

High-Fidelity Ionosphere-Thermosphere Modeling: a Physics-Based Discontinuous Galerkin Approach

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MIT Portugal
2024 Annual Conference

1. Motivation

- Big interest towards the exploitation of the **Low-Earth Orbiting (LEO)** region of the atmosphere \Rightarrow mega-constellations of satellites.
 - Need for accurate **trajectory prediction** in orbits heavily influenced by **atmospheric drag**.
 - Need for **ionospheric characterization** due to impact of ionospheric and geomagnetic disturbances on **global navigation systems** or **power grids**.
 - **Physics-based models** of the ionosphere-thermosphere to improve forecasting capabilities of empirical models.
- \triangleright Introduce modern **high-order numerical methods** for physics-based space weather modeling [1].
- Ability to resolve physics and multiscale variations.

2. Computational Approach

Exasim



github:exasim/Exasim publication:SoftwareX

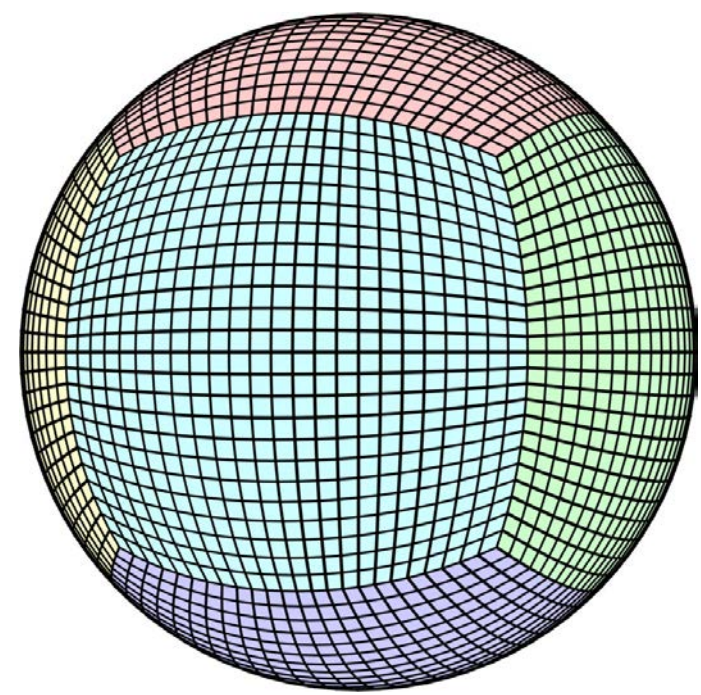


Figure 1: Cube-sphere mesh.

- High-order **discontinuous Galerkin (DG)** code [2].
- **Implicit-in-time**: DIRK temporal schemes.
- **Matrix-free** approach, optimized for **GPUs**.
- Automatic code generation.
- **Cube-sphere meshes** to avoid pole singularities.

3. Physics-Based Model

Physics-based ionosphere-thermosphere model:

- Conservation equations of mass, momentum, energy and charge.
- **Non-hydrostatic formulation** in the rotating Earth.
- Multiple neutral and ion species
 - \triangleright **Neutrals**: O, O₂, N, N₂, NO, He
 - Chemically frozen mass fractions for neutrals. Variable physical properties with altitude.
 - \triangleright **Ions**: Neutrals: O⁺, O₂⁺, N⁺, N₂⁺, NO⁺, He⁺
 - Full chemical treatment for ions.

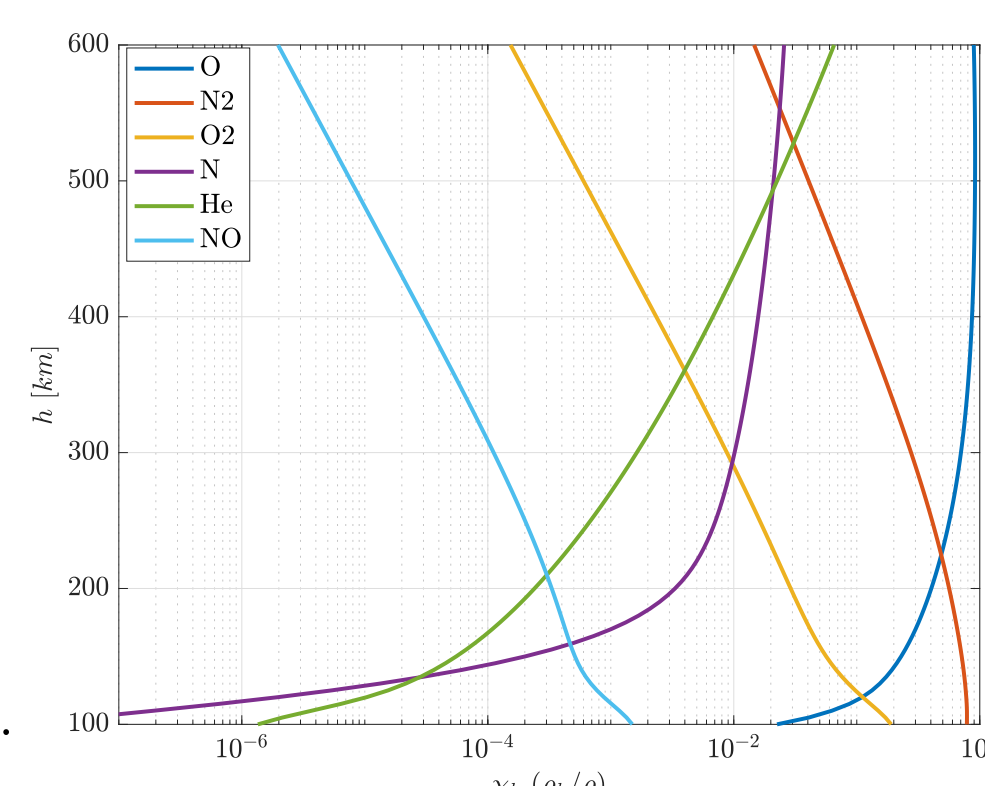
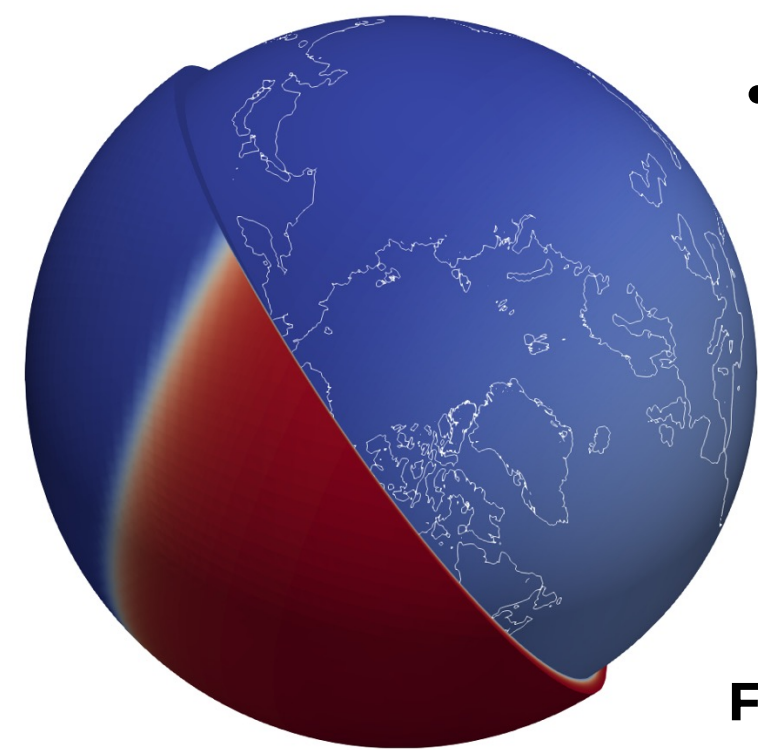


Figure 2: Altitude distribution of chemically frozen neutral mass rates.

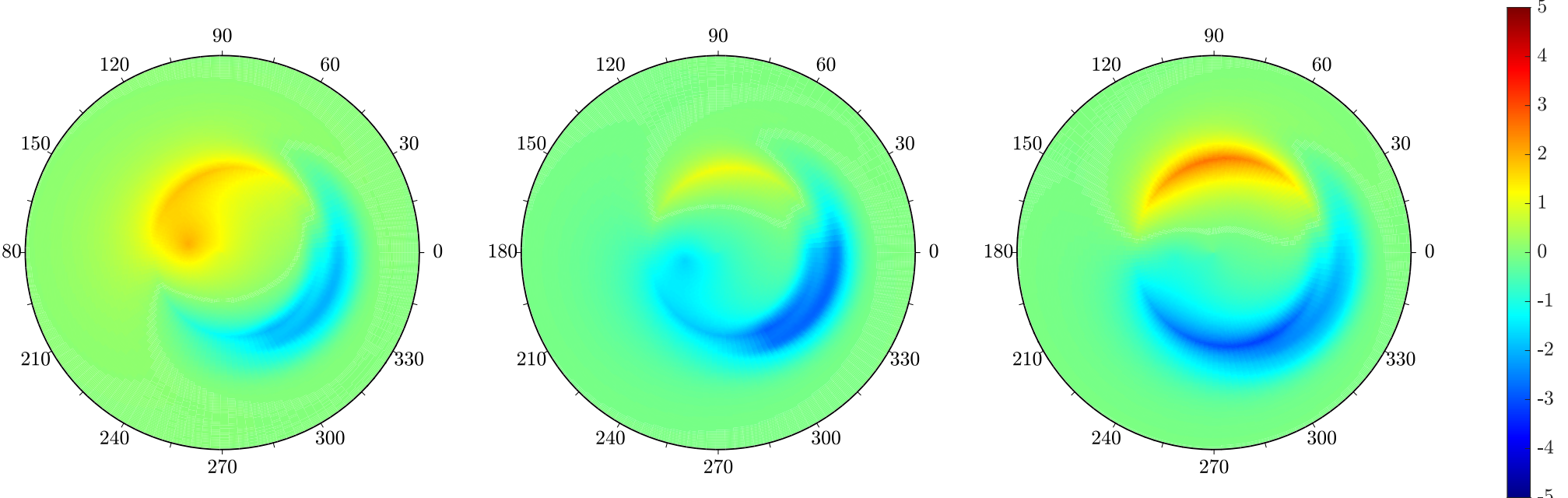


- Heating source due to solar **EUV radiation**.
 - \triangleright Measures amount of energy being transferred due to **photoionization**.
 - \triangleright Based on EUVAC model [3], driven by the F_{10.7} index and empirical and measured data of the **EUV spectrum**.

Figure 3: EUV heating source distribution on the globe at a given time.

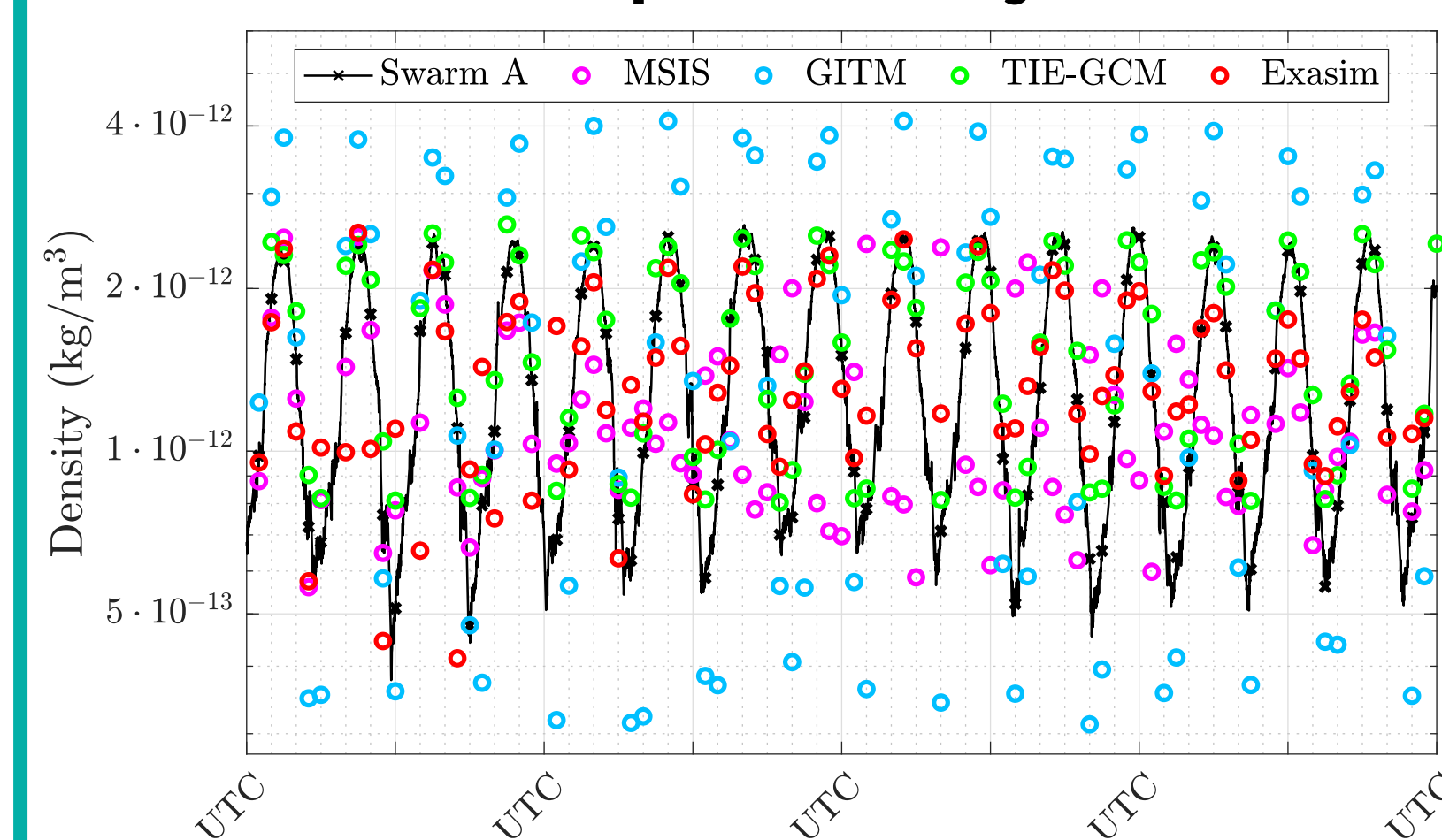
- External description of the magnetic field (eccentric dipole, IGRF).
- Prescribed **electric field** at high-latitudes:
 - \triangleright **Open-closed field line boundary approximation (OCFLB)** for the high-latitude potentials.

Figure 4: North hemisphere electric potential patterns using an open-closed field line boundary approximation at different instants of time. Representation in magnetic coordinates.



4. Computational Studies

Neutral thermosphere study: validation with Swarm A satellite data



	MSIS	GITM	TIE-GCM	Exasim
RMS error	0.5325	0.4871	0.1531	0.2528

- Characterization of thermospheric density for 2014 spring equinox.
- **Quadratic approximation** on a cube-sphere mesh with nearly **220k elements** (30M dofs).
- **Error within common ranges** for physics-based thermospheric models.

Figure 5: Density along the Swarm A trajectory (top) and RMS error with respect to accelerometer data [5] (bottom) for Exasim, MSIS [4], GITM [6] and TIE-GCM [7].

Ionosphere-thermosphere tests: chemistry model performance

- **Chemistry model** accounting for photoionization, recombination, ion-neutral, neutral-neutral and 3-body reactions.
- **Implicit in time**. Time-steps dominated by the flow.
- Possibility of **ion transport** for any of the species.

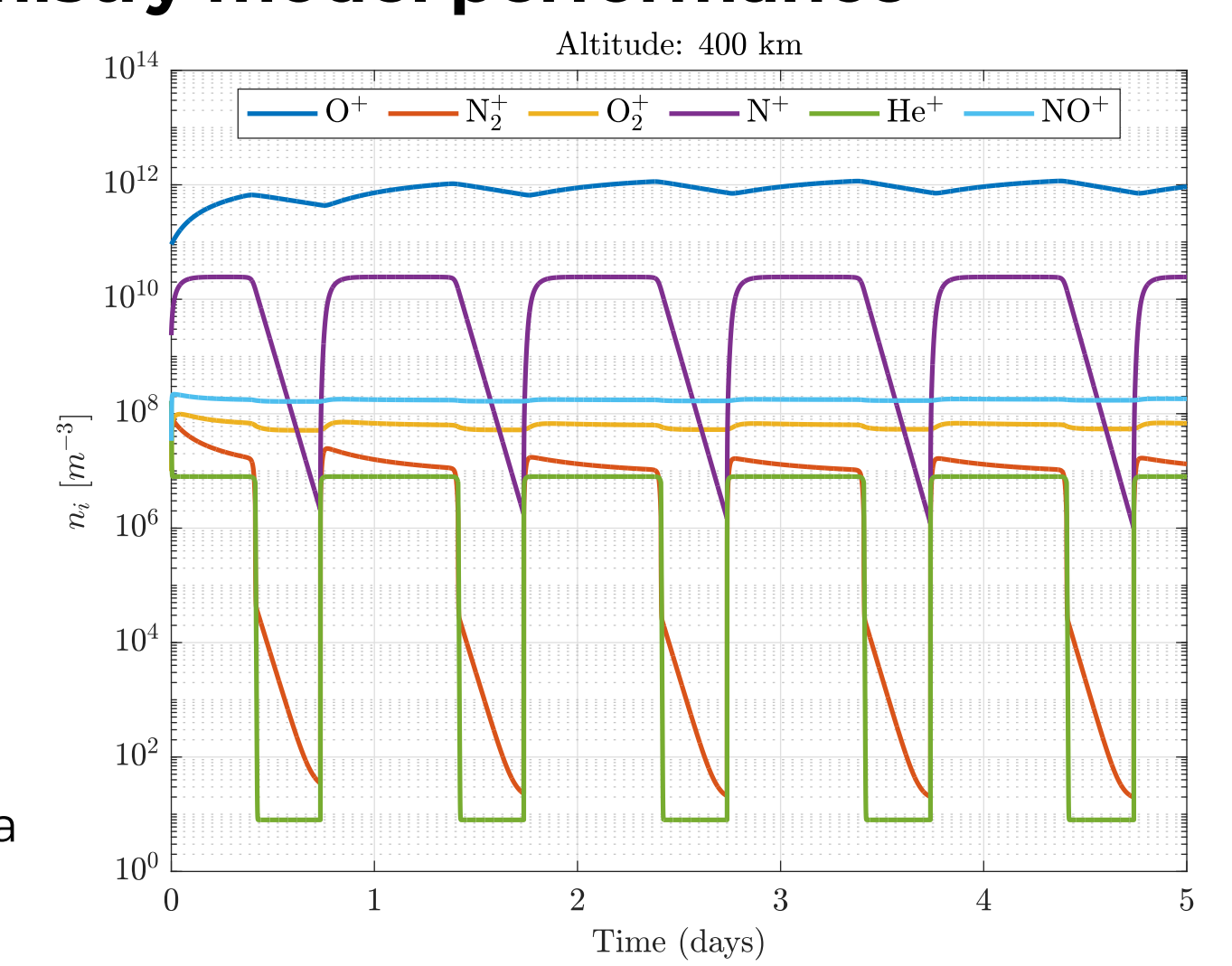


Figure 6: Time evolution of ion number densities at a given altitude location (400km).

5. Conclusions

High-order DG method for space weather modeling.

- Implicit solver with automatic code generation.
- Matrix-free approach, optimized for GPU computing.

Thermospheric model: neutral gas mixture under EUV heating.

- Close reproduction of **dynamical behavior** of the thermosphere.

Ionospheric model

- Introduction of charged species (ions, electrons) and chemistry model.

Ongoing work

- Consistent electrodynamic representation for full ionospheric validation.

References

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Acknowledgements

This research used the GPU computational resources of the Oak Ridge Leadership Computing Facility, supported by the Office of Science of the U.S. Department of Energy (DE-AC05-00OR22725). Simulation results for GITM [6] and TIE-GCM [7] have been obtained through the Community Coordinated Modeling Center (CCMC) simulation services at NASA Goddard Space Flight Center.

Co-funded by:

