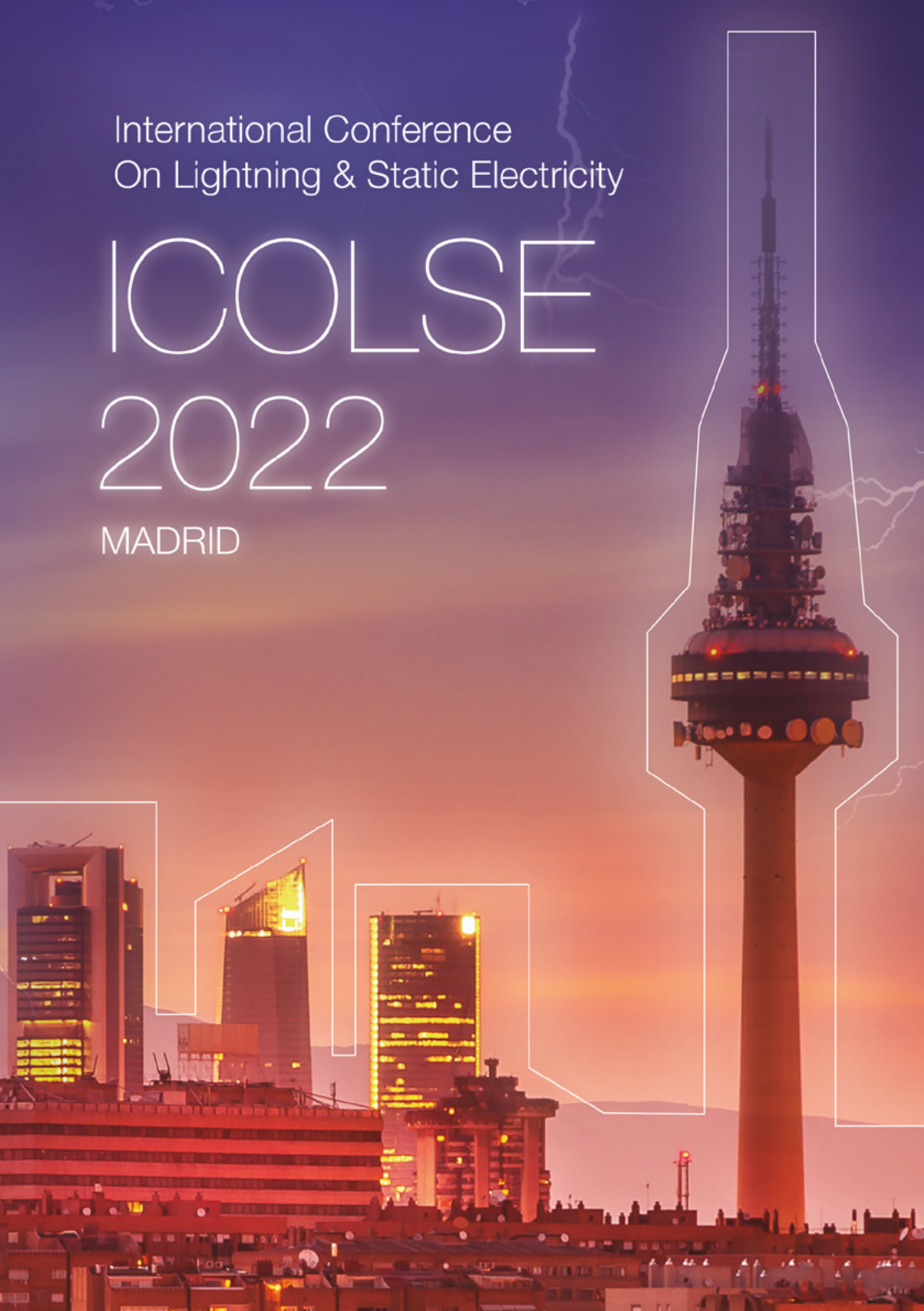
International Conference
On Lightning & Static Electricity

# ICOLSE 2022

MADRID



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ICOLSE 2022 ORGANIZING COMMITTEE MADRID

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LCOE Laboratorio Central Oficial de Electrotecnia

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# AGENDA

## September 12

| | Auditorium |
|---|---|
| 13:00 | Registration Open |
| 15:00 | Opening |
| 15:30 | Keynote 1 |
| 16:00 | Keynote 2 |
| 16:30 | Coffee Break |
| 17:00 | Keynote 3 |
| 17:30 | Keynote 4 |
| 18:00 | Exhibitiors Presentations |
| 19:30 | Welcome Party |
| 21:00 | |

## September 13

| | Auditorium | Room C |
|---|---|---|
| 8:00 | Registration Open | |
| 9:00 | Session 1A | Session 1B |
| 10:45 | Coffee Break | |
| 11:20 | Session 2A | Session 2B |
| 13:00 | Lunch | |
| 14:30 | Exhibitiors Presentations | |
| 15:00 | Technical Tour LCOE Visit | |





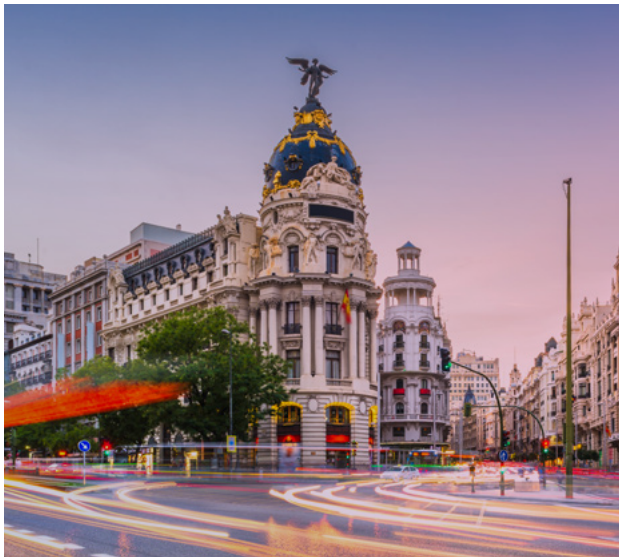
# AGENDA

## September 14

| | Auditorium | Room C |
|---|---|---|
| 8:00 | Registration Open | |
| 9:00 | Session 3A | Session 3B |
| 10:45 | Coffee Break | |
| 11:20 | Session 4A | Session 4B |
| 13:00 | Lunch | |
| 15:00 | Session 5A | Session 5B |
| 16:45 | Coffee Break | |
| 17:20 | Session 6A | Session 6B |
| 19:45 | Cultural Tour Prado's Museum | |
| 21:30 | Banquet | |
| 23:00 | | |

## Septiembre 15

| | Auditorium |
|---|---|
| 9:00 | Registration Open |
| 10:00 | Keynote 5 |
| 10:30 | Keynote 6 |
| 11:00 | Coffee Break |
| 11:30 | Keynote 7 |
| 12:00 | Keynote 8 |
| 12:30 | Closing |
| 13:00 | Lunch |
| 14:30 | |



# WELCOME

The **International Conference on Lightning & Static Electricity** (ICOLSE) is a biennial conference focused on lightning phenomenology, effects on and protection of aircraft and other air vehicles, and a wide variety of ground-based systems and facilities such as alternative energy (wind, solar), space launch, telecom, railways, recreational theme parks...

Conference sessions will also address static electricity generation, effects, and protection for aerospace vehicles and industrial facilities. After a one year delay due to COVID-19 crisis, **ICOLSE come back in 2022.**





**ICOLSE will be held in Madrid for the first time in its history**. Capital city of Spain, Madrid is a leading destination for meetings tourism thanks to its unique and specialized offering for this segment. Major assets include its meeting and exhibition centers, its special venues, an extensive hotel infrastructure and its excellent connectivity and outstanding transport network. This in conjunction with other aspects such as its highly professional tourism industry, the safety of the destination and its extensive range of cultural and leisure activities, makes Madrid the best choice for any professional event.

Madrid region is the location of one of the more important sites of AIRBUS, with an important role in the Defense and Space areas, together with some of the more relevant Spanish research centers and universities working in different aspects of lightning and static electricity.

We hope to see you in **Madrid next 12-15 September 2022** to enjoy for an exciting and fruitful conference.

*The Organization Committee.*

## CONFERENCE *HISTORY*

The International Conference on Lightning & Static Electricity is a biennial conference with the aim bringing together experts from all fields on the subject of lightning and static electric. It is concerned with all aspects of lightning interaction with ground, air and sea systems. Papers will be presented that contain original material to promote discussion at all levels and address problems of present and future technologies.

ICOLSE aims to encourage a real understanding of atmospheric electricity environmental hazards. A full programme of papers on topics from phenomenology, through measurement, design, protection, testing and computational modelling will be presented.

Last three ICOLSE editions saw more than 200 attendees in average representing several companies, government agencies, universities and other organizations. The progress made in advancing the disciplines of lightning and static electricity was evident in the technical programs as well as through workshops and special sessions provided.

## List of previous conferences:

- Hosted by Wichita (USA) **2019**
- Hosted by Nagoya (Japan) **2017**
- Hosted by Toulouse (France) **2015**
- Hosted by Seattle (USA) **2013**
- Hosted by Oxford (UK) **2011**
- Hosted by Pittsfield (USA) **2009**
- Hosted by Paris (France) **2007**
- Hosted by Seattle (USA) **2005**
- Hosted by Blackpool (UK) **2003**
- Hosted by Seattle (USA) **2001**
- Hosted by Toulouse (France) **1999**

# CONFERENCE *COMMITTEE*

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**David García**
Expert EME System Engineering AIRBUS DS Co-chair

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**Carmen Guerra**
Assistant Professor of Aeronautics and Astronautics
Massachusetts Institute of Technology (MIT)

**Fernando Cano**
Lightning Direct Effects Senior Engineer AIRBUS DS

**Fernando Garnacho**
R&D Director Official Central Laboratory of Electrotechnics (LCOE)
Foundation for the Promotion of Industrial Innovation (F2I2)

International Conference On Lightning & Static Electricity

**Guadalupe Gutiérrez**
EME Modelling & Simulation Senior Engineer AIRBUS DS

**Joan Montanya**
Professor Lightning Research Group Electrical Engineering
Department Polytechnic University of Catalonia (UPC)

**Jorge Rovira**
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Foundation for the Promotion of Industrial Innovation (F2I2)

**José Ignacio Plaza**
Expert EME System Engineering AIRBUS DS

**Manuel Añon**
Head of Electromagnetic Compatibility Area National Institute
of Aerospace Technology (INTA)

**Óscar Berenguer**
Expert EME System Engineering AIRBUS DS

**Pedro LLovera**
Professor Electrical Technology Institute (ITE) Polytechnic
University of Valencia (UPV)

**Salvador González**
Professor Electromagnetism and Physics of Matter Department
University of Granada (UGR)

**Viñas Quero**
Lightning Direct Effects Senior Engineer AIRBUS DS

## KEYNOTE SPEAKERS

Prof. Carmen Guerra
Dr. Franck Flourens
Dr. Christian Karch
Prof. Joan Montanyà
Prof. Kazuo Yamamoto
Dr. Ulrich Jakobus
Prof. Pedro Llovera-Segovia
Mr. Fernando Cano
Mr. José Ignacio Plaza

12 Sept

# CONFERENCE *PROGRAM*

## September 12

### OPENING *SESSION*

15:00–15:30
Auditorium
**OPENING**

15:30 – 16:00
Auditorium

### KEYNOTE 1

## DE-CARBONATION OF AVIATION, NEW MODES OF AIR TRANSPORT: DOES IT BRING NEW CHALLENGES FOR EMH AND LIGHTNING PROTECTION?

*Dr. Franck Flourens*

Lightning and ESD protection community has successfully overcome many challenges over the past two decades bringing the latest generation of air vehicles to life. One can think at the massive reliance on composite materials or the embedding of more control critical functions with complex interdependences. The question addressed in this talk is about the next chapter! What are the next significant challenges and opportunities the EMH community must be ready to face in the next two decades? The evolution of aviation platforms is dictated by the two undisputable drivers that are safety and economics. In the very last years, manufacturers started to consider a third driver, now fully part of the overall analysis of the product performances: the environmental footprint. The first way in reducing such footprint is by significantly reducing the fuel consumption, providing economic advantage at the same time. However, social pressure, at least in Western countries, and international commitments on climate change, are pushing the civil aviation industry towards radical change. This change is supported by the introduction of new technologies (e.g. electrification, hybrid propulsion, sustainable aviation fuels, H2…), new modes of operations (e.g. formation flight, predictive weather conditions…) and by doing a significant effort to ban nasty substances (e.g. cadmium plating…) and to develop bio sourced materials (e.g. composites). Amazingly, the emergence of these new technologies also allows completely new concepts of commercial aerial vehicle (VTOL, UAM…) to be developed and marketed bringing their own specific problematics. On top of those technological evolutions, the transformation of the industrial development processes enabled by massive digitalization suggests to adapt the conventional design and V&V approaches used for lightning protection taking opportunity of the new system engineering methods (Model Based, multi-partners convergence loops, multi-disciplinary optimisation methods). The overall lightning/ESD/EMH protection community must be part of this journey by first, understanding the potential implications of those changes, and then by putting in place the necessary methodological infrastructure supported by adequate standards, guidance material and simulation means. The talk will highlight a few fields of investigations and orientations by using examples for which mastering some aspects of the lightning protection or ESD or more generally speaking, E3/EMH, can become a decisive enabler.





12 Sept

16:00 – 16:30
Auditorium

### KEYNOTE 2

## A GAS DISCHARGE PHYSICS PERSPECTIVE TO LIGHTNING PROTECTION OF AIRCRAFT

*Prof. Carmen Guerra-García*

Lightning attachment to aircraft has been investigated for almost a century, and even though lightning risks are not a concern in aviation safety, as strict protection and mitigation measures are embedded in today's fleet, lightning protection is as much of as a science as an art. The state of the practice heavily relies on historical information, experience, and testing: an approach that has worked extremely well while aircraft variations have been incremental. Looking at the landscape of new aircraft, it is questionable if these methods will be directly applicable to vehicles with significantly different geometries (blended wing bodies, air-taxis); new concepts that will make electromagnetic compatibility more critical (all electric aircraft); new fuels that will introduce new constraints and thresholds when dealing with ignition safety (hydrogen aircraft); and new materials, as we continue to increase the use of composites in structural components. This contribution will argue that the lightning protection design of all these vehicles can no longer be primarily guided by prior experience, and new methods to deal with the lightning threat will need to be devised. This includes defining novel methods for assessment of the lightning threat, as well as innovations for protection and risk reduction, but also revisiting some fundamental physics of the problem. Research will be presented on (1) fundamental aspects of lightning phenomenology, including those that relate to gas discharge physics in the aircraft environment. This also includes mathematical models, advanced laser-diagnostics to determine gas discharge properties of the precursors of the lightning arc (e.g., streamer corona regimes) and wind tunnel experiments. (2) Efforts to develop physics-based models of lightning attachment to enable design by analysis, rather than having to rely on experience and testing. (3) The development of early-warning and risk reduction measures, rather than focusing exclusively on mitigation.

16:30 – 17:00
Machine's Hall
**COFFEE BREAK**

12 Sept

17:00 – 17:30
Auditorium

## KEYNOTE 3

### ELECTRIC, ATMOSPHERIC AND MICROPHYSICAL PROPERTIES OF THUNDERSTORMS PRODUCING LIGHTNING TO WIND TURBINES

*Prof. Joan Montanyà*

The evaluation of the lightning occurrence to tall objects such as wind turbines, is frequently only related to the height of the structure and the ground flash density in the area. However, this simplistic view does not consider the characteristics of the electrified thundercloud. In our previous works we have shown, by means of the Lightning Mapping Array (LMA), the interactions of lightning to wind turbines and tall structures. Contrary of what it can be thought, thunderstorms with large vertical development (convective clouds and deep convective clouds), do not pose favorable conditions for lightning to interact with wind turbines despite they produce high intra-cloud (IC) and cloud-to-ground (CG) lightning activity. In mid latitudes, most of the lightning occurrence in tall structures is in the form of upward lightning. This work will present a review of the electric, atmospheric and microphysical properties of thunderstorms favoring lightning to wind turbines and tall towers. In summary: Lightning to wind turbines or tall structures do not occur during the main thunderstorm season (case of mid latitudes). It is more frequent during transitional periods. The characteristics of these thunderstorms will be reviewed. Upward lightning, in particular self-initiated, is related to colder environments where the charge regions of the cloud are close to ground. One of the most favorable conditions for the occurrence of upward flashes appears when the melting layer (e.g. seen by the radar bright band) of the cloud is at the level or even lower than the location of the tall tower. In such case, tall objects are more exposed to the negative charge region allowing to self-initiation of upward positive leaders. We identified that downward flashes to wind turbines are produced in thunderstorms with a tripolar charge structure, but being the lowest positive charge dominant and closer to the ground compared to other convective clouds. In downward negative flashes to wind turbines or tall towers, stroke peak currents tend to be higher than the median. This is found in our research with the LMA and by direct current measurements in a tall tower in Brazil. In the tropics, two regimes of lightning to wind turbines are expected: downward flashes with high peak currents and upward flashes initiated by a nearby flash (typically +CG). We will present ground and space-based observations of lightning involving tall towers.





12 Sept

17:30 – 18:00
Auditorium

## KEYNOTE 4

### A MULTIDISCIPLINARY DESIGN APPROACH OF AIRCRAFT RADOMES

*Dr. Christian Karch*

Today's commercial aircraft and large unmanned aerial vehicles (UAVs) use a wide array of communication types to ensure safe and efficient use of controlled airspace for flight operations. These communication technologies range from human/voice radio transmissions to airborne satellite communication applications. Communication systems require a transmitter mounted on an aircraft or an UAV and use a wideband electromagnetic signal to send or receive messages to the ground or to satellites. The communication antennas are enclosed in dielectric radomes that protect the antennas from environmental impacts like wind, rain, ice, sand, UV radiation, lightning strikes and provides aerodynamic stability during the flight. Ideally, the radomes should be fully transparent to the incoming and out-going electromagnetic signals. However, the radome wall structure even made from low-lossy dielectric materials degrades the electromagnetic performance of the enclosed antennas. In addition, the lightning protection system made from solid or segmented diverter strips which is usually placed on outer radome surface can further decrease the radar antenna performance significantly. In our experience, the conventional practice to design the antenna-radome and lightning protection system separately to certain given specifications reaches its limits, since the performances of the radome structure in different disciplines are often in conflict with each other. Therefore, a multidisciplinary design approach to investigate simultaneously the radome-antenna mechanical, thermal and electromagnetic properties of the radar-antenna system is needed. The lightning strike protection constraints that are considered at the end of the conventional development phase shall be fully taken into account during the early electromagnetic design phase of the radome-antenna system. A multidisciplinary design proved and supported by experimental means can lead to optimization of the overall radome performance and ensure a high level of lightning strike protection efficiency.

18:00 – 19:30
Auditorium

EXHIBITORS PRESENTATIONS

19:30 – 21:00
Machine's Hall

WELCOME PARTY

# September 13

## SESSION 1A *LIGHTNING DIRECT EFFECTS*

9:00 – 9:20
Auditorium

### CURRENT DISTRIBUTION AND CAPABILITY ON CARBON FIBRE COMPOSITE MATERIALS, COPPER FOIL AND FASTENERS

*Valentín García Martínez, Agustín Alcaide Fernández, Óscar Berenguer Monge and Guadalupe Gutiérrez Gutiérrez*

This article explores (1) how to carry electrical currents on the CFRP structure using non-bolted metallic conductors, (2) the current capability of a fastened junction between an element representing an A/C skin (CFRP+ECF) and a metallic element representing an A/C frame and (3) how the AC is distributed in the presence of fasteners. For all cases (1)/(2)/(3), tests were carried out; additionally, in case (3) simulations were also performed. Precisely, in each (1)/(2)/(3) case, following use case were tested: (1) Transferring currents in the internal CFRP structure: Use of co-cured metallic strips and use of co-cured and co-bonded copper foil. (2) Current capability of the skin: Dimple washers, additional copper foil strip, copper foil overlapping and sealant. (3) Current distribution: A test varying the frequency of the AC from 50 to 5000 Hz was performed. Following relevant magnitudes were recorded in the junctions during the tests: Electrical resistance, thermal elevation for a permanent injection current, thermal elevation for a sudden injection of current and current distribution among the fasteners. Furthermore, in case (3), simulations have been performed in order to analyze the behavior of the current distribution in the bolts. The simulated model represents the fastened junction between the skin (metal or CFRP) and a metallic frame, with a cable running parallel to the skin and perpendicular to the frame. A current is injected in the cable to the metallic frame and extracted through the skin.

9:20 – 9:40
Auditorium

### DEVELOPMENT OF A TECHNIQUE TO MEASURE VOLTAGES ON CFRP SURFACES DURING LIGHTNING DIRECT EFFECTS TESTING

*Aysh Yapa, Simon Evan and Timothy Jackson*

This paper demonstrates the successful development of an easy-to-implement technique for measuring voltages on Carbon Fibre Reinforced Plastic (CFRP) surfaces during Lightning Direct Effects (LDE) testing, with careful management of two key aspects - control of electromagnetic interference and electrical contact with the CFRP surface. The work verified that careful minimisation of the size of voltage measurement loops effectively rendered inductive coupling to a negligible level. Readily available off-the-shelf oscilloscope probes were proven to be a suitable choice, provided that a simple digital Low-pass Filter (LPF) was used to remove high-frequency noise from measurements. An epoxy-based method of attaching measurement electrodes to exposed carbon fibres on the CFRP surface was demonstrated to be a suitable choice for both DC and lightning strike testing, whereas a screw-based method was found to be suitable only for DC testing. Simple resin abrasion using emery paper, a milling machine, and a multimeter to determine the point of fibre exposure was demonstrated to be effective to make electrical contact with the surface carbon fibres.

9:40 – 10:00
Auditorium

### ANALYSIS OF LIGHTNING CURRENT DISTRIBUTION IN THE JOINTS OF A CARBON FIBER COMPOSITE APPLIED TO AN AIRCRAFT

*Renan H. de Moraes Callegari, Jose Pissolato Filho and Ricardo A. de Araujo*

The analysis and studies of the effects on aircraft by lightning strikes allow the aerospace industry has valuable information about the phenomenon, reducing damage and guaranteeing a safe flight. However, as it is a random behaviour event, in terms of intensity, the number of discharges, and coupling modes, the subject still offers a wide field of research. The discharge usually strikes one extremity of the aircraft and steps out at the other; these points are generally the wingtips, the plane's nose, or the empennage's end. For this reason, any material used in the aircraft structure must safely conduct electrical currents from lightning from the point of impact. Thus, the carbon composites used in the external construction of the aircraft must allow adequate electrical current paths between parts of the structure, minimizing damage to joints and especially preventing the formation of arcing or sparks.

10:00 – 10:20
Auditorium

### INFLUENCE OF DISCHARGE ELECTRODE SHAPE ON LIGHTNING TEST OF COMPOSITE LAMINATE

*Yoshiyasu Hirano, Takeo Sonehara and Toshio Ogasawara*

In this study, an experimental investigation was conducted to elucidate how the electrode difference affect the mechanical loads generated by the impulse lightning current and the damage behaviour of the composite laminate in simulated lightning tests. Arc entry lightning test using a jet diverting electrode and three types of round tip electrodes with different tip diameters was performed using an impulse current generator (ICG). The deformation response of the back surface of the specimen was measured by the 3D DIC analysis using pair of high-speed

cameras, and the effect of the electrode shape on the deformation behaviour of the CFRP specimen was investigated. The resultant internal damage of the specimen was assessed with ultrasonic C-scanning. The specimens were quasiisotropic laminates made of IMS60/#133 prepreg and were compared under two conditions: with and without LSP protection. The specimen surface was coated with epoxy primer and polyurethane enamel paint. No internal damage was observed in the protected laminate, while significant delamination damage was observed in the non-protected laminate. The results of the displacement response analyzed by the DIC suggest that the use of a jet diverter is effective in reducing the mechanical load due to the impulse current, and that the difference in tip diameter for the round tip electrode may not have any effect on the difference in mechanical load. On the other hand, no clear difference was observed in the deformation behaviour of the non-protected laminate specimens regardless of the electrode used. It is possible that the gasification and ejection of matrix resin generated when the CFRP laminate is damaged has a greater effect on specimen deformation response than the mechanical loading caused by the impulse current. On the other hand, the difference in electrode shape affected the shape of specimen internal damage, suggesting that the difference in electrode shape may affect the arc root development behaviour and current penetration inside the specimen.

10:20 – 10:40
Auditorium

## LIGHTNING-INDUCED DEGRADATION OF FASTENED COMPOSITE SYSTEMS

*Louisa Michael, Derek R. Tuck, Philipp A. Boettcher, Brian P. Justusson and Brian A. Carpenter*

Aerospace composite laminate construction is widely used in various airframe components. Composite structures are often joined with other structure and substructure via fasteners that are inevitably exposed to lightning strike currents. The interaction of a lightning strike with a fastener can lead, through complex electrical, mechanical, and thermochemical processes, to the degradation of the strength of the fastened structure. Although degradation can often be seen on the surface as damage via paint discoloration, surface ablation, or surface delamination, a larger subsurface volume of material might be affected by the electrical current and thermo-chemical processes resulting in a heat affected zone and multi-planar delamination. Together, these effects have the potential to degrade the structural performance of the joint. In this work, a series of electro-mechanical tests is performed in order to evaluate the effect of lightning strikes of varying amplitudes on structural composite. The experimental methodology includes subjecting a single-fastener aerospace-composite lap joint to scaled A-waveform electric current pulses to determine the combined electromagnetic and structural effect on the system. Following the electrical test, the tested articles undergo a non-destructive inspection to quantify the extent of the damage, from which the relation between heat-affected zones extents and current levels is given. Finally, electrically-tested articles undergo a bearing test and the structural effect of the lightning strike on the structural properties of the fastened system is determined and implications on composite structural performance is assessed.





## SESSION 1B *LIGHTNING EFFECTS ON WIND TURBINES*

9:00 – 9:20
Room C

## A NEW COATING FOR REDUCING WIND TURBINE BLADE LIGHTNING DAMAGE

*Christopher Szlatenyi, Adam Janik, Pascal Mickelson, John Cooney, Neal Fine, Andy Plumer, Edson Montrond and Patrick Mytinger*

A novel wind turbine blade coating has been developed that reduces lightning damage to the blades. It enhances the effectiveness of existing lightning protection systems comprised of a down conductor and one or more surface mounted lightning receptors. It can be applied as a retrofit to existing turbines or applied to new blades. The coating consists of small discrete conductive elements that locally enhance the electric field in the air above the elements to promote the early formation of a surface flashover. This helps leaders emanating from the existing receptors travel faster and farther over the blade surface to connect with the downward stepped leader from the clouds before competing streamers that originate from the blade's interior have a chance to puncture through the skin and cause damage. A key feature of the coating is that it is does not provide a conductive pathway for the strike. Rather, it enables a conductive channel of ionized air adjacent to and above the surface. This non-sacrificial operation allows the coating to remain effective and undamaged even after multiple strikes. The coating was empirically developed over the past three years using extensive small-scale and large-scale high voltage and high current testing. The first phase consisted of testing flashovers across small samples up to 100 mm in length with voltages up to 70 kV. Subsequent optimization used 610 mm square panels combined with a 2-meter air gap in a high voltage lab capable of reaching 2.4 MV. The material, size, shape, and concentration of the elements in the coating were carefully optimized to a narrow range of parameters found to be most effective. In the final formulation, the metric of average flashover time was reduced, on average, by 76% compared to a baseline topcoat. The coating's mechanical performance was also tested to ensure the improved lightning protection does not come at the expense of the other functions a topcoat is designed to perform. Photos demonstrate the desired increase in streamer and leader activity around the lightning receptor with the coating. Excellent damage resistance was verified with full-scale currents

up to 200 kA. Finally, the coating was validated with IEC standard initial leader attachment tests on GE 1.5sle wind turbine blade tips 5 meters in length. Results showed a significant increase in the level of protection with the coating properly applied compared to a blade without the coating. Field tests are scheduled on multiple turbines at two operational wind farms beginning in the summer of 2022.

9:20 – 9:40
Room C

## INVESTIGATION OF WEATHER CONDITIONS LEADING TO DIFFERENT TYPES OF LIGHTNING STRIKES MEASURED IN WIND TURBINE BLADES

*Javier López, Stephan Vogel, Lisa Carloni and Søren F. Madsen*

The growing demand for sustainable energy has triggered the constant development of taller wind turbines with longer blades. The exposure of larger wind turbines to lightning is unquestionable, no matter if it is onshore or offshore installations. Since lightning damages are still one of the largest drivers of downtime and repair cost, understanding lightning exposure, and the protection strategies for mitigating damages, is key for lowering the Levelized Cost of Energy. Lightning exposure is partly related to the overall lightning activity of an area, but also to the orography and weather conditions, specifically the relative distance of the wind turbines to the thunderclouds and the direction of approach of thunderstorms. Under certain conditions tall structures can trigger the inception of upward lightning from the structures. This paper presents an analysis of four wind power sites and the weather conditions during storms that affected the wind turbines with direct lightning strikes to the blades. The lightning measurements have been performed directly in the wind turbine blades by an appropriate lightning measuring system (Certified to Annex L of IEC 61400-24 for Local active lightning detection systems). This work unveils how different types of meteorological conditions and terrain topography lead to different types of lightning. A better understanding of how exposure relates to the local weather in the installation area is a key factor to improve the input for the blade design processes, to perform root cause analysis of damages due to lightning and to schedule operations onsite improving cost and performance.

10:00 – 10:20
Room C

## WIND TURBINE BLADE LPS DESIGN PROCESS REVISITED – LEVERAGING ON LATEST KNOWLEDGE FROM ACTUAL LIGHTNING MEASUREMENTS IN WIND TURBINES

*Søren F. Madsen, Stephan Vogel, Javier Lopez and Lisa Carloni*

The present paper addresses some recent lightning measurements in actual wind turbines, to demonstrate the amount of data that is currently collected, and the information provided. Basic statistical analysis is conducted on the 1125 lightning waveforms obtained, and the implications on design and verification processes for blades are suggested. Some reflections on the increased industry openness are shared, which is already benefitting the general understanding of lightning exposure, and the future standards on the topic.

10:20 – 10:40
Room C

## ENHANCED LIGHTNING PROTECTION FOR WIND TURBINE BLADES (REVISITED 2022)

*Billy Martin, Brock Milford, Rob Gerlach and Harlan Sharpe*

Lightning strikes continue to be an extremely perplexing problem to the wind turbine industry as the industry expands into more areas of the world where environmental conditions can be extremely destructive and therefore expensive. Adding to the issue is the fact that the turbine blades continue to increase in size and complexity, both in aerodynamic shape and advanced material composition. A short review of data available on the internet shows that the impact to the industry accounts for hundreds of thousands of dollars yearly. Of course, this damage is not just limited to the wind turbine blade itself, but typically is the focus of the lightning protection system. This has been shown to be the more difficult aspect of the lightning strike problem. There can also be considerable damage to the control system and electrical components but means of protection are generally easier to incorporate if the protection of the blade itself is incorporated properly. The wind turbine industry has recognized the need for lightning protection from the early days of the deployment of the turbines in the field. As such, a standard has been developed (IEC 61400-24) that provides guidance on lightning certification and testing. Though protection schemes have evolved in their effectiveness, the existing lightning protection systems still often are unable to safely and effectively transfer the lightning current, resulting in considerable damage to the blades and control systems. This damage often causes deactivation of the turbine until the damaged components are repaired or replaced. It should be noted that lightning is “different” in different parts of the world. Strikes in the North Sea occur less often but of higher amplitude than in the panhandle of Texas, for example. Though there are no exact numbers, and depending upon multiple factors, such as location (i.e., turbines in the Mid-West may get struck more than those in the Northeast), turbines can generally be expected to be struck by lightning once a year. In some cases, turbines are struck multiple times in a single storm event. In accordance with Y. Wang and W. Hu: 1) Lightning strike damage accounts for 23.4% of wind turbine failures, 2) Blades are the most vulnerable components, which show the highest frequency, highest repair cost, and longest downtime of approximately 10 days per lightning incident. In 2017, researchers at Wichita State University

began the development of an enhanced multi-layer covering to protect turbine blade surfaces from consecutive lightning strikes. The research resulted in the application of patent and licensing of the product for tech transfer to commercialize the product. In addition, field trails were begun in 2018 and documented in an ICOLSE paper in 2019. The research has continued, and the design finalized. Additional field trails began in 2021 and have continued in 2022. These field trails have resulted in the final development of the installation techniques, which are much more streamlined and economical than the initial procedures. More importantly, they have shown the ability to be easily customized to the various blade designs that are deployed around the world. In addition, the turbine blades that have been included in the field trails, which are in the Texas panhandle, have been struck by several individual lightning strikes of various amplitudes. In each case, they have shown the successful ability of the product to transfer the lightning current to the existing lightning protection scheme without any damage to the turbine blade. This paper will revisit the design changes that have been incorporated into the original multi-layer covering that offers enhanced capability of the existing lightning protection scheme of the turbine, testing which has been accomplished, (both in the lab and in the field), along with any further testing planned in the future.

10:45 – 11:15
Machine's Hall
COFFEE BREAK

## SESSION 2A *NUMERICAL MODELING AND ANALYSIS 1*

11:20 – 11:40
Auditorium

### NUMERICAL ANALYSIS OF LIGHTNING INDUCED TRANSIENTS IN ELECTRO-ELECTRONIC SYSTEMS INTERFACING AN EXTERNALLY MOUNTED SENSOR

*Diego Faria Amaral, José Antônio de Souza Mariano, Lollan Naru Nonaka and Sidney Osses Nunes*

This paper describes a computer analysis developed to evaluate the expected lightning induced transients in a critical aircraft equipment interfacing an externally mounted sensor subject to a direct lightning attachment. At first, a discussion of the coupling mechanism in a metal airframe is presented. Once it is established an understanding of the coupling process, by modeling and testing a metal airframe, the article progresses to the evaluation of a case where the skin material is replaced by a quasi-isotropic carbon fiber composite laminate. Finally, it was also investigated the effects of the inclusion of a metal strip, to divert the current from the cabling, and the addition of cable raceways in the composite





mounted installation. The results found for lightning induced transients, in each different proposed installation, provided valuable comparative effects expected for each airframe construction design and an indication of the level of protection to be considered for each respective system application.

11:40 – 12:00
Auditorium

### PREDICTION OF LIGHTNING STRIKE-INDUCED DAMAGE OF COMPOSITE AIRCRAFT STRUCTURES

*Albertino Arteiro, João Pedro and Christian Karch*

The present study provides a short overview of the aircraft lightning strike phenomenon as well as a modelling and simulation approach for lightning-induced damage of protected CFRP structures. The intra-laminar and inter-laminar lightning-induced damage and the mechanical response of protected CFRP structures are numerically calculated. Structural FE calculations are performed using the commercial software Abaqus/Explicit. The progressive damage analysis, including inter-laminar damage simulation by means of a cohesive zone formulation at the interface between UD CFRP plies, is used to assess the effect of damage on the response of the CFRP laminates subjected to lightning strike loads. It is shown that taking damage mechanics into account is essential in the representation of the dynamic response of the laminated CFRP plate subjected to a transient lightning strike event. The obtained numerical results using the developed numerical approach agree well with experimental data and provide a new insight on the physics of lightning-induced damage of protected CFRP structures subjected to a lightning strike.

12:00 – 12:20
Auditorium

### SHOCK WAVES FROM A LIGHTNING DISCHARGE

*Robert Honke and Christian Karch*

The analytical and numerical analysis of lightning direct effects on composite structures has mainly been focused on thermo-electric effects of different lightning current components. Mechanical forces created by the electric current flow, by blasting of materials (epoxy resin, metallic protection, coatings) or by shock waves caused by a supersonic expansion of the plasma channel have rarely been taken into account so far. The objective of this paper is a description of lightning shock waves caused by a rapid temperature rise of the lightning plasma channel due to resistive Joule heating. In this context it is first of all necessary to understand the underlying physical mechanisms of this effect. Furthermore, theoretical models for the interpretation of experimental tests as well as for reliable prediction of the magnitude of the shock wave pressure pulses have to be provided. Finally, the temporal and spatial propagation of the shockwaves and pressures that are needed as input for the simulation of mechanical damage

prediction of composite structures are derived from semi-analytical and numerical CFD computations. It is shown that the strong shockwave approximation, which provides reliable results for the very early stage of shock wave formation, is perfectly adequate to correctly describe the mechanical damage of composite structures.

12:20 – 12:40
Auditorium

## LIGHTNING SIMULATION VERSUS DCI TECHNIQUE APPLIED TO LIGHTNING PHENOMENON

*Guadalupe Gutiérrez, Raúl Molero, Hugo Tavares, Hirahi Galindo, Enrique Pascual and Salvador González*

The Direct Current Injection (DCI) technique is a complex method which involves both a testing campaign and electromagnetic (EM) simulations. Consequently, it takes a long time, carries many costs, and requires a lot of effort in a complicated post-process. The present paper shows that only with the lightning simulations, also involved in the DCI process, similar and useful information can be obtained. The test case consists of an aircraft cockpit manufactured as a hybrid structure composed of metal, carbon fibre composite and expanded copper foil. It is equipped with a realistic electrical installation including seven metal boxes as dummy equipment and two over-braided harnesses with several inner conductors. This cockpit is used to perform the validation of a lightning simulation compared with measurements using DCI technique post-processed to be applied to a lightning threat. To this end, a low-level DCI test has been carried out on the cockpit, and the results have been post-processed so as to introduce the in-flight versus on-ground correction factor and transform them into time domain responses to a full lightning stroke. On the other hand, the same lightning simulation required to obtain the correction factor has been used to calculate the currents induced on the cabling. Good agreement has been achieved between lightning simulations and post-processed DCI technique considering a margin which takes into account the difference between two measurements of the same observable. Deviations obtained are explained making use of images of surface current distribution which can be obtained from simulations. Thus, the validity of these lightning simulations within the established margin is demonstrated, and we can conclude that lightning simulations performed with representative EM models can be reliably used to detect problematic cable routes or equipment locations in order to implement suitable solutions. This example illustrates the benefits of using EM simulations in order to reduce costs and time to deliver, and also their potential benefit in improving the aircraft safety by using them from the earlier stages of the design to the end of service of the aircraft, by predicting the behaviour of the object in configurations which could not be addressed by test, and by checking a larger number of probes, which could even be placed in non-accessible areas.





12:40 – 13:00
Auditorium

## INFLUENCE OF SPECIMEN SIZE ON DAMAGE REGION PREDICTION IN NUMERICAL MODELLING OF CFRP PANELS EXPOSED TO LIGHTNING STRIKE

*Cien Xiao, Minqi Xie, Zeyang Zhao, Jiapeng Bian, Yin Fan, Xiuhua Chen and Yakun Liu*

Carbon Fibre Reinforced Polymer (CFRP) composites have been widely used in lightning-prone systems, such as aircraft, wind turbines etc. A valid modelling of the damage response of CFRPs subjected to lightning strikes is of importance to understand the complex mechanisms and offer essential guidance in the design of lightning protection. In this study, we find that the damage response of CFRPs to lighting strikes is influenced by the specimen size configured in the modelling. Different ratios in the length/width of specimen change the thermal budget injected to different laminates of CFRPs and regulate the thermal damage behaviours. The damage progression in CFRPs is mainly governed by the pronounced orthotropic properties of the laminates. When the ratio is close to 1, the damage regions of CFRPs tend to be centralized at the arc attachment and show milder damage area but severer damage depth compared to other ratios. The finding helps diminish the misinterpretation in the numerical modelling of damage prediction of CFRPs to lightning strikes.

# SESSION 2B *LIGHTNING STANDARDS AND SAFETY*

11:20 – 11:40
Room C

## IMPROVEMENTS IN LIGHTNING HIGH VOLTAGE TESTING

*Prof. Chris C. R. Jones, Dr. Simeon J Earl, Dr Ana Vukovic and Prof. Phillip Sewell*

High voltage tests for lightning protection evaluation are quite hard to do well. Though Mil-Std-1757A is now obsolete, it is still quite widely used as a source of test methods, and more recent standards (Mil-Std-464 and ED84/ARP5412) have merely copied significant parts of the high voltage test descriptions from Mil-Std-1757A (i.e. the waveform specifications). Recent HV tests to a radome have highlighted a number of deficiencies and oddities in the available specifications which are discussed in this paper. These include the specification of which waveform is appropriate for specific tests and the importance of establishing the actual puncture strength of the test article to ensure the test to a real article is valid. Other issues discussed include how the design of test electrodes affect the field strength on the test object and the growth of streamers, and the exposure of tested dielectrics to repeated high electric fields. Recommendations are then made on how the specifications and standards should be modified to address the issues raised, and on research work that is needed to better understand how good replication of the natural condition might be accomplished.

11:40 – 12:00
Room C

## HIGH VOLTAGE TEST FOR A RESEARCH OF REDUCING THE NUMBER OF AIRCRAFT LIGHTNING STRIKE

*Hiroyuki Tsubata, Takayuki Nishi, Hiromitsu Miyaki, Shintaro Kamiyama and Takao Okada*

Most of lightning strikes to aircrafts are thought to be triggered by the aircraft itself. When an aircraft flies near thunderclouds, leaders are formed from a local concentration of electric field on the surface of the aircraft, and one of the leaders connects to a leader that comes from thunderclouds, and then the high lightning current flows through the aircraft. The Japan Aerospace Exploration Agency (JAXA) and SUBARU focus on this leader initiation and are seeking the way to reduce the frequency of aircraft lightning. High voltage impulse discharge tests were conducted for a simple shape and an aircraft shape. Both are made from aluminium. Those were suspended in the air under a relatively wide electrode (1200mm) with a 600-800mm gap to the ground. In general, if the discharge gap is too short, leaders won't be appeared, so that the setting of the size was considered enough to observe the leaders that propagates from the specimens. Also, uniform electric fields with Rogowski shaped electrode was used to prevent that the leaders from the electrode appear quicker than that of the specimen. Even though the results obtained in the laboratory can't be applied directly to the natural lightning to an aircraft in flight, this experiment was worth enough to realize the basic patterns of discharge phenomena of a floating object. Two still cameras and a high-speed video camera was used to observe those discharges, and the detail sequence of how the leader was formed and growing and turned into a flashover was observed. The up-and-down method was used to estimate 50% flashover voltage, and there was a significant difference depending on the combination of the body shape, attitude, the electrical charge to the body and electrodes' polarity. The results show that the body shape, the body attitude, and the electrical charge to the body were playing the important role for a breakdown.

12:00 – 12:20
Room C

## EXPERIMENTAL STUDIES OF THE SWEEPING OF LIGHTNING ARCS ALONG AN AERONAUTICAL MATERIAL AND THE ARC REATTACHMENT PHENOMENON

*Rafael Sousa, Vincent Andraud, Clement Zaepffel and Philippe Lalande*

In this work, we describe the realization of an original facility allowing the experimental investigation of the sweeping of lightning arcs on aeronautical materials. The study is composed of three main parts. First, we present the current generator able to create electric arcs up to 1.5 m long





respecting the C-waveform standards. This involves the development of a DC-to-DC converter and the use of an initial charging voltage not exceeding 2.5 kV. The second step is to create the relative motion between the electric arc and the aeronautical test sample. For this purpose, two approaches are studied and tested. First, we develop a dedicated low voltage electromagnetic (EM) launcher based on a railgun technology, able to propel samples of 150 g up to 80 m/s. A second approach, using an open-section wind tunnel, is performed to create an external airflow on the arc column, leading to the relative motion between arc and electrode. The flow in the wind tunnel can reach 80 m/s. The last part of the paper is dedicated to the coupling of the long electric arc with the aeronautical sample in a relative motion condition. We present preliminary results of a test campaign using an aeronautical aluminum NACA 0012 profile while varying some key parameters such as current level, sample length, speed and polarity. The effect of these parameters in the arc root dynamics, the dwell time and the reattachment process is presented and discussed. Finally, we highlight the similarities and differences in the two displacement approaches.

12:20 – 12:40
Room C

## METHODOLOGY AND DETECTION OF LIGHTNING STRIKES IN DOWN-CONDUCTORS VIA SIGFOX NETWORK

*Jan Mikeš and Pavel Ková*

Lightning poses a risk to buildings, people, and technical equipment. The lightning air-terminal and down-conductor are the basic protection against direct lightning discharge. From the point of view of the reliable function of the lightning conductor, the key is to monitor the passage of the lightning current through the lightning conductors and to inform the building manager in real-time so that he can carry out the appropriate checks. We will present a system for contactless monitoring of lightning attacks, and experimental results with the testing by the lightning impulse current generator (LICG). Finally, we present an IoT system for large-scale monitoring.

12:40 – 13:00
Room C

## NOISE REDUCTION IN ACTUAL TRANSIENT MEASUREMENT OF AIRCRAFT LIGHTNING TESTING BY UTILIZING COMPONENT A GENERATOR WITH A SEMICONDUCTOR SWITCH

*Taro Ito, Keisuke Kawamura, Yoshifumi Ikeda, Seiichi Kawasaki, Yoichi Nakai and Hideo Yamakoshi*

A semiconductor switch is employed in Component A generator instead of conventional mechanical switch in aircraft lightning actual transient test. One order of magnitude noise reduction is observed in open circuit voltage responses. Causes of the

noises are discussed. Electro-magnetic (EM) shielding at both ends of cables under test becomes unnecessary in most cases for Component A measurements with introduction of the semiconductor switch. Simple shielding for Component H measurements is developed considering frequency range and levels of noises associated with the Component H responses. The semiconductor switch of the generator shows durability through three thousand shots of operation.

13:05 – 15:00
Machine's Hall
LUNCH

14:30 – 15:00
Auditorium
EXHIBITORS PRESENTATIONS

TECHNICAL TOUR

15:00 – 18:00
LCOE

## September 14

### SESSION 3A *LIGHTNING INDIRECT EFFECTS AND ZONING*

9:00 – 9:20
Auditorium

### RESEARCH ON LIGHTING PROTECTION OF HEAVY HELICOPTER

*Shaodong Zhang and Ting Hu*

In order to reduce the weight of heavy helicopters, composite materials are widely used. The composite has high fatigue resistance and corrosion resistance. On the premise of meeting the structural strength of the body, its structural weight coefficient can be reduced to less than 30%. However, the introduction of composite materials into the helicopter body structure brings the special problem of lightning hazard. Lightning strike has direct and indirect impact on helicopter. The direct impact of lightning stroke mainly includes the following two aspects. One is that the communication antenna exposed outside the fuselage is often damaged by lightning, resulting in communication system failure. On the other hand, the electrical conductivity of composites is poor, so it is difficult to conduct the current in a short time when lightning strikes. When the temperature rises sharply, the composites are deeply stratified or severely ablated, resulting in structural damage. In terms of indirect impact, the high voltage and strong current generated by lightning strike will cause damage to helicopter systems, magnetization of individual helicopter components and interference to electronic equipment. Under low protection or no protection device, it may cause permanent damage to the helicopter and affect the normal operation of the system. Even worse, it may cause disastrous consequences. The lightning attack accident of Mi-26, the biggest heavy helicopter in the world, was studied in the article. The direct effect of the attack was that the trailing edge of tail rotor and glass reinforced plastic pipe girder were detached by the sheering force and centrifugal force, which made the hammer brace unbalanced with a physical tearing of about 1m as the secondary damage. In order to investigate the cause of lightning stroke accident of Mi-26 helicopter, the 3D model of Mi-26 helicopter is established. The TLM (transmission line matrix method) of MS studio of CST is used to simulate and analyze the surface current distribution and internal electric field distribution when a specific lightning stroke path hits the tail rotor of Mi-26 helicopter. The analysis shows that when lightning strikes the composite structure, it leads to structural failure or large-area damage. Based on the guidance and standards of DOT / FAA / CT-89 / 22 and the interim defense standard 59-113 of the British MoD, several improvement measures are given. Typical lightning protection included adding wire and wire netting to the structure's surface which has possibility of direct lightning adherence.







9:20 – 9:40
Auditorium

### DETERMINATION OF LIGHTNING INDUCED EFFECTS IN AERONAUTIC SYSTEMS BY ANALYTICAL FORMULATION

*Y. Corredores, L. Pniak, P-E Levy, S. Lallechere and F. de Daran*

When a lightning strike reaches aircrafts, we can observe two different effects: (i) mechanical and thermal constraints in the structure (direct effects); (ii) undesired currents and voltages on harness and equipment induced by lightning current circulating on the structure (indirect effects). The increase in the number of electric systems in aircrafts makes it critical to predict and evaluate indirect effects to ensure safety and system availability. In order to specify the system protections, lightning tests would be the most relevant method to estimate undesired currents and voltages. Nevertheless, experimental tests are expensive, time consuming and require the exact system topology to be representative. In this framework, numerical simulations can also predict indirect effects. In order to perform them, several software based on diverse methods (e.g., Finite Difference in Time Domain (FDTD), Method of Moment (MoM), Finite Element (FE), Partial Element Equivalent Circuit (PEEC) are used. For large and complex structures, mesh must be small enough compared to the wavelength (100 MHz, ~3 m) leading to a noticeable simulation time and computing resources. Most of the time, some

design choices (e.g., harness routing and ground connections) are achieved at system level without been optimized by simulation. Due to their computing costs (mostly time and memory here); simulations are usually scheduled at the end of the system design, just before certification phase. Therefore, Safran Tech investigates fast and accurate simulation tools to help designers take relevant decisions at system level at early stage in the design process. PEEC method is particularly interesting for the first part of a system definition. It readily provides an equivalent electric circuit representing the structure, harness and equipment. Considering the lightning wavelength and dimensions of the structure, a surface formulation of the PEEC method is preferred. The definition of the equivalent electrical circuit requires the calculation of the (N×N) impedance matrix of the modeled structure (assuming N unknown equivalent electrical parameters). Conventional PEEC methods solves equation numerically, meaning the equation is resolved through numerical approaches. For a few dozen of surfaces, the calculation is fast enough (~ ms) but an increase in the surface number N leads to an exponential increase in simulation time and computing resources, wasting PEEC advantages over the other methods. First, this paper will present the progress for fast and strict simulations with an original implementation of the PEEC method (namely Surface PEEC, S-PEEC). Further, we will demonstrate the ability of the proposed methodology to assess the current distribution and coupling effects in canonical structures subject to a lightning strike.

9:40 – 10:00
Auditorium

## CORRELATION BETWEEN HIGH-LEVEL AND LOW-LEVEL TRANSFER FUNCTIONS OF INDUCED LIGHTNING STRIKE TESTING

*Hugo Tavares, Roger Farias, Fernando Cano, Guadalupe Gutiérrez, Raúl Molero and Ángel Ramírez*

There are a variety of different tests which can be carried out in order to evaluate the potential effects of a lightning event to an aircraft. High-level current tests are generally useful for assessing the actual damage on structures, meanwhile low level tests are the common approach for establishing the transfer functions of the external environment applied on the component to the internal environment resulting on systems. In this paper we compare the results obtained in a high level lightning strike testing campaign with the results coming from a low level direct current injection testing campaign both carried out on the same aircraft hybrid cockpit (CFC/metal). The tests results are complemented/compared with simulation activities. Additionally, ad-hoc test set-up were manufactured for each test campaigns and are analysed also in this paper.





10:00 – 10:20
Auditorium

## EVOLUTION OF THE LIGHTNING ZONING GUIDELINE AND COMING CHALLENGES FOR LIGHTNING PROTECTIONS OF UNCONVENTIONAL PLATFORMS

*Sonia Zehar, Marc Meyer, Bernard Tagliana and Ivan Revel*

The lightning zoning is a cornerstone in the upstream lightning hazards analysis, in the purpose to define the threat at rotorcraft and at system levels, for both lightning direct and indirect effects. From 2014 to 2018, the regulatory working groups SAE-AE-2 and EUROCAE WG31 have reviewed the lightning zoning document. A new issue was released (ED-91A or ARP5414B), as the result of the analysis of in-service experience (location and type of damage and failures), and leading to a better adaptation of the standard to the reality for the various types of aircraft including rotorcraft. This zoning of rotorcraft was a common work between five Helicopters manufacturers based on an initial proposal of Airbus. The main modification consists in the suppression of the lightning zone 2 (high probability of sweeping strike) of the airframe and of the zone 1 (high probability of attachment) on the nose. As the airframe is mainly in zone 3 (low probability of attachment), there is a need to consider the local effect of the protrusions (antennas, FLIR cameras…) on the zoning, and the possible creation of local zones 3 direct attachment (peak up to 40KA) or zone 1 (peak up to 200 KA). That work shows consequently the need to have a prediction tool to support the assessment of the local threat, and in particular to evaluate the effect of protrusions on the attachment risk. This is mentioned in ED-91A/ ARP5414B that there is a need of validation. Such an activity is obviously essential for new shapes as VTOL with multi-rotor configurations for which experience is rather absent. Existing electromagnetic tools can be used, but still need validation for a better prediction. The final goal would be to have a validated mean of compliance or at least as an intermediate step a help for the design of protections and the certification phases. The first part of the paper provides an overview in terms of in service experience and zoning tool based on Airbus experience. The second part reports the results obtained on a complete Helicopter with the Airbus electromagnetic numerical tool for primary attachment locations prediction, the limitations of such a prediction tool and the recommendations in terms of utilization of the tool and associated protection policy.

10:20 – 10:40
Auditorium

## COMPUTATIONAL ZONING OF UNCONVENTIONAL AIRCRAFT

*S Austin, C Guerra-Garcia and J Peraire*

The protection of aircraft from lightning strikes, both triggered and intercepted,

is an essential component in the aircraft development and certification process. In the past, lighting strikes to aircraft have caused catastrophic accidents that have promoted extensive studies into the mechanisms behind lightning events and their mitigation strategies. These recommendations have led to protective measures in the form of wire mesh and diverter strips on nonmetallic surfaces, removing sources of spark-triggered ignition in the fuel system, adequate grounding and wire bundle shielding strategies, and route management to avoid thunderstorms. While significant progress has been made in aircraft lighting protection, much of what we know about aircraft triggered lightning comes from historical experience and testing. Next generation aircraft designs may not conform to the same assumptions under which models for existing aircraft are valid. We present a general computational tool for the prediction of the first and second attachment points on arbitrary aircraft geometries. The tool couples numerical electrostatics simulation to a predictive attachment model, and uses open source software which is freely available. The attachment model follows similar methods developed by Onera and the University of Padova in the 1990s, but accounts for both positive and negative first leader inception. Additionally, a feature to determine the optimal aircraft charge has been incorporated into the tool, following prior work by our team on triggered-lightning risk-reduction measures. The tool will be demonstrated by application to the MIT D8 “Double Bubble” aircraft.

## SESSION 3B
## *ELECTROSTATICS*

9:00 – 9:20
Room C

### ELECTRIFIED ICE NEEDLES FAST FORMATION UNDER THE INFLUENCE OF ELECTRIC FIELDS

*Leandra P. Santos, André Galembeck and Fernando Galembeck*

Atmospheric electricity formation and storage occur in humid air under pressure and temperature gradients, producing the electric fields that trigger lightning. Many authors discussed the relevant events and mechanisms delivering atmospheric electrification, but a comprehensive picture has not yet emerged. This work describes experimental and theoretical results on the effect of electric fields on water vapor, evidencing the positive feedback between electricity and water vapor condensation progress. Vapor condensation under a field produces electrified needles and dendrites under conditions relevant to the formation of atmospheric electricity. Two new findings explain the enhancement of vapor condensation under a field due to the decrease or elimination of the energy barrier of the nucleation of the condensed phase. Water vapor clusters acquire charge under the electric field, thus decreasing the surface tension of water and ice nuclei and thus enhancing nuclei formation and growth rates, following the Classical Nucleation Theory (CNT). Beyond, new experimental evidence shows the participation of a nonclassical (NC) phase-separation mechanism triggered by the electric field. The two agents produce needle-shaped ice that is not the prevalent crystal habit. Increasing the rates of phase change also increases the rate of electrification in any environment; following discoveries initiated by Volta and Lord Armstrong long ago and later verified by other authors that observed spontaneously electrified ice jumping in different contexts, the excess charge of partially condensed steam exiting vapor turbines or of water evaporating or condensing at metallic surfaces, growing as an active research area. The Maxwell-Wagner-Sillars effect predicts that any isolated droplet of water, ice crystal, or aerosol particle within the atmosphere should always carry a charge since it is under a non-zero electric potential gradient. An additional factor is the lower binding energy of H+ ions at water or ice surfaces than OH–. Beyond water, non-polar substances like carnauba wax and naphthalene also undergo electrification during freezing. On the practical side, some industries currently explore the electro-freezing effect. The present work adds new experimental and theoretical results to an already large but dispersed body of information showing how electrification and phase change feedback mutually, to the point of provoking Coulomb explosions.







9:20 – 9:40
Room C

### ESD THREAT AT TANKER RECEIVER CONTACT PHASE DURING AIR-TO-AIR REFUELLING OPERATIONS – OVERVIEW AND KEY TEST ASPECTS

*Fernando Cano, Carlos Prieto, David García and Agustín Alcaide*

During an aircraft flight, the electrostatic charge on it is built up by means of different charging mechanisms: aircraft internally generated charge (engine exhaust…), induced charge redistribution and precipitated charge generated in the aircraft interaction with the external atmosphere. The electric charge accumulation and the associated eventual discharging processes can be source of several problems such as RF noise on radio receivers, generation of potential ignition sources in explosive atmospheres and damage or malfunction of electronic devices. This paper focusses on the description and characterization of the specific Electro-Static Discharge (ESD) threat produced during the contact phase of Air-to-Air Refuelling (AAR) operations between two aircrafts. Both the tanker and receiver aircrafts accumulate certain level of electrostatic charge depending on the particular characteristics of each platform and the external atmospheric conditions faced by each of the aircrafts prior to their encounter. Considering the different means of electrostatic charge accumulation, tanker and receiver aircrafts may become charged at different potentials and even with

different polarity. This fact may result in the appearance of an electric arc, which equilibrates the electrostatic potential between both aircrafts when they are close enough during the AAR contact phase, with the consequent risks that it entails. This paper intend to provide a complete overview of the AAR ESD threat starting from the description of the phenomena, through the different publications and standards that stablish requirements or provide support for its characterisation, up to the possible verification methods that can be used to evaluate this threat. Then, the paper includes some examples of the verification approach followed on the evaluation of two different systems: The ARBS that is based on a mast system installed at the tail of the aircraft and the AR Kit that consist of a removable kit that can be installed inside the fuselage of the C-295 platform to provide AAR capability by means of a deployed hose. In those cases the verification approach is mainly carried out by means of High Voltage (HV) tests, therefore, the most relevant test parameters and the key aspects to be considered during the ESD test are identified and discussed.

9:40 – 10:00
Room C

## EXPERIMENTAL INVESTIGATION OF PRECIPITATION-STATIC DISCHARGERS IN WIND

*Claire Johnson, Benjamin C. Martell and Carmen Guerra*

Aircraft and other airborne vehicles naturally acquire electrical charge during flight, due mainly to frictional charging by precipitation particles such as ice, snow, rain, or dust. If not properly managed using precipitation-static dischargers, or p-static wicks, corona discharges can form on the sharp edges of radio antennae, causing communication interference that impairs flight safety. The basic operation of these passive devices of charge control is explained by the onset of a controlled corona discharge at the tip of the wick whenever the aircraft acquires charge beyond the inception threshold of the discharge. Whereas testing standards are in place to quantify the charge dissipation rates of the wicks and their electromagnetic noise, these typically ignore aspects inherent to being airborne, such as sub-atmospheric pressure conditions or wind advection. In this work, wind tunnel experiments are conducted to characterize the behavior of corona discharge from commercial p-static wicks, mounted in standard testing configurations, subjected to DC voltage, and exposed to wind. The results from this experimental campaign reveal the effects of wind speed on the discharge properties, including which discharge mode is being favored (e.g., glow versus streamer corona), the streamer burst pulsation frequency, as well as current characteristics. These observations have implications in terms of the discharging efficiency of p-static wicks as well as their interference frequencies.







10:00 – 10:20
Room C

## PROGRESS TOWARDS ATMOSPHERIC CORRECTION FOR AEROSPACE ELECTRIC DISCHARGE APPLICATIONS

*Sofia P. Mavidou, David Clark and A. Manu Haddad*

In combating the threat of irreversible climate change, all sectors will need to reduce their carbon dioxide emissions and wider environmental impact. In addition, the rising cost of fuel and maintenance and the quest for continual improvement in aircraft performance has led the aviation industry to the challenge of transitioning from traditional mechanical systems and subsystems to electrical equivalents. In this work, different electrode configurations, simulating the divergent field distributions present in aircraft electrical systems, are examined with adjustable gap distance and variable pressure to simulate flying altitudes. The temperature and humidity in the test vessel are monitored continuously during the tests, but not controlled. We present initial results showing the effect of atmospheric pressure on the partial discharge inception and breakdown voltages in standard electrode configurations.

10:20 – 10:40
Room C

## EXPERIMENTAL STUDY OF THE CHARGE SATURATION LEVELS OF AN AIRCRAFT WITH AN ACTIVE ELECTROSTATIC CHARGE CONTROL SYSTEM

*Pol Fontanés, Benjamín Martell, Hector Candela, Joan Montanya and Carmen Guerra*

Artificially charging an aircraft might reduce the chances of lightning to it. In this study, we explore the saturation levels at which an UAV can be charged using artificial electrostatic charge control based on ion emission. The paper presents measurements of the aircraft's charging level achieved, as well as the ion cloud released from it. The experimental setup emulates the inflight electrical characteristics inside the laboratory. For these experiments we report on charging negatively the aircraft and we found out that the model could be sustain up to -35kV in a stable way. Also, we confirmed that the charging potential stabilizes when the emitted ions are recaptured by the aircraft, at a fixed voltage and wind speed. We tested, successfully, three techniques to further emit ions after the stabilized potential (for constant applied voltage and wind speed) was reached and provide measurements of the spatial structure of the ion cloud as it is released by the aircraft.

10:45 – 11:15
Machine's Hall
COFFEE BREAK

## SESSION 4A *LIGHTNING PROTECTION OF MATERIALS, DEVICES AND SYSTEMS 1*

11:20 – 11:40
Auditorium

### AUTOMATED FIBER PLACEMENT OF LIGHTNING PROTECTION SURFACER FOR CARBON FIBER REINFORCED PLASTIC

*Larry Hebert*

Carbon fiber reinforced plastic (CFRP) aircraft skins having complex curvature are often fabricated using a process called automated fiber placement (AFP) to consolidate the CRFP prepreg. This process uses specialized robotic application equipment to apply very narrow strips of CFRP prepreg edge-to-edge in layers across the surfaces of the layup. Each strip can be oriented to tailor the physical properties of the final part as desired. Application of expanded foil-based lightning strike protection films have been attempted through AFP equipment; however, protection performance is difficult to obtain with the narrow format of the material and the material does not resist the dynamic forces encountered in the robot. A conductive lightning strike protection prepreg has been developed for application through AFP machines at widths down to 6.35 mm (0.25 inch) wide. This narrow conductive prepreg has been created to be robust enough to survive the dynamic forces introduced by the AFP robot during the application process. Layup of this conductive prepreg can be applied by the AFP robot, in a tailored fashion, on a part to balance weight against strike protection levels for elevated efficiency and speed. This paper reviews the design, construction, application and test results achieved with this Lightning Strike Protection prepreg.

11:40 – 12:00
Auditorium

### ELECTROMAGNETIC CHARACTERIZATION OF ALUMINIUM FOAM PANELS FOR APPLICATION IN AVIONICS BAY

*Óscar M. Berenguer, Alberto Martín, Raúl Molero, Abderrahim Khamlichi, Ángel Ramírez and Antonio Portolés*

Aircraft are subjected to lightning strikes which can produce direct and indirect effects. Direct effects (LDE) are associated to structural damages while indirect effects (LIE), due to lightning currents circulating through the structure, has the potential to induce electromagnetic interferences (EMI), as power surges or transients into wires or equipment, that can reach the sensitive electronic equipment used in aviation industry, known as avionics. These equipment contain a large number of frequency generating components, digital circuits, PCBs, switching power supplies and many other sub-components that are susceptible to EMI, which can produce avionic equipment performance to degrade or even malfunction. This phenomenon is lower over a metallic aircraft, where the current from an impact can be quickly conducted away, but it's critical for structures made with less-conductive materials as carbon fiber composites. One major way to reduce these EMI effects over safety critical avionic, is to install them in a solid metallic or metallized composite panels enclosure compartments, called avionics bay, which provide among other characteristics such as rigidity, thermal conductivity, acoustic isolation and easy access, electromagnetic shielding for equipment, harnesses and connectors installed on it. Shielding not only reduces EMI emissions, but it also improves susceptibility performance from outside interferences. In addition, it has been observed for a long time that these compartments are increasingly saturated due to mainly more aircraft composite primary structures and the increasing use of electrical/electronic systems. Some of the disadvantages with these aforementioned avionics bay materials are mainly the high weight in the case of metallic bays and time-cost of repairs in metallized composite bays. Aluminium foam is an ultralight material of great interest and specific properties due to its particular structure, with a low density as well as acceptable mechanical properties. It is thought that they could improve many of the current avionics bay properties at the time of reducing weight. This paper aims to perform a preliminary electrical, lightning and electromagnetic characterization study of an aluminium foam material, Alporas denomination, with two different thickness, 10mm and 25mm.

12:00 – 12:20
Auditorium

### INITIATION OF ELECTRICAL DISCHARGE AT THE TRIPLE JUNCTION OF THE LIGHTNING PROTECTION OF AN AIRCRAFT RADOME

*F. Padoan, D. Clark, A. Haddad. C. Karch and P. Westphal*

The shape of the radar antenna and its lightning protection diverter strips can cause air ionization and streamer inception, which may lead to lightning attachment. In this paper, we are particularly investigating the field enhancement at the triple junction point formed by the metallic diverter strip, the radome material and the surrounding air. In this work, a tangent ogive shape radome geometry has been implemented in the simulation, adopting the EUROCAE standard configuration for lightning laboratory tests, to compute the magnitude of electric fields in the dielectric material and its surrounding air, and to evaluate the temperature conditions at the triple junction point using Magnetohydrodynamic equations. Various solid diverter strip design geometries have been then considered with the aim to control the discharge initiation and reduce the electromagnetic shielding effect on the radar communication. Laboratory tests were conducted on a commercial aircraft radome to validate the simulations.

12:20 – 12:40
Auditorium

## DEVELOPMENT OF THIN COPPER COATINGS BY PHYSICAL VAPOR DEPOSITION AS AN ALTERNATIVE TO TRADITIONAL LIGHTNING STRIKE PROTECTION METHODS

*Margarita Barrio, María Rodríguez, Vanessa García, Laura Sánchez, Bernardo López and Óscar Rodríguez*

Since the inception of carbon fiber reinforced polymers (CFRP) and, specially, since their extensive use in technological applications, the fabrication of conductive coatings on CFRPs has been a topic of intensive study. This is partly due to the fact that their low electrical conductivity is too low for some applications. In this work, we present thermal evaporation as a method for metallizing carbon fibre reinforced thermoplastic polymer (CFRTP) with the aim of developing electrical coatings for lightning strike protection (LSP). This technique is part of the family of physical vapour deposition (PVD) methods, and it is a way to develop continuous and homogeneous coatings with a low density of defects. This is important to achieve films with low electrical resistivity. The metallization is carried out on thermoplastic poly-ether ether ketone (PEEK) reinforced with carbon fibre (CF/PEEK), as an alternative to copper meshes and expanded copper foil (ECF) for LSP of aircrafts and for other smaller components. One of the main aspects considered in this work has been the adhesion between the layer and the substrate. In order to enhance the adhesion between the coating and the substrate, the surfaces of the laminates were modified using chemical wet methods, sanding and plasma activation. The adhesion has been tested with a Tesa tape to qualify the adherence according to the activation method. Also, infrared spectroscopy in the attenuated total reflection mode (ATR-FTIR) has been used to detect chemical surface changes after plasma modification. The removal of organic contaminants is, probably, the reason behind the good adhesion observed. Then, the resulting coatings have been visualized using optical microscopy to characterize their thicknesses along the coupon. Finally, with the purpose of evaluating the electrical conductivity of the coatings, four-probe tests have been done to obtain the sheet resistance values of each layer. In conclusion, using thermal evaporation, copper layers with a very good adhesion and with thicknesses between 3 and 4.5 μm have been deposited on the CFRTP substrates. These copper coatings with these range of thicknesses present volume resistivity values of the same order of magnitude to those of pure bulk copper (1.72·10-6 Ω cm), i.e. between (4.8 ± 0.6)·10-6 Ω cm and (6.9 ± 0.3)·10-6 Ω cm. These values of resistivity are better than most of those found in the literature for Cu films grown with other techniques (cold plasma, electroless, etc…) on CFRP. The resistivity for the thicknesses mentioned would be suitable for the dissipation of the electrical charges generated by the lightning strike impact.







## SESSION 4B *LIGHTNING AND ATMOSPHERIC PHENOMENOLOGY*

11:20 – 11:40
Room C

## INTERFEROMETER OBSERVATIONS OF UPWARD LIGHTNING AT THE SÄNTIS TOWER – PRELIMINARY RESULTS

*Antonio Sunjerga, Mark A Stanley, Mohammad Azadifar, Toma Oregel-Chaumont, William Rison, Farhad Rachidi and Marcos Rubinstein*

We present the preliminary results of an experimental campaign in the summer of 2021, during which interferometric observations of ascending lightning were made at the Säntis tower. The Säntis Tower is a 124-m tall telecommunications tower installed at the top of the 2504-m high Säntis Mountain. The tower has been instrumented for lightning measurements since 2010 and it is consistently struck by lightning more than a hundred times a year. The used interferometer system is capable of resolving radiation sources along the lightning propagation path with an accuracy of few meters and to time resolve it with microsecond accuracy.

11:40 – 12:00
Room C

## TRANSFERRED CHARGE OF LIGHTNING CURRENT WAVEFORM OBSERVED AT TOKYO SKYTREE

*Toru Miki, Ami Kudo and Mikihisa Saito*

Tokyo Skytree is a free-standing independent broadcasting tower, which height is 634m-ASL, located on a flat terrain about 8 km inland in Tokyo, Japan (35.71N, 139.81E). Because of its height, many lightning flashes may strike to the tower. The authors have conducted lightning current observation with the Rogowski coils at the tower since 2012. At Tokyo Skytree, we have confirmed 34 downward initiated lightning flashes and 62 upward-initiated lightning flashes to the tower as of end of December 2021 for about 10 years. The lightning current parameters are most essential values for the lightning protection design associated to the lightning flash to the ground. Thus, the authors have evaluated the lightning parameters through the lightning current observation at very high tall-structure. The authors evaluate the correlation relationship among some lightning parameters for both downward lightning and upward lightning, such as between the current amplitude of the return stroke and the transferred charge, for example. The authors also denote the relationship between some lightning parameters and the -10 degrees isotherm obtained with NuWFAS developed by CRIEPI at the time of the flash occurred. According to those evaluations, the authors mention

the analysis of the magnitude of the flashes associated with the -10 degrees isotherm in the sky.

12:00 – 12:20
Room C

## WINTER LIGHTNING TRIGGERED BY WIND-TURBINES: THE CASE OF SNOWSTORM FILOMENA

*Nicolau Pineda, Ferran Fabró, Joan Montanyà, Jesús A. López, Gloria Solà and Oriol Rodríguez*

Winter storm Filomena battered the Iberian Peninsula on the 9-10th January 2021, covering the eastern half of Spain with a huge amount of snow. Apart from the historical snowfall, lightning activity was observed during this snowstorm episode. Although most of lightning was oversea, lightning hotspots were observed in different regions across the Iberian Peninsula, such as Galicia, Asturias, Catalunya and Andalucia. A closer look at the inland lightning hotspots showed wind turbines in the close vicinity of most of the lightning. The analysis of the ERA5 variables has shown that environmental conditions were prone to winter lightning. One of the most representative is the height of the –10 °C isotherm, a key variable for cloud electrification. A low height of the –10 °C enhances electric fields at the top of tall man-made structures, like the wind turbines, favouring the inception of upward lightning. Moreover, moving blades are exposed to stronger local electric fields than static objects, favouring the initiation of stable lightning leaders and subsequent lightning strokes.

12:20 – 12:40
Room C

## ON-SITE EXPERIMENTS AND ELECTROMAGNETIC MODELLING TO CHARACTERIZE CORONA DISCHARGES IN VHF-BAND

*Guillaume Dehan, Hélène Galiegue, François Issac and Alexandre Chabory*

Corona discharges have been shown to disrupt aeronautical VHF communications after some research on broadband noises carried out by the Electromagnetics and Antennas research group of ENAC laboratory. A stand-alone measurement device is set up and installed on a 25 m test tower to characterize corona discharges events. The measurements show differences in behaviour and coupling mode whether the discharges are positive or negative. In addition to this experimental work, an electromagnetic modelling has been done using the experimental measurements in order to reproduce experimental results and retrieve the coupling mechanisms between the positive and negative discharges on the pylon.

13:05 – 15:00
Machine's Hall
LUNCH







## SESSION 5A *NUMERICAL MODELING AND ANALYSIS 2*

15:00 – 15:20
Auditorium

## USING SIMULATIONS TO EVALUATE HARNESS TRANSIENTS IN SMALL COMPOSITE AIRCRAFT FOR LIGHTNING ENVIRONMENTS

*Kellan Kremer, Cody Weber, Stephen Board, Guido Hunziker and Justin McKennon*

This paper demonstrates how simulation models can be used to produce wire harness transient levels, similar to lightning compliance levels (TCLs), for a small composite aircraft. In addition to understanding baseline design levels, simulations have the added benefit to perform design sensitivity assessments to explore optimal protection designs. It is critical to understand EM properties of composites and cable harness shielding to get accurate coupling results. A collaboration with Glenair helped to identify appropriate harness transfer impedance parameters to use within the model. Some discussion is provided about the compliance process and having a 200 kA Component A lightning requirement on these small composite aircraft.

15:20 – 15:40
Auditorium

## DC COMPUTATION ON A FULL FDTD MODEL DESIGNED FOR INDIRECT LIGHTNING EFFECTS

*Thibault Volpert*

The objective of this paper is to show how a FDTD (Finite Differences in Time domain) software with thin oblique wire models, usually used to compute induced lightning indirect effects in aerospace systems, can be applied to evaluate DC currents on internal cables. A classical indirect lightning computation on a complex industrial system will evaluate time domain current responses on wires but needs a lot of computational resources in order to obtain the late-time currents responses. The direct current response on these wires will then give us access to the integral value of the whole time domain responses. This will allow reduction of the time domain exploration of the initial simulation and to accurately extrapolate late-time currents. Moreover this type of DC computation gives access to the resistances values between any points of the studied system; which can be considered as a “numerical ohmmeter”.

15:40 – 16:00
Auditorium

## A NUMERICAL SOLVER TO ASSESS THE IMPACT OF WIND, GEOMETRY, AND ALTITUDE ON ARTIFICIAL CHARGE CONTROL OF AIRCRAFT USING CORONA DISCHARGE

*Hector Candela, Pol Fontanés, Michele Urbani, Joan Montaña and Carmen Guerra-García*

Prior work by members of the team has shown that active charge control might reduce the risk of aircraft-triggered lightning. Controlling the net charge of an aircraft can be achieved by using corona discharge. For a positive corona, positive ions are generated by the discharge and advected away by the wind, charging the aircraft negatively. The charging phase is inherently transient but for a given geometry, applied voltage and wind speed the system rapidly reaches a steady state of charging. This work develops new numerical tools with the goal of accelerating the simulation capabilities to investigate methods to artificially charge an aircraft. The ultimate objective of the model is to study the transient phase of the charging process. As a first step, this contribution presents preliminary results for the steady state solution using a model under construction. The results from the newly developed electrostatic solver show a notable increase in speed versus commercial solvers, which is the most expensive component of the simulations.

16:00 – 16:20
Auditorium

## SENSITIVITY ANALYSIS OF AIRCRAFT SHIELDINGS FOR LIGHTNING INDIRECT EFFECTS BY A NOVEL S-FDTD

*Miguel Ruiz, Enrique Pascual, Guadalupe Gutiérrez, Hirahi Galindo, Luis Díaz, Amelia Rubio and Salvador González*

This paper presents an extension of the stochastic FDTD method to predict the variance of fields coupled through multilayered lossy thin panels. The subgridding boundary condition subcell model is employed in an unconditional Crank-Nicolson formulation. A discussion on the effect of the influence of material parameters is done in the context of the assessment of the shielding effectiveness of typical aircraft fuselages.

# SESSION 5B *FUEL TANKS AND FUEL SYSTEMS*

15:00 – 15:20
Room C

## DEVELOPMENT OF MATERIAL VERIFICATION TEST PROCEDURE FOR EDGE GLOW PROTECTION PERFORMANCE

*A. Bigand, I. Revel, F. Flourens and M. Cross*





When a high current density flows in a Carbon Fiber Reinforced Plastic (CFRP) part, the resulting voltage drops within the material associated with the strong electrical anisotropy of the laminate can lead to electrical breakdowns or hotspots at the cut edges of the material or on the inner surface of the panel. The phenomenon occurring at the edge is called “Edge Glow” which can be considered as an ignition hazard. In order to limit its intensity or even better, to avoid the phenomenon to occur, much work has been performed in order to improve the equipotentiality of the carbon layers in the bulk of the laminate by increasing the transverse conductivity (i.e. Z-conductivity) through the introduction of electrical contacts between plies. In order to validate a new CFRP material, the performance assessment was based on a lightning test performed on several T-joints which were very expensive and time consuming to manufacture, making the overall development process slow and not compatible with the program objectives and constraints. In order to support the development of new carbon material in a more efficient way, a simplified assessment test is presented in this paper that focuses only on the performance against edge glow independently from the final assembly solution. In that respect, the Edge Glow protection performance becomes inherent to the material properties and does not depend any more on the detailed design of the part, which is exactly the target set for future composite tank developments. With this new method, the sample is made of one small coupon of CFRP with 2 fasteners installed in interference fit and misaligned to enhance voltage drop apparition under direct current injection. Although it was not possible to link directly macroscopic parameters such as the voltage drop and current with the microscopic phenomenon associated with the apparition of light at cut edges, this method, based on camera measurements, enabled a quick and economical assessment of the performance for a new material against edge glow.

15:20 – 15:40
Room C

## FUEL TANK FASTENER SPARKING: DEVELOPMENT OF A THRESHOLD DATABASE AND THE BENEFITS OF COMPUTATIONAL ELECTROMAGNETICS SIMULATION FOR CERTIFICATION

*Rebeka Khajehpour, Alyssa González, Cody Weber and Eric Miller*

Prevention of catastrophic effects due to fuel vapor ignition is a key part of any aircraft certification effort. One potential fuel vapor ignition source is arcing and sparking resulting from lightning currents conducted through airframe components, such as fasteners and joints. The most common method of demonstrating adequate ignition source prevention involves extensive testing of a large variety of fasteners and fastener configurations. Fastener test levels are based on current densities distributed throughout the aircraft,

obtained through full vehicle lightning testing and simulation. The fastener design handbook contains a sample of the testing and simulation effort used to identify potential ignition sources in fuel tanks. Findings and data published in the (project reports) handbook serve as baseline engineering evaluation for industry to reduce the overall quantity of tests required during the fuel tank design process. Several factors were studied for their impact fastener non-sparking thresholds. There are three phases associated with this study. Phase 1 of this project focused on developing a public fastener database for non-sparking thresholds due to conducted lightning currents in coupon level tests representing metal fuel tanks. This included both nominal and faulted fastener installations. Phase 2 involved the development of a metal fuel tank lightning design handbook and was carried out by EMA. The focus of this phase was to demonstrate how lightning environments could be established in aircraft fuel systems using validated numerical simulations. Phase 3 of this project focused on developing a public fastener database for lightning non-sparking thresholds in coupon level tests in carbon fiber reinforced plastic (CFRP) fuel tanks for both nominal and faulted fastener installations. This paper provides the background for the project, findings of each phase of this study, and opportunities for future work. All work done during this project is publically available to be used as a design guide. This project was funded by KART grants and done in partnership with EMA.

15:40 – 16:00
Room C

## BENEFIT AND DRAWBACK OF AN EXPLICIT TWO PROTECTION FEATURES APPROACH FOR COMPLIANCE WITH 25.954

*Andrew Fay and Christelle Kutyla*

EUROCAE Working Group 31 and SAE AE2 committees have jointly developed a “Users Guide” detailing supplementary guidance material, to that provided in AC 25.954-1 and AMC 25.954 for showing compliance with the airworthiness regulation 14 CFR 25.954, amendment 25-146 (CS25.954 amendment 26) regarding lightning protection of fuel tanks and systems. This User Guide will be published in 2022 as “ARP 6205: Transport Airplane Fuel System Lightning Protection”. The equivalent EUROCAE publication being ED 303 with the same content and title. Whilst this ARP/ED sets out to encourage a consistent compliance approach across industry, it also recognises and details alternative proven industrial options where appropriate that one can select. One such option is the means by which an applicant can demonstrate that a fuel tank design concept or solution provides acceptable Fault Tolerance in accordance with the regulation. There are two main approaches, the first involves identifying all credible faults that could occur during the life of an aircraft and, one by one, verify in the presence of each fault the lightning protection capability of a design concept remains acceptable. The second approach, and the primary topic of this paper, is defined as the “Fault Tolerance by Redundancy Method”. In essence this is a means by which, for each individual ignition source, two independent protection features are identified and implemented as part of the fuel tank design concept. Compliance of each protection feature is then verified by fully disabling the other protection features in turn. A further check is necessary to ensure no common mode effect can defeat both protection features simultaneously. There are pros and cons for using either method. These will be described and their significance will be discussed. Some examples are as follows: Simplicity of test methodology, numbers of test samples required for each verification test programme, applicability to new technology concepts where limited to no in service history may exist, potential for errors or omissions, etc. A specific focus will be given to the Two Protection Features approach where, the benefits of using such a method as a conceptual design tool, early in the programme, can minimise risks as the fuel tank design develops through to a mature, certifiable solution as well as quickly providing the evidence to support continued in service operation, even in the event of a potential late detection of a manufacturing quality escape.



16:00 – 16:20
Room C

## PRESSURE MEASUREMENTS NEAR FASTENERS EXPOSED TO LIGHTNING STRIKE CONDITIONS

*Dejan Nikic, Brendan Finn and Jason Damazo*

Fastened joints used in aircraft structure are vulnerable to lightning strike-generated spark events. Imperfect electrical contact at the fastener results in energy deposition and material vaporization in the small semi-isolated volume between the fastener and the structure. This creates a dynamic pressure impulse and sparks in this volume. Traditionally the internal sides of fastened joints have been covered with a sealant material to prevent sparks from escaping into potentially flammable environments, such as in-wing fuel tanks. However, there is considerable uncertainty in the pressure capable of impelling these sparks and thereby in the required strength of the protection features. To improve our understanding of the pressures to which protection features are subjected, experiments were performed on a novel test specimen design capable of producing repeatable lighting strike-representative spark events, and the dynamic pressure in an enclosed volume around the fastener of the test specimen was measured. Particular emphasis was placed on the interior side of the fastener where a nut or collar is located. Typical test specimens used for lightning testing are not reliable spark generators due to high variability

in the manufacturing process; this manifests in both the energy content and the location of the generated sparks varying wildly from test-to-test. This motivated us to develop a new test specimen capable of producing a highly repeatable spark at a predetermined location. Variations on this specimen were developed to produce metal and/or carbon fiber reinforced polymer (CFRP) sparks at various energy levels. Additionally, the construction of these specimens enabled us to perform accurate energy measurements to obtain the energy deposition within the fastened joint. We performed a series of experiments on each specimen variation during which we measured the dynamic pressure within the small volume around the fastener. Necessary precautions were taken to ensure that pressure build-up was contained within the volume and there was no leakage outside of the measured volume. The new test specimens demonstrated good repeatability in spark location, energy, and resulting dynamic pressure. This enabled us to develop a relationship between the dynamic pressure and deposited energy that correlates well with an analytical model. Corresponding measurements were performed on test articles which are equivalent to production aircraft components. While energy measurements were not possible on these articles, we were able to measure the dynamic pressure and confirmed similar behavior to the pressures measured with our newly developed test specimens. These findings will be used to support modeling efforts underway and to provide additional requirements, with regards to containment pressure, to the designers of protection schemes used in fastened joints.

16:45 – 17:15
Machine's Hall
COFFEE BREAK

## SESSION 6A *LIGHTNING PROTECTION OF MATERIALS, DEVICES AND SYSTEMS 2*

17:20 – 17:40
Auditorium

### IN SITU X-RAY PHASE-CONTRAST IMAGING OF SPARK EROSION OF AERONAUTICAL FASTENERS

*A. Jarnac, R. Sousa Martins, C. Zaepffel, F.Tholin, P. Blanchet, V. Désangles, L. Guitard, A. Stolidi and P. Lalande*

In the context of lightning strike impacting aeronautical fasteners, we investigate the in situ behaviour of fasteners subject to a current level of a few kA by using high-speed X-ray phase-contrast imaging in a synchrotron facility. It reveals that the fastener erosion occurs in two time scales. On a microsecond timescale, hot particles are ejected from cavity walls of the Carbon fibre reinforced polymer due to sparking / arcing phenomena, whereas on a sub-millisecond time scale, the fastener wall is melted due to the electrical energy deposited in the arc-fastener interface. The experimental observations have served as input into an electro-thermal model of electric contact. The estimated melted depth is in good agreement with the measured one. The nature of the internal damages has been confirmed by using X-ray phase tomography. The DOI for the data is the following: 10.15151/ESRF-ES-650701038.

17:40 – 18:00
Auditorium

### ELECTRICAL RESISTANCE MEASUREMENTS OF CARBON FIBRE REINFORCED POLYMER (CFRP) MATERIALS. MEASUREMENT TECHNIQUES, METHODS AND PITFALLS TO AVOID: A CASE STUDY

*Peter English, Sofia Sampethai, Andrzej Tabecki, Melissa Riley, Chris Ruffell, Stuart Lewis and Jan Kozak*

Lightning strikes are a relatively common event to aircraft and can cause considerable damage due to high energy electrical current passing through the aircraft structure. Traditionally composite aircraft are protected from lightning strike by expanded metal foil mesh embedded in the composite. Alternatively, metallic lightning strike protection (LSP) coatings have also been investigated. Current aircraft design incorporates a range of mechanically fastened structural joint assemblies, which are often located in the electrical current path and these joints may reduce electrical conductivity performance. On post lightning strike inspection, these joint assemblies are sometimes subject to damage and require repair. Maintaining electrical continuity across joints in composite panels can be quite difficult to achieve. Electrical continuity is important for lightning strike protection (LSP) and for protection against High Intensity Radiated Fields (HIRF). Innovative jointing techniques were explored and developed under the Clean Sky 2 project "C-JOINTS". A follow-on project named "D-JOINTS", currently in progress, is examining mathematical modelling and software development of a design tool to aid in the sizing of certain components associated with these joints. As part of the mathematical modelling of the design tools for predicting the lightning and HIRF behaviour of these composite aircraft panels and components, it is clear that electrical resistivity, or its reciprocal, conductivity, is an essential parameter to quantify. However, electrical resistivity values for CFRP materials are very difficult to find in the literature. One the major reasons for this apparent lack of data is perhaps that the electrical properties of CFRP materials are enormously variable and are very dependent upon both the composition and fabrication methods of the material itself. Moreover, it is well known that the electrical properties of CFRP panels are anisotropic, i.e., the lengthwise properties are quite different from the through-thickness properties, but this difference is not often quantified. Given the apparent lack of data in the literature, but, more importantly, the inherent material and process dependability of the parameters, it becomes apparent that these parameters need to be determined individually for each material

composition and its manufacturing process. This case study describes the development of relatively simple-to-implement measurement tools and procedures. Perhaps more importantly, it highlights some of the pitfalls encountered in evolving these test methods and describes how the problems were resolved. Once developed, these test methods gave encouragingly consistent results over a range of panel thicknesses. The electrical resistivity data for the composite material employed in the project is presented with the caveat that this data is particular to this material and its manufacturing methods. Both lengthwise and through-thickness measurements are presented. A brief description of the D-JOINTS project and its progress to date will be included to provide some background information as to the requirement for these measurements. This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 887042. The authors acknowledge the support and guidance provided by Evektor, the Topic Manager of the D-JOINTS project.

18:00 – 18:20
Auditorium

## DESIGN OF LIGHTWEIGHT PERFORATED COPPER FOIL FOR LIGHTNING PROTECTION OF FIBER REINFORCED PLASTIC

*Larry Hebert*

Expanded foil wide area conductors have been successfully applied on the exterior of fiber reinforced plastic skins for protection from lightning strike. These materials have provided adequate protection to the vehicle, but the weight penalty of covering large regions of the skin surface is impactful. Very thin, lightweight, wide area foil conductors have been developed and embedded into lightweight epoxy surfacing prepregs to provide strike protection with significantly less weight penalty to the vehicle. This paper reviews the design, construction and test results achieved for conductors that have been designed in a digital environment and fabricated by plating and/or laser cutting to the digital definition.

18:20 – 18:40
Auditorium

## CALCULATION OF PARTIAL LIGHTNING CURRENT AND OVERVOLTAGES INDUCED INTO PIPELINE CAUSED BY A NEARBY LIGHTNING AND ITS SURGE PROTECTION

*Eduard Shulzhenko, Martin Hannig, Manfred Kienlein and Tobias Braun*

This paper presents a numerical approach for evaluation of the injected partial lightning currents and overvoltages into an underground pipeline system due to a nearby lightning strike. This approach allows to analyse the stress on the insulation coating of the burial pipelines as well as support by a design or by validation





of the existing overvoltage protection system for the pipeline. First, the coupling mechanism through the soil is analysed by using of XGSLab software package. This would help to design a second numerical model in EMTP-ATP expanded with surge protective devices for observation of a complete underground pipeline system. The transient analysis for the first positive lightning stroke is performed for both cases: without and with overvoltage protection concept with consideration of the lightning protection levels LPL I and LPL II and with consideration of the surge protective devices as a part of internal lightning protection system. The approach also considers the insulation failure which would occur in several places along the pipeline, which injects additional partial lightning currents into the system, since the dielectric strength of the pipeline's coating during the high peak values of the lightning currents and the high specific soil resistance could be easily exceeded. The aim of this paper is however, to provide a numerical approach for an accurate reproducing of the partial lightning currents and overvoltages which occur on the pipeline as a result of the nearby lightning strike and insulation failures. The investigation is conducted for different configurations of the soil with different soil resistivities. The case with a relatively high soil resistivity can represent the worst-case scenario for the installed surge protective devices (SPDs) since they are stressed in this case the most (more partial lightning current will be conducted from the impacted area into the pipeline with low resistivity). The SPDs installed at the earth-termination system (ETS) to conduct the partial lightning current direct into the ground, are always stressed more than SPDs at the insulating flanges connecting two pipelines (of course in case if the required low earth resistance is achieved at the ETS).

# SESSION 6B *LIGHTNING EFFECTS ON OTHER VEHICLES*

17:20 – 17:40
Room C

## TREND OF LIGHTNING ATTACHMENT POINTS AND DAMAGES ON AUTOMOBILES BASED ON LATEST STATISTICAL DATA UP TO 2021

*Kazuo Yamamoto and Kento Korasaki*

The automobiles with a small environmental load such as electric, hybrid and plug-in hybrid vehicles include a lot of electrical and electronic devices. In addition, with the improvement of safety performance and the spread of autonomous driving technology, the number of electric and electronic devices installed in automobiles has been improved and the number is increasing rapidly. These devices are vulnerable to electromagnetic disturbances such as the transient electromagnetic fields generated inside the automobile caused by a lightning strike may cause the devices to failures and/or malfunctions. Damage to the electronic devices inside an automobile

caused by a lightning strike may lead to a major accident depending on the driving conditions and the surrounding environment. From such background, it is necessary to understand the current situation regarding the lightning damage of automobiles, etc. and to take rational countermeasures against lightning. In this research, we clarified the latest lightning damage trends through Web surveys and field surveys, and reported the results of summarizing the transition in lightning attachment points and damage aspects.

17:40 – 18:00
Room C

## OVERVOLTAGE AND OVERCURRENT INSIDE THE VEHICLE DUE TO LIGHTNING STRIKE

*Ryota Isobe and Kazuo Yamamoto*

Automobiles with a small environmental load such as electric and hybrid vehicles are equipped with more electronic devices for control than gas-powered automobiles. In recent years, gas-powered vehicles equipped with safety devices such as airbags, and the number of electronic components installed are increasing. When an automobile is hit by a lightning strike, the lightning current flows from the body through the internal gears and from the wheels to the ground, but at that time, the shunt current, overvoltage and electromagnetic field generated inside the vehicle can cause the break downs and malfunctions of the control and electrical system. In this paper, the results of an experimental study on the overvoltage and shunt current inside the vehicle are introduced when a front-engine front-drive (FF) monocoque-structured vehicle is hit by a lightning strike.

18:00 – 18:20
Room C

## LIGHTNING CURRENT DISTRIBUTION ON A SMALL FOUR-WHEEL DRIVE VEHICLE

*Mayuka Takakuwa and Kazuo Yamamoto*

In recent years, due to the effects of global warming, vehicles with low environmental load such as electric vehicles and fuel cell vehicles have become widespread. In addition, the safety role of electrical and electronic equipment installed in automobiles, such as airbags and collision safety systems, is increasing. In the near future, with the electrification of vehicles, it is expected that self-driving cars will become widespread. Compared to gasoline-powered vehicles, these vehicles use more electronic components for control and may be vulnerable to electromagnetic disturbances caused by surges such as lightning. Since the car body is generally made of metal, a Faraday cage is constructed, but it is clear that there are many gaps near the windows and wheels, and electromagnetic fields enter through the gaps. When a car is hit by lightning, the lightning current flows from the body to the ground via







the internal gears and the wheels. At that time, a transient electromagnetic field is generated in the vehicle, and this kind of transient electromagnetic field causes malfunction or failure of electronic devices. At present, regarding the lightning protection method for automobiles, the basic contents of the test method have been established by JASO TP19002 “Guidelines for vehicle testing against automobiles and lightning strikes”. However, lightning countermeasures for electrical and electronic equipment inside the vehicle have not been studied. The importance of lightning protection for such equipment is increasing. In this paper, the test to investigate the current distribution of a small four-wheel drive vehicle are conducted, and a numerical electromagnetic field analysis model based on the measured results is established, and several characteristics relating shunt current distributions are clarified.

18:20 – 18:40
Room C

## EFFECTS OF LIGHTNING ON UAM AIRCRAFT: LIGHTNING ZONING AND INDIRECT EFFECTS ON THE CABLE HARNESS

*Dong-Hyeon Kim, Yun-Gon Kim, Jae-Hyeon Jo, Hakjin Lee and Rho Shin Myong*

Various types of UAM aircraft are being actively developed depending on the presence or absence of fixed-wing that generate lift and the propulsion methods. Small UAM aircraft are more vulnerable to lightning strikes than conventional aircraft due to the increased use of composite materials, electric propulsion systems, and onboard electronic equipment. Airworthiness certification is required for UAM aircraft because they are not only manned vehicles but also fly at low altitudes over urban areas. However, the current efforts to develop certification guidelines and standards in the lightning environment of UAM aircraft are just beginning. This study first analyzes the procedures that demonstrate compatibility with the lightning zoning and lightning indirect effects proposed in the Aerospace Recommendations, SAE ARP 5414B and SAE ARP 5415B. It then presents lightning zones for the vector-thrust type OPPAV and ducted-fan type Nexus 4EX UAM models. Finally, it develops a lightning strike model and analyzes the indirect effects of lightning on the cable harness based on the new model.

CULTURAL TOUR

19:45 – 21:30
Prado’s Museum

21:30 –23:00
Palace Hotel
BANQUET

## September 15

### CLOSING *SESSION*

10:00 – 10:30
Auditorium

### KEYNOTE 5

#### NECESSITY OF COUNTERMEASURES AGAINST LIGHTNING DAMAGE IN AUTOMOBILES

*Prof. Kazuo Yamamoto*

In recent years, automobiles have become indispensable in our lives as a means of transporting people and goods. In the world, global warming is progressing due to greenhouse gas emissions such as CO2. As a results, the average temperature is on the rise. In such a situation automobiles with a small environmental load, such as electric and hybrid vehicles, are rapidly becoming widespread as CO2 reduction measures. Automobiles with a small environmental load are equipped with more electronic devices for control than gasoline-powered automobiles. In recent years, gasoline-powered vehicles equipped with safety devices such as airbags, and the number of electronic components installed are increasing. When an automobile is hit by a lightning strike, the lightning current flows from the body through the internal gears and the wheels to the ground, but at that time, the transient electromagnetic field generated inside the vehicle can cause the breakdowns and malfunctions of the control and electrical system. In this lecture, we will first introduce the lightning damage aspect of automobiles that has occurred in recent years. In Japan, a test method for confirming the lightning resistance of automobiles is published as JASO (Japanese Automotive Standards Organization) TP (Technical Paper). In this lecture its contents are also introduced. In addition, we will introduce an example of constructing numerical electromagnetic field analysis models that can reproduce the current shunting and the electromagnetic field aspects in the automobile when there is a lightning strike and an example of lightning damage countermeasures proposed based on it.

10:30 – 11:00
Auditorium

### KEYNOTE 6

#### ELECTROSTATIC CHARGE MEASUREMENTS: MEASUREMENT EQUIPMENT AND SPECIAL CONFIGURATIONS

*Prof. Pedro Llovera-Segovia*

Measurement of electrostatic charge or electrostatic potentials in objects can be performed by, in principle, well known basic experimental setups. Commercial equipment is easily available and the physical bases of the problem are well established. However, electrostatic measurements are a special case were extreme care has to be taken to avoid large error measurements due to the influence of the measuring setup or the misinterpretation of the results. First, the specificity of the measuring equipment has to be well understood such as the difference between field mills, induction probes and electrostatic (also called feedback) probes. Very often, results are provided in volts but the interpretation highly differs according to the instruments. Besides, the electrostatic instruments create some artificial boundary conditions around the measured object such as the introduction of grounded planes or the cancellation of electric field. This influence hast to be also taken into account to reach a good interpretation of the measurement. These situations can be analyzed in simple cases such as flat or thick grounded objects (coated surfaces, textiles) or floating objects (belts, suspended or flying objects).

11:00 – 11:30
Machine's Hall
COFFEE BREAK

11:30 – 12:00
Auditorium

### KEYNOTE 7

#### ADVANCES ON EMC SIMULATION FROM BOARD TO SYSTEM LEVEL, INCLUDING LIGHTNING

*Dr. Ulrich Jakobus*

We have seen a significant increase in the number of electronic, electrical and communication systems and components in many industries during the last decade. As a consequence, Electromagnetic Compatibility (EMC) has become a key and more sensitive topic for system and equipment manufacturers and their suppliers in a wide variety of industries, including aerospace, defense, automotive, communications, railway, consumer electronics and others. Key applications where EMC simulation is rapidly growing cover emissions, immunity, lightning effects, High Intensity Radiated Fields (HIRF), Electromagnetic Pulses (EMP), shielding effectiveness and radiation hazard, among others. Advanced model build and solver technologies are required to address these simulations, together with integrated cable modeling solutions. This presentation will talk about advances in electromagnetic simulation for EMC, including the convergence between simulation, high-performance computing and artificial intelligence, and while showing representative real use cases.

12:00 – 12:30
Auditorium

### KEYNOTE 8

#### PARTICULARITIES AND FUTURE CHALLENGES OF LIGHTNING AND ESD PROTECTION IN MILITARY PLATFORMS

*Mr. José Ignacio Plaza and Mr. Fernando Cano*

The protection of aircrafts against adverse effects of lightning strikes and electro-static charges is a matter becoming more relevant by the time

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associated to the extended use of composite materials on primary structural elements and increased integration of on-board electronic systems managing critical functions, or in the military world related to the increase in mission profiles. This sentence is repeated many times during last two decades in all specialised forums and publications, however, the technical discussions, solutions, proposed approaches etc. for the introduction of adequate protection means against these threats seems to be, in most of the cases, linked to the civil regulation and certification processes. On the other hand, military platforms have interesting particularities and considerations that may vary from this traditional civil approach. Just starting, it should be highlighted that military aircrafts are specifically out of the scope of the ICAO agreement for aviation safety. During last years and recent projects there is a tendency trying to harmonise requirements between different military airworthiness authorities (such as the EMAR) and also with civil regulations and certification processes. Many recent programs, such as the Airbus A400M, have a hybrid civil-military approach for certification. This keynote provides an overview on these particularities on military platforms from the initial stage of requirements/ regulation and certification processes to some specific technical examples where the military approach needs to cover certain aspects not considered during a typical civil lightning/ESD certification process (e.g. in-flight refuelling operations, installation of big external sensors as surveillance radars, SIGINT systems or Magnetic Anomaly Detectors, or even the installation of self-protection systems as chaff and flare dispensers, etc.) . Finally, the most relevant challenges expected for future programs in military applications will be identified and an overview of these topics will be discussed.

12:30 – 13:00
Auditorium
CLOSING

13:00 – 15:00
Machine's Hall
LUNCH





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International Conference
On Lightning & Static Electricity

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