A physics-guided non-ergodic ground motion model for the Groningen, Netherlands region

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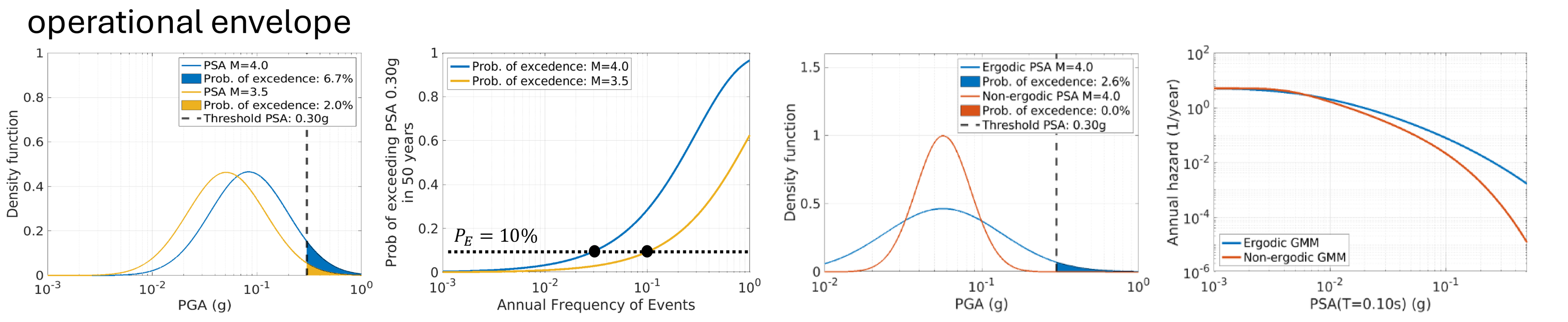
Abstract

We have been developing a computationally efficient methodology for non-ergodic ground motion models (NGMMs) aiming to fully describe the systematic path and site effects. Using a 3D velocity model derived from geophysical data for the Groningen field, we performed a series of 3D numerical simulations to generate a synthetic ground-motion dataset, illuminating seismic wave propagation paths not represented in the empirical datasets. A Gaussian Process (GP) model was fitted to the synthetic data to extract the repeatable path and site effects. A new kernel function was designed to model the path effects based on the correlation of the entire ray-path vectors, directly capturing azimuthal and path-length effects. Ground motion observations were used to adjust the site effects, addressing the velocity model limitations in the shallow layers. A Kernel-flows based regression approach is implemented to determine the GP hyper-parameters through cross-validation, anticipating to improve the predictive performance of the model compared to traditional MLE-based methods. Assimilating large sets of empirical and simulated data necessitated the development of efficient sparse approximations and the use of high-performance computing. Using the Sparse Cholesky Factorization we were able to reduce the memory and computational complexity from $O(N^2)$ and $O(N^3)$ to $O(N\log(N)^d)$ and $O(N\log(N)^{2d})$, respectively. While the use of the open-source coding language Julia, which is optimized for parallel computing scalability, will allow us to take advantage of the additional resources in HPC environments.

The development of non-ergodic ground motion models for Oil and Gas (O&G) operations will allow shareholders to directly characterize the seismic hazard along with its epistemic uncertainty, providing a valuable tool for risk-informed decision-making.

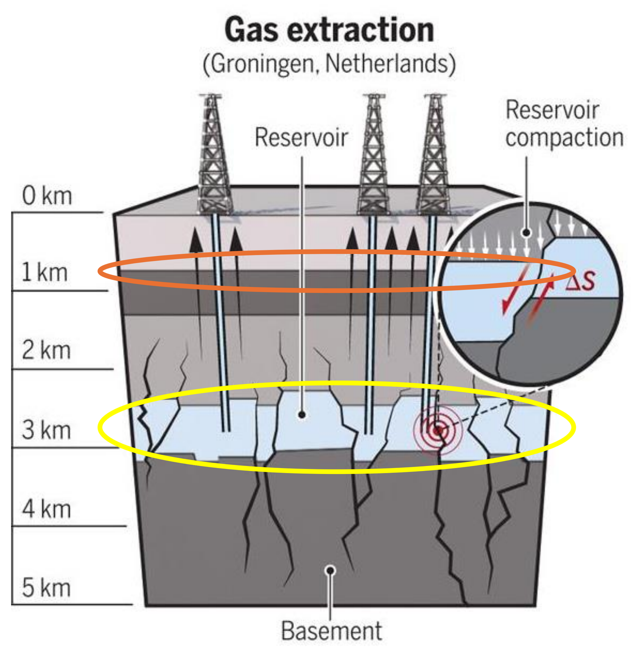
Motivation

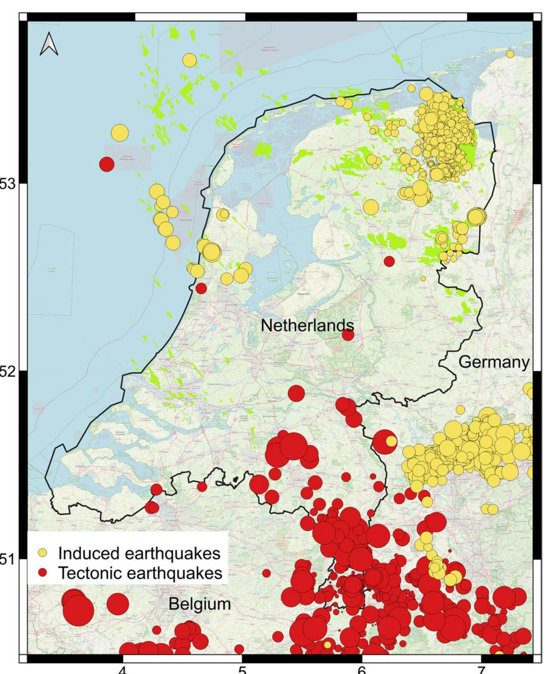
Current O&G operations rely on a traffic light system with a maximum allowable magnitude threshold (M_u), such that extraction activities do not trigger an event exceeding M_u, or to halt operations if such an event occurs. However, such scheme does not account for the frequency of earthquakes and ground-motion variability given the size of an event, potentially underestimating the hazard exposure. Addressing this issue requires a probabilistic approach to characterize seismic sources and ground motion to evaluate the hazard. Non-ergodic ground motion models (NGMMs), informed by physical data and simulation efforts, provide an opportunity to reduce aleatory variability and better characterize epistemic uncertainty, enabling a more accurate estimation of the operational envelope



Groningen Seismicity

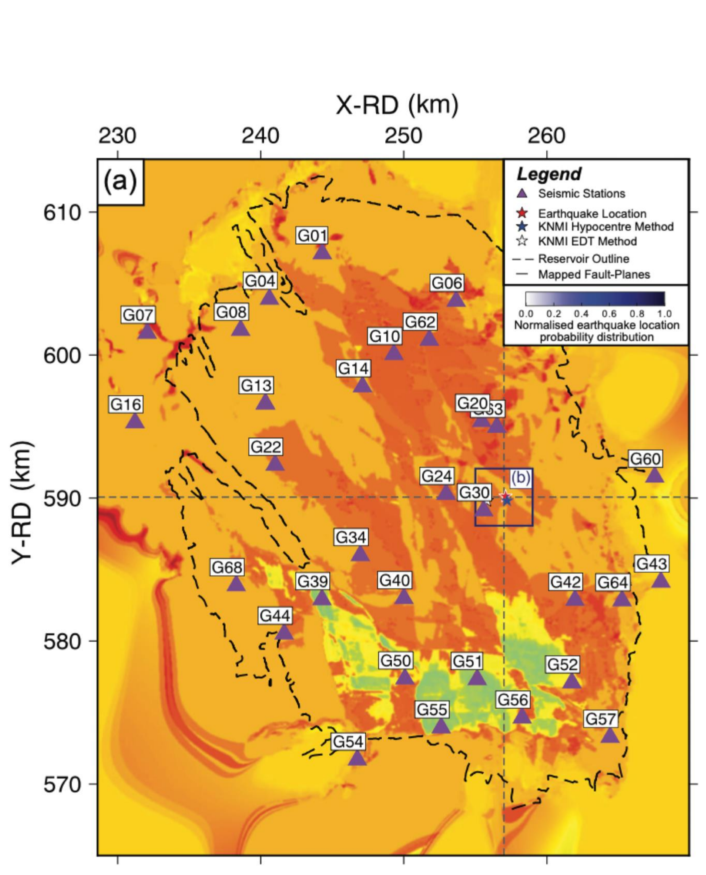
Induced earthquakes in Groningen, Netherlands, are triggered by the reactivation of pre-existing faults, resulting from the compaction of the Rotliegend reservoir layer, located around 3 km deep, due to natural gas extraction. The largest recorded event was a M 3.5 in 2012. Ground motions experience significant amplification near the surface due to a sharp impedance contrast at a depth of approximately 800 m.

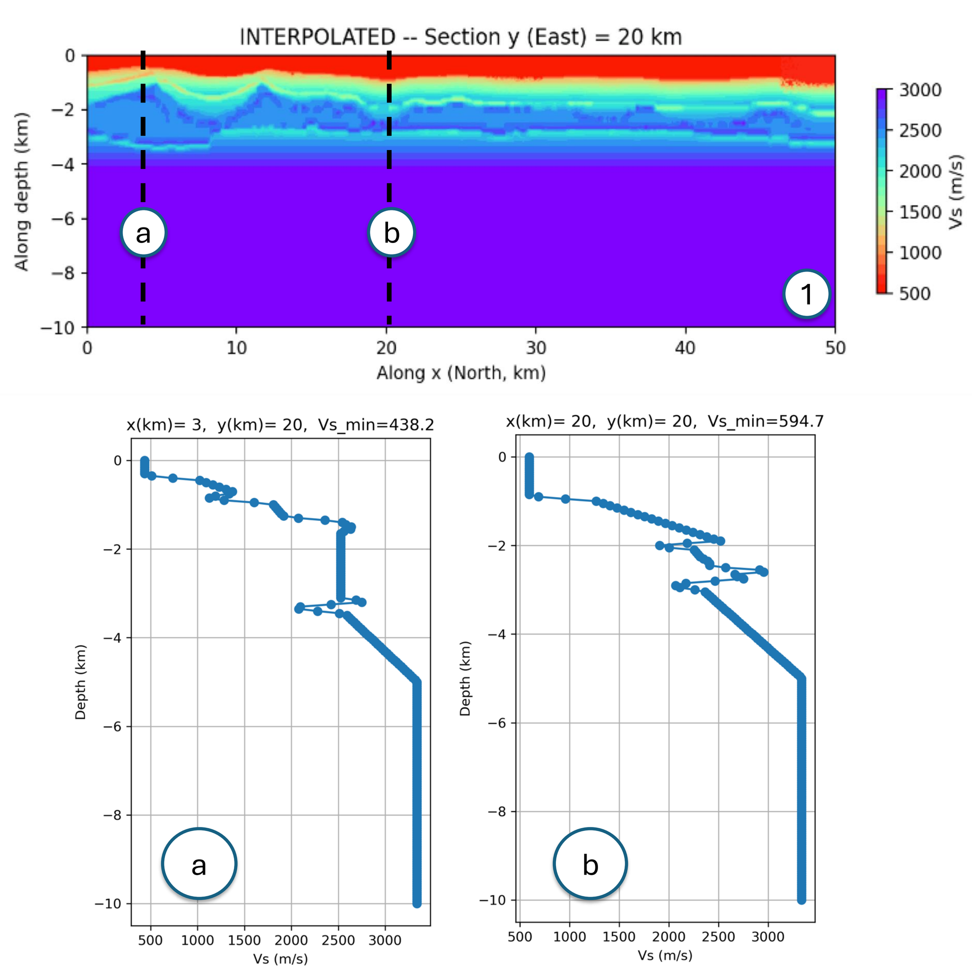




Groningen Velocity and Attenuation Models

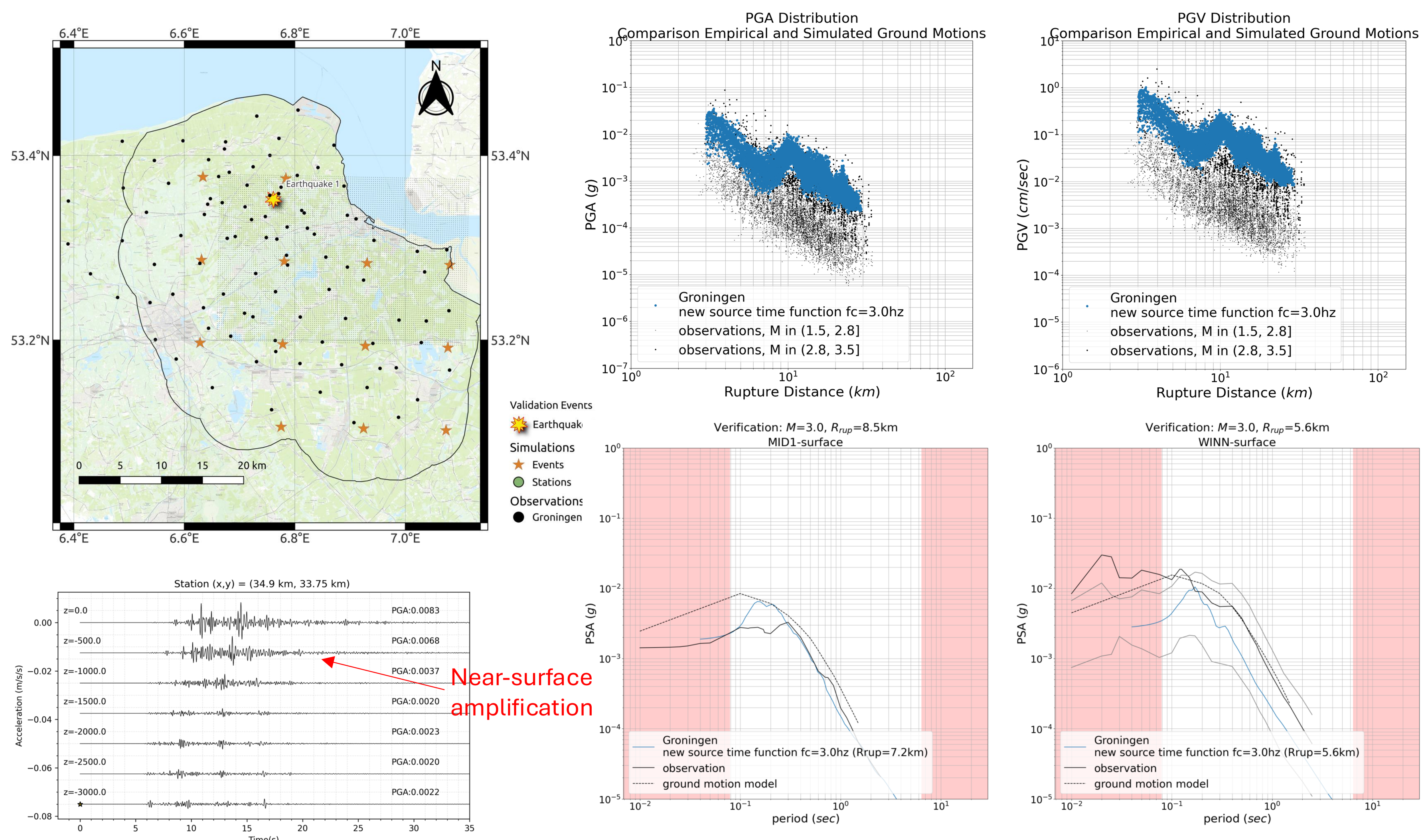
A published 3D velocity model (Kuiver et al., 2017) was employed in SPECFEM to simulate the propagation of seismic waves from the reservoir to the surface, while a minimum shear-wave velocity of $500 m/sec$ was applied to reduce computational cost.





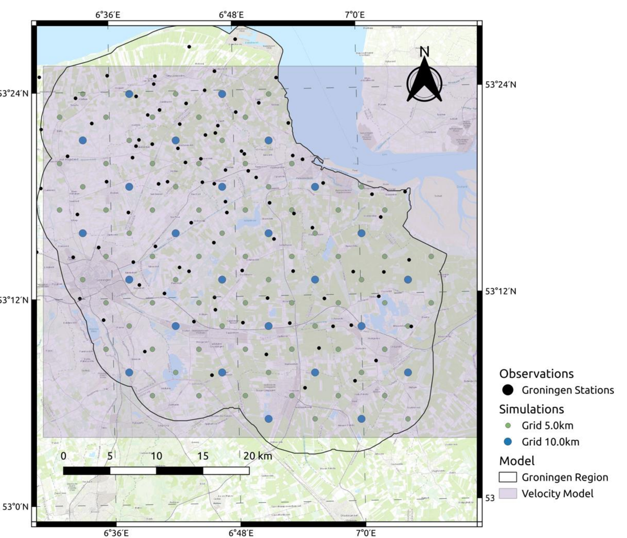
Simulation Validation

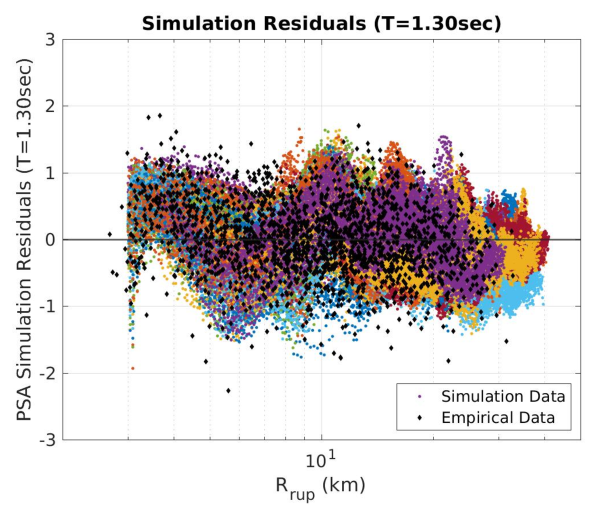
A limited number of point-source simulations were conducted at real event locations for validation purposes. The comparisons showed that the 3D simulations were able to produce similar frequency content within the usable frequency range and capture the complex wave propagation and surface amplification patterns observed in real data.



Scenario Simulations

Following the validation, a large number of simulations were conducted on a 5 km-spaced grid for the events, with recordings made at 250 m spacing in the center and 1 km spacing at the edges of the Groningen field. A total of 98 simulations were performed, generating 800,000 ground motion records. These simulations were run on a 30-GPU cluster, with each simulation taking approximately 3.5 hours to complete.





Path Kernel Desing and Regression

A new GP kernel was designed to directly characterize the correlation of path vectors, implicitly capturing the source/site locations, path length, azimuthal dependencies, and reciprocity effects into the correlation structure.

Assume a kernel for the underlying base field:

$$y \sim N\left(0, \kappa_b(\vec{x}, \vec{x}')\right)$$

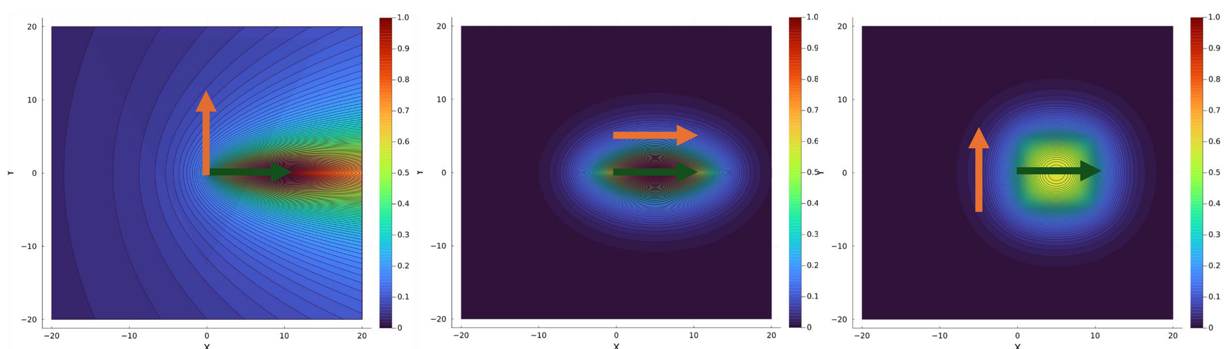
with $\kappa(\vec{x}, \vec{x}') = \langle \phi(\vec{x}), \phi(\vec{x}') \rangle$

Define vector correlation as covariance integral along the path:

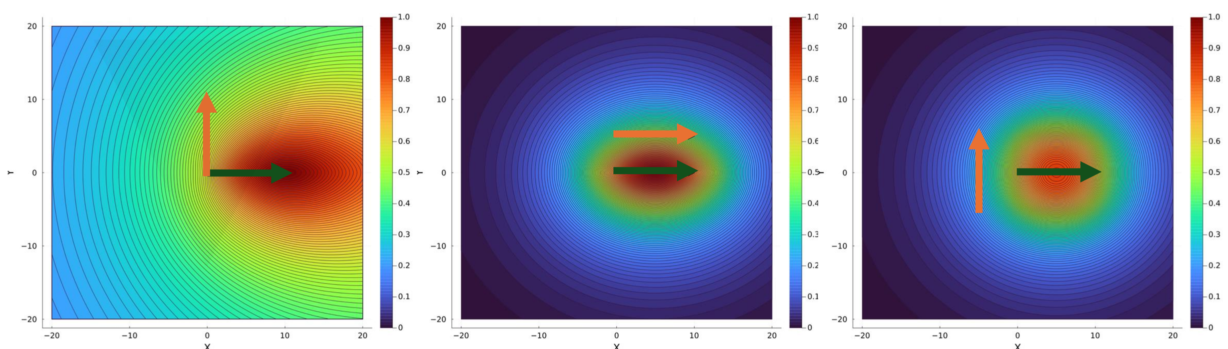
$$\kappa_p([\vec{x}_e, \vec{x}_s], [\vec{x}_e', \vec{x}_s']) = \left\langle \int_{\vec{x}_s}^{\vec{x}_e} \phi(\vec{x})dx, \int_{\vec{x}_s'}^{\vec{x}_e'} \phi(\vec{x})dx \right\rangle$$

which is equivalent to:

$$\kappa_p([\vec{x}_e, \vec{x}_s], [\vec{x}_e', \vec{x}_s']) = \iint_{\vec{x}_e, \vec{x}_e'}^{\vec{x}_s, \vec{x}_s'} \kappa_b(\vec{x}, \vec{x}')\, d\vec{x} d\vec{x}'$$

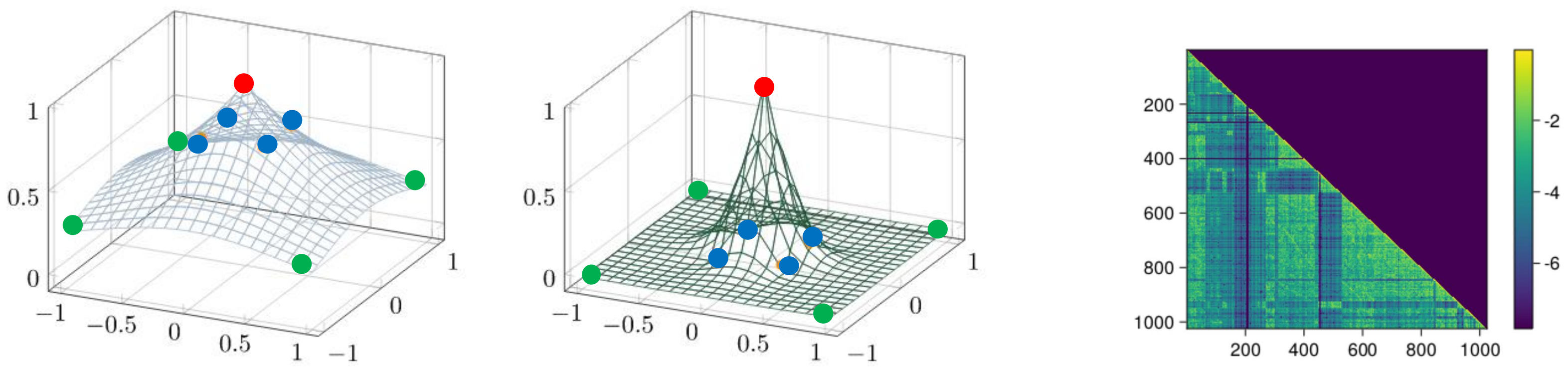


Correlation structure for path vectors with larger lengths than correlation length scale.

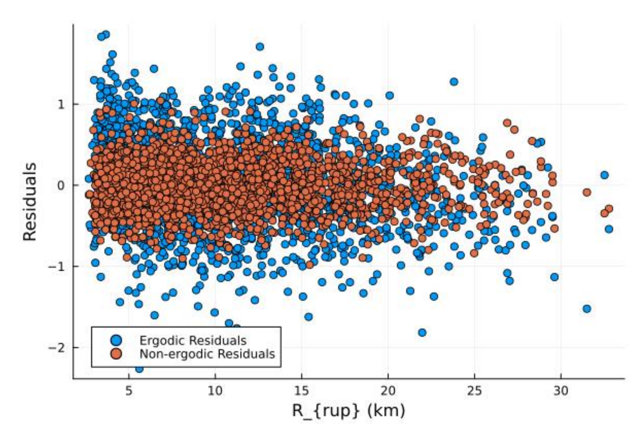


Correlation structure for path vectors with larger lengths than correlation length scale.

Computational efficiency was improved by manipulating the precision matrices, Σ^{-1}, directly, which exhibits a faster decay compared to the covariance, Σ (Schafer et al., 2021). A min/max ordering scheme was applied to identify large value elements, representing the Σ^{-1} as sparse.



The non-ergodic NGMM regression is currently in progress. GP hyper-parameters have been estimated using Kernel flow regression on a training subset sampled via a Sobol sequence to cover the entire domain, while forward predictions utilize the aforementioned sparse approximation. Preliminary results show approximately a 30% reduction in standard deviation compared to the ergodic model. Further refinements in hyper-parameter training are anticipated to further reduce the aleatory variability.



Acknowledgments

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