Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

custEM 1.0

- Finite element solutions on unstructured meshes
- Support for all inductive EM methods
- Land-based, marine, airborne or hybrid setups
- Python, open-source, examples, documentation

Controlled-Source Electromagnetics

CSEM

Transient Electromagnetics

TEM

Natural-Source Electromagnetics

MT

www

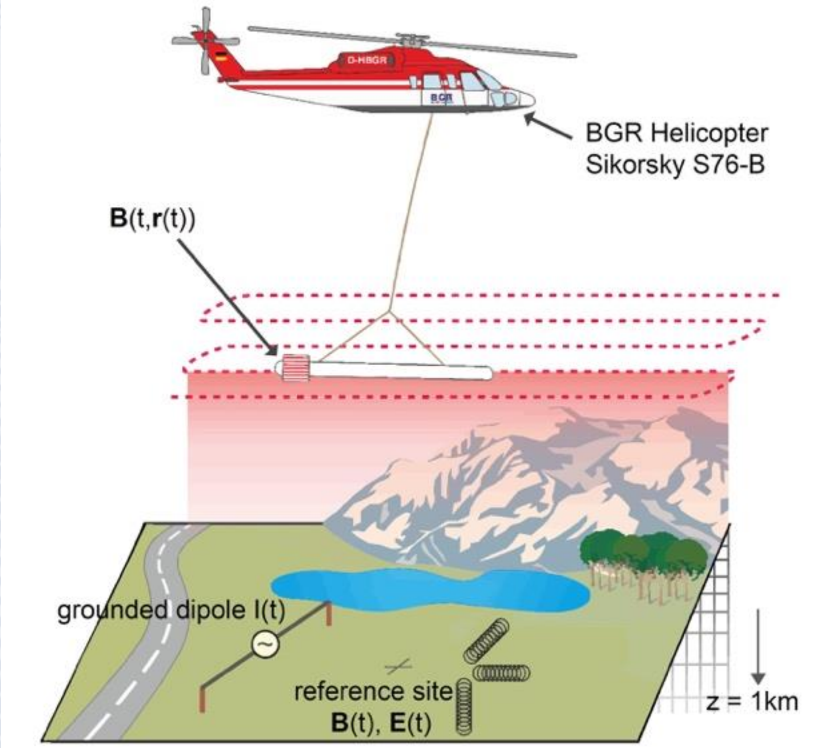
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Start



The joint research project DESMEX (Deep Electromagnetic Soundings for Mineral EXploration) is founded by the Federal Ministry for Education and Research (BMBF) project r4 to develop a semi-airborne controlled-source electromagnetic (CSEM) exploration system for deep mineral deposits down to 1 km depth. Grounded electric dipole transmitters provide strong signals to cover flight areas with 6x8 km dimensions. A SQUID-based and an induction coil receiver system are towed by a helicopter and referenced with ground stations.

DESMEX partners

1/3

DESMEX
custEM
CSEM
TEM
MT

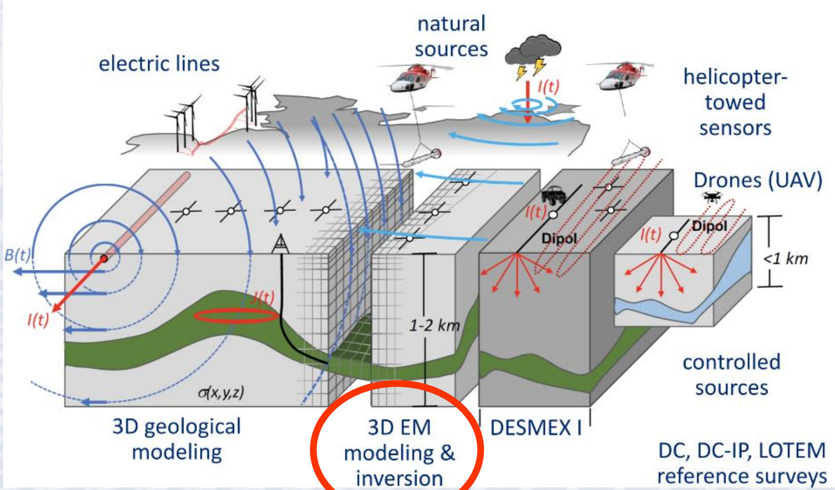
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for
Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Federal Ministry of Education and Research
FONA



DESMEX has commenced in 2015. In 2019, the continuation project DESMEX II was launched. DESMEX II includes not only manned helicopter, but also unmanned drone operations. In addition, we conduct helicopter-based natural-source AFMAG surveys and consider induced-polarization effects. We aim at real-world cases to bring the technologies closer to application. LIAG is the responsible project partner for developing multi-dimensional inversion routines for all data.

project webpages

WWU BGR LIAG IPHT

DESMEX II partners

WWU Münster, IGM Geophysics Cologne, BGR, LIAG, Leibniz IPHT (Leibniz-Institut für Photonische Technologien), supracon (SQUID and Microfabrication Technologies), terratec Geophysical Services, DMT, iMAR Navigation & Control

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

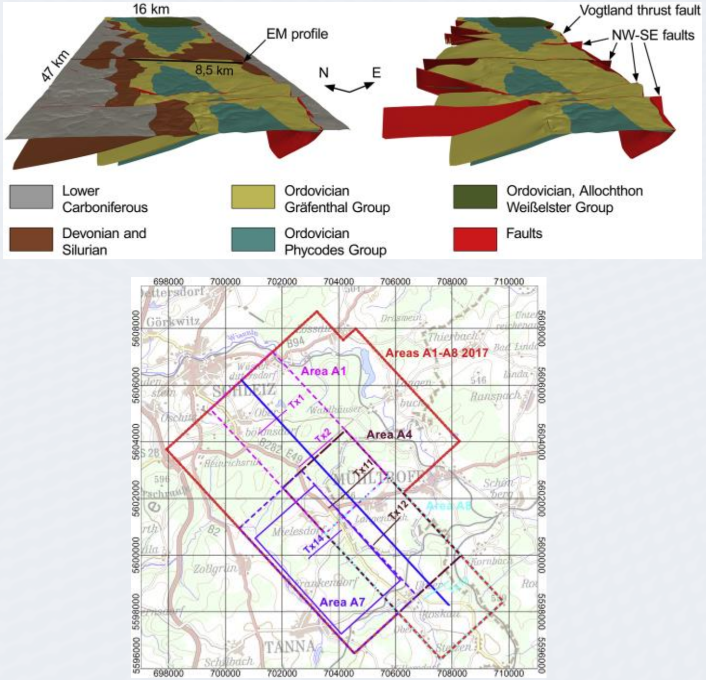
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

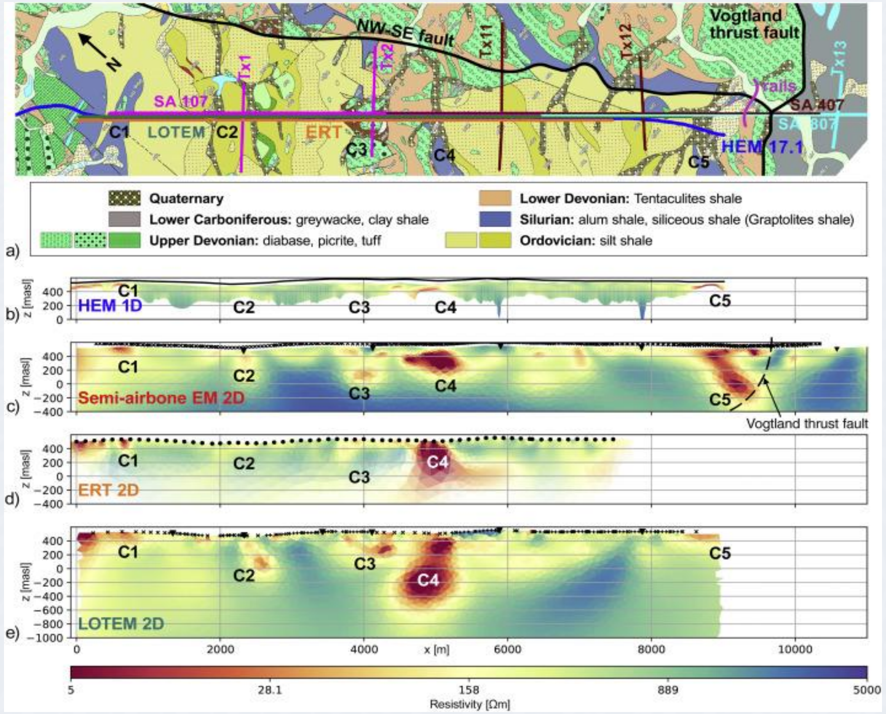
Raphael Rochlitz & Thomas Günther

References (DESMEX)

Steuer et al. (2020): Comparison of novel semi-airborne electromagnetic data with multi-scale geophysical, petrophysical and geological data from Schleiz, Germany. *Journal of Applied Geophysics* 182: 104172, doi: 10.1016/j.jappgeo.2020.104172

1/5





3/3

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

IAG Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

References (DESMEX)

Smirnova et al. (2020): Exploring Kiruna iron ore fields with large-scale, semi-airborne, controlled-source electromagnetics. *First Break* 38/10: 35-40, doi: 10.3997/1365-2397.fb2020070

2/5

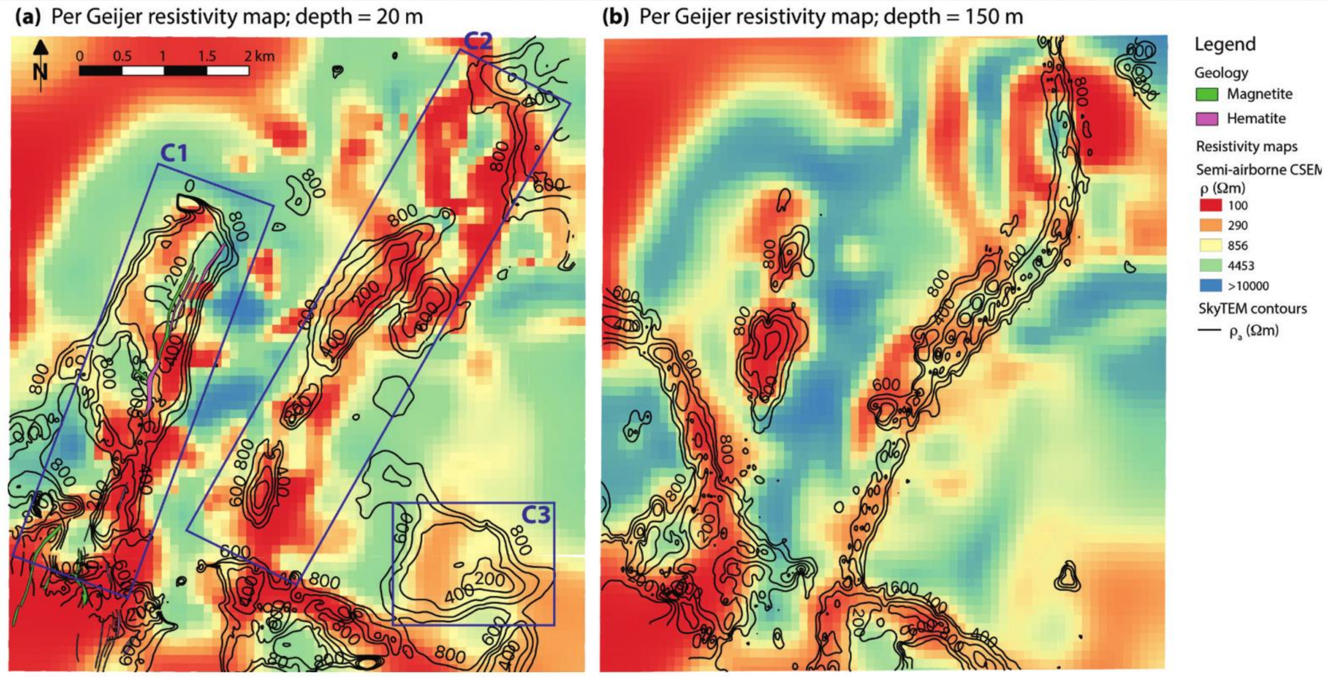


Figure 5 Plan view of 3D EM semi-airborne inversion model together with SkyTEM results. SkyTEM resistivity maps at about 50 m (a) and 150 m (b) depth are shown with black isolines that overlay the semi-airborne model. Main anomalies C1, C2, and C3 are marked with blue rectangles.

3/3

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

References (DESMEX)

3/5

Smirnova et al. (2019): A novel semiairborne frequency-domain controlled-source electromagnetic system: Three-dimensional inversion of semiairborne data from the flight experiment over an ancient mining area near Schleiz, Germany. *Geophysics* 84/5: E281-E292, doi:10.1190/geo2018-0659.1

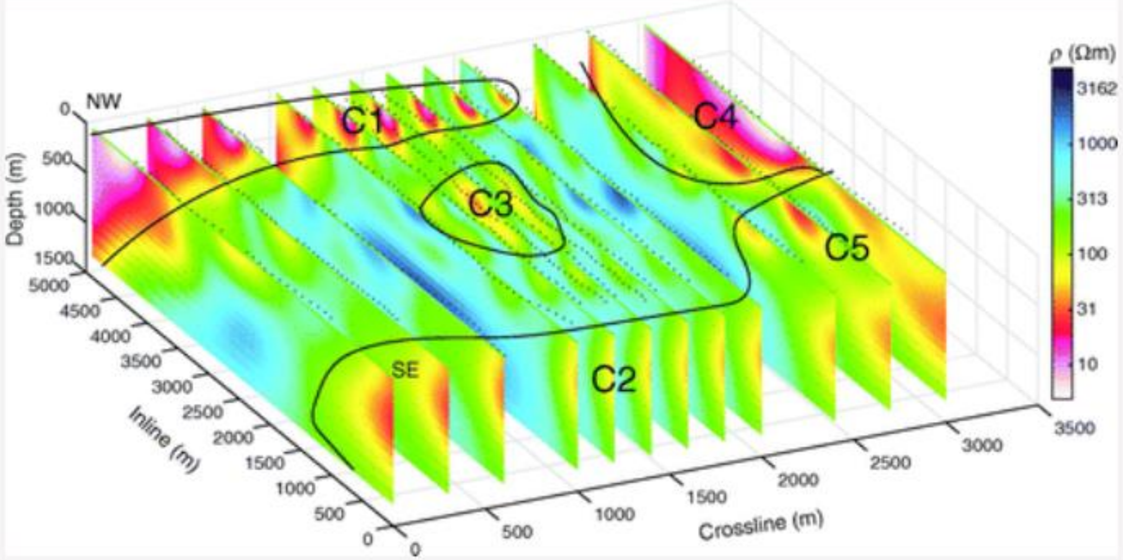


Figure 11. The 3D inversion of the semiairborne EM data. Northwest–southeast slices of the 3D inversion model. The black circles show the positions of the sites, and C1–C5 denote conductive anomalies.

3/3

Start

DESMEX

custEM

CSEM

TEM

MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

References (DESMEX)

Becken et al. (2020): DESMEX: A novel system development for semi-airborne electromagnetic exploration. *Geophysics* 85/6: E253-E267, doi: 10.1190/geo2019-0336.1

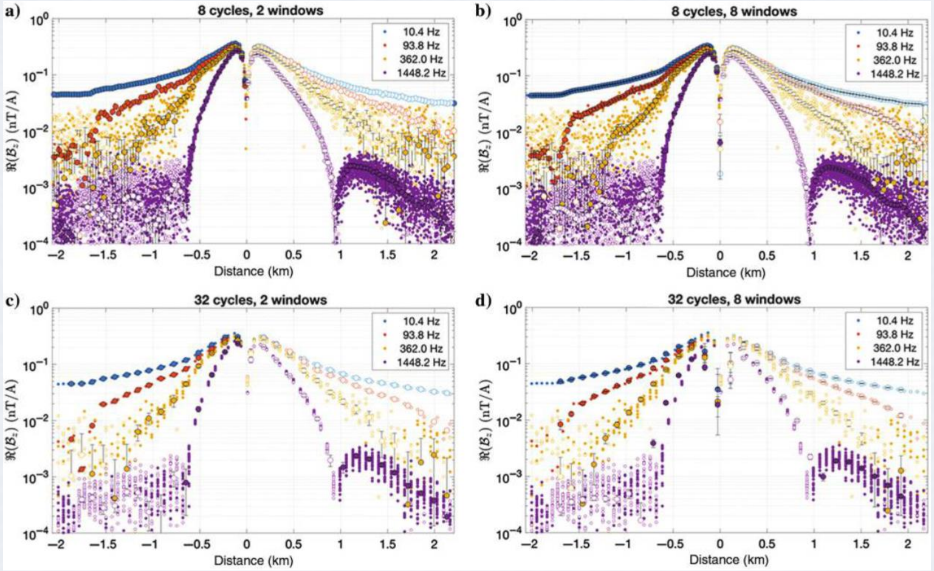


Figure 9. The real part of the transfer function estimates $B_z(\mathbf{r}, \omega)$ for source TxB4 and along flight line 22 for selected estimation frequencies and using the induction coil data. Estimates are obtained for an STFT window length of eight cycles and regression over (a) two adjacent windows and (b) eight adjacent windows, and estimates for an STFT window length of 32 cycles and regression over (c) two adjacent windows and (d) eight adjacent windows. The filled symbols correspond to positive values, whereas open symbols correspond to negative values. Dots depict the ratio of Fourier coefficients within each frequency band, whereas circles show the regression estimates over multiple bands.

3/3

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

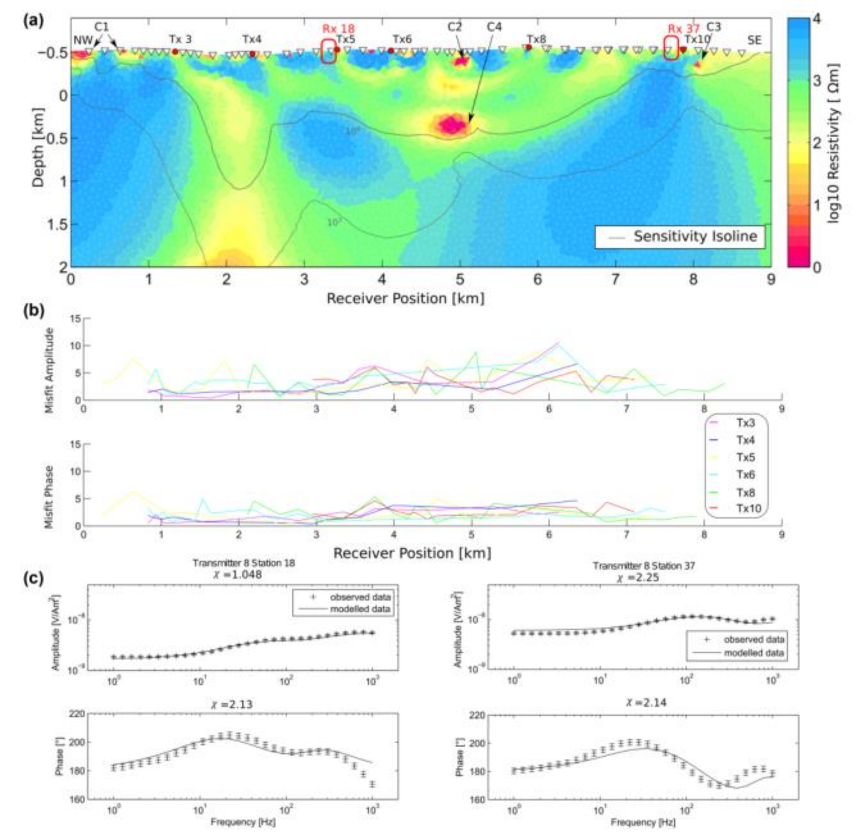
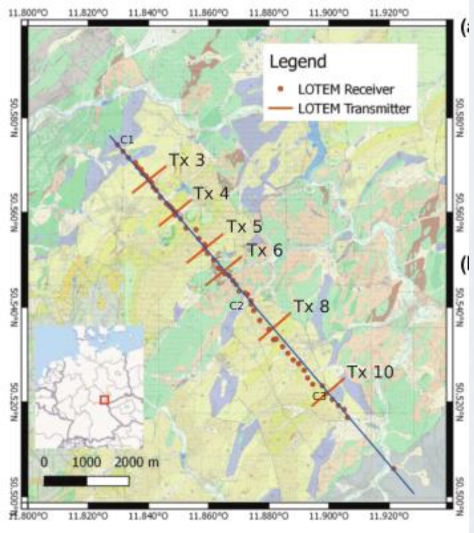


Figure 12 2.5D inversion of electric field data using the open source CSEM inversion code MARE2DEM. (a) Obtained 2D conductivity model. After 20 iterations, the RMS is reduced from 11.25 to 3.7. (b) Error-weighted misfit along the profile for phase and amplitude. (c) Observed data and model response for two exemplary stations marked in red and utilizing transmitter location Tx8. The four local high conductive structures are marked as C1, C2, C3 and C4.



5/5

References (DESMEX)

Mörbe et al. (2020): Deep exploration using long-offset transient electromagnetics: interpretation of field data in time and frequency domain. *Geophysical Prospecting* 68/6: 1980-1998, doi: 10.1111/1365-2478.12957

3/3

Start

DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

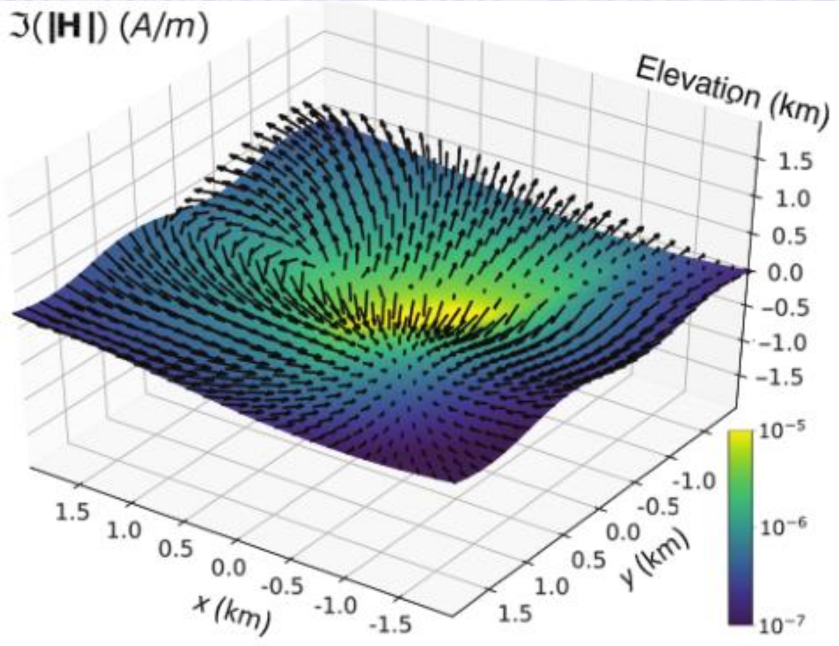
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Sponsored by the Federal Ministry of Education and Research
FONA BMBF

Start

The open-source Python toolbox custEM was primarily designed for the 3D finite-element (FE) modeling of controlled-source electromagnetic (CSEM) surveys with arbitrary geometries on unstructured meshes. We extended the capabilities of custEM by implementing multiple approaches for time-domain (transient) electromagnetic (TEM) and magnetotelluric (MT) data. **References:**



Source code:

https://gitlab.com/Rochlitz.R/custEM/

Documentation:

https://custem.readthedocs.io

Installation:

1. Download *Anaconda*
2. `conda create –n custEM custem`

1/4

DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

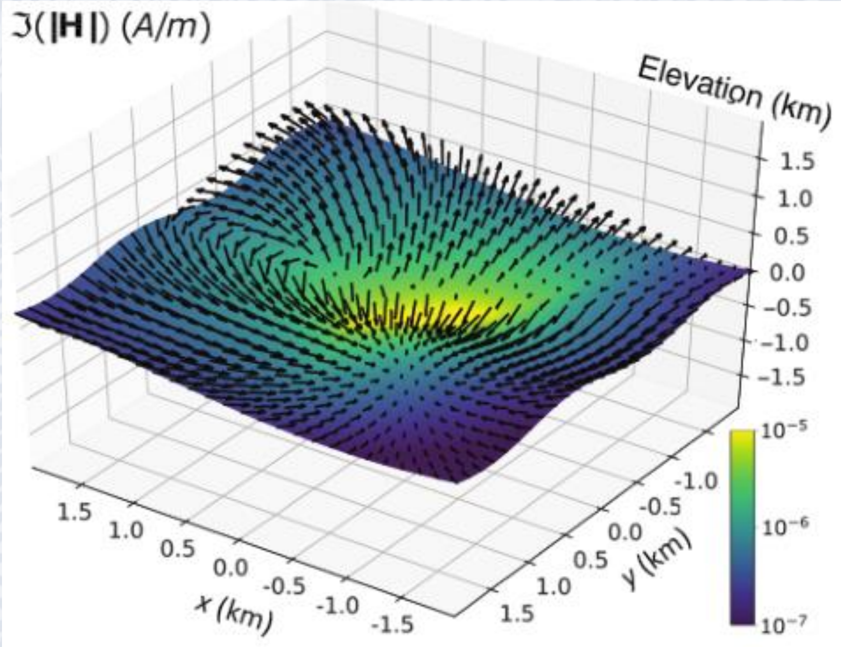
Raphael Rochlitz & Thomas Günther

Rochlitz, R., Skibbe, N. and Günther, T., (2019), *custEM: customizable finite element simulation of complex controlled-source electromagnetic data*, GEOPHYSICS Software and Algorithms.

Rochlitz, R. (2020), *Analysis and open-source Implementation of Finite Element Modeling techniques for Controlled-Source Electromagnetics*, PhD thesis, Westfälische Wilhelms-Universität Münster, Germany.

Rochlitz, R., Skibbe, N. and Günther, T., (2021), *Evaluation of three approaches for simulating time-domain electromagnetic data using the open-source software custEM*, GJI, under review.

Description:



Source code:

https://gitlab.com/Rochlitz.R/custEM/

Documentation:

https://custem.readthedocs.io

Installation:

1. Download *Anaconda*
2. `conda create –n custEM custem`

1/4

Start

DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

IAG
Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

SPONSORED BY THE Federal Ministry of Education and Research
FONA BMBF

Start

Third-party packages used by custEM

(logos are linked to the project webpages)

mesh generation

TetGen
A Quality Tetrahedral Mesh Generator and 3D Delaunay Triangulator

pyGIMLi
Geophysical Inversion & Modelling Library

finite-element kernel

FEniCS Project
2019.1.0

linear algebra / solver

PETSc

MUMPS

primary-field solutions

COMET

custEM

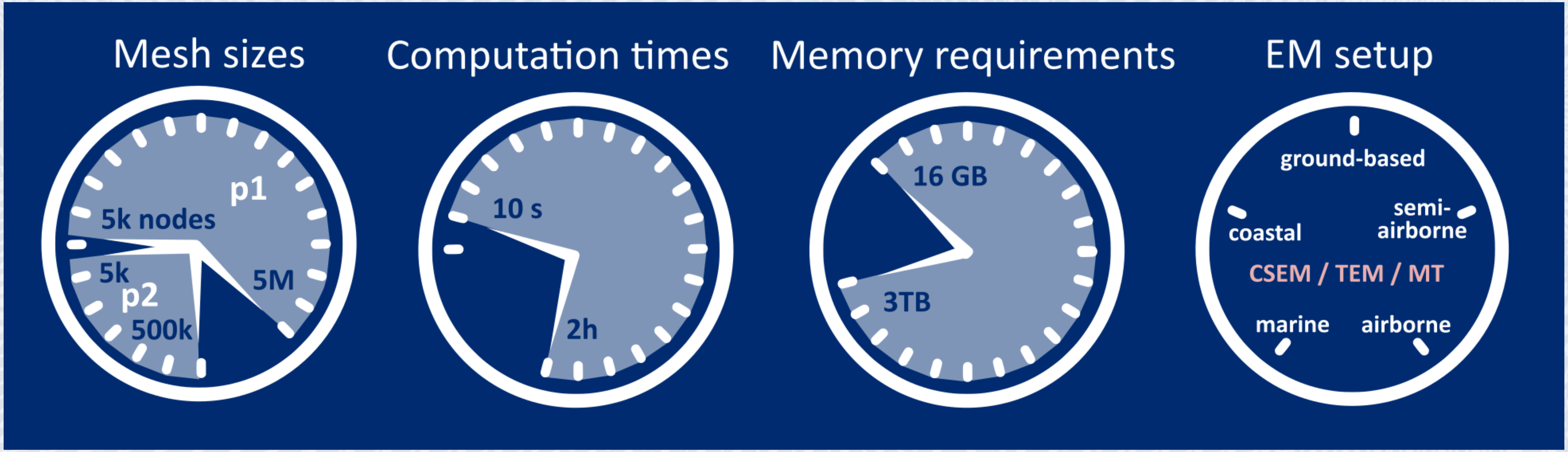
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Performance

Start

- Computational resources heavily geometry-dependent
- Runtimes in the range of a few minutes per setup often possible with smart mesh design
- Almost all forward problems can be solved on a machine with 32 procs and 256 GB RAM



DESMEX
custEM
CSEM
TEM
MT

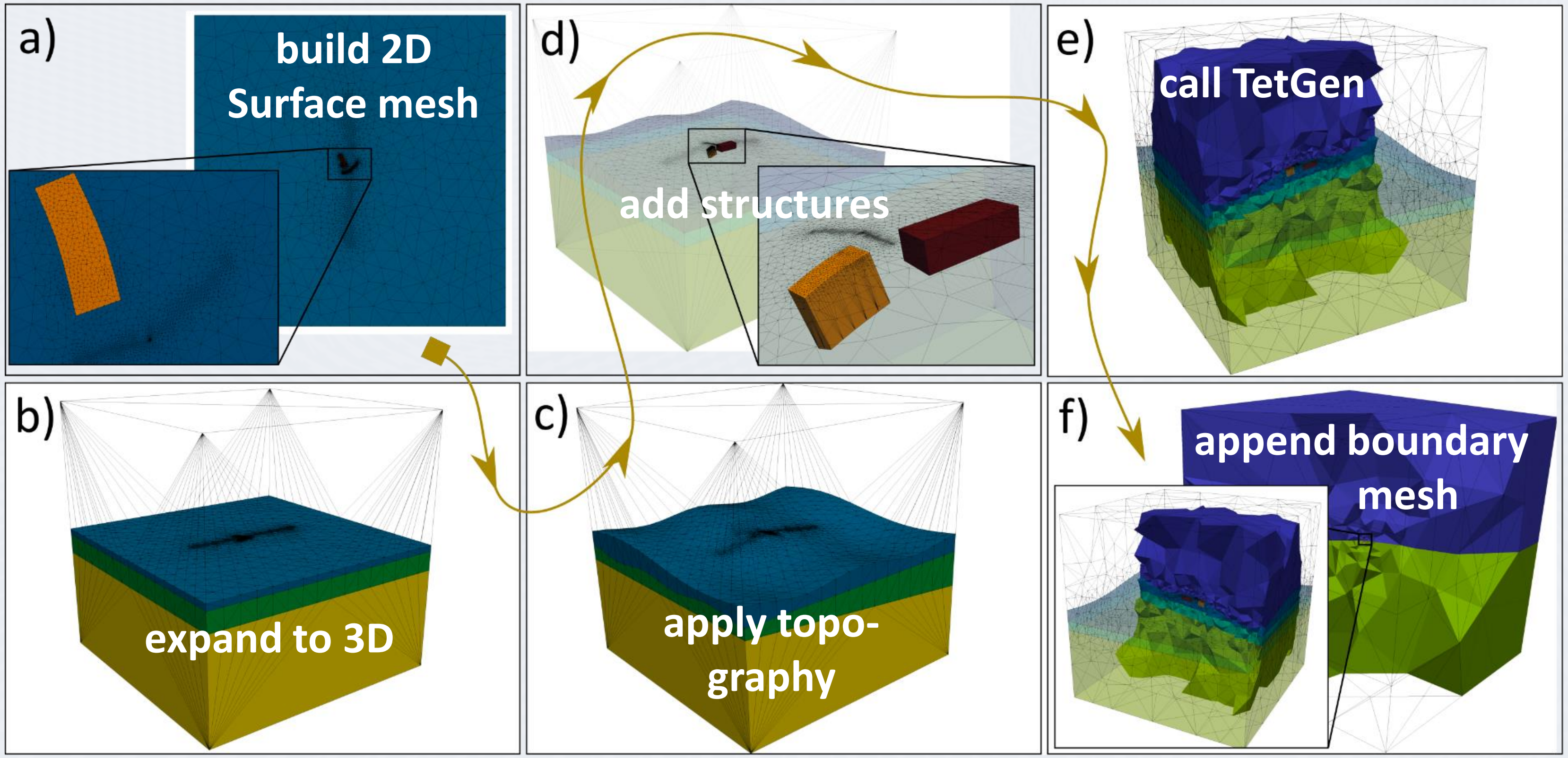
3/4

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Mesh generation – procedure



How to model an EM setup with custEM?

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Mesh generation – code example

```
# mesh generation script for 1D IP validation example

import numpy as np
from custEM.meshgen import meshgen_utils as mu
from custEM.meshgen.meshgen_tools import BlankWorld

rx = mu.line_x(0, 200, y=100, z=-1)
rx_refined = mu.refine_rx(rx, 1, 30)

M = BlankWorld(name='ip_3l_fine',
               x_dim=[-1e4, 1e4], y_dim=[-1e4, 1e4], z_dim=[-1e4, 1e4],
               preserve_edges=True)

M.build_surface(insert_line_tx=[mu.line_y(-100, 100, x=-200, n_segs=49)],
                insert_paths=rx_tri)

M.build_layered_earth_mesh(3, [-100, -200])
M.add_brick([-100, -200, -50], [50, 300, -20], cell_size=1e4)
M.add_rx(rx)
M.extend_world(10, 10, 10)
M.call_tetgen(tet_param='-pq1.4aA', export_vtk=True)
```


How to model an EM setup with custEM?

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Raphael Rochlitz & Thomas Günther

Run simulation – called with „mpirun –n python MYSCRIPT.py"

```
# computation script for 1D IP validation example

from custEM.core import MOD
import numpy as np

freqs = np.logspace(0, 4, 5)

M = MOD('my_ip_mod', 'ip_31_fine, 'E_t', p=2, overwrite_results=True,
        overwrite_mesh=True, serial_ordering=True)

M.MP.update_model_parameters(frequencies=freqs,
                             sigma=[1e-8, 1e-2, 1e-1, 1e-3],
                             ip_m=[0, 0.7, 0.5, 0],
                             ip_tau=[0, 1., 0.1, 0],
                             ip_c=[0, 0.8, 1.0, 0]
                             )

M.FE.build_var_form(ip=True)
M.solve_main_problem(auto_interpolate=True)
```

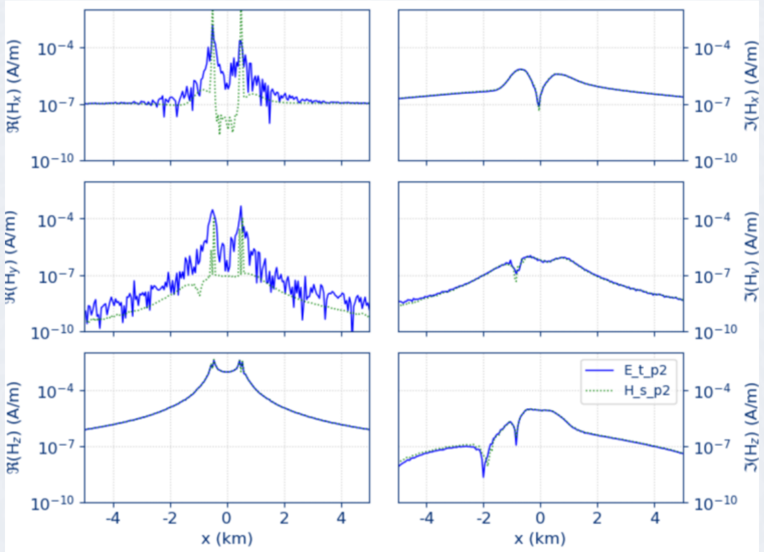

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Raphael Rochlitz & Thomas Günther

Leibniz Institute for Applied Geophysics

Plot results – with plotting tools


```
# plot some data from frequency-domain example 3

from custEM.post import PlotFD

mod = 'example_3_p1_aniso_E'
mesh = 'example_3_mesh_p1_loop'

P = PlotFD(mod=mod, mesh=mesh, approach='E_t',
           s_dir='./plots', label_color='#002C72')

line = 'x0_-5000_x1_5000_y_0_z_0_n_200_line_x'
P.import_line_data(line, approach='E_t', key='Et')
P.import_line_data(line, approach='H_s', key='Hs')

P.plot_line_data(key='Et', EH='H', label='E_t_p2',
                 lw=1, ls='-', ylim=[1e-10, 1e-2])
P.plot_line_data(key='Hs', EH='H', label='H_s_p2',
                 lw=1, ls=':', new=False)
```



How to model an EM setup with custEM?

4/4

Start

DESMEX

custEM

CSEM

TEM

MT

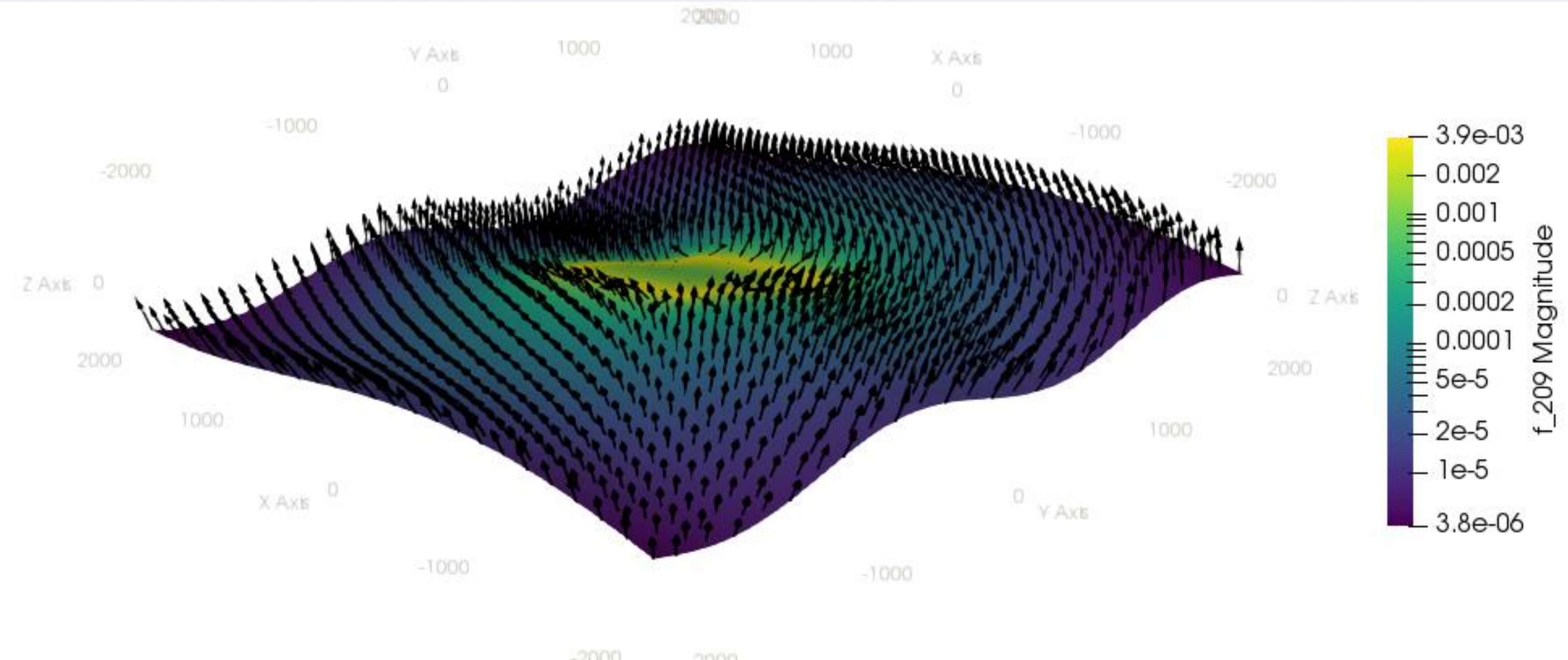
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Plot results – with Paraview

5/5



How to model an EM setup with custEM?

4/4

Start

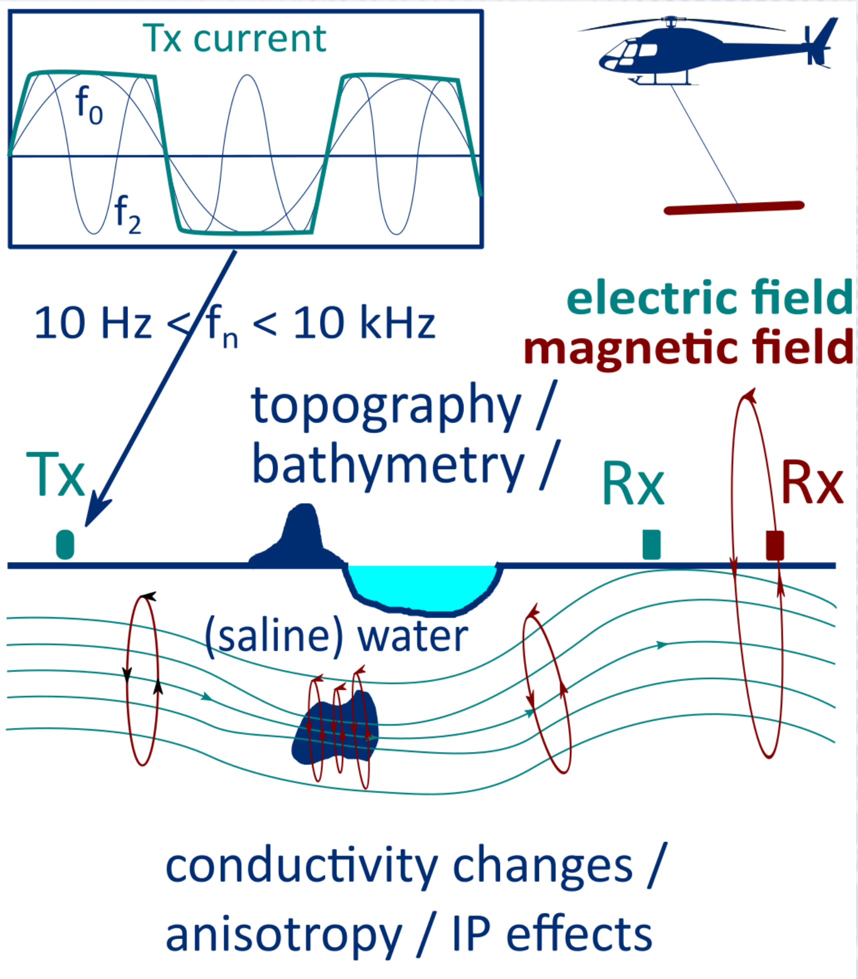
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther



- 3D semi-airborne CSEM data finite-element modeling primary motivation for custEM, starting with the development in 2016/2017.

Methodology:

- Total & secondary electric, magnetic & potential field formulations on different finite element types
- Support of fully anisotropic material properties as well as induced-polarization (IP) parameters
- Total electric field formulation with Nédélec elements shows highest robustness, full flexibility and best performance with direct solver MUMPS

1/4

Start

DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

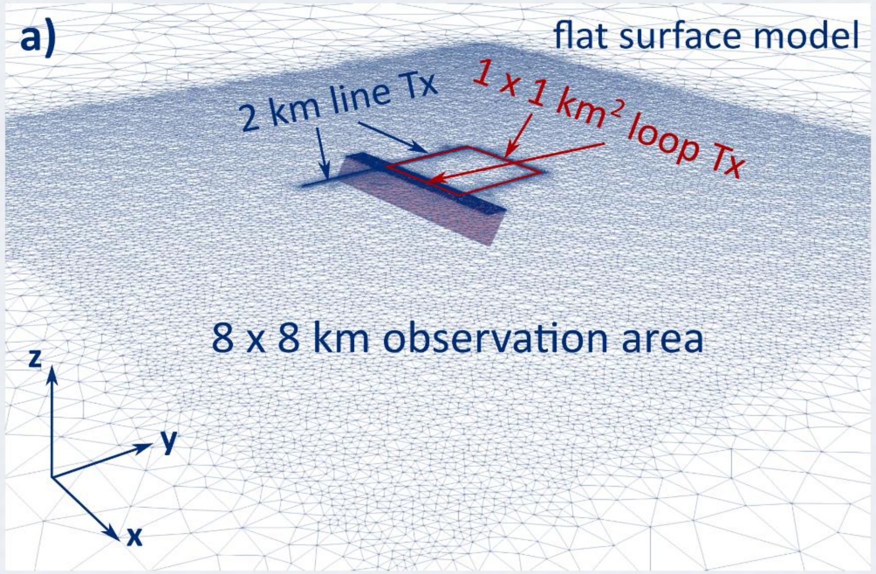
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

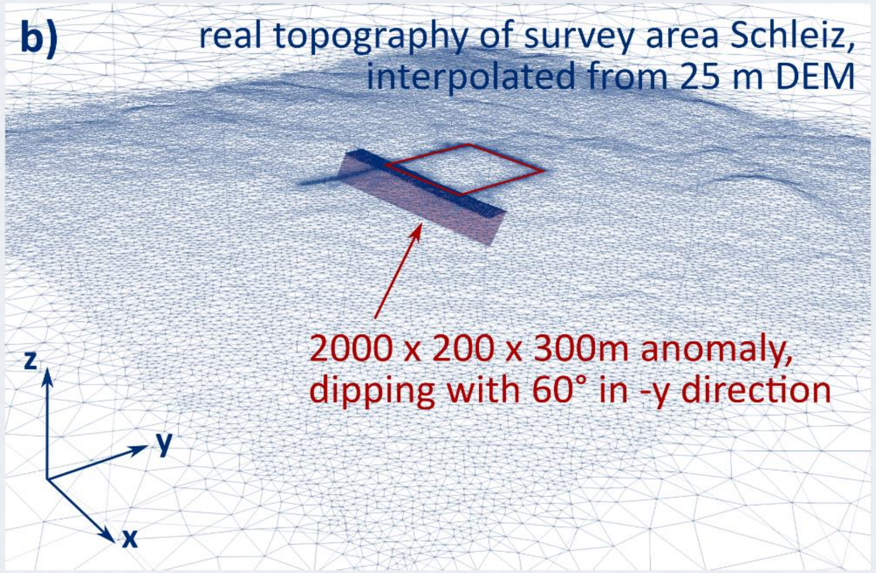
Raphael Rochlitz & Thomas Günther

3D CSEM

investigating effects of topography for semi-airborne data

- Modeling study corresponds to real semi-airborne experiments conducted in Schleiz, Germany, 2017
- Comparing flat vs real topography model for different sources, varying anomaly-conductivites and multiple frequencies





Start
DESMEX
custEM
CSEM
TEM
MT
2/4

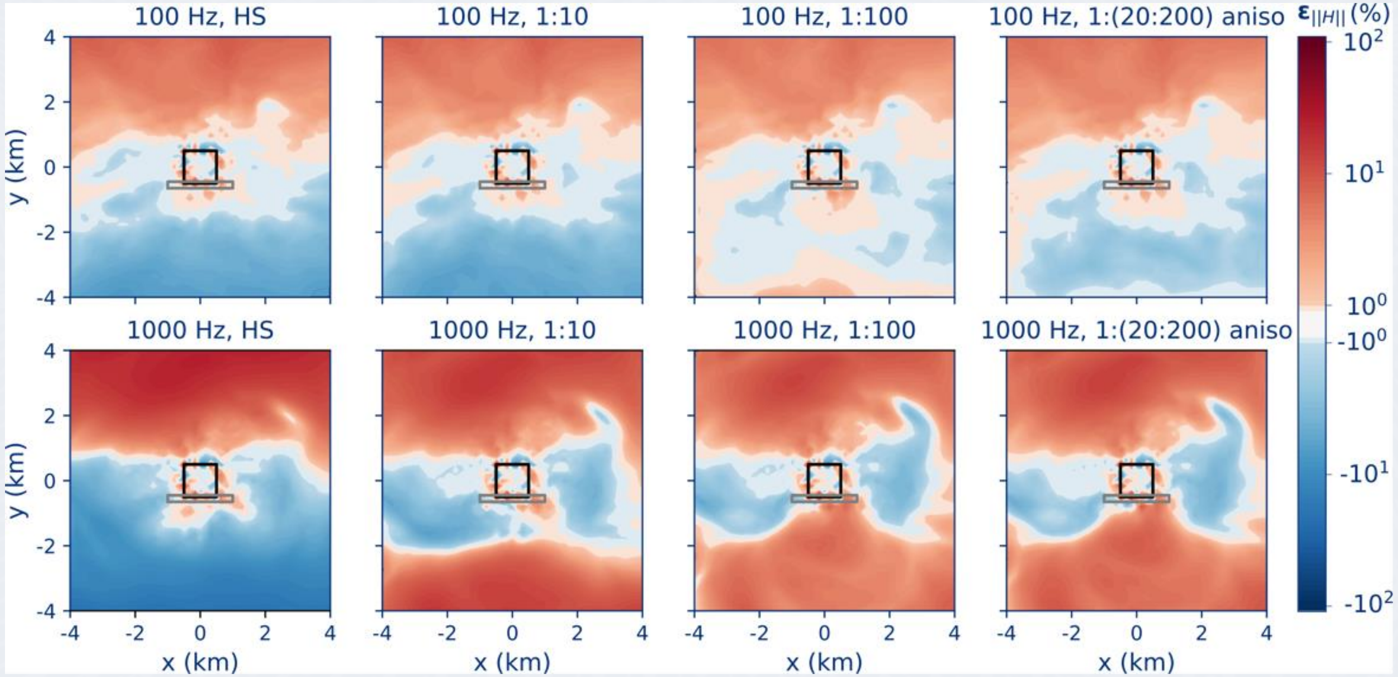
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Magnetic field magnitude variations (%) between flat and topography model on 8 x 8 km^2 flight area, 50 m above surface, loop Tx
- Strong influences from varying anomaly-conductivities from left to right



3D CSEM

investigating effects of topography for semi-airborne data

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Marlim R3D is a marine real-world industry CSEM model
- Comparison of results for one sea-bottom Rx (light blue cross) and one broadside Tx line (lower red line) exploiting reciprocity

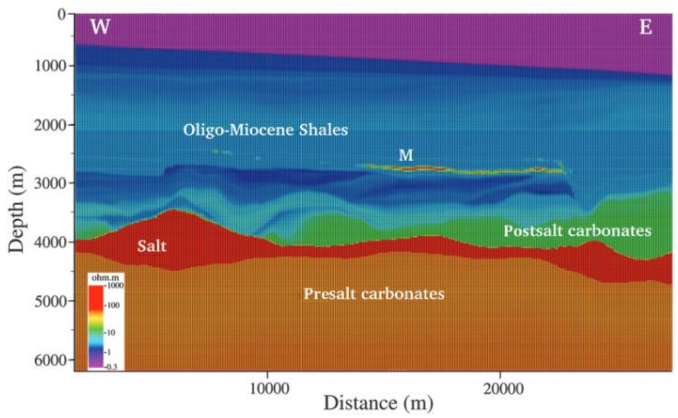
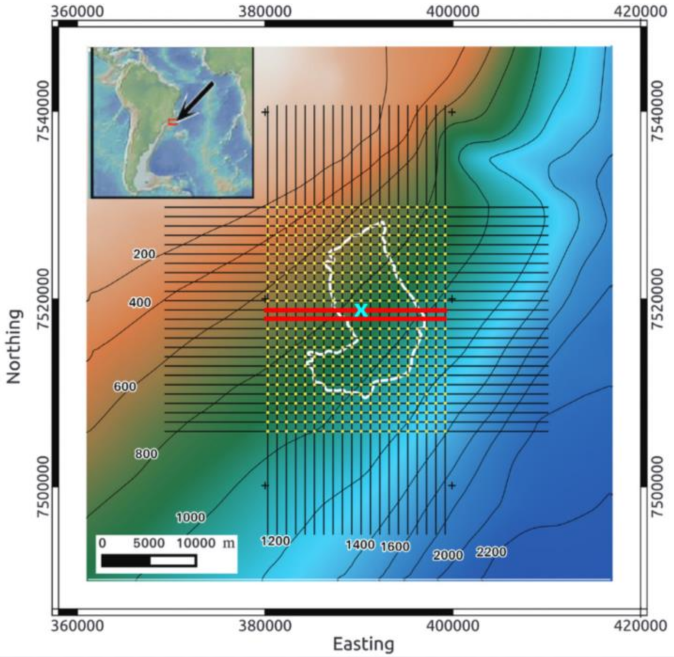


Figure 3. Cross section of the MR3D vertical resistivity along the east–west towline 04Tx013. Marlim oil-prone turbidites (M) appear as thin resistive bodies.

Correa and Menezes (2019)



3D CSEM

cross-comparison of marine Marlim R3D model

visit: (Correa & Menezes, 2019)

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Using geological layer constraints for tetrahedral mesh generation in custEM for accurate mapping of conductivity contrasts between layers

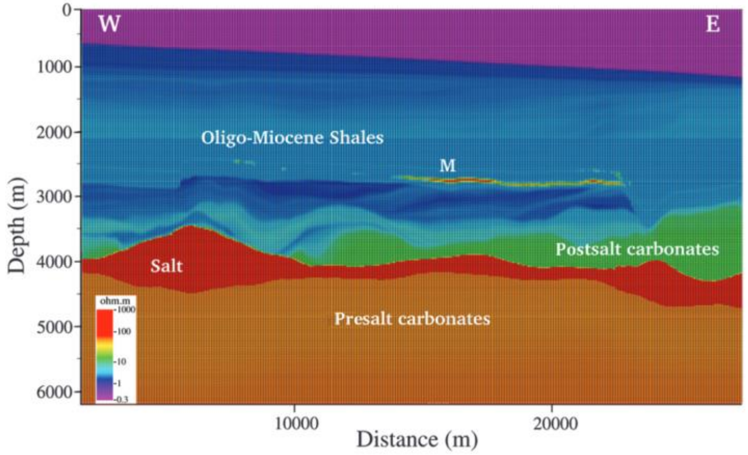
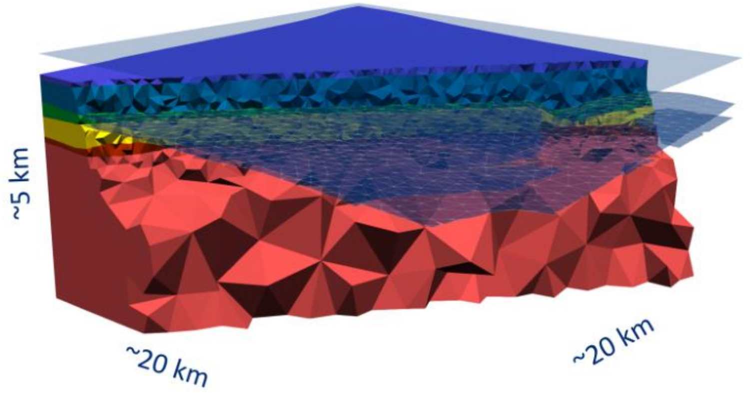


Figure 3. Cross section of the MR3D vertical resistivity along the east–west towline 04Tx013. Marlim oil-prone turbidites (M) appear as thin resistive bodies.

Correa and Menezes (2019)

Constraining lithological horizons using interface-information from reflection seismic surveys



3D CSEM

cross-comparison of marine Marlim R3D model

visit: (Correa & Menezes, 2019)

3/4

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Leibniz Institute for Applied Geophysics

Raphael Rochlitz & Thomas Günther

Federal Ministry of Education and Research
FONA
BMBF

- Element-wise interpolation of VTI-anisotropic conductivities provided on regular grid
- Extrapolation of provided conductivities on appended boundary mesh

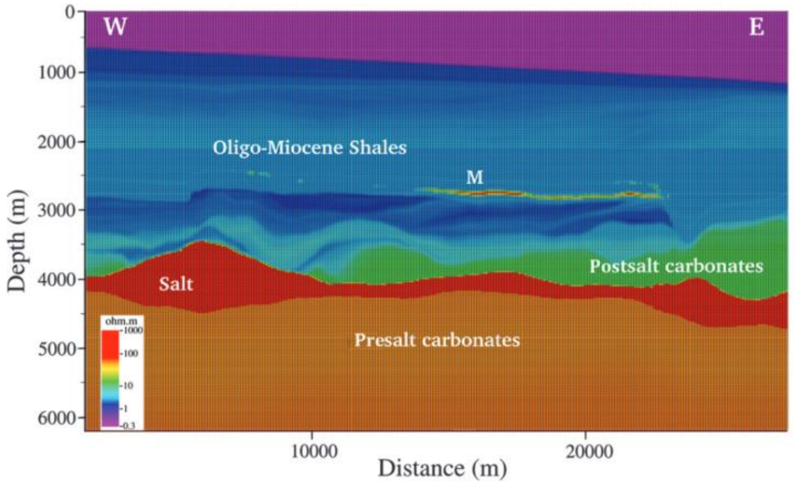
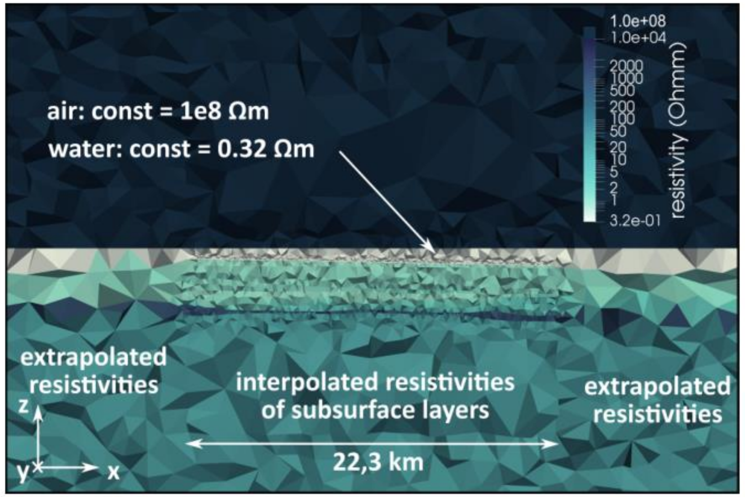


Figure 3. Cross section of the MR3D vertical resistivity along the east–west towline 04Tx013. Marlim oil-prone turbidites (M) appear as thin resistive bodies.



interpolated resistivities on custEM mesh

3D CSEM

cross-comparison of marine Marlim R3D model

visit: (Correa & Menezes, 2019)

Start

DESMEX

custEM

CSEM

TEM

MT

3/4

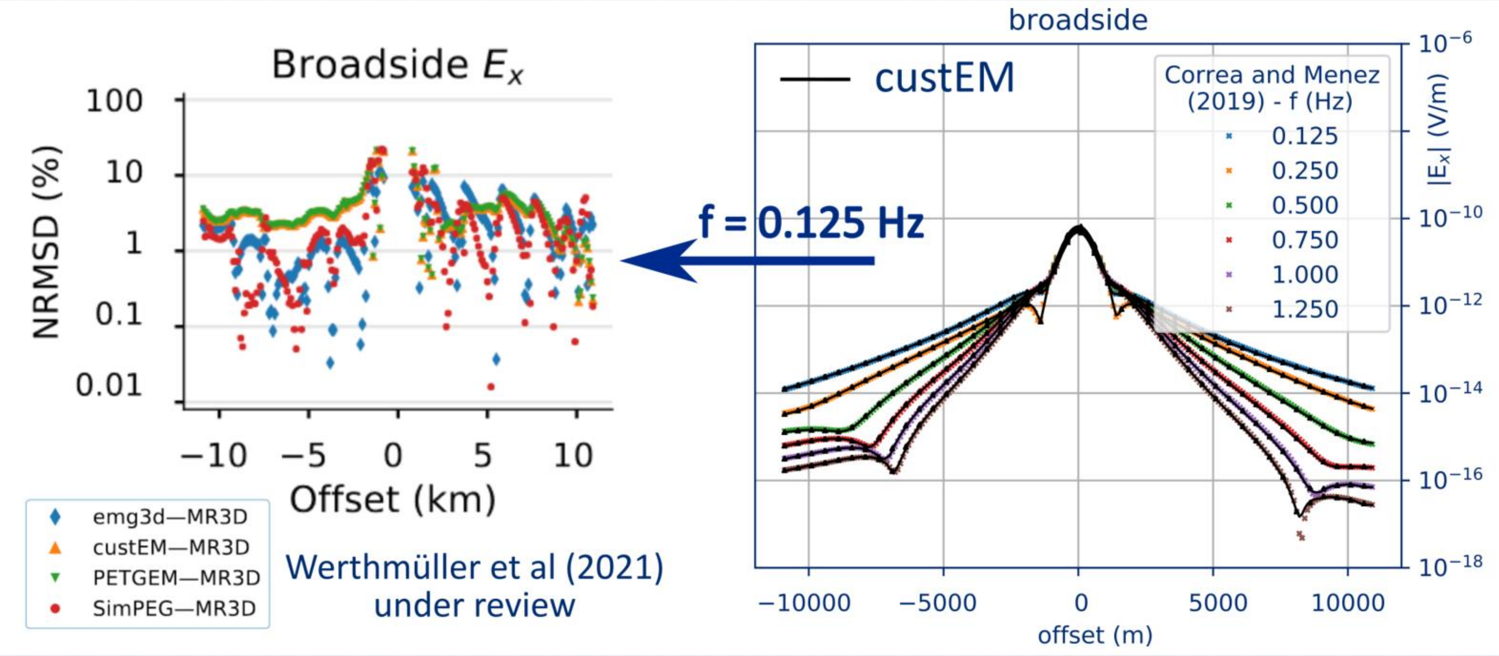
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Comparison of custEM solutions against reference data provided by Correa & Menezes (2019), magnitude of $\mathbf{E}_x$ component on broadside line
- Part of open-source code validation study: Werthmüller et al. (2021)

4/4



3D CSEM

cross-comparison of marine Marlim R3D model

visit: (Correa & Menezes, 2019)

Start
3/4
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

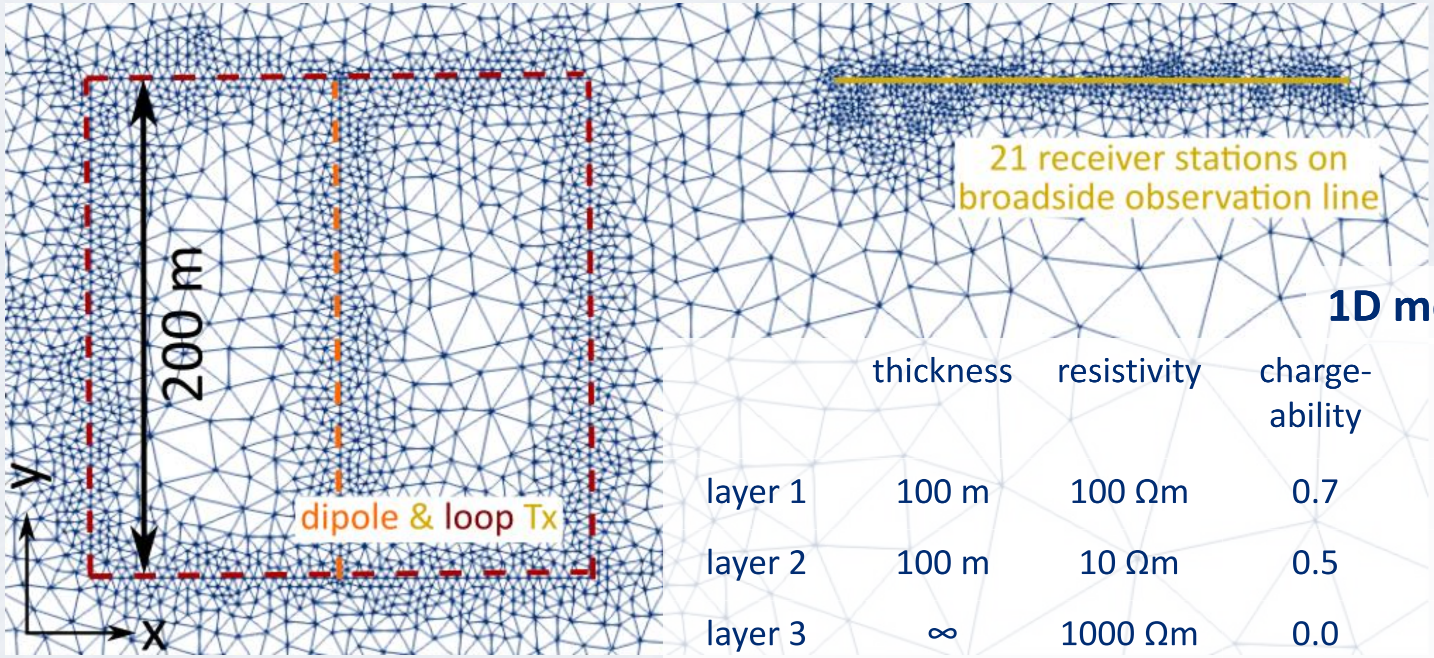
IAG
Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Federal Ministry of Education and Research
FONA

- 1D geometry with three layers, test for grounded and ungrounded Tx
- Only layers 1 & 2 exhibit IP effects
- One observation line with y-offset for non-zero horizontal components



1D model parameters

	thickness	resistivity	charge-ability	relax. time	c - exponent
layer 1	100 m	100 Ωm	0.7	1.0	0.8
layer 2	100 m	10 Ωm	0.5	0.1	1.0
layer 3	∞	1000 Ωm	0.0	0.0	0.0

1D IP

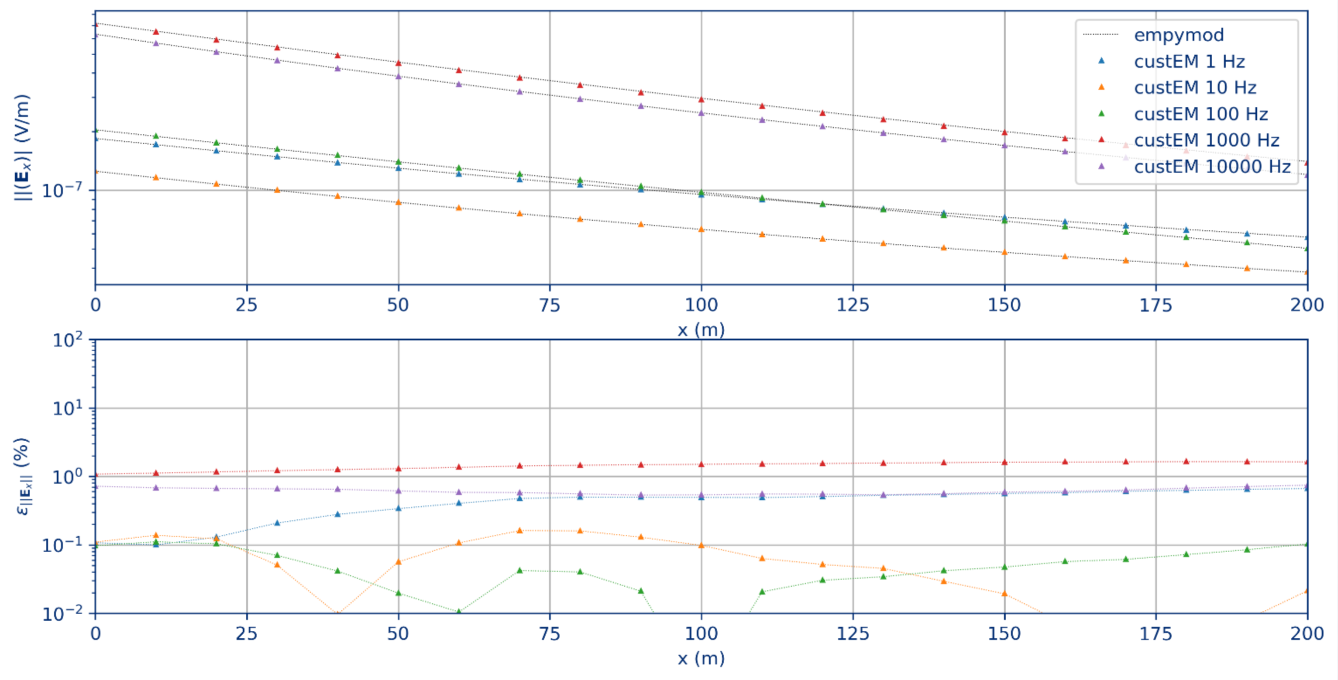
validation against semi-analytic solutions (*empymod*)

1/3
4/4
Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Raphael Rochlitz & Thomas Günther

- Comparison for grounded dipole Tx
- Magnitude of $\mathbf{E}_x$ component



2/3

1D IP

validation against semi-analytic solutions (*empymod*)

4/4

Start

DESMEX
custEM
CSEM
TEM
MT

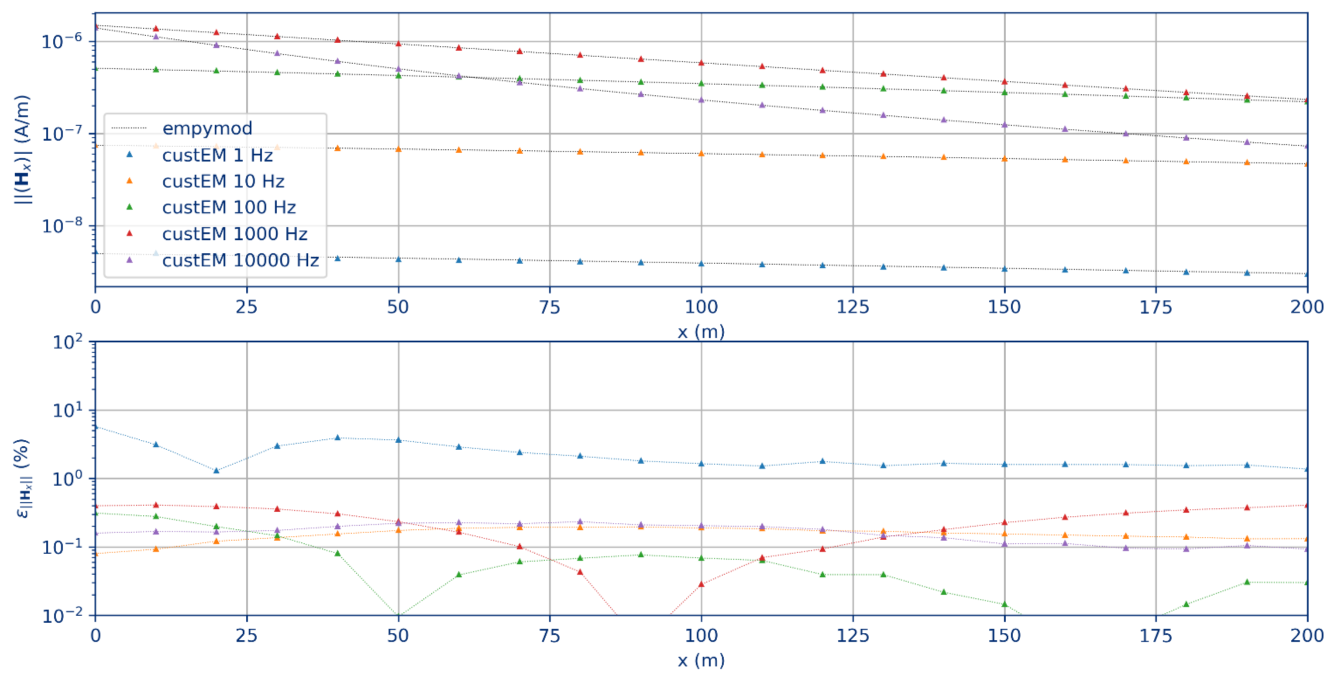
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Comparison for ungrounded loop Tx
- Magnitude of $\mathbf{H}_x$ component



3/3

1D IP

validation against semi-analytic solutions (*empymod*)

4/4

Start

DESMEX

custEM

CSEM

TEM

MT

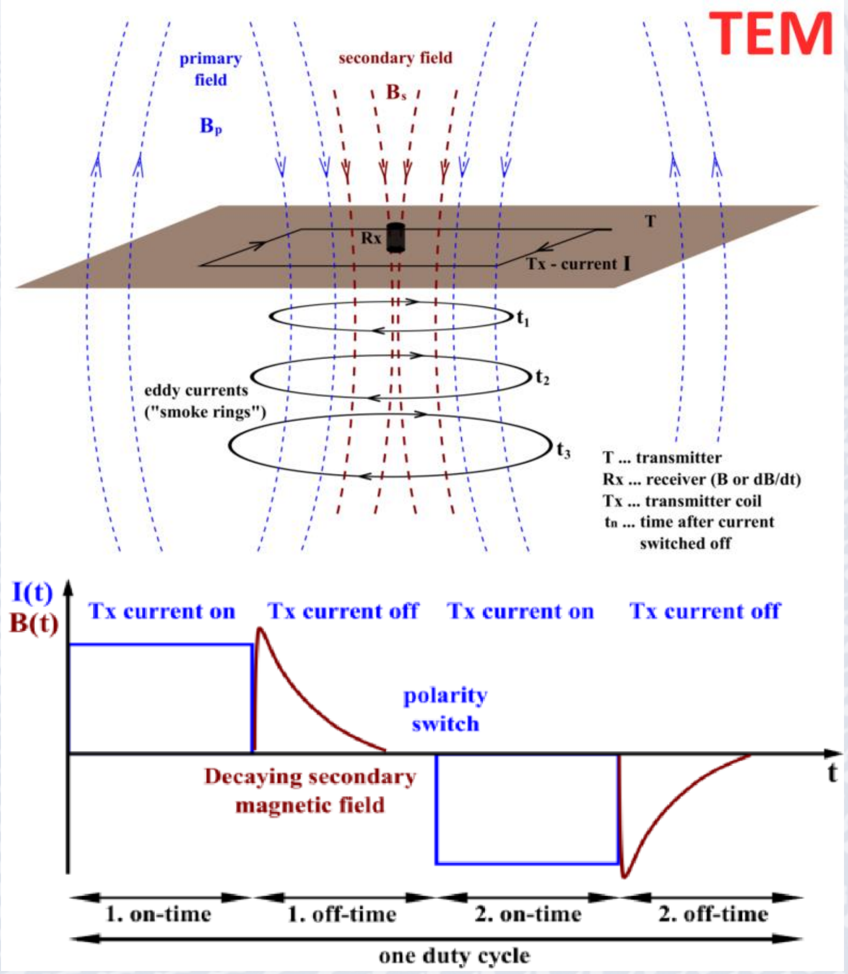
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

Federal Ministry of Education and Research
FONA
BMBF



- Methods for simulating time-domain (TEM) data added to custEM in 2020 for arbitrary geometries and impulse & step response data

Methodology:

- Implicit Euler (IE), Fourier-transform-based (FT) and Rational Arnoldi (RA) methods based on total electric-field formulation
- Arbitrary impulse or step current waveforms
- Optimized exploitation of re-used matrix factorizations in all methods with MUMPS to speed up simulations

1/3

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

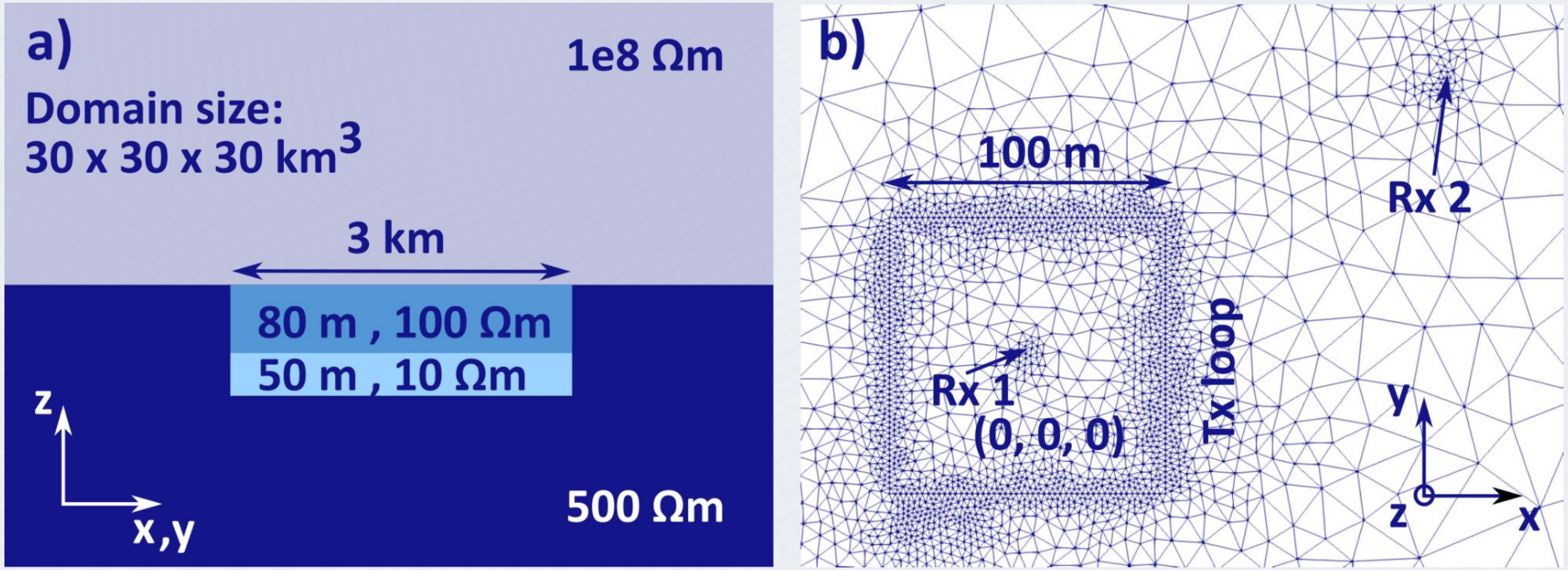
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

1D TEM

- Central-loop and out-of-loop geometry
- 1D layout with three layers
- appended halfspace-like boundary mesh to reduce boundary artifacts

validation against semi-analytic solutions (*empymod*)



2/3
Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

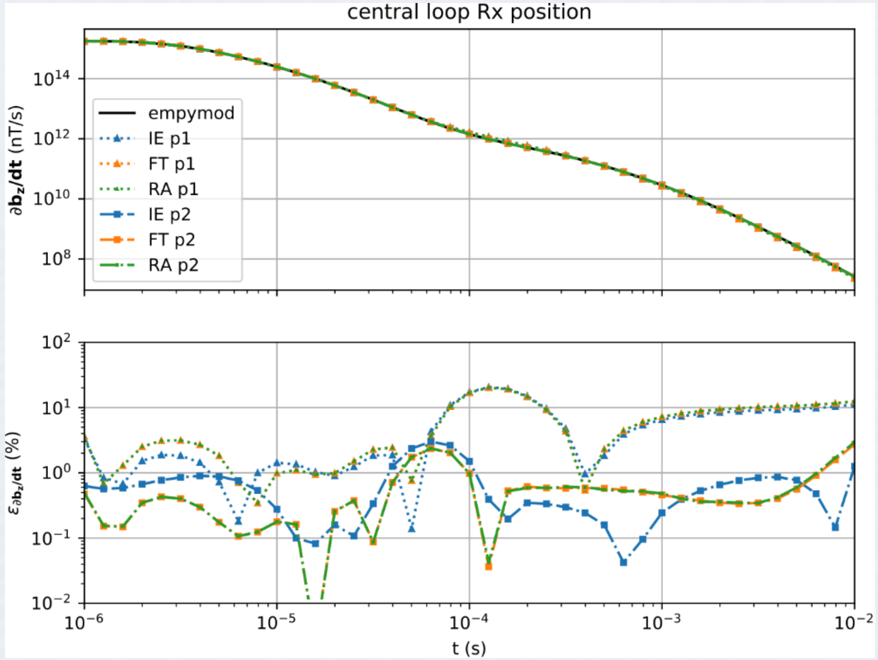
Leibniz Institute for Applied Geophysics

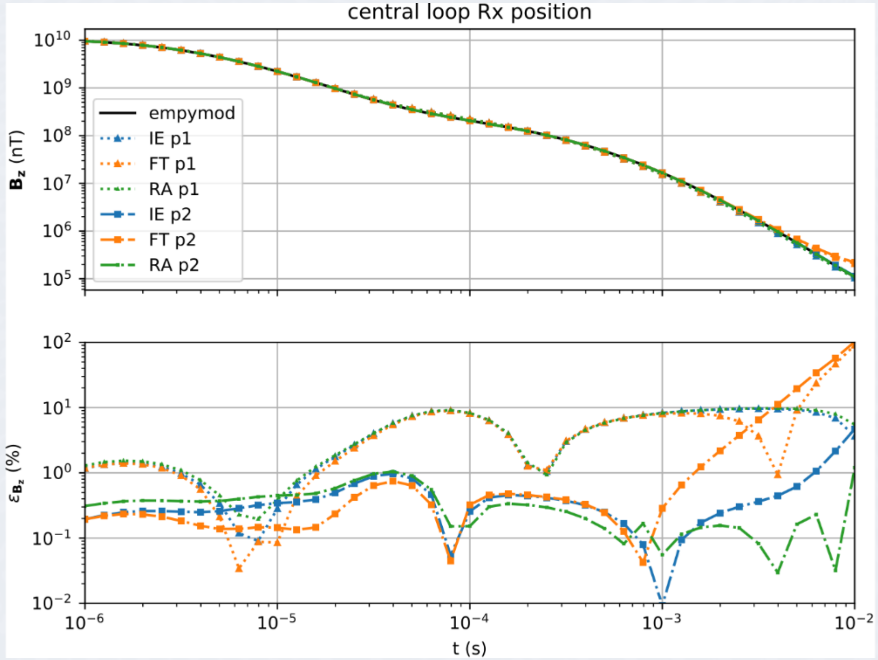
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Central-loop validation against *empymod* reference solution
- IE, FT and RA methods, first (p1) and second (p2) order polynomials
- Impulse (**db/dt**, left) and step (**b**, right) response data with misfits

2/3





1D TEM

validation against semi-analytic solutions (*empymod*)

Start
2/3
DESMEX
custEM
CSEM
TEM
MT

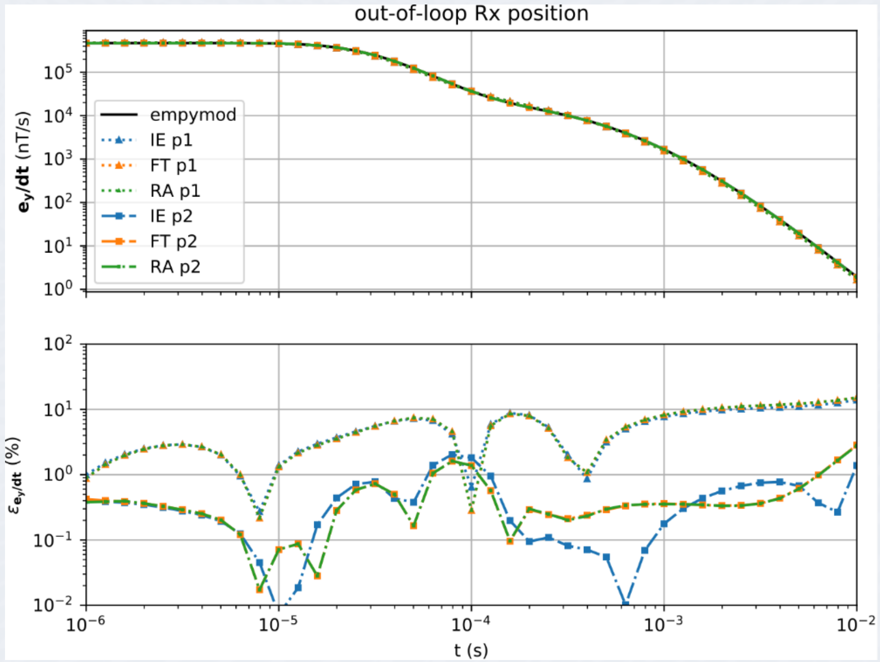
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

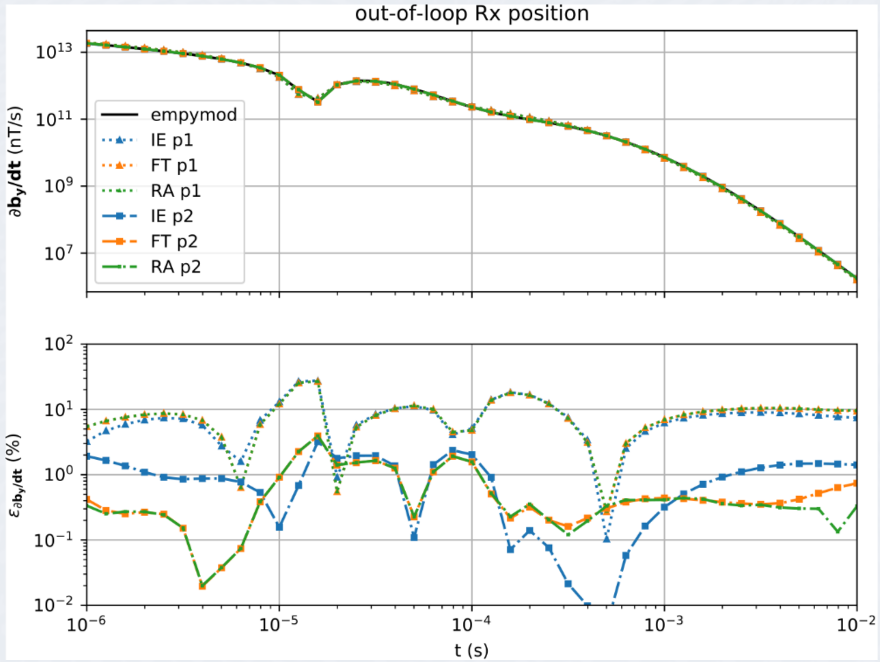
Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

- Out-of-loop position (100 x 150 m offset from center)
- IE, FT and RA methods, first (p1) and second (p2) order polynomials
- Electric (**e**, left) and impulse (**db/dt**, right) response data with misfits





1D TEM

validation against semi-analytic solutions (*empymod*)

Start
DESMEX
custEM
CSEM
TEM
MT
2/3

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for
Applied Geophysics

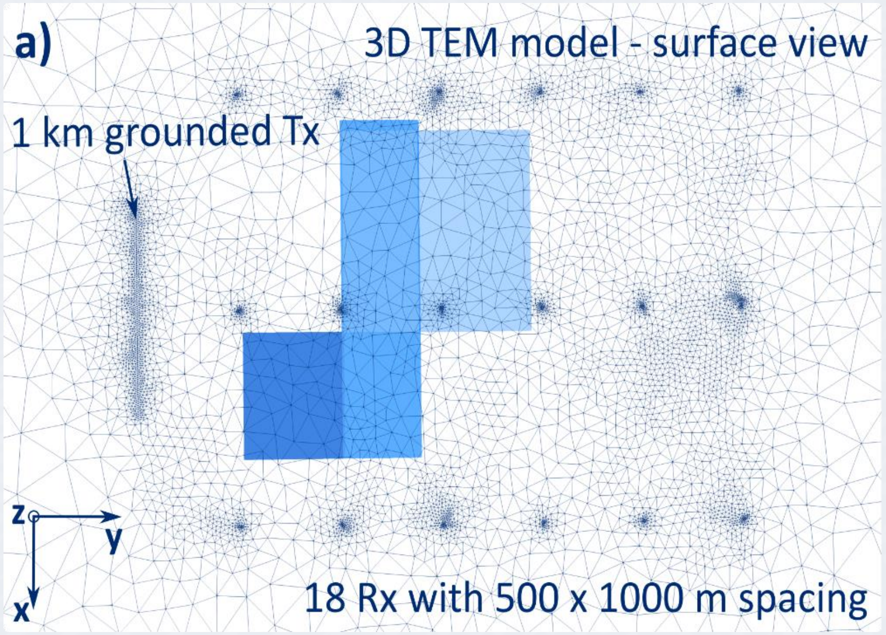
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

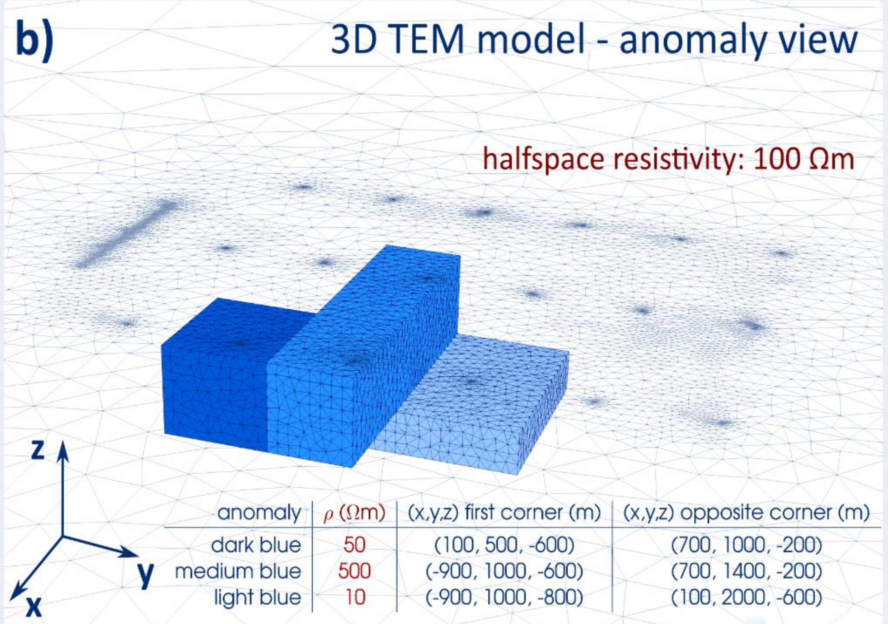
Raphael Rochlitz & Thomas Günther

3D TEM

validation of blocky model against *SLDMEM*

- Halfspace with three embedded blocks
- Large-scale LOTEM setup with grounded wire source
- Three receiver lines, each with six receivers and 500 m spacing





anomaly	ρ (Ωm)	(x,y,z) first corner (m)	(x,y,z) opposite corner (m)
dark blue	50	(100, 500, -600)	(700, 1000, -200)
medium blue	500	(-900, 1000, -600)	(700, 1400, -200)
light blue	10	(-900, 1000, -800)	(100, 2000, -600)

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for
Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

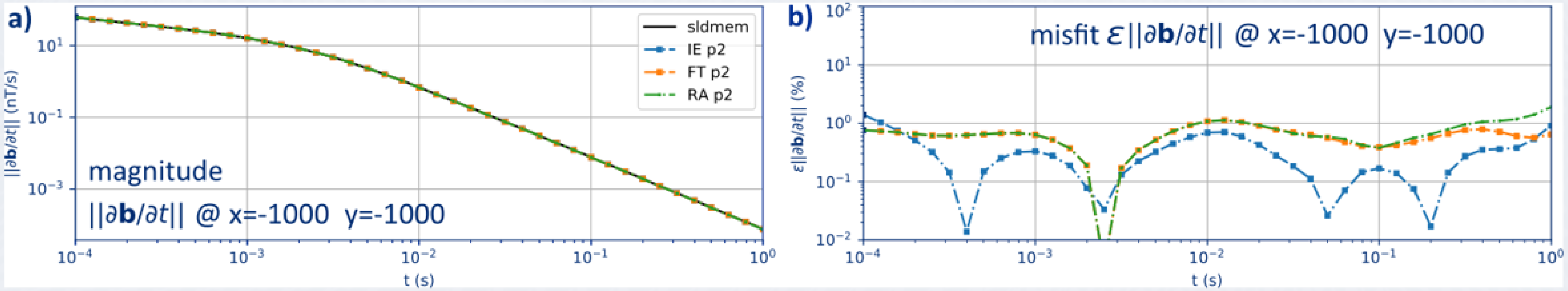
Raphael Rochlitz & Thomas Günther

Sponsored by the Federal Ministry of Education and Research
FONA BMBF

- Comparison of impulse-response against SLDMEM
- Receiver position: x = 1000, y = -1000
- IE, FT and RA methods, second (p2) order polynomials

3D TEM

validation of blocky model against *SLDMEM*



We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

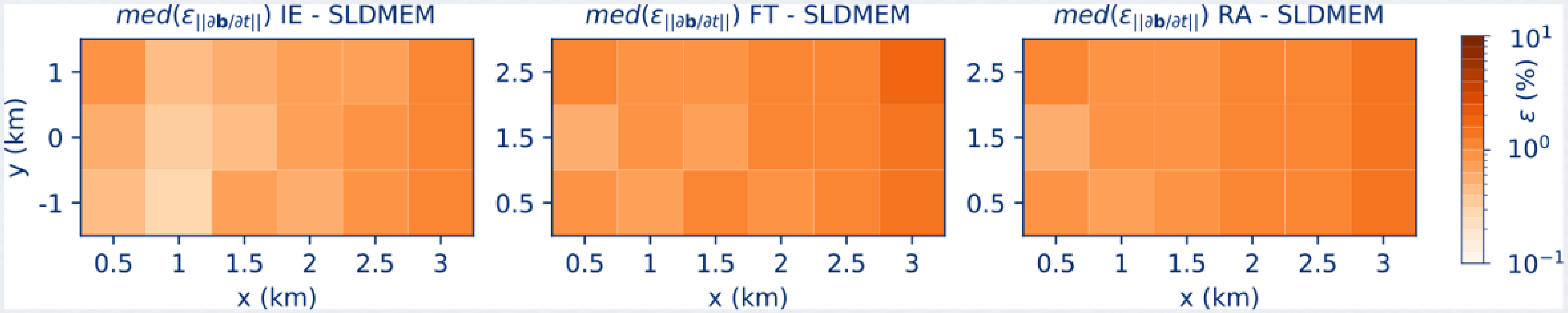
Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther

3D TEM

validation of blocky model against *SLDMEM*

- Statistical analysis for all receiver stations
- Color-coded median of the misfits of all 41 data samples per transient
- Median misfit of around 1 % for all three methods



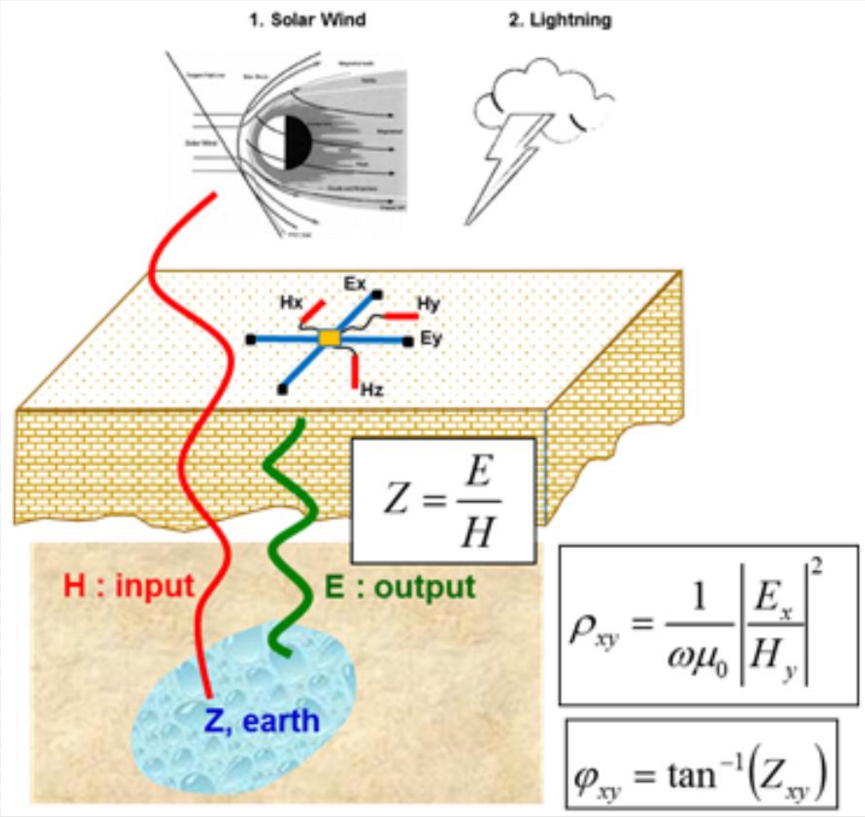
runtime	runtime	runtime
≈20 min	≈120 min	≈2 min

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther



$$Z = \frac{E}{H}$$

$$\rho_{xy} = \frac{1}{\omega\mu_0}\left|\frac{E_x}{H_y}\right|^2$$

$$\varphi_{xy} = \tan^{-1}(Z_{xy})$$

Image source (13.04.2021):
https://www.geocap.nl/handbook/exploration/mt-field-school/

- 3D natural-source modeling most recent feature in custEM (since 2021), supporting classic MT as well as AFMAG simulations

Methodology:

- Adaption of total electric-field formulation for finite-element CSEM simulations
- Using two different polarizations as source, implemented as inhomogeneous Dirichlet-boundary conditions on top of the model domains
- Using direct solver MUMPS, which showed to be capable to handle frequencies down to 0.0001 Hz

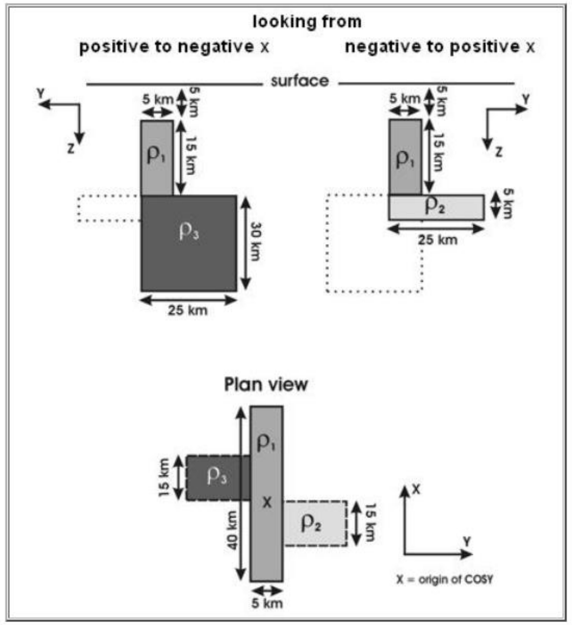
1/2

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

Raphael Rochlitz & Thomas Günther



Dublin Test Model 1

- Common land-based MT survey geometry
- Four independent forward modeling reference solutions available
- Frequencies from 0.0001 to 10 Hz

1/3

3D MT

validation with Dublin test Model I

Start

	extend in x (km)	extend in y (km)	extend in z (km)	resistivity (ohm-m)
Body 1	-20 to 20	-2.5 to 2.5	5 to 20	10
Body 2	-15 to 0	-2.5 to 22.5	20 to 25	1
Body 3	0 to 15	-22.5 to 2.5	20 to 50	10000

https://www.mtnet.info/workshops/mt3dinv/2008_Dublin/dublin_3dmodel.html

2/2

DESMEX
custEM
CSEM
TEM
MT

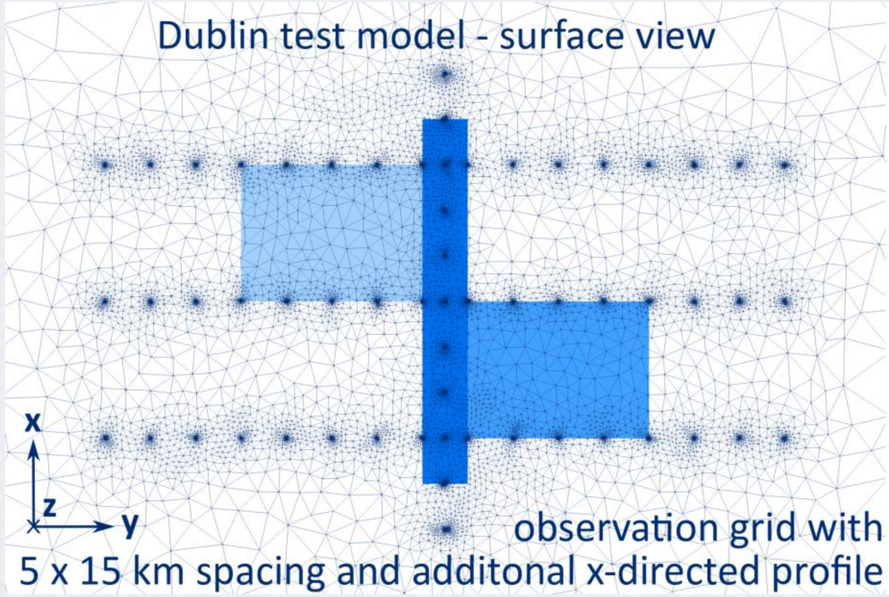
We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

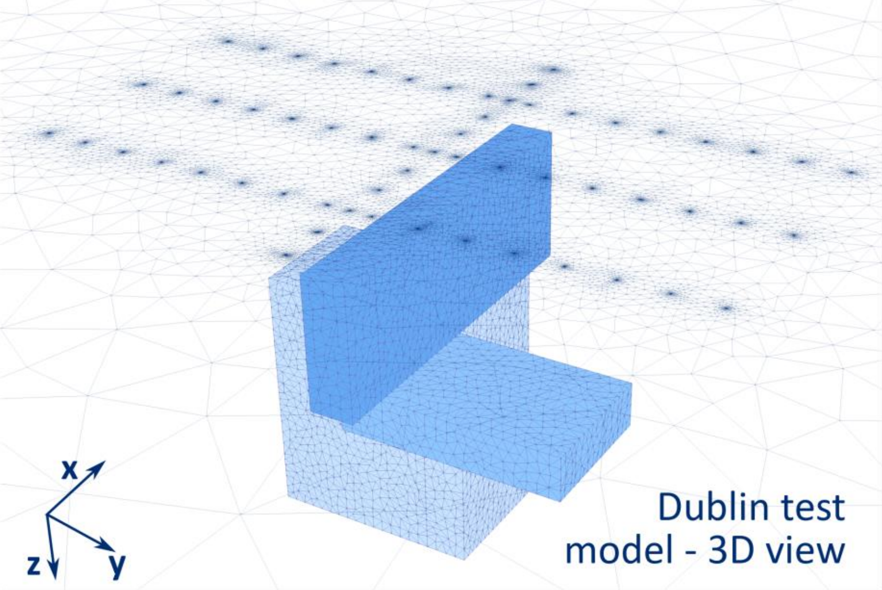
3D MT

validation with Dublin test Model I

2/3

- Discretization of Dublin model with custEM (central part of mesh)
- Large mesh extent > 1000 km to avoid boundary artifacts
- Highly refined receivers positions with 1m edges around receivers





2/2

Start

DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.

Leibniz Institute for Applied Geophysics

Open-Source 3D Finite-Element Modeling of Electromagnetic data with custEM 1.0

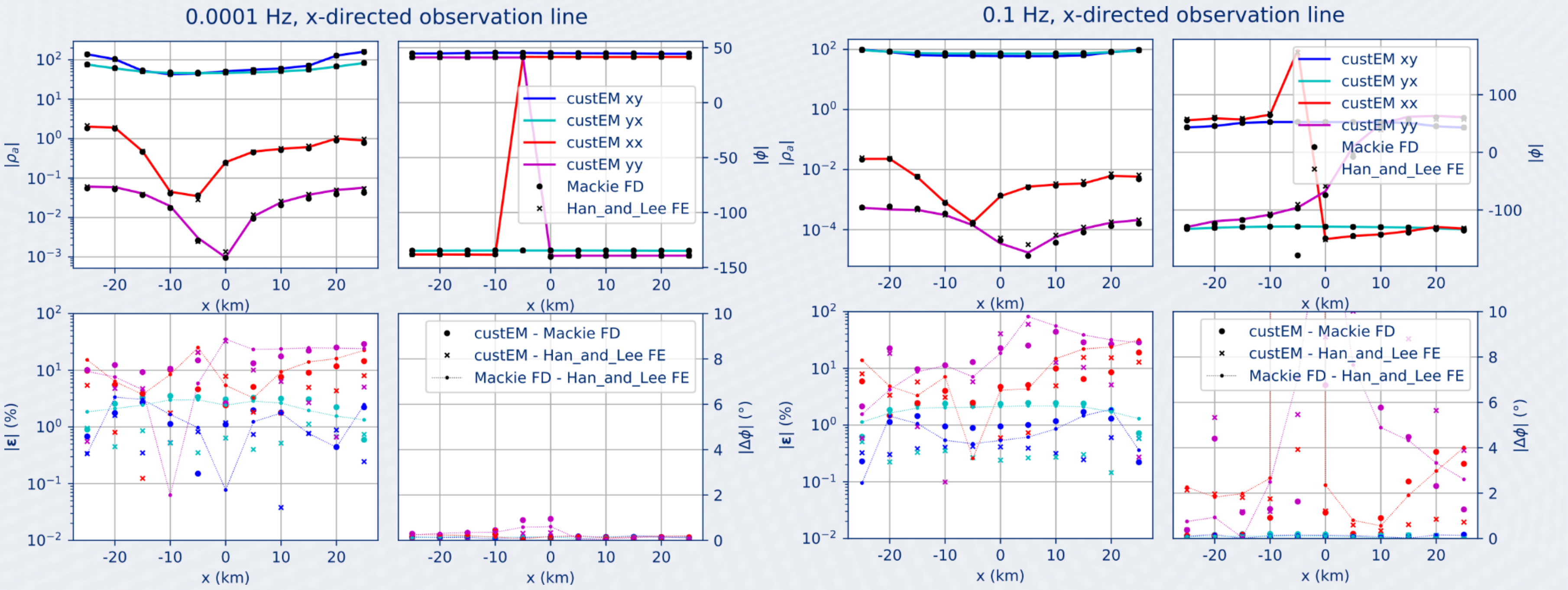
Raphael Rochlitz & Thomas Günther

3D MT

validation with Dublin test Model I

- custEM results vs. two references (Mackie & Han and Lee)
- left: apparent resistivity, right: phase
- top: data curves, bottom: normalized mean misfit.

3/3



2/2

Start
DESMEX
custEM
CSEM
TEM
MT

We thank the developers of FEniCS, pyGIMLi, COMET & TetGen for providing their tools to the community. We are especially thankful to Nico Skibbe, Ralph-Uwe Börner, Marc Alexander Seidel, Dieter Werthmüller, Feiyan Wang & Michael Becken for their valuable advice and contributions during the past months, without which it would not have been possible to reach today's state of custEM. DESMEX/DESMEX II were funded by the Germany Ministry for Education and Research (BMBF), program Fona-r4, grants 033R130D/033R130DN.