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Lightning Protection Design Methodology for a Very Large Non Rigid Airship

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ABSTRACT

Successful lightning protection design is important for the CargoLifter CL 160 large non-rigid transport airship. Non-rigid airships, like balloons, have few hard structures so alternative means need to be designed to collect and conduct lightning currents. The helium lifting gas ionizes at one third the field intensity required for air so spark formation in ambient electric fields is more likely to originate inside a helium filled envelope than in the air outside of it. Protection development is being accomplished by a combination of high voltage strike attachment tests on scale models, and numerical analyses of electric fields.

INTRODUCTION

A fleet of CL 160 airships is planned to carry out air cargo operations with short and long haul flights in many areas of the world. Their large size (260 m long and 65 m wide) makes them more susceptible to lightning than smaller airships or balloons. Flight altitudes will generally be 2000 m or less, where cloud to earth lightning strikes happen most frequently. The objectives of the CL 160 lightning protection design are to protect the airship against catastrophic effects of lightning and also to enable the airship to continue operating without the need for repair of lightning damage until arrival of the time and location for scheduled maintenance, since facilities for gaining access to locations on the airship that might experience lightning damage may not be readily available. This differs from the usual lightning protection requirement for airplanes that they be able to continue flight to a safe landing at the next available airport. The protection is necessary also for certification by airworthiness authorities. These requirements apply also to lightning indirect effects (induced transients) as well as direct (physical damage) effects. The same protection requirements apply also to High Intensity Radiated Fields (HIRF) and Electromagnetic Interference (EMI) effects to enable safe operations in a wide variety of environments ranging from close-in interactions with ships to industrial and military facilities, worldwide.

Since the CL 160 will always be in flight and rarely taken into a Hangar It is expected to be exposed to potential lightning strike conditions for many more hours per year than are most airplanes, and most of the strikes that it would receive will be cloud-earth flashes that are usually more intense than the intracloud variety that are experienced more commonly by aircraft. This is in contrast to some other airships that have traditionally been kept away from lightning conditions by terminating flights and removal to a non storm area or to a Hangar. The CL 160's will often be far away from a Hangar. Even when docked at a mast for load exchange and refueling operations these airships will be exposed to ambient weather conditions, including lightning. These combined effects are referred to generally as “lightning and electromagnetic effects” or, “Lightning/EME”

The German airworthiness certifying authority Luftfahrt Bundesamt (LBA) has established Transport Airship Requirements (TAR) for certification of the CL 160 and other transport airships, and the Lightning/EME requirements in the TAR are nearly the same as those incorporated in US Federal Aviation Regulations (FAR) and European Joint Aviation Authorities (JAR) presently applicable to transport aircraft.

The CL 160 operational considerations, the lightning environment, some of the technical challenges, and the test and analysis methods and facilities being employed to achieve a successful design are described in the following sections of this paper.

OPERATIONAL CONSIDERATIONS AND THE LIGHTNING ENVIRONMENT

OPERATIONAL CONSIDERATIONS

Avoidance of lightning strikes by meteorological prediction is the preferred CargoLifter philosophy. However most of the transport airplane traffic operating on Instrument Flight Rules (IFR) fly mainly over clouds up to 40 000 ft compared to the airship flight envelope below clouds up to 6 000 ft (2000 m). Most of the lightning strikes that these airplanes experience are the intracloud variety that do not reach the earth and do not contain stroke currents as intense as those that have been recorded in cloud to earth flashes.

About 10% of all lightning strikes to transport airplanes will reach the ground and can hit also low flying airships.

A wide variety of meteorological services and products in compliance with the ICAO regulations are available all over the world to support the en route planning of all IFR and VFR flights. These services are well adapted to the requirement for fixed wing airplanes and helicopters.

The designated maximum speed for the CL160 will be between 80km/h and 120km/h. In comparison to a normal aircraft this is relatively slow, but in comparison to a normal cargo ship, it is very fast.

The maximum flight duration for a large transport aircraft is about 16 hours. In the long range configuration the CL160 can stay up to one week in the air and travel a distance of up to10 000 km.

To satisfy the specific airship pilots’ needs concerning meteorological navigation, an additional meteorological information service especially adapted for airship navigation is required. Moving map, storm scopes and weather radar is standard equipment for normal aircraft and helicopters.

CargoLifter meteorologists and partners are working on a new software tool to overlay a normal aeronautical chart (moving map) displayed on screen with additional information overlayed from significant weather charts or created from radar station data. This will be displayed in a moving animation to give trend information to the CL 160 pilots.

A short demonstration movie of this display is to be included in the presentation of this paper.

LIGHTNING ENVIRONMENT AND EXPOSURE

The CL 160 is being designed to meet its protection requirements in the lightning environment that has been defined for aircraft [1]. This standard describes the currents that an air vehicle can experience once it is struck by lightning, but it does not differentiate between the two ways that lightning strikes to an air vehicle can be initiated. The two known lightning strike processes are considered in the protection design, and the protection features eventually installed on the airship must accommodate each.

First, lightning can be triggered by the airship. In this case, the airship is in the presence of large static electric fields caused by thunderstorm electrification. The airship structure can locally increase these fields by a significant factor at various airship locations, such that streamers originate at these locations and eventually create a strike.

Second, an approaching stepped leader can also induce streamers from the airship, leading to a lightning strike.

Additional effort is being applied to enable the lightning protection system to fail safe following strikes more intense than described in [1]. This is in recognition of the greater exposure time of the CL 160 to cloud to earth lightning at low altitudes, where more intense lightning currents may occur.

The airship will generally fly in heights not larger than about 2000 m above sea level. That means it will generally be exposed to the high amplitudes of cloud to ground lightning strikes. Due to the very large size of the CL 160 m this will occur with a significant higher probability than for the usual conventional aircraft. Intracloud strikes will occur to the CL 160 with a lower probability. Of course, the regions where a particular CL 160 operates will play a significant role in the exposure. Operations in the intertropical convergence zone (+/- 20 degrees of latitude), and in far northern regions where clouds in winter are at the CL 160 flight levels, for example, will produce more strikes than operations in temperate regions where clouds are above CL 160 flight levels and thunderstorm frequencies are lower. Avoidance of some lightning conditions may be possible as noted above, but during docking and load exchange procedures the airship will respond as might a tall building. These considerations lead to a prediction of somewhere between 1 and 4 lightning strikes per airship per year.

LIGHTNING STRIKE ZONING

The certifying authorities have recognized that not all of the lightning flash currents will enter or exit from the same location on an aircraft, because of the aircraft geometry and flight envelope, and have defined lightning strike zones [2] that can be applied to establish which components of the lightning environment are applicable to each surface and structure. Some lightning currents may “sweep” alongside and reattach to a surface at multiple locations during the flash lifetime so these surfaces receive not all of the lightning flash currents. These lightning strike zone definitions are also applicable to an airship.

Three different situations, shown in Figure 1, have to be considered for location of the lightning strike zones of the airship.

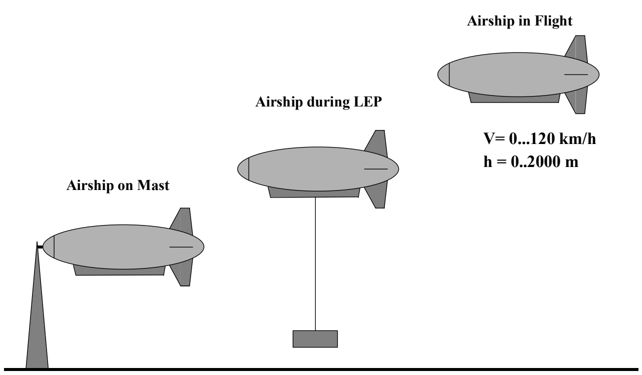


Figure 1. Airship Zoning Situations

- Airship moored on the mast
- Airship during the load exchange process (LEP)
- Airship during flight

A speed of up to 120 km/h has to be taken into consideration in determining possible lightning leader and channel sweeping distances.

Application of the zone location guidelines in [2] yields the zone locations for all exposure situations. The consequence is that the upper envelope and outer empennage surfaces and the keel lower surfaces are generally located in zone 1B, the lightning strike zone which has to experience the highest requirements consisting of the fast and slow electric fields and all flash current components defined in [1]. Some other surfaces of the empennage and keels are in zones 2A or 2B. All of the fixed structures are exposed to zone 3 conducted currents. The currents applicable in Zones 1B, 2B, and 3 are shown in Figure 2.

Lightning Zone	Voltage Waveforms	Current Waveforms
1B	A, B, D	A, B, C, D, H
2B	A	B, C, D, H
3	-	A, B, C, D, H

Figure 2. Survey of the Lightning Environment Waveforms

Due to the fact that the speed of the airship can be very low or zero, the 1A, 2A and 1C zones are generally not considered. They are covered by the relevant B-zones.

With respect to protection against the indirect effects the lightning Multiple Stroke and Multiple Burst environments are also considered.

PROTECTION DESIGN APPROACH

A major part of the CL 160 lightning protection design effort is focused on protection of the envelope. Smaller airships and some balloons have successfully (evidently, for strike experience data is not kept by any certifying agency) been protected by a single catenary wire suspended some distance above the envelope; however the very large size of CL 160 makes this approach insufficient. Additional lightning conductors will be necessary and a major design challenge is to place these conductors so that they will prevent envelope punctures or other damage associated with internal or external surface flashovers.

High voltage tests to evaluate helium breakdown and lightning leader field effects on 2 m and 4 m long, 1 m diameter helium filled cylinders of candidate envelope materials have been carried out at Lightning Technologies, Inc. (LTI) at Pittsfield, Massachusetts, USA. Tests with High Current components A, B, C and D are also being carried out on candidate lightning conductor designs and conductor interfaces to reach successful designs and installation procedures for the lightning conductors.

Additional tests to evaluate DC electric field and lightning leader effects on cylinder and larger helium filled envelope material shapes are being carried out at the new high voltage laboratory of Brandenburg Technical University (BTU), at Cottbus, Germany, which is located close to Brand, the location of CargoLifter Development GmbH.

HELIUM IONIZATION TESTS

Data on the ionization and breakdown potential of helium gas is not readily available in the literature (unlike air, for which a very large and consistent data base exists) so helium breakdown tests were conducted on 1 m gaps with standard 0.5 inch (12.5 mm) square rod electrodes at LTI and on smaller needle gaps at BTU. The arrangement for the 1 m gap tests, and subsequent tests of breakdowns inside helium filled envelope cylinders is shown on Figure 3 and a typical breakdown within the 1 m helium filled cylinder Is shown in Figure 4.

Rod Gap Enclosure and Cylinder at LTI

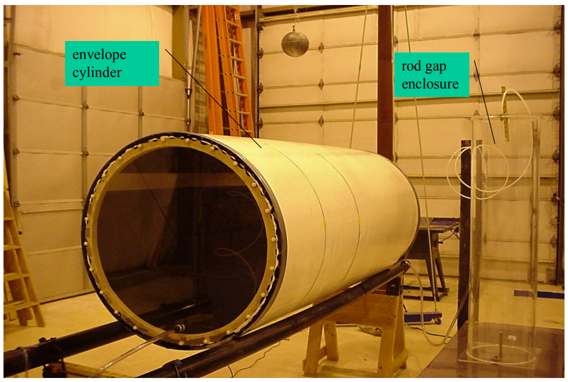
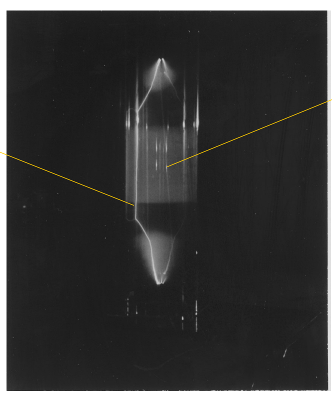


Figure 3. Arrangements for Helium Tests

Arcover along cylinder wall



glow discharge

Figure 4. Helium Breakdown in Cylinder

Prior tests with air in the cylinder yielded a critical flashover voltage (CFO) for the 1 m rod-rod gap of 600 kV which is in accord with prior published data. The CFO is the applied voltage that results flashover of the gap 50% of the time.

Tests of the same gap within a 99%+ purity helium environment showed partial breakdowns of the same 1m rod - rod gap beginning at 230 kV (approx) into glow (i.e. "cold" streamer formation) at 60% of this voltage and ionization of the Helium into a luminous conducting condition whose volume resistivity averaged about 70 ohm-meters. The luminous condition is visible in the 30 cm diameter transparent plastic cylinder of Figure 4. When the gap was significantly overvoltaged, complete sparkovers occurred, usually along part of the inner surface of the plastic cylinder.

Tests were also conducted with helium concentrations of 86%, 95%, 98%. The concentration percentages are calculated from volumes of He flowed through the cylinder, and are therefore not precise. At 86%, breakdown occurs at 270kV/m on the rise of the 1.2 x 50 us voltage waveform which was set to reach the air breakdown voltage of 600+kV. At 99% the He breaks down at the crest (peak) of a 190kV impulse voltage.

The helium breakdown process appears to begin in the classical fashion with short concentrated streamers at each electrode and a uniform glow (cold) discharge across the gap, that is most apparent at the higher He concentrations. At slightly higher generator voltage settings, the gap is bridged with a "hot" arc.

Similar tests were made at BTU with an 11 cm needle gap with lightning impulse and DC voltages applied and these results showed nearly the same 1:3 relationship of breakdown voltages with air as had been recorded from the 1 m rod-rod gap tests..

These test results indicate that in the presence of strong electric fields, flashovers would be more likely to occur inside rather than outside of a helium filled envelope.

The large HV-laboratory at BTU with its dimensions of 30 x 24 x 15 meter was used to investigate the behaviour of candidate lightning conductor arrangements on a 4 m long, 1 m diameter cylinder which represents a 1:65 scale of the CL 160 envelope cross section at the center of the airship. Tests on larger models, representing smaller scaless are planned.

Figure 5 will give a first impression of the BTU lab with its high voltage AC-, DC- and impulse test generators. Also one of the largest environmental test chamber in Germany can be seen with a size of 7 x 5 x 8 meters, a temperature range of –50 … +80 degree centigrade and a humidity range of 10%…95%. This chamber will be used for tests of the conductor designs in rain and ice conditions.

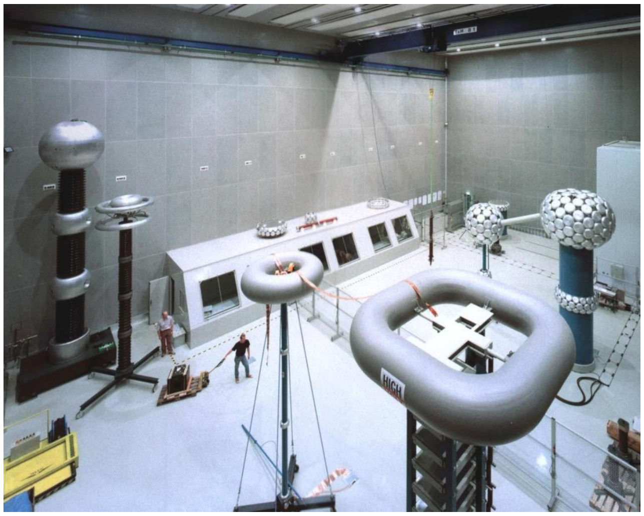


Figure 5: HV-test lab at Brandenburg Technical University at Cottbus, Germany

To model the different natural phenomena, different test circuits must be used. For example, electric field conditions representing airship initiated leaders in a static electric field are applied from a 1500 kV HV-DC source and a large flat electrode with diameter of 2 meters to simulate a cloud charge

Naturally approaching lightning leaders were simulated by a lightning impulse generator with its rated voltage up to 1800 kV and the standard pulse form of 1.2/50 us was used. To validate effectiveness of a conductor on the exterior of the cylinder with another impulse waveform, switching impulses with 250/2500 us up to 1400 kV were also applied. One such test is illustrated in Figure 6. In this test flashover occurred to the conductor on the exterior surface and no electrical activity can be seen through the transparency at the ends of the cylinder.

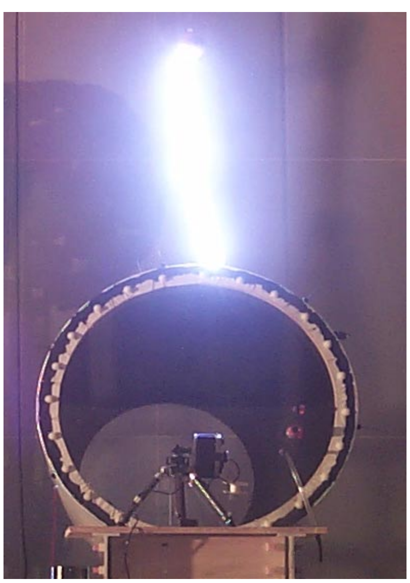


Figure 6. Lightning Leader Voltage Test on the 1:65 scale cylinder

Continuing current effects on envelope materials due to surface flashovers are being evaluated with simulated lightning current arc channels alongside typical envelope materials using long duration alternating current (AC) arcs. These arcs were produced by a set of cascaded AC transformers to reach a maximum voltage of 1000 kV (rms). By using a special reactance between the HV electrode and the cylinder a short circuit current can by realised with a first peak in the range of 1-3 kA followed by several amperes for about 1 or 2 seconds.

Tests on a larger scale model of the CL 160 with candidate lightning conductor arrangements are planned. Such a model is pictured in Figure 7, without conductors present.

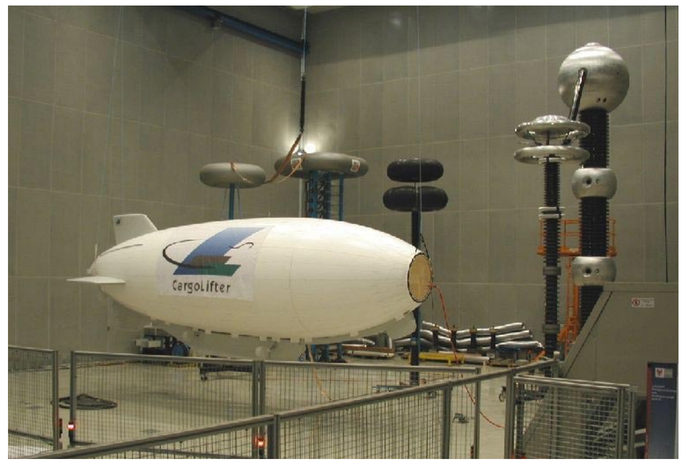


Figure 7. 1/25 Scale Model of CL 160 in BTU HV Laboratory

NUMERICAL SIMULATION

BACKGROUND - Numerical simulation plays a significant role in the lightning verification of the airship for at least two reasons. First, the vehicle is much too large to perform full scale vehicle testing. Second, by the time such testing could ever be done, it would be too late. It is necessary to understand and solve the lightning issues during the design process, long before the vehicle is assembled.

Numerical simulation is used in close partnership with the testing described earlier in this paper. Both approaches have limitations and advantages, and together they form a complementary capability allowing the creation of protection designs with a high degree of confidence.

NUMERICAL METHODS – Several simulation packages are used in the airship design:

- EMA3D – This is a 3D time domain finite difference application produced by Electro Magnetic Applications, Inc. It is used to model the airship and airship components in 3D. This package can directly import vehicle geometry from CATIA, the CAD system used by CargoLifter.

- Method of Moments (MOM) – This is an unnamed package developed by EMA used to obtain detailed information about the static electric field structure in the vicinity of various lightning conductors on the airship. This is useful because EMA3D can realistically model the entire airship with a cell size on the order of 1 m, given the existing capability of single processor workstations. However, in order to more fully understand the envelope protection issues, especially those with regard to helium already discussed, it is necessary to evaluate the field structure on a micro-scale, on the order of millimeters. This capability also allows for accurate inclusion of the envelope material properties in the simulation.

- MHARNESS – This is a time domain finite difference application produced by Electro Magnetic Applications, Inc. It is a solution of the multiple conductor transmission line equations, and is used to model complex wire harnesses on the airship. It can account for various shielding layers, connector design, harness layout, and bonding issues.

APPLICATION – The activities described in this paper have related to protection of the CL 160 envelope.
As noted earlier the basic approach is to apply a set of conductors along the envelope exterior surface, with the expectation that these strips will intercept any lightning strikes and thereby prevent damage to the envelope. A major design problem, therefore, is to determine where to apply these strips.

This is a complex lightning attachment problem, because as shown by the tests, the helium properties allow breakdown to occur within the helium volume before breakdown occurs in the air surrounding the envelope. The lightning strike initiation and attachment process, therefore, might begin with initial streamer development within the envelope, and if this occurs, the envelope will be punctured. The lightning protection strips must therefore limit the helium fields to less than breakdown levels so that lightning will first attach to the protection conductors.

As noted earlier the protection design and numerical analyses must consider the possibilities of airship initiated lightning leaders as well as naturally occurring lightning leaders.

In the first case, lightning can be initiated ("triggered") by the presence of the airship in strong static electric fields caused by thunderstorm electrification. The airship structure can locally increase these fields by a significant factor at various airship locations, such that streamers and lightning leaders originate at these locations and eventually propagate to cloud charge regions of sufficient potential to initiate a lightning strike. In this case the objective of the protection conductors is therefore to make sure that these initial streamers originate outside the envelope.

Second, an approaching stepped leader can also induce streamers from the airship, and again the protection strips must ensure that these initial streamers originate outside the envelope.

From a static field point of view, the difference between the two scenarios is that the first one involves numerical solutions for impressed uniform electric fields caused by cloud charges, and the second involves impressed nonuniform fields caused by the approaching leader channel.

Airship Triggered Lightning – For this type of simulation, uniform static electric fields are assumed as the originating lightning environment. These fields are assumed to exist in all three coordinate directions: parallel to the airship axis of travel; horizontal and perpendicular to the axis of travel; and vertical. Simulations are done for each of these orientations.

EMA3D is used to compute the airship interacted fields for each orientation with a 1 m resolution. The incident electric fields are created with a plane wave Huygens' surface. This surface creates an incident time domain step function electric field with a slow rise time. Although the solution is dynamic, it proceeds until a steady state is reached.

A typical result is shown in Figure 8.

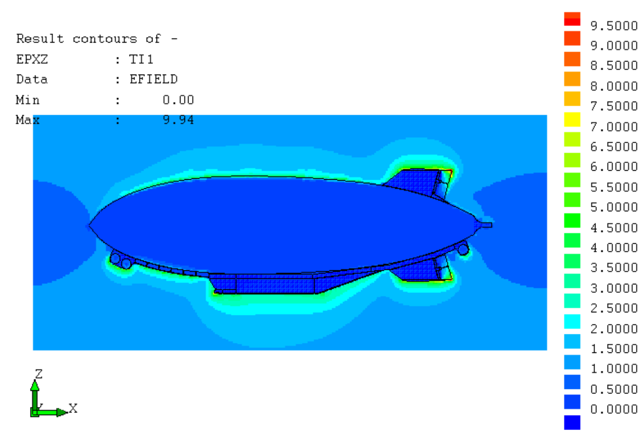


Figure 8. Typical Example of Airship Field Enhancement Factors for a Vertical Uniform Incident Static Electric Field for Triggered Lightning Evaluation

Lightning Caused by an Approaching Leader – For this type of simulation, nonuniform static electric fields caused by an approaching leader are assumed as the originating lightning environment. Numerically, it would also be possible to create these fields from a Huygens' surface, but this involves the extra work of creating the appropriate sources on this surface for an approaching leader.

Instead, a simpler approach is taken. The fields from a 1 km long leader having a linear charge density of 1 C/km are computed as shown in Figure 9 which also shows an airship shape for illustration purposes. The approach is to replace the linear charge density with an equivalent point charge, such that the incident fields in the vicinity of the likely attach points are the same. This creates some error in the field distribution elsewhere on the airship, but accuracy is really only required in the vicinity of the attach points.

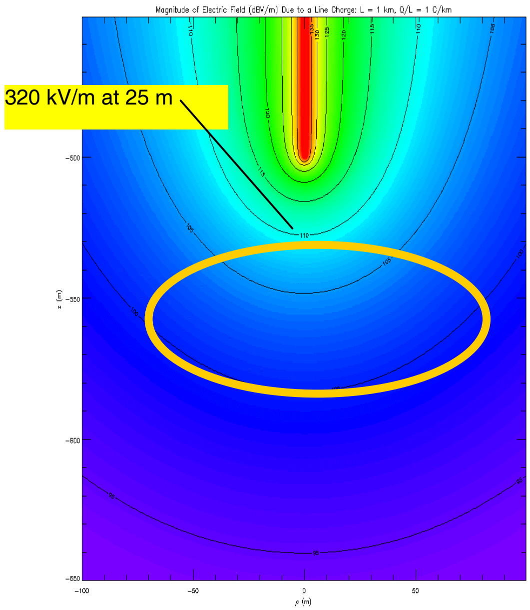


Figure 9. Fields from an Approaching Stepped Leader 1 km long and having 1 C/km linear charge density

This approach also has the advantage that it can be used in the direct simulation of laboratory scale model attachment testing, because a spherical electrode is used as a source there as well.

An example of field distributions on the airship for this case is shown in Figure 10.

Electric Field Microstructure – Once the fields are computed on a 1 m resolution, the fields with much finer resolution can be obtained. The general approach is to obtain the linear electrostatic charge densities on the lightning protection strips from EMA3D. These charge densities are then used as sources for the 2D MOM code, which models the strips as infinitely long, and the fields are computed at any location near the conductor. In addition to the linear charge density, the incident field is also added to the solution. The resolution can be very fine, and cells on the order of 1 mm are used.

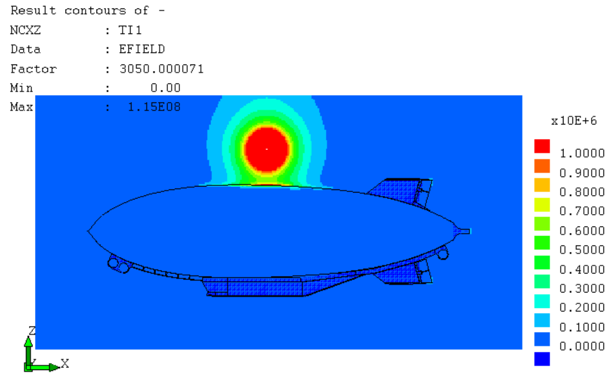


Figure 10. Field Distribution on the Airship Due a Leader 25 Meters above

CONCLUSION

Numerical simulation is used closely in combination with testing. Laboratory testing, described earlier in this paper, is used to perform attachment lightning testing on scale model airship protection designs. The same numerical approach described here is also applied to these laboratory test configurations with candidate conductor arrangements included. The result has been a good correlation of laboratory results with the numerical results. This then gives a high level of confidence that the numerical approach can then be used to extend the laboratory scale model results to the full size vehicle in flight.

ACKNOWLEDGMETS

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