

# 3D CSEM Forward Modelling

Key features and first results of our recently developed finite-element code



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## Introduction

- 3D controlled-source electromagnetic modelling code in frequency domain
- Using unstructured tetrahedral meshes of finite-elements
- First order Nédélec basis functions - vector edge interpolation functions [1]
- Dirichlet boundary conditions
- Model parameters: electric resistivity and magnetic permeability

- Calculation of the electric fields in an edge-based manner
- Curl-Curl-Equation for the electric field (E) with time dependency of  $e^{i\omega t}$ :

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{E} - i\omega \frac{1}{\rho} \mathbf{E} = i\omega \mathbf{J}_{source} \quad (1)$$

- Planned to be incorporated in the inversion framework EMILIA [2] as a 3D module

## Achievements

### Key Features

**Receiver implementation**

The receivers are located in the middle of the air-earth facet of the receiver-earth element.

Edge i	Node i <sub>1</sub>	Node i <sub>2</sub>
1	1	2
2	1	3
3	2	3
4	2	4
5	4	2
6	3	4

**Source implementation**  
Example: HED in x-direction

Extended HEDs and magnetic loop sources are implemented following the same concept.

The 3D forward modelling is stable over three frequency decades using the same mesh.

**Ex & Ey**

**Hx, Hy & Hz**

### Testing Model

**"hom"** (100 Ωm half-space)

**"lay"** (1D layered model)

**"cubes"** (3D model with cubes)

Model dimension: 10 x 10 x 10 km  
 Mesh [4]: ~60000 dof

38 inline receivers

ρ<sub>1</sub> = 100 Ωm  
 ρ<sub>2</sub> = 10 Ωm

refined mesh around source, receivers and anomalies

TetGen

The open source solver PARDISO [5] is applied to solve the system of equations.

A semi-analytic solution utilising the Fast Hankel transform (FHT) from EMILIA [2] is used for comparison.

### Code validation

**45°** **inline**

**implement into EMILIA [2] framework**

Flowchart showing integration with EMILIA framework:

```

            graph TD
            A[Data and methods: MT, RMT, GSM, TET, FEM, DOR] --> B[3D FEM & SEM]
            B --> C[MT, RMT, DOR, CSEM]
            C --> D[Remainder models: 1-D, 2-D, 3-D]
            D --> E[Non-linear model requires inversion]
            E --> F[Linearised data resolution analysis]
            F --> G[Assessment]
            G --> H[Regulation]
            H --> I[Smoothness Structural petrophysical prior info]
            I --> J[Appropriate discretisation]
            J --> K[Remainder models]
            K --> L[Non-linear model requires inversion]
            L --> M[Linearised data resolution analysis]
            M --> N[Assessment]
            N --> O[Regulation]
            O --> P[Smoothness Structural petrophysical prior info]
            P --> Q[Appropriate discretisation]
            Q --> R[Remainder models]
            R --> S[Non-linear model requires inversion]
            S --> T[Linearised data resolution analysis]
            T --> U[Assessment]
            U --> V[Regulation]
            V --> W[Smoothness Structural petrophysical prior info]
            W --> X[Appropriate discretisation]
            X --> Y[Remainder models]
            Y --> Z[Non-linear model requires inversion]
            Z --> AA[Linearised data resolution analysis]
            AA --> AB[Assessment]
            AB --> AC[Regulation]
            AC --> AD[Smoothness Structural petrophysical prior info]
            AD --> AE[Appropriate discretisation]
            AE --> AF[Remainder models]
            AF --> AG[Non-linear model requires inversion]
            AG --> AH[Linearised data resolution analysis]
            AH --> AI[Assessment]
            AI --> AJ[Regulation]
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            AK --> AL[Appropriate discretisation]
            AL --> AM[Remainder models]
            AM --> AN[Non-linear model requires inversion]
            AN --> AO[Linearised data resolution analysis]
            AO --> AP[Assessment]
            AP --> AQ[Regulation]
            AQ --> AR[Smoothness Structural petrophysical prior info]
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            AS --> AT[Remainder models]
            AT --> AU[Non-linear model requires inversion]
            AU --> AV[Linearised data resolution analysis]
            AV --> AW[Assessment]
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            AX --> AY[Smoothness Structural petrophysical prior info]
            AY --> AZ[Appropriate discretisation]
            AZ --> BA[Remainder models]
            BA --> BB[Non-linear model requires inversion]
            BB --> BC[Linearised data resolution analysis]
            BC --> BD[Assessment]
            BD --> BE[Regulation]
            BE --> BF[Smoothness Structural petrophysical prior info]
            BF --> BG[Appropriate discretisation]
            BG --> BH[Remainder models]
            BH --> BI[Non-linear model requires inversion]
            BI --> BJ[Linearised data resolution analysis]
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            BL --> BM[Smoothness Structural petrophysical prior info]
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            BP --> BQ[Linearised data resolution analysis]
            BQ --> BR[Assessment]
            BR --> BS[Regulation]
            BS --> BT[Smoothness Structural petrophysical prior info]
            BT --> BU[Appropriate discretisation]
            BU --> BV[Remainder models]
            BV --> BW[Non-linear model requires inversion]
            BW --> BX[Linearised data resolution analysis]
            BX --> BY[Assessment]
            BY --> BZ[Regulation]
            BZ --> C0[Smoothness Structural petrophysical prior info]
            C0 --> C1[Appropriate discretisation]
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            C436 --> C437[Non-linear model requires inversion]
            C437 --> C438[Linearised data resolution analysis]
            C438 --> C439[Assessment]
            C439 --> C440[Regulation]
            C440 --> C441[Smoothness Structural petrophysical prior info]
            C441 --> C442[Appropriate discretisation]
            C442 --> C443[Remainder models]
            C443 --> C444[Non-linear model requires inversion]
            C444 --> C445[Linearised data resolution analysis]
            C445 --> C446[Assessment]
            C446 --> C447[Regulation]
            C447 --> C448[Smoothness Structural petrophysical prior info]
            C448 --> C449[Appropriate discretisation]
            C449 --> C450[Remainder models]
            C450 --> C451[Non-linear model requires inversion]
            C451 --> C452[Linearised data resolution analysis]
            C452 --> C453[Assessment]
            C453 --> C454[Regulation]
            C454 --> C455[Smoothness Structural petrophysical prior info]
            C455 --> C456[Appropriate discretisation]
            C456 --> C457[Remainder models]
            C457 --> C458[Non-linear model requires inversion]
            C458 --> C459[Linearised data resolution analysis]
            C459 --> C460[Assessment]
            C460 --> C461[Regulation]
            C461 --> C462[Smoothness Structural petrophysical prior info]
            C462 --> C463[Appropriate discretisation]
            C463 --> C464[Remainder models]
            C464 --> C465[Non-linear model requires inversion]
            C465 --> C466[Linearised data resolution analysis]
            C466 --> C467[Assessment]
            C467 --> C468[Regulation]
            C468 --> C469[Smoothness Structural petrophysical prior info]
            C469 --> C470[Appropriate discretisation]
            C470 --> C471[Remainder models]
            C471 --> C472[Non-linear model requires inversion]
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            C473 --> C474[Assessment]
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            C475 --> C476[Smoothness Structural petrophysical prior info]
            C476 --> C477[Appropriate discretisation]
            C477 --> C478[Remainder models]
            C478 --> C479[Non-linear model requires inversion]
            C479 --> C480[Linearised data resolution analysis]
            C480 --> C481[Assessment]
            C481 --> C482[Regulation]
            C482 --> C483[Smoothness Structural petrophysical prior info]
            C483 --&gt
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