2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Detection Efficiency Analysis of Atmospheric Discharges Using AS3935 Sensor

Data Correlation of LINET Network

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***Abstract*— The AS3935 integrated circuit manufactured by Austria Micro Systems is a device with great opportunity of research into efficiency and operational feasibility, since sensors of this nature are not the focus of large companies of ray monitoring for the management of lightning hazards and proximity of storms. This article presents an efficiency analysis of the Storm Detector sensor with an IC - AS3935, compared to the LINET lightning monitoring network, regarding the detection efficiency and accuracy of classification of lightning. Between December 17, 2018 and March 3, 2019, over 10900 lightning events were detected on the city of Curitiba / PR / Brazil. The calculations showed that the Storm Detector has a DE of ~76% in a radius of 20 km. An expression for calculating the distance of the event deduced from the sensor data is also displayed and validated in comparison to the distance of the sensor calculated by the network.**

Keywords*— *AS3935; Lightning detector; detection efficiency; classification accuracy; location accuracy

I. INTRODUCTION

A source of lightning discharges are positive and negative charges separated in the cloud. Lightning discharges are generally divided into three classes, such as intra-cloud discharge (IC), cloud-to-cloud discharge (CC) and cloud-to-ground discharge (CG). Especially with CGs, downward lightning flashes (–CG) account for about 90 percent or more of global CG lightning, and that of 10 percent or less are positive lightning flashes (+CG) [7; 8; 9].

Measurement of the electromagnetic radiation produced by lightning discharge is suitable for the investigation of the electrical property of lightning discharges. Lightning discharge radiates electromagnetic wave from a few Hz to s a few hundred of MHz [2; 12; 13]. The different process of lightning discharge causes each frequency band of the electromagnetic wave. The electromagnetic waves of VHF (Very High Frequency, 30 MHz – 300 MHz) band are radiated by extending leader and streamer in the process of initial breakdown discharge. Return stroke of lightning discharge radiates VLF (Very Low Frequency, 3 kHz – 30 kHz) and LF (Low Frequency, 30 kHz – 300 kHz) waves. ELF (Extremely Low Frequency, 3 Hz – 3 kHz) waves are radiated by whole CG process including continuing current which flow continuously for the time period of few millisecond – hundreds of milliseconds after the lightning return stroke[1; 3].

Most of lightning occur in the developed convection clouds which often brings concentrated heavy rain and results in flash floods and wreaks enormous damage. There is a commonly held view that strong updraft and graupel-ice mechanism [10] in the mixed phase region of the cloud pose electrical charge separation in the cloud. Previous studies suggested that there is correlation between occurrence frequency of lightning and meteorological parameters, such as precipitation, radar reflectivity, and updraft of thunderstorms. Reference [11] show that seasonal and diurnal analysis of rainfall and lightning climatology in Florida illustrate the correlation between lightning occurrence and convective rainfall. Reference [4] suggested that the storms that produce larger number of CG flashes tend to produce longer lag time. The behavior called as lightning jumps is that total lightning frequency rapidly increase in advance of severe weather.

Many lightning monitoring systems operates at the VLF spectrum of electromagnetic waves, which are radiated by return strokes and uses techniques like TOA - Time Of Arrival or ATD – Arrival Time Difference, to estimate the location of the atmospheric discharge[5; 6]. These systems have a high detection efficiency (DE), Location Accuracy(LA) and Classification Accuracy(CA). However, to access lightning data in areas where communication access is absent or has low financial resources, a cheap detector operating in the LF spectra, like the AS3935 Integrated Circuit manufactured by Austria Micro System, offers an acceptable performance for academic use, rural environments and for logistic management of technical teams in electric power companies. Then, the objective of this study is to use the LINET data to corroborate the DE and CA parameters, without the intention of replacing the current lightning monitoring systems, because the AS3935 is a short distance storm detector that can be used to enhance the degree of storm risk analysis in regions where the lightning monitoring network's data is not used, whether due to the lack of communication or low financial resources. Also, the construction of a device capable of detecting atmospheric discharges at short distances, accessible to civilian users, government entities, department and public agencies, becomes a great advance in technical and scientific development.

II. AS3935 Specifications

A. General Description

The AS3935 is a programmable fully integrated Lightning Sensor IC that detects the presence and approach of potentially hazardous lightning activity in the vicinity and provides an estimation on the distance to the head of the storm. The embedded lightning algorithm checks the incoming signal pattern to reject the potential man-made disturbers[14].

Lightning sensor warns of lightning storm activity within a radius of 40 km. Distance estimation to the head of the storm down to 1 km is done in 14 steps. Detects both cloud-to-ground and intra-cloud (cloud-to-cloud) flashes.

AS3935 uses a programable detection levels enabling threshold setting for optimal controls. Antenna Tuning to compensate variations of the external components. Supply voltage range 2.4V to 5.5V.

The AS3935 can detect the presence of an approaching storm with lightning activities and provide an estimation of the distance to the leading edge of the storm, defined as the minimum distance from the sensor to the closest edge of the storm.

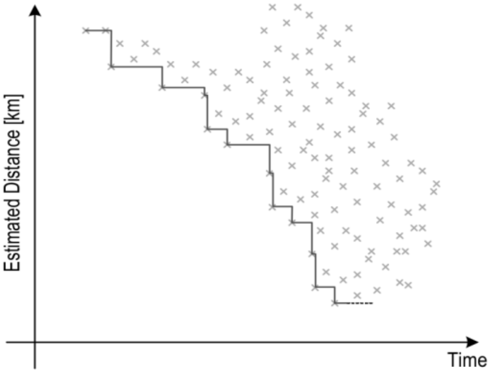

Fig. 1. The estimated distance to the leading edge of the thunderstorm. Font: Datasheet, AS3935 Franklin (2012)

B. Configuration Options

The AS3935 has many configuration options. For each set of configurations, the performance of the device behaves according to a different DE X Radius curve according to [14]. However, there are two main configuration options that governs the AS3935 performance: The Watchdog (WDTH) and The Spike Rejection (SREJ) parameters.

C. The Storm Detector Device

The Group of Atmospheric Electricity Phenomena, from the Department of Electrical Engineering at Federal University of Paraná has built 3 printed circuit boards that receives the AS3935 and the other components.

The AS3935 board was also attached to a board made by the Group containing an ESP32, choose to be the micro controller for the device. The ESP32 is a System-on-Chip (SoC) consisting in a Xtensa® Dual Core 32 Bits CPU that can run up to 240 MHz, embedded WIFI, Bluetooth LE, Real Time Clock, I^2C and SPI buses [15]. The micro controller board also contains an Ublox NEO-6M GPS Module for sensor geolocation and clock synchronization source, and a 16 GB SD Card for data logging. It can act as a data logger and a Web Server, to visualize lightning events at a real time basis.

The Storm Detector antenna is the MA-5532-AE inductor, manufactured by Coilcraft, which is developed to work specifically with AS3935 Integrated Circuit [16]. Reference [16] also says that the inductor is designed for antenna applications from 500 KHz to 2 MHz, which makes it suitable for the Storm Detector.

The device firmware was produced using C++ language, using Arduino IDE as the programing software. The Visualization Tool for computers was made using Python language both for firmware interaction and graphical interface, which was made using python web modules integrated with GUI modules.

III. Data Collect of Storms Using Storm Detector Device

A. Storm Detector Setup

According to [14], the AS3935 has the best DE when configured with WDTH = 0000 and SREJ = 0000, which makes AS3935 performs at 45% of DE when the storm is overhead. Early tests demonstrated that the sensor mutes at this configuration when in a noisy environment, so WDTH and SREJ was set to 0001, best suited to the environment according to our experiment.

Along with these configurations, the sensor environment was set to indoors due to the sensor location (inside the house), the Noise level was set to 1 – 28 μV_{rms} for indoors environment [14] – and the Disturbance mask was enabled to avoid man made disturbers. The setup is represented in Fig. 2.

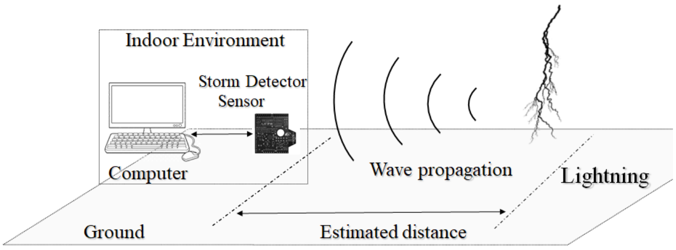

Fig. 2. Storm Detector Setup Description

B. Collection Period, Site and Data Collected

The data of Storm Detector was collected between December 17, 2018 and March 3, 2019. The collection site is located at north side of Curitiba City, a house owned by one of the researchers, which was responsible to collect and analyze the sensor data. The geolocation of the collection site is Latitude 25º 22' 51''S and Longitude 49º 14' 40'' W.

The data collected along the collection period was 10964 lightning events, to be classified as a true or a false event, in comparison to the choose lightning monitoring network.

C. Lightning Network Selection

The network data to compare and classify the Storm Detector data was received from Starnet and LINET networks. The lightning data of LINET network was used because LINET arrays in Germany and Brazil are identical in its basic features. All lightning data of LINET are classified an CG and IC discharges, an excellent opportunity for comparisons of thunderstorms. Also, the LINET data file has many more lightning events – 49135 events, of which 19186 matches the Storm Detector expected detection range and time the sensor was up - than the Starnet file – 7694 events, of which only 1800 events matches the same criterion.

The LINET network[23] is an european lightning network with high detection efficiency – around 90% - and high precision location – around 150 m – which is a great opportunity for distance comparison between Storm Detector and the distance calculated using the geolocation given by the LINET data.

IV. Data Correlation between Storm Detector and LINET Detection Network

A. Data pre-process

The LINET and Storm Detector data files were pre-processed to avoid including hours that the Storm Detector device was off in analysis, and to limit the radius around the device to about 40 km. The distance of event relative to the sensor was calculated using the Haversine equation. The pre-processed files were then indexed based on event timestamp for True Event Classification. The distance of the event was grouped in 10 km clusters to eliminate effects of the positioning error in both files and is informed through its cluster midpoint.

B. True Event Classification

The indexed data was processed to determine true and false events of Storm Detector using as criteria the timestamp difference between the network and the sensor, because there was a little time drift – about 5 seconds – between the measurements. The matched events are classified as true events, the unmatched as false events, and the LINET unmatched events are classified as fail to warn events, to help with the calculation of probability of detection and fail to warn rate, presented in this paper.

V. Calculus of Detection Efficiency and Classification Accuracy of Lightning – Storm Detector Sensor

A. Relative Stroke Detection Efficiency (RSDE)

The stroke detection efficiency is defined as the fraction of strokes detected from the total number of really occurring strokes[20]. Also, detection efficiency is equivalent to the probability of detection (POD) of lightning discharges by an LLS[18].

Relative detection efficiency is a measure of how well a given site in the network is being observed relative to the best network region [19; 20]. Considering the LINET network and the radius data, we performed the correlation of distance measurements between the LINET and Storm Detector sensor.

Since the CG radius data set used as a reference is generally collected in areas with higher values of DE (known from other independent observations), the resulting RDE can be approximated with the absolute detection efficiency (ADE) [20; 21].

It is possible to determine the RSDE of Storm Detector ($RSDE_{SD}$) as a function of distance, simply dividing the true events of Storm Detector (NE_{SD}) by the events informed by LINET network (NE_{LINET}) reported at the same distance δ:

$$RSDE_{SD}(\delta) = NE_{SD}(\delta)/NE_{LINET}(\delta) . \quad (1)$$

The DE of LINET is an absolute measure, so, the absolute DE for Storm Detector is obtained multiplying the RSDE by LINET DE for a given distance δ in km:

$$ADE_{SD}(\delta) = RSDE_{SD}(\delta) * DE_{LINET}(\delta) \quad (2)$$

B. Detection efficiency computation

The computation of (1) and (2) gives the plot showed in Fig. 3. The DE is informed as a percentage. An expression was found for the absolute DE of Storm Detector sensor as a function of distance, through logistic regression, given as:

$$ADE_{SD}(\delta) = 88.11\ (1 - 1/(1 + 309.6\ exp(-0.2888\ \delta)))\ , \tag{3}$$

where, the absolute DE of Storm Detector is given as a percentage and δ is the event distance of Storm Detector sensor. Equation (3) allows the ADE extrapolation for other distances values than the centroids defined in Data Pre-process. The dashed line in Fig. 3 is a plot of (3).

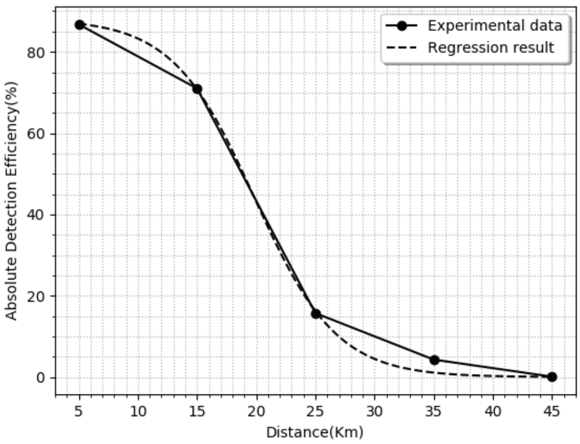

Fig. 3. Absolute Detection Efficiency of Storm Detector per distance.

Fig. 3 shows that Storm Detector sensor has a very good ADE at short ranges, about 20 km, and ADE decreases at a fast rate for long distances. The total detection efficiency in the radius of 40 km is 14.06%, which is far worse than in the radius of 20 km, 75.37% .

C. Classification Accuracy (CA)

Classification Accuracy (CA) is a new parameter that appeared with the recent capability of Lightning Location System (LLS) to detect Cloud-to-Cloud (CC) or Intra-Cloud (IC) discharges. Is defined as the percentage of CC/IC or Cloud-to-Ground (CG) classification by the LLS against the real class of the event of correct events classification in terms of CG or CC/IC [22]. Although the AS3935 Integrated Circuit does not provide a classification index for the events, it is possible to determine how good it is in this matter, because it claims to detect both IC and CG discharges.

Data correlation between Storm Detector sensor and LINET network shows, for the true events, that 14.4% of the true events are listed as CC or IC events and 85.6% are named as CG events, shown in Fig. 4. It also indicates that Storm Detector informs mainly about hazardous events to the ground – which is the main function of the sensor.

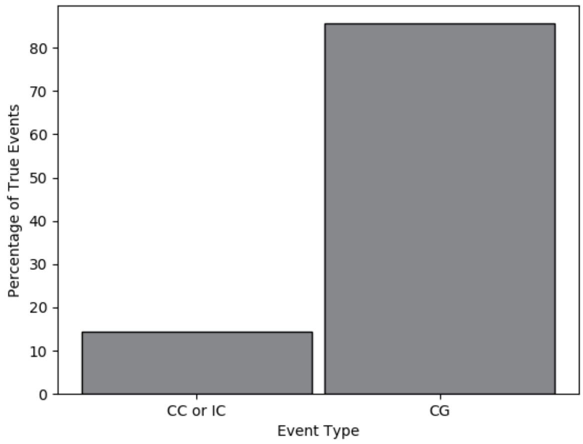

Fig. 4. Storm Detector True Events x LINET Classification

VI. Distance Analysis of the Storm Detector

A. Statistical Distance Estimation of AS3935

Reference [14] says that the lightning algorithm is broken into three blocks:

- Signal validation: Verification that the incoming signal can be classified as lightning.
- Energy calculation: Calculation of the energy of the single event.
- Statistical distance estimation: According to the number of stored events (lightning), a distance estimate is calculated.

Since the informed distance is the head of the storm and not the event distance, for distance accuracy analysis of Storm Detector device, it is better to have another way to compute the distance parameter by event, not by storm, because the data correlation between LINET and Storm Detector sensor contains matched events and the calculated distance for LINET network reported events.

An insight came due to the fact that, in an approaching storm, when the AS3935 indicates a change in distance estimation, from a far to a near distance, the energy fall into a very specific range of values. That fact is an evidence that the informed distance is related to the energy parameter in some way.

B. AS3935 Distance Empirical Expression

The raw data file of Storm Detector sensor was used to search the change of distance estimation of the approaching storm and to extract the energy and informed storm distance. We made use the natural logarithm of the energy to ease the result interpretation. The experimental data was plotted to visualize the result, as it is showed in Fig. 5. It shows clearly that the maximum value for a given range is associated with the distance indicated, because lower values tend to be equal to the maximum value of the next distance.

We found an expression for the distance using the maximum values through polynomial regression and is given as:

$$L_E(\delta) = -1.667 \times 10^{-5}\,\delta^3 + 0.003501\,\delta^2 - 0.2563\,\delta + 13.5 \quad , \quad (4)$$

where, L_E represents the natural logarithm of the energy parameter and δ is the distance in km. Equation(4) allows extrapolations of the estimated distances for energies different than the maximum values defined as more representative of the informed storm distance of Storm Detector sensor. The dashed line in Fig. 5 is a plot of (4).

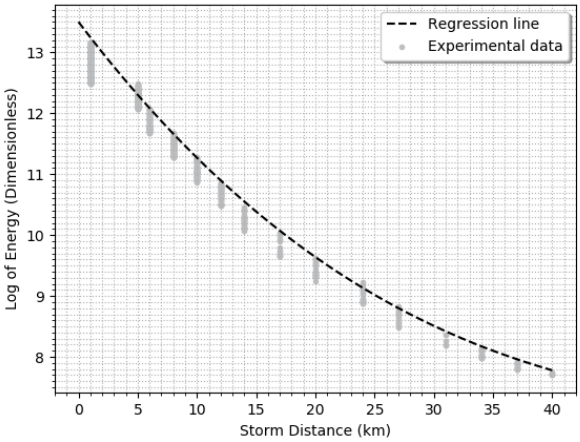

Fig. 5. L_E X Storm Distance experimental data and polynomial regression.

C. Empirical Distance Expression Validation

The Equation (4) was validated against the true data of Storm Detector sensor calculating the roots of (4) to each event energy parameter. The linear regression of the calculated distance for Storm Detector sensor and the calculated distance using the geolocation reported by LINET network data and sensor position, shows that it has a linear dependency between the two distances, as showed in Fig. 6.

The correlation coefficient (r-value) calculated with linear regression is 0.9723 and the Pearson coefficient (p-value) calculated is 0.0, which suggest a strong relationship between the two distances. Although the AS3935 energy parameter has no physical meaning, these two statistical tests suggests that (4) is strongly correlated with the LINET network calculated distance, leading to conclude that the energy parameter is strongly correlated to storm distance. The error between the LINET network and Storm Detector sensor calculated distances was computed and plotted in an histogram, along with 90% confidence interval and normal distribution fitting, as it showed in Fig. 7. The standard deviation of histogram is 1.84km with a mean value of -0.26 km with a 90% confidence interval of +/- 3km.

VII. Probability of Detection and False Alarm Rate of the Storm Detector

Reference [17] methodology set four parameters to evaluate lightning risk warnings:

- Effective Alarm (EA) is the warning that was triggered before the CG lightning occurred inside the area of concern(AOC);
- Lead Time (LT) is the time interval between the time of the warning and the occurrence of a CG lightning inside the AOC;
- Failure to warning (FTW), when the CG lightning occurs in the AOC without previous warning;
- False Alarm (FA) is an alarm triggered without the occurrence of a CG inside the AOC.

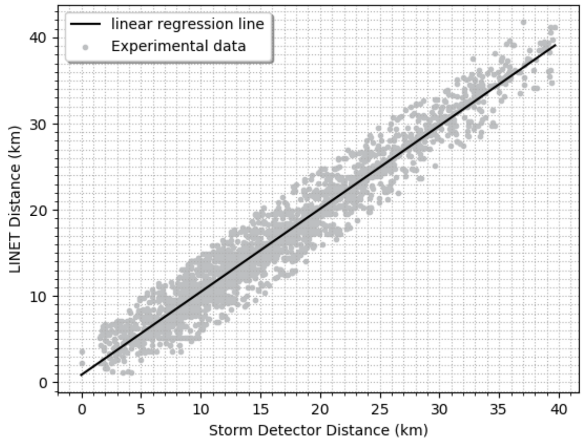

Fig. 6. Dependency of calculated distance of Storm Detector and LINET calculated distance.

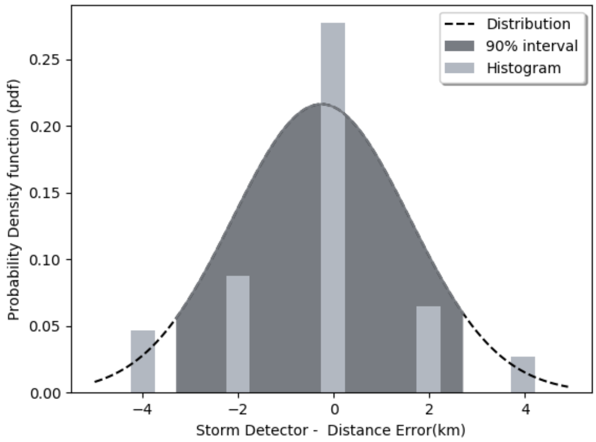

Fig. 7. Probability density function of the distance error of (4).

The EA, FA and FTW parameters are used to compute two statistical parameters, the Probability of Detection (POD), which is the ratio between of successful warnings of the total events in the AOC, and the False Alarm Rate (FAR), which is the ratio of the FA to the total number of alarms triggered by the device[17].

Formally, POD parameter is defined as:

$$POD = EA / (EA+FTW) \quad , \quad (5)$$

and FAR is defined as:

$$FAR = FA / (EA+FA) \quad . \qquad (6)$$

For POD and FAR computation, EA is defined as the true events of Storm Detector data, FA is defined as the events that does not find a match with LINET data, and FTW is defined as LINET events that does not find a correspondence in True Events processing, which also defines AOC as the distance radius of 50 km. The computation of the parameters for the clustered distances - Fig. 8.

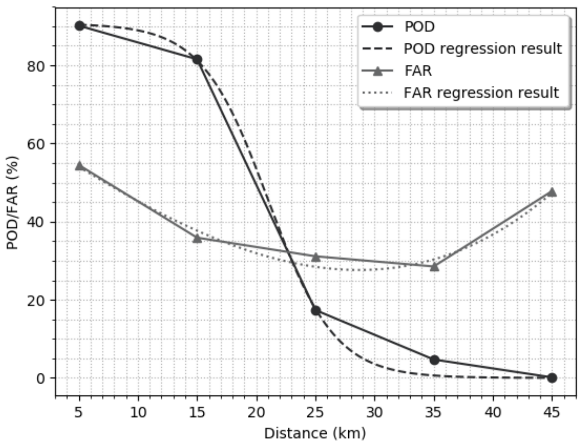

Fig. 8. Probability of Detection (POD) and False Alarm Rate (FAR) by distance of Storm Detector sensor.

Also, an expression was found through logistic and polynomial regression for POD and FAR, which allows extrapolation for other distance values than the centroids defined in Data Pre-process. The POD obtained expression is given as:

$$POD(\delta) = 91.01(1 - 1/(1 + 1500 \exp(-0.3489\, \delta))) \,, \qquad (7)$$

where, POD is given as a percentage and δ is the distance in km. The FAR obtained expression, as a percentage is given as:

$$FAR(\delta) = 6.717 \times 10^{-4}\, \delta^3 + 0.005342\, \delta^2 - 1.962\, \delta + 63.66 \,, \qquad (8)$$

Fig. 8 shows that Storm Detector has a very good POD at short ranges, about 20 km, and POD decreases at a fast rate for long distances. The total POD in the radius of 40 km is 15.62%, which is far worse than in the radius of 20 km, 83.94%. The FAR parameter, although it variates along the AOC radius, can be roughly considered constant and the total FAR value in the radius of 40 km is 40.02%, nearly the FAR value in the radius of 20 km, 42.86%. The POD curve is also quite similar to the ADE curve, since POD also interpreted as DE.

VIII. Conclusion - Evaluation of Operability of the Storm Detector

The lightning detection characteristics evaluated in this work demonstrates how well the AS3935 IC, named by it's device by Storm Detector sensor, performed as a storm detector device and also a storm distance estimator device, in an indoor environment.

The DE determination shows that, for a radius limit of 20 km, the Storm Detector sensor performs better than expected, but for a radius range of 20 - 40 km is lower than predicted by the Fig. 2 and Fig.3, which predicts for the choosed configuration of WDTH and SREJ a DE of about 20% in the detection limit, which was calculated to less than 1%. The reasons to this behavior is object of further works.

The Classification event showed in Fig. 5 shows that Storm Detector classifies and warns more CG events than CC/IC events. That fact indicates that the device mainly informs about hazardous events to the ground, which is the main function of the device – alert about danger of atmospheric discharges in the vicinity, up to 40 km.

The POD/FAR analysis showed a very interesting performance, similar to found in [17] for an Electric Field Mill sensor, for the same range. The FAR is near the same value, although the POD is better for the Storm Detector sensor.

Reference [17] found a POD of 58% and a FAR of 41% for a threshold of 1 kV/m for a radius of 10 km, and for Storm Detector sensor was found a POD of 83.94% and a FAR of 42.86% for a radius of 20 km. The detection range of Storm Detector sensor is twice of the range of Electric Field Mill, for comparable FAR and POD parameters, leading to conclude that Storm Detector sensor performs better regarding early warnings about atmospheric discharges.

The distance analysis shows a peculiar results, because although [14] is not sure of that the distance estimation is precise, the polynomial regression of the energy parameter against the distance estimation, both given by the AS3935, suggests that it can give a precision of 3 km regarding the estimated distance. Equation (4) also enables future works about the Storm Detector device, like data correlation between two or more devices in a line basis of 20 km, which by the way would increase the distance estimation precision.

Thus, the Storm Detector sensor device is well suited for short range detection of a radius of 20 km, with a reasonable distance estimation accuracy and good POD/FAR rates, along with an ADE comparable to the DE of LINET network.

The inductor acting as an antenna on the Storm Detector sensor correctly answers the theory of propagation of electromagnetic waves in free space, showing that by detecting the waves in the spectrum of the LF in the near field (5 - 30 km), it achieves an efficiency of detection higher when compared to far field detection (over 30 km).

Acknowledgment

The Group of Electricity Atmospheric Phenomena and of Signal Propagation System would like to thank of Carlos Augusto Morales Rodrigues (USP/IAG - Starnet and LINET), by confidence in to provide and to disponibility of the data.

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