMs) (Murphy *et al*., 2008; Montanya *et al*., 2008; Beasley *et al*., 2008; Aranguren *et al*., 2009). These studies had shown that the EFM measurements were strongly influenced by the characteristics of the place where it was installed, for example: the cloud charge center height in that region, the topography, and so on. Thus, the effectiveness of lightning warning methods using electric field data changes in one region to another. It is important to note that all the studies took place in the Northern hemisphere. Naccarato *et al*. (2008) showed a preliminary analysis comparing automatic warnings triggered only by EFM and those based only in CG lightning discharge occurrence in a specific region in Southeastern Brazil.

The present study extends the former analysis carried out by Naccarato (2008) for the same region, located in São José dos Campos, state of São Paulo, comparing data from one EFM to the CG lightning data provided by the Brazilian Lightning Detection Network (BrasilDAT) to evaluate how the atmospheric electric field variation data can be used to support the decision-making process of generating a lightning risk warning.

BASIC CONSIDERATIONS

EFM

EFMs are designed to determine the relative strength of the electric field by comparing its level in a known, stable, uncharged, and reference object. When an uncharged sensor plate is exposed to an electric field, it becomes charged. Thus, unlike lightning detection systems, which respond to fast transients in the electromagnetic field generated by lightning, EFMs detect the electrostatic field and relatively slow changes in that field. They detect the presence of charge separation and net charge directly above and in the immediate surroundings of the sensor. Depending on where the charge is located, the effective detection range of an EFM varies from a few kilometers to perhaps as much as 20 km (Murphy *et al.*, 2008). Field changes in the order of a fraction of a second are due to the overall rearrangement of the thundercloud charge distribution, which is produced by a lightning flash, and slower field changes are due to cloud electrification and rearrangement of space charge in the atmosphere. Hence, since the conditions are constantly changing, there is a need to constantly measure the strength of the electric field, which is translated into the need to alternately read the charged state of the sensor plate, discharge it, and read again. This is accomplished by repeatedly exposing the sensor plate to the external electric field to charge it, then shielding the plate to allow it to discharge. The process of exposing (charging) and shielding (discharging) the sensor plate from the electrical field is accomplished by means of a rotary shutter, consisting of a motor-driven, mechanically complementary rotor/stator pair. As the motor rotates, the shutter alternately opens to allow the external electric field to charge the sensor plate, and then it closes (Fig. 1) in order to shield the sensor plate to discharge or reset, in preparation for the next measurement.

The main advantage of the EFM is the protection from the occurrence of the first CG lightning strike.

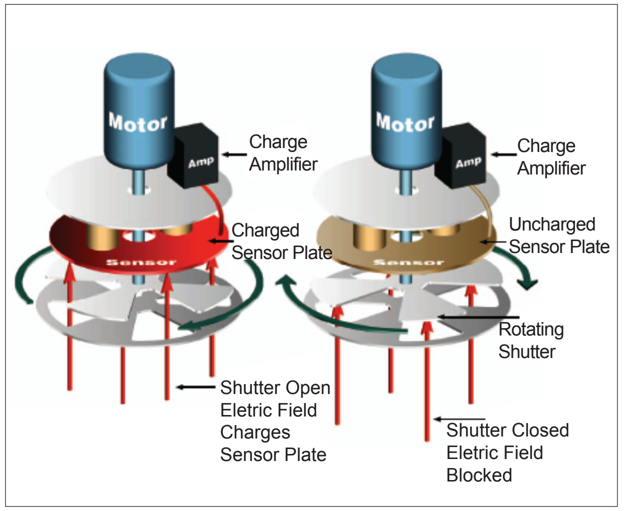

Figure 1. Diagram of operation of an electric field mill.

Electric field meters are typically factory calibrated using a parallel plate method, where a uniform electric field is developed by applying a known voltage between parallel conductive plates. Each EFM is factory calibrated in a parallel plate calibration fixture with the instrument aperture mounted in upward-facing. A linear fit of the calibration data results in a calibration equation expressed as:

$$E = f.V \tag{1}$$

The multiplier f is a function of the EFM electrode dimensions and the characteristics of the charge amplifier's electronic circuit. The manufacturer of the EFM used in this study estimated that the measurement accuracy of f for the instrument calibrated in the parallel plate electric field calibrator is ±1%.

However, when monitoring the Earth's electric field, Eq. 1 is valid only if the instrument aperture is mounted flush with the Earth's surface and upward-facing. Yet, for permanent outdoor measurements of electric field, a flush-mounted and upward-facing orientation is problematic because of dirt, bird droppings, rain, and so on, collecting on the sense electrodes and fouling the measurement. Consequently, a downward facing and elevated configuration is used for long-term field applications. Inverting the EFM reduces the effective gain, while increasing it height above ground enhances the gain, with respect to an ideal upward-facing flush-mounted geometry. A site correction factor *Csite* is necessary to correct f for non flush-mounted configurations. The corrected multiplier becomes as Eq. 2:

$$E = Csite.f.V \tag{2}$$

In this equation, f is unique for each EFM, yet independent of a given site, whereas *Csite* is unique for each given site, yet independent of the particular EFM used at the site. *Csite* is typically determined by using a flush-mounted upward-facing unit in the vicinity of the site that needs correction. An upward-facing calibration kit was used to hold the EFM in a flush-mounted upward-facing position. The collected data from both units, the upward-facing unit and a downward facing EFM installed in a specific site, are plotted (Fig. 2). A best-fit line computed from the data resulted in the *Csite*.

LLS

A LLS can locate CG lightning flashes with detection efficiency (DE) higher than 80% and location accuracy lower than 500 m, due to its network of precise sensors that detect the electromagnetic radiation of the lightning channels.

Furthermore, based on quality criteria and correction parameters, the central processing unit (responsible for computing the solutions based on the sensor reports) can discriminate more than 90% of the intracloud (IC) discharges from CG lightning strokes. In Brazil, there is a LLS operating since 1998, called BrasilDAT. Nowadays, this network is composed by 36 sensors as shown in Fig 3.

The BrasilDAT overall DE was already estimated by a DE model (DEMo) recently developed by the ELAT Group (Naccarato and Pinto Jr., 2008). A large area of the country is covered by an 80% or higher DE network.

COMPLEMENTARY OBSERVATIONS

Charge separation inside a thunderstorm cloud causes a reversal of the electrostatic polarity and an increase in the

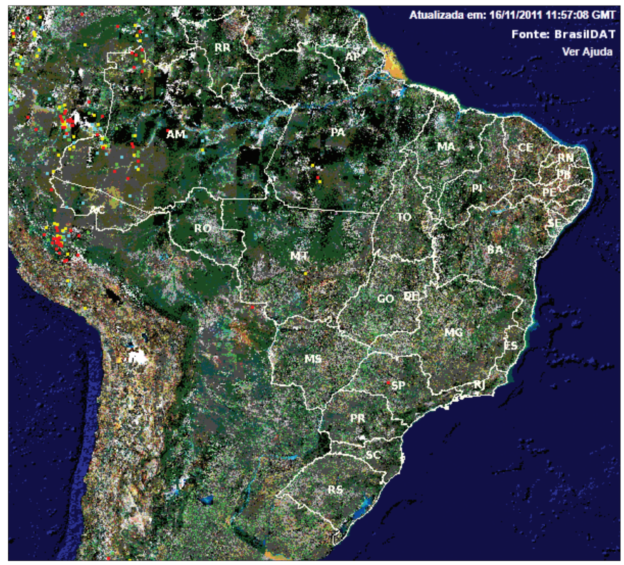

Figure 3. Area covered by BrasilDAT network.

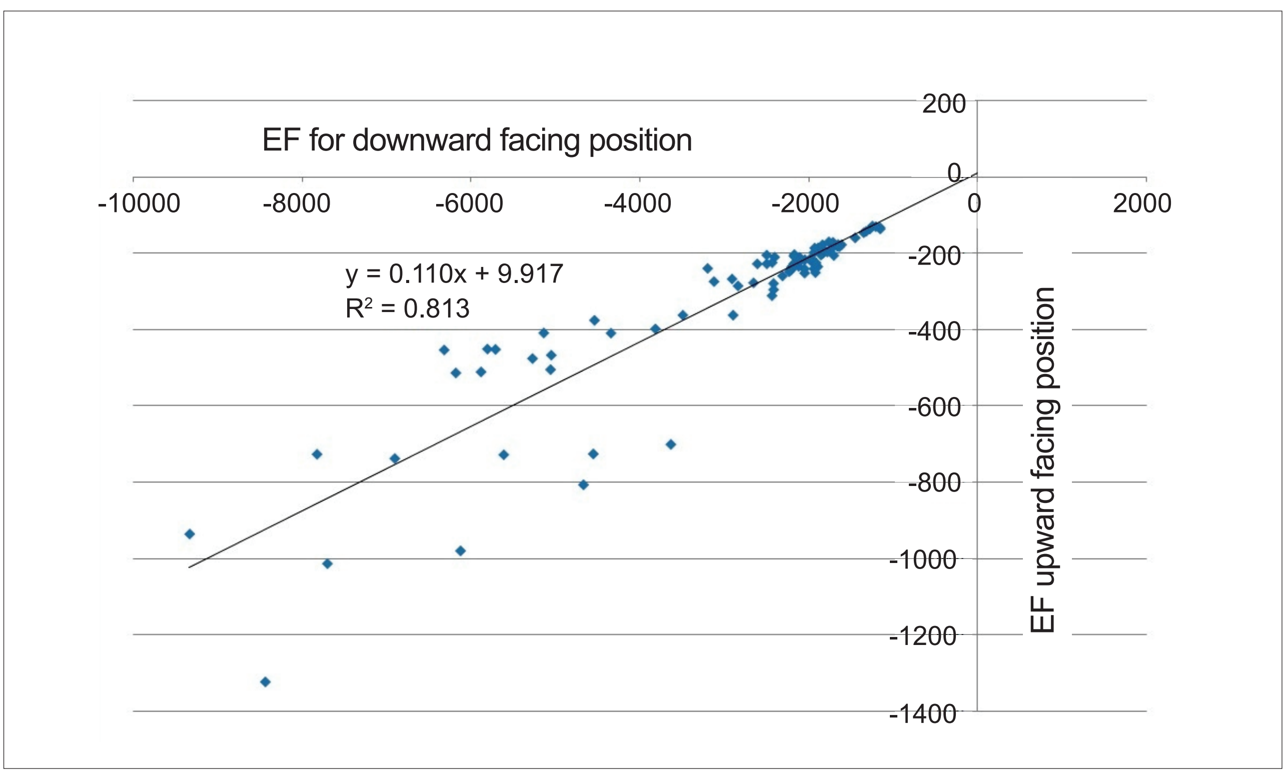

Figure 2. Determination of *Csite*.

magnitude of the field measured by an EFM in its vicinity. These characteristics can be used to trigger a warning, given that charge separation has to precede lightning. However, in not all cases does the field reverse polarity at a particular EFM site as a storm develops, and the exact magnitude reached by the field depends strongly on the distance between the EFM and the cloud charge regions (Murphy, 1996). Thus, a warning system using a fixed threshold for the field magnitude may or may not pick up all storms.

A LLS has a greater effective detection range (about hundreds of kilometers) than an EFM (about one or two tens of kilometers). Thus, a LLS is more effective than an EFM to detect cases where a mature thunderstorm moves toward the area of concern (AOC) from elsewhere.

LLS is a complex measurement system that by itself can help to provide a relative accurate CG lightning forecast to a particular area. However, the main disadvantages of a LLS are the very high installation and maintenance costs and it is not able to forecast the first CG lightning strike. Thus, the main reason for using EFMs is their capability of detecting the development of a thunderstorm directly over the AOC (Fig. 4).

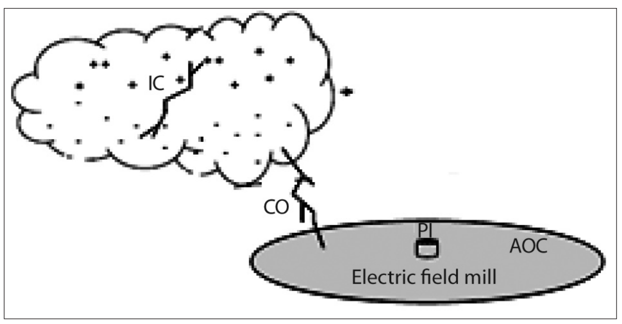

Figure 4. Area surrounding the sensor installation site.

OBJECTIVES

The main objective of this study was to define criteria that will be used by an atmospheric electric field monitoring system to provide lightning risk warnings.

Since the AOC is located in a region that has good coverage by the BrasilDAT, it is possible to compare the warnings generated by the EFM to the CG lightning data provided by BrasilDAT in order to evaluate the rate of false warnings and/or fail to warning based on some critical field thresholds.

METHODOLOGY

An atmospheric electric field database from November, 2007 to nowadays was created using an EFM installed in São José dos Campos (23º19'48.20"S and 45º48'31.85"W) in the Southeast region of Brazil. This period includes the summer seasons of 2007/2008 and 2008/2009 (from November to February). For the same period and region, it was selected the CG lightning data provided by the BrasilDAT network in order to perform a comparative analysis between the lightning warnings and the CG lightning strikes, which effectively occurred inside the AOC.

There were multiple thunderstorms that moved over the AOC during the period of the study. Some of them started and developed directly over the AOC. In the others cases a mature thunderstorm moved towards the AOC from elsewhere. Most of them moved from South to the North, following the direction of the valley formed by two chains of mountains named "Serra do Mar" and "Serra da Mantiqueira", where the city of São José dos Campos is located.

Therefore, the main purpose of this analysis is to simulate lightning warnings based on the atmospheric electric field measurements provided by the EFM and to compare them to the CG lightning data provided by the BrasilDAT network after some time from the beginning of warning. Thus, it is possible to evaluate the performance of the atmospheric electric field monitoring system. In order to simulate EFM automatic warnings, the equipment is assumed to be installed in the center of the AOC.

High frequency oscillations due to the rearrangement of cloud charge by lightning are also detected by the EFM during a thunderstorm. These fast field changes have to be removed from the dataset to avoid that the lightning-caused field changes make the field rise above the threshold level used in a warning system. The use of a 60-second average of the EFM measurement values is assumed to be a satisfactory smoothing technique to filter high frequency oscillations. Figure 5 shows an example of this smoothing technique.

The warnings will be evaluated based on the following parameters:

- effective alarm (EA) is the warning that was triggered before the CG lightning occurred inside the AOC;
- lead time (LT) is the time interval between the time of the warning and the occurrence of a CG lightning inside the AOC;
- failure to warning (FTW), when the first CG lightning strikes the AOC area without a previous warning;

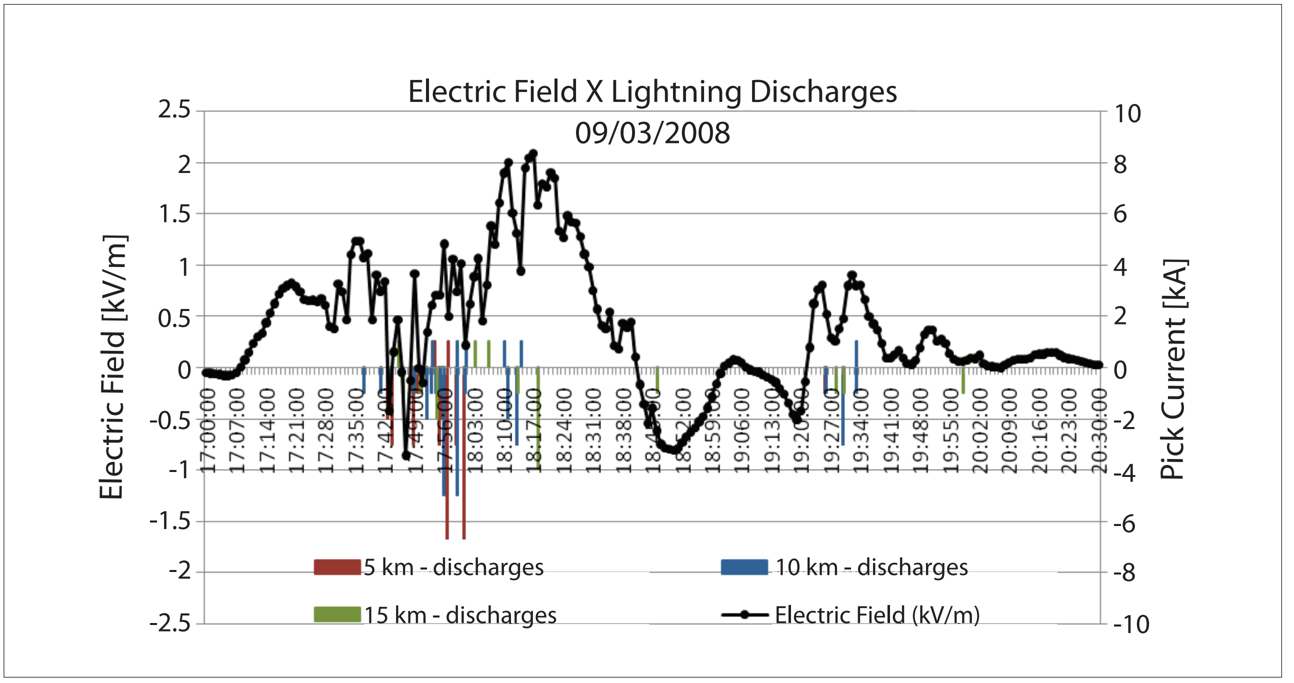

Figure 5. Example of the smoothing technique.

- false alarm (FA) is a warning triggered without the subsequent occurrence of a CG lightning inside the AOC after 45 minutes since the trigger.

The forecast verification will be done based on the contingence table described in Table 1.

Table 1. Contingence table.

		Observed		
		Yes	No	Total
Forecast	Yes	EA	FA	Forecast
	No	FTW	CNW	Not Forecast
	Total	Observed	Not Observed	Total

EA: effective alarm; FA: false alarm; FTW: failure to warning; CNW: correctly not warned.

Two statistical variables will be used in this study: the probability of detection (POD), which is simply the ratio of the number of successful warnings to the total number of episodes of a CG in the AOC, and the FA rate (FAR), which is the ratio of the number of FA to the total number of alarms (Eqs. 3 and 4).

$$POD = EA / (EA + FTW) \tag{3}$$

$$FAR = FA / (EA + FA) \tag{4}$$

They will help evaluating how the atmospheric electric field data could be used to better support the correct threshold level trigger of a lightning risk warning.

The analysis will be done for both circular and annular regions. On one hand, the influence of the number of EA, FA and FTW is better denoted using the annular regions ranging from 0 to 5 km; 5 to 10 km, and 10 to 15 km. On the other hand, to calculate the POD and the FAR is better to use areas surrounding the sensor installation defined as circles with 5, 10 and 15 km of radius. The analysis for each area is going to be done using several critical electric field thresholds: +/- 0.5; +/- 0.8; +/- 0.9; +/- 1.0; +/- 1.2; and +/- 1.5 kV/m. The warning is classified as successful if one or more CG lightning strike(s) is(are) detected inside the AOC up to 45 minutes after the warning is triggered. A delay time (DT) of 45 minutes is adopted to alarm extinction. This value was chosen as the mid-range of the active phase of a storm cloud found in literature. The count of DT is restarted every time an alert criterion is detected.

RESULTS AND DISCUSSION

The total number of EA, FA and FTW was analyzed as a function of critical electric field threshold and the distance of sensor installation site. The behavior of the EA, FA and FTW total numbers are resumed in Table 2.

Table 2. Total number of EA, FA and FTW.

	Distance range (km)	Critical electric field threshold (kV/m)					
		0.5	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**
Total nr of EA	0 to 5	29	28	28	26	19	15
	5 to 10	55	44	47	44	38	30
	10 to 15	56	53	52	48	41	34
Total nr of FA	0 to 5	40	41	39	37	42	34
	5 to 10	15	25	21	18	23	19
	10 to 15	13	16	16	13	20	15
Total nr of FTW	0 to 5	12	17	19	18	23	24
	5 to 10	39	46	48	47	54	59
	10 to 15	63	72	71	74	77	81

EA: effective alarm; FA: false alarm; FTW: failure to warning.

Figure 6 shows the behavior of the EA, FA and FTW total numbers as a function of the electric field threshold. The results show that the total number of EA decreases, while the electrical field threshold increases. But it shows a steady value between 0.8 and 1.0 kV/m dropping again from this point. There is a significative increase in the total number of EA when the annular region is changed from 0 to 5 km to 5 to 10 km. However, between the annular regions of 5 to 10 km and 10 to 15 km, the total numbers of EA are very close, suggesting that there is no significant gain changing the annular region from 5 to 10 km to 10 to 15 km.

The FA behavior shows a smooth oscillation with the smaller number of FA occurring for the threshold of 1.0 kV/m. It is very interesting the significant decrease in the total number of FA when the annular region is changed from 0 to 5 km to 5 to 10 km. But, in the same way that EA, between 5 to 10 km and 10 to 15 km the total numbers of FA are very close, suggesting that there is no significant gain changing the annular region from 5 to 10 km to 10 to 15 km. The total number of FTW increases when the distance range is increased, which shows a smooth oscillation between 0.9 and 1.0 kV/m.

Figure 7 shows the behavior of the total number of EA, FA and FTW as a function of the distance from the sensor. It is possible to note that the total number of FA and FTW does not suffer significant modification when the electric field threshold increases. Also, it is possible to note that there is no significant change in the total number of EA when the annular region changes from 5 to 10 km to 10 to 15 km for all electric field thresholds. In general, the

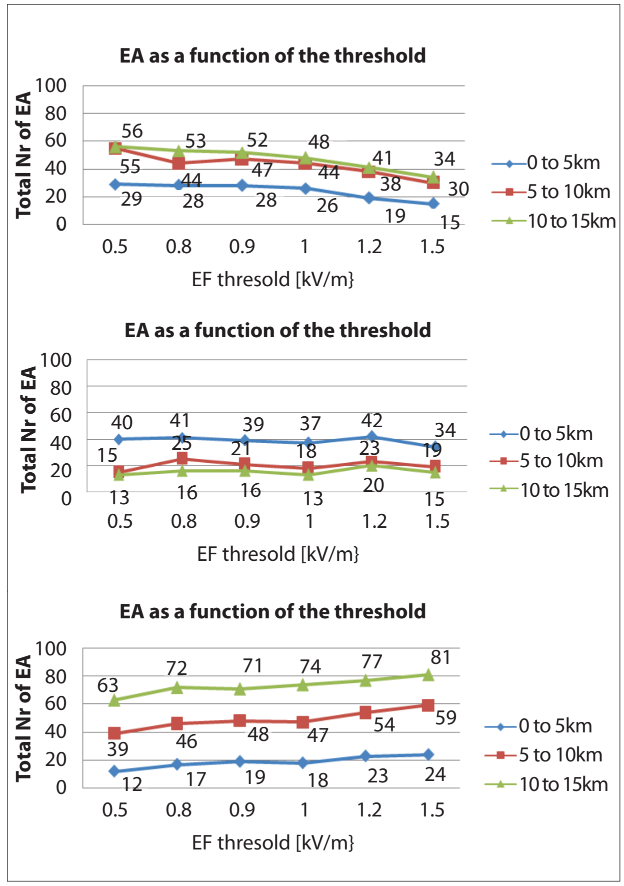

Figure 6. Total number of EA, FA, and FTW as a function of electric field threshold.

total number of EA continuously decreases when the field threshold increases, after 1.0 kV/m, and for the annular region 5 to 10 km and bigger EA is smaller than FTW.

Therefore, from the point of view of total number of events of EA, FA and FTW, apparently the most interesting critical electric field threshold to be used is the level of 0.9 kV/m for the annular region of 5 to 10 km. Though the annular region from 10 to 15 km shows the biggest number of EA events, it also shows a high number of FTW.

Taking into account safety, it is better to adopt a configuration that results in a small number of FTW, although resulting in a EA reduction and some increase in the FA number, mainly when the total numbers of EA for the annular region of 5 to 10 km and 10 to 15 km are very close, as shown in Figs. 5 and 6.

The ratio of predicted CG flashes *versus* FTW shows larger values (between 6:1 and 2:1) for all electric field thresholds when the actuation area of the sensor is restricted to a radius of 5 km as shown in Table 3. The ratio shrinks as the sensor's actuation area increases, reaching 1:1, i.e., for each predicted CG flash there is another that the sensor failed to predict.

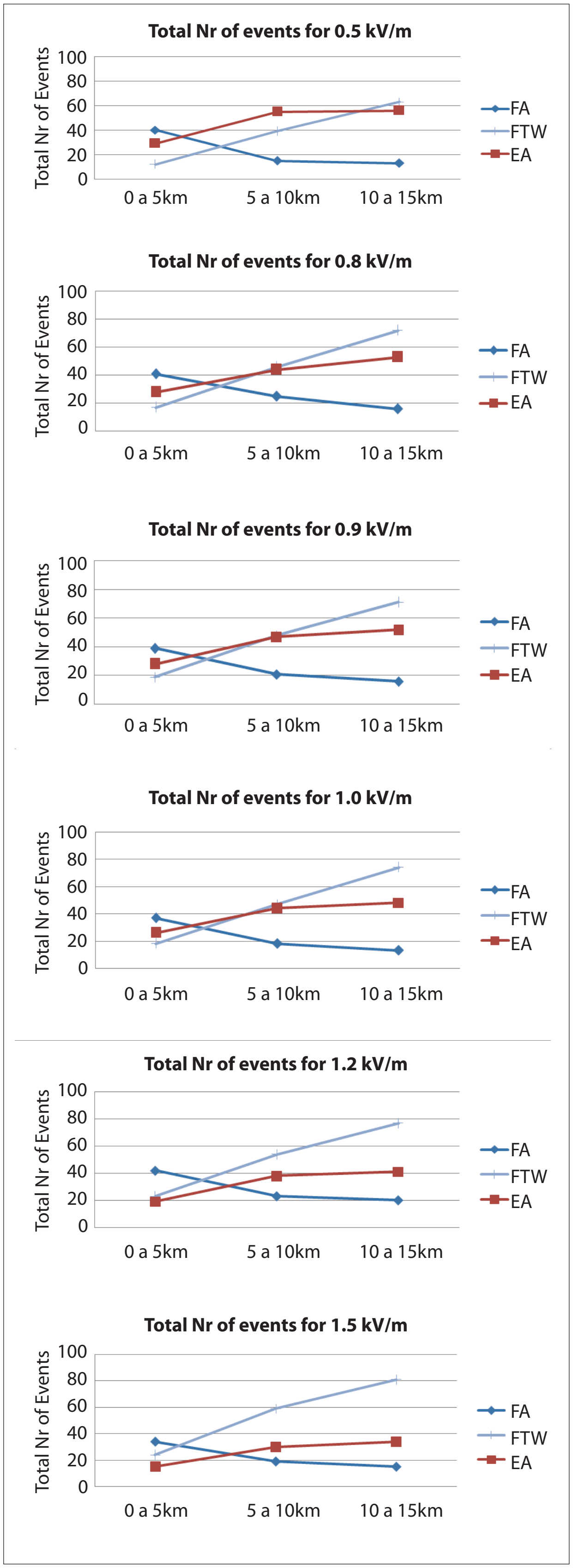

Figure 7. Total numbers of EA, FA and FTW as a function of the distance range of sensor.

Table 3. Relationship between predicted CG flash *versus* FTW.

	Distance range (km)	Critical field threshold (kV/m)					
		0.5	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**
(EA + FA)/ FTW	5	6	4	4	4	3	2
	10	3	3	3	2	2	1
	15	2	2	2	2	1	1

EA: effective alarm; FA: false alarm; FTW: failure to warning.

However, the ratio of predicted CG flash *versus* FTW is an approximated notion of warning effectiveness. The POD results in a more adequate indicator inasmuch as it takes into account the EA instead of the predicted CG flash number, indicating the percentage of lightning events observed, indicated as "yes" in the contingency table (Table 1), which have been properly warned (Eq. 3). The POD as a function of the electric field threshold and sensor's actuation area is shown in Table 4.

Table 4. Probability of detection.

	Radius (km)	Critical field threshold (kV/m)					
		0.5	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**
EA/(EA + FTW)	5	73	64	62	61	48	41
	10	67	59	60	58	49	43
	15	58	52	52	50	44	39

EA: effective alarm; FA: false alarm; FTW: failure to warning.

The use of the electric field threshold of 0.9 kV/m together with the area with a radius of 10 km, suggested by previous analyses, leads to a POD value of 60%, bigger than values found in some past studies. Using an electric field threshold of 1.0 kV/m, Aranguren *et al*. (2009) found 37.5% for POD in Catalonia, Spain, and Murphy *et al*. (2008) found 34.4% in Florida. Naccarato *et al*. (2008) in a previous study carried out in the same area of the present paper, analyzing a dataset of 30 days and continuous records and using a threshold of 0.5 kV/m and distance range of 10 km, found that 82.4% of the discharges inside their AOC were correctly warning. Beasley *et al*. (2008) observed that the electric field magnitude exceeded 1.0 kV/m, inside an area with radius of 10 km around the strike point and ten minutes before the first stroke, in 66.0% of the cases.

The fair-weather electric field could present values of some few hundred Volts/m due to some disturbances (e.g., mist, smoke, etc.) and they could influence the number of

FA. FAR indicates the percentage of FA related to the total number of predicted flashes (Eq. 4). FAR as a function of the critical field threshold and sensor's actuation area is shown in Table 5.

Table 5. False alarm rate.

	Radius (km)	Critical field threshold (kV/m)					
		0.5	**0.8**	**0.9**	**1.0**	**1.2**	**1.5**
	5	57	59	57	58	68	68
FA/(EA + FA)	10	38	46	41	41	50	49
	15	32	38	35	35	43	42

EA: effective alarm; FA: false alarm.

The use of electric field threshold of 0.9 kV/m together with the area with a 10 km radius, suggested by previous analyses, leads to a FAR value of 41%, smaller than the ones obtained by Aranguren *et al*. (2009) (87.0% - Catalonia region, Spain) and Murphy *et al*. (2008) (74.1% - Florida, USA) in the previously mentioned studies (Table 6). Although the previous analyses have pointed the threshold of 0.9 kV/m like the more interesting to use, for the purpose of comparing it with previous studies, Table 6 shows the values related to the threshold of 1.0 kV/m.

With regards to the information in Table 6, it is important to note that:

- Beasley (2008) used data concerning only the lightning that effectively occurred inside the AOC to analyze the warning system efficiency;
- Murphy and Naccarato (2008) did not analyze in their studies the LT;
- Naccarato (2008) did not relate the DT – the warning duration time interval – and used the threshold of 0.5 kV/m to trigger warnings; and
- Beasley and Murphy (2008) used the data from the network of EFM at the Kennedy Space Center and the adjacent Cape Canaveral Air Force Station that comprises 31 sensors, though Murphy had analyzed the data from only two sensors in the network.

CONCLUSIONS

With the purpose of evaluating how the atmospheric electric field variation data can be used to support the decision-making process of generating a lightning risk warning, it was used information from an atmospheric electric field database from November, 2007 to February, 2009 using an EFM in Southeastern Brazil. Since the area of interest lies in a region with excellent coverage of BrasilDAT, it was possible to compare the warnings generated by the proposed system to the CG lightning data provided by BrasilDAT in order to evaluate the rate of false warning and/or fail to warning based on some electric field thresholds.

The analysis was carried out for both circular and annular regions. The influence of the numbers of EA, FA and FTW is better denoted using the annular regions of 0 to 5 km, 5 to 10 km and 10 to 15 km. To calculate the POD and the FAR, it is better to use areas surrounding the sensor installation defined as circles with 5, 10 and 15 km of radius. The analysis for each area was done using several electric field thresholds: +/- 0.5; +/- 0.8; +/- 0.9; +/- 1.0; +/- 1.2; e +/- 1.5 kV/m. As a result of the reduction of atmospheric electric field data provided by the sensor installed in AOC and lightning provided by BrasilDAT, it was possible, for each of the areas of alert proposals, to obtain the following parameters: the number of EA; the number of FA; and the number of FTW.

From the analysis of these parameters, it was possible to conclude that, apparently, the critical electric field threshold more interesting to be used is the level of 0.9 kV/m in association with a distance range of 10 km around the point where the sensor was installed.

Table 6. Resume comparing studies in the literature.

	Sensors used	Threshold (kV/m)	LT (min.)	DT (min.)	POD (%)	FAR (%)
Beasley (2008)	30	1.0	9.0 - 12.0	10.0	66.0	-x-
Murphy *et al*. (2008)	2	1.0	-x-	15.0	34.4	74.1
Naccarato *et al*. (2008)	1	0.5	-x-	-x-	82.4	17.6
Aranguren *et al*. (2009)	1	1.0	6.5	30.0	37.5	87.0
Present study	1	1.0	13.0	45.0	58.0	41.0

-x-: not analyzed in the study.

To this electric field threshold, the choice of distance range of 10 km is justified by the fact that, from a security standpoint, it is preferable to have a greater number of FA and less FTW, than otherwise.

Values found for the POD (58%) and for the FAR (41%), using the electric field threshold of 1.0 kV/m and area with a radius of 10 km are significantly better than the ones found by Aranguren *et al*. (2009) in Catalonia. However, they show worse performance than that found by Naccarato *et al*. (2008) in the same region of this study. It is important to note that, like this paper, both studies used data from only one sensor. Nevertheless, Naccarato *et al*. (2008) adopted the threshold of 0.5 kV/m to trigger a warning, which resulted in high values of POD as a consequence of a large number of EA and a small number of FTW.

The values of POD found by Murphy *et al*. (2008) and Aranguren *et al*. (2009) (34.4 and 37.5%, respectively) are smaller than those found herein probably due to the fact that they are using a small DT, which tends to decrease the number of EA diminishing as a consequence the POD. Besides that, it is important to note that, as mentioned in the Introduction, the electric field sensor's measurements are strongly influenced by the local characteristics of the installation site (cloud center charge height in that region, topography, etc.). Therefore, measurements from sensors installed at sea level (Murphy – Florida) can result in a smaller POD as a consequence of a bigger distance to the center charge of the cloud than the one carried out in higher places (Aranguren – Terrassa, Spain – 300 m above the sea level).

This study was carried out in a region located 800 m above the sea level. It is understood that the height of the center charge of the cloud varies with the latitude. Therefore, the effectiveness of lightning warning systems that use electric field data varies as a function of this parameter (Florida – 24º N; Terrassa – 41º N; São José dos Campos – 23º S).

Thus, the system based on only one sensor, assuming an area with a radius of 10 km around it and an electric field threshold of 0.9 kV/m to trigger the warning, showed a very interesting performance (POD=60% and FAR=41%) compared to the studies found in literature. The average time interval before the first lightning occurrence (LT) found in this study (13 minutes) is higher than that found in the mentioned studies. Other methodologies and additional criteria can be used to increase POD and to decrease the FAR. The use of an electric field-mill network is a choice and another one is based on the use of simultaneous data from both lightning detection and location network combined with electric field measurements and meteorological radar.

REFERENCES

Aranguren, D., *et al*., 2009, "On the lightning hazard warning using electrostatic field: Analysis of summer thunderstorms in Spain". Atmospheric Research. doi:10,1016/j.elstat.2009.01.023.

Beasley, W.H., Williams, D.E., Hyland, P.T., 2008, "Analysis of surface electric-field contours in relation to cloud-to-ground lightning flashes in air-mass thunderstorms at the Kennedy Space Center". 20th International Lightning Detection Conference (ILDC). Proceedings. Tucson.

Holle, R.L., Murphy, M.J., Lopez, R.E., 2003, "Distances and times between cloud-to-ground flashes in a storm". International Conference on Lightning and Static Electricity (ICLSE). Proceedings. Blackpool.

Lengyel, M.M., 2004, "Lightning casualties and their proximity to surrounding cloud-to-ground lightning", M.S. Thesis. University of Oklahoma.

Montanya. J., *et al*., 2008, "Total lightning, electrostatic field and meteorological radar applied to lightning hazard warning". 20th International Lightning Detection Conference (ILDC). Proceedings. Tucson, CD-ROM.

Murphy, M.J., 1996, "The electrification of Florida thunderstorms". PhD thesis, University of Arizona.

Murphy, M.J., Cummins, K.L., 2000, "Early detection and warning of cloud-to-ground lightning at a point of interest". 2nd Symposium on Environmental Applications. Proceedings. American Meteorological Society, Long Beach, p. 172-177.

Murphy, M.J., Demetriades, N.W.S., Cummins, K.L., 2002, "Probabilistic early warning of cloud-to-ground lightning at an airport. 16th Conference on Probability and Statistics in the Atmospheric Sciences". Proceedings. American Meteorological Society, Orlando, p. 126-131.

Murphy, M.J., Holle, R.L., 2006, "Warnings of cloud-to-ground lightning hazard based on combinations of lightning detection and radar information". 19th International Lightning Detection Conference (ILDC). Proceedings. Tucson, CD-ROM.

Murphy, M.J., Holle, R.L., 2005, "A warning method for the risk of cloud-to-ground lightning based on total lightning and radar information". International Conference on Lightning and Static Electricity (ICLSE). Proceedings. The Boeing Co., Seattle.

Murphy, M.J., Holle, R.L., Demetriades, N.W.S., 2008, "Cloud-to-ground lightning warnings using electric field mill and lightning observations". 20th International Lightning Detection Conference (ILDC). Proceedings. Tucson.

Naccarato, K.P., Pinto Jr., O., Ferreira Jr., H.H., 2008, "Cloud-to-ground lightning forecast based on lightning location system information and electric field-mill data". International Conference on Grounding and Earthing (GROUND 2008) & 3th International Conference on Lightning Physics and Effects (LPE). Proceedings. Florianópolis, Brazil.

Naccarato, K.P., Pinto Jr., O., 2008, "Improvements in the detection efficiency model for the Brazilian lightning detection network (BrasilDAT)". Atmospheric Research. In press. doi:10,1016/j.atmosres.2008.06.019.