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Lightning Simulation Notes

Note 1

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Simulation of Electromagnetic Aspects of Lightning

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In testing complex electronic systems for their vulnerability to lightning interference and electrical damage, it is necessary that the test include a simulation. For a simulation one requires that the experimental conditions be sufficiently close to the true physical environment that valid conclusions can be drawn concerning the response in such a criterion environment. Present commonly used test procedures, particularly for the direct-strike case, are in general not simulations. For the case of distant lightning, commonly used EMP simulation techniques are applicable with some modification in the sources (pulsers).

Electromagnetic processes peculiar to the direct-strike case are reviewed with respect to their implications for lightning electromagnetic simulation. At low frequencies (quasistatic) there are important surface-charge-density and corona effects in addition to the surface-current-density effects. At resonant frequencies the frequency-spectral content of the excitation and properties of the arc (attachment, detachment, time history, spatial distribution, resistance, etc.) are significant. Of great compexity in all this are the nonlinear aspects of the arc and corona around the system of interest. The complexity of these various processes requires rigor in the simulator design. Potential simulation concepts are presented and their relative merits are discussed.

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I. INTRODUCTION

In an engineering discipline concerned with the reliable performance of some complex electronic system in an intense electromagnetic environment, there comes the question of the demonstration of the performance in such an environment. Such a system is in general so complex that one cannot have a complete understanding of its response to such an environment from first-principle calculations. While one may be able to calculate whether or not the signals at some electronic elements are sufficient to cause failure, some is not good enough (even though the information can still be useful). Given some definition of the mission of the system (in the electromagnetic environment) one must be able to determine whether or not the mission will be accomplished in the presence of the environment. This requires that there be no failures (in the mission accomplishment sense) in any of a certain subset of the electronic elements; such electronic elements (black boxes, subsystems, etc.) are usually referred to as <u>mission critical</u>. More importantly it is required that one know that there be no such failures with high confidence. There are possible exceptions to this stringent a requirement if sufficient redundancy is built into the system, but this is a more complicated question. In general the system complexity and the possibility (or even probability) that there are important signal paths which are not even identified (even implicitly) in the formal statement of the system design (blueprints, etc.), makes a reliance on first-principle analysis usually untenable for system vulnerability assessment.

Since system-level testing (experimentation) is required for high confidence assessment, the question arises as to what is an adequate test. One might think of an arbitrary electromagnetic stimulus as a test, but what assurance would one have that the system response would bear any significant relationship (for assessment) to its response in the real environment of interest. For the test to be useful it should be reasonably closely related to the real environment of interest and this relationship should be quantitative. Ideally this real environment is summarized in the form of a valid criterion. Paraphrasing an earlier definition [6], A lightning electromagnetic criterion is:

> a quantitative statement of the physical parameters of the lightning environment relevant to the electromagnetic response of a system of interest in a volume of space and a region of time and/or frequency extended to contain all physical parameters having a non-negligible influence on any of the electromagnetic response parameters.

Normally one will have to state some range or bounds of the parameters, and the time functions (waveforms) and/or frequency spectra may be specified in simplified analytic form, a form which, however, should quantitatively include all relevant environmental parameters.

To test to such a criterion in a way which is quantitatively related to it requires a special kind of test referred to as a simulation. For lightning (electromagnetic) simulation the definition of nuclear electromagnetic pulse (EMP) simulation can be adapted [7].

> Lightning (electromagnetic) simulation is an experiment in which the postulated lightning exposure situation is replaced by a physical situation in which:
>
> 1. the lightning sources are replaced by a set of equivalent sources which to a good approximation produce the same excitation (including reconstruction to the extent feasible) to the total system under test or some portion thereof as would exist in the postulated nuclear environment, and
>
> 2. the system under test is configured so that it reacts to sources (has the same Green's function) in very nearly the same way and to the same degree as it would in the postulated lightning environment.
>
> A lightning (electromagnetic) simulator is a device which provides the excitation used for lightning simulation without significantly altering the response of the system under test by the simulator presence.

Lightning (electromagnetic) simulation naturally divides into types according to the types of lightning environments to be simulated. If the system of interest is sufficiently distant from the lightning stroke and its associated ionization, the simulation problem is somewhat simplified due to the ability to separate the incident and scattered fields at the system; this case is briefly discussed later. A much more difficult case is that of a direct lightning strike to the system because of the complex electromagnetic field structure, the time-varying electromagnetic properties (conductivity, etc.) of the lightning arc and corona around the system, and the nonlinear properties of the lightning arc and corona. This latter case is very important because of both the intense electromagnetic fields present and the poorly understood nonlinear and time-varying electromagnetic parameters of importance in this lightning source region. These source-region phenomena are of fundamental importance to the lightning simulation problem (for the direct strike); some of the implications of these phenomena for simulator design are discussed in this note.

There is a fundamental limitation in how far we can go in designing a lightning (electromagnetic) simulator; namely one must know what he is to simulate. The detailed physical processes of the lightning arc and corona are poorly quantitatively understood. How then does one simulate it? One can try to have "real" arcs and corona, but how can one be sure that all the relevant physical parameters have been properly controlled. In a direct-strike situation such questions can be very important, while for distant strokes the problem can be reduced to the locally incident electromagnetic fields and electromagnetic properties of the local materials. Particularly in the direct-strike situation the reader should note that the present considerations concerning a lightning simulator are based on the current limited understanding of the lightning arc and corona. As our understanding of the lightning physics becomes more detailed, more rigorous design constraints may be placed on the simulator.

II. Simulation of Distant Lightning

If, as indicated in figure 2.1, the lightning arc is distant from the system of interest, the lightning interaction is greatly simplified. Let S be a closed surface bounding an interior volume V which contains the system of interest. For simplicity let the system be in "free space" such as an in-flight missile or aircraft.

Let all the current and ionization associated with the lightning arc be outside S (i.e., not in V). Then the field equivalence principle can be invoked by noting that the incident field in V (in the absence of the system) is determined by imposing the tangential components of the original $\vec{E}$ and $\vec{H}$ on S via equivalent electric and magnetic surface current densities on S [8,11]. These equivalent currents also give zero fields outside S. Having referred the incident fields to equivalent sources on S, note that the incident fields are somewhat decoupled from the lightning arc. We do not need to understand the details of the lightning arc if we have sufficient knowledge of the incident fields (say by measurement of such fields).

Introducing the system into V there are now scattered fields which propagate away from the system through S. These fields can scatter from the lightning arc (in general a nonlinear process) and in turn rescatter from (interact with) the system thereby changing the system response. To avoid this interaction of the system with the lightning arc one can require that the system be sufficiently far from the arc that the interaction via the multiply scattered waves be sufficiently small as to be insignificant. In this latter approximation the system can be considered as responding to the lightning incident fields in a manner decoupled from the arc physical processes.

In this case of the system distant from the lightning arc the simulation problem is greatly simplified. The problem becomes similar to that found in many EMP simulation problems in which the system is away from the source region. Referring to figure 2.1 the equivalent sources on S can be approximately synthesized with sets of electric and magnetic dipoles to correspond to any desired incident field (consistent with Maxwell's equations with no sources in V). This is the PARTES simulation concept which is quite general, but perhaps complex to implement [8].

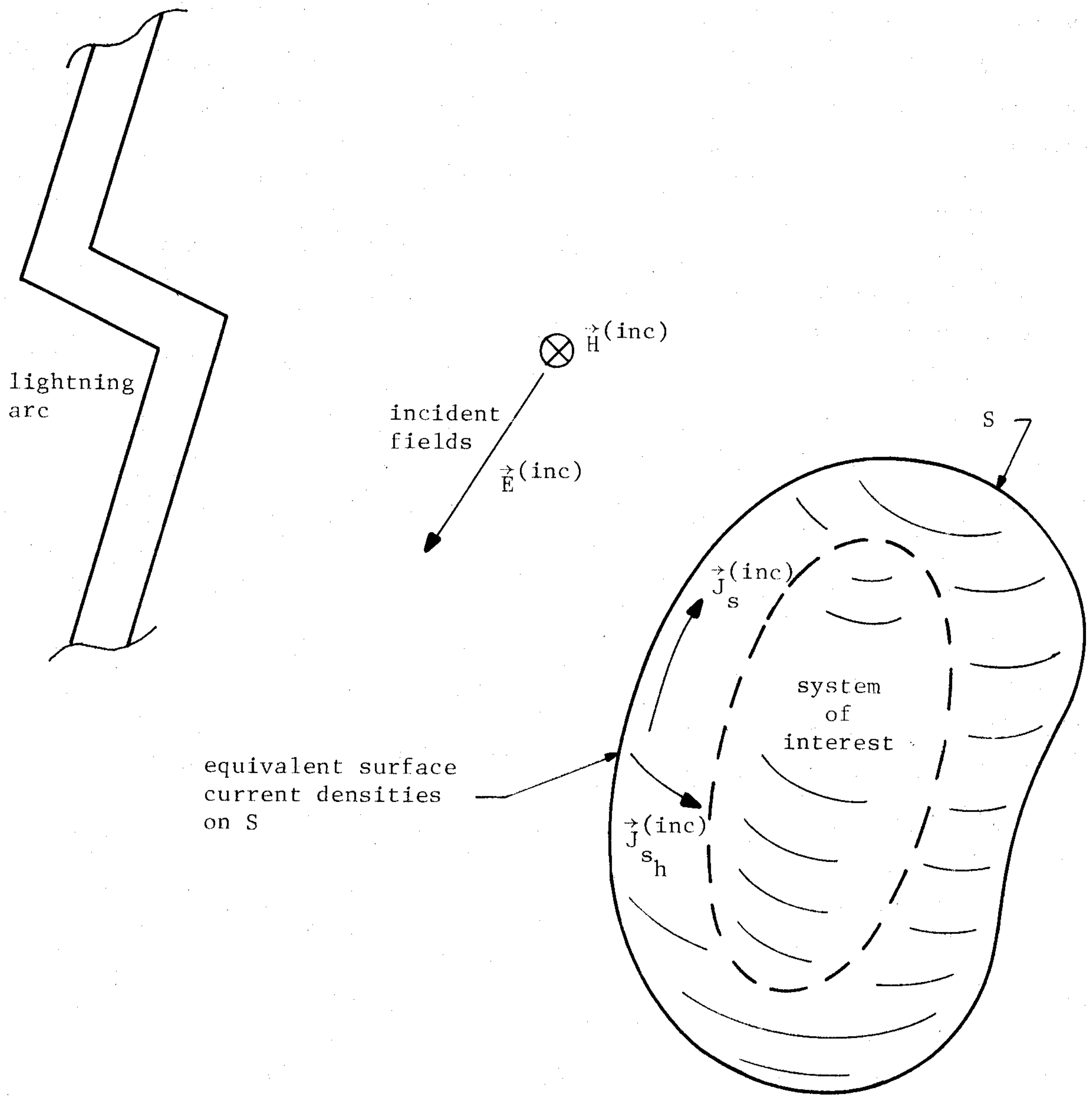


Figure 2.1. Fields Incident on System Away from Lightning Arc

If the system is sufficiently distant from the lightning arc that the incident fields can be considered as an approximate plane wave, then the problem further simplifies. The high-altitude EMP (below the source region) is also approximated as a free-space plane wave; various EMP simulator types produce an approximation of this type of field [7]. One of the most applicable types is the guided wave or TEM-transmission-line simulator constructed with parallel plates and conic sections for launch and/or termination of the wave. Note, however, that while the spatial forms (plane waves) are common between the cases of distant lightning and high-altitude EMP, the temporal forms (waveforms) are not the same. Thus while the simulator proper (electromagnetic-field-forming structure (waveguide, antenna, etc.)) can be used for both simulation problems, one needs different waveforms with different frequency spectral contents; this can be achieved by the use of different sources (pulsers, etc.) to drive the simulator proper. Hence some EMP simulators can also be used for lightning simulation for the case of distant lightning provided there are changes in the driving sources.

The discussion here has centered on the case of an in-flight system distant from lightning because of the simplifications thereby introduced. Similar considerations apply to the case of a system on or near the earth surface. If the system is sufficiently distant from the lightning stroke a plane-wave approximation can still be made, except that the ground reflection should also be included. This problem is also encountered in the case of the high-altitude EMP incident on systems near the ground surface. A commonly used simulator for this type of EMP is a hybrid EMP simulator shaped as an impedance loaded arch (half loop) connected to the earth with a generator in one position in the arch [7]. This simulator includes the incident and reflected waves at the ground surface, but again for application to the simulation of distant lightning the required waveforms are different requiring a modification in the simulator sources.

III. Simulation of Direct-Strike Lightning

A more interesting and more difficult type of lightning (electromagnetic) simulation is that concerned with a direct strike including arc attachment to and detachment from the system and corona surrounding the system. Since in general the stimulus is larger than that from distant lightning, the direct-strike case is important to understand and design against.

The first and fundamental problem to observe is that the system is in contact with the nonlinear and time-varying source. As such the separation into incident fields followed by system response discussed in the previous section is no longer applicable. A surface S surrounding the system as in figure 2.1 now has current passing through S into (and out of) V. The problem no longer separates into incident and scattered fields. The system is in the source and influences the evolution of the lightning arc. The interaction of the fields with the system is in turn influenced by the nonlinear, time-varying arc which can change the electromagnetic properties of the system (e.g., natural frequencies), and by the nonlinear, time-varying corona which can influence the response of the external penetrations (apertures and antennas) on the system.

Subsequent sections of this note consider some of the important aspects of the interaction of direct-strike lightning with the system, and the implications of the processes for lightning simulator design. Beginning with the recognized low-frequency current effects, the lightning interaction and simulator design are extended to include charge (more generally normal-current-density) effects and the associated corona. Then the arc-conductance effects are considered as well as the interaction of peripheral parts of the simulator with the test object. The inclusion of all these effects leads to a more rigorous simulator design.

IV. Quasistatic (Low-Frequency) Considerations

Consider first the case that wavelengths of interest are large compared to the exterior system dimensions; this is the low-frequency or quasistatic regime. For this part of the lightning interaction problem one can think of the current flowing through and charge on the aircraft as producing responses which are separable from each other, at least as an approximation.

While the magnetic fields associated with the lightning-arc current flowing on the system surface can penetrate through a metallic surface at sufficiently low frequencies, this type of penetration is usually not of dominant significance because the shield inductance and resistance (of the basic metal) make a low-pass filter with a very low roll-off frequency. (Note that for some composite materials with conductivities much lower than those of typical metals this magnetic distributed type of penetration can be of greater significance.) For typical systems such as aircraft the important penetrations are generally more discrete (spatially localized) in nature; they include apertures, antennas, and various direct conductive penetrations such as power, signal lines, mechanical control cables, etc. For the present discussion consider the cases of small apertures and antennas as illustrated in figure 4.1.

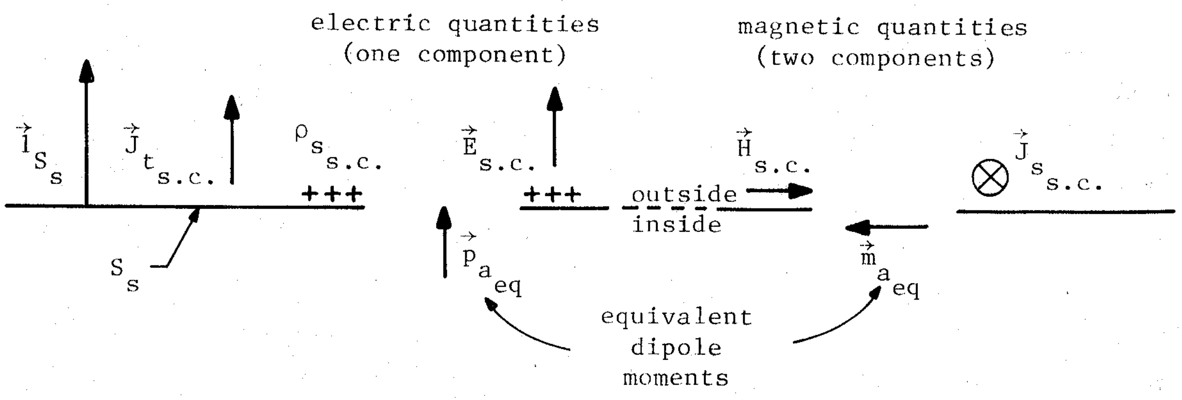
Consider, as in figure 4.1A, the case of small apertures. In the linear approximation the fields inside an exterior conducting system surface (at positions not near the aperture) are derived from equivalent dipole moments at the aperture. By an equivalent dipole moment is meant that vector quantity which, when substituted in the formulas for fields in free space [9], approximately gives the correct fields over a volume of space of interest, at least in the low-frequency asymptotic form for positions not close to the aperture. In this sense we can write

$$\tilde{\vec{p}}_{a_{eq}}(s) = \tilde{\overleftrightarrow{P}}_{a_{eq}}(s) \cdot \tilde{\vec{D}}_{s.c.}(s) = \varepsilon_o \tilde{\overleftrightarrow{P}}_{a_{eq}}(s) \cdot \tilde{\vec{E}}_{s.c.}(s)$$

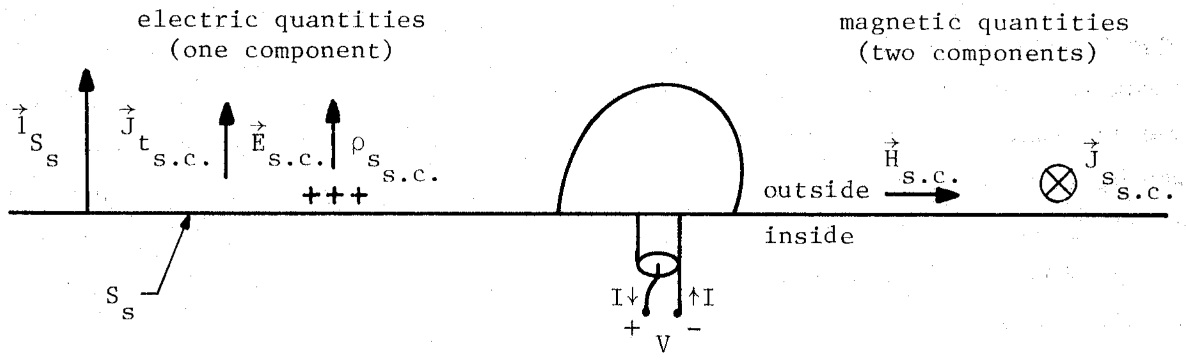
≡ equivalent electric dipole moment

$$\tilde{\vec{m}}_{a_{eq}}(s) = \tilde{\overleftrightarrow{M}}_{a_{eq}}(s) \cdot \tilde{\vec{H}}_{s.c.}(s) = \frac{1}{\mu_o} \tilde{\overleftrightarrow{M}}_{a_{eq}}(s) \cdot \tilde{\vec{B}}_{s.c.}(s)$$

≡ equivalent magnetic dipole moment



A. Apertures



B. Antennas

Figure 4.1. Quasistatic Interaction Mechanisms for Small Penetrations

$s \equiv \Omega + j\omega \equiv$ complex frequency or Laplace-transform variable (4.1)

$\sim$ indicates Laplace transformed quantity (for, in general, two-sided Laplace transform)

where the subscript s.c. ($\equiv$ short circuit) indicates the electromagnetic fields on the system exterior with the aperture closed (shorted). These short-circuit fields can also be related to the corresponding surface current and surface charge densities via the unit outward-pointing normal vector $\vec{1}_{S_s}$ to the system boundary surface S_s as

$$\begin{aligned} \vec{E}_{s.c.} &= \frac{1}{\varepsilon_o} \rho_{s_{s.c.}} \vec{1}_{S_s} \\ \vec{H}_{s.c.} &= -\vec{1}_{S_s} \times \vec{J}_{s_{s.c.}} \end{aligned} \tag{4.2}$$

Assuming for the foregoing that the system exterior (outside S_s) is free space with

$$\begin{aligned} Z_o &= \frac{\mu_o}{\varepsilon_o} \simeq 377\ \Omega \qquad \text{(wave impedance)} \\ c &= \frac{1}{\sqrt{\mu_o \varepsilon_o}} \simeq 3 \times 10^8\ \text{m/s} \qquad \text{(speed of light)} \end{aligned} \tag{4.3}$$

one can make some observations concerning the relative magnitudes of the electric and magnetic types of aperture penetration. Considering the case of an open aperture (say a circular hole) first note that the equivalent polarizabilities

$$\begin{aligned} \tilde{\overleftrightarrow{P}}_{a_{eq}}(s) &\equiv \vec{1}_{S_s} \vec{1}_{S_s} \tilde{P}_{a_{eq}}(s) \qquad \text{(equivalent electric polarizability)} \\ \tilde{\overleftrightarrow{M}}_{a_{eq}}(s) &\equiv \left[\overleftrightarrow{1} - \vec{1}_{S_s} \vec{1}_{S_s} \right] \cdot \tilde{\overleftrightarrow{M}}_{a_{eq}}(s) \qquad \text{(equivalent magnetic polarizability)} \end{aligned} \tag{4.4}$$

have units (meter)^3, making them some kind of equivalent volumes. Furthermore an open hole (perhaps covered with an insulator) has polarizability components of order d^3 where d is a characteristic dimension of the aperture (say the radius of a circular hole). Specifically the dominant components of the electric and magnetic polarizabilities of an unloaded circular aperture are about equal, and frequency independent for wavelengths $\lambda \gg d$.

For the case that the short-circuit electric field is the same magnitude as Z_o times the short-circuit magnetic field, i.e., for

$$|\tilde{\vec{E}}_{s.c.}(s)| \simeq Z_o |\tilde{\vec{H}}_{s.c.}(s)| \tag{4.5}$$

and assuming (as above) comparable equivalent aperture polarizabilities, i.e.,

$$|\tilde{\overleftrightarrow{P}}_{a_{eq}}(s)| \simeq |\tilde{\overleftrightarrow{M}}_{a_{eq}}(s)| \tag{4.6}$$

where for dyads (or matrices) the magnitude $||$ is the 2 norm (or spectral or euclidean norm) [10], then we have from (4.1)

$$|\tilde{\vec{p}}_{a_{eq}}(s)| \simeq \frac{1}{c} |\tilde{\vec{m}}_{a_{eq}}(s)| \tag{4.7}$$

provided $\tilde{\vec{H}}_{s.c.}$ is oriented approximately in a direction corresponding to the largest components of $\tilde{\vec{M}}_{a_{eq}}$. This result (4.7) is precisely that for making the far fields (r^{-1} terms) in the dipole formulas comparable for both electric and magnetic dipoles [5]. The near fields (r^{-2} and r^{-3} terms) are dominantly electric for electric dipoles and magnetic for magnetic dipoles. Thus, for a significant class of apertures, comparable short-circuit exciting fields (related by Z_o as in (4.5)) give comparable fields penetrating the aperture.

Now consider direct-strike lightning. Figure 4.2 illustrates the case of some elongated object of radius a (with length >> a) which might represent a missile or aircraft. Let arc 1 first attach to one end followed by arc 2 detaching from the other end. For quasistatic (slow time variation) considerations with current I flowing through the system we have a typical short-circuit magnetic field on the system surface

$$H_{s.c.} \simeq \frac{I}{2\pi a} \tag{4.8}$$

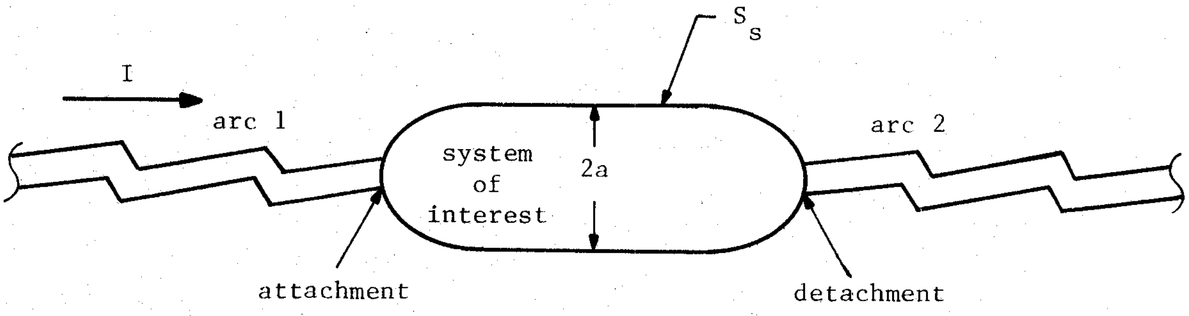


Figure 4.2. Quasistatic Surface Fields for Direct-Strike Lightning

The corresponding short-circuit electric field can be estimated by noting that an arc leaving the system surface occurs when the breakdown electric field of air has been exceeded. This implies an electric field of

$$E_{s.c.} \simeq 3 \text{ MV/m} \tag{4.9}$$

or a little less because of the system's operating altitude. Letting

$$a \simeq 1 \text{ m} \tag{4.10}$$

let us consider two cases:

Case 1:

$$\begin{aligned} I &\simeq 200 \text{ kA} \\ H_{s.c.} &\simeq 30 \text{ kA/m} \\ \frac{E_{s.c.}}{H_{s.c.}} &\simeq 100\ \Omega \end{aligned} \tag{4.11}$$

Case 2:

$$\begin{aligned} I &\simeq 20 \text{ kA} \\ H_{s.c.} &\simeq 3 \text{ kA/m} \\ \frac{E_{s.c.}}{H_{s.c.}} &\simeq 1000\ \Omega \end{aligned} \tag{4.12}$$

These cases of interest then give quasistatic E/H ratios on the system surface comparable to Z_o. Thus the quasistatic electric and magnetic fields are of comparable importance for penetration through a class of apertures.

For this result the effect of corona on the polarizabilities has not been included. Our estimate of the quasistatic electric field in (4.9) is based on streamers (arcs) leaving S_s. One form of such breakdown can be considered a corona around much of S_s. One can readily show that the magnetic-field change associated with bounded variations in the air conductivity around local perturbations of S_s (such as apertures) is small in the quasistatic (low-frequency) limit [2]. Basically a bounded conductivity change over a small region does not significantly alter an external magnetic field provided the skin depth (or diffusion depth) in the region is large compared to the size of the region. However, the case for the electric field is quite different. The air conductivity σ directly combines with the electric field $\vec{E}$ producing the current density $\vec{J}$ $(= \sigma\vec{E})$. The low-frequency local continuity of the current density clearly indicates that changes in σ change $\vec{E}$ in a comparable way. This change in σ can then change the equivalent electric dipole moment and the corresponding electric polarizability by changing the charge distribution in the vicinity of the aperture, including in the air as well. Note that the nonlinear (and poorly known) character of the corona near the aperture significantly complicates the problem and requires the analysis to be conducted in time domain. It may be interesting to view this electric response in terms of the total current density

$$\vec{J}_{t_{s.c.}} \equiv \left(\sigma + \varepsilon \frac{\partial}{\partial t}\right) \vec{E}_{s.c.} \qquad (4.13)$$

which includes the local corona conductivity.

The case of electrically small antennas on S_s is indicated in figure 4.1B. Analogous to the aperture-penetration formulas (4.1) one has the linear response of such antennas as

electric:

$$\begin{aligned} \tilde{V}_{o.c.}(s) &= -\tilde{\vec{E}}_{s.c.}(s) \cdot \tilde{\vec{\ell}}_{eq}(s) \\ \tilde{I}_{s.c.}(s) &= -s\tilde{\vec{D}}_{s.c.}(s) \cdot \tilde{\vec{A}}_{eq}(s) \end{aligned} \qquad (4.14)$$

magnetic:

$$\begin{aligned} \tilde{V}_{o.c.}(s) &= s\tilde{\vec{B}}_{s.c.}(s) \cdot \tilde{\vec{A}}_{eq}(s) \\ \tilde{I}_{s.c.}(s) &= \tilde{\vec{H}}_{s.c.}(s) \cdot \tilde{\vec{\ell}}_{eq}(s) \end{aligned} \qquad (4.15)$$

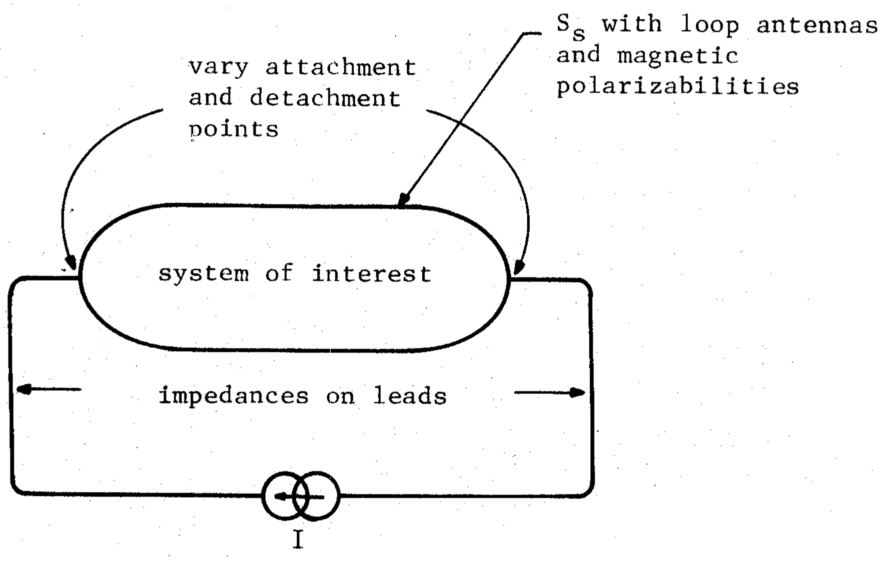
for open-circuit voltage and short-circuit current. Note that the electrically small antennas are usually characterized by equivalent lengths (or heights) and equivalent areas. While these are generally functions of frequency, simple electric- and magnetic-dipole antennas have frequency-independent equivalent lengths and areas in the electrically small regime [4]. In the quasistatic regime of the system the direct-strike lightning current is important for magnetic antennas, and the lightning charge is important for electric antennas.

Note that as in the case of apertures the corona in the vicinity of the antenna needs to be considered. The effect of corona conductivity on the response of magnetic antennas is not of first-order importance at low frequencies [2]. It is, however, of fundamental importance to the response of electric (or current-density) antennas [1,3].

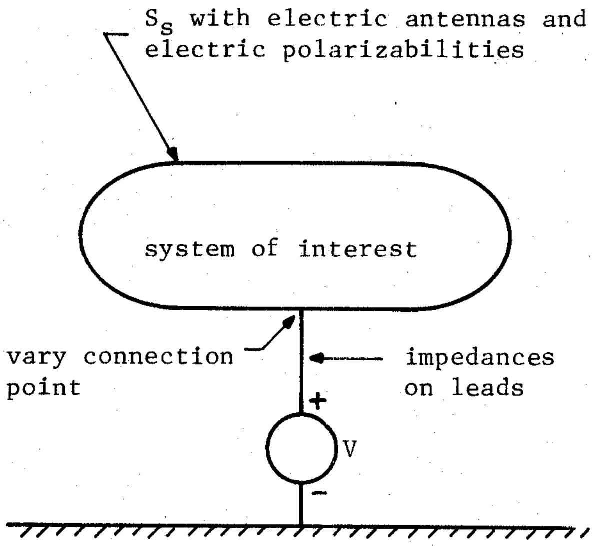
Noting the importance of both current and charge at low frequencies on the system of interest, one might attempt to simulate this part of the direct-strike lightning environment as illustrated in figure 4.3. The technique indicated in figure 4.3A is currently commonly employed, but note that as used it gives a large current with a (relatively) small voltage on the system. Beyond present practice, various types of impedance loading in the leads connecting to the pulse generator (and various impedances with the pulse generator) can be used to tailor the driving waveform and the response of the system by controlled loading of the system exterior.

The complementary simulation for the low-frequency charge is indicated in figure 4.3B. This charge or voltage simulation raises the potential of the system relative to some ground reference, such as a ground plane. This can be thought of as a high-impedance simulation in contrast to the low-impedance simulation for current. The capacitance of the system with respect to the ground reference is used to determine the required voltage (V) needed to produce the desired total charge (Q) on the system.

For both the current and charge quasistatic simulation one should be careful of lead placement and proximity of the system of interest to other objects (such as buildings, earth, etc.) because these all influence the distribution of the surface current and charge densities on S_s. In other words one should minimize what is referred to as the simulator/test-object interaction



A. Current (or tangential magnetic field)



B. Charge (or normal electric field)

Figure 4.3. Current and Charge Low-Frequency Simulation

[7]. Combining the two quasistatic techniques one might have a somewhat more complete simulation as indicated in figure 4.4. Here one has two sources V_1 and V_2 with associated impedances $\tilde{Z}_1$ and $\tilde{Z}_2$ together with a ground reference to establish the desired V and I on the system at low frequencies.

Note that, while our discussion in this section has been centered on the quasistatic regime for the system, the nonlinear character of the lightning arc and corona on S_s limits one's ability to completely separate the quasistatic regime from the higher-frequency regime. The early-time and resonant response all affect the lightning arc and corona which in turn influence the quasistatic response.

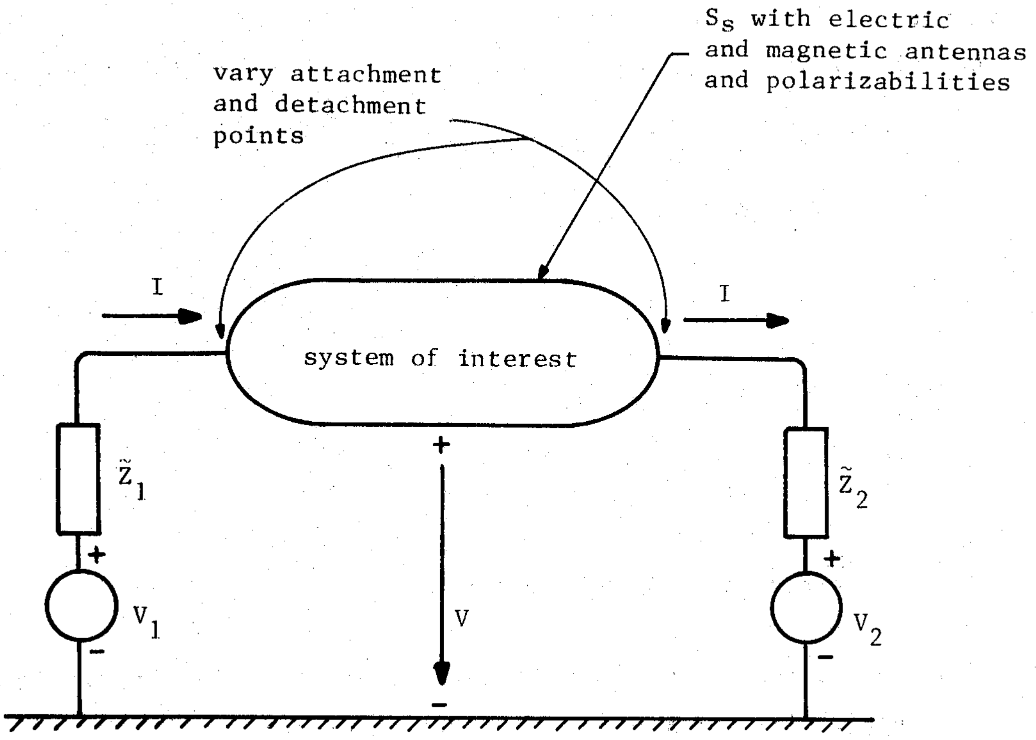


Figure 4.4. Combined Current and Charge Low-Frequency Simulation

V. Exterior System Resonances

It is well known that typical electromagnetic scatterers resonate in a manner characterized by damped sinusoids in time domain. These complex natural frequencies s_α are poles in the complex-frequency or s plane. Generalizing on this observation has led to the singularity expansion method (SEM) for the representation of the electromagnetic scattering process for linear (and to date time invariant) scatterers. There is a considerable literature now developed to which the reader may refer [13,14]. We are not concerned here with the general theory, but are concerned with some of its implications for the lightning external interaction and corresponding lightning simulation.

Consider an integral equation of the general form [14]

$$\left\langle \tilde{\overleftrightarrow{Z}}(\vec{r},\vec{r}\,';s) + \tilde{\overleftrightarrow{Z}}_\ell(\vec{r},s)\;\delta(\vec{r}-\vec{r}\,')\;;\;\tilde{\vec{J}}(\vec{r}\,',s)\right\rangle = \tilde{\vec{E}}_s(\vec{r},s)$$

$$\begin{aligned} \tilde{\vec{E}}_s(\vec{r},s) &\equiv \text{source or incident electric field} \\ \tilde{\overleftrightarrow{Z}}_\ell(\vec{r},s) &\equiv \text{impedance loading (such as lightning arc)} \\ \tilde{\vec{J}}(\vec{r},s) &\equiv \text{response current density} \\ \tilde{\overleftrightarrow{Z}}(\vec{r},\vec{r}\,';s) &\equiv \text{impedance kernel} \end{aligned} \tag{5.1}$$

with <,> indicating the domain of integration (the region over which the current density (or at least its relevant portion) exists.

Ignoring for the moment the nonlinear and time-varying character of the air conductivity in the lightning arc, let us approximate the impedance loading by the reciprocal of the air conductivity (times the dyadic identity). Without the arc one can find the exterior natural frequencies of the system from

$$\begin{aligned} \left\langle \tilde{\overleftrightarrow{Z}}(\vec{r},\vec{r}\,';s_\alpha^{(0)})\;;\;\vec{j}_\alpha^{(0)}(\vec{r}\,')\right\rangle &= \vec{0} \\ \vec{j}_\alpha^{(0)}(\vec{r}) &\equiv \text{natural mode without arc} \\ s_\alpha^{(0)} &\equiv \text{natural frequency without arc} \end{aligned} \tag{5.2}$$

where $\vec{r},\vec{r}\,'$ is here only over the system. In the moment method (MoM) [12] the impedance kernel is converted into a matrix $(\tilde{Z}_{n,m}(s))$ which allows one to find the natural frequencies from

$$\det\left((\tilde{Z}_{n,m}(s_\alpha^{(0)}))\right) = 0 \tag{5.3}$$

Now including the arc conductivity in an approximation as linear and time-invariant, we have a new equation for natural frequencies as

$$\left\langle \tilde{\overleftrightarrow{Z}}(\vec{r},\vec{r}\,';s_\alpha^{(1)}) + \tilde{\overleftrightarrow{Z}}_\ell(\vec{r},s_\alpha^{(1)})\ \delta(\vec{r}-\vec{r}\,')\ ;\ \vec{j}^{(1)}(\vec{r}\,')\right\rangle = \vec{0}$$

$$\vec{j}_\alpha^{(1)}(r) \equiv \text{natural mode with arc} \tag{5.4}$$

$$s_\alpha^{(1)} \equiv \text{natural frequency with arc}$$

with $\vec{r},\vec{r}\,'$ over the system plus arc. In general one does not expect the set of $s_\alpha^{(1)}$ to equal the set of $s_\alpha^{(0)}$ given their different defining equations. Furthermore, as the arc conductivity is varied the natural frequencies $s_\alpha^{(1)}$ will in general also vary. Similar observations can be made concerning the natural modes $\vec{j}_\alpha^{(1)}(\vec{r})$ and the amplitudes of these resonances known as coupling coefficients.

In order to have the $s_\alpha^{(1)}$ be correctly included in the simulation it is in general necessary that the arc conductance per unit length be properly included in the simulation. At least near the system, then, the leads from the pulse generators in figures 4.3 and 4.4 can be impedance loaded to approximate some desired arc conductance per unit length. If the lead lengths from their connections to the system are sufficiently long one can get at least some of the natural frequencies and natural modes (on the system) to approximate those appropriate to the desired arc conductance per unit length.

One should regard this arc-conductance part of the simulation as a necessary condition in the resonance regime of the system. It is not in general a sufficient condition because of the nonlinear and time-varying character of the real lightning arcs. In addition there is the corona surrounding the system under direct-strike lightning conditions which may also have some influence on the resonance-region response. To include these nonlinear and time-varying conductivities in the simulation may require a very realistic simulation with "real" current levels, voltages, and surrounding atmosphere with arcs and corona.

VI. Making Simulator a "Part" of a Long Lightning Arc

Previous sections have considered some of the aspects of the interaction of direct-strike lightning with electronic systems from the viewpoint of simulating such aspects with pulsers and impedances directly connected to S_s. However, such simulation is limited by the nature of the lightning arc, especially in its nonlinear and time-varying characteristics. This is further complicated by the limited state of quantitative knowledge concerning the detailed physical processes in the arc and the resulting conductance per unit length, tortuousity, etc.

A possible approach to lightning simulation which at least partly avoids some of these difficulties consists in constructing an arc in air and letting this arc attach to and detach from S_s. This arc is generated by an appropriate high-voltage pulse generator with impedance loading as illustrated in figure 6.1. The arc might be initiated at some high-voltage electrode, propagate toward the system of interest (perhaps meeting streamers from the system), attach to the system, charge the system, detach from the system, propagate toward a return conductor (such as a ground plane), and close to the return conductor, thereby completing the current path through the pulse generator.

This type of simulation might be referred to as dual-arc lightning simulation, referring to the two arcs connected to the system in figure 6.1. How closely this simulates the direct-strike lightning phenomenon depends potentially on various physical parameters. The arcs should be sufficiently long to simulate the important aspects of the natural phenomenon. For the simulation of in-flight conditions for the system (as for an aircraft or missile) one may wish to control the local air density, water-vapor content, etc. Clearly what is required for the environmental details can be a rather complex question.

A less complete form of the type of simulation in figure 6.1 would use only one arc in air. One might have an attachment single-arc simulation by electrically connecting the system to the return conductor to the pulser (through perhaps some distributed impedance). An alternate approach would be a detachment single-arc simulation obtained by connecting the system to the high-voltage electrode in figure 6.1 (again perhaps with special impedances). Both of these techniques allow charging of the system (with resulting large electric fields). However, the sequential charging and discharging in the nonlinear, time-varying arc manner is not fully accomplished.

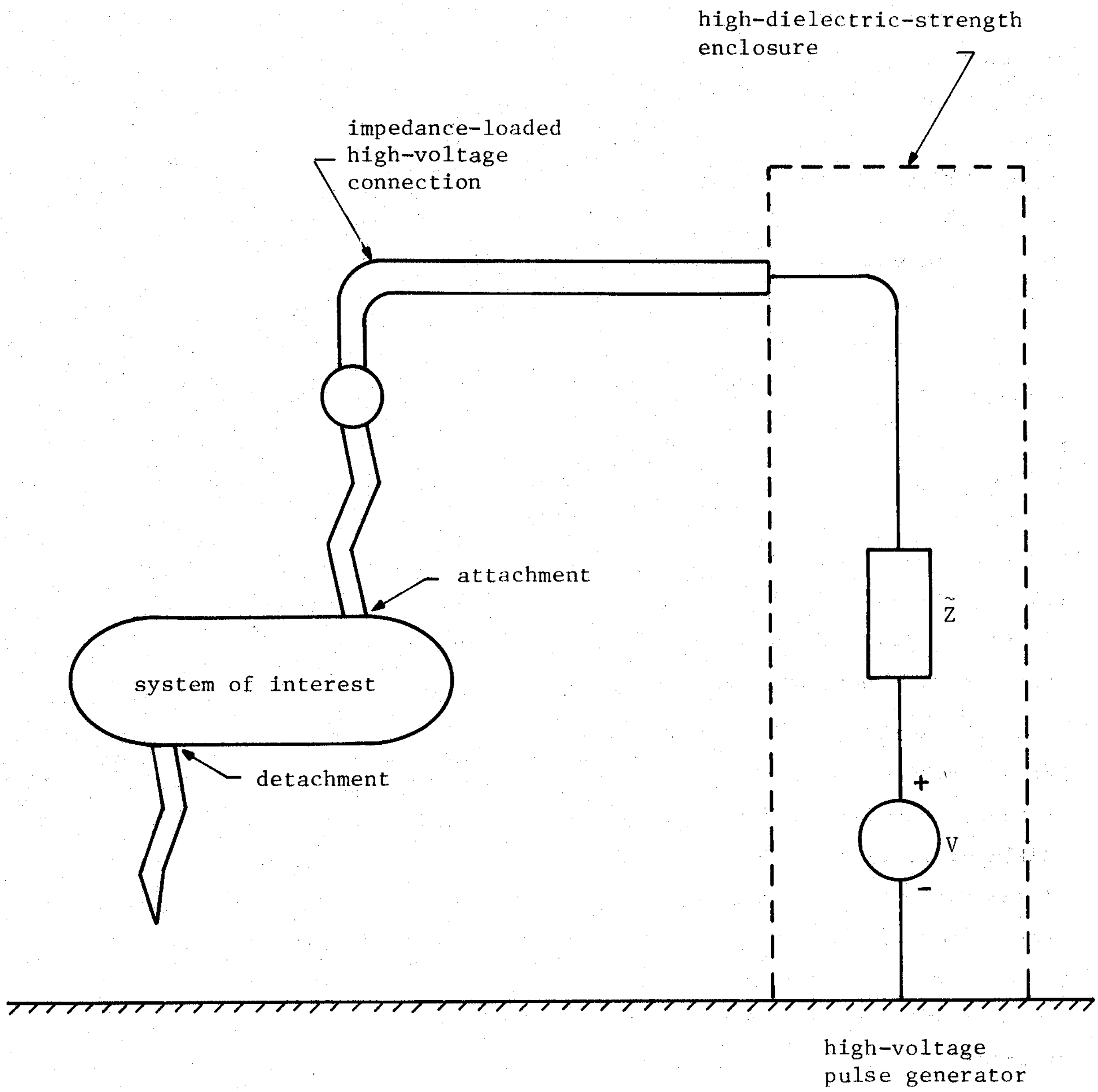


Figure 6.1. Dual-Arc Lightning Simulation

VII. Summary

As one may now realize, there are several possible improvements that can be incorporated into lightning testing to make the test a simulation. Associated with various identifiable physical processes in the lightning interaction with electronic systems, one can formulate corresponding constraints on the simulator design. While this leads to improved simulator designs, this is not necessarily complete because of the limited understanding of the lightning physical processes by the scientific/engineering community. For distant lightning, except for some waveform questions, the simulation problem is similar to a class of EMP simulation and thereby relatively well known. For direct-strike lightning the situation is quite complex and little understood by comparison.

For direct-strike lightning one can consider the physical processes involved to develop simulator design. Quasistatic considerations lead to the importance of both current and charge on the system, thereby requiring the simulator to produce large voltage as well as large current. In the resonance region SEM considerations lead to the requirement of simulating the lightning arcs in both geometry and impedance properties, at least near the system. Both low frequencies and resonance frequencies require that the non-arc conductors and other objects be positioned away from the system under test so as to not undesirably modify the system response. At high frequencies (short wavelengths compared to system dimensions) the problem is very messy making it difficult to identify specific aspects of the simulation associated with this regime.

By successively imposing the various constraints on lightning simulation one can progressively improve the realism of the simulation. Given the state of lightning understanding at a given time (such as the present) one can design a simulator which is consistent with this understanding. Such understanding already indicates that considerable improvement in lightning simulation is needed as discussed here. However, there is still the fundamental need of obtaining an adequate understanding of the lightning electromagnetic environment.

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