Global Journal of Science Frontier Research: A
Physics and Space Science
Volume 20 Issue 1 Version 1.0 Year 2020
Type : Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4626 & Print ISSN: 0975-5896

Remote Sensing Network in Tropical Zones for Lightning Monitoring

By Horacio Torres & Daniel Aranguren

National University of Colombia

Abstract- The aim of this letter is to introduce the Tropical Network of Remote Sensors (TRONSE), which is composed of Total Lightning Detection Systems - TLDS, electrostatic field sensors registered in Colombia as PreThor, and an information management system developed to monitor lightning activity in Tropical regions. These networks are part of the research work contributing to the analysis of magnitudes of the lightning parameters within the spatial concept and for applications in lightning protection in tropical areas. Several research results have shown the influence of latitude in the lightning phenomena and how the magnitude of lightning parameters is not necessarily valid in geographical zones all over the world. They are different in tropical latitudes to those in temperate ones.

Keywords: lightning in tropical zones, lightning remote sensing, spatial variations of lightning parameters.

GJSFR-A Classification: FOR Code: 090905

REMOTESENSINGNETWORKINTROPICALZONESFORLIGHTNINGMONITORING

Strictly as per the compliance and regulations of:

Remote Sensing Network in Tropical Zones for Lightning Monitoring

Horacio Torres [α] & Daniel Aranguren [σ]

Abstract- The aim of this letter is to introduce the Tropical Network of Remote Sensors (TRONSE), which is composed of Total Lightning Detection Systems - TLDS, electrostatic field sensors registered in Colombia as PreThor, and an information management system developed to monitor lightning activity in Tropical regions. These networks are part of the research work contributing to the analysis of magnitudes of the lightning parameters within the spatial concept and for applications in lightning protection in tropical areas. Several research results have shown the influence of latitude in the lightning phenomena and how the magnitude of lightning parameters is not necessarily valid in geographical zones all over the world. They are different in tropical latitudes to those in temperate ones.

Keywords: lightning in tropical zones, lightning remote sensing, spatial variations of lightning parameters.

I. Introduction

Modern research on the physics of lightning began in the early 20th century with the work of Wilson [1]. In the global circuit context, Wilson first suggested that thunderstorms are charge pumps, which maintain the potential difference between the Earth's surface and the upper atmosphere (the ionosphere's potential). Whipple [2] compared the diurnal variation in Brooks' results [3] and in the initial electric field measurements over the ocean, thus finding evidence that the global circuit contribution is dominated by a superposition of effects from three major zones of convection: tropical South America, Africa and the Maritime Continent (Southeast of Asia and Australia). More recent observations [4] of the ionosphere's potential and NASA satellite observations support this idea [5].

Although past evidences [6], [7] suggest that tropical regions present a semiannual cycle with maximum lightning activity occurring during spring and autumn in both hemispheres, it has been found [8] that the cycle of lightning activity in Colombia (tropical land) depends on several factors but mainly upon the atmospheric circulation effects. Electrical atmospheric activity varies from region to region (spatial aspect) as well as from month to month (temporal aspect).

Although tropical South America, Central Africa and the Maritime Continent areas were identified at the beginning of the 20th century as having high atmospheric electrical activity, the information available in the world on the characteristics and magnitudes of lightning was based mostly on studies carried out in semitropical or temperate zones, but scarce in Tropical Zones.

This research work is very important to continue to statistically verify the variation of the lightning parameters such as the Keraunic level, the ground flash density, the lightning peak current etc., in the tropical zone, with respect to the temperate zone as in the USA., Europe or Asia. These results are fundamental for the design of protection against lightning and its statistical variation makes that the standards of temperate latitudes of protection again lightning, such as IEC62305, IEEE1410, EN50536 and others must take into account this spatial variation and thus mitigate the high mortality by lightning [46], [47] or the high failure of electrical and electronic equipment [45] that occurs in the tropical zone [11].

II. Fundamental Aspects of Lightning Parameters

a) Lightning Peak Current (LPC)

In order to estimate the Lightning Peak Current in tropical zones, Torres et. al. (1996) [8] estimated the return stroke of LPC from 167 electric field measurements performed with a parallel-plates antenna and Lightning Location Systems installed in Colombia. The results show preliminary evidence that LPC higher than in other latitudes could be expected for a tropical zone such as Colombia.

Visacro et. al. [9] and Wilks [10] found that the lightning peak current mean values (40 and 45 kA for the first stroke and 16 kA for subsequent strokes) are higher than other reported values.

The knowledge of spatial behavior of lightning parameters is significant for the design, maintenance and operation of power systems and in the performance of warning techniques. It is essential to strengthen this research line in order to learn the differences between magnitude of lightning parameters measured in north, south and tropical latitudes as well as the differences between plain, mountain or coast zones, and the daily, seasonal and multiannual variations, in order to update lightning parameters for protection of electric power systems with worldwide

Author α σ: Keraunos SAS, National University of Colombia, Research Program of Acquisition and Analysis of Signals PAAS-UN.
e-mails: htorress@keraunos.co, htorress@unal.edu.co
Author ρ: Now cast GmbH. e-mail: betz@lmu.de

validity. Figure 1 shows a comparison of cumulative probability of Lightning Peak Current between CIGRE (International Council on Large Electric Systems for its acronym in French) and four tropical sites (Malaysia, Rhodesia, Brazil and Colombia) [11].

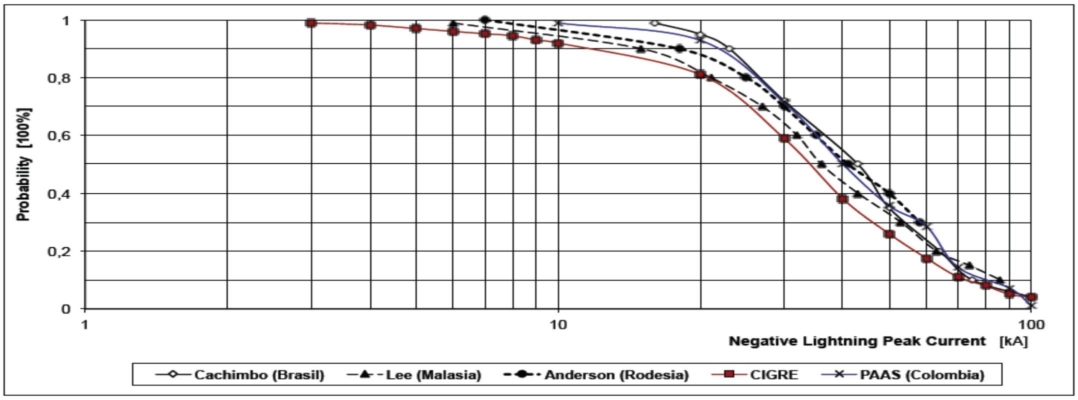

Figure 1: Comparison of cumulative probability of lightning peak current from CIGRE and four tropical sites (Malaysia, Rhodesia, Brazil, and Colombia). Taken from [11]

On the basis of a comparison of lightning current probability distributions obtained around the world, it is possible to state a hypothesis on the latitude dependence of lightning current. Additionally, there are preliminary evidences that higher values can be expected on tropical countries. Recently, Cooray [12] proposed that the experimental data show that the peak currents of first and subsequent lightning return strokes increase with decreasing latitude. The reason for this dependence of current amplitude is explained using the fact that the height of the charge centers increases, as the latitude decreases. The results obtained show that the peak value of first and subsequent return stroke currents is around 42 kA and 15 kA, respectively, in tropical regions. This theoretical prediction is in agreement with available experimental data provided by instrumented 8 towers [13], [14].

The results on the behavior of lightning activity in the tropical regions, compared with the activity in temperate regions are presented by Torres [11], [13], [14]. According to the displacement of the Intertropical Confluence Zone (ITCZ - Global scale) over Colombia (located between 4°S and 13°N Latitude), lightning activity in the southern (Amazons Region) and northern (Caribbean Region) tends to be unimodal (maximum activity in January-February and August-September respectively), whilst in the central Region (Andean mountains) the development tends to be bimodal (maximum activity in April-May and August-September-October). Aka and Ianoz [15] in West Africa presented similar results, where the general trends of lightning activity are similar to the trends in Colombian central region (Andean Mountain), located between similar latitudes.

b) Ground Flash Density (GFD) and Keraunic Level (Td)

The necessity to measure the Ground Flash Density (GFD), as opposed to the Keraunic level (Td), the Td is well known. Nonetheless, the latter is still an accepted parameter used for characterizing certain region of atmospheric electrical activity. Moreover, the gathered time series data of thunderstorm days is very important for statistical analysis when the GFD is not yet measured, which means, it is an unknown parameter.

The traditional equation relating GFD values to Td, GFD = 0,1.Td is only valid in temperate regions. The mentioned equation, developed by Anderson and Eriksson and based on lightning measures obtained from Lightning flash counters located in South Africa, has shown good results when they are compared to Lightning data in temperate zones but not necessarily in tropical regions. This circumstance has motivated research studies of Lightning parameters in Tropical zones, especially in Colombia, Mexico and Brazil, which have collected lightning data from their own Lightning Location Systems.

- GFD vs. Td relationship obtained from Colombian Lightning Location System - LLS data and Anderson's equation were evaluated, finding great errors that show the necessity of developing new adequate equations for Colombian lightning behavior [16]. The errors found in applying that equation in Colombia have reached values up to 1568% [16], [17]. In addition, other Td vs. GFD relationships were found in mountainous tropical regions of Mexico and Brazil as follows [17]:

$$GFD = 0{,}024T_d^{\ 1.12} \quad \text{México}$$

$$GFD = 0{,}030.T_d^{\ 1{,}12} \quad \text{Brazil}$$

$$GFD = 0{,}0017.T_d^{\ 1{,}56} \quad \text{Colombia}$$

The similarity between the relations found in Brazil and Mexico may be attributed to the comparable location in terms of latitude (Mexico [16–280 North] and Minas Gerais, Brazil [18-220 South]). However, the relation found in Colombia (2-100 North), which is located closer to the equator, presents a different behavior.

Moreover, a different behavior of Lightning parameters in tropical zones has been observed for both mountainous and coastal regions, therefore, different equations have been obtained for each type of region [18].

III. Tropical Network of Remote Sensors (TRONSE)

To continue the research work on the spatial variation of the lightning parameters, we have developed a Tropical Network of Remote Sensors (TRONSE) and software, in some countries of the tropical zones. Additionally, the ASIM (Atmosphere Space Interaction Monitor) project has been integrated into the network.

TRONSE is composed by total lightning detection systems - TLDS, electrostatic field sensors and technology tools for Big Data management and Data Analytics applications. TRONSE is a network that began to be built in 2011 with the Colombian network, with coverage of neighboring countries such as Panama and part of Venezuela. Subsequently, new networks have been installed in other countries of the tropical zones. The coverage area is surrounded to the east and north by large coastal areas in the Pacific Ocean and Caribbean Sea; to the west by the largest jungle in the world, the Amazon; separated from each other by the Andes mountain range, with very high peaks, extensive plateaus and large branches that give rise to very complex and unique conditions, enhanced by the continuous influence of the ITCZ.

The main contribution of TRONSE to the spatial study of the lightning parameters has been the installation of more than 43 antennas of location of lightnings in Mexico, Colombia and Peru, which will have more and better information of the lightning parameters (Keraunic levels, Ground Flash Density, Polarity, Lightning Peak Current etc.) in tropical zone and, in the future, to compare these results statistically with data from other similar networks located in temperate latitudes such as the USA, Europe and Asia.

a) ASIM (Atmosphere Space Interaction Monitor) project

Complementary to lightning detection systems, the research group PAAS-UN is working together with European researchers on the ASIM project.

The terrestrial origin of intense bursts of Gamma radiation discovered in the atmosphere (TGFs) is one of the mysteries of the investigations on the physics of lightning that remain unresolved.

Since the discovery of the emission of gamma rays in the Earth's atmosphere, there have been observations that relate the appearance of these emissions with the presence of lightnings. The mission of the ASIM project is to clarify this point.

The TGF´s are much more common than expected phenomena that occur throughout the earth's surface. They are associated with storm zones with electric shocks. They occur between the cloud layer and the ionosphere. Their morphology and dynamics is much more complex than expected. Its distribution in length indicates that they are more frequent on the continents, in tropical zones as Colombia.

The ASIM project has benefited from the cooperation with the National University of Colombia (Research Group PAAS-UN) to establish a network of optical systems to monitor the TLE activity of this region. The University has several available sites covering continental areas such as Santa Marta and the Caribbean (San Andrés Island). The firm Keraunos has networks of electric field mills (PreThor) and data of the Colombian Total Lightning Detection System – CTLDS.

The European Space Agency (ESA for its acronym in English) received in Valencia, Spain, and the ASIM observatory. It's a lightning, ultraviolet; X-ray and Gamma rays observatory that will help understand the global electrical circuit and was installed in the Columbus module on the International Space Station (ISS for its acronym in English). Its launch took place on April 2, 2018 in Cape Canaveral, Florida using a Falcon-9 SpaceX rocket. Once attached the observatory to the Columbus module, its mission is to measure the phenomena above the great storms and its high-energy detector will allow obtaining new data on the violent outbursts of terrestrial gamma rays.

The support given by Colombia to the ASIM project through the research group PAAS-UN, has been the installation around the city of Santa Marta, Colombia, of an observatory of terrestrial antennas known as Lightning Mapping Array (LMA), which is a three-dimensional system for locating total lightnings and information from the network of atmospheric thunderstorm data CTLDS owned by the firm Keraunos. The data analysis of LMA observatory in Santa Marta and a doctoral thesis currently developed by a student at the Polytechnic University of Barcelona, have been fundamental in the understanding of the phenomenon of the terrestrial lightning, that have been basis of work in European universities of the ASIM project (Catalonia, Valencia, Denmark, Norway, Poland) for the understanding of the terrestrial phenomenon of lightning that is now expected to develop from the ISS.

In 2015, seven antennas were mounted around the city of Santa Marta, Colombia, from where the lightning activity between clouds and ionosphere is captured. Now, these antennas have been moved to the city of Barranca, Colombia, since it has been established that the Catatumbo area - including the area of Venezuela- presents the highest lightning activity in the world [44].

With the support of an oil company, the assembly of the antennas in the city of Barranca began, thus creating one of the Largest lightning measurement centers in the world with equipment developed in Colombia (PreThor), CTLDS monitoring system owned by the Colombian firm Keraunos and the information that will be sent from the NASA International Space Station, to follow the steps to the luminous elves; that could give additional lights, about global warming.

b) Total Lightning Detection System TLDS

Total Lightning Detection Networks TLDS are commonly linked to thunderstorm monitoring systems Class II in accordance with standards EN50536 and IEC62793, which are defined as: "detection of IC and CG lightning discharges (phases 2 to 4)" [19], [20]. TLDS have been deployed in the last years along some Latin-American countries; Aranguren et al. [21], [22] described total lightning detection networks in Colombia and other countries; this group is currently known as the Colombian Total Lightning Detection System – CTLDS and is based on the VLF/LF technology widely known as LINET. The LINET technology was introduced in 2004 by Betz et al [23] with a detection technique based on a modified Time of Arrival – TOA - method, adapted to identify and locate intra-cloud strokes, with a 3D functionality. The performance of LLS based on the LINET technology has been widely studied in different researches throughout the world, whose results have been published in papers and technical reports by research centers and meteorological services [23-25].

The CTLDS, widely used in several applications of early thunderstorm detection and lightning localization, currently covers about 90% of the country's continental territory, where more than 99% of the population is covered with a theoretical Detection Efficiency higher than or equal to 90%, as discussed in [21], [22]. The current Total Lightning Detection System - TLDS, was initiated in Colombia as the CTLDS and then extended to neighboring countries, recently Peru, and is described in Figure 3. The sensor base line throughout the network varies from 157 to 360 km, with an intermediate gap in the Amazon area. The TLDS is operative throughout a region dominated by two main conditions: tropical location and the Andes mountain range with very high peaks. A theoretical calculation of the CG Stroke Detection Efficiency – SDE was performed based on the detection efficiency simulations given in [26], Appendix A, and a reference current distribution peak was taken, according [26], section 5.2; it is given in Figure 3. Previous analyses of Detection Efficiency for the CTLDS were published in [21], [22], [27], [28]. High detection efficiency is expected in central areas with high number of surrounding sensors; nonetheless, most of the areas present very high mountains, deep valleys and complex orography in general, where the TLDS performance statistics are not accurately known. Figure 2 gives the altitude of the sensor sites described in Figure 3; note that most of the sensors in Colombia are installed at low altitude, with an average altitude of 701 m.s.l and a maximum of 2702 m.s.l; in contrast, sensors located in Peru have an average of 2123 m.s.l, with a maximum of 4337 m.s.l.

Aranguren et al. [27] and González [28] studied the detection efficiency and location accuracy based on real lightning strikes on power transmission towers along mountainous and flat regions in central Colombia, considering two different power transmission systems and periods of time. The lightning-strike reference towers (direct or very close lightning strikes on shielding wires) were those that showed insulation damages due to flashovers. The accurate time reference was provided by the power protection devices. In summary, 97% (64 out 66) outages caused by lightning strikes correctly matched, in time and position, to the TLDS detections of very close CG flashes, that is, at distances shorter than a few hundred meters. Further works of relative lightning detection efficiency at high altitudes as well as studies based on lightning ground truth events from video reference are currently under development.

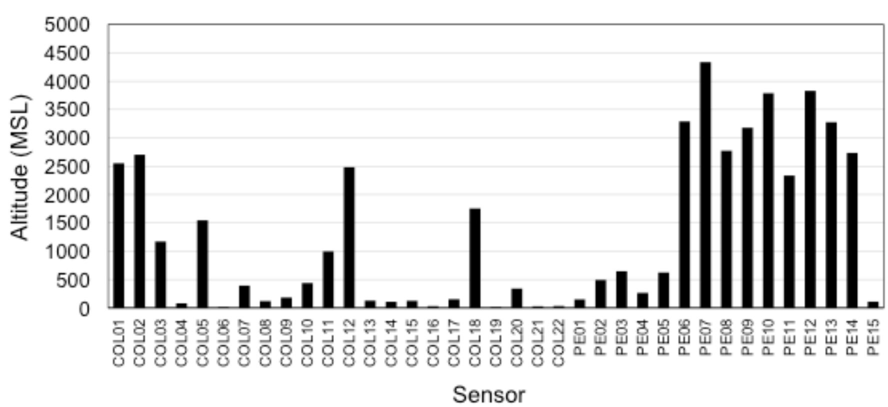

Figure 2: Altitude of the sensor sites that conform the described TLDS.

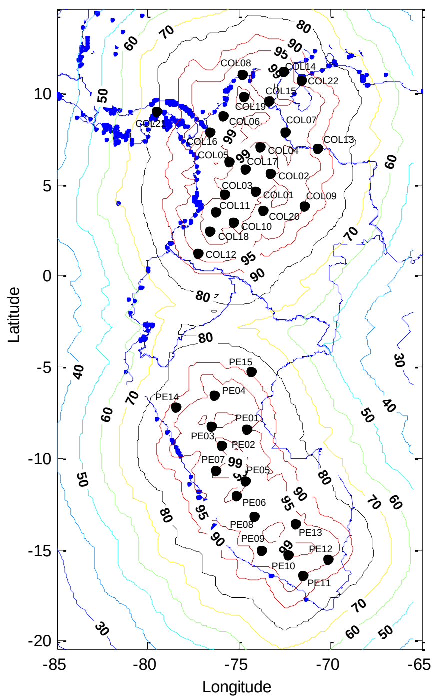

Figure 3: Total lightning detection network and its detection efficiency in Tropical countries.

c) Electrostatic field monitoring

The Field Strength Meter – FSM (electric field mill type), registered in Colombia as PreThor, corresponds to the measurement principle classified as thunderstorm monitoring systems Class I according to standards EN50536 and IEC62793, which is defined as: "detection of the thunderstorm over its entire lifecycle (phases 1 to 4)" [19], [20]. As it is well known, in fair weather conditions the environmental electric field is approximately 100 V/m. Storm clouds are characterized by generating electric field variations reaching levels of up to 15 kV/m in flat areas. As the storm cloud approaches the measurement point, changes in the electric field amplitude and polarity (usually, from positive to negative), are observed. These two effects are commonly used as criteria to timely detect the lightning risk within a region of interest, through the activation of an early alarm. This area is defined within the measurement range of the electric field sensor, which can reach up to 20 km (30 km or longer in mountainous areas). Figure 4 illustrates the typical behavior of the electric field signal (given in blue) recorded when a storm cloud approaches the measurement site. The red dots indicate the lightning strike distance to the sensor site. In this case the lightning activity approaches to the measurement point from a distance of approximately 60 km. As it gets closer, there are changes in the electric field magnitude, where, the greater the instantaneous variation ΔE, the greater the electric charge transferred by the flash or the closer the discharge to the measurement point occurs.

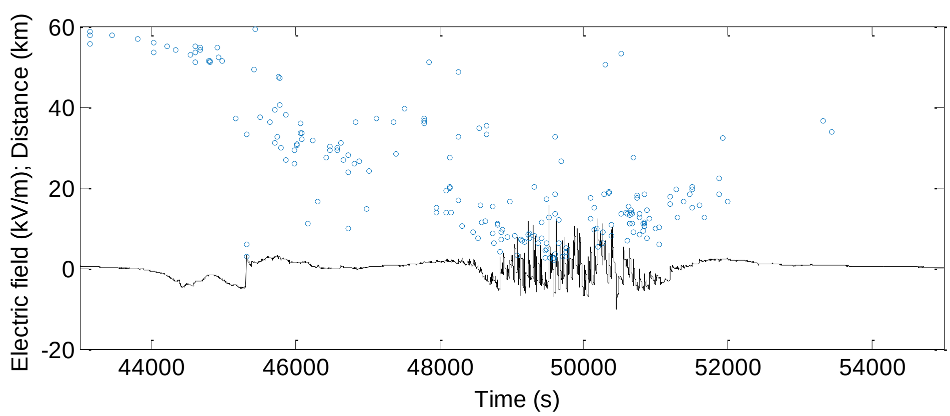

Figure 4: Measure of the electric field (black line) versus flash distances (blue dots) recorded by an electric field mill station in Bogotá (2600 m.s.l) during a thunderstorm event on November 17, 2010 [29]

In spite of the electric field measurement being recognized as the most direct way to monitor the thunderstorm electrical evolution, it involves a lot of uncertainty and ambiguity in relation to its calibration. The electrostatic structures of thunderclouds have been deeply studied typically under almost ideal measurement conditions, as published by Jacobson et al [30], Koshak et al [31], Krider et al. [32], and many others, by using a high number of electric field sensors on flat terrain, short baselines, and installed under quite controlled locations, free of neighboring elements which could influence on the site error. An important amount of electrostatic field sensors has been deployed throughout the area described in Figure 2, during the last years. Most of them intended to setup thunderstorm warning systems and some of them installed to conform experimental networks for scientific purposes. However, the measurement conditions are far from ideal; records of electric field measurements are available from electrostatics field sensors installed up to 4550 MSL (Cusco, Peru), on very irregular terrain and affected by several additional local factors. The performance of electrostatic field sensors under last complex conditions has been poorly studied.

Specifically, Aranguren et al. [29], Lopez [33] and Lopez et al. [34] have investigated the measurement patterns under real complex orographic conditions within the tropical area given in Figure 2. Orographic effects and pattern profiles of the electric field changes ΔE versus the lightning striking distance for last no-ideal conditions were investigated by Aranguren et al [29] who carried out a comparative analysis using atmospheric electric field records during thunderstorm seasons in sort of locations and situations. Thunderstorm electric field patterns at the ground level were studied by using modified electric field sensors [29], [35] installed in Bogotá - Colombia, in 2010; conventional electric field mills in mountainous areas of Navarra - Spain, in 2009 and electric field records provided by the Advanced Ground Based Field Mill (AGBFM) Network in Kennedy Space Center (KSC), Florida, USA, during 2009.

Absolute reference patterns are not possible regarding the atmospheric electrostatic field. However electrostatic field records in Florida (electric field changes ΔE versus cloud-to-ground flash strike distances) represent one of the best reference distributions, useful even for tropical regions, as developed by Aranguren [29]. Figures 5 and 6 show the electric field changes ΔE measured in San Martín – Colombia, at 130 m.s.l; and Cusco – Peru, at 4,550 MSL; as a function of the cloud-to-ground flash distance. The sensor type, installation characteristics and calibration factors are practically the same in both cases. Maximum electric field changes ΔE for very close CG flashes in the lowland case are in general lower than 10 kV/m; on the contrary, at high elevation as in the second case, the nearby flashes cause maximum electric field changes around 30 kV/m or even higher.

Figure 7 allows comparing the behavior of the mean magnitude of the electric field change ΔE measured by electrostatic field sensors installed in Bogotá - Colombia, at 2,600 MSL and at a north latitude of 4.64°; together with Cusco –Peru, at 4,550 m.s.l and at a south latitude of 14.47° and the reference curve obtained from the Advanced Ground Based Field Mill (AGBFM) Network – AGBFM in Florida, at 0 m.s.l and at a north latitude of 28.50° (discussed in [29]). All electric field changes ΔE, as those shown in Figures 5 and 6, were used to obtain the mean ΔE values at each distance and to adjust a point charge model, as explained in Aranguren [50]. Mean magnitudes of sudden electric field changes for CG flashes at long distances, that is to say longer than 10 km, are practically the same in all cases; however, for short distances the mean magnitudes vary considerably. For very short distances, around 0 km, the mean magnitude of the electric field change is close to 3.5 V/m in the first case (elevation of 130 MSL) and around 9.7 kV/m in the second one (elevation of 4,550 m.s.l).

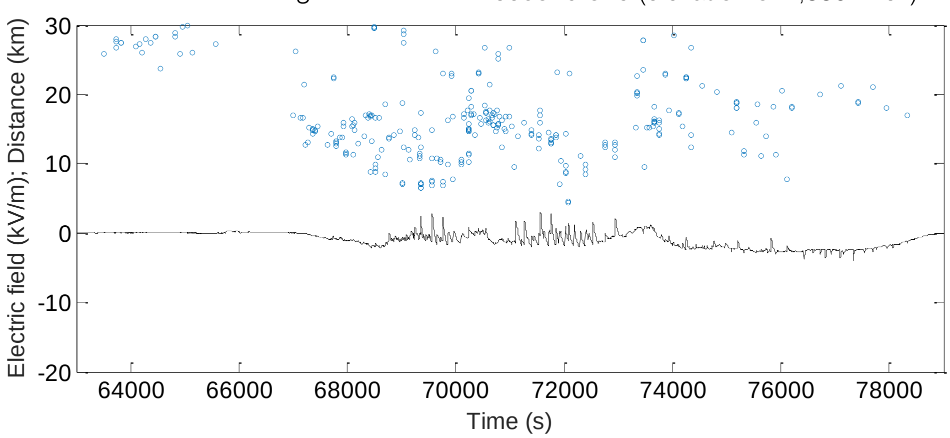

Figure 5: Electric field recorded (black line) versus flash distances (blue dots) recorded in San Martín - Colombia (130 m.s.l), during a thunderstorm event on July 23, 2018.

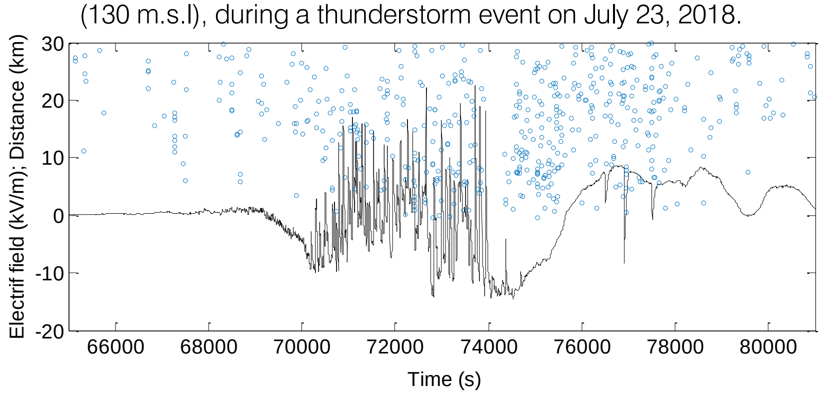

Figure 6: Electric field (black line) versus flash distances (blue dots) recorded in Cusco – Peru (4550 MSL), during a thunderstorm event on November 15, 2017.

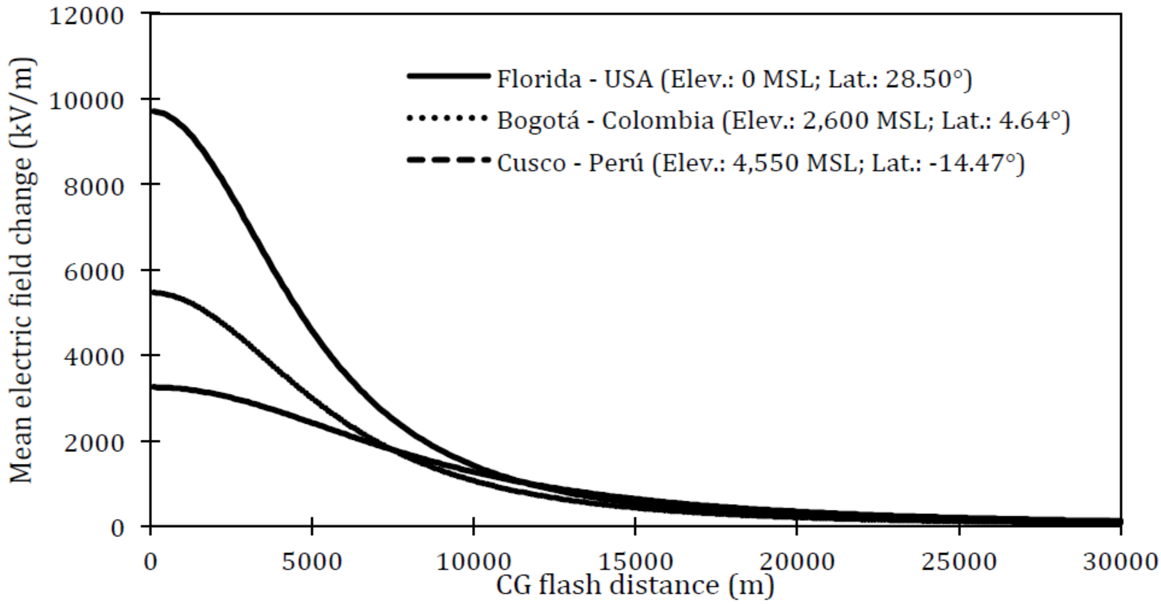

Figure 7: Profiles of the electric field change ΔE for different electrostatic field sensors in Bogotá, Cusco and Florida. Field sensors in remarkably different altitudes.

Last magnitudes result logical and expected given the fact that the relative altitude of the cloud charges respect to the sensor position becomes lower as the terrain elevation is higher. As an additional influencing factor, the vertical growth of thunderclouds in the tropics is expected to be greater due to the higher tropopause altitude. Recent papers by Lopez et al. [36], [37] have studied the altitude of electric charge centers in tropical thunderclouds by using a LMA (Lightning Mapping Array) in Colombia and have found that the majority of leader flashes are initiated at altitudes between 10 and 11 km, and that this altitude is in average 2 km higher than similar thunderstorms in Europe, studied by using a similar LMA system, at a north latitude around 41° where most of the flashes are initiated at around 8 km. References of similar analyses in Florida by using LDAR-II (Lightning Detection and Ranging) [38] show that charge altitudes in Florida thunderstorms do not present a wide difference with respect to the observations at the tropics.

The 3D total lightning detection system supported on LINET methods also provides valuable information regarding the charge altitudes. Aranguren et al. [14] reported the frequency distribution of the IC stroke heights obtained in central Colombia and found a median height of 10.2 km. Hoeller et al. [24] published the IC emission height frequency for Brazil, Benin and Australia; in all three cases the median heights vary from 10 to 11 km. Figure 8 describes the relative frequency of IC emission heights in Colombia and Peru obtained from the TLDS described in Figure 2. The median emission heights (and standard deviations) in Colombia and Peru are 10.2 km (3.09 km) and 10.8 km (3.18 km) respectively. No significant differences are observed between the two distributions. The reported heights are a little higher in the dataset from Peru than in Colombia's, but that difference could be explained by a systematic error associated to the terrain elevation at the sensor sites which causes that important corrections be applied for the IC height calculation in the lightning location algorithm.

Having explained the above, the behavior of the electrostatic field changes ΔE in the high mountain conditions of the Andean and tropical regions is mainly affected by the relative low altitude of the cloud charge centers. Additional special situations result when the measurement point is located on the top of a hill or inside a valley; in the first case the cloud electric field can be measured at longer distances, that is, up to 30 km or longer; in contrast to the second one where the measurement range is reduced. Therefore, each electric field sensor used under the Andean and tropical conditions described along this paper has its own measurement characteristic. Such unique characteristics of each place influence the performance of the sensor network applications, such as the early warning systems.

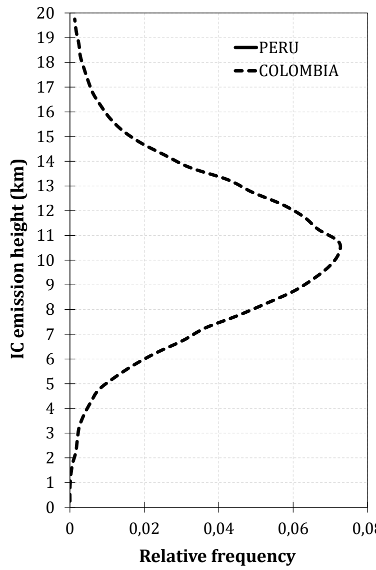

Figure 8: Relative frequency of the IC emission height given by the total lightning detection systems in Colombia and Peru.

IV. Thunderstorm Early Warning Systems

(Guidelines or hints for any reader if they're interesting to learn anything from this work.)

The TRONSE system is envisioned as an integrated information network where all data is indistinctively used to study and develop high effective lightning early warning systems, among many other applications. The warning criteria definition and verification are based on the reprocessing of all available historical data in the area of interest. For example, the available large datasets of total lightning are used to analyze an initial simple circular area scheme composed by the Monitoring Area – MA (geographic area used to provide a valid warning for the target area) and the Surrounding Area – SA (geographic area in which a Lightning Related Event – LRE causes a potential danger); the common used warning verification statistics such as False Alarm Ratio – FAR (ratio of false alarms to the total number of alarms) and Probability Of Detection – POD (ratio of effective alarm with respect to the total number of situations with LRE in the SA), among others, are evaluated. Simple sensitivity analyses allow understanding how FAR, POD and others vary when the settings are moved and static early warning systems are then tuned; however, current Machine Learning tools allow developing dynamic early warning systems.

Table 1 describes some of the lightning warning verification studies carried out in the TRONSE area by using CG lightning detection, total (CG+IC) lightning detection and electric field measurement – EFM under different situations. Each study was performed to find the best criterion to maximize POD and minimize FAR (warning area sizes and shapes, as well as, BIAS and Critical Success Index - CSI were also evaluated in some references, but not given here). CG lightning detection on simple area schemes was initially studied in Colombia using a data series of CG flashes from 1997 to 2001 [39]. Lightning data in that case was provided by the lightning location system described in [25] whose flash detection efficiency was estimated around 60% to 80%. Poor POD and FAR was found for early warning systems on the Colombian mountain ranges. Lightning warnings derived from electric field sensors at high altitude (Bogotá, 2600 MSL) were performed by Aranguren [29] by using a simple threshold criterion; POD of 0.92 and FAR of 0.6 were obtained. Very similar results were obtained some years later when the electrostatic field measurement was evaluated at very high altitude (Cusco, 4550 m.s.l) with POD of 1 and FAR of 0.56 [40]. The First warning verifications based on EFM under complex mountainous conditions (deep valley: Valle de Aburrá (1490 m.s.l) was conducted by Lopez et al. [33], [34]; the best performance obtained showed POD of 0.68 and FAR of 0.46 when exhaustive warning criteria beyond the simple electric field threshold was tested. Total lightning detection was introduced by Aranguren et al. [41] and Inampués [42] in combination with an EFM network along a large area in the Colombian Eastern Plains; POD of 0.96 and FAR of 0.45 were obtained. High or very high POD has been apparently easy to obtain in mountainous areas when EFM are supporting the lightning warning systems; on the contrary, the FAR has resulted in a difficult optimization subject. The most recent studies, such as the one performed by Chávez et al. [43] in 2018, took into account a comprehensive and iterative search of lightning warning criteria based on both EFM and total lightning detection. A combined criterion of CG and IC stroke rates and electric field vs time patterns allow obtaining a significantly improved FAR of 0.22.

Table 1: Studies about lightning warning verifications in the TRONSE area

Location and year	Data and criteria	POD	FAR
Entire Colombian territory; Inampués et al 2009 [39]	CG lightning detection within a simple area scheme.	Lowland: 0.6 to 0.9 Mountain: 0.3 to 0.7	Lowland: 0.6 to 0.8 Mountain: 0.7 to 0.9
Bogotá – Colombia; high altitude; Aranguren 2011 [29]	EFM	0.92	0.6
Medellin – Colombia; Mountainous area; Lopez 2011 [33] and Lopez et al 2012 [34]	CG lightning detection and EFM; conventional method and exhaustive EFM criteria.	Conventional: 0.64 Exhaustive: 0.68	Conventional: 0.69 Exhaustive: 0.46
Colombian Eastern Plains; Aranguren et al. 2013 [41] and Inampués 2014 [42]	Total lightning detection (CG+IC) and EFM; exhaustive criteria.	0.96	0.45
Cusco – Peru; very high altitude. Chávez et al. 2018 [40]	EFM.	1.0	0.56
Magdalena River Valley – Colombia. Chávez et al. 2018 [43]	Total lightning detection (CG+IC) and EFM.	0.92	0.22

V. Discussion

Several research results have shown the influence of latitude in the lightning phenomena and how the magnitude of lightning parameters is not necessarily valid in different geographical zones all over the world. Some measurements suggest that those are different in tropical latitudes than in temperate ones. It is essential to enhance this research in order to learn the differences between magnitude of lightning parameters measured in north, south and tropical latitudes as well as the differences between plain, mountain or coastal zones, and the daily, seasonal and multiannual variations, in order to upgrade the parameters for lightning protection. Taking into account the above, the main contribution of the TRONSE system is to provide new information in large quantities about the lightning phenomena under very special conditions of tropical weather, large coastal and great mountain ranges. However, the physical models used to interpret the measurements must themselves be revalidated. Both, the evaluation of lightning detection efficiency and the calibration of the electrostatic field measurement are based on reference physical parameters obtained from accepted reference measurement systems; such reference parameters are for example the peak current distribution in the case of CG lightning detection, or cloud charge models in the case of the electric field. Such reference distributions are very poor, practically not available, in tropical areas and even less available under high mountain conditions. This paper discussed about some of those references physical parameters. On the other hand, the use of thunderstorm warning systems has increased in recent years in the tropical regions, with a growing demand in terms of optimal performance; such purpose intrinsically involves the use of advanced techniques of Big Data management and data analytics as it was partially discussed here. (Expand the discussion on Big Data technologies)

VI. Conclusions

The deployment of a remote sensing network for lightning monitoring throughout the countries of the tropical zones was presented. Particular characteristics of this region are denoted by the influence of large coastal areas, the largest jungle in the world, the Amazon, a very high and complex mountainous system, the Andes, and the influence of the Intertropical Convergence Zone. Total lightning detection and electrostatic field measurement conform the TRONSE system with sensors located at altitudes from the sea level to more than 4.500 MSL. The primary purpose of the TRONSE system is to contribute to the systematic study of the occurrence and amplitude parameters of lightning in the Tropics, but also, in the study of the operative principles, models and performance of lightning monitoring systems in such conditions. Total lightning data and LMA information provided coherent data about the altitudes associated to the IC stroke emission and the cloud main charges (10 to 11 km). In addition, electrostatic field measurements at altitudes from the sea level to 4550 m.s.l showed how the vertical cloud structure influences the behavior of the electrostatic field at high mountains, where the main factor is the relative lower altitude of the charge centers.

A cumulative experience about the use of total lightning data and electrostatic field measurements in thunderstorm warning systems under tropical and Andean mountain conditions was presented. Performance statistics for lightning warning verification showed that the commonly used warning parameters (CG lightning detection on simple warning areas, or, EFM thresholds) do not produce very reliable or effective systems, in some sort of typical situations.

Having explained the above, the behavior of the electrostatic field changes ΔE in the high mountain conditions of the Andean and tropical regions is mainly affected by the relative low altitude of the cloud charge centers. Additional special situations result when the measurement point is located on the top of a hill or inside a valley; in the first case the cloud electric field can be measured at longer distances, that is, up to 30 km or longer; in contrast to the second one where the measurement range is reduced. Therefore, each electric field sensor used under the Andean and tropical conditions described along this paper has its own measurement characteristics. Such unique characteristics of each place influence the performance of the sensor network applications, such as the early warning systems.

Several research results have shown the influence of latitude in the lightning phenomena and how the magnitude of lightning parameters is not necessarily valid in geographical zones all over the world. They are different in tropical latitudes to those in temperate ones. And it has effects in mortality rate by lightning and in the design of power systems.

The systematic study of Holle [46] reveals, for example, that in the USA the mortality rate from lightning was 0.2 deaths per million inhabitants in the period 2000-2006. In Australia the mortality is 0.1 deaths per million inhabitants in the period from 1980s to 1989. In France were 0.2 deaths per million inhabitants in the period from 1990 to 1995. In Japan was a little over zero fatalities per million inhabitants in the period from 1990-1997. In contrast, the mortality rate for all Colombia, a typical tropical country, was 2.0 per million inhabitants per year over the period 2000-2017, [27], [28].

Funding

For more than three decades, this research work received financial funds from public and private companies, mainly from the Department of Science and Technology of Colombia COLCIENCIAS and the National University of Colombia.

Acknowledgments

The authors are grateful for the support provided by the Research Program of Acquisition and Analysis of Signals of the National University of Colombia PAAS-UN in each experimental work that in part helped acquire the information that allowed the development of this research. To the Colombian oil company ECOPETROL for its support in the areas of measurement and to the Industrial University of Santander for its academic support. The authors thank the firm Keraunos for its support with lightning data.

Conflicts of Interest

The authors declare no conflict of interest.

References Références Referencias

1. Wilson, C.T.R., "Investigations on lightning discharges and on the electric field of thunderstorms", Phil. Trans. R. Soc., vol. A221, p.73, 1920.
2. Whipple, F.J.W., "On the association of the diurnal variation of electric potential in the weather with the distribution of thunderstorms over the globe", Quart. J. Roy. Met. Soc., vol. 55, pp 1-17, 1929.
3. Brooks, C.E.P., "The distribution of thunderstorms over the globe", Geophys. Mem. London, vol 24, pp 147-164, 1925.
4. Markson, R., "Tropical convection, ionospheric potentials, and global circuit variation", Nature, vol 320, pp 588-594, 1986.
5. Williams, E. R. et al. "A radar and electrical study of tropical hot towers", Journ. of Atm. Sci., Vol. 49 (1991) 1386-1395.
6. Cooray, V. Jayaratne, K.P.S.C., "Characteristics of lightning flashes observed in Sri Lanka in the tropics", J. Geo. Res., vol 99, pp 21051-21056, 1994.
7. Williams, E. R., "Global circuit response to seasonal variations in global surface air temperatures", Mon. Wea. Rev., 1994.
8. Torres, H., Rondon, D., Briceño, W., Barreto, L., "Lightning peak current estimation analysis from field measurements in tropical zones", Proceedings 23rd. ICLP, Florence, Italy, Sep.1996.
9. Visacro, S; Soares Jr, A; Schroeder, M. A. O; Cherchiglia, L. C. L; De Souza, V. J.: "Statistical Analysis of Lightning Current Parameters: Measurements at Morro do Cachimbo Station". Journal of Geophysical Research, Vol. 109, D01105, 2004.
10. Wilks D. S. Statistical Methods in the Atmospheric Sciences, volume 2nd Edition. Elsevier, 2005.
11. Torres, H. Space and time in the lightning parameters, test on a research hypothesis (in Spanish), Research work presented to the National University of Colombia for promotion to the category of Full Professor. Bogotá, UN, June 1998.
12. Cooray, V., "Latitude dependence of peak lightning return stroke current- A theoretical explanation", Proceedings ICLP 2018, Sep, Rzeszow Poland, Sep, 2018.
13. Torres, H. Lightning. Myths, Legends, Science and Technology (in Spanish). Ed. Unibiblos, Bogotá, 2002, Bogota, Colombia ISBN: 958-70-1213-5.
14. Torres, H. The Lightning in the tropic (in Spanish). Master notes collection. Ed. UN, Bogotá, Colombia, 2015. ISBN 978-958-775-454-4.
15. Aka, A., Ianoz, M. "A single station for nearby ground flashes position in West Africa: Analysis of some experimental data" Proceedings 21rd. ICLP, pp. 301-306, Berlin 1992.
16. Torres, H, "Ground Flash Density: definition of the appropriate grid size and a proposal of relationship Ng vs. Td for Tropical zones" Activity Report of Tf C4.01.02-B. Working Group C4.01 "Lightning". CIGRE Dallas, Tx., USA, September 2003.

17. IEEE 1410, 2010 Guide for improving the lightning performance of Electric Power Overhead Distribution Lines.
18. Younes, C. "Evaluation of Lightning parameters in Colombia from LLS and Satellite data" (In Spanish) MSc. Thesis, National University of Colombia, Bogotá, 2002.
19. EN50536. Protection against lightning – Thunderstorm warning systems. European Committee for Electrotechnical Standardization, 2010.
20. IEC62793. Protection against lightning – Thunderstorm warning systems. International Electrotechnical Comission, 2015.
21. Aranguren D., Inampues J., López J., Torres H., Betz H. Cloud to ground lightning activity in Colombia and the influence of Topography. Journal of Atmospheric and Solar-Terrestrial Physics, https://dx.doi.org/10.1016/j.jastp.2016.08.010. 2016.
22. Aranguren D., Inampues J., López J., Torres H., Betz H. Overview of the cloud to ground lightning activity in Colombia. International Conference on Grounding and Earthing & 6th International Conference on Lightning Physics and Effects Manaus, Brazil, May, 2014.
23. Betz, H.-D., K. Schmidt, P. Oettinger, and M. Wirz, "Lightning Detection with 3D-Discrimination of Intracloud and Cloud-to-Ground Discharges", J. Geophys. Res. Lett., Vol. 31, L11108, doi:10.1029/2004GL019821, 2004.
24. Höller, H, Betz, H.-D., Schmidt, K, Calheiros, R., May, P., Houngninou, E., Scialom, G. "Lightning characteristics observed by a VLF/LF lightning detection network (LINET) in Brazil, Australia, Africa and Germany". Atmos. Chem. Phys., 9, 7795-7824, 2009.
25. Betz, H.-D., K. Schmidt, B. Fuchs, W. P. Oettinger, and H. Höller, "Cloud Lightning: Detection and Utilization for Total Lightning measured in the VLF/LF Regime", J. of Lightning Research, Vol. 2, 1-17, 2007.
26. CIGRE Task Force C4.404A. "Cloud-to-Ground Lightning Parameters derived from Lightning Detection Systems. The effects of the performance" CIGRE Technical Brochure, num. 376, 2009.
27. Aranguren D., González J., Cruz A., Inampués J., Torres H., Sarmiento P. Lightning strikes on power transmission lines and lightning detection in Colombia. 2017 International Symposium on Lightning Protection (XIV SIPDA), Natal, Brazil, 2017.
28. Gonzalez J., Aranguren D., Inampués J., Cruz S., Torres H., Gomez J., Arango C., Asenjo F. Lightning Information Management Systems, a Usefull Tool to Take Accurate Decitions. Study Case: Chivor – Rubiales Transmission Line. International Conference on Lightning Protection 2018, Rzeszow, Poland.
29. Aranguren, D. "Performance of electrostatic field sensors in thunderstorm warning systems" (in Spanish), Doctoral Thesis, National University of Colombia, Bogotá, 2011.
30. Jacobson E. A. Krider E. P. Electrostatic field changes produced by Florida lightning. Journal of the Atmospheric Sciences, 33:103–117, 1976.
31. Koshak W. Krider E. Analysis of lightning field changes during active Florida thunderstorm. Journal of Geophysical Research, 94(D1): 1165–1186, January 1989.
32. Krider E. P. Electric field changes and cloud electrical structure. Journal of Geophysical Research, 94(D11), 1989.
33. Lopez, J. "Methodology for predicting thunderstorms from environmental electrostatic field measurements and lightning localization systems in mountainous areas" (in Spanish), MSc thesis, National University of Colombia, Manizales, 2011.
34. López J., Pérez E., Herrera J., Aranguren D., Porras L. Thunderstorm warning alarms methodology using electric field mills and lightning location networks in mountainous regions. International Conference on Lightning Protection (ICLP), Vienna, Austria, 2012.
35. Aranguren D. Aponte J. Romero J. Guevara M. Torres H. Baquero G. Pérez E. Rondón D. Design, construction and calibration of two e-field machines used to measure tropical thundercloud e-field on the ground and aloft. VIII International Symposium on Lightning Protection VIII SIPDA, Sao Paulo, Brazil, pages 184 - 189, 21st-25th November 2005.
36. López J., Montanyà J., van der Velde O., Romero D., Aranguren D., Torres H, Taborda J. First data of the Colombian Lightning Mapping Array – COLMA. International Conference on Lightning Protection - ICLP. Estoril, Portugal, 2016.
37. López J., Montanyà J., van der Velde O., Romero D., Fabró F., Aranguren D., Torres H, Taborda J. First results of the Colombian Lightning Mapping Array. EGU General Assembly 2016.
38. Maier L., Lennon C. L., Britt T., and Schaefer S., 1995: Lightning Detection and Ranging (LDAR) System Performance Analysis. Proceedings of the 6th Conference on Aviation Weather and Systems, Paper 8.9.
39. Inampués J., Aranguren D., Torres H., Montanya J. Santoyo I., Olarte E., Younes C. Analysis of lightning forecasts in Colombia based on the lightning detection network data. X International Symposium on Lightning Protection 9th-13th November, 2009 – Curitiba, Brazil
40. Chavez J., Juaréz M., Inampués J., Aranguren D. Evaluation of the lightning warning system – Mina Constancia. Technical Report. Hudbay Minerals - Keraunos, 2018.
41. Aranguren D., Inampues J., López J., Torres H., Betz H., Moehrlein M. Electrostatic field and

lightning detection applied to thunderstorms nowcasting in Colombia. XII SIPDA, Bello Horizonte, Brazil, 2013.

42. Inampués, J. C. "Lightning prediction and smart grid" (in Spanish). MSc Thesis, National University of Colombia – Bogotá, 2014.
43. Chavez J., Juaréz M., Inampués J., Aranguren D. Evaluation of the lightning warning system – Gran Tierra Energy operations. Technical Report. Gran Tierra Energy - Keraunos, 2018.
44. Albrecht, R., et. al. "Where are the lightning hotspot on Earth?" 2016. Bull. Amer. Meteor. Soc. doi: 10.1175/BAMS-D-14-00193.145. ISA Annual Report (in Spanish), Colombia, 1989.
45. N. Navarrete, M. A. Cooper, R. Holle. "Lightning fatalities in Colombia from 2000 to 2009". Nat Hazards. DOI 10.1007/s11069-014-1254-9.
46. M. A. Cooper. "Lightning injuries". Wilderness Medicine, Fifth ed. Auerbach, Mosby. 2007.