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Computation of locations of possible stepped leader attachment points on an aircraft flying under thunderstorm conditions

Abstract

In case of flight in a thunderstorm region, a lightning strike on the aircraft might occur. For better lightning protection, the locations of points on the aircraft skin where a stepped leader can be attached should be delimited. In this paper, the areas of the skin of an aircraft where a stepped leader might be attached are defined through an approach based on the fact that electrostatics and potential flow theory have the same mathematical background. This is done by computing the distribution of the electrostatic field on the metallic parts of the skin of the aircraft due to the ambient electric field. In any area of the skin, where the electric field resulting from the combination of the ambient electric field and the local electric field can ionize the air, attachment points of a stepped leader might exist. The advantage of this approach is a decreased computational time and computer memory needed, as compared to a full Computational Physics approach. The areas of the skin of a generic airliner delimited through this approach, at least qualitatively, are in agreement with photos taken under real thunderstorm conditions.

Keywords: aircraft, electric field, stepped leader, lightning, strike

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Theodore I Lekas
Department of Aerodynamics and Flight Mechanics, Hellenic Air Force Academy, Greece

Correspondence: Theodore I Lekas, Department of Aerodynamics and Flight Mechanics, Hellenic Air Force Academy, Dekelia AFB, TGA 1010, Dekelia, Attika, Greece, Email tlekas@hotmail.com

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List of symbols

U = electrostatic potential (V)

x,y,z = coordinates of a target point at the initial frame of reference (m)

x_k, y_k, z_k = coordinates of panel corner points at the initial frame of reference (m)

$\vec{n}$ = normal unit vector of a given panel, pointing outwards

$\vec{E}_{AMB}$ = local ambient electric field strength (V/m)

$\vec{E}_{DIST}$ = disturbance electric field strength caused by the aircraft (V/m)

$\vec{E}_{R}$ = resultant electric field strength at a given point (V/m)

q = electrostatic charge strength (C)

Introduction

During flight, an aircraft acquires an electric charge distribution mainly due to skin friction with the surrounding airflow and exhaust gas polarity. This makes the aircraft to induce an electrostatic field at any point of its surrounding area. In case of flight in a region of the atmosphere where an ambient electrostatic field exists, as for instance in the vicinity of a thunder cloud, electrostatic charging on the metallic parts of the skin of the aircraft will be created. The electrostatic field due to the resultant electrostatic charge distribution can trigger a lightning strike on the aircraft.[1-3]

There is evidence that a wide body airliner can trigger an attached flash if it is close enough to a thunder cloud, due to the significant perturbation of the cloud electric field it creates.[4,5] Aircraft geometry also affects flash triggering. In 90 % of the cases, lightning strike is initiated by the aircraft. Non metallic parts are also concerned since their electric and thermal resistivity is higher as compared to metallic parts. This results in puncturing or local melting, which in turn can affect flight safety in the case of an all wing integrated fuel tank (fuel vapor ignition and explosion). The electric and electronic onboard devices can also be affected by an electric surge. Due to forces of electromagnetic origin, metal skin dislocation may occur.[6]

Engines exhaust gases are slightly more ionized than the surrounding air,[7] so they are not expect to trigger a lightning strike. This is supported by the fact that entry points were never observed on the engine exhaust, except in the case where the engine exhaust is located at an extremity of the aircraft. In contrast, lightning is often observed in the case of rocket exhaust plumes. No evidence exists showing that jet - engined aircrafts are stuck more often than piston engined ones. Radar electromagnetic beam is considered too weak to ionize the surrounding air, so no flash can be triggered.

The steep rise in temperature or the shock wave associated to an attached flash may disrupt the airflow in front of an air intake. Smaller engines are more affected than bigger ones, for this reason fuselage mounted engines are more affected. Jet engine flame out, stall or roll back may occur. Wing mounted engines are much less affected because, due to their size, flash effects are insufficient to disrupt the inlet airflow.

Standard advice to pilots is to remain at least 20 nautical miles displaced from any Cumulonimbus cloud. The dangers from Turbulence, Wind Shear, and Icing associated with Cumulonimbus clouds are far greater than the threat of Lightning. They receive weather updates and most aircraft have on board weather radar which shows the storms clouds. However, the limitation of radar for avoiding lightning associated with clouds is that radar usually only picks up rain, not the cloud itself. So, aircraft can experience occasional encounters with hail, and with lightning, without warning. Fortunately, new generation radars have features that detect wind shears and other forms of precipitation.

Standard advice to pilots is to remain at least 20 nautical miles displaced from any Cumulonimbus cloud. The dangers from Turbulence, Wind Shear, and Icing associated with Cumulonimbus clouds are far greater than the threat of Lightning. They receive weather updates and most aircraft have on board weather radar which shows the storms clouds. However, the limitation of radar for avoiding lightning associated with clouds is that radar usually only picks up rain, not the cloud itself. So, aircraft can experience occasional encounters with hail, and with lightning, without warning. Fortunately, new generation radars have features that detect wind shears and other forms of precipitation.

Cumulonimbus clouds are associated to lightning strikes, rain, wind shear, turbulence and icing. The freezing level is also a flight altitude where a lightning strike might occur. The danger from heavy rain, wind shear, turbulence and icing is by far greater than the threat of lightning. In any case, pilots are advised to circumvent these clouds and fly at a distance of at least 20 nm away of them and receive weather updates. Most airliner are equipped with weather radars. The drawback is that radar can detect rain, not the cloud itself, so occasional encounters with hail or lightning can happen without warning. This makes that there is a limitation of radar capacities in avoiding areas of possible lightning strikes, although new generation radar are able to detect wind shear and other type of precipitation. As a consequence, lightning protections are mandatory.

These protections include wire bundle shields, ground straps, structure expanded foils, wire mesh, aluminum flame spray coating, embedded metallic wires, metallic picture frames, diverter strips, metallic foil liners, coated glass fabric or bonded aluminum foils.[8] Another kind of protection is proposed by an MIT research project. It is based on the fact that when an aircraft flies in an area where an ambient electrostatic field exists, its surface becomes charged like an electric dipole. According to MIT researchers, the use of adequate sign electric charge generators on the aircraft surface could alleviate the corresponding electric field. This approach seems to work, at least at a conceptual level.

In order to better design and use protection devices, the amount and the distribution of electrostatic charges acquired by the aircraft should be known.[9-11] The knowledge of the local electrostatic field distribution, due to the induced charge distribution, on the aircraft external surface will permit to better positioning all the needed protection devices. No fast computing approach was so far found in the literature. Such an approach could alleviate computer speed and memory issues, being a useful tool for aircraft configuration parametric study during the design phase. It would permit improved combined aerodynamic and lightning protection efficiency.

In this work, an approach for computing the electrostatic charge distribution acquired by an aircraft of arbitrary geometry flying under an ambient electric field of given strength, is discussed. This approach uses singularities and is based on the fact that electrostatics and potential flow theory have the same mathematical background. Unlike to a full Computational Physics approach, it needs only a grid on the surface of the aircraft instead of a grid on the surface and around it. This is a considerable saving in computer time and memory. Once the electrostatic charge distribution on the aircraft surface is computed, the corresponding electrostatic field distribution is easily obtained according to Gauss theorem.

Presentation of the approach

The external surface of an aircraft of arbitrary geometry is described by a number of points combined so as to form panels. The coordinates of these points are in a global frame. The origin of the global frame is located at the nose of the aircraft. The x-axis coincides with the longitudinal axis of the aircraft and is directed towards the tail. The y-axis is parallel to the span and points to the right wing according to a pilot's view. Z-axis is such that the global frame is a right orthogonal one.

All corner points of a panel lie on the same plane. The dimensions of each panel are sufficiently small, while the number of panels is adequate to avoid gaps. Each panel carries a homogeneous electrostatic charge distribution, which has to be calculated. The electrostatic charge of the metallic parts of the aircraft skin induces an electric field at any point at their vicinity.

Due to the common mathematical background of electrostatics and potential flow theory, the aerodynamic potential of a source/sink distribution on a panel[12] can also be used for electrostatic calculation purposes. In this work, positive and negative electric charges distribution is used instead of sources and sinks. The electrostatic potential U of each panel is expressed in a panel frame (local frame G, $\vec{l}$, $\vec{t}$, $\vec{n}$, G being the centroid of the panel).

For electrostatic purposes, the equation describing the flow potential (equation 1) is adequately modified by including the electrical permittivity of the air.

$$U=\frac{q}{4\pi\varepsilon_0}\left\{\left(\frac{(x-x_1)(y_2-y_1)-(y-y_1)(x_2-x_1)}{d_{12}}\ln\frac{r_1+r_2+d_{12}}{r_1+r_2-d_{12}}+\frac{(x-x_2)(y_3-y_2)-(y-y_2)(x_3-x_2)}{d_{23}}\ln\frac{r_2+r_3+d_{23}}{r_2+r_3-d_{23}}+\frac{(x-x_3)(y_4-y_3)-(y-y_3)(x_4-x_3)}{d_{34}}\ln\frac{r_3+r_4+d_{34}}{r_3+r_4-d_{34}}+\frac{(x-x_4)(y_1-y_4)-(y-y_4)(x_1-x_4)}{d_{41}}\ln\frac{r_4+r_1+d_{41}}{r_4+r_1-d_{41}}\right)\right\} \quad (1)$$

Where: $d_{12}=\sqrt{(x_2-x_1)^2+(y_2-y_1)^2}$

$d_{23}=\sqrt{(x_3-x_2)^2+(y_3-y_2)^2}$

$d_{34}=\sqrt{(x_4-x_3)^2+(y_4-y_3)^2}$, $d_{41}=\sqrt{(x_4-x_1)^2+(y_4-y_1)^2}$,

$m_{12}=\frac{y_2-y_1}{x_2-x_1}$, $m_{23}=\frac{y_3-y_2}{x_3-x_2}$, $m_{34}=\frac{y_4-y_3}{x_4-x_3}$, $m_{41}=\frac{y_1-y_4}{x_1-x_4}$, and

for k=1 to 4

$r_k=\sqrt{(x-x_k)^2+(y-y_k)^2+z}$, $e_k=(x-x_k)^2+z^2$, $h_k=x_k y_k$

q is the electrostatic charge per unit area carried by the panel, ε_0 is the electrical permittivity of the air (8,85 10^{-12} F/m), and x_k, y_k, z_k and x, y, z are the coordinates respectively of the panel corners and of the point at which the potential will be calculated. All coordinates in equation (1) are expressed in a local (panel) frame. For this reason a transfer from the global frame to the local one and vice versa is needed.

The electric field $\vec{E}$ induced by this panel at any point of the surrounding space is calculated according to equations 2:

$$\vec{E}=-\overrightarrow{gradU} \quad (2)$$

The electrostatic field $\vec{E}_{RES}$ induced by the aircraft at any point of its vicinity is the resultant of the field created by the electrostatic charges of the aircraft due its exhaust gases $\vec{E}_{EXHAUST}$, the electrostatic field due to the charges acquired due to the airflow friction $\vec{E}_{FRICTION}$

and the electrostatic field $\vec{E}_{DIST}$ created by the charge distribution on the aircraft skin due to the ambient electrostatic field $\vec{E}_{AMB}$, as shown in equation (3).

$$\vec{E}_{EXHAUST} + \vec{E}_{FRICTION} + \vec{E}_{DIST} = \vec{E}_{RES} \quad (3)$$

$\vec{E}_{EXHAUST}$ and $\vec{E}_{FRICTION}$ are independent of the local electrostatic field $\vec{E}_{AMB}$ and will be not considered here.

Since the hull of an aircraft is a Faraday cage, the module of the electrostatic field at any point internal to the aircraft equals to zero. The boundary condition corresponding to this is (equation 4):

$$\vec{E}_{DIST} + \vec{E}_{AMB} = \vec{0} \quad (4)$$

$\vec{E}_{DIST}$ can be written as (equation 5):

$$E_{DIST} = \sum_{J=1}^{N} q_J \vec{\varepsilon}_{iJ} \quad (5)$$

where, $\vec{\varepsilon}_{iJ}$ is the induced electric field at any point i, by a panel j carrying a distribution of unit electrostatic charges and N is the number of panels approximating the external surface of the aircraft. q_j is the (unknown) value of the electrostatic charge effectively carried by the panel j due to $\vec{E}_{AMB}$.

Equation (4) is a vector equation, so it corresponds to three algebraic ones, is the boundary condition to be satisfied at any internal point inside the aircraft and can be rearranged as follows (equation 6):

$$\vec{E}_{DIST} = -\vec{E}_{AMB} \quad (6)$$

Figure 1 shows an arbitrary position of vectors $\vec{E}_{DIST}$ and $\vec{E}_{AMB}$ at an internal point G_I close to the skin. All vectors in figure 1 are expressed in the global frame.

Figure 2 shows the relative positions of point G_I and the centroid G of the panel above.

The coordinates of point G_I in the global frame are respectively:

$$G_{iX} = G_X - GG_i n_X$$

$$G_{iY} = G_Y - GG_i n_Y$$

$$G_{iZ} = G_Z - GG_i n_Z$$

where GG_I is the distance between points G and G_I.

According to figure 1, two mixed products can be formed. Since a mixed product represents a volume, equation (6) is satisfied only if the volumes represented by the mixed products are equal (equation (7)).

$$\begin{pmatrix} E_{DISTX} & -XT & -XL \\ E_{DISTY} & -YT & -YL \\ E_{DISTZ} & -ZT & -ZL \end{pmatrix} = \begin{pmatrix} E_{AMBX} & XT & XL \\ E_{AMBY} & YT & YL \\ E_{AMBZ} & ZT & ZL \end{pmatrix} \quad (7)$$

where $\vec{E}_{DISTX}$, $\vec{E}_{DISTY}$, $\vec{E}_{DISTZ}$, $\vec{E}_{AMBX}$, $\vec{E}_{AMBY}$ and $\vec{E}_{AMBZ}$ are the component of $\vec{E}_{DIST}$ and $\vec{E}_{AMB}$ in the global frame.

E_{DISTX} , E_{DISTY} , E_{DISTZ} respectively are equal to (equations 8):

$$E_{DISTX} = \sum_{J=1}^{N} q_J \varepsilon_{iJ} \text{ , } E_{DISTY} = \sum_{J=1}^{N} q_J \varepsilon_{YiJ} \text{ ,}$$

$$E_{DISTZ} = \sum_{J=1}^{N} q_J \varepsilon_{ZiJ} \quad (8)$$

and also

XT=t_x, YT=t_Y, ZT=t_Z If $\vec{E}_{AMBX} \cdot \vec{t} > 0$, XT=-t_x, YT=-t_Y, ZT=-t_Z If $\vec{E}_{AMBX} \cdot \vec{t} < 0$,

XL=l_x, YL=l_Y, ZL=l_Z If $\vec{E}_{AMBX} \cdot \vec{l} > 0$ and XL=-l_x, YL=-l_Y, ZL=-l_Z If $\vec{E}_{AMBX} \cdot \vec{l} < 0$.

Where

t_X , t_Y , t_Z and l_X , l_Y l_Z , are the components of vectors $\vec{t}$ and $\vec{l}$ in the global frame.

The combination of equations (7) and (8) gives (after some algebra), the boundary condition to be satisfied at any control point G_i inside the aircraft.

By applying this boundary condition, to N internal points, a system of N x N linear algebraic equations is obtained. The solutions of this system are the values and the sign of the electrostatic charges q_j due to $\vec{E}_{AMB}$ and carried by the panels approximating the external surface of the aircraft. The computation is made using a modified in house aerodynamic computer code based on panel method. Once the electrostatic charges for each panel are computed, the vector electrostatic field $\vec{E}_{DIST}$ at the centroid G of any panel of the aircraft skin can be calculated using Gauss theorem. It must be pointed out that points G and G_i are located close to each other. If the module of $\vec{E}_{RES} = \vec{E}_{DIST} + \vec{E}_{AMB}$ exceeds 300 KV/m a possibility of a lightning strike exists.

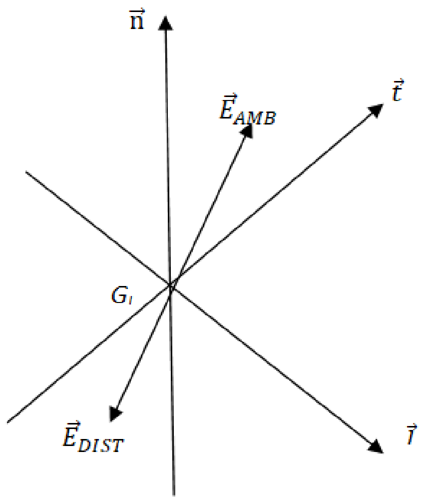

Figure 1 Vectors $\vec{E}_{AMB}$ and $\vec{E}_{DIST}$ expressed in a local frame based at internal point G_i.The axes of this frame are parallel to the corresponding axes of the panel located on the surface.

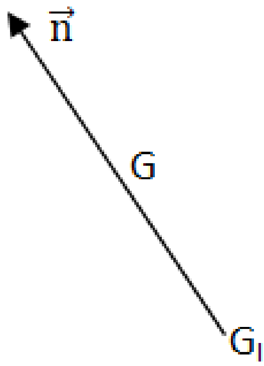

Figure 2 Relative positions of points G and G_I.

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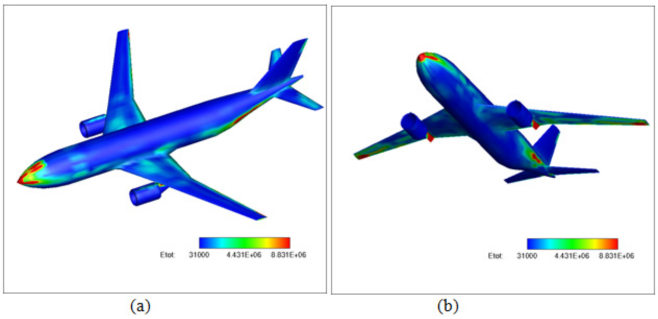

Figure 3 Local electric field strength distribution (absolute value) on the aircraft surface view from above (a) and from below (b) for an ambient field strength of 75.10^3 V/m.

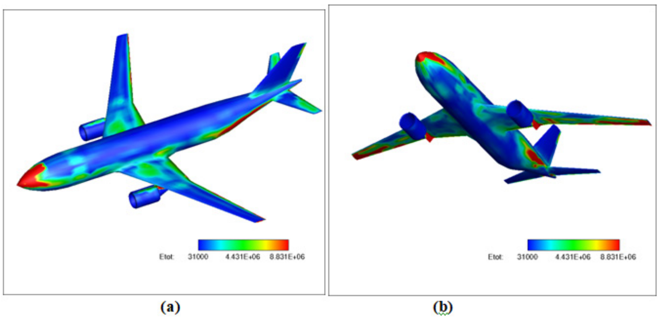

Figure 4 Local electric field strength distribution (absolute value) on the aircraft surface view from above (a) and from below (b) for an ambient field strength of 150.10^3 V/m.

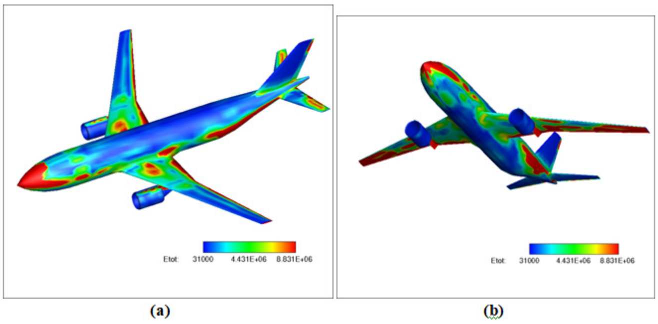

Figure 5 Local electric field strength distribution (absolute value) on the aircraft surface view from above (a) and from below (b) for an ambient field strength of 300.10^3 V/m.

Results

A generic airliner geometry of 50 m length and 60 m wingspan is created. The linear algebraic equation system is solved using a singular value decomposition method.[14] The aircraft was in level flight and exposed to a horizontal ambient electric field of various strength.

Figures 3(a) to 5(b) show the distribution of the local electric field strength distribution, in absolute values, on the aircraft external surface, for strength of $\vec{E}_{AMB}$ equal to 75.10^3 V/m (according to,[15] (figures 3(a),3(b)), 150.10^3 V/m (figures 4(a),4(b)) and 300.10^3 V/m (figures 5(a),5(b)).

In all cases, on the aircraft external surface, there are regions where the local electric field strength (in absolute value) is stronger than 3.10^6 V/m. These regions are observed at the nose and tail cone and at the junction of the wings, the horizontal and the vertical stabilizer with the fuselage. Similar regions are also observed on the fuselage, on the upper and lower surface of the wings and the horizontal stabilizer, as well as on their respective trailing edges and tips. Regions where a local high strength electrostatic field is present are also at the vertical stabilizer trailing edge and tip, as well as on the nacelle pylons.

All the above regions are extended, while new regions appear, as the strength of the ambient electrostatic field increases. According to the strength of the local electric field at each point of the external surface of the aircraft, the surrounding air can be ionized or not. If so, a stepped leader can be attracted by the aircraft at a point of its skin and leave by another one. The closer to the red color a region of the aircraft surface is, the more probable it will attract a stepped leader. In the same way, the closer to the red color an area is, the more probable a stepped leader will leave from there.

Photos 1 to 5 taken from the web[16] under real thunderstorm conditions shows an, at least qualitative, agreement with the results of the presented approach.

Photo 1 Attachment point in front of the vertical stabilizer.

Photo 2 Attachment points on the nacelle pylons and the rear cone of the fuselage.

Photo 3 Attachment points on the engine nacelle, the upper surface of the wing, the wing tip and the tip of the vertical stabilizer.

Photo 4 Attachment point at the nose.

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Photo 5 Attachment point on the fuselage.

Conclusion

The need for better lightning protection of an aircraft requires the location of areas on the aircraft skin where stepped leaders might be attached. In this paper, this is done through an approach based on the fact that potential flow theory and electrostatics have the same mathematical background. The areas computed this way are, at least qualitatively, in agreement with photos taken under real thunderstorm conditions.

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Conflicts of interest

Author declares that there is no conflict of interest.

References

1. Jones JJ. Electric Charge Acquired by Airplanes Penetrating Thunderstorms. *Journal of Geophysical Research*. 1990;95(10):16589–16600.
2. Uman MA, Rakov V. The interaction of lightning with airborne vehicles. *Progress in Aerospace Sciences*. 2003;39(1):61–81.
3. Morgan D, Hardwick CJ, Haigh SJ, et al. The Interaction of Lightning with Aircraft and the Challenges of Lightning Testing. *Aerospace Lab Journal*. 2012;5:1–10.
4. Reazer JS, Serrano AV, Walko LC, et al. Analysis of correlated electromagnetic fields and current pulses during airborne lightning attachments. *Electromagnetics*. 1987;7:509–539.
5. Mazur V. Triggered lightning strikes to aircraft and natural intracloud discharges. J Geophys Res. 1989a;94:3311–3325.
6. Lightning Direct Effects Handbook. Report Reference Number: AGATE-WP3.1-031027-043-Design Guideline; 2002.
7. Pierce ET. Perturbations produced by Jet Aircraft on the Earth's Electric Field. *Journal of Applied Meteorology, Notes and Correspondence*. 1964;3:805–806.
8. Petrov NI, Haddad A, Petrova GN, et al. Study of Effects of Lightning Strikes to an Aircraft, Recent Advances in Aircraft Technology, Dr. Ramesh Agarwal (Ed.), ISBN: 978-953-51-0150-5, InTech.
9. DOT/FAA/AR-04/13: General Aviation Lightning Strike Report and Protection Level Study, Final Report, Office of Aviation Research Washington, DC 20591; 2004.
10. Fisher FA, Plurner JA. Lightning Protection of Aircraft, General Electric Company; 1977.
11. Ravichandran R, Myong RS, Lee S. Computational Investigation of Lightning Strike Effects on Aircraft Components. *Int'l J of Aeronautical & Space Sci*. 2014;15(1):44–53.
12. Katz J, Plotkin A. Low-Speed Aerodynamics, From Wing Theory to Panel M Panel Method. McGraw-Hill Inc; 1991.
13. Grant IS, Phillips WR. *Electromagnetism*. Manchester Physics (2nd ed.). John Wiley & Sons; 2008.
14. Press WH, Teukolsky SA, Vetterling WT, et al. Numerical Recipes in Fortran 77. Volume 1 of FORTRAN Numerical Recipes, Press Syndicate of the University of Cambridge; 1997.
15. Merceret FJ, Ward J, Mach D, et al. On the Magnitude of the Electric Field Near Thunderstorm - Associated Clouds. *Journal of Applied Meteorology and Climatology*. 2008;47(1):240–248.
16. https://www.shutterstock.com/el/search/airplane+lightning

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