Efficient Representation of Lightning and Other Transient Processes in the GEC

Victor P. Pasko and Jaroslav Jánský

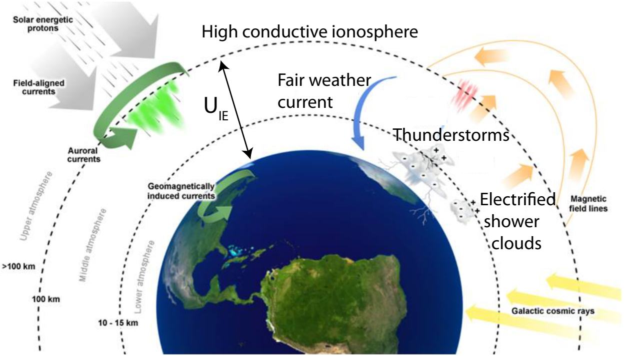
Pennsylvania State University

vpasko@psu.edu

06/22/2016

Introduction of Global Electric Circuit (GEC)

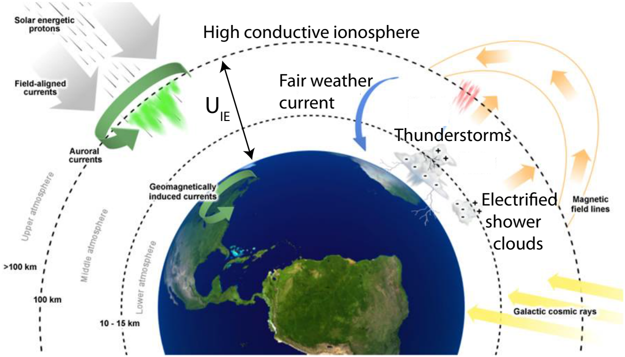
- GEC – Layer between high σ Earth and Ionosphere
- Main generators – Thunderstorms and ESC produce upward current
- Downward fair weather current toward Earth closes GEC
- Potential between Earth and Ionosphere – Ionospheric potential



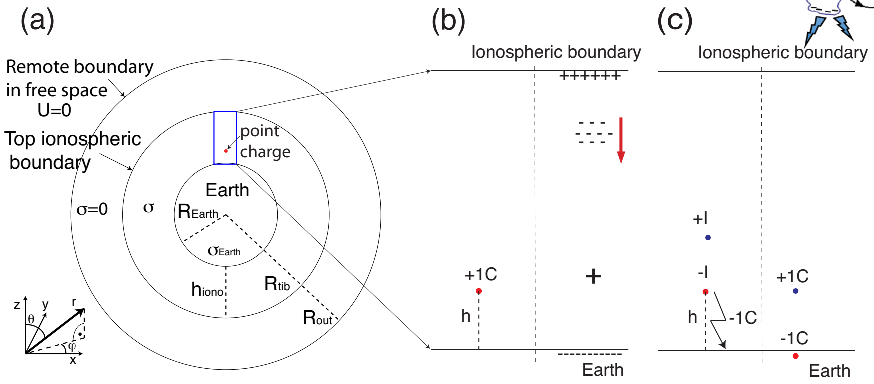
Project FESD:ECCWES (*http://sisko.colorado.edu/FESD/*)

Previous GEC Modelling

- Challenges: multiscale behaviour
  - space (local lightning discharges vs. whole Earth)
  - time (fast lightning discharges vs. long thunderstorm charging)
- Time dependent (implicit) modelling in spherical coordinates:
  Browning, Tzur and Roble, 1987: *JAS*, **44**, 15, 2166-2177.
  Stansbury et al., 1993: *JGR*, **98**, D9, 16591-16603.



Outline of Model Components



(a) Schematically (drawn not to scale) full view of Earth, top ionospheric boundary, and zero potential remote boundary.

(b) Zoom in view of the volume where the initial point charge is introduced (left) and schematic representation of movement of charges (right).

(c) Zoom in schematics of a thunderstorm and CG lightning discharge.

Impulse Response Formulation

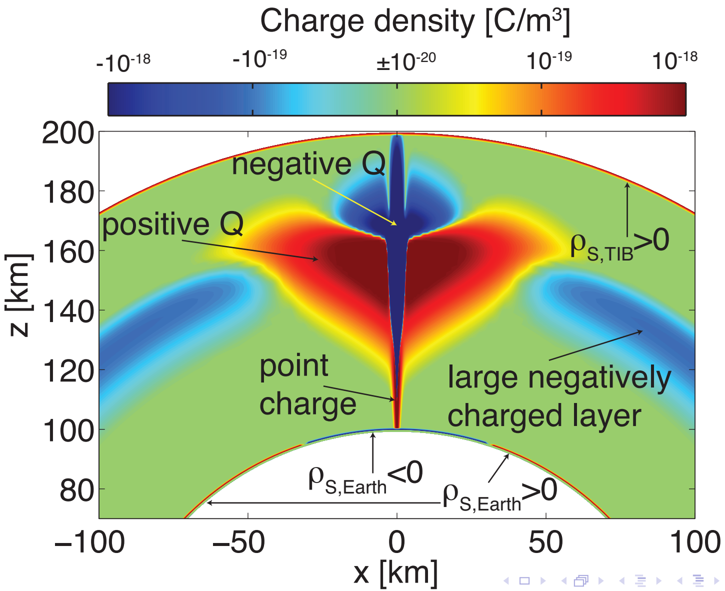
- Time dependent continuity equation coupled with Poisson's equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\sigma \vec{E}) = S_{\mathrm{cur}}, \quad \nabla \cdot \vec{E} = \rho/\varepsilon_0$$

- Impulse response of potential: Relaxation of potential after instantaneous input of point charge $1\,\mathrm{C}$ - $\phi^{\mathrm{IR}}(\vec{r}, t)$ $[\mathrm{V/C}]$
- In GEC, knowing source current $I(t)$ and impulse response of quantity (e.g., potential $\phi^{\mathrm{IR}}(\vec{r}, t)$) gives knowledge of time evolution of potential $\phi(\vec{r}, t)$ anywhere in the domain using convolution:

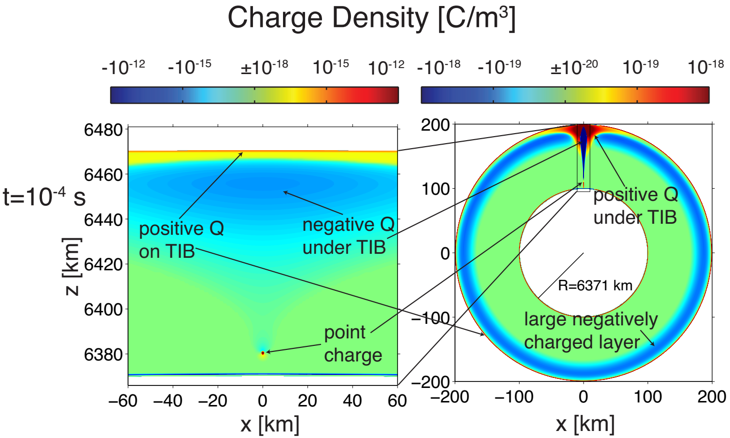
$$\phi(\vec{r}, t) = I(t) * \phi^{\mathrm{IR}}(\vec{r}, t)$$

Impulse Response – Charge Density Evolution

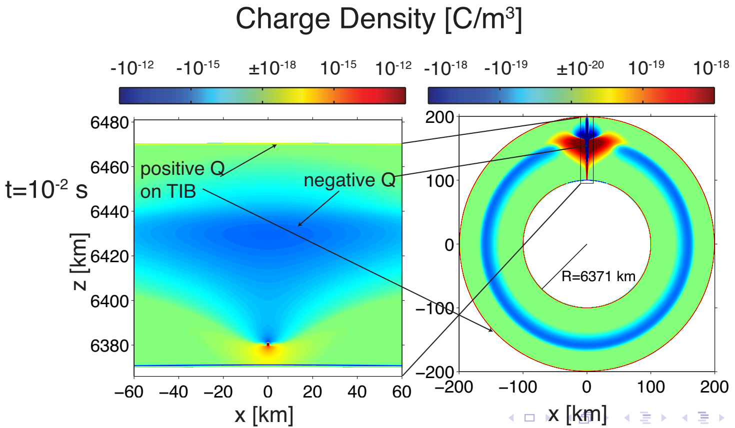


Impulse Response – Charge Density Evolution

- $t = 10^{-4}$ s - induction of positive Q on TIB and negative Q under TIB
- Local effects – above source point charge
- Global effects – spherical large negatively charged layer

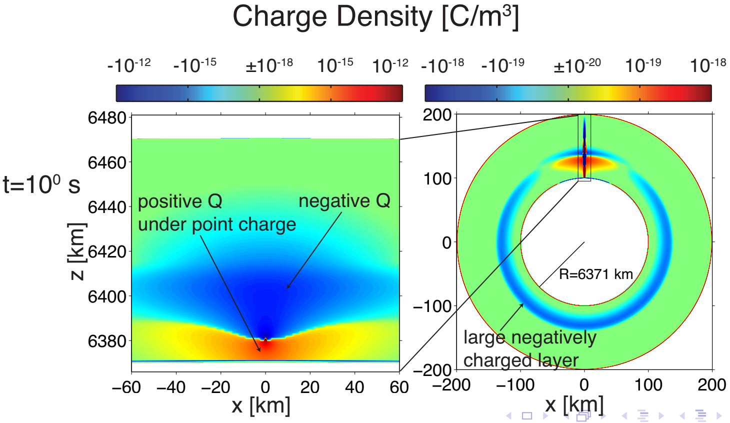


- $-Q$ moving down locally and globally as spherical layer as "moving capacitor plate" model (MCP)
  Greifinger and Greifinger, 1976: *JGR*, **81**, 13, 2237-2247.
- Positive charge is now induced everywhere on TIB



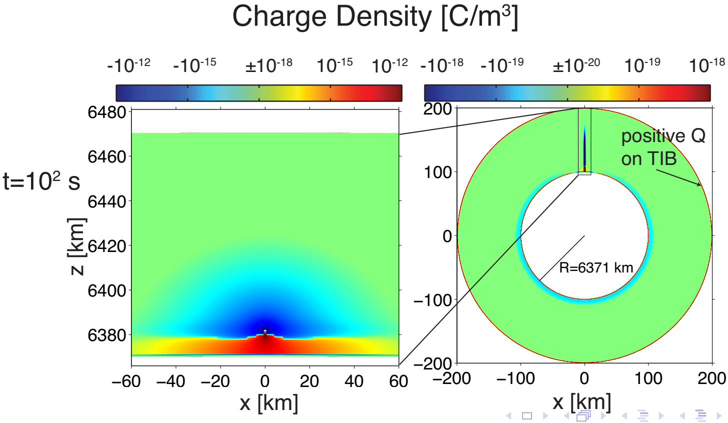
Impulse Response – Charge Density Evolution

- $-Q$ moving down locally and globally as spherical layer as "moving capacitor plate" model (MCP)
  Greifinger and Greifinger, 1976: *JGR*, **81**, 13, 2237-2247.
- $t = 10^0\,\mathrm{s}$ - neutralization of source point charge starts



Impulse Response – Charge Density Evolution

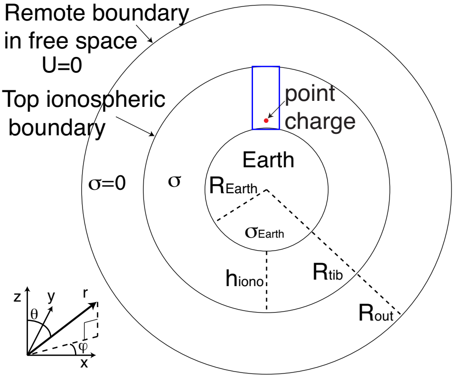
- $t = 10^2$ s - large negatively charged layer neutralizes Earth charge
- Locally around source - charge is not yet neutralized
- Globally – Positive charge homogenously distributed on TIB
- $t = 10^4$ s - Only charge in domain is on TIB, everywhere else $\rho = 0$



Ionospheric Potential

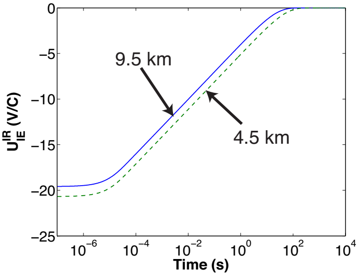
- Ionospheric potential U_{IE} – Average difference between TIB and Earth

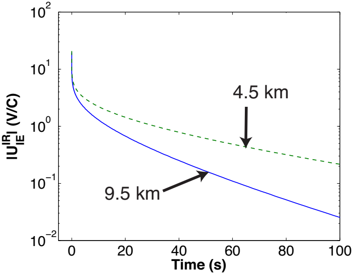
$$U_{\mathrm{IE}} = \frac{\oint_{\mathrm{TIB}} \phi \, \mathrm{d}S}{S_{\mathrm{TIB}}} - \frac{\oint_{\mathrm{Earth}} \phi \, \mathrm{d}S}{S_{\mathrm{Earth}}}$$



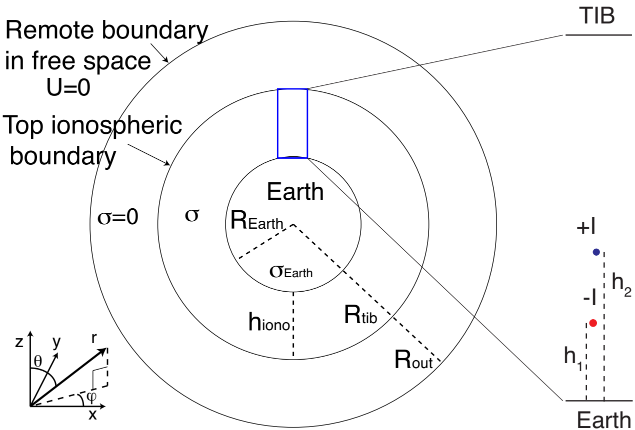
Impulse Response of Point Charge – U_{IE}

- For $h = 9.5\,\mathrm{km}$
  - Negative ionospheric potential
  - Short time scales – logarithmic drop with t (MCP model)
  - Long time scales – exponential drop ($t \sim \frac{\varepsilon_0}{\sigma(9.5\,\mathrm{km})}$)
  - Convergent state – Charge is homogeneous on spherical TIB – $U_{\mathrm{IE}} = 0$
- For $h = 4.5\,\mathrm{km}$
  - Higher peak value of U_{IE}
  - Longer relaxation of U_{IE} – ($t \sim \frac{\varepsilon_0}{\sigma(4.5\,\mathrm{km})}$)



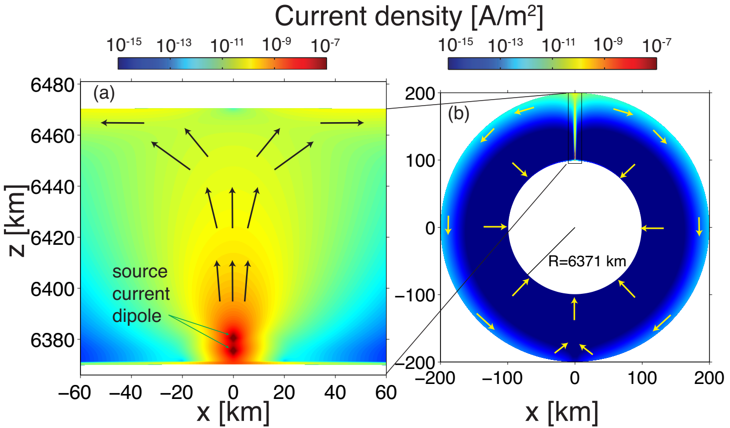


- Dipole
  $I = 1\,\mathrm{A}$
- $h_1 = 4.5\,\mathrm{km}$
- $h_2 = 9.5\,\mathrm{km}$
- $\theta = 0°$
- Steady state obtained at $t = 10^4\,\mathrm{s}$



Current Distribution of Electrified Thunderstorm

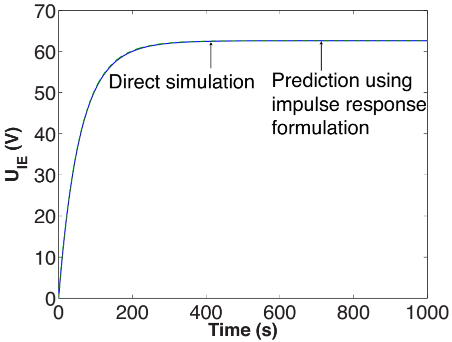
- Above source – upward current
- Top ionospheric boundary – horizontal current distributing charge
- In fair weather region – downward constant current



FESD ECCWES

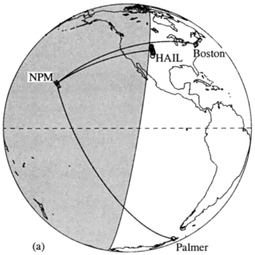
- For current dipole:

$$U_{\mathrm{IE}}(t) = I_{\mathrm{s}} * U_{\mathrm{IE}}^{\mathrm{IR}}(t, h_1 = 9.5\,\mathrm{km}) - I_{\mathrm{s}} * U_{\mathrm{IE}}^{\mathrm{IR}}(t, h_2 = 4.5\,\mathrm{km})$$

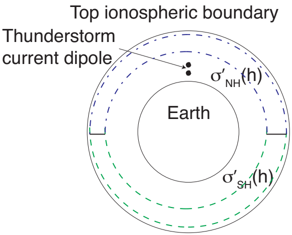


- Results are published in [Jánský and Pasko, JGR, 119, 10184, 2014].

- Gamma-ray burst on August 27, 1998 – influence on VLF [Inan et al, *GRL*, **26**(22), 3357-3360, 1999], no influence on ELF [Price and Mushtak, *JASTP*, **63**, 1043-1047, 2001].



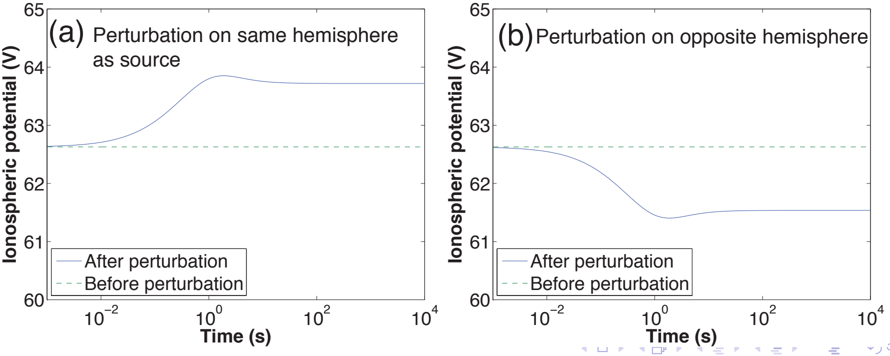
The shaded part of the globe is illuminated by gamma ray flare [Inan et al, *GRL*, **26**(22), 3357-3360, 1999].



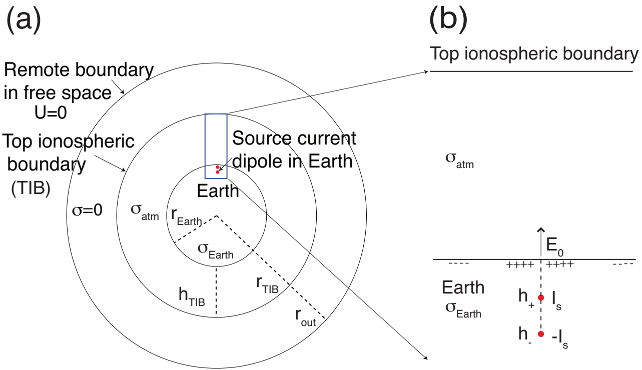
Conductivity is increased to $10\,\sigma$ above $20\,\mathrm{km}$ either on same or opposite hemisphere as reference thunderstorm.

Ionospheric Potential Change

- Ionospheric potential changes by $1\,\mathrm{V}$.
- The small differences due to perturbation (less than 2%) are caused by the small contribution of conductivity above $20\,\mathrm{km}$ to the total resistance of the atmosphere.
- See more in [Jánský and Pasko, JGR, 120, 10654, 2015] and poster presentation on Wednesday MLTS-02.



- Our GEC model provides tool to study coupling of lithosphere and atmosphere used for study of origin of Earthquake lights due to currents generated inside the Earth from rock stress [Freund et al., Phys. Chem. Earth, 31, 389, 2006].
- See more at poster presentation on Wednesday MLTS-04.



Acknowledgement

This research was supported by NSF FESD grant AGS-1135446.