Lightning Protection of the Artemis Spacecraft

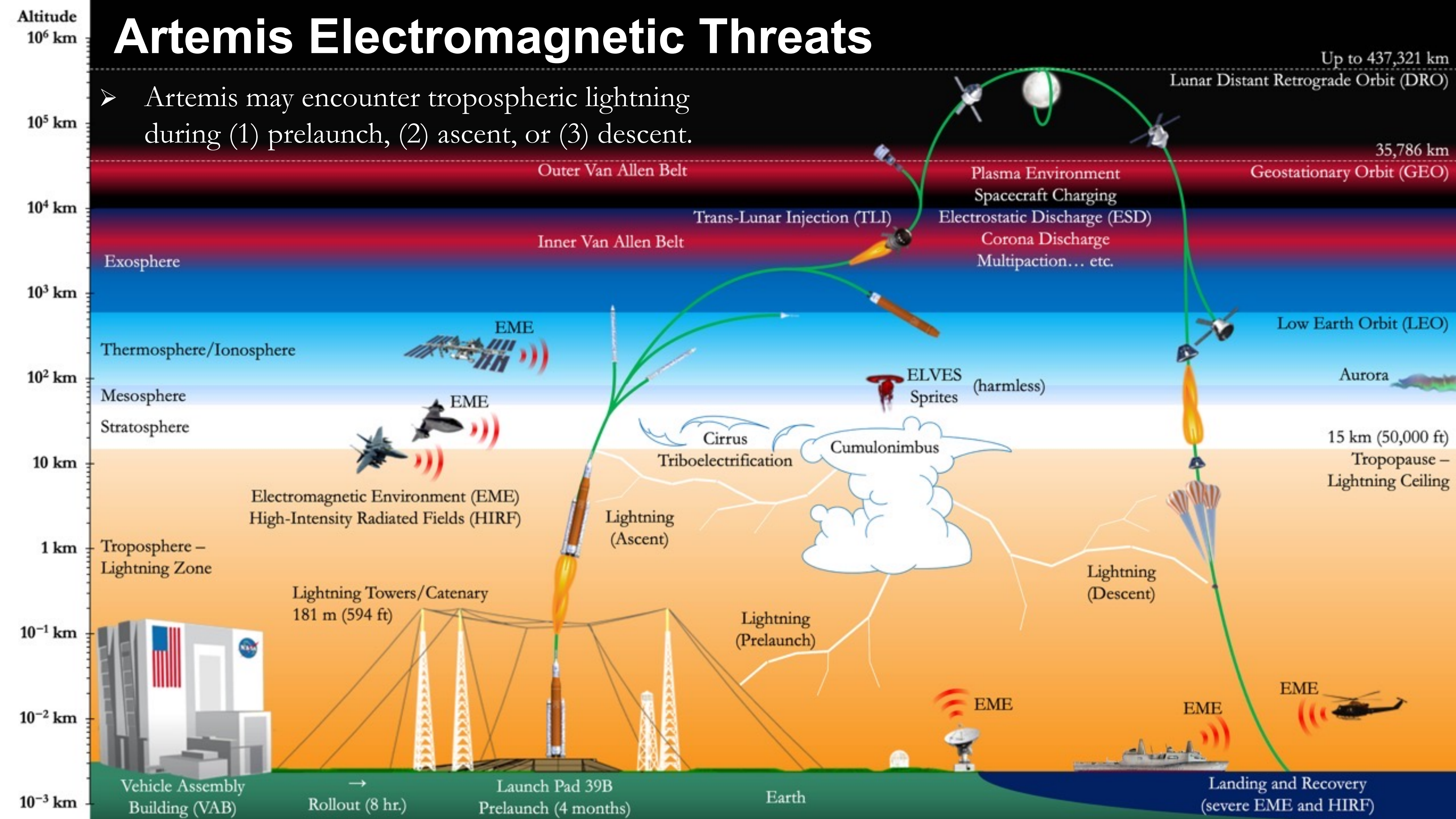
Advisor: Edgar A Bering, PhD
University of Houston

Student: Nathan S Roberts, PhD Candidate
NASA Johnson Space Center (JSC)
Electromagnetic Environmental Effects (E3)
Artemis Lead E3 Engineer
Orion E3 System Manager

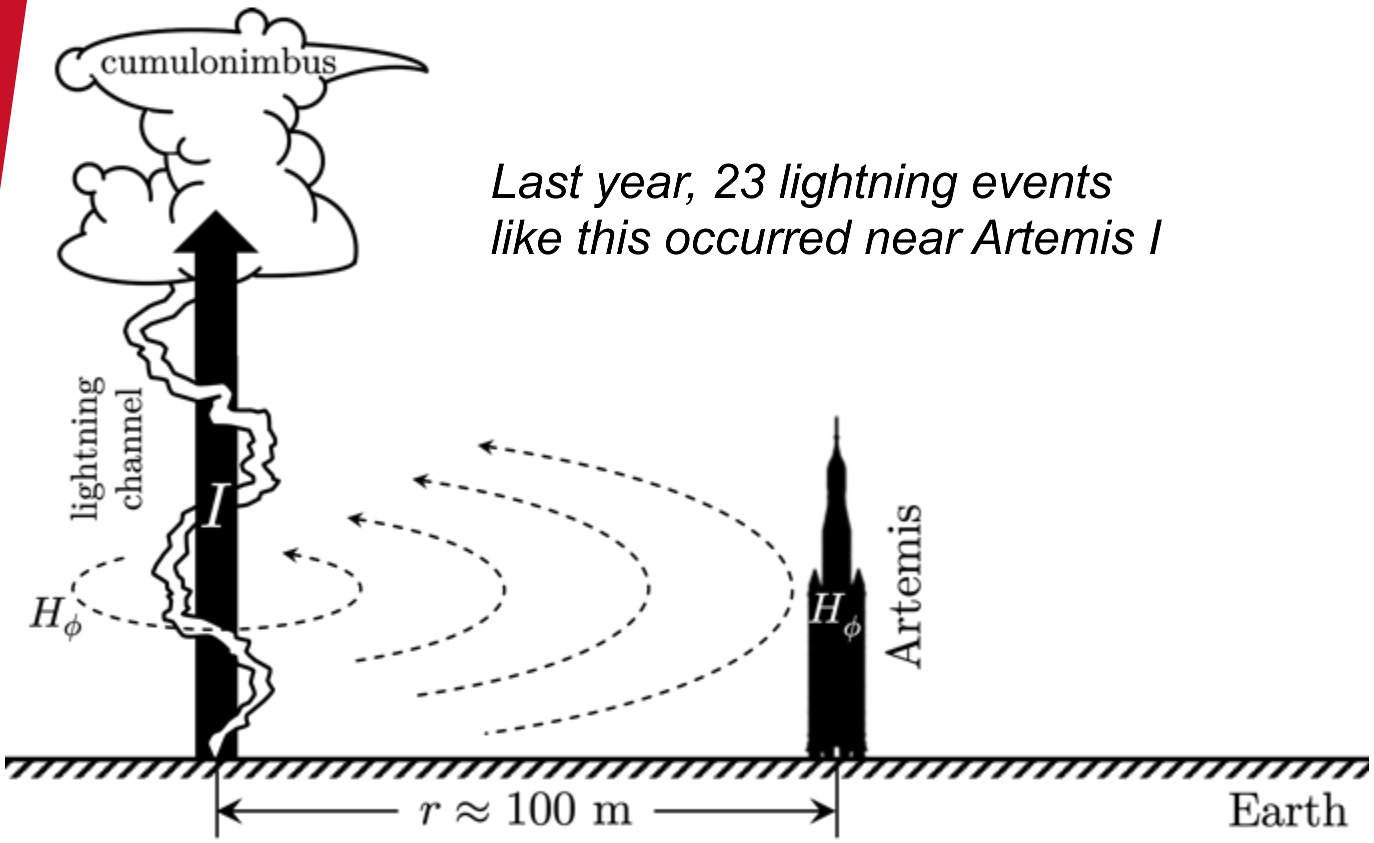
February 18, 2023

Artemis Electromagnetic Threats

- Artemis may encounter tropospheric lightning during (1) prelaunch, (2) ascent, or (3) descent.



Simple Magnetostatic Approximation



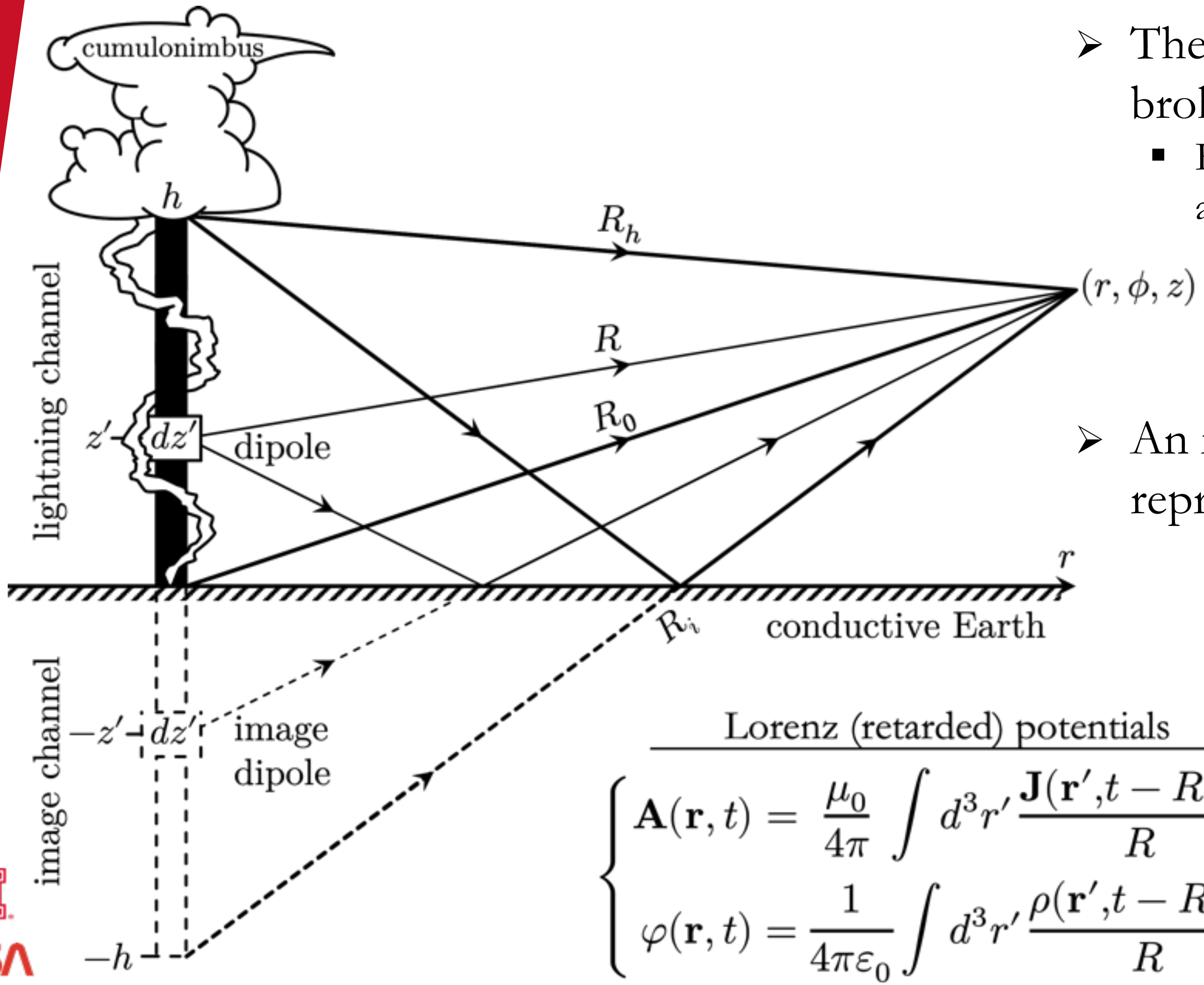
Last year, 23 lightning events like this occurred near Artemis I

$$\oint_C \mathbf{H} \cdot d\mathbf{L} = I$$

$$H_\phi = \frac{I}{2\pi r} = \frac{100{,}000 \text{ A}}{2\pi(100 \text{ m})} \approx 159 \text{ A/m}$$

- Assume all of the zigzagging, horizontal components of the lightning channel cancel out.
  - We are left with just a straight vertical wire of current I.
- Assume the lightning current is constant and lasts forever.
  - But real lightning flashes and disappears within microseconds.
- For a typical peak current of 100,000 A, at 100 m away, Ampere's circuital law gives 159 amperes per meter (A/m).

Dipole Method of Images I



- The lightning channel is broken into a stack of dipoles.
  - Each current-carrying dipole has an infinitesimal height dz'.
- An image channel of dipoles represents ground reflections.

$$R = \sqrt{r^2 + (z - z')^2}$$

Lorenz (retarded) potentials

$$\begin{cases} \mathbf{A}(\mathbf{r}, t) = \dfrac{\mu_0}{4\pi} \displaystyle\int d^3r' \, \dfrac{\mathbf{J}(\mathbf{r}', t - R/c)}{R} \\ \varphi(\mathbf{r}, t) = \dfrac{1}{4\pi\varepsilon_0} \displaystyle\int d^3r' \, \dfrac{\rho(\mathbf{r}', t - R/c)}{R} = -c^2 \int_0^t dt' \, \nabla \cdot \mathbf{A} \end{cases}$$

Lorenz gauge

$$-c^2 \nabla \cdot \mathbf{A} = \frac{d\varphi}{dt}$$

Dipole Method of Images II

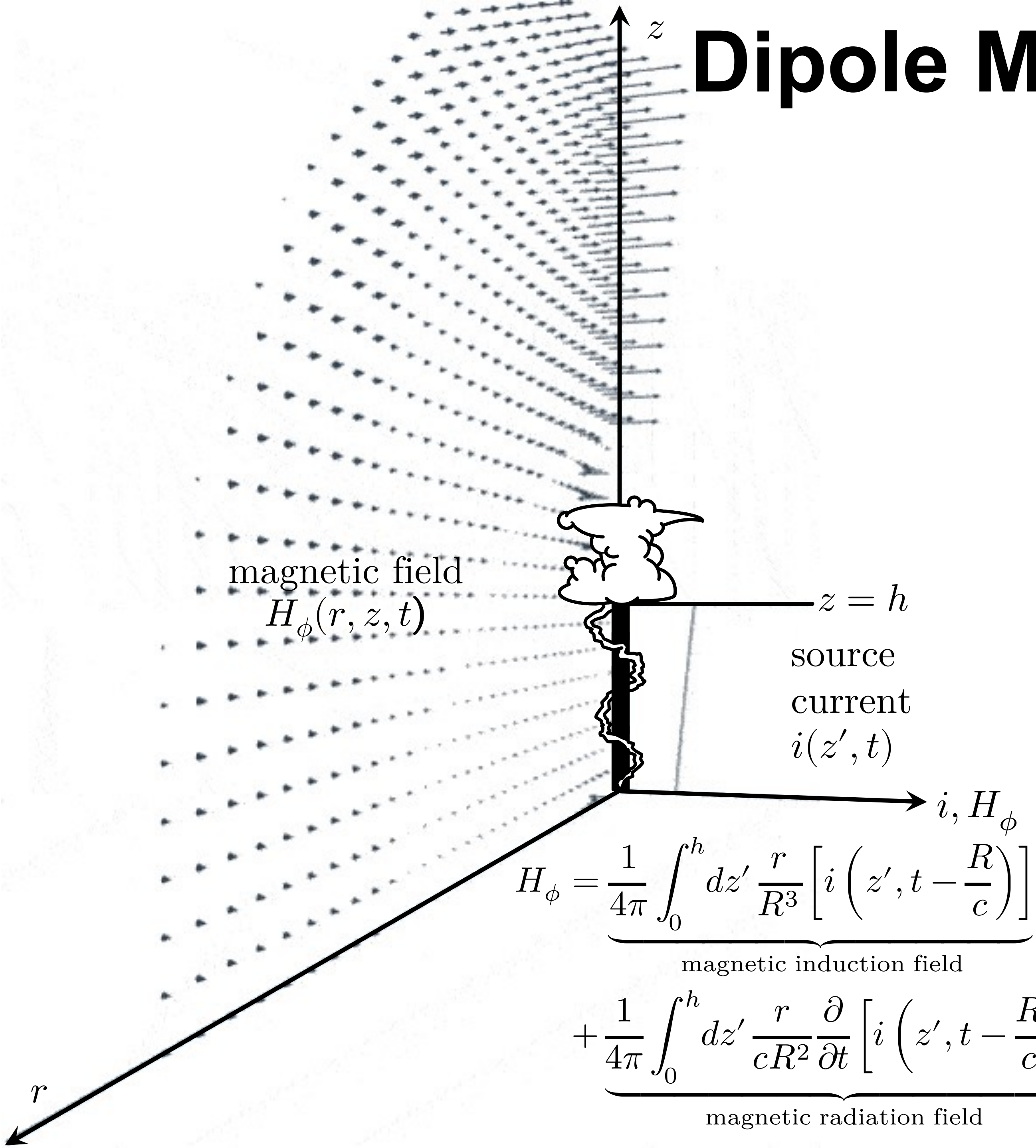
- Derive fields from potentials/gauge introduced by Ludvig Lorenz (1861-1867).
- The resulting integrals are complicated and usually must be solved numerically.
- Only one well-known analytical solution exists in the literature.
  - Rubenstein & Uman (1989) use a Heaviside step function for the source current $i(z', t)$.
  - But the step function is not a very realistic lightning current; it stays switched on forever.

$$H_\phi = \underbrace{\frac{1}{4\pi}\int_0^h dz' \frac{r}{R^3}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{magnetic induction field}} + \underbrace{\frac{1}{4\pi}\int_0^h dz' \frac{r}{cR^2}\frac{\partial}{\partial t}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{magnetic radiation field}}$$

$$\begin{aligned} E_r = &\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{3r(z-z')}{R^5}\int_{\frac{R}{c}+\frac{z'}{v}}^t dt' \left[i\left(z', t'-\frac{R}{c}\right)\right]}_{\text{electrostatic field}} \\ &+\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{3r(z-z')}{cR^4}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{electric induction field}} \\ &+\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{r(z-z')}{c^2R^3}\frac{\partial}{\partial t}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{electric radiation field}} \end{aligned}$$

$$\begin{aligned} E_z = &\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{2(z-z')^2-r^2}{R^5}\int_{\frac{R}{c}+\frac{z'}{v}}^t dt' \left[i\left(z', t'-\frac{R}{c}\right)\right]}_{\text{electrostatic field}} \\ &+\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{2(z-z')^2-r^2}{cR^4}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{electric induction field}} \\ &-\underbrace{\frac{1}{4\pi\varepsilon_0}\int_0^h dz' \frac{r^2}{c^2R^3}\frac{\partial}{\partial t}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{electric radiation field}} \end{aligned}$$

Dipole Method of Images III

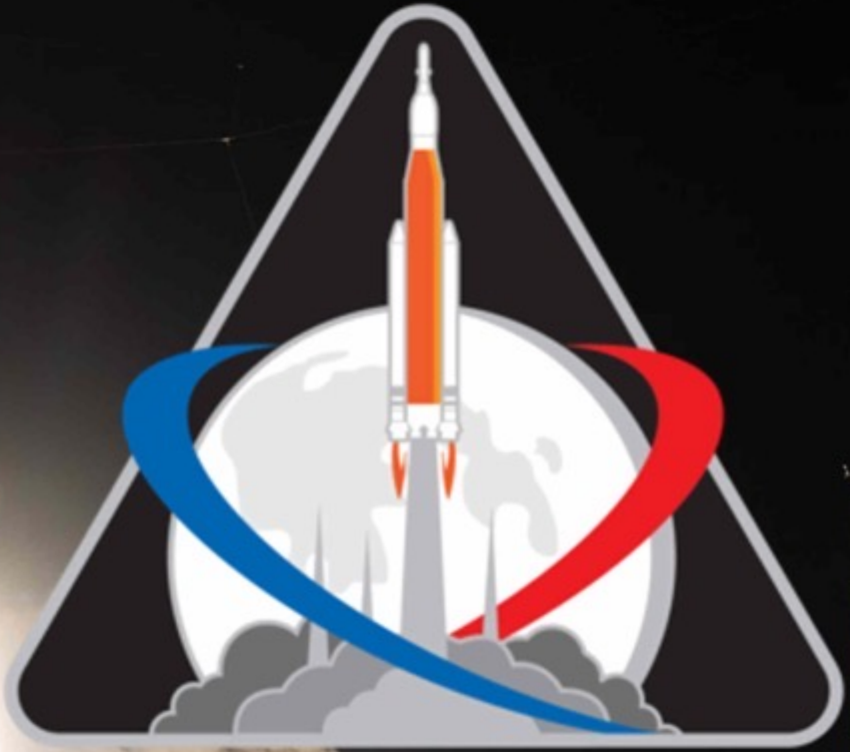


$$H_\phi = \underbrace{\frac{1}{4\pi}\int_0^h dz'\,\frac{r}{R^3}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{magnetic induction field}} + \underbrace{\frac{1}{4\pi}\int_0^h dz'\,\frac{r}{cR^2}\frac{\partial}{\partial t}\left[i\left(z', t-\frac{R}{c}\right)\right]}_{\text{magnetic radiation field}}$$

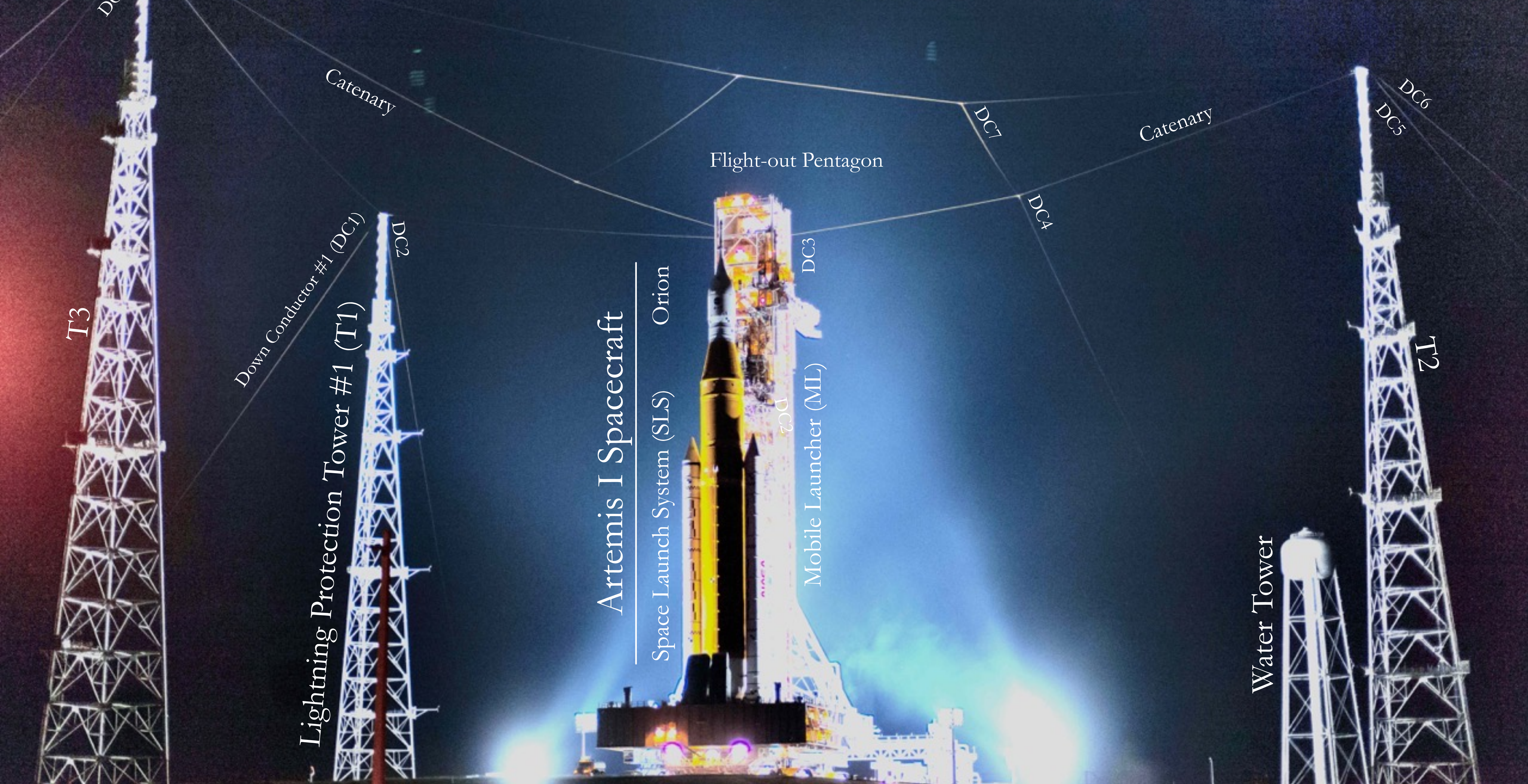
- We are working to publish a paper with new exact solutions that decay more naturally.
  - We often gain significant insight from purely analytical solutions.
  - Enables us to more easily manipulate variables and plot diagrams like the one at left.
- But analytical solutions are too simple for more complicated geometries or assumptions.
  - We find numerical/computational methods very convenient for more specific problems.
  - We will take advantage of Finite Element Method (FEM) modeling in the Time Domain (FETD).

Artemis I

- 3 lightning protection towers watch over Artemis as it prepares for launch.
- These iconic towers are featured on the Artemis I mission patch.



Launch Pad 39B



Insulator

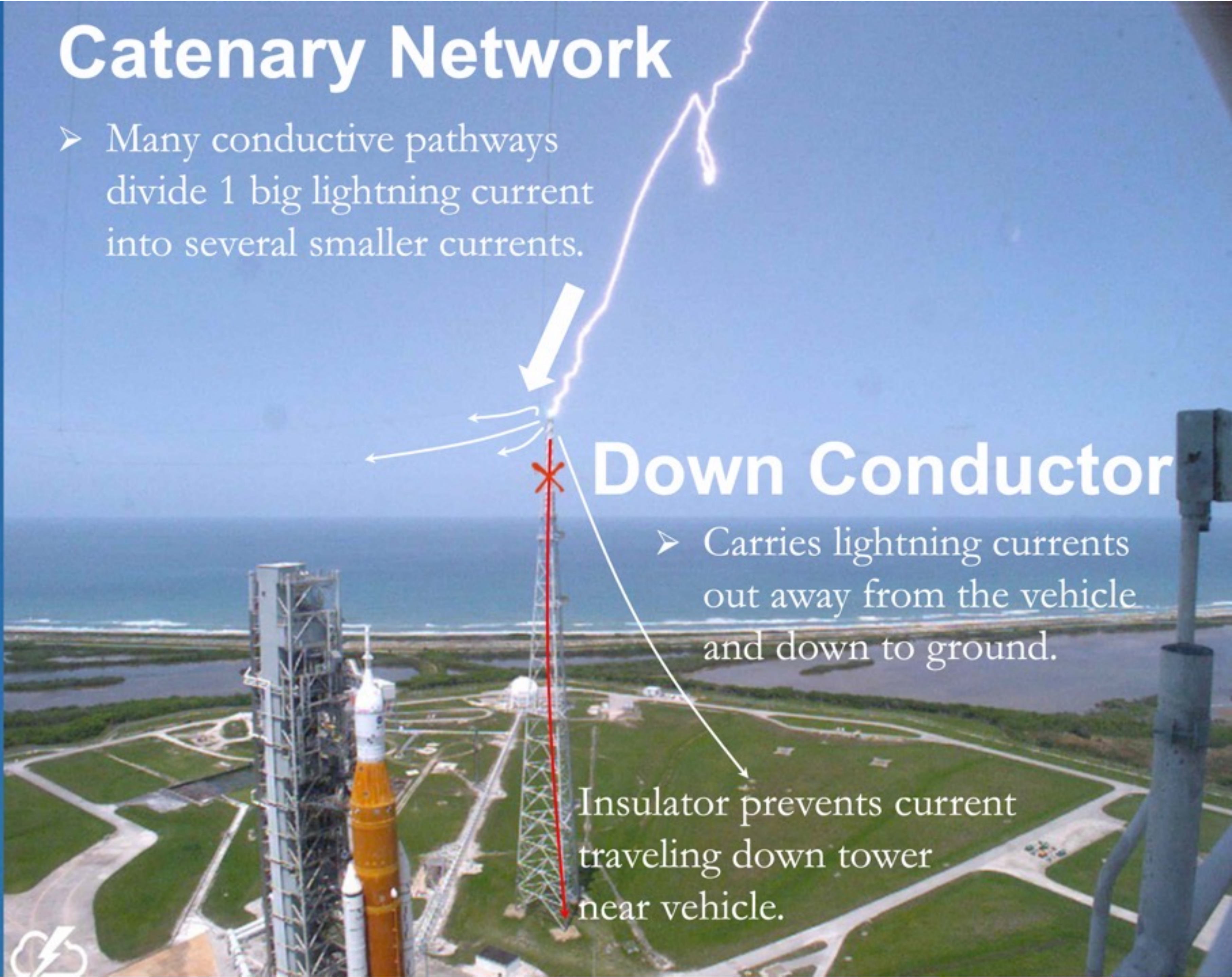
- Fiberglass to prevent electric current flow.
- Helical strakes help stabilize tower during high winds.
  - Reduces force from vortex shedding.

Catenary Network

- Many conductive pathways divide 1 big lightning current into several smaller currents.

Down Conductor

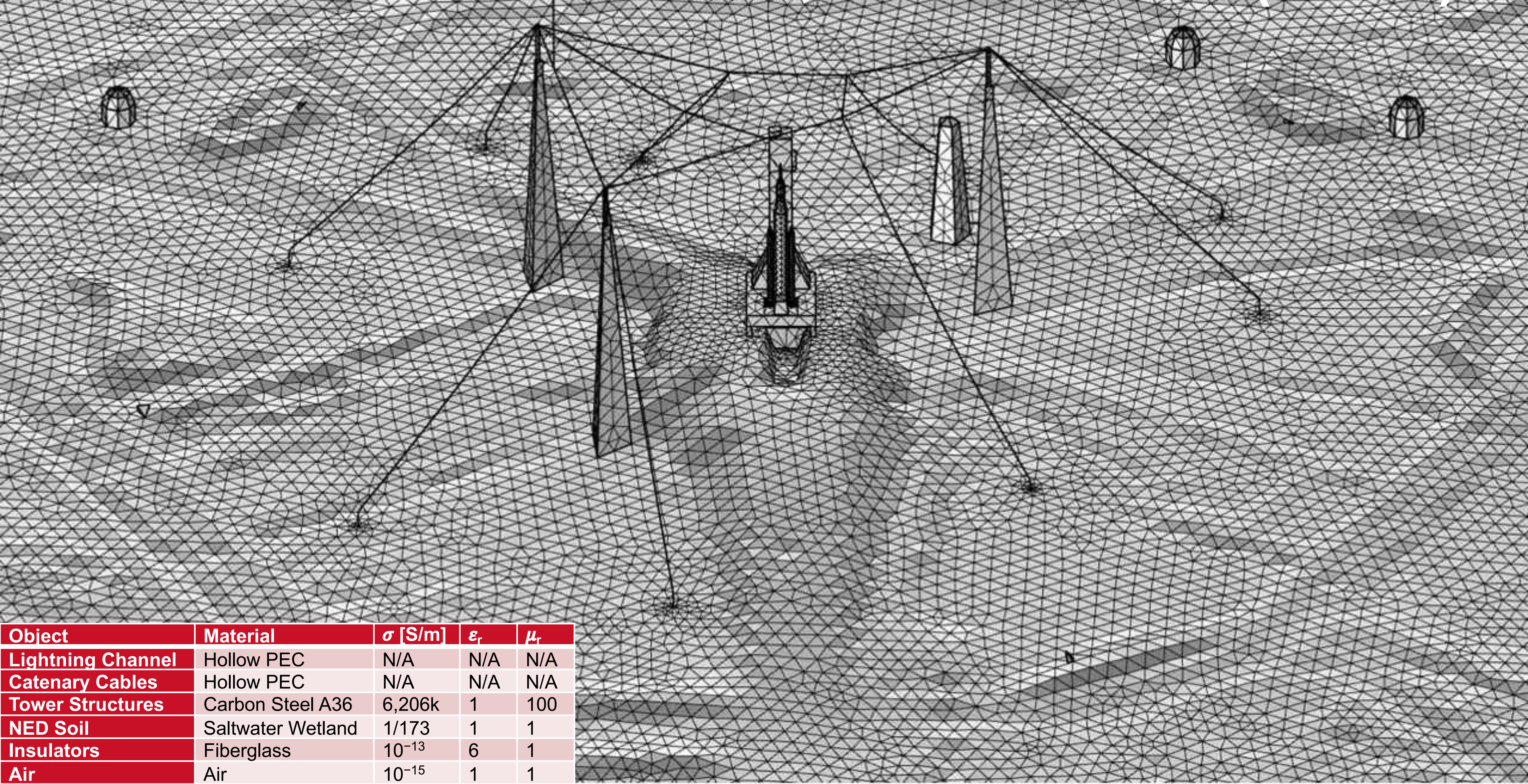
- Carries lightning currents out away from the vehicle and down to ground.




Original Image
can be cloudy and dark during a thunderstorm


Luminance Channel
superimposed over clear-skies image

Finite Element Method, Time Domain (FETD)

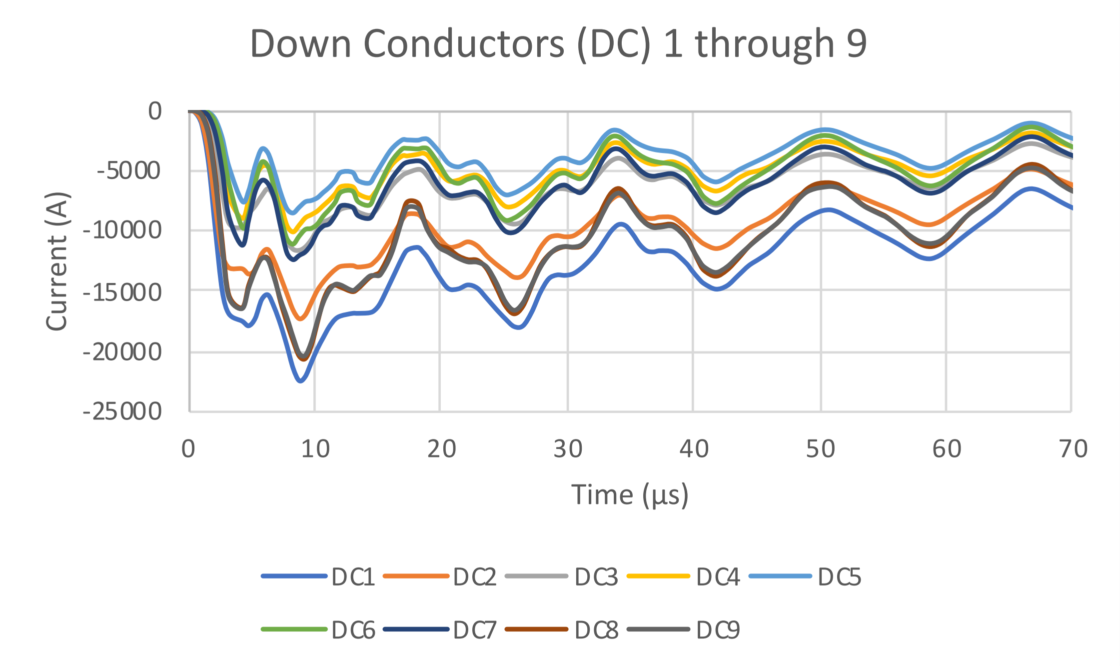


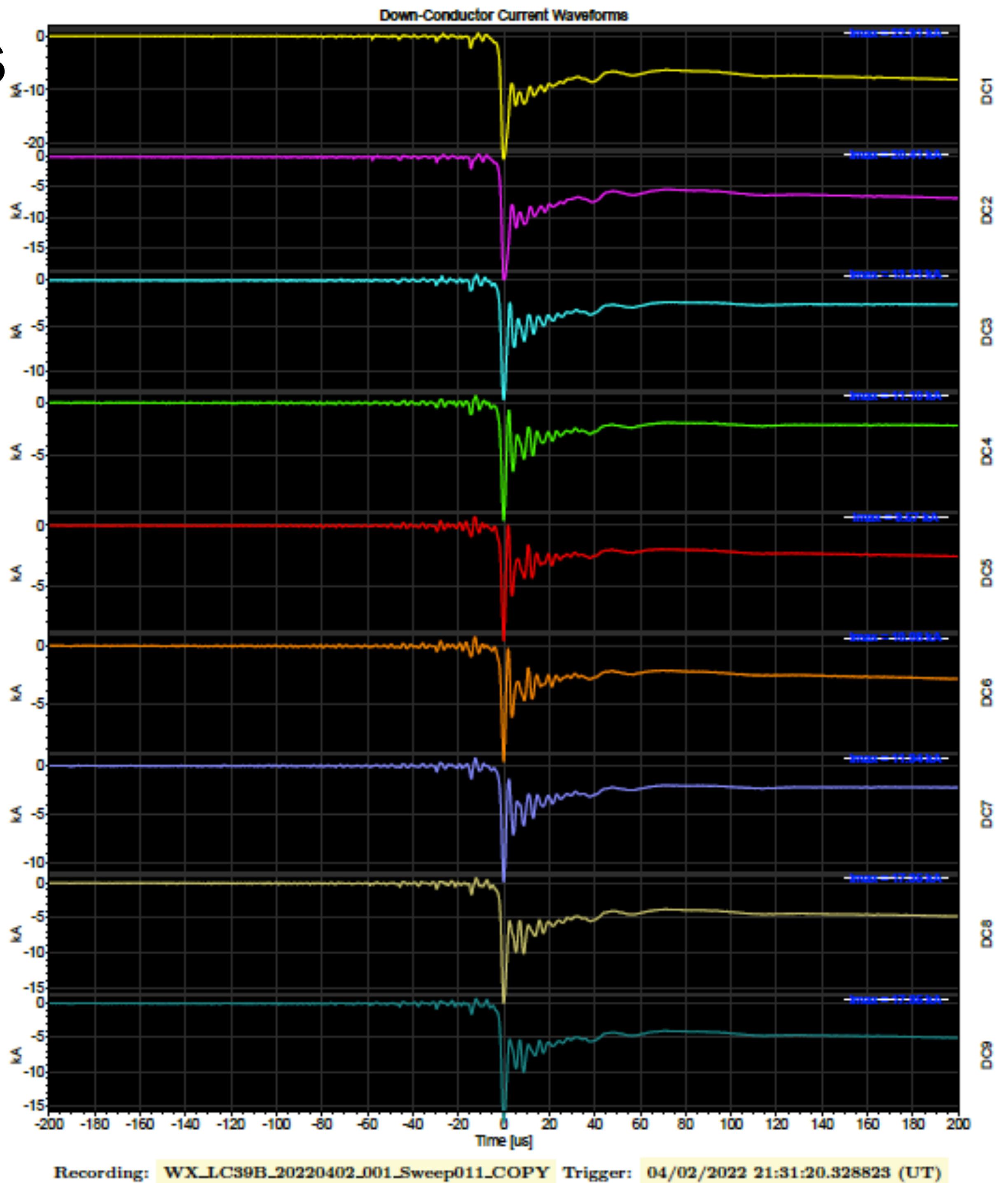
Object	Material	σ [S/m]	ε_r	μ_r
Lightning Channel	Hollow PEC	N/A	N/A	N/A
Catenary Cables	Hollow PEC	N/A	N/A	N/A
Tower Structures	Carbon Steel A36	6,206k	1	100
NED Soil	Saltwater Wetland	1/173	1	1
Insulators	Fiberglass	10^{-13}	6	1
Air	Air	10^{-15}	1	1

Down Conductor Results

➢ The peak values and waveforms are in reasonable agreement with the measured data.

Peak Values	Measured	Calculated
DC1	−22910 A	−22365 A
DC2	−20410 A	−17362 A
DC3	−13210 A	−11522 A
DC4	−11100 A	−9977 A
DC5	−9570 A	−8615 A
DC6	−10080 A	−11002 A
DC7	−11940 A	−12429 A
DC8	−17350 A	−20631 A
DC9	−17650 A	−20319 A



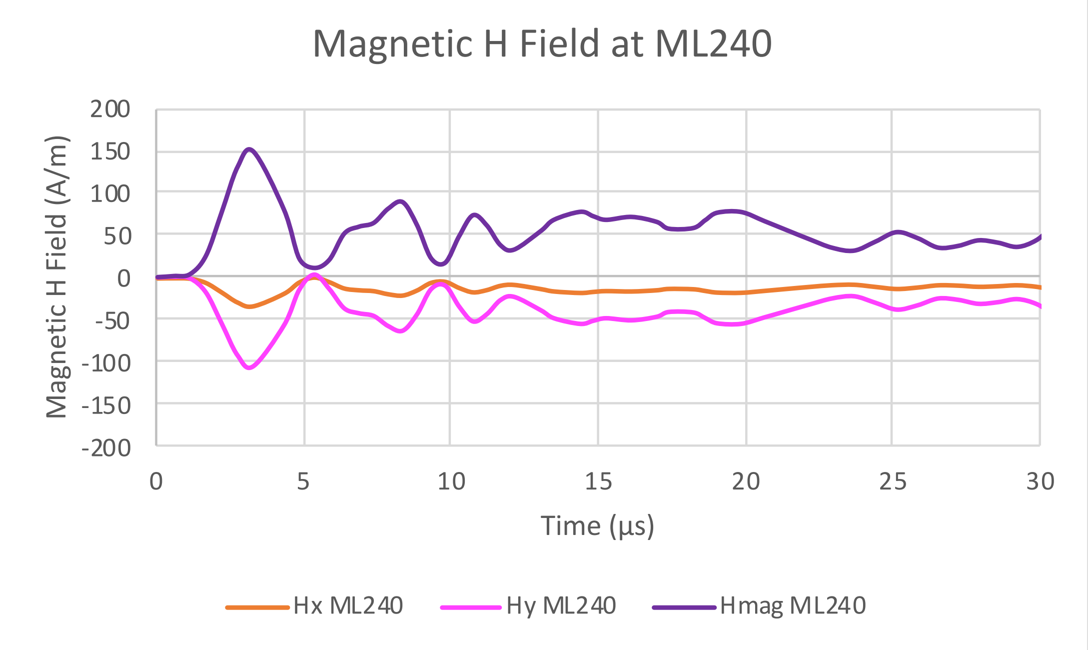


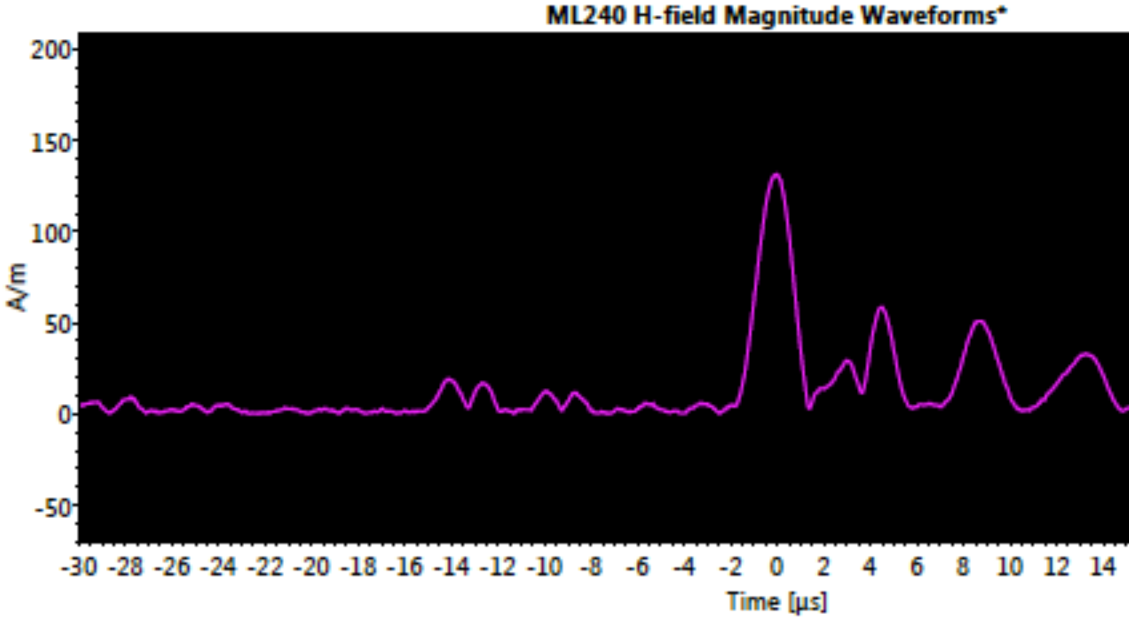
ML240 Magnetic Field

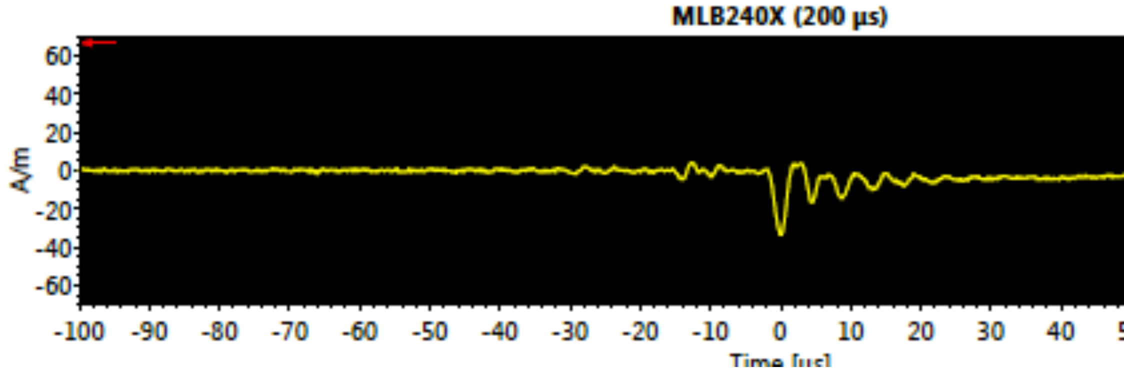
- Some of the main questions about this strike:
  - Was the ML240 magnetic field really that high?
  - Were the ML240 sensors in error?

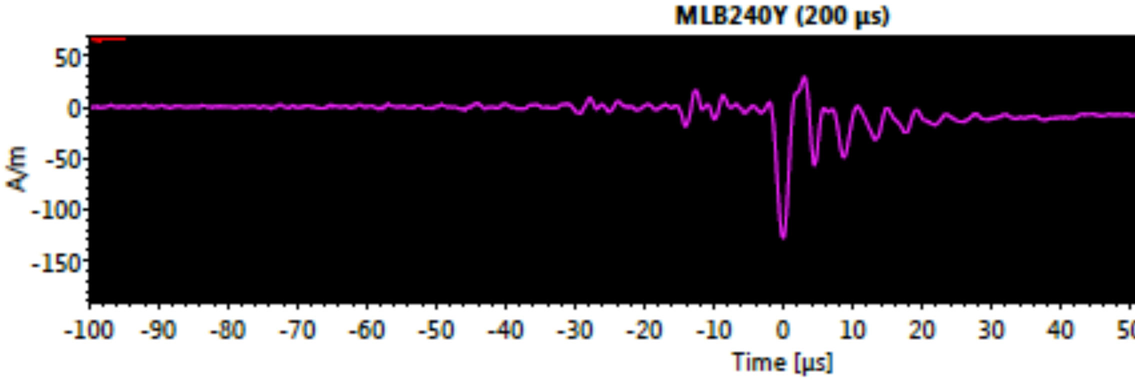
- Our model confirms that the magnetic fields were really that high!

Peak Values	Measured	Calculated
Hx ML240	−34.34 A/m	−34.67 A/m
Hy ML240	−128.32 A/m	−105.69 A/m
Hmag ML240	+131.81 A/m	+149.12 A/m









Questions?