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Conclusions and recommendations
Final Document

1. INTRODUCTION

Based on international symposiums held in different parts of the world, the National University of Colombia, the research group PAAS-UN and the Colombian Association of Faculties of Engineering (ACOFI), with support from the Colombian Institute of Science and Technology (COLCIENCIAS) have invited worldwide expert researchers from many countries to the World Meeting on Lightning (WOMEL) to discuss the progress in scientific and technological knowledge of the phenomenon of lightning and propose future research approaches.

WOMEL event was held in the city of Cartagena de Indias, Colombia from 6th to 8th April 2016.

2. INVITED RESEARCHERS

Austria:	Gerhard Diendorfer
Brazil:	Silverio Visacro, Alexander Piantini.
Chile:	Johny Montaña
Colombia:	Horacio Torres, Camilo Younes, Ernesto Pérez, Daniel Aranguren, Mauricio Vargas, Norberto Navarrete, Favio Casas.
Germany:	Hans Dieter Betz
Italy:	Carlo Alberto Nucci
Japan:	Masaru Ishii
Malaysian:	Chandima Gomes
Mexico:	Francisco de la Rosa, Carlos Romualdo Torres
Paraguay:	Humberto Berni
Spain:	Joan Montaña, Blas Hermoso
Sweden:	Vernon Cooray
Switzerland:	Marcos Rubinstein, Fahrad Rachidi
USA:	Vladimir Rakov, Earle Williams, Mary Ann Cooper
Venezuela:	Carmen Vásquez

3. METHODOLOGY AND PROGRAM

The methodology and the developed program during the event were:

Each guest researcher was invited to give a maximal of 20-minute talk about what he wrote in the contribution previously received the event. The mission of the Chairman and Co-Chairman was to

lead an exchange of views about the discussed treated in the issues and to present the most important conclusions at the end of the session.

The following sessions were the issues realized in the WOMEL event:

Wednesday April 6th, 10:00-12:00

Session 1: Lightning Physics and climate change. Speakers: J. Montanya, F. Rachidi-M. Rubinstein, E. Williams and M. Vargas.
Chairman: J. Montanya – Co-Chairman: C. Younes

Wednesday April 6th, 14:00-16.00

Session 2: Global characterization of lightning parameters. Speakers: V. Rakov, G. Diendorfer, HD Betz, S. Visacro
Chairman: F. Rachidi – Co-Chairman: D. Aranguren.

Wednesday April 6th, 16:20-18:20

Session 3: Lightning protection in tall structures. Speakers: M. Ishii, B. Hermoso, J. Montanya
Chairman: G. Diendorfer – Co-Chairman: M. Vargas

Thursday April 7th, 08:00-10:00

Session 4a: Lightning effects in human beings and social impact. Speakers: MA Cooper, N. Navarrete, Ch. Gomes and Favio Casas. Guests: DIPSE, indigenous S. Mindiola (Comunidad Arhuaca), D. Aranguren (Keraunos).
Chairman: MA Cooper Co-Chairman: J. Montaña

Thursday April 7th, 10:20-12:20

Session 4b: Lightning effects in human beings and social impact. Speakers: MA Cooper, N. Navarrete, Ch. Gomes and Favio Casas. Guests: DIPSE, indigenous S. Mindiola (Comunidad Arhuaca), D. Aranguren (Keraunos).
Chairman: Ch. Gomes – Co-Chairman: D. Aranguren

Thursday April 7th, 14:00-16:00

Session 5: Protection of electric power networks, Part 1. Speakers: E. Perez, CA. Nucci, A. Piantini.
Chairman: S. Visacro – Co-Chairman: E. Perez

Thursday April 7th, 16:20-18:00

Session 6: Applications of protection against lightning. Speakers: H. Berni, ABB, Y. Mendez and F. de la Rosa.
Chairman: Y. Mendez – Co-Chairman: J. Montaña

Friday April 8th, 08:00-10:00

Session 7: Protection of electric power networks, Part 2. Speakers: C. Romualdo, C. Vasquez. Guest: L. Porras, P. Durán, A. Rojas.
Chairman: A. Piantini – Co-Chairman: M. Vargas

Friday April 8th, 10:20-12:20

Session 8: Future research on lightning. All guests.
Chairman: CA. Nucci, M. Rubinstein and H. Torres

4. *SUMMARY OF SESSIONS*

Session 1: Lightning Physics and climate change.

This session remarks the importance that lightning research has nowadays, especially because the climate change and global warming phenomena. It is well known that weather and lightning have a strength relationship and all the conferences have some common places.

As a big conclusion, an issue that has no doubt about if exists or not is the global warming. The dependence of lightning activity on this phenomena demands to keep studying and analyzing if a dependence exist or not and if yes, how correlated is this with the issue.

Additionally, warmer places create more severe storms that imply the creation of bigger lightning activity centers of multicellular storms. The study of storm clouds and the ways of lightning inception, especially how leader phenomena is created is a very important aspect to remark. Lightning is still a natural phenomenon with a lot of uncertainty about the entire process.

Lightning leaders are still poorly understood. Different aspects of lightning leaders are taking into account that includes high-speed video observations of lightning leaders, investigations of bidirectional development of leaders by means of radio mapping systems, research on the high energy emissions produced by lightning leaders and the study of upward leader initiation from wind turbines and development. In a second part, the need of an improved lightning leader model is exposed and proposed as future work. Lightning leader models can be approached by different ways depending on the purpose but agreement between all the approaches is still not complete.

An electrostatic model of the lightning leader channel for negative cloud-to-ground discharges was presented in this session by using the Charge Simulation Method (CSM), which was initially conceived for stepped leaders even assuming tortuosity and branching; however, it can be also applied to model dart leader channels. The thundercloud was represented by two spherical charge centers. A positive center was located in the upper part of the cloud and a negative center in the lower part, each one having the same uniform charge density but opposite polarity, like a dipolar structure. The leader channel was modeled on the basis of the bipolar/bidirectional concept, assuming that the channels extend away from a starting point at the bottom of the lower negative charge center, with opposite directions and polarities, and their net charge is zero.

<u>Session 2</u>: Global characterization of lightning parameters.

CIGRE Working Group C4.407: Brochure on Lightning Parameters for Engineering Applications, 2013. (Previous: Berger (1975), Anderson and Eriksson (1980)):

- 80% or more of negative cloud-to-ground lightning flashes are composed of two or more strokes (Anderson and Eriksson: 55%)
- One-third to one-half of lightning flashes create two or more terminations on ground, GPFD ≈ 1.5 to 1.7 GFD (Anderson and Eriksson: 1.1)
- Median return stroke peak current for the first stroke is about:
  - 30 kA (Switzerland, Italy, South Africa, and Japan)
  - 45 kA (Brazil)
- Median peak current for subsequent strokes is about:
  - 10 - 20 kA (Switzerland, triggered and upward)
  - 18 kA (Brazil)
- The average probabilistic value measured by Berger and taken by CIGRE and IEC is 30 kA, whereas the average probability value measured in Brazil, Colombia, or Rhodesia, in tropical area by different methods and at different times is about 42 kA
- Direct current measurements on instrumented towers: Austria, Brazil, Canada, Germany, Japan, and Switzerland
- Except for Brazil and Japan, the majority of observed flashes are of upward type.
- There is no evidence of a systematic dependence of negative cloud-to-ground lightning parameters on geographical location, except maybe for first and subsequent return-stroke median peak currents.
- At the present time, the available information is not sufficient to confirm or refute a hypothesis on dependence of negative cloud-to-ground lightning parameters on geographical location or season.

Long-term studies on Lightning Location Systems (ALDIS/EUCLID) and direct lightning current measurements (Gaisberg Tower).

<u>Peak current distributions of negative first strokes:</u>
The stated median peak current of about 30 kA is significantly higher than according values obtained from LLS data in different regions of the world, where median peak currents of first strokes are more in the range from 15 kA – 20.
Possible reasons:

- LLS first stroke data are contaminated by lower current subsequent strokes or by misclassified IC discharges
- Ip vs Ep is not applicable to first strokes in CG lightning in general
- Equation to calculate peak current is valid but a smaller value for the return stroke velocity needs to be used in this equation for first strokes

<u>Peak currents of positive strokes and IC discharges</u>
Similar to first stroke peak currents in negative CG lightning, up to now no validation is available

for the LLS peak current estimates for positive discharges and IC discharges.

Misclassification rates of LLS

Today the contamination rate of the CG stroke peak current distributions by misclassified IC discharges (erroneously classified as CG) is not well-understood and likely one of the most significant differences in data from different LLS.

Parameters determining initiation of upward lightning from tall objects

More than 15 years of observations of upward lightning from the GBT show that there are a number of open questions regarding the driving parameters for the observed lightning occurrence.

"Lightning and its effects in all its details and complexity is still far from being well understood and remains one of the fascinating and great mysteries of nature".

Key contributions on lightning detection (last decade):

- Availability of GPS enabled use of TOA (Time-Of-Arrival) techniques for locating stroke positions in both 2D and 3D, giving rise to most remarkable improvements. The location error could be reduced, and more refined techniques became feasible such as a 3D locating method based solely on VLF/LF stroke signals.
- Introduction of the TOA-based LDS with 3D locating of IC strokes in large-areas allows more insight into occurrence pattern and nature of ill-understood IC strokes, enables improved recognition of severe thunderstorms, and provides an independent method for CG-IC discrimination.

Contributions focused on natural negative CG lightning:

Events measured at Morro do Cachimbo Station MCS (Brazil) instrumented tower:

- Two operational periods (1985-1998 and 2008- 2015). Peak current of negative flashes are 40-50% higher than those in Berger (1970). (45 kA avg))
- Development of a representative waveform for the first return stroke current, quite different from the frequently referred waveforms by Berger (1970).
- Negative upward lightning measured at MCS since 2010 show specific features when compared to those of temperate regions, notably a larger amplitude in the initial stage and a much shorter duration.
- The most impressive result is the charge transferred in the initial stage for practically all events very close to 6 C.
- The measurements of current of natural negative CG lightning in the pre-return stroke phase at MCS allowed improving the interpretation of the process preceding the attachment.
- The most relevant results obtained at MCS correspond to the simultaneous records of lightning quantities (current measured at tower base, close (45 m) and distant (700 m) electric field, luminosity) and video-records acquired with a high-speed camera since 2014.

Several studies in the Colombia-Venezuela region have reported GFD values higher than 20 flashes/km^{2}year (well identified locations such as the Magdalena River Valley and Maracaibo Lake, etc. with GFD up to 60) and KL values higher than 100-thunderstorm days/year.

The application of international standards (e.g. for lightning risk assesment (IEC62305) or evaluation of power failure rates (IEEE1410)) using the realationship GFD (or KL) values produce results which usually surpass the "tolerable" or "acceptable" limits.

If the relation GFPD = 1.5 GFD is used, the technical problem increases, then: *¿Are lightning international standards, in its current form, entirely applicable in Colombia (and similar tropical countries)?*

***Session 3*: Lightning protection in tall structures.**

This session focused on the issue of the effects of lightning on tall structures such as wind turbines.

On the engineering side, higher frequencies of troubles at transmission lines or wind turbines in winter due to lightning than those in summer have been experienced in the winter thunderstorm area of Japan, despite the much smaller number of lightning strokes in winter observed by lightning location systems (LLS).

By the recent development of observation instruments such as digital high-speed cameras and LMA, combined with the knowledge on the frequent occurrence of lightning hits on tall structures, there will be more chances than before to observe detailed physical parameters related to lightning attachment, leading to development of practical semi-physical models that are useful in engineering purposes.

Regarding wind turbines there was no documents, no specific standard, only the old standard for structures protection. Later, emerged the actual standards IEC 62305-1-2-3-4 and due to the rapid growing of numbers and power of wind turbines appeared the specific standard for lightning protection of wind turbines IEC 61400-24.

Lightning protection of tall structures is mainly based on geometrical or non-physical models, which are not always accurate for very high structures.

Given recent developments and measurements, it is important to consider physical parameters related to lightning attachment in lightning protection models for tall structures.

***Session 4*: Lightning effects in human beings and social impact.**

An Incomplete History of Lightning

- Since 2000, many people have become involved in lightning safety around the world.
- The Lightning Safety Group (LSG) was a meeting of US lightning experts since 1998.
- Results of this conscience about lightning generate rules as '30-30 rule', (30 seconds count between the first lightning seen and the first thunder heard).(resume activity 30 minutes after the last thunder heard)
- Take into account people beliefs, type of audiences (children vs. adults), (urban areas vs. rural areas).

- Media have the role of promoting lightning safety information to prevent injuries and deaths.

Need of Low-Cost Lightning Protection Schemes for Small-Scale Applications

- Despite the building and structures need lightning protection; some factors prevent a sizable percentage of community in implementing such protection systems in small structures.
- Factors: complexities of design and implementation, cost, aesthetic concern, material theft and socio-cultural aspects.
- Solution: Improve the lightning protection in buildings with reinforced steel structure at a very competitive cost.
- Protection schemes for small structures are more appropriate than personal lightning protection devices, due to the high cost per capita.
- Difference between a standard lightning protection system and those designed for small structures and portable application is the second one may not have a comprehensive earthling component (economic and strategic limitation).
- System is designed to have equipotential with structure = Faraday Cage.
- Protection is meant only for those who are inside the protective system.

Lightning injuries in Colombia. From lack of awareness to prevent

- First approach to the problem of lightning injuries in Colombia
- Lightning injuries should be classified as trauma; they are highly preventable.
- A total of 757 lightning-related deaths were identified in 10 years (males: 80%, children: 12%)
- The overall annual lightning death rate in Colombia is 1,78 per million per year. (2000-2009)
- Home: 35%, workplace: 20%, public roads: 13%.

An Analytical Perspective to Lightning Risk Management

- Risk management has defined parts: identification, evaluation, implementation of controls and management control.
- The overall annual lightning death rate in Colombia is 2,04 per million per year. (from 2000-2012).
- Share alerts on social networks "crowdsourcing"
- Include the lightning strike prediction parameter in risk assessment.

The head (*Mamo*) of the indigenous community Arhuaca of Colombia presented his worldview regarding the phenomenon of lightning, emphasizing the relationship of respect that should exist between human beings and natural phenomena.

Based on different presentations in this world meeting and taking into account the conclusions, comments and suggestions about failures, injured, accidents, losses, outages generated by lightning effects, we propose to create an International Research Institute in order to develop studies, assessments, consultations and knowledge, helped on experiences of researchers and engineers on lightning and related subjects.

***Session 5 and 7*: Protection of electric power networks. Part 1 and part 2**

On the theoretical aspects in this session it was discussed the principal developments on lightning return stroke current modeling for the calculation, analysis of the LEMP coupling to overhead lines, the development of models, simulation tools, effect of irregular ground characteristics on lightning induced voltages calculation, analysis of branched lines, estimation of lightning performance of distribution lines/systems including effect of complex-shape networks and connection of power system devices.

On the experimental results it was presented experimental results performed on scale models and on real distribution networks.

The results presented on the scale tested was focused on the validation of theoretical modelling with experimental results, on the analysis of the effect of the nearby buildings and on the influence of surge arresters, shielding wire on the protection of overhead distribution networks.

The results on real networks, were focused on analyze induced voltages waveform characteristics its possibility to correlate with Lightning Location System Data.

As main conclusions of the session, can be summarize in the following:

- Important developments on lightning induced voltages made on the past decades, have contributed to understand and to improve the lightning performance of distribution networks.
- On the modeling aspects it was shown that several factors contribute to enhance or reduce the lightning induced voltages such as: lightning parameters, distribution network configuration, non-uniform and non-homogeneous grounds, among others.
- The lightning induced voltages could be reduced significantly using line surge arresters, shielding wires and groundings on the distribution network.
- The experimentation on this subject has led to understand that lightning induced voltages are strongly dependent on the network complexity, including not only the network characteristics but also the surroundings.
- Lightning is one of the main causes of problems and failures on transmission and distribution lines.
- Nowadays, the most widely methods to mitigate the problems caused by lightning on power networks are:
  - Efficient location of the ground wires in order to obtain an effective shielding
  - Reduce footing resistance at critical towers by traditional or artificial methods
  - Installation of line surge arresters in critical towers and/or phases of the lines.

***Session 6*: Applications of protection against lightning.**

Lightning and Power Systems

- In advance reliability studies and rough short-term estimates should be included: variation of lightning incidence from year to year, seasonal variations, type of thunderstorm

including current characteristics, flash and stroke rate.

- The current time derivative (dI/dt) is essential to determine the effect of connecting leads to surge protective devices and for assessing the risk of back flashover.
- Time interval between strokes is important for evaluations of transmission line outage caused by unsuccessful reclosing operations.
- 30 to 50% of negative flashes contain continuing currents lasting 40 ms. or longer, positive flashes have continuing current components in order of 100 A that can affect surge arresters.
- Peak current estimates provided by lightning location systems must be used with caution, because some networks will have additional sources of error.
- Shield wires on MV distribution lines to avoid direct flashes are not sufficient to prevent lightning-caused fault.
- In medium voltage, back flashover and induced voltage are the major causes of line outage.
- Circuits without grounded neutral, having a low BIL and CFO, operating in areas of high GFD or high resistivity of the soil, can experience far more outage due to close lightning than those due to direct strokes.

5. RECOMMENDATIONS FOR FUTURE RESEARCH ON LIGHTNING.

Lightning Physics and climate change

- Intracloud lightning propagation and the effects that this part of the phenomenon has and its relation to novel electric power systems and tall structures such as wind turbines and communication towers, as well as the impact of lightning activity on aeronautical systems, is an important aspect to be analyzed with methods like VHF mapping and other newer technologies.

- Another aspect that is important to remark is that long time scale analyses derived from geostationary orbit satellites and Schumann resonances studies are necessary to define the dependence of lightning activity on global temperature.

- Human activity and the development of technologies highly sensitive to EMC related to lightning phenomena should be continuously analyzed in order to improve our knowledge, the protection of human beings and to solve problems related with our dependence of the technology in a better way.

- In the near future leader models such as the Bi-Leader Models must be improved. One of the reasons is that current efforts to explain the intense TGF emissions pass through an understanding of the leader development.

- An important focus point for future research on lightning is trying to unify the leader definition and process models This demands a better understanding of the way global warming influences the creation of storms, especially severe storms.

- *Global characterization of lightning parameters:*

Stroke detection efficiency:

- The radiated field amplitude depends on the assumed speed of the return stroke, which is known to differ between 1st and subsequent RS. In practice, however, this distinction is not applied. The reported statistical CG peak current is lower than the currently accepted value of 30 kA.
- Most of the tower strikes represent only subsequent strokes rather than 1st RS.
- More measurements of natural 1st RS at specific instrumented sites are needed. (Downward CG)

IC Strokes: VLF/LF Observations of Cloud Lightning:

- In consideration of extensive experimental data it appears justified to add IC strokes as frequent and characteristic part for discharge processes into the listing of lightning parameters.
- Task for the future to improve IC-CG discrimination in VLF/LF-based LDS, because the traditional waveform discrimination has serious problems, and the alternative TOA-technique (introduced in 2004, LINET LDS) is not yet a general standard. Successful implementation of this relatively new technique requires highly optimized and calibrated detection systems with precise hardware technology and sophisticated software procedures.
- According to the research hypothesis about the spatial and temporal variation of the parameters of lightning (most based on the results of Berger, 1975), these should be reviewed and re-evaluated.

- *Protection of electric power network and Lightning protection in tall structures*

- Overvoltage calculations using advanced Numerical Electromagnetic Analysis – NEA
- Influence of the presence of buildings and other structures around the lines
- Lightning and renewable energy systems
- Improvements of models, which allow estimate accurately LIV.
- Improvement of the accuracy of the lightning parameters since they are the input for calculations
- It is recommended to improve the lightning detection systems and extend the use of this data for lightning protection of tall structures.
- Lightning smart-grid applications
- Behavior of power equipment subject to lightning surges.
- Analysis of lightning location systems data to estimate stroke current distributions, ground flash density and lightning performance of transmission/distribution lines.
- Development of models, which consider the probability of failure on lines with surge arresters.
- Recommend failure rates considering different voltage levels, geographical location, climate change and critical loads.

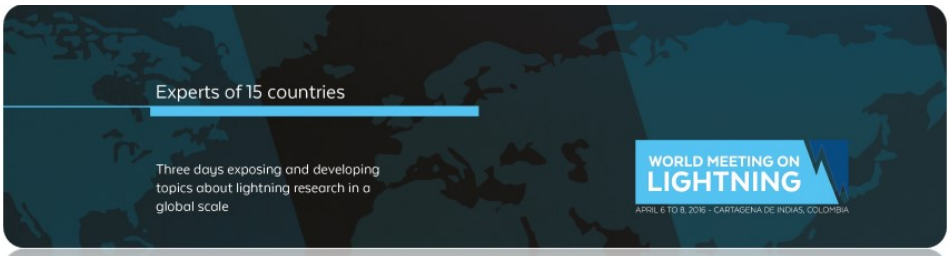
- *Lightning effects in human beings and social impact*:

- Programs and measurements to prevent lightning fatalities need to be focused on the type of population and their beliefs.
- Structural design needs final appealing to the socio-cultural norms of society.
- Evaluate possible treatments to prevent or reduce neurological damage.
- Suggestions:
  - Mass media messages
  - Messages oriented according to the target audience
  - Bring improvements in housing construction and generation of protection systems
- The research institute proposed will be focus on parameters, characteristics and behaviour of lightning occurring in tropical zone. The institute will be hosted in National University of Colombia and will be supported by Universidad Federico Santa Maria (Chile) and Universidad Industrial de Santander (Colombia). It will have some local partners as Keraunos, Segelectrica and SIATA and international partners as Centro de Modelado Cientifico from Universidad de Zulia (Venezuela) and many other universities, research centres, researchers, professors, engineers and experts from different disciplines as a results of alliances of this world meeting.
- Activities of the institute include training, consultancy, risk assessment, design and evaluation of protection systems in compliance with international and local standards from the ethic, responsible and sustainable point of view. Due to cultural differences, beliefs and social aspect, all actions carried out, proposal solutions and results have to consider a holistic vision of the problem.
- In order to begin making this initiative intends to make the "Declaration of Cartagena", where the main discussed recommendations at this event are placed.

Applications of protection against lightning:

- It is appropriate to try to obtain regional estimates of peak current distributions to help in the interpretation of lightning problems.
- For an effective and reliable analysis of lightning protection, it is appropriate to use the technology that has been developed in Colombia and is part of the Colombian Technical Standard NTC 4552, called 3P Technology. This technology develops in an integral way three factors to mitigate the damage and, in general, the negative effects of lightning: Prediction, Prevention and Protection.

** **Note:**



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