Disentangled and interpretable feature extraction for the reduced order modeling of Earth electron radiation belts

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The Earth radiation belts

- Population of energetic particles trapped in the near-Earth space vicinity by the geomagnetic field.
- Cover the great majority of existing orbits.
- The particle dynamics is highly coupled with solar activity and can strongly affect spacecraft components and mission.

Distance Regularized Siamese twin Auto-Encoder

- An auto-encoder alternative that focuses on both distance-preservation and disentanglement in the latent space [2].
- Done through the addition of two appropriate loss terms to a reconstruction loss function.
- Results compared with various auto-encoder variants (AE, VAE) and Principal Component Analysis (PCA).

Latent space structure

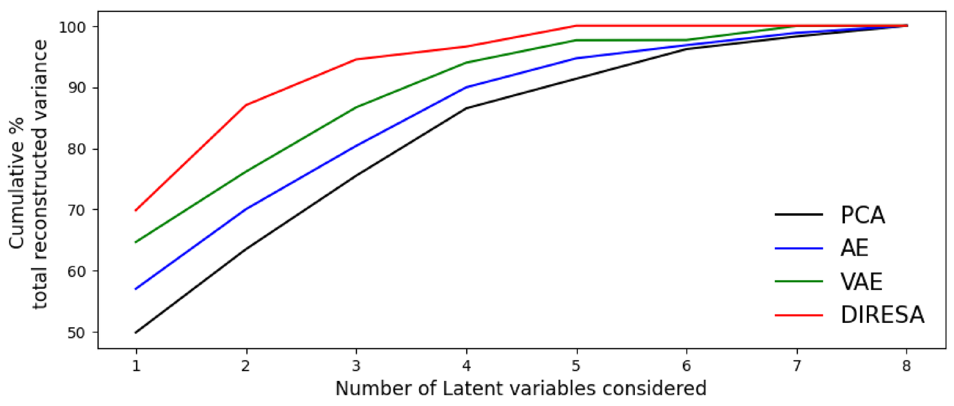

Figure 3: Cumulative contribution to the total test set reconstructed variance.

- DIRESA allows to truncate additional latent variables.
- DIRESA latent variables are more information intensive.

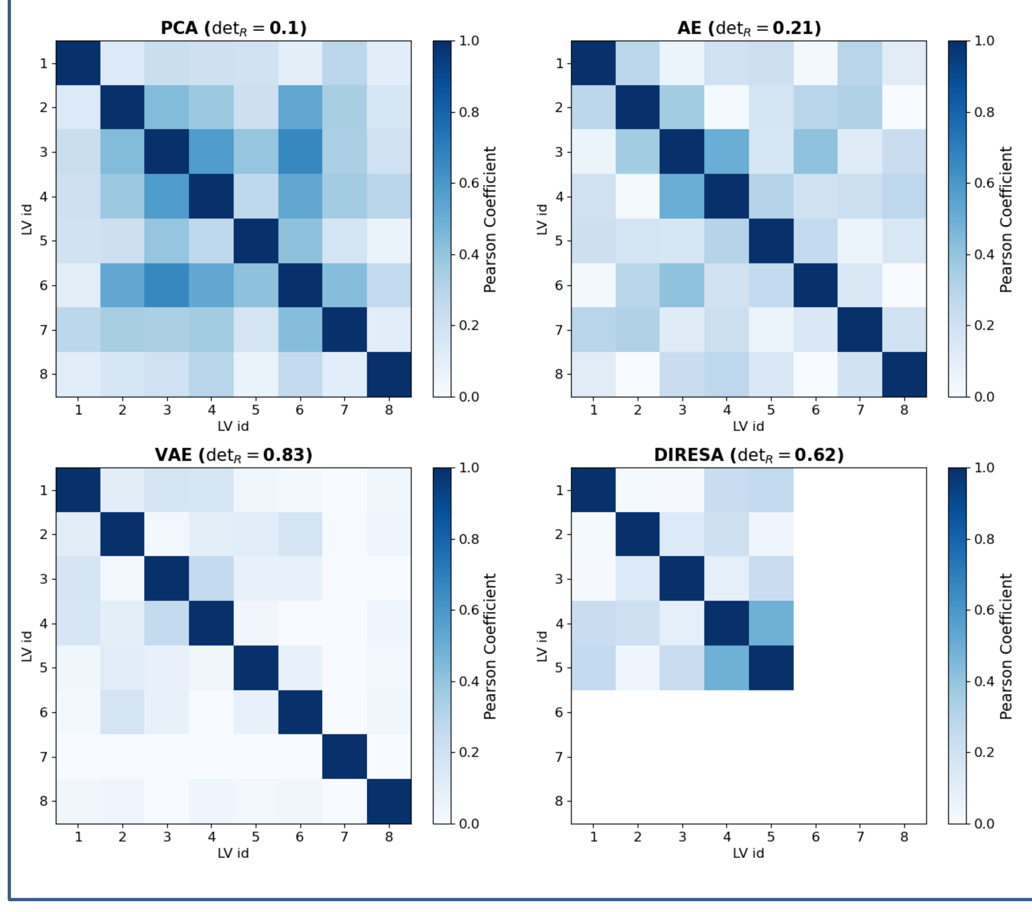

Figure 4: For PCA, AE, VAE and DIRESA, absolute value of the correlation matrix for the latent variable obtained on the test set.

- DIRESA is better than PCA at generalizing disentanglement.
- DIRESA most prominent latent variables are also the most disentangled.

Reconstruction Performances

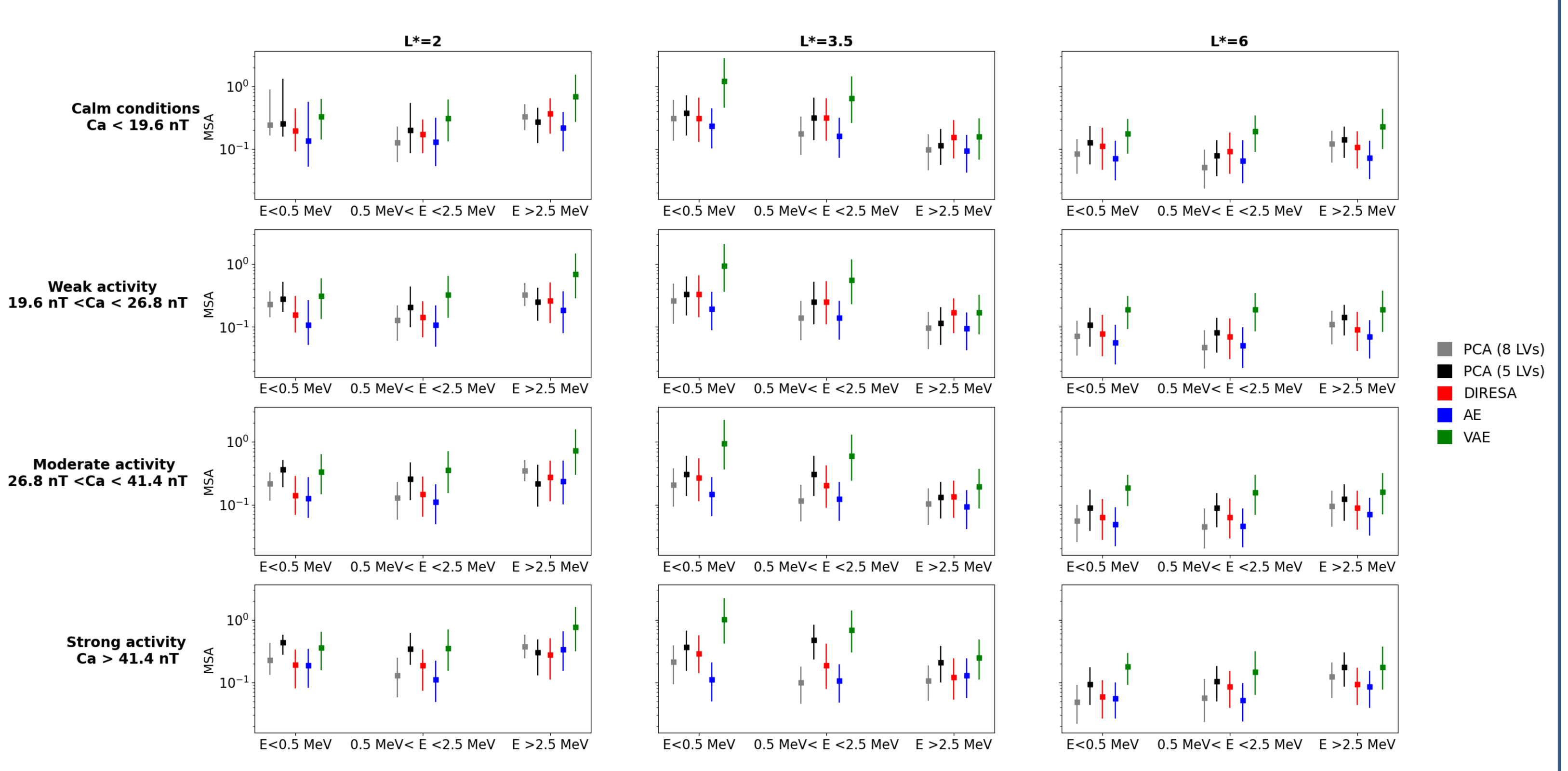

Figure 5: Median symmetric accuracy over the testing period for the different investigated methods at various L* and geomagnetic conditions. The errorbars represent the 25th and the 75th quantiles symmectic accuracies.

- With the same number of LVs, DIRESA performs better than PCA, especially under strong geomagnetic conditions.

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Objectives

- Develop a reduced order model (ROM) of the Earth electron radiation belts driven by geomagnetic parameters available over a long-term historical record.
- Accelerate the hundreds of runs over very long periods required in data assimilation-based space climate studies.
- Here, we primarily focus on the reduction of electron fluxes to a small set of disentangled, interpretable latent variables (LV).

Data

- Long-term simulation of the electron radiation belt obtained by solving a three-dimensional diffusion equation with the 3D Salammbô code [1]

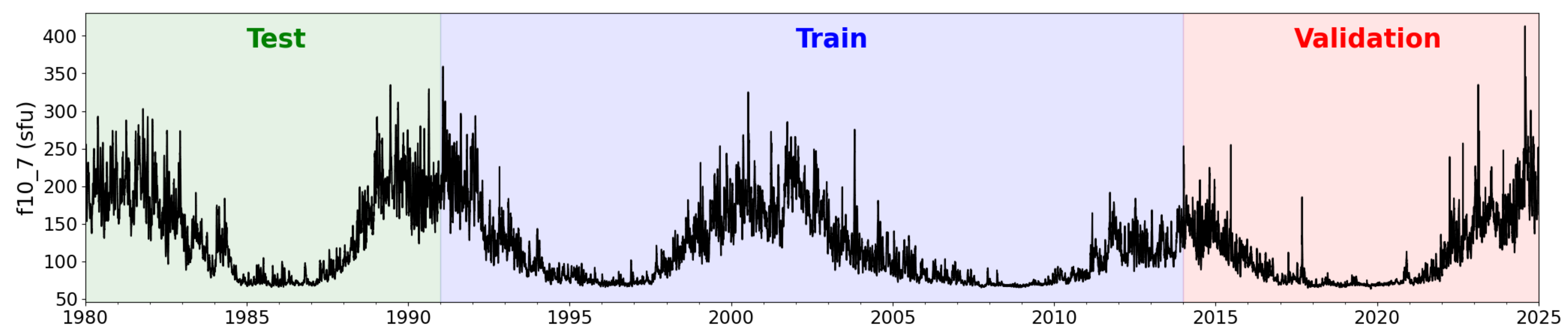


Figure 1:Temporal coverage and partitioning of the simulation period.

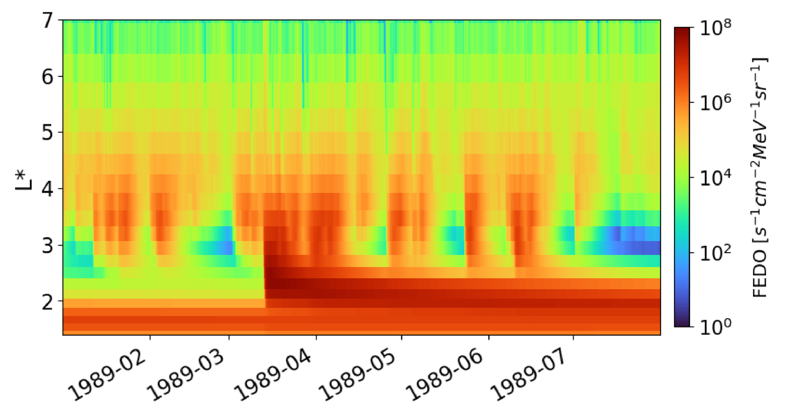
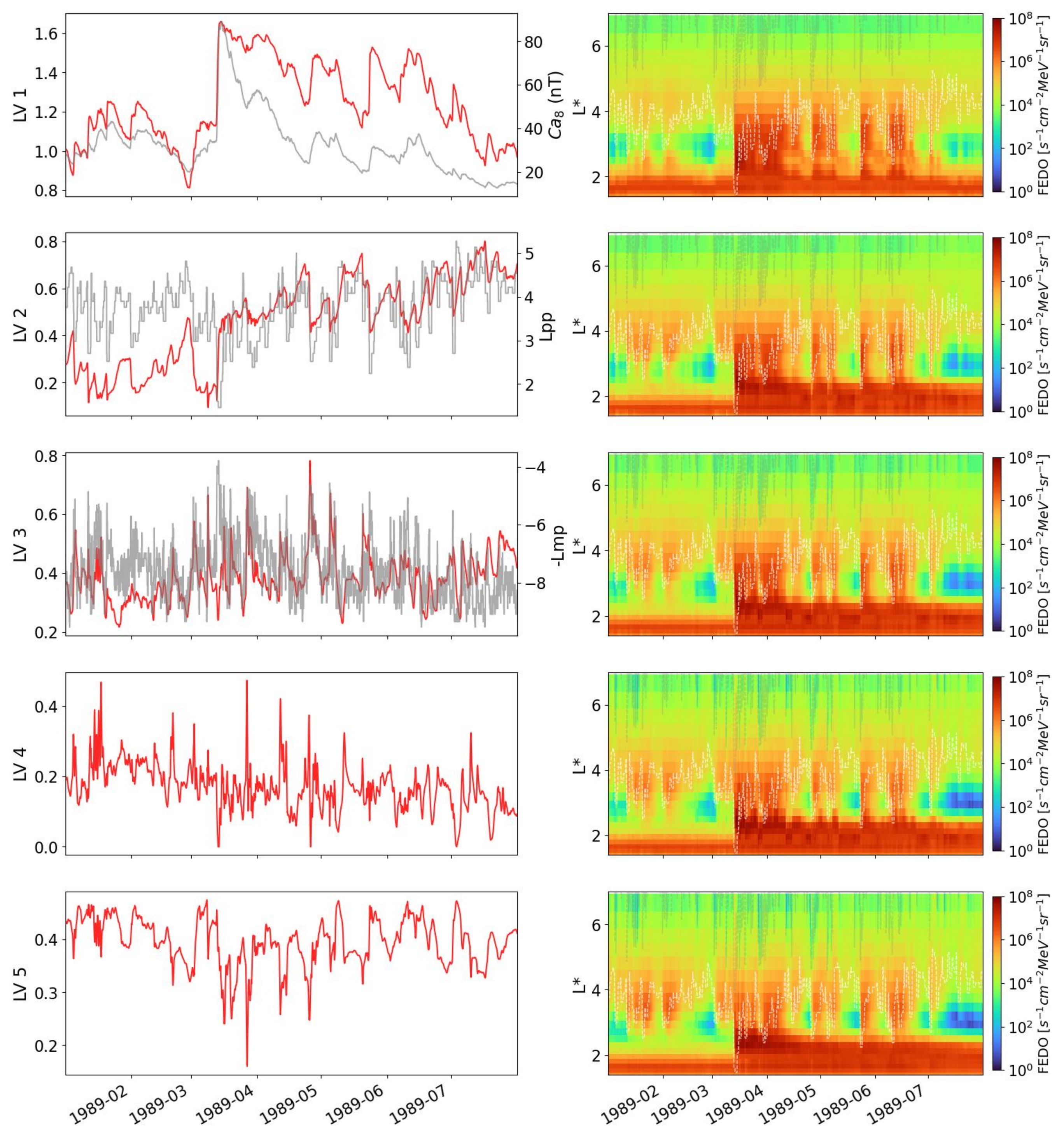


Figure 2: Simulated test set electron fluxes at 1MeV.

→ 4707 hourly measurements of omnidirectional differential electron fluxes over the simulation period.

Latent space interpretation

Figure 6:
Left column:
Temporal evolution of the latent variables obtained with DIRESA *(red),* and the Ca_8, Lpp and Lmp parameters *(grey)*.
Right column from top to bottom:
1 MeV electron fluxes reconstructed with DIRESA from the progressive addition of LVs. The *white* (resp. *grey*) line represents the evolution of Lpp (resp. Lmp).



- The most prominent latent variables exhibit straight links with external geomagnetic parameters.
- Although less interpretable, LV 4 and LV5 still have an impact on the total reconstruction.

Future Steps

- **Drive the LV dynamics with the most appropriate geomagnetic parameters.**
- **Estimation of electron fluxes on past periods with no available spacecraft data.**

References

[1] Dahmen,N.,Sicard,A.,&Brunet,A. (2024,August). Climate Reanalysis of Electron Radiation Belt Long-Term Dynamics Using a Dedicated Numerical Scheme. IEEE Transactions on Nuclear Science,71(8),1598–1605. doi: 441 10.1109/TNS.2024.3368014
[2] Paepe, G. D., & Cruz, L. D. (2025, July). DIRESA, a Distance-Preserving Nonlinear Dimension Reduction Technique Based on Regularized Autoencoders. Artificial Intelligence for the Earth Systems, 4(3). doi: 10.1175/AIES-D-24-0034.1