Operational analysis of electric field mills as lightning warning systems in Colombia

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***Abstract*— Electrostatic field measurements obtained in Bogotá-Colombia during thunderstorm episodes in November (common raining season due to the intertropical confluence zone over central Colombia) were used to study the performance of an isolated electric field sensor and analyze its most important operational characteristics. Distances from each flash to the studied sensor were obtained by using the Colombian lightning location system. The ΔE vs distance relation allowed defining a charge model which can be used as a reference for calibrating other electrostatic field sensors to be used as lightning warning systems.**

Keywords- thunderstorms, electric field mill, operational analysis, lightning warning system

I. Introduction

Electrostatic field sensors are among the most used thunderstorm detection devices in lightning warning systems. Standards such as EN50536 [1] and ACRP report 8 [2] recommend electric field mills as thunderstorm detection devices due to their ability to monitor the buildup of the local electrostatic field which precedes a lightning strike. However many uncertainties related to the topography, neighboring elements and local weather conditions affect their measurements. Hence, more operational studies about electric field mill's performance are needed for different latitudes and meteorological conditions in order to improve the thunderstorm forecasts derived from this kind of detectors.

Since 1914 many scientists have used the ΔE vs distance curves in order to investigate the electric charge associated with lightning flashes. Most of the studies have been carried out in Europe [3-5], South Africa [6-8] and USA [9-12]; almost no researches have been done in tropical region; taking into account that the lightning parameters in this zone present important differences compared to those in typically studied regions; the uncertainties about the field mills performance in the tropic increase.

This paper uses the same techniques applied by mentioned experiments; however the main objective is not to find charge solution but to develop a calibration methodology able to characterize electric field sensors in non-ideal installation conditions. Nine storm days in Bogotá - Colombia are used to characterize an experimental electric field mill.

In Bogota, the pass of ITCZ twice a year originates stormy seasons during April-May and October-November. Commonly thunderstorms in Colombia are influenced by topographic conditions. The formation activity of deep vertical development cloudiness like cumulonimbus related to lightning flashes, are mostly originated in ascent orographic of the moist air mass as a result of warming differences given by solar radiation. In contrast to what happens in other latitudes, the origin causes and life cycle of the thunderstorm depends on local features that have not been extensively studied, so the uncertainty in forecasts is high.

There are another kind of thunderstorm forms created by a drastic directional change of wind from north that bring all the moist mass located in the Magdalena´s Valley, interacting positively with the updrafts caused by the strong difference in land use between the savannah and the city (density difference). This kind of formation doesn´t depends on the ITCZ location but the local circulation. The storm episodes analyzed in this paper were consistent with the second kind of thunderstorm form.

II. Models

As it has been concluded by Wilson [3], Jacobson and Krider [9], Maier and Krider [10] and others, generally cloud to ground flashes can be represented by a point charge model as described in Fig. 1. If the ground is considered as a flat conductor, the electric field change ΔE at the ground level produced by a flash is given by equation (1) , where ΔQ is the punctual charge change, H is the charge height, *xi* and *yi* are the distance differences from the charge coordinates to the evaluation point.

By comparing charge solutions derived from the electric field mill network in Florida (31 sensors) and VHF detections given by LDAR (Lightning Detection And Raging) Murphy [13] found that many cloud to ground flashes are better represented by a bipolar model as described in Fig. 2., In this model an additional effect of a punctual charge in the LPCC (Low positive charge center) is included; therefore the electric field change ΔE at the ground level can be computed by adding the ΔEs related to each point charge.

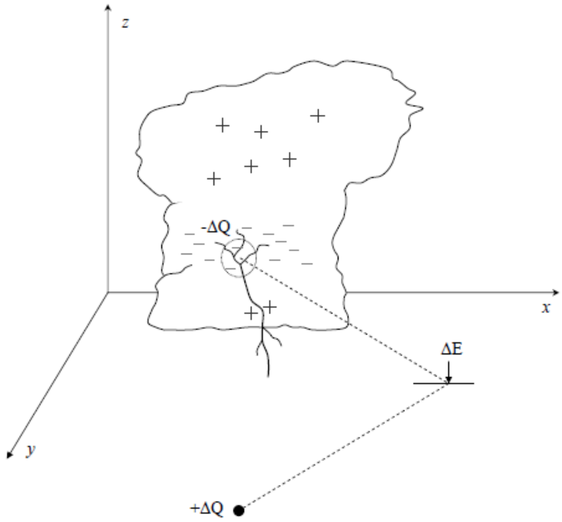


Fig.1. Point charge model

$$\Delta E = \frac{2\Delta Q H}{4\pi\varepsilon_0\left(H^2 + x_i^{\,2} + y_i^{\,2}\right)^{3/2}} \qquad (1)$$

Many studies such as [11, 13-14] have found that the point charge change ΔQ can be well represented by a log-normal distribution as given in (2); where μQ is the median of ΔQ and σln(Q) is its standard deviation.

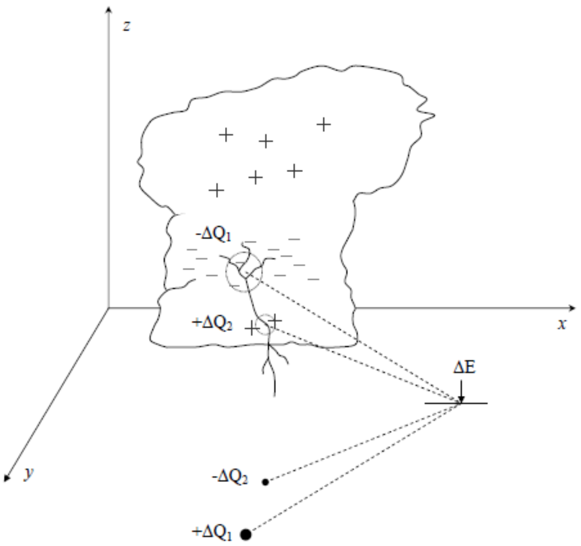


Fig. 2. Bipolar charge model

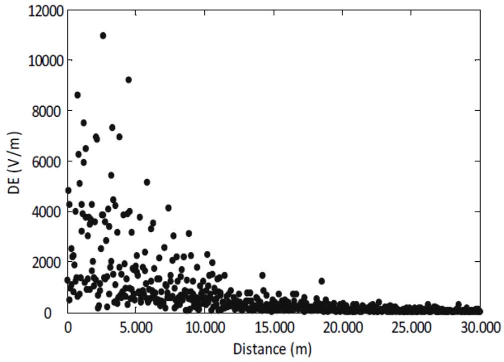
$$\ln(\Delta Q) \approx N\left(\mu_Q, \sigma_{\ln(Q)}\right) \qquad (2)$$

Fig. 3 shows the behavior of 600 simulated electric field changes at random distances, calculations were done by using the point charge model. ΔEs shown in Fig. 3 were computed considering a log-normal distribution of point charges ΔQ and taking into account a normal distribution of the height H.

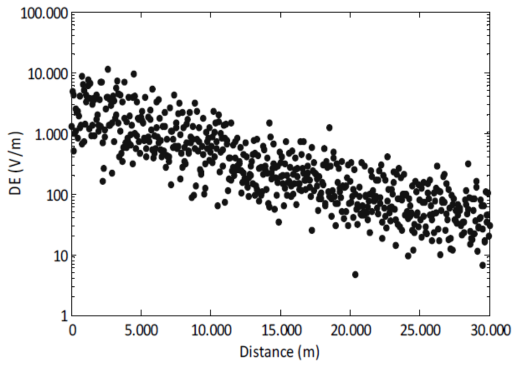
Median and standard deviation for ΔQ and H were taken from results in [11] where Florida thunderstorms have been studied. Fig. 3a (lineal scale for ΔE) allows observing the maximum expected ΔE values for any distance from 0 to 30 km; Fig. 3b (log scale for ΔE) shows the minimum and maximum ΔE limits for any distance.

Dataset shown in Fig. 3 is consistent with the measurements taken by an electrostatic field sensor installed in ideal conditions and in Florida. Therefore, the sensor's external errors affect the ΔE vs distance relation, introducing changes in the amplitudes or the ΔE behavior as a function of the distance.

A calibration method can be based on studying the ΔE vs distance relation at a given electrostatic field measurement site and on comparing it with a given pattern distribution obtained from the thunderstorm conditions in the region.



a.



b.

Fig. 3. Electric field changes ΔE vs distance for 600 simulated cloud to ground flashes, considering the log-normal distribution. a. normal scale b. log scale.

III. MEASUREMENT SYSTEM

The thunderstorm electrostatic field was measured by using a field mill designed and manufactured in the National University of Colombia [15, 16]. The main operational characteristics of the sensor are summarized in Table I. Eight induction windows are periodically shielded by a metallic helix rotating at 2250 r.m.p. The output signal V0(t) can be computed by using equation (3), where ε0 is the air dielectric permittivity, A(t) is the measurement surface area varying over time; C(t) is the sensor's variable capacitance and E is the incident electrostatic field.

$$V_0(t) = \frac{\varepsilon_0 EA(t)}{C(t)} \quad (3)$$

The 320 Hz output signal is digitalized at 100 kS/s using a resolution of 14 bits. Amplitude and polarity of the incident electrostatic field are computed by processing the digitalized signal; last process provides finally 5 samples per second of the measured electric field. The time stamp is provided by a GPS Garmin 18 x antenna.

TABLE I
FIELD MILL CHARACTERISTICS

Parameter	
Sensitivity	500 µV/V/m
Resolution	2,44 V/m
Digital resolution	14 bits signed
Maximum sample rate	140 MS/s
Range	+/- 20 kV/m
Output signal	+/- 10 V
Motor	Brushless
Time stamp	Synchronized with a server

The measurement station was installed over a 12 m – building in the National University Campus (Fig. 4); this condition introduces a site error which amplifies the electric field measured by the sensor. A finite elements simulation showed that the theoretical electric field amplification due to the building is a factor close to 9.6. An experimental amplification factor obtained from the ΔE vs distance curve is discussed below.

On the other hand, Bogotá is located at 2555 MSL, but over a large flat region in the Sabana de Bogotá; this condition causes that the experimental sensor is not affected by complex topographical effects and the charge models described above are applicable; only an altitude correction is needed.

Fig. 4 shows the experimental field mill; it was inverted in order to reduce measurement interferences caused by the rain and nearby storms.

Fig. 4. Electric field mill

Cloud-to-ground lightning location data were given by the SID system (Sistema de Información de Descargas) operating in Colombia.

IV. DATA AND ANALYSIS

Table II presents the thunderstorm episodes measured in Bogotá. 9 out 16 measured thunderstorm days allowed obtaining 491 ΔE from cloud-to-ground flashes which were unambiguously matched with the lightning location system detections. A distance range from 0 to 30 km was considered.

TABLE II
THUNDERSTORM EPISODES STUDIED IN BOGOTÁ

Date (dd/mm/yyyy)	**Local time**	**CG Flashes**
04/11/2010	13:00	141
15/11/2010	17:45	21
17/11/2010	13:37	99
19/11/2010	17:00	54
20/11/2010	12:05	38
22/11/2010	15:08	14
25/11/2010	13:00	68
27/11/2010	13:45	37
28/11/2010	13:28	11
Total	--	491

Most of the storm cases occurred in the Sabana de Bogotá as isolated cells. As an example Fig. 5 shows the cloud-to-ground lightning detections given by SID on November 17, 2010. In this event the storm was initially detected 140 km northeast Bogotá and moves to the measurement point. Fig. 6 gives a diagram for the flash-sensor distance vs time for the event on November 17. The dots illustrate distance and time for each flash; the continuous line corresponds to the instantaneous electrostatic field measured by the sensor. Fig 6a illustrates the last 60 km during the approach of the thunderstorm; note how the electric field measure is affected when the cloud-to-ground lightning activity is nearer than 20 km; in addition a polarity change can be detected when the storm-sensor distance is close to 10 km.

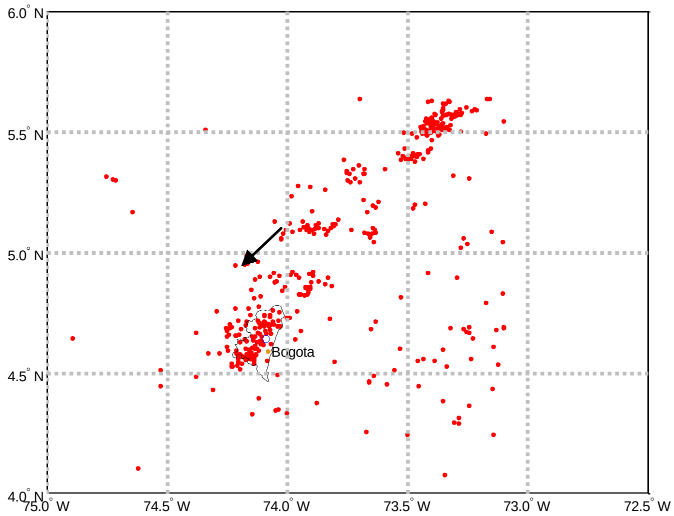
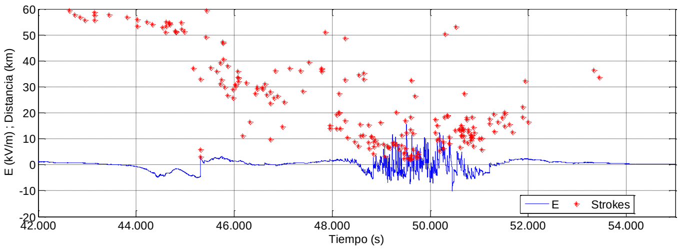


Fig. 5. Cloud-to-ground flash detections during the storm episode on November 17, 2010.



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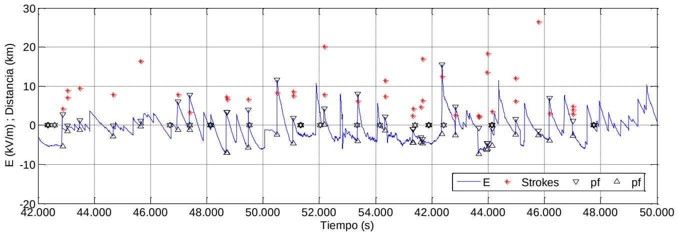


b.

Fig. 6. Electrostatic field measurement and cloud-to-ground lightning distances on November 17, 2010. a. Approaching phase for 60 km. b. Storm activity over the sensor site.

Fig. 6b shows the timelines interval when the thunderstorm was closer and the measured electric field exposed the highest values. Each detected cloud-to-ground lightning has an electric field change ΔE related. Note how strokes of the same flash share the same electric field change. In fig. 6b, pi and pf denotes the initial and final point for each ΔE.

All storm episodes presented small time errors between the time stamp given by the synchronization server in the field mill system and the stroke time given by the lightning location network. Table II presents the storm episodes in which the time error could be unambiguously identified. Very intense episodes with high lightning rates were neglected due to the time error was not calculable.

V. RESULTS

Storm episode on November 17 presented the ΔE vs distance distribution shown in Fig. 7. Most of the storms cases in Table II behaved as isolated cells similar to the episode on November 17; ΔE vs distance patterns were similar in all cases. In general terms, storm events analyzed in Bogotá were consistent with previous studies with isolated field mills such as Wormell (1939) [5], Jacobson and Krider (1976) [9] and others.

The Electric field changes ΔE vs distance distribution for the complete dataset of the nine storms in Table II is shown in Fig. 8; note how the data for the complete dataset are consistent with the theoretical curve described in section II.

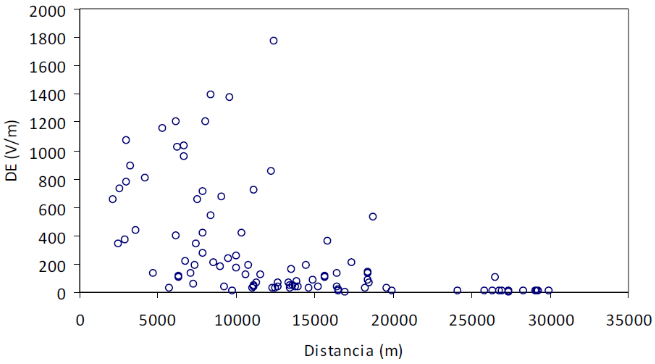


Fig. 7. Electric field changes ΔE vs distance for cloud-to-ground flashes during the storm episode on November 17, 2010.

Distribution in Fig. 8 was fitted by using point charge and bipolar models (section II). The solutions were obtained by applying a non-lineal least square optimization procedure; (4) gives the objective function C2 in which ΔEci is the electric field change computed based on the unknown parameters H and ΔQ (or H1, H2, ΔQ1 and ΔQ2 if the bipolar charge model is used), ΔEmi is the electric field change measured and N is the total number of measured ΔE, in this case 491.

$$C^2 = \sum_{i=1}^{N} \left(\Delta E_{ci}(H, \Delta Q) - \Delta E_{mi} \right)^2 \qquad (4)$$

The solution procedure starts by defining initial values for H and ΔQ parameters. An iterative process based on the Marquardt Method [17] allows obtaining the model parameters that best fit the measured electric field changes by minimizing function C2.

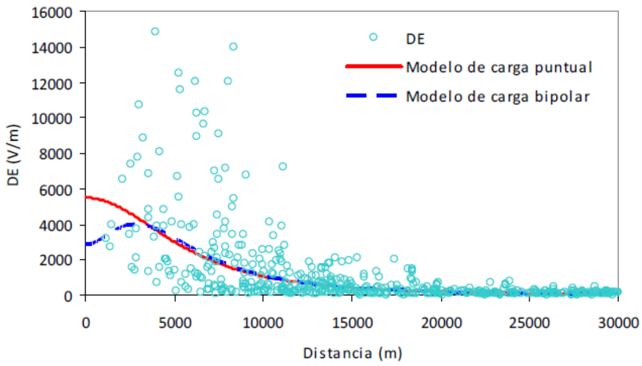
Table III presents the point and bipolar charge solutions for the 491 ΔE measured in Bogotá. The point charge solution height was 9658 MSL; as discussed by Murphy (1996) [13]; the solutions based only on a point charge tend to be vertically displaced towards higher altitudes. The altitude of the obtained point charge solution seems to be higher than expected.

The bipolar charge solution was -22 C at 8414 m and 6,8 C at 6316 m (above the sea level); last values are consistent with previous studies carried out in Florida such as Murphy (1996) [13].

TABLE III
CHARGE SOLUTIONS FOR THE NINE THUNDERSTORM EPISODES IN BOGOTÁ

Model	**H (m)***	**ΔQ (C)**
Point charge	7103	-15,4
Bipolar charge	5862, 3761	-22, 6,8

*With respect to the local terrain altitude (2555 MSL)



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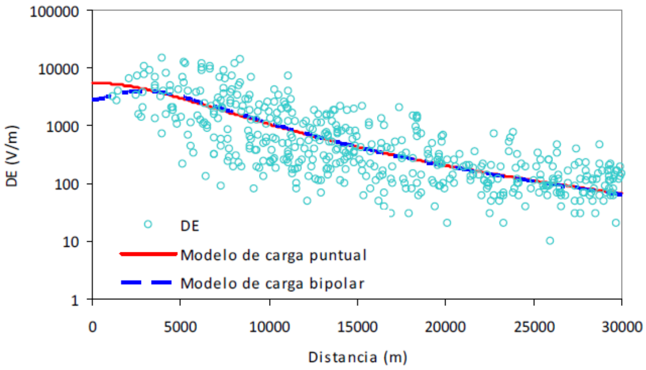

b

Fig. 8. Electrostatic field changes ΔE vs distance distribution for the nine thunderstorm episodes in Table II. a. Lineal scale distribution b. Log scale distribution.

Fig. 8 presents the point and bipolar charge model curves obtained with the solutions listed in Table III. As it can be noted, the two models agree in the range distance from 3 to 30 km; for shorter distances there is a great difference. High errors are normal in the 0-5 km range due to the simplification based on point or bipolar charges is not valid for representing the cloud charge region neutralized by a lightning flash. In addition, the lightning location error is more noticeable at short distances.

Results given by Table III are significant for the knowledge about the thundercloud electrical structure in the tropics. The point charges ΔQ are ambiguous due to the site error of the sensor is involved. Despite the obtained point charges were consistent with previous researches in other countries, some uncertainty is introduced because of the site error was computed theoretically not experimentally. In contrast, the H parameter is unambiguous and reliable; the form how the ΔE vs distance curve decays has a unique solution for the height H and in is not dependent on the ΔE solution. In that way we can state that the cloud charges during cloud-to-ground flashes in the studied episodes were located at mean heights of 8414 and 6316 MSL (for the negative and positive charges respectively).

Last results are relevant in a "scientific degree" for the cloud electrical structure research; however this paper focuses on an "operational degree" study which looks for obtaining a calibration pattern for electrostatic field sensors installed in non-ideal conditions and in a tropical zone.

In order to find a statistical pattern for the ΔE measured by the experimental field mill it was carried out a regression analysis for the dataset in Fig. 8. Due to the charge change ΔQ presents a log-normal distribution, the ΔE is also log-normal for a given distance; therefore a log conversion for the ΔE is needed. The independent variable is the distance d whereas log(ΔE) is the dependent one.

Fig. 9 presents the regression analysis. The best fitting is found when a third-order polynomial is used. The continuous black line corresponds to the mean ΔE. The confidence interval - CI of 95% (red dashed lines) represents the interval where the mean ΔE has 95% probability to be located; the CI limits are 3,5 and 9,76 kV/m for d = 0. The prediction interval PI of 95% (black dashed lines) shows the region for the measured ΔE with 95% probability; the PI limits are 0,49 and 43,3 kV/m for d = 0.

Fig. 9 and the regression results (CI and PI limits) can be considered as a pattern distribution to be taken as a reference for other field mills installed in non-ideal conditions and involved in lightning warning systems. In addition, the charge solutions presented in Table III can be used to fit the site error for a given sensor.

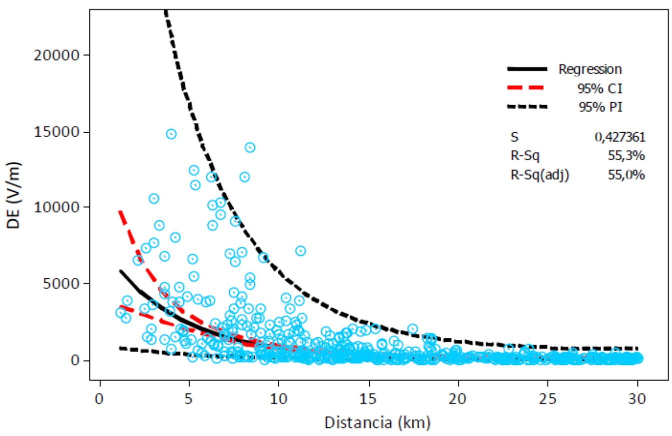

Fig. 9. Regression analysis for the experimental electric field mill in Bogotá.

VI. Conclusions

An electrostatic field mill station in Bogotá – Colombia, located at 2555 MSL over flat terrain, allowed obtaining a reference distribution for the ΔE measurements. Nine thunderstorm episodes during 2010 were analyzed to obtain a ΔE vs distance pattern conformed by 491 cloud-to-ground flashes. As a result, the measured distribution fits a bipolar charge model with heights of 8414 and 6316 MSL and charges of -22 and 6,8 C.

Last physical parameters can be used as a reference for fitting electric field mills in other installation conditions. Despite different causes for thunderstorms formation are observed Bogotá, all storms present the same characteristics and the charge solutions tend to be similar as described in previous sections. Generally, most of the storms in central

Colombia are created orographycally and are similar to those studied in this paper.

A regression analysis showed the statistical behavior of the measured ΔE for any distance. In that way, for calibrating any given electrostatic field sensor installed in other conditions in central Colombia; it is possible to compare both the mean values and the dispersion of the datasets.

ACKNOWLEDGMENT

The authors would like to acknowledge National University of Colombia by providing Electric field measurement.

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