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MTGeophysics.jl: A software repository for magnetotelluric research and applications

Pankaj K Mishra [1¶]

1 Geological Survey of Finland (GTK), Espoo, Finland ¶ Corresponding author

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Software

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Summary

The magnetotelluric (MT) method uses natural electromagnetic field variations to image subsurface electrical resistivity at depths ranging from tens of metres to hundreds of kilometres. It is widely used in geophysical exploration for natural resources, including minerals, geothermal energy, and groundwater, as well as in the characterisation of sites for CO_2 storage and in studies of crustal and lithospheric structure. The MT inverse problem is, however, inherently non-unique: many distinct resistivity models reproduce the observations equally well. Conventional practice nonetheless reports a single regularised model, with no quantitative measure of its uncertainty.

MTGeophysics.jl is a Julia package developed to address this limitation. Its principal aim is the quantification of uncertainty in MT model building, advancing interpretation from a single deterministic model, through an ensemble of plausible models, towards the full posterior distribution (Figure 1). The package also provides tools for data analysis, mesh generation, masking, forward modelling, inversion, model analysis and visualisation for MT research and applications.

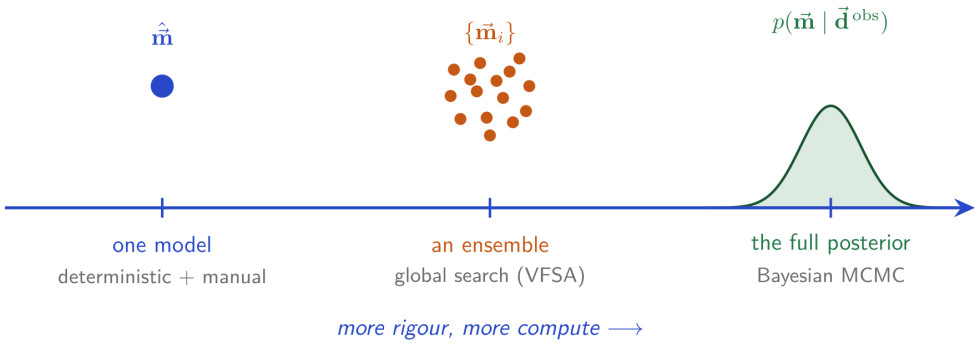


Figure 1: The vision behind MTGeophysics.jl. Deterministic inversion yields a single regularised model $\hat{\mathbf{m}}$; an ensemble of plausible models $\{\mathbf{m}_i\}$ and, ultimately, the full posterior distribution $p(\mathbf{m} \mid \mathbf{d}^{\mathrm{obs}})$ characterise model uncertainty with increasing rigour and computational cost. The package aims to make ensemble-based uncertainty quantification routine and to provide a practical path towards the full posterior.

Statement of need

Sampling many models consistent with the data, rather than a single regularised model, is computationally demanding in 3D, because a regional mesh carries millions of free parameters and every candidate model requires a full electromagnetic forward solve.

MTGeophysics.jl addresses this gap with a stochastic inversion workflow based on Very Fast Simulated Annealing (VFSA) (Sen & Stoffa, 2013) that produces an *ensemble* of plausible 3D models, summarised by its mean, median, and standard deviation. The workflow reuses the community-standard ModEM forward solver (Egbert & Kelbert, 2012; Kelbert et al., 2014) by reading and writing its native file formats, so it slots into established MT practice without asking users to change their models, data, or solver.

The package targets MT researchers and students who want an open-source toolkit that builds on Julia's strengths in numerical computing, composability, and interactive graphics (Bezanson et al., 2017). It is designed as a research repository and as a core component of a broader JuliaGeophysics ecosystem: forward solvers, data structures, and inversion routines are meant to be reused and recombined, so that new ideas can be prototyped without rebuilding core MT tooling.

State of the field

Several open-source codes support MT research. ModEM (Egbert & Kelbert, 2012; Kelbert et al., 2014) is widely used for deterministic 3D MT inversion on structured grids. FEMTIC (Usui, 2015; Usui et al., 2017) performs 3D MT inversion on unstructured meshes, incorporating topography, bathymetry and galvanic distortion, and FEMTIC-DABIC (Song et al., 2026) extends it with statistical selection of the regularisation parameter. jif3D (Moorkamp et al., 2011) is a multi-physics joint inversion framework that combines 3D MT with gravity, magnetic and seismic data. MARE2DEM (Key, 2016) provides adaptive finite-element 2D modelling and inversion of MT and controlled-source electromagnetic data, and custEM (Rochlitz et al., 2019) offers 3D finite-element electromagnetic forward modelling. MTpy (Kirkby et al., 2019) provides Python utilities for MT data handling and visualisation, while pyGIMLi (Rücker et al., 2017) and SimPEG (Cockett et al., 2015) are general geophysical inversion frameworks that include MT modules. HiQGA.jl (Ray, 2021) provides deterministic and probabilistic (trans-dimensional Bayesian) inversion for several geophysical methods.

MTGeophysics.jl complements these tools, with a focus on stochastic inversion and ensemble-based uncertainty quantification that is practical in 3D. Because many 3D MT models and datasets are held in ModEM formats, the package reads and writes those files directly and uses ModEM as its 3D forward solver, so it fits into existing workflows without converting meshes or data. Building instead on a larger framework would have required that conversion, which motivated a standalone package. The package also includes its own pure-Julia 1D and 2D forward solvers and inversion routines. It is intended to work alongside the existing open-source ecosystem in magnetotelluric research.

Software design

The central design choice in MTGeophysics.jl is reduced model parameterisation, the strategy that makes stochastic 3D inversion tractable. Stochastic inversion becomes intractable if every mesh cell is a free parameter: the search space is too large and each proposal requires an expensive forward solve. Rather than perturbing the full grid, the VFSA workflow perturbs a small set of radial-basis-function (RBF) control points and maps them back to the mesh with a compactly supported Gaussian RBF (truncated at 3σ), as shown for one iteration in Figure 2.

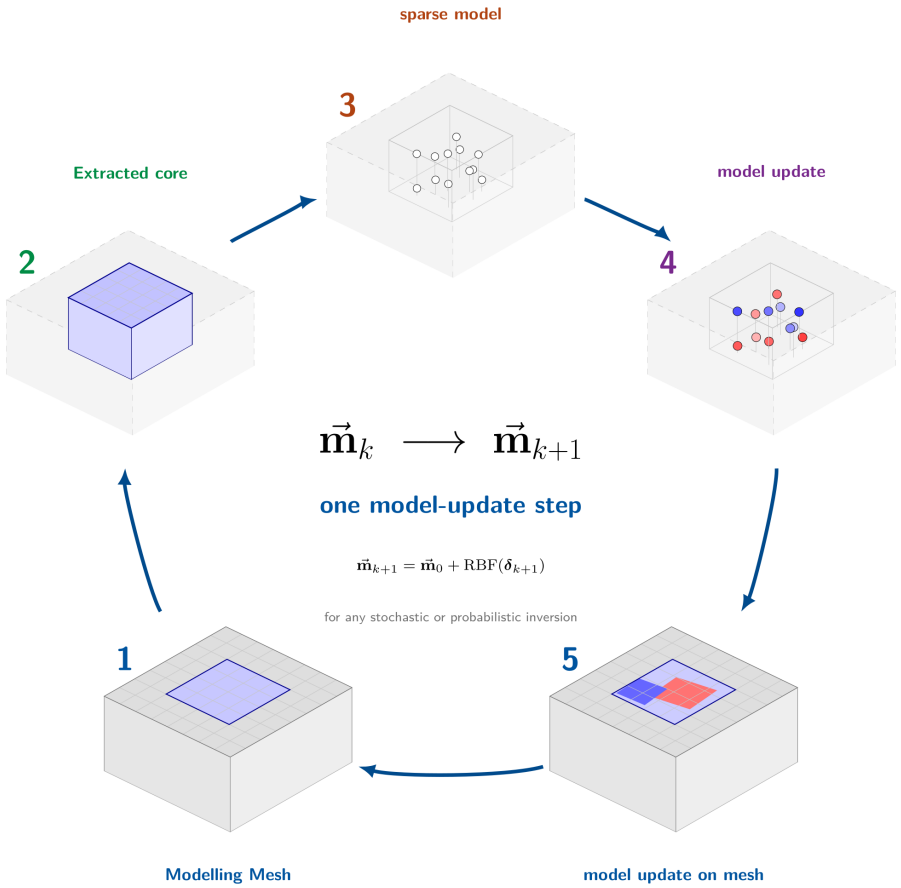


Figure 2: One VFSA iteration as a sparse-model update loop. The padded modelling mesh (1) is reduced to its core (2), sampled at M random control points, the *sparse model* (3), perturbed by the VFSA rule (4), then mapped back to the full padded mesh by compactly supported Gaussian-RBF interpolation (5) for the ModEM forward solve, advancing $\mathbf{m}_k \to \mathbf{m}_{k+1}$.

The trade-off is resolution: structure finer than the control-point spacing and RBF width cannot be represented, so both are user-set parameters. The resulting ensemble consists of independently optimised models rather than samples from a posterior distribution; its spread indicates where the data weakly constrain the model rather than providing calibrated uncertainty. A low-dimensional representation is also what would make fully Bayesian sampling affordable in 3D.

Around this core, the package is organised as a single Julia module with separate layers: ModEM 3D data and model I/O; a 1D module that solves the layered-earth impedance recursion exactly, with Fréchet derivatives by automatic differentiation; a 2D module that assembles sparse finite-difference operators for the TE and TM modes; and inversion modules for 1D, 2D and 3D: deterministic inversion, which in 3D is left to ModEM, and stochastic inversion by VFSA, with adaptive simulated annealing (ASA) as a further 3D option. For 1D and 2D problems, the package uses its own forward solvers and runs chains in parallel threads; in 3D it calls ModEM as a subprocess, runs each chain as an independent job and computes ensemble statistics across the completed runs. Because ModEM is reached only through its files, the forward solver can be swapped. Visualisation uses GLMakie (Danisch & Krumbiegel, 2021) for interactive 3D slice viewers, with coordinate reprojection via Proj.jl and shapefile overlays, and CairoMakie for static figures. All model, data and control files are plain text, and argument-driven example scripts make every workflow reproducible from the command

line. Detailed usage is described in the package documentation.

Development is continuing in two directions: portable, GPU-accelerated forward solvers written in pure Julia, which would remove the dependence on an external solver, and neural surrogates of the forward problem, which together aim to make full Bayesian inversion computationally practical. These components are experimental and not part of the current release. Implicit neural representations, which have been applied to 3D gravity inversion (Mishra, Laaksonen, et al., 2026), offer a further route to a compact, continuous model parameterisation.

MTGeophysics.jl is intended to support the latest two Julia releases (currently versions 1.13 and 1.12). Continuous integration runs the test suite on both versions under a virtual display, so the visualisation layer is also exercised. The tests cover the 3D data structures and ModEM I/O, analytic checks of the 1D solver, physical-consistency and finite-difference Fréchet checks of the 2D solver, the COMMEMI benchmark generators, and end-to-end 1D and 2D inversions.

Benchmarks and validation

The package is validated at two levels. The COMMEMI 2D benchmark models (Zhdanov et al., 1997) are generated natively by `helpers/benchmarks_2D.jl`, so the 2D forward and inversion workflows can be exercised from the repository without external downloads. At regional scale, the 3D VFSA workflow has been applied to USArray MT data from the Cascadia subduction zone (Patro & Egbert, 2008) and compared with a deterministic ModEM inversion (Mishra, Kamm, et al., 2026): the ensemble mean recovers the major conductive structures, while the ensemble standard deviation indicates where the data poorly constrain the model. The comparison is reproduced in the package documentation.

Research impact statement

MTGeophysics.jl supports ongoing magnetotelluric research at the Geological Survey of Finland (GTK) and opens uncertainty-aware MT interpretation to the wider community. The package has been in development on GitHub since August 2024 and has attracted external users, who have reported issues, requested features and contributed fixes.

The package and the research built on it have been presented to the geophysics and scientific-computing communities by the author and collaborators, including at the EGU General Assembly 2026 (Mishra, Kamm, et al., 2026), the 27th Electromagnetic Induction Workshop (EMIW 2026), and JuliaCon 2026. MTGeophysics.jl was also used to participate in the MT3DINV-4 workshop (Memorial University of Newfoundland, 2026), a community 3D MT inversion benchmarking exercise in which many groups inverted a common real field dataset acquired over the Raglan mining district in northern Quebec, Canada.

AI usage disclosure

Different versions of Claude (Anthropic) and Codex (OpenAI) were used over the duration of development of this package to implement ideas, reorganise the repository, write documentation and tests, and edit this paper. The GitHub Copilot coding agent contributed a small number of commits, and is also used to check for continuous integration (CI) errors on GitHub; Dependabot is used to keep dependency versions current. All AI-generated code and text were reviewed, tested, and verified by the author for correctness.

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