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

Análisis operacional de molinos de campo eléctrico como sistemas de alerta de tormentas eléctricas en Colombia

D. Aranguren, J. López, E. Pérez, J. Herrera, L. Aragón, H. Torres

***Abstract* — Electrostatic field measurements taken in Bogotá, Colombia, during thunderstorms in November (the rainy season due to inter-tropical confluence zone over central Colombia) were used to study the performance of an isolated electric field sensor and analyse its most important operational characteristics. The distances from each flash to the studied sensor were obtained by using the Colombian lightning location system. The ΔE *cf* distance ratio led to defining a charge model which could be used as a reference for calibrating other electrostatic field sensors to be used as lightning warning systems.**

***Keywords*: thunderstorm, electric field mill, operational analysis, lightning warning system.**

***Resumen* — Medidas de campo electrostático realizadas en Bogotá durante episodios de tormenta en noviembre de 2010 (típicamente temporada de lluvias dada por el paso de la zona de confluencia intertropical por el centro de Colombia) fueron usadas para estudiar y analizar las características operacionales más importantes de un sensor de campo electrostático aislado. Las distancias de cada descarga nube-tierra con respecto al sensor obtuvieron a partir de los datos suministrados por el SID (Sistema de Información de Descargas). Los ΔE en función de la distancia permitieron definir un modelo de carga puede ser utilizado como sistema de referencia para la calibración de otros sensores de campo electrostático a ser implementados en sistemas de alerta de tormentas eléctricas.**

***Palabras claves*: tormenta eléctrica, molino de campo eléctrico, análisis operacional, sistemas de alerta de tormentas eléctricas.**

D. Aranguren is PhD student in Electrical Engineering of the National University of Colombia and cooperates with the research group PAAS. National University of Colombia, Bogotá and manager of the company Keraunos (e-mail: hdarangurenf@unal.edu.co, daranguren@keraunos.co).

E. Pérez, PhD, is with the Department of Electrical Engineering, National University of Colombia, Medellín (e-mail: eperezg@unal.edu.co).

J. Herrera, PhD, is with the Department of Electrical Engineering, National University of Colombia, Medellín (e-mail: jherreram@unal.edu.co).

J. López is MSc student in Electrical Engineering of the National University of Colombia and cooperates with the research group PAAS. National University of Colombia, Medellín (e-mail: jalopez@unal.edu.co).

L. Aragon is with the Colombian Air Force, MSc student in Meteorology of the National University of Colombia and cooperates with the research group PAAS. National University of Colombia, Bogotá (e-mail: glaragonr@unal.edu.co).

H. Torres is Titular Professor of the Department of Electrical Engineering, National University of Colombia, Bogotá (e-mail: htorress@unal.edu.co).

1. INTRODUCTION

Electrostatic field sensors are among the most used thunderstorm detection devices in lightning warning systems. Such as EN50536 (EN50536 Std, 2010) and ACRP report 8 (ACRP, 2008) 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 to improve thunderstorm forecasts derived from such detectors.

Since 1914 many scientists have used the ΔE *cf* distance curves to investigate electrical charges associated with lightning flashes. Most studies have been carried out in Europe (Wilson, 1916, pp.555-574; Wormell, 1939), South Africa (Schonland et al, 1927; Schonland et al, 1928) and the USA (Jacobson and Krider, 1976; Murphy et al, 1996); almost no research has been done in tropical regions. Uncertainty about field mill performance in the tropics increase when it is taken into account that lightning parameters in this zone present important differences compared to those in typically studied regions.

This paper uses the same techniques applied by the aforementioned experiments; however, the main objective was not to find a charge solution but to develop a calibration methodology for characterising electric field sensors in non-ideal installation conditions. Nine storm days in Bogotá, Colombia, were used to characterise an experimental electric field mill.

When the inter-tropical convergence zone (ITCZ) passes twice a year in Bogota it leads to stormy seasons during April-May and October-November. Thunderstorms in Colombia are normally influenced by topographic conditions. The formation activity of deep vertical development cloudiness such as cumulonimbus related to lightning flashes mostly originates in the orographic ascent of a moist air mass as the result of warming differences due to solar radiation. By contrast with what happens in other latitudes, the origin causes a thunderstorm life-cycle to depend on local features which have not been extensively studied so far, so uncertainty in forecasts is high.

Other kinds of thunderstorm forms are created by a drastic directional change of wind from the north, bringing the moist mass located in the Magdalena Valley; this interacts positively with the updrafts caused by the strong difference in land use between the savannah and the city (density difference). This kind of formation does not depend on ITCZ location but on local circulation. The storm episodes analysed in this paper were consistent with the second form of thunderstorm.

2. MODELS

As it has been concluded by Wilson (Wilson, 1916, pp.555-574), Jacobson and Krider (Jacobson and Krider, 1976; Maier et al, 1986) and others, cloud to ground (CG) flashes can generally be represented by a point charge model as described in Figure 1. If the ground is considered as a flat conductor, the ΔE electric field change at ground level produced by a flash is given by equation (1) , where ΔQ is the precise charge change, H is the charge height, x_i and y_i are the distance differences from the charge coordinates to the evaluation point.

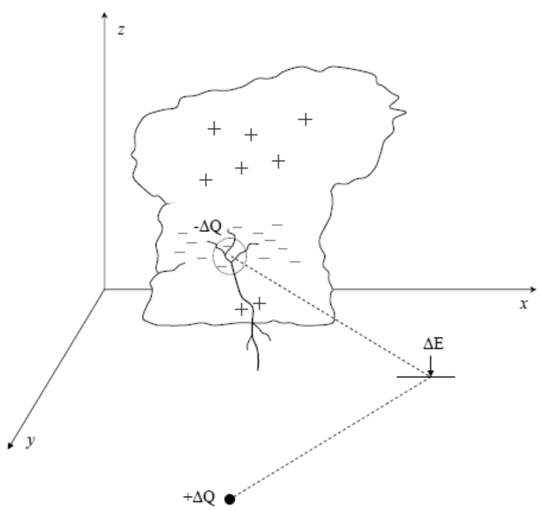


Fig. 1. Point charge model

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

Murphy (Murphy, 1996) found that many CG flashes are better represented by a bipolar model by comparing charge solutions derived from the electric field mill network in Florida (31 sensors) and VHF detections given by Lightning Detection And Raging (LDAR), as described in Figure 2. An additional effect of a precise charge in the low positive charge centre (LPCC) is included in this model; the electric field change ΔE at ground level can thus be computed by adding the ΔEs related to each point charge.

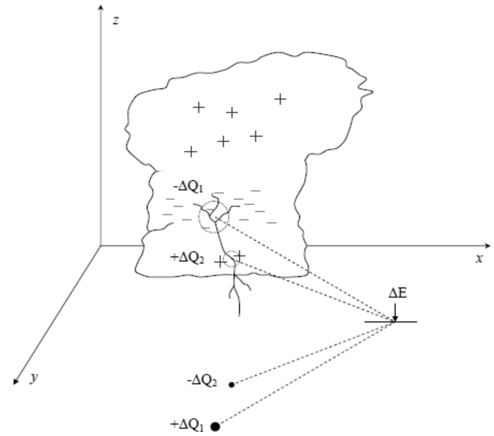


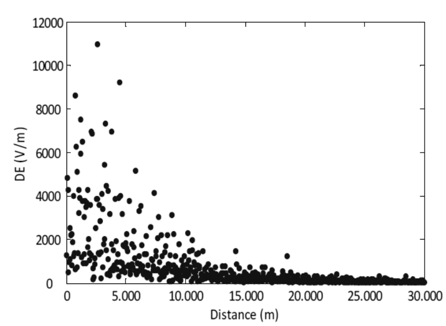
Figure. 2. Bipolar charge model

Many studies such as (Krider, 1989; Murphy, 1996; Montanya, 2004) have found that the point charge change ΔQ can be well represented by a log-normal distribution as given in (2); where μ_Q is the median of ΔQ and $\sigma_{\ln(Q)}$ is its standard deviation.

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

Figure 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 Figure 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 (Krider, 1989) where Florida thunderstorms have been studied. Figure 3a (lineal scale for ΔE) allows observing the maximum expected ΔE values for any distance from 0 to 30 km; Figure 3b (log scale for ΔE) shows the minimum and maximum ΔE limits for any distance.

Dataset shown in Figure 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.



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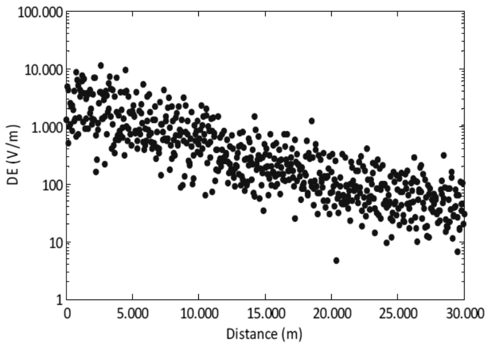

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Figure. 3. Electric field changes ΔE cf distance for 600 simulated CG flashes, considering log-normal distribution. a. normal scale b. log scale.

3. MEASUREMENT SYSTEM

A thunderstorm electrostatic field was measured by using a field mill designed and built in the Universidad Nacional de Colombia (Aranguren et al, 2005, pp.184-189; Press et al, 1992). The main operational characteristics of the sensor are summarised in Table 2; eight induction windows were periodically shielded by a metallic helix rotating at 2,250 rpm. The output signal $V_0(t)$ could be computed by using equation (3), where ε_0 was the air dielectric permittivity, $A(t)$ was the measurement surface area varying as time elapsed, $C(t)$ was the sensor's variable capacitance and E was the incident electrostatic field.

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

The 320 Hz output signal was digitalised at 100 kS/s using 14 bit resolution. Incident electrostatic field amplitude and polarity were computed by processing the digitalised signal; the latter process provided 5 samples per second of the electric field being measured. The time stamp was 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 on a 12 m high building on the Universidad Nacional de Colombia's campus (Figure 4); this introduced a site error which amplified the electric field measured by the sensor. A finite elements simulation showed that theoretical electric field amplification due to the building gave a factor close to 9.6. An experimental amplification factor obtained from the ΔE *cf* distance curve is discussed below.

Bogotá is located 2,555 metres above sea level (masl) but on a large flat region on the nearby savannah; this causes experimental sensor not to be affected by complex topographical effects and the charge models described above are applicable; a correction is only needed for altitude.

Figure 4 shows the experimental field mill; it was inverted reduce measurement interference caused by rain and nearby storms.

Figure. 4. Electric field mill

CG lightning location data was provided by the discharge information system (DIS) operating in Colombia.

4. DATA AND ANALYSIS

Table 2 presents the thunderstorm episodes measured in Bogotá; 9 out of 16 measured thunderstorm days led to obtaining 491 ΔE from CG flashes which were unambiguously matched with lightning location system detection. A 0 to 30 km distance range 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 storms occurred on the savannah near Bogotá as isolated cells. Figure 5 shows CG lightning detection given by SID on November 17th, 2010. In this event, the storm was initially detected 140 km northeast of Bogotá and moved to the measurement point. Figure 6 gives a diagram for flash-sensor distance *cf* time for the event on November 17th. The dots illustrate distance and time for each flash; the continuous line corresponds to the instantaneous electrostatic field measured by the sensor. Figure 6a illustrates the last 60 km during the approach of the thunderstorm; note how electric field measurement became affected when CG lightning activity was closer than 20 km; in addition a polarity change could be detected when the storm-sensor distance was close to 10 km.

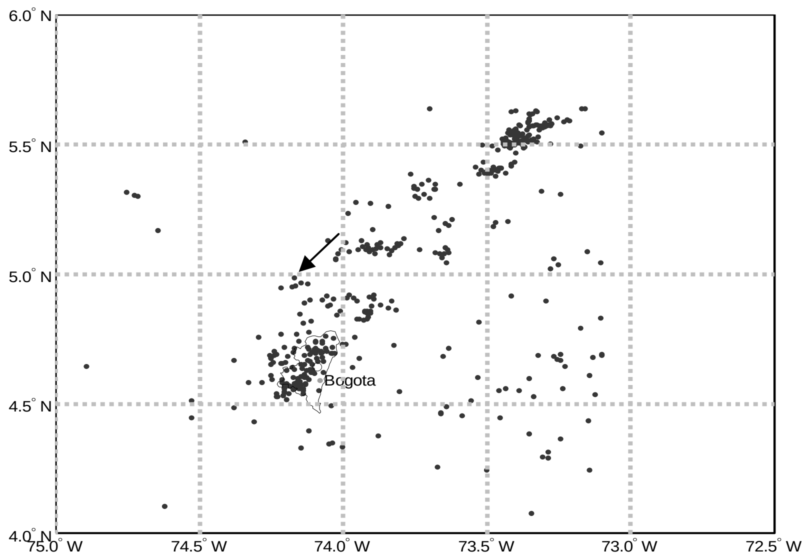
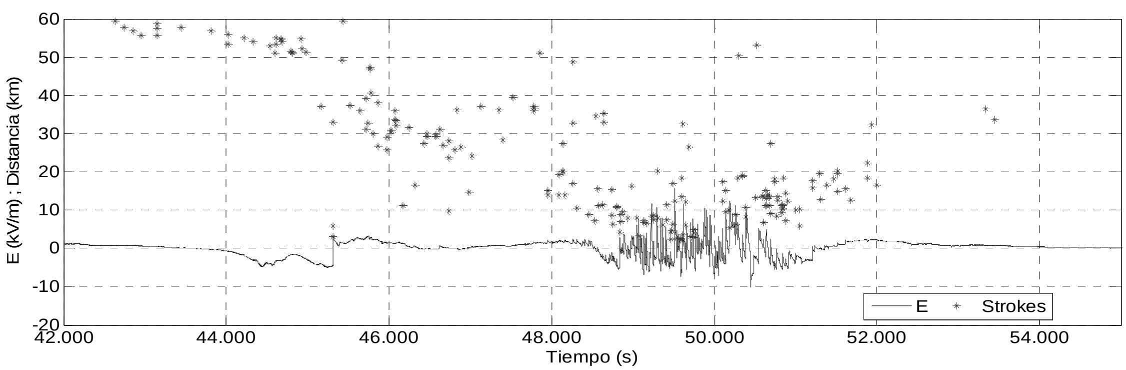


Figure 5. CG flash detection during the storm episode on November 17th, 2010



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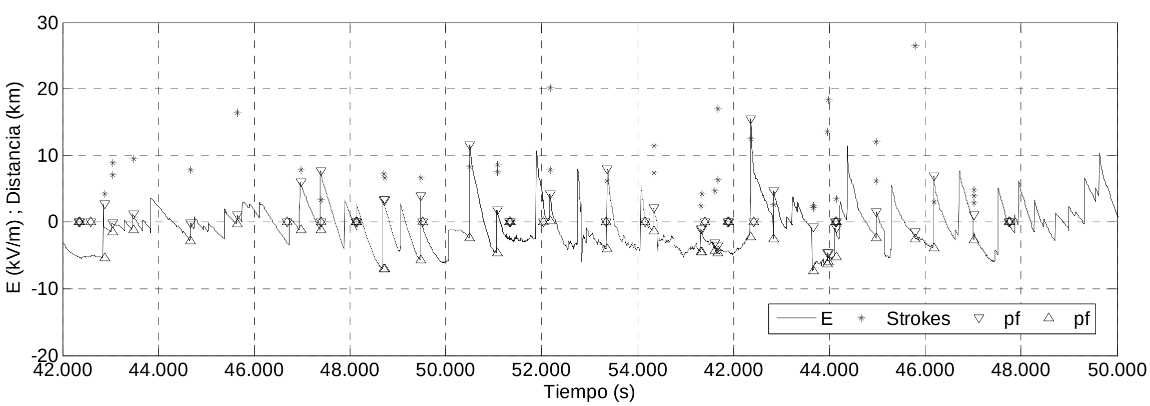

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Figure 6. Electrostatic field measurement and cloud-to-ground lightning distances on November 17, 2010. a. Approaching phase for 60 km. b. Storm activity over the sensor site.

Figure 6b shows the timeline interval when the thunderstorm was closer and the measured electric field having the highest values. Each detected CG lightning strike had an ΔE related electric field change. Note how strikes from the same flash shared the same electric field change.

In Figure 6b, pi and pf denote the initial and final point for each ΔE.

All storm episodes presented small time errors between the time stamp given by the synchronisation server in the field mill system and the strike time given by the lightning location network. Table 2 presents the storm episodes in which the time error could be unambiguously identified. Very intense episodes having high lightning rates were neglected as the time error was not calculable.

5. RESULTS

The storm episode on November 17th presented the ΔE *cf* distance distribution shown in Figure 7. Most storm cases in Table 2 behaved as isolated cells similar to the episode on November 17th; ΔE *cf* 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 (Wormell, 1939), Jacobson and Krider (Jacobson and Krider, 1976) and others.

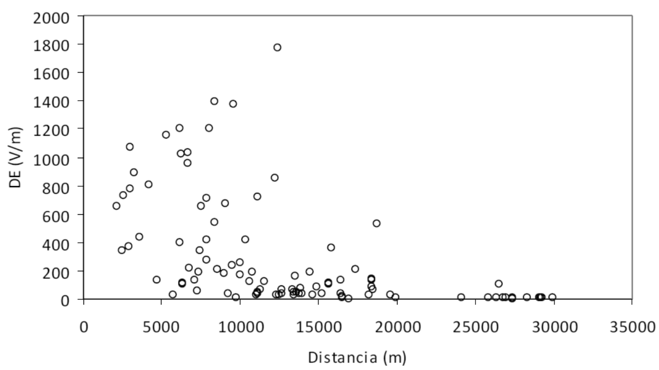

Figure 7. Electric field changes ΔE *cf* distance for cloud-to-ground flashes during the storm episode on November 17th, 2010

Electric field changes ΔE *cf* distance distribution for the complete dataset of the nine storms in Table 2 is shown in Figure 8; note how the data for the complete dataset is consistent with the theoretical curve described in section 2.

Distribution in Figure 8 was fitted by using point charge and bipolar models (section 2). The solutions were obtained by applying non-lineal least square optimisation; (4) gives the objective function C^2 in which ΔE_{ci} is the electric field change, computed on unknown parameters H and ΔQ (or H_1, H_2, ΔQ_1 and ΔQ_2 if the bipolar charge model were used), ΔE_{mi} was the electric field change measured and N was the total number of measured ΔE; in this case 491.

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

The solution procedure started by defining initial values for H and ΔQ; an iterative process based on the Marquardt Method led to obtaining the model parameters that best fit the measured electric field changes by minimizing function C^2.

Table 3 presents the point and bipolar charge solutions for the 491 ΔE measured in Bogotá. The point charge solution height was 9,658 masl; as discussed by Murphy (Murphy, 1996); solutions based only on a point charge tend to be vertically displaced towards higher altitudes. The altitude of the obtained point charge solution seemed to be higher than expected

The bipolar charge solution was -22 C at 8,414 masl and 6.8 C at 6m316 masl; latter values were consistent with previous studies carried out in Florida, such as that by Murphy (Murphy, 1996).

Table 3. 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

*Regarding local terrain altitude (2555 masl)

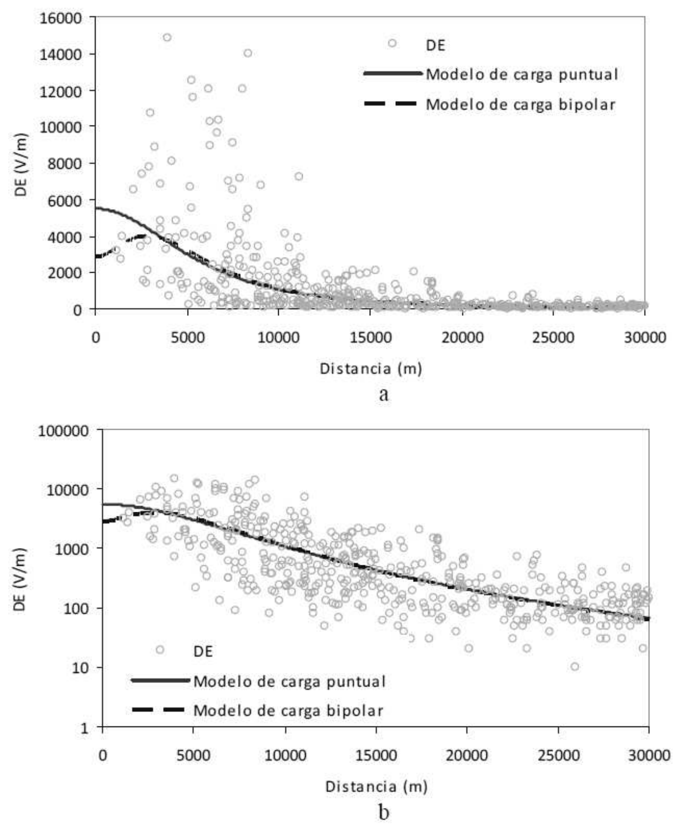

Figure. 8 Electrostatic field changes ΔE *cf* distance distribution for the nine thunderstorm episodes shown in Table 2. a. Lineal scale distribution b. Log scale distribution

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

The results given by Table 3 are significant for knowledge about thundercloud electrical structure in the tropics. Point charges ΔQ were ambiguous due to the site error of the sensor involved. Despite the obtained point charges being consistent with previous research in other countries, some uncertainty was introduced because the site error was computed theoretically not experimentally. By contrast, the *H* parameter was unambiguous and reliable; the way the ΔE *cf* distance curve decayed had a unique solution for height *H* and was not dependent on the ΔE solution. In may thus be stated that the cloud charges during CG flashes in the studied episodes were located at mean heights of 8,414 and 6,316 masl (for the negative and positive charges, respectively).

The latter results are relevant to a "scientific degree" for cloud electrical structure research; however this paper has focused on an "operational degree" study, aimed at obtaining a calibration pattern for electrostatic field sensors installed in non-ideal conditions and in a tropical zone.

Regression analysis for the dataset in Figure 8 was carried out to find a statistical pattern for the ΔE measured by the experimental field mill. Due to the charge change, ΔQ had a log-normal distribution; the ΔE was also log-normal for a given distance and therefore log conversion for ΔE was needed. The independent variable was distance *d* whereas *log*(ΔE) was the dependant one.

Figure 9 presents the regression analysis. The best fitting was found when a third-order polynomial was used. The continuous black line is mean ΔE. The 95% confidence interval (CI, red dashed lines) represents the interval where mean ΔE had 95% probability of being located; CI limits were 3.5 and 9.76 kV/m for $d = 0$.

Prediction interval PI (95%CI, black dashed lines) showed the region for the measured ΔE with 95% probability; PI limits were 0.49 and 43.3 kV/m for $d = 0$.

Figure 9 and the regression results (CI and PI limits) could be considered as a distribution pattern 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 3 could be used to fit the site error for a given sensor.

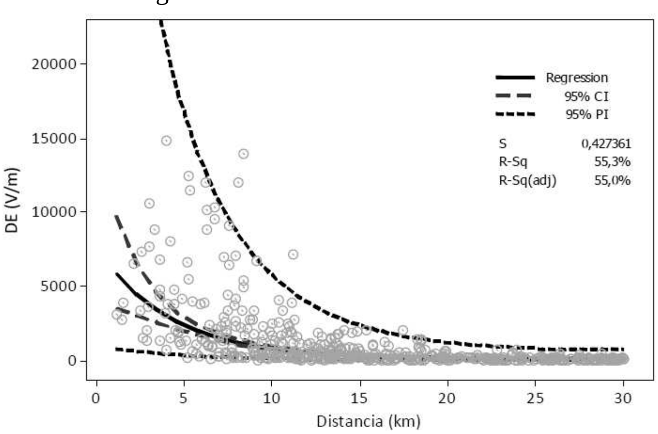

Figure 9. Regression analysis for the experimental electric field mill located in Bogotá

6. CONCLUSIONS

An electrostatic field mill station in Bogotá, Colombia, located at 2,555 masl on flat terrain, led to obtaining a reference distribution for ΔE measurements. Nine thunderstorm episodes during 2010 were analysed to obtain a ΔE *cf* distance pattern formed by 491 CG flashes. As a result, the measured distribution fit a bipolar charge model having 8,414 height, at 6,316 masl and -22 and 6.8 C charges.

Such physical parameters can be used as a reference for fitting electric field mills in other installation conditions. Despite different causes for the thunderstorm formations observed in Bogotá, all storms present the same characteristics and the charge solutions tend to be similar, as described in previous sections. Most storms in central Colombia are orographically created and are similar to those studied in this paper.

A regression analysis showed the statistical pattern for the measured ΔE for any distance. Calibrating any given electrostatic field sensor installed in other conditions in central Colombia would mean that it is possible to compare datasets' mean values and dispersion.

7. ACKNOWLEDGEMENT

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