Drone-based geophysical surveys - Electromagnetic method

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Contents

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Electro-magnetic surveys

- Faraday's law: $\nabla \times \mathbf{E} = -d\mathbf{B}/dt$
- Ampère's law: $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
- Constitutive equations: $\mathbf{B} = \mu\mathbf{H}$ and $\mathbf{E} = \sigma\mathbf{J}$ (and $\mathbf{D} = \varepsilon\mathbf{E}$)
- Changes in the amplitude and phase of the measured EM field are related to changes in the electrical conductivity (σ) or resistivity (ρ) inside the earth
    - **Time domain** (pulse) **systems** (most airborne systems)
    - **Frequency domain** (time harmonic) **systems** (e.g. Slingram)
    - **Active** (controlled source) vs. **passive** (natural field) methods
- Data interpretation by numerical modelling and inversion
    - Maps, cross-sections and 3D mesh models of resistivity
- Applications in geological mapping, geotechnical and groundwater investigation and mineral exploration

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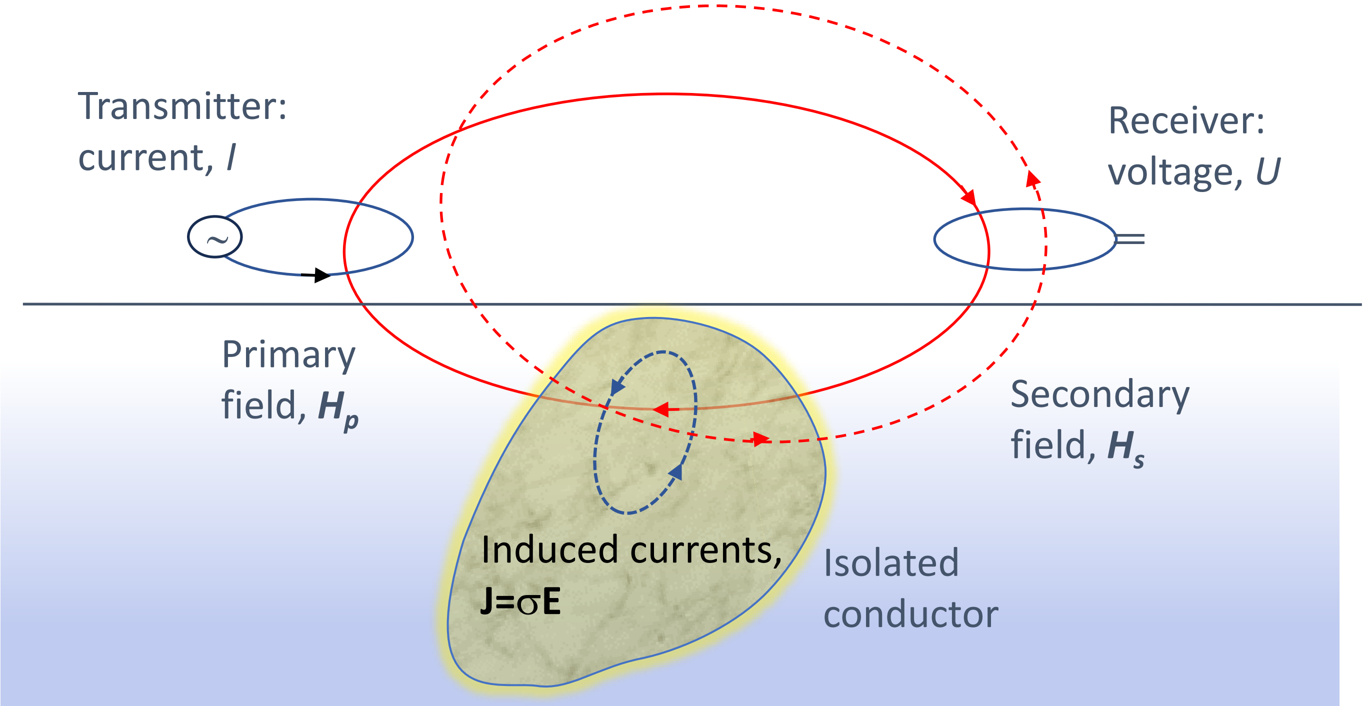
Frequency-domain EM

- The primary EM field ($\mathbf{H}_p$) due to harmonic time-varying current ($I \cdot \sin\omega t$) in the transmitter loop induces currents ($\mathbf{J}_s$) in conductive targets of the sub-surface
- The currents creates a secondary magnetic field ($\mathbf{H}_s$)
- The receiver measures the total field ($\mathbf{H}_t = \mathbf{H}_p + \mathbf{H}_s$)



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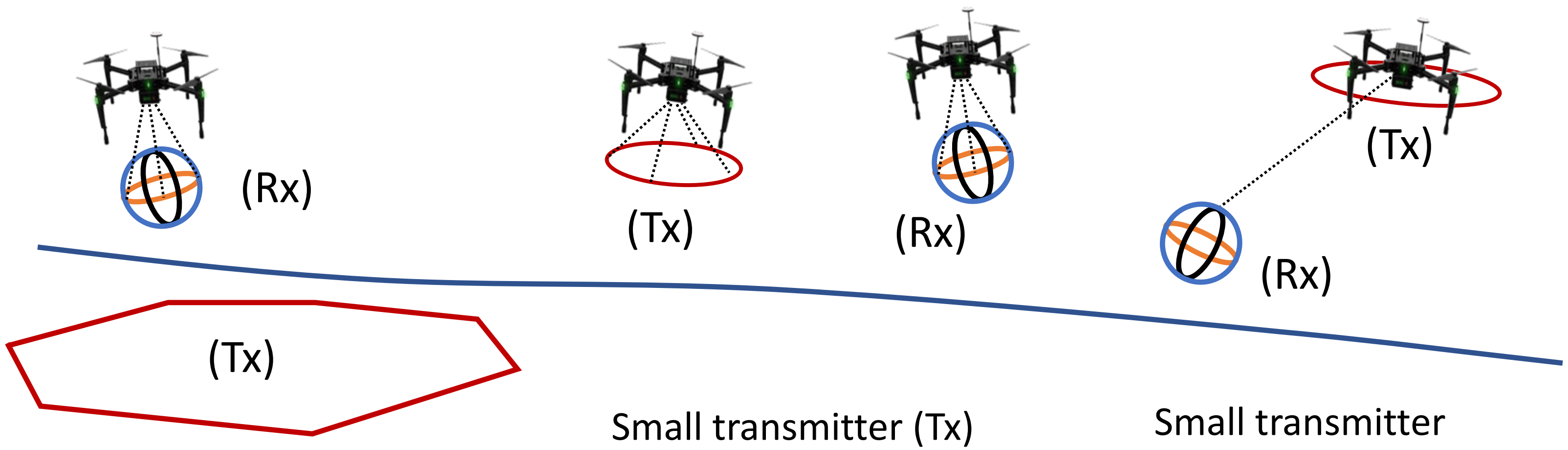
Drone-based EM system operation modes

A) Semi-airborne system

B) Two-drone system

C) Single-drone system



Large fixed transmitter loop (Tx) is set on the ground and receiver (Rx) is towed by a drone

Small transmitter (Tx) loop is carried by one drone and receiver (Rx) is towed by another drone.

Small transmitter loop is attached to the drone, and the same drone tows the receiver

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Two existing EM systems

- **Canadian, GEM Systems VLF-EM (below)**
  - Towed bird (< 7 kg), 2 frequencies 15-30 kHz
- **German, MGT Radio EM (right)**
  - Towed 3-axis induction coil (6.5 kg), 1-300 kHz
  - VLF frequencies and man-made EM fields

(https://www.gemsys.ca/uav-vlf/)


(https://www.mgt-geo.com/technology.html)

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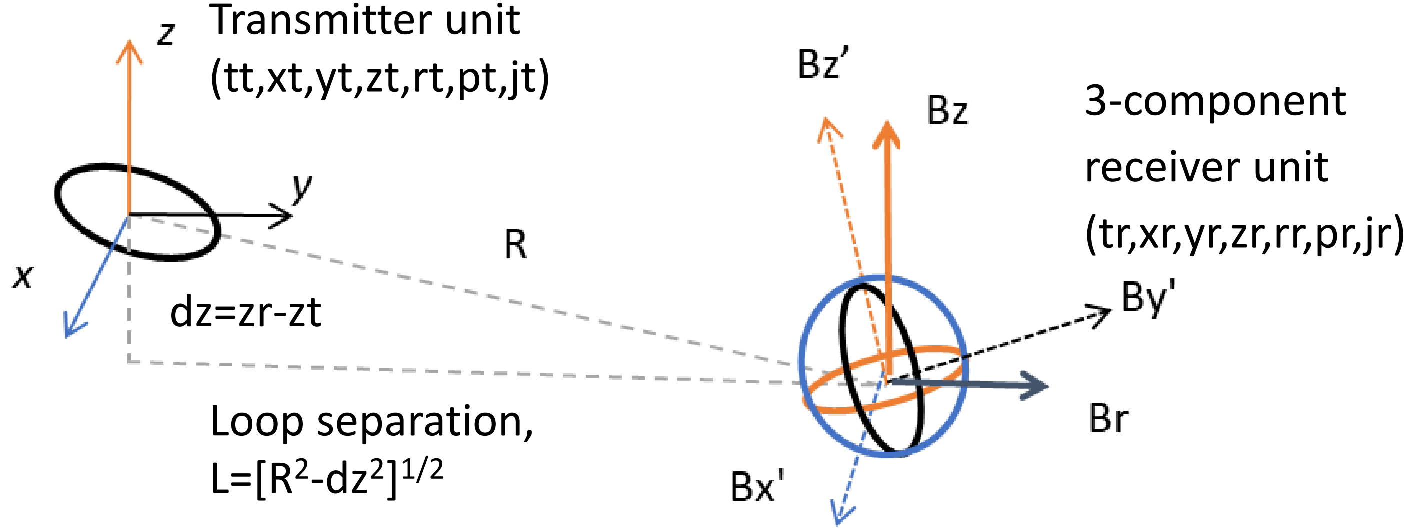
Radai's Louhi EM system - main concept

- GNSS units of the transmitter (Tx) and receiver (Rx) measure their position (*x,y,z*) and time (*t*)
- Inertial measurement units (IMU) measure their attitude (*r,p,j*)
- Measured magnetic field *B'=(Bx',By',Bz')* is rotated from device coordinates to world coordinates *B=(Bx,By,Bz)* and synchronized in time with Tx current to yield in-phase and quadrature components



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Louhi ground loop EM transmitter

- Insulated copper wire laid out on ground surface (polygon)
- Surface area e.g. 100 m by 100 m
- 2-3 kW gasoline generator + DC power source
- Impedance tuner (minimizing resistance maximises current)
- 3 simultaneous frequencies
  - 2.6, 4.2 & 9.2 kHz
- Transmitter current 1-3 A (moment up to 30 kAm^2)
  - Current is measured and stored

(photo by M.Pirttijärvi)

Louhi 3-component EM receiver (v.2023)

- Towed ”birdie”
    - Size ca. 70 x 70 x 80 cm
    - Total length 1.3 m
    - Mass ca. 1.3 kg
    - Standalone unit (3S LiPo)
    - Sampling time 1 s
    - GNSS for position and time
    - IMU for orientation
- Gives NED components of the magnetic field (B-field, pT)
- Phase calibration coming soon


(photo by M.Pirttijärvi)

Coot VTOL – Vertical Take-off and Landing drones

- Vertical take-off and landing
  - Wing-span 2.45 m
  - Weight 12 kg with 12S LiPo's
  - 4 x 1000 W + 2000 W engines
  - Flight speed ca. 20 m/s
  - Endurance 2 h (alone)
  - Endurance 1 h (towing)
  - Max range 70 km
- 3-axis FG magnetometer in a tail-boom (Radai's normal magnetic data processing using ELM)

(photo by M.Pirttijärvi)

Semi-airborne towed EM system

- Tow-line 20 m long
- Flight speed 20 m/s
- Flight paths 50-60 km long
- 50-100 m line separation
- Sampling time 1 s
- Sampling distance 20 m

(photo by M.Pirttijärvi)

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Louhi EM receiver towed by Coot VTOL drone
Savukoski, Sokli, 2023-09-19, video by M.Kumpula

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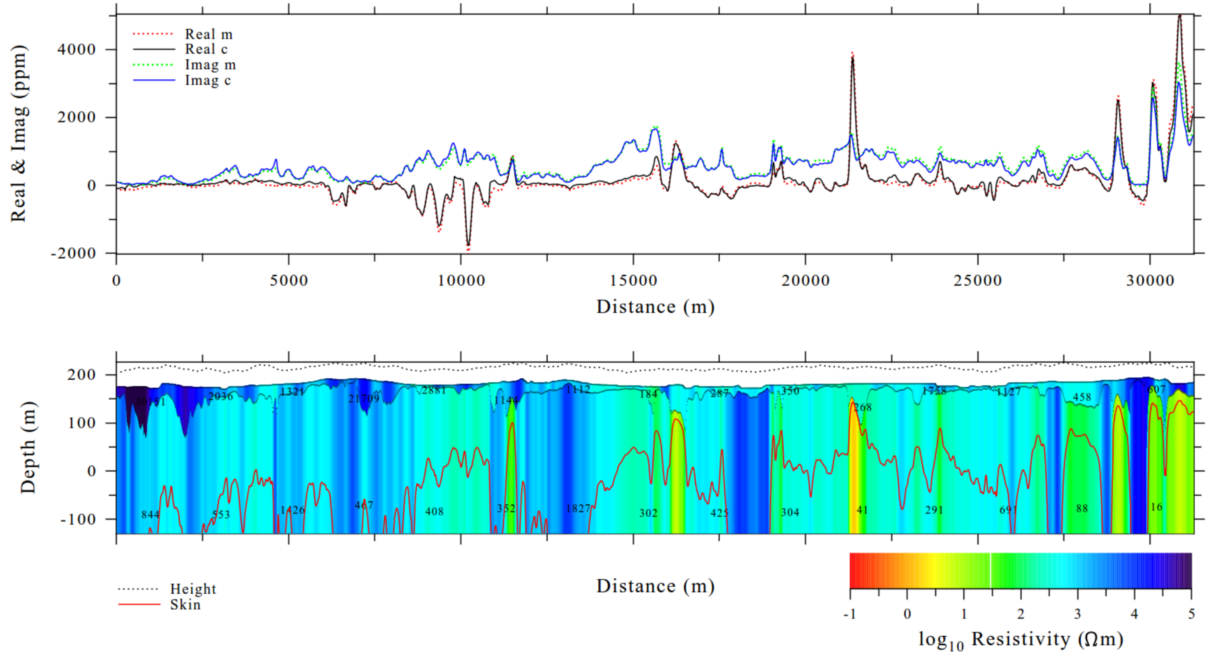
AEM data interpretation with Aeminv 3.2

- 1D EM inversion (layered earth resistivity model)
  - Maps of overburden and basement resistivity
- Joint inversion of AEM and magnetic data
  - Magnetic susceptibility utilized (corrects in-phase data)
- Other highlights: dipole-dipole & fixed loop systems, lateral (Occam) constraining (1D/2D), DEM data, sedimentary maps, parameter elasticity, barometric height.



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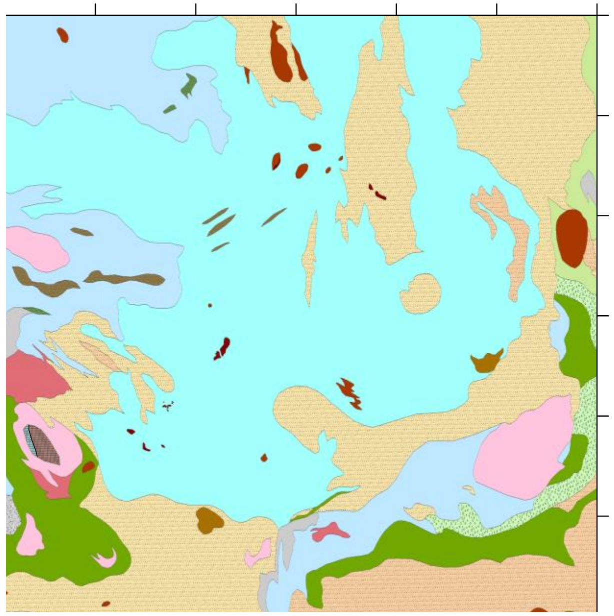
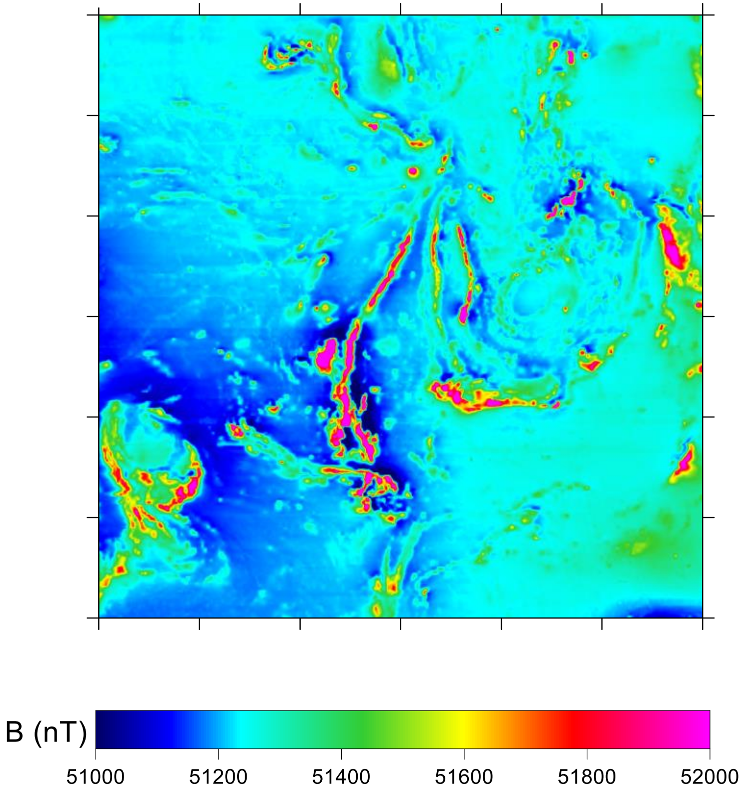
1D example: GTK data from Nivala map sheet

Lithological map (1:200k)
Geological Survey of Finland)



Magnetic field (nT)



(Pirttijärvi et al., 2015)

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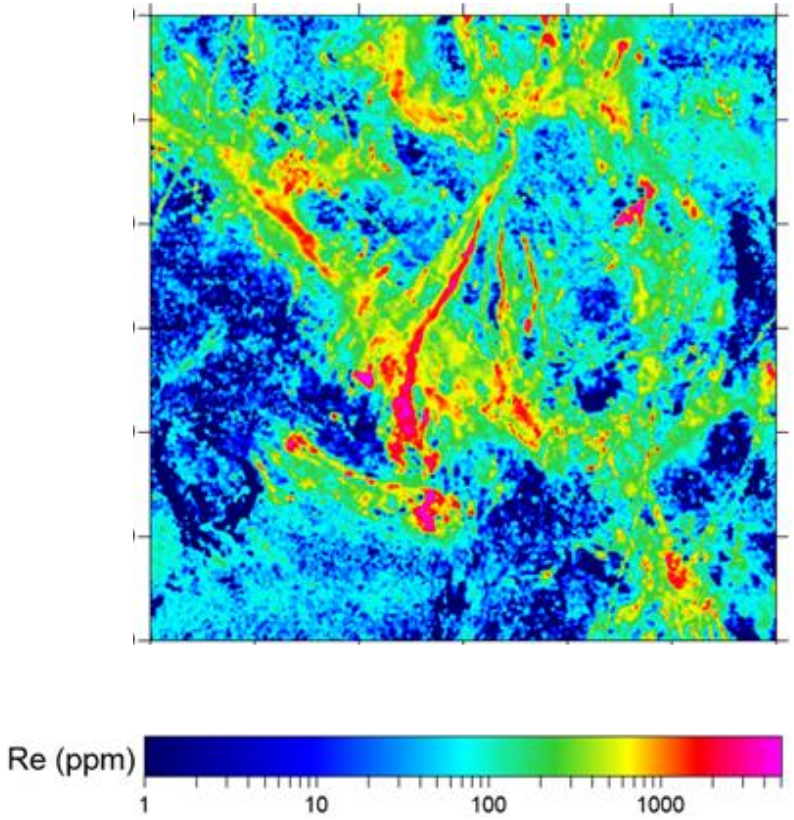
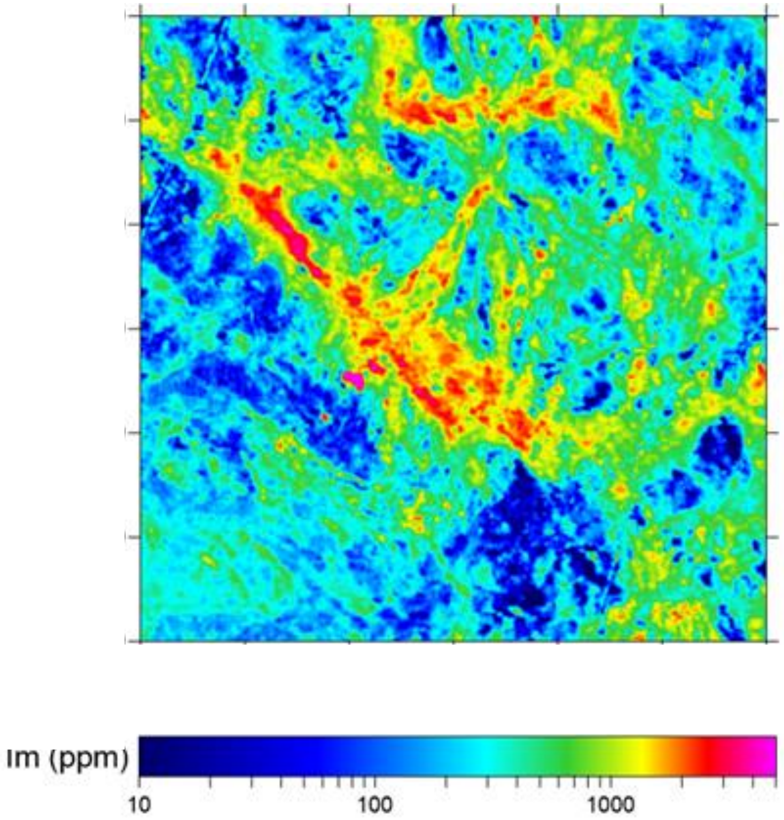
1D example: in-phase & quadrature data

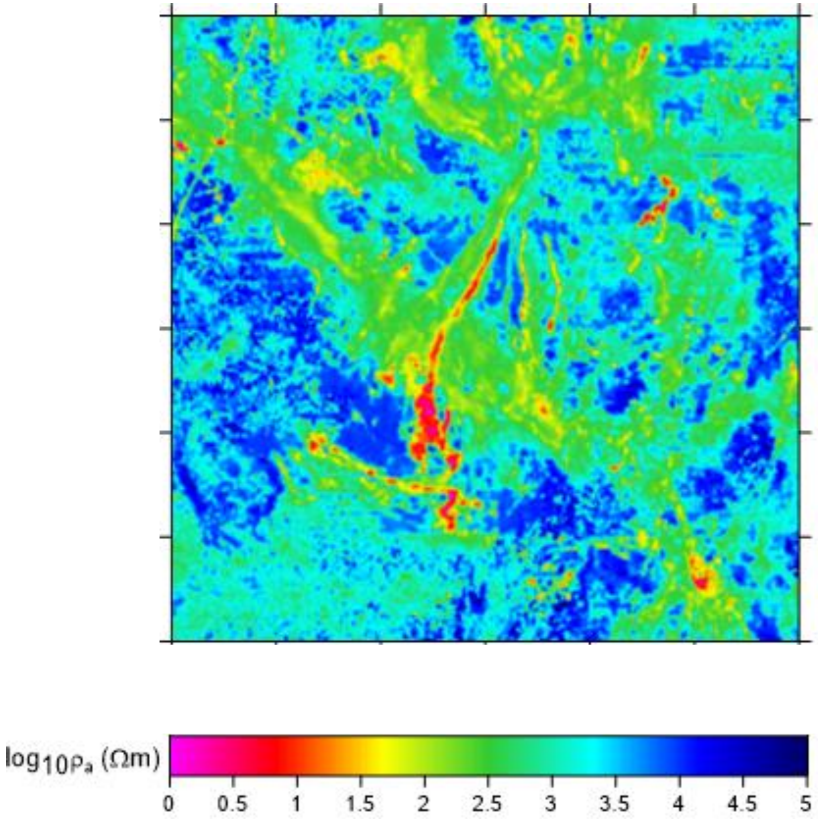
In-phase, 3 kHz



Quadrature, 3 kHz



Trad. apparent resistivity



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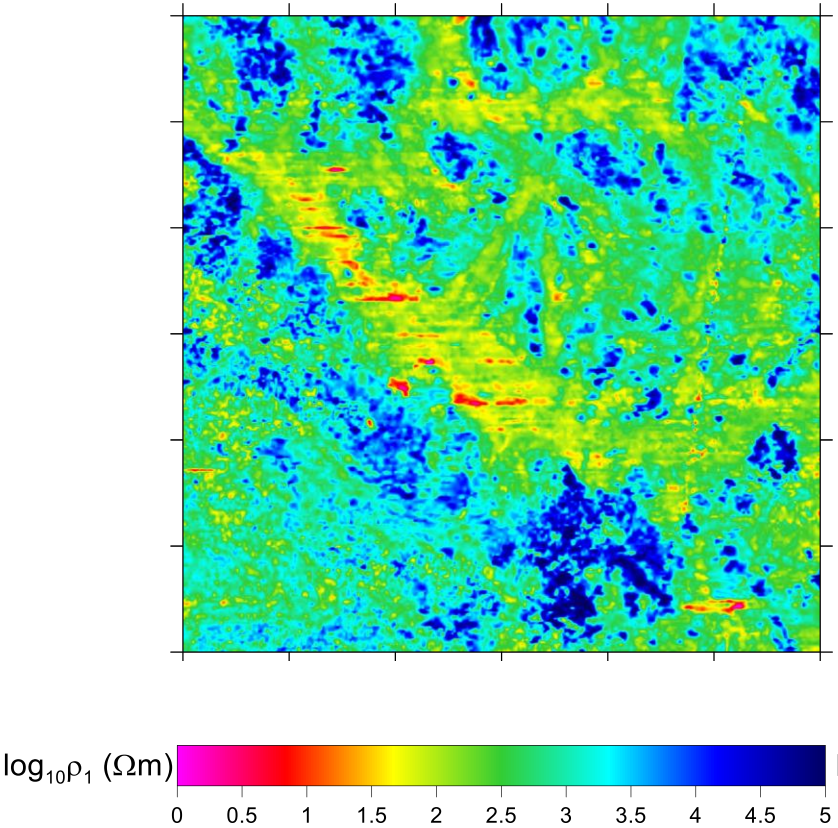
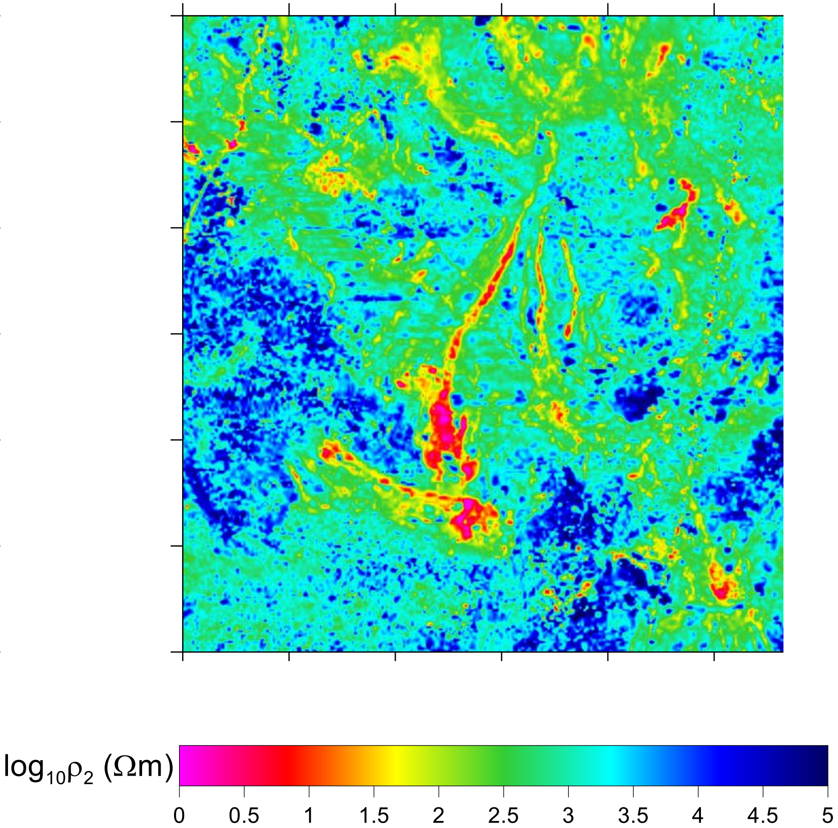
1D example: 2-layer inversion results

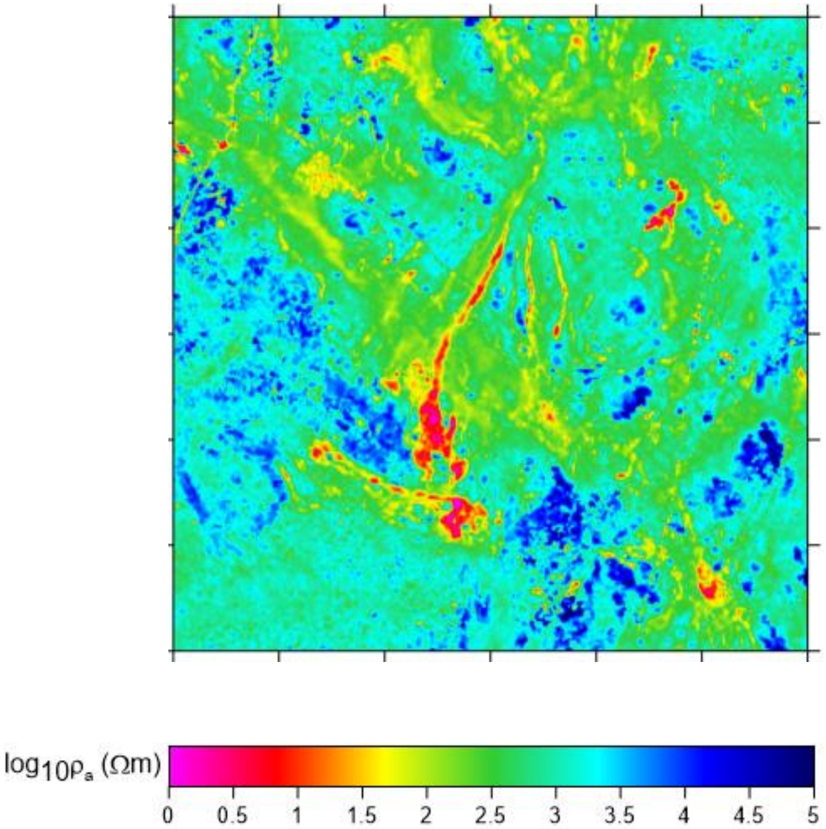
Overburden(soil) resistivity



Basement (bedrock) resistivity

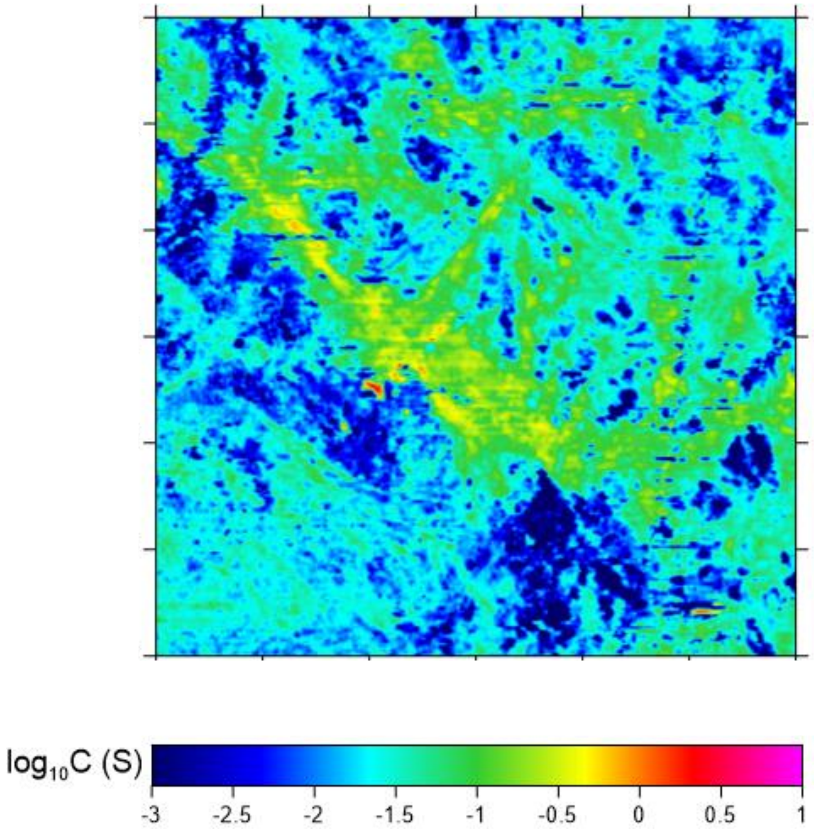


Trad. apparent resistivity

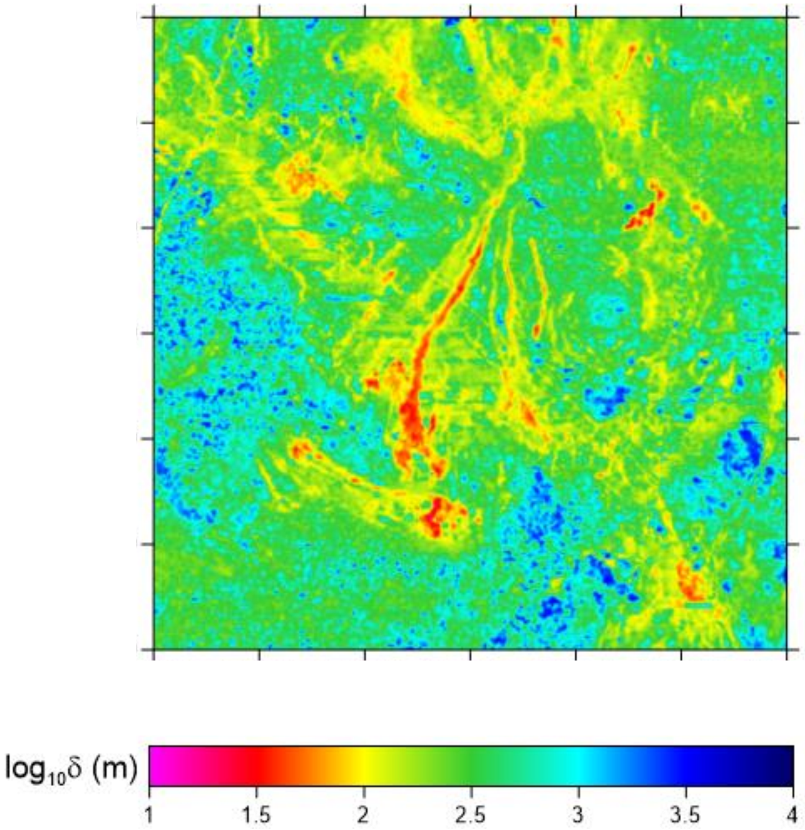


1D example: 2-layer inversion results (cont.)

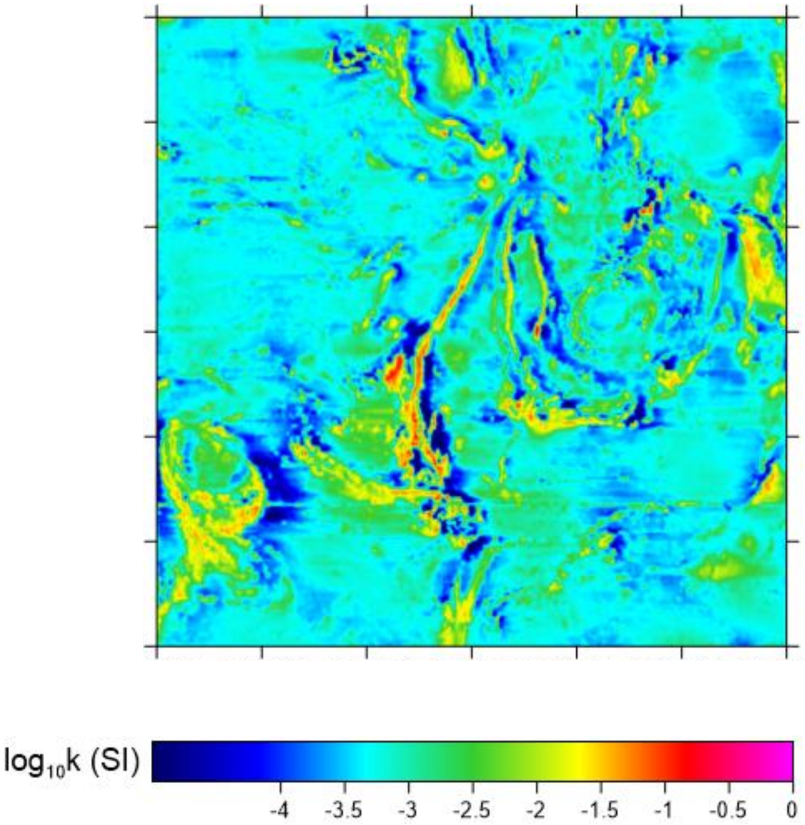
Overburden (soil) conductance



Cumulative skin depth



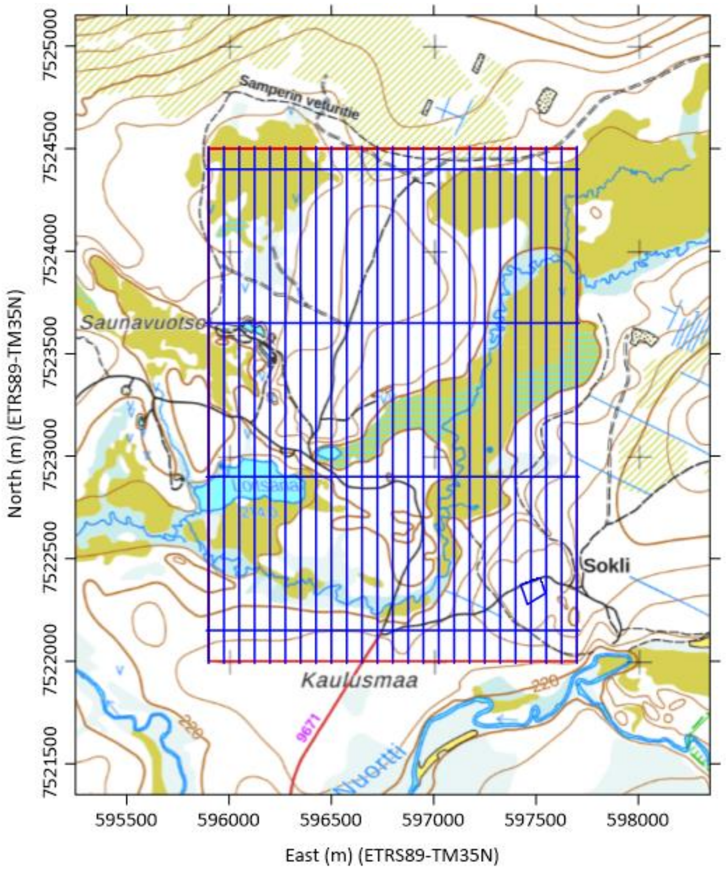
Magnetic susceptibility



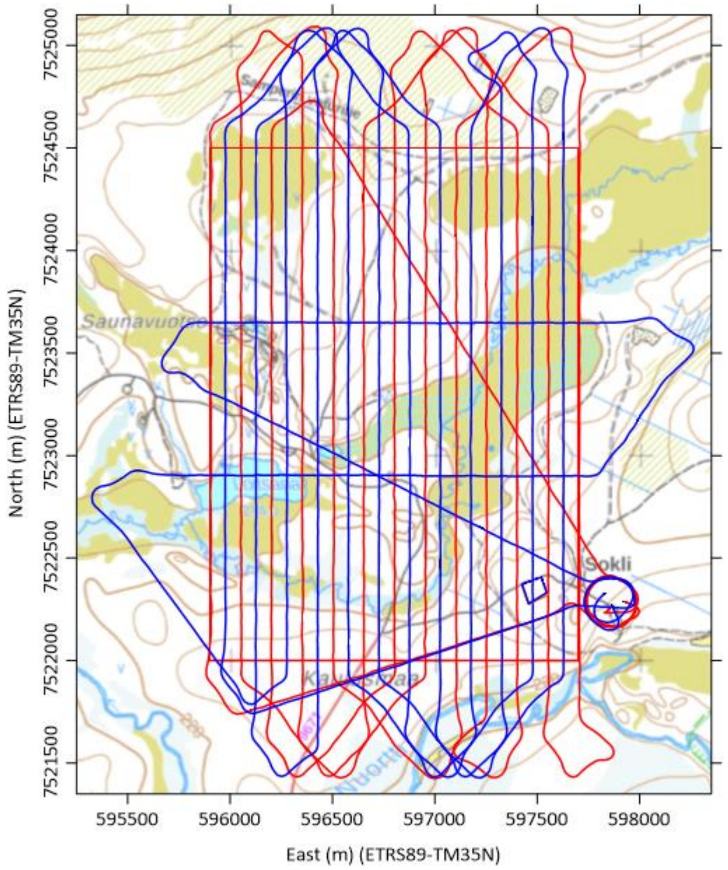
Sokli EM survey, Sep 2023

- DroneSOM test survey
- Savukoski, North-Finland
- Surface area 4.5 km^2
- 75 m line separation
- Total 65 line-km + 2 tie-lines
- Two flights; ca. 55 km long
- Single loop (bad weather)

Survey area, planned lines



Realized 2 flight paths



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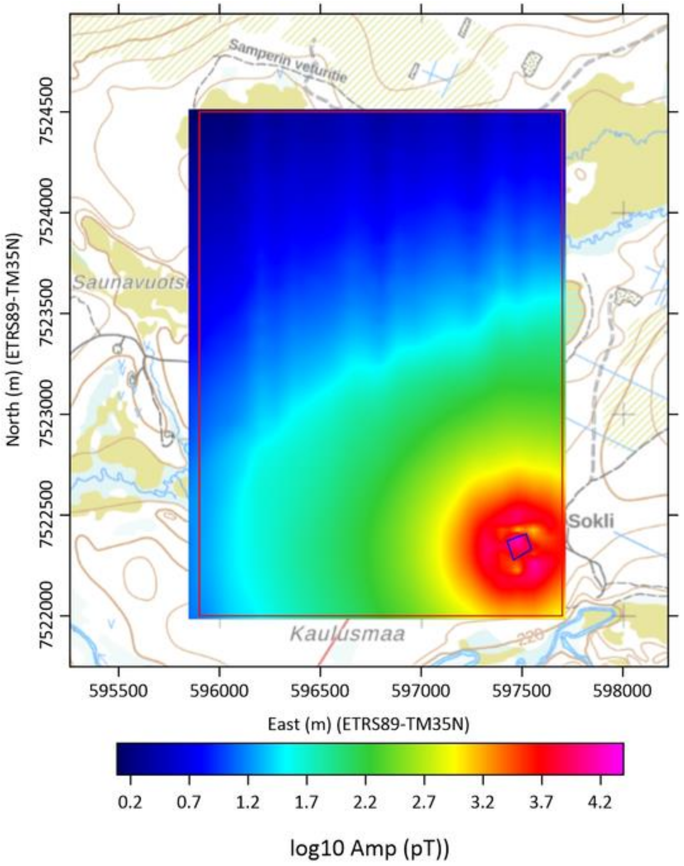
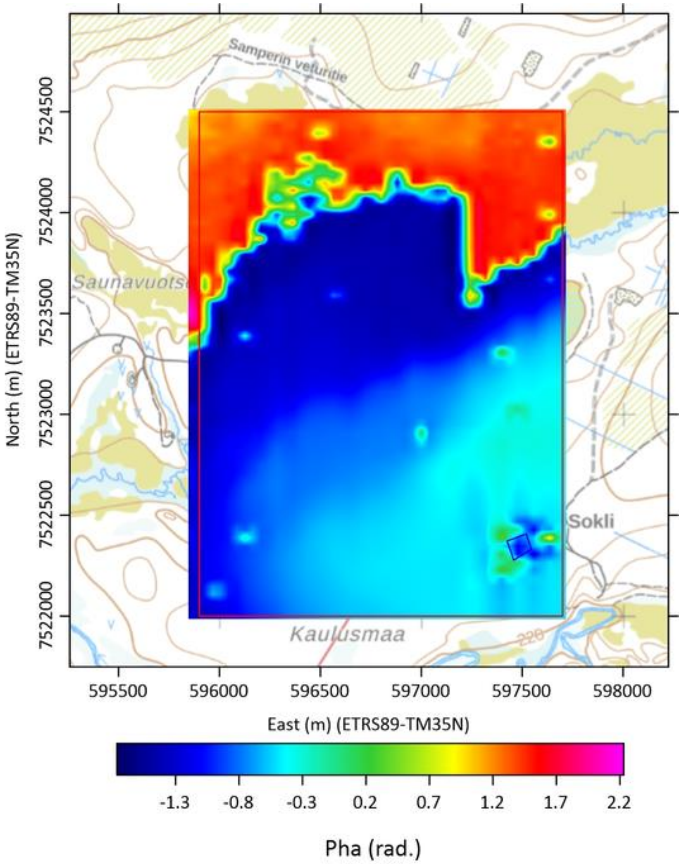
Sokli EM survey: NED data 2 kHz

Down component

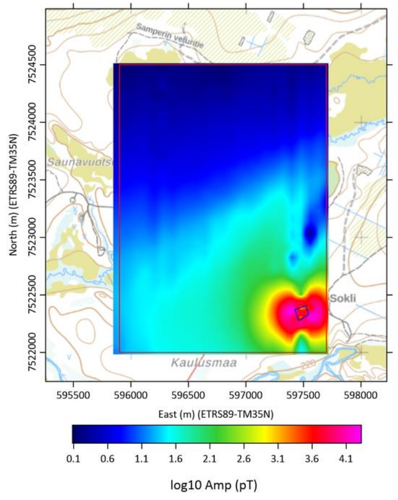
Amplitude

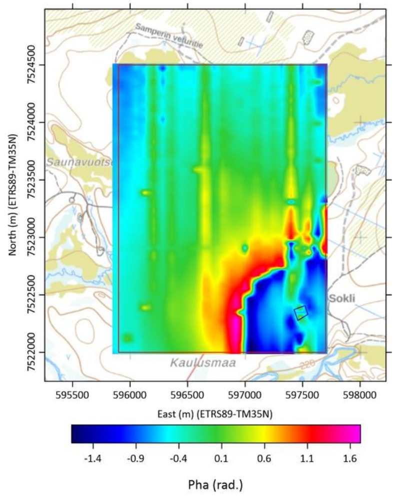


Phase

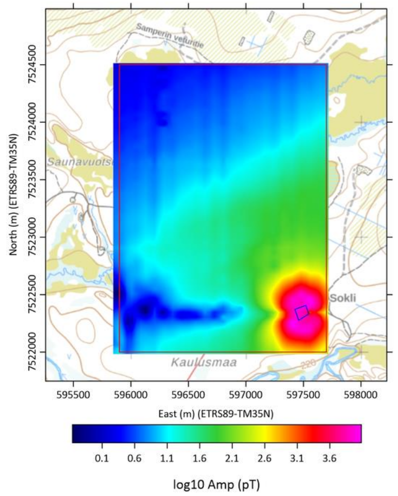


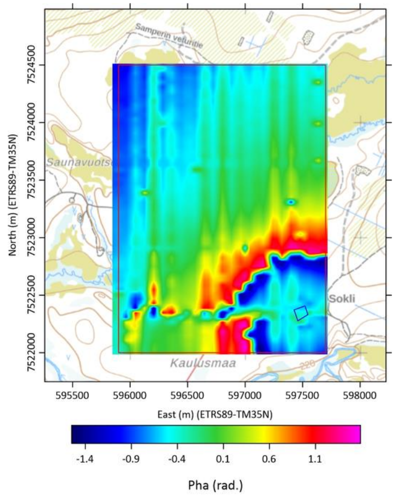
East





North

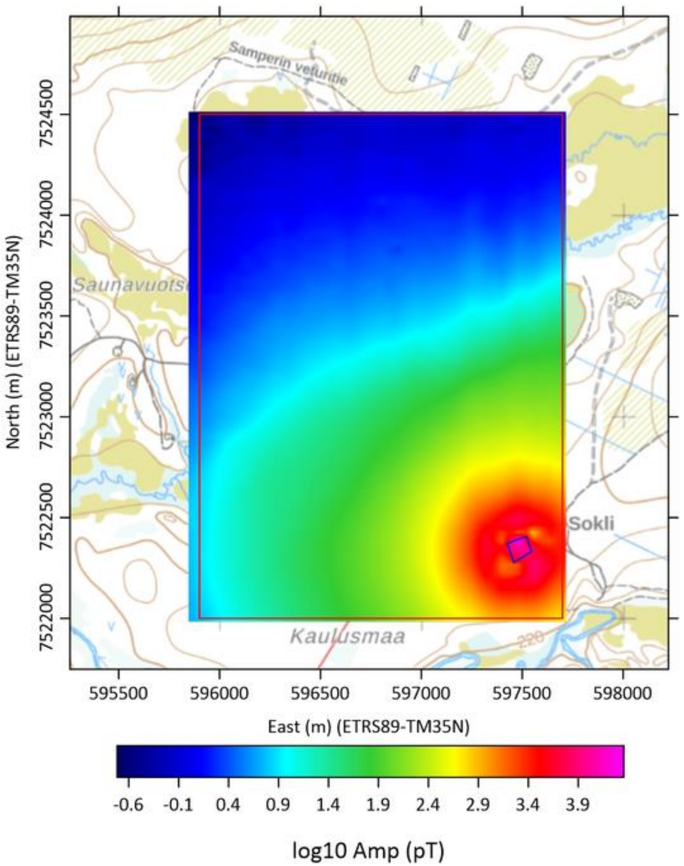




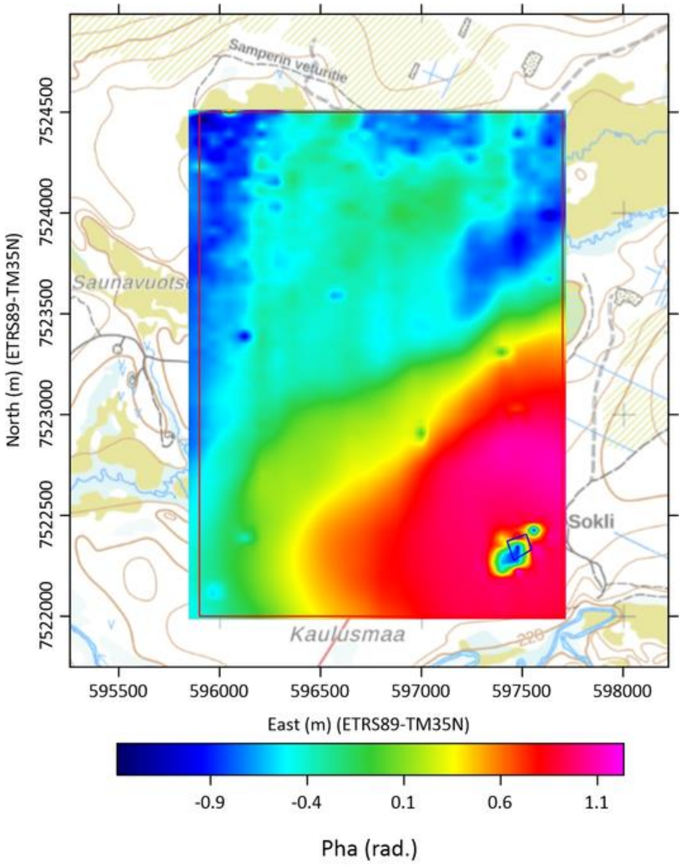
Sokli EM survey: NED data 4 kHz

Down component

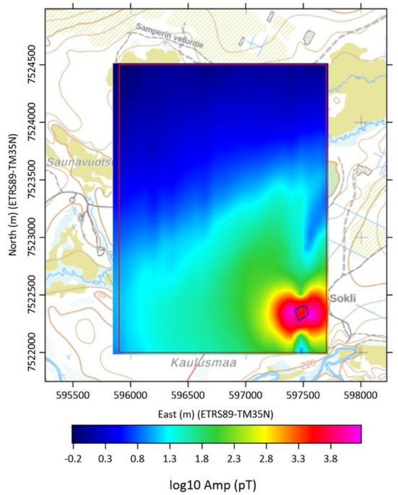
Amplitude

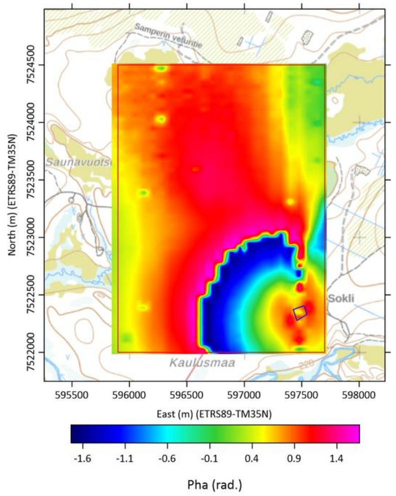


Phase

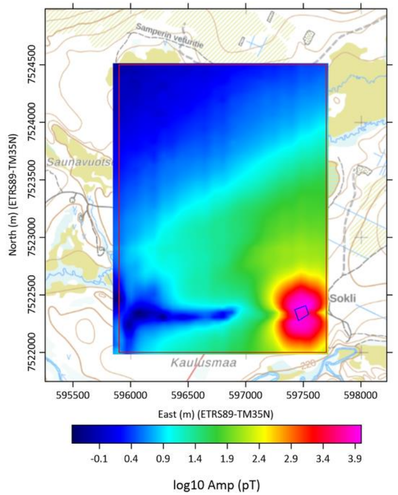


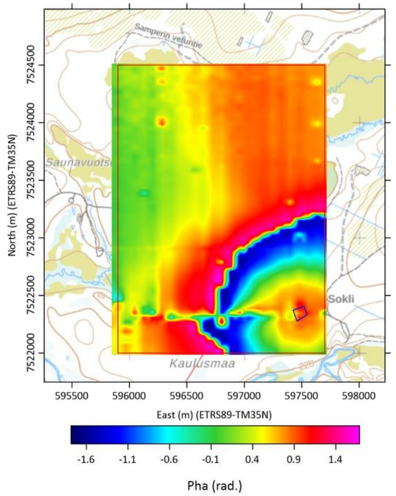
East





North





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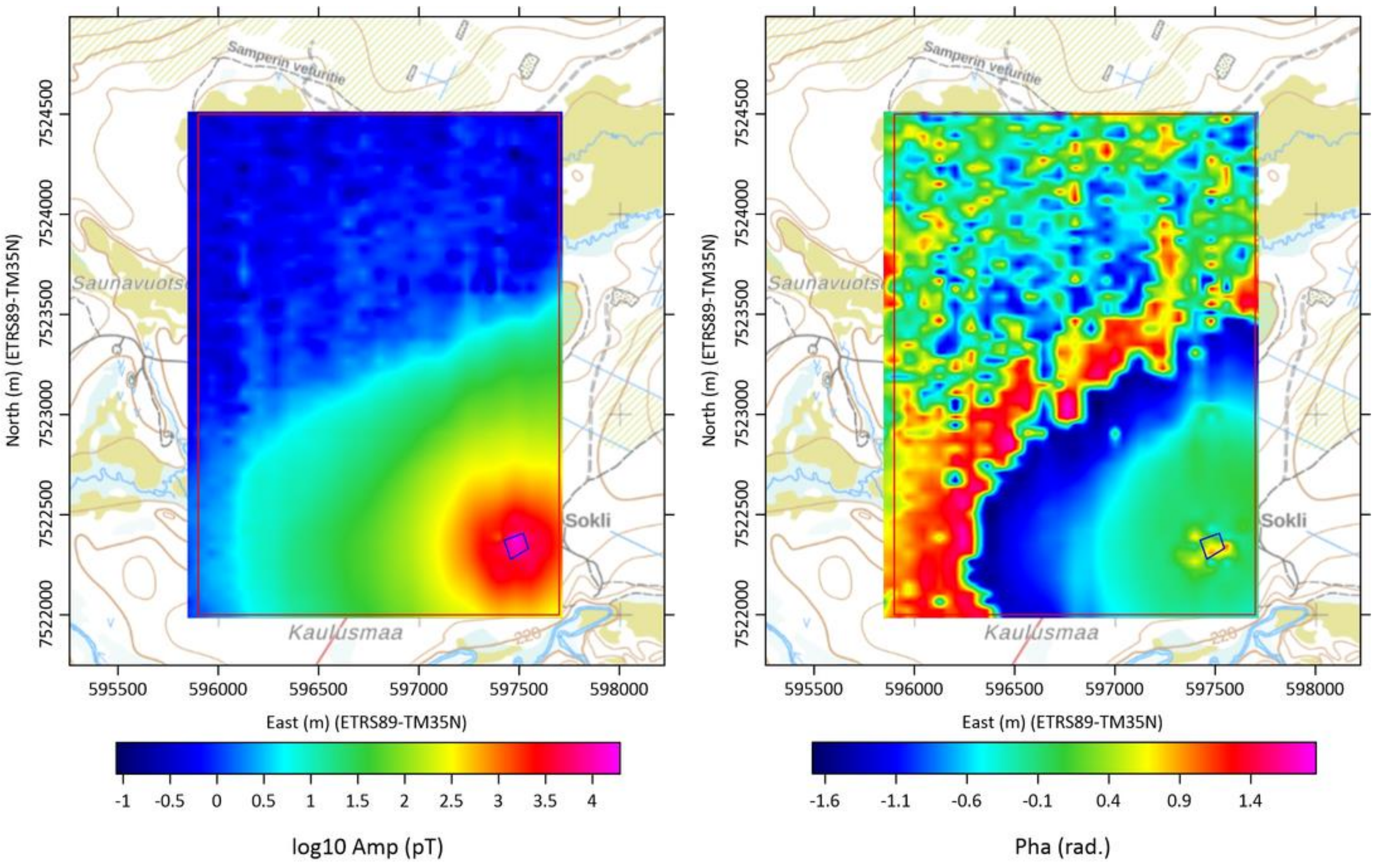
Sokli EM survey: NED data 9 kHz

Down component

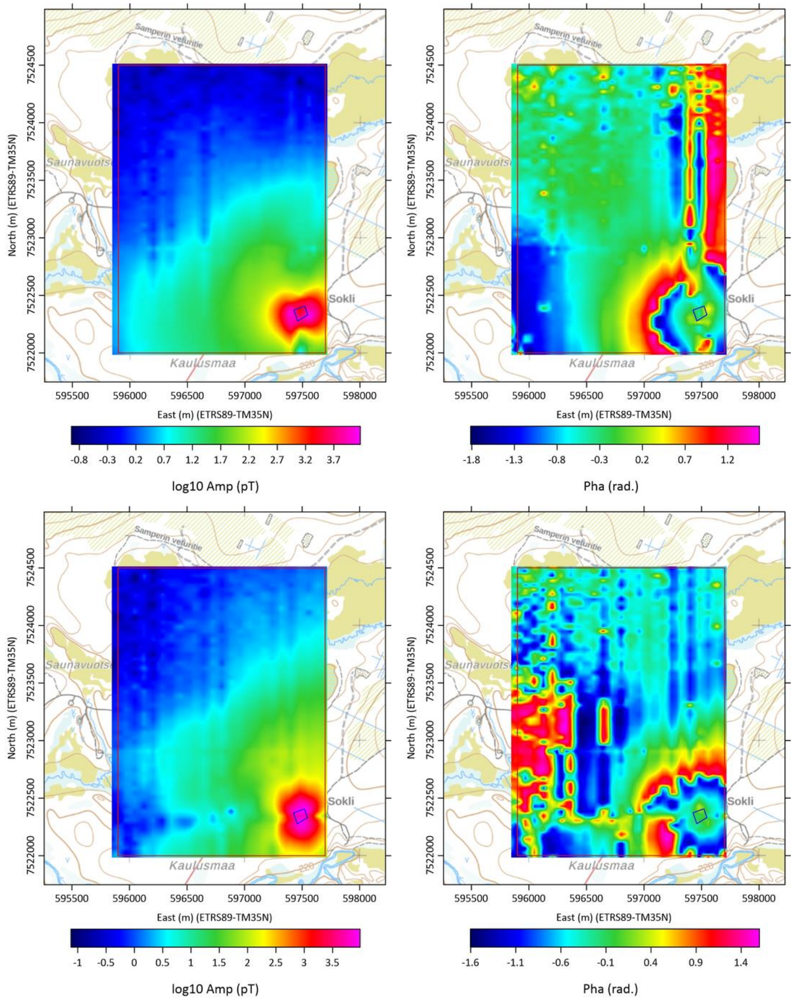
Amplitude

Phase



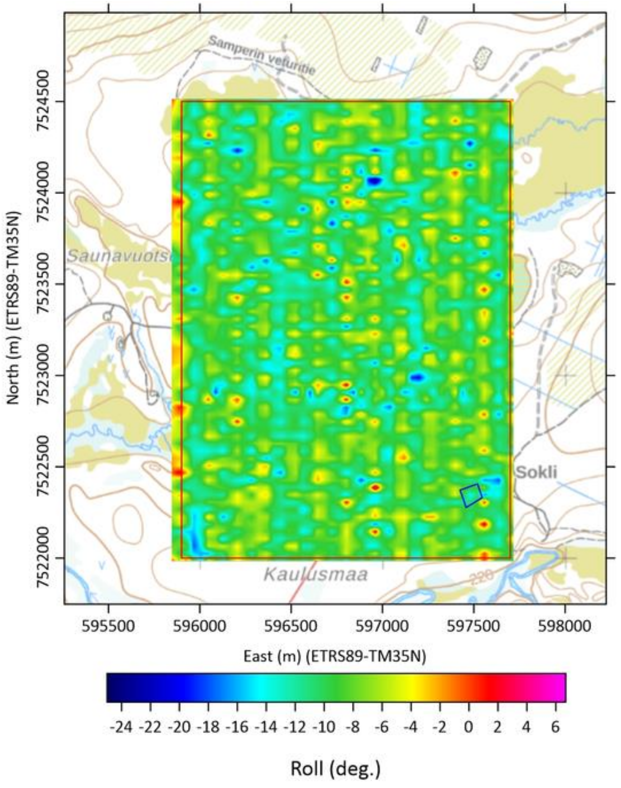
East

North

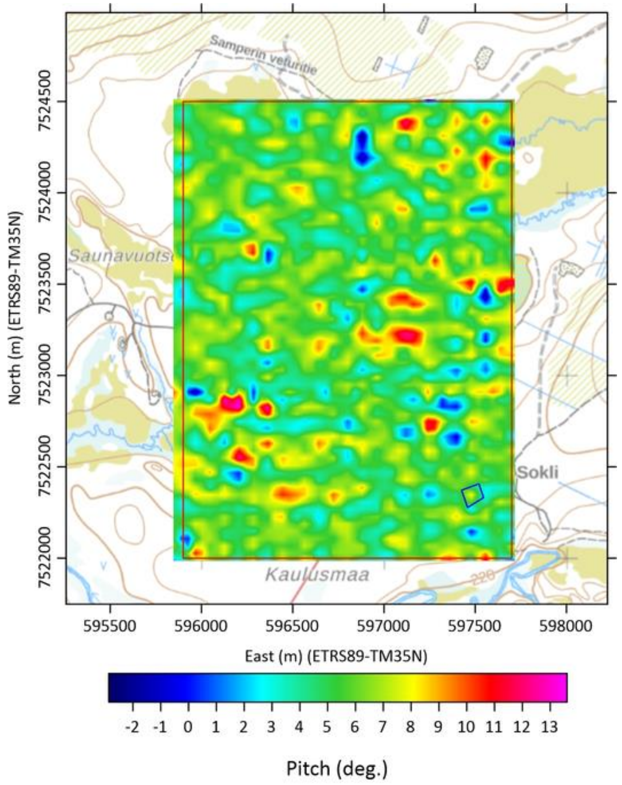


Sokli EM survey: Orientation

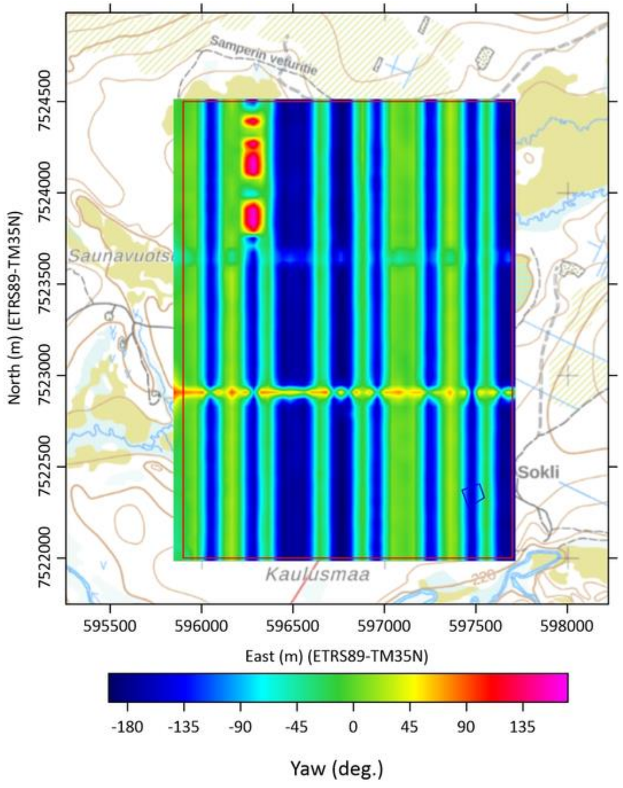
Roll



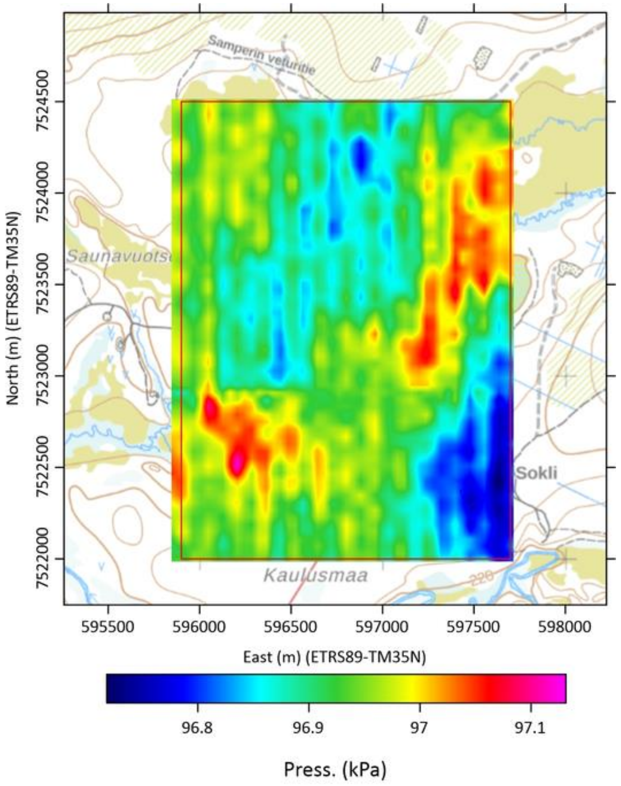
Pitch



Yaw



Pressure

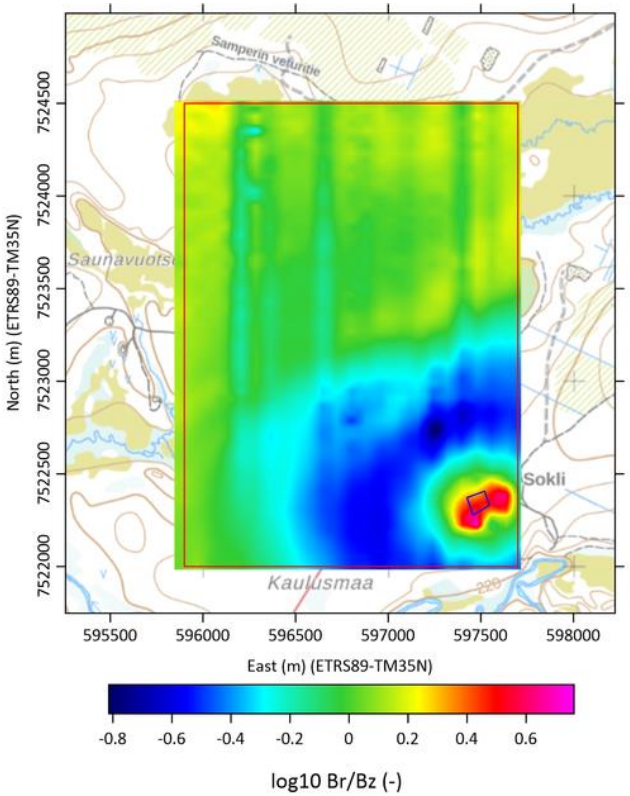


Sokli EM survey: Br/Bz-ratio & $\Delta\phi = \tan^{-1}(Bz/Br)$

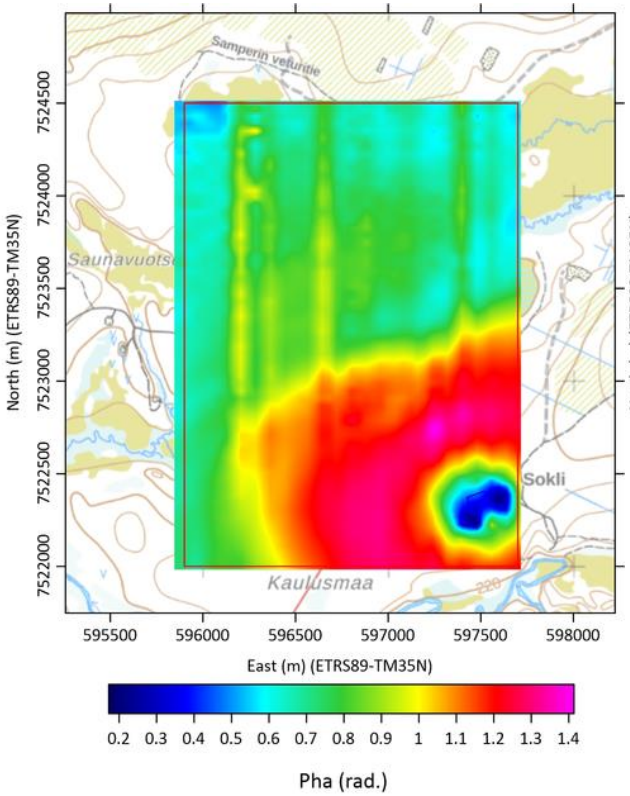
2 kHz

4 kHz

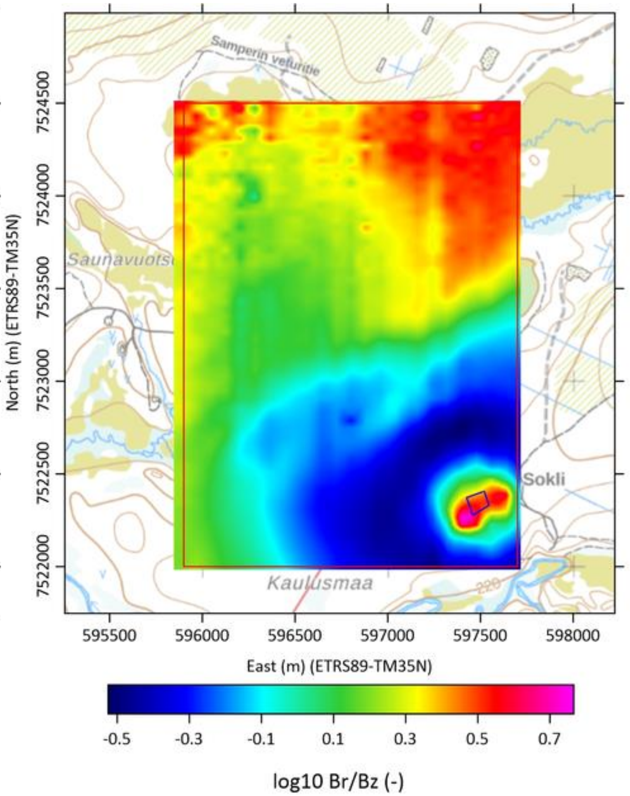
Br/Bz



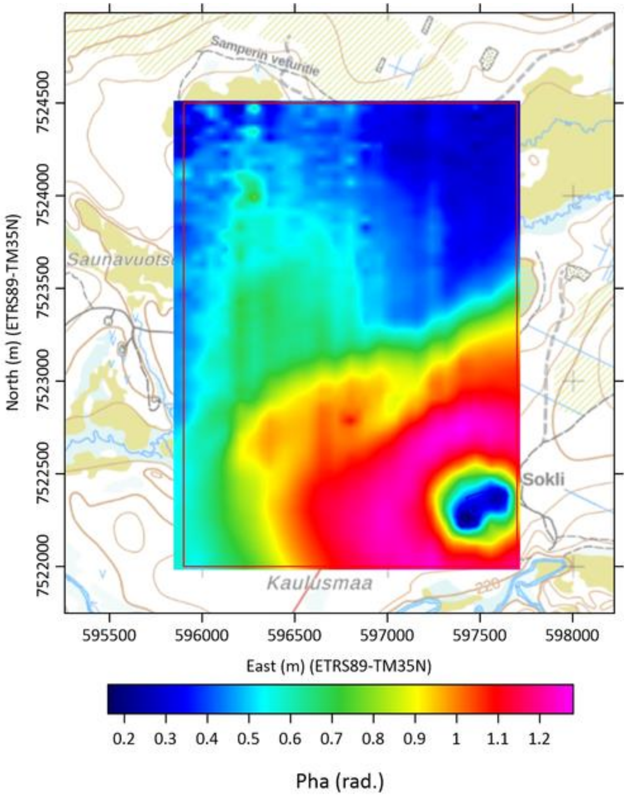
$\Delta\phi$



Br/Bz



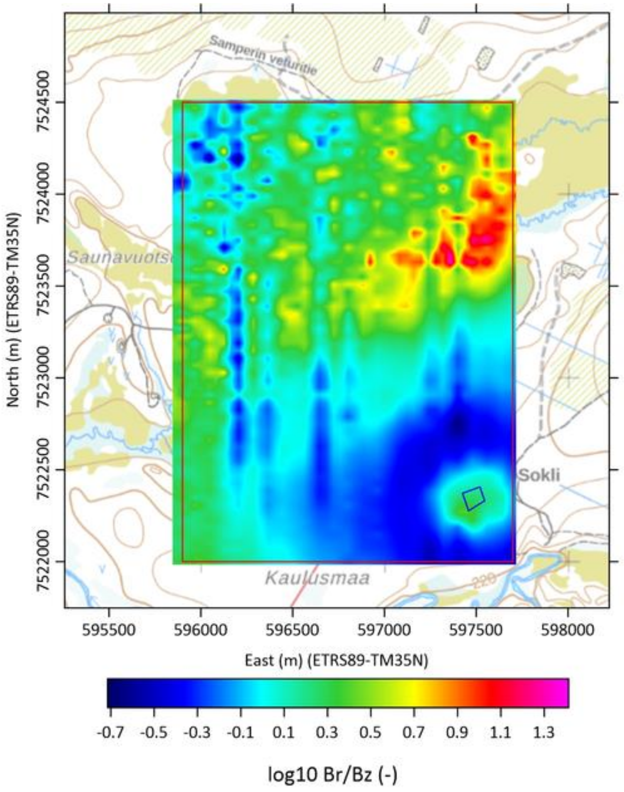
$\Delta\phi$



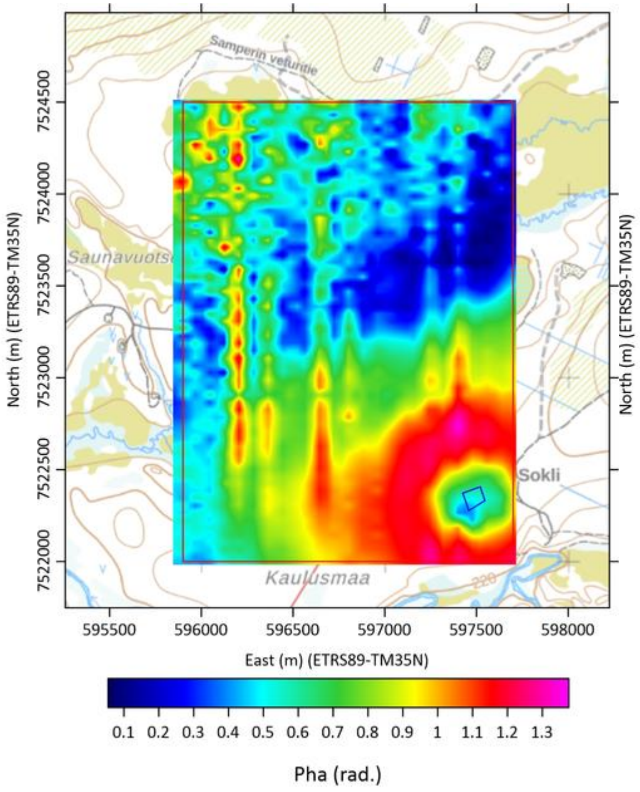
Sokli EM survey: Br/Bz-ratio, TMI & Altitude

9 kHz

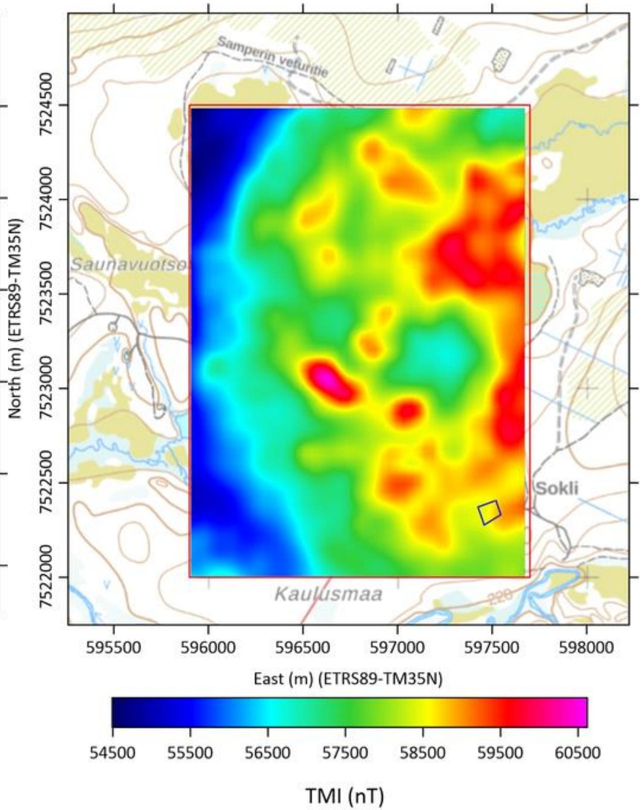
Br/Bz



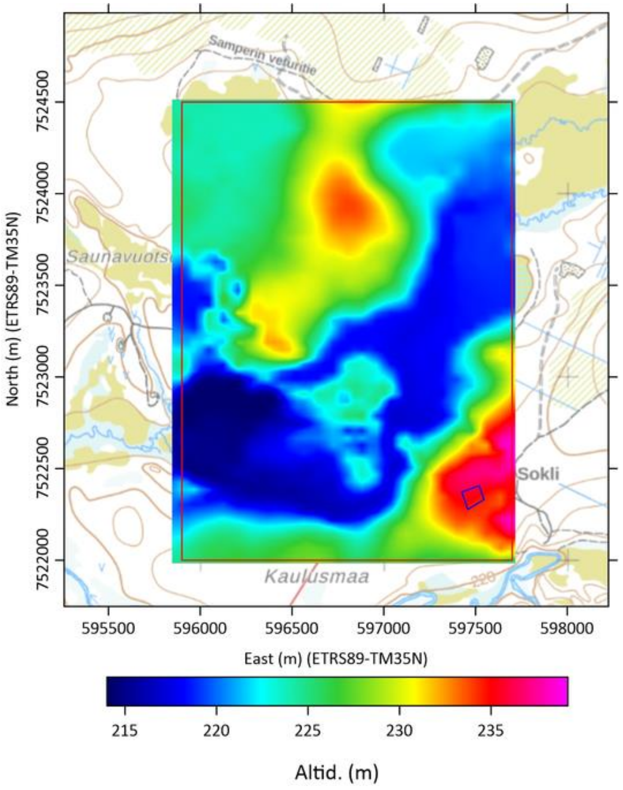
$\Delta\phi$



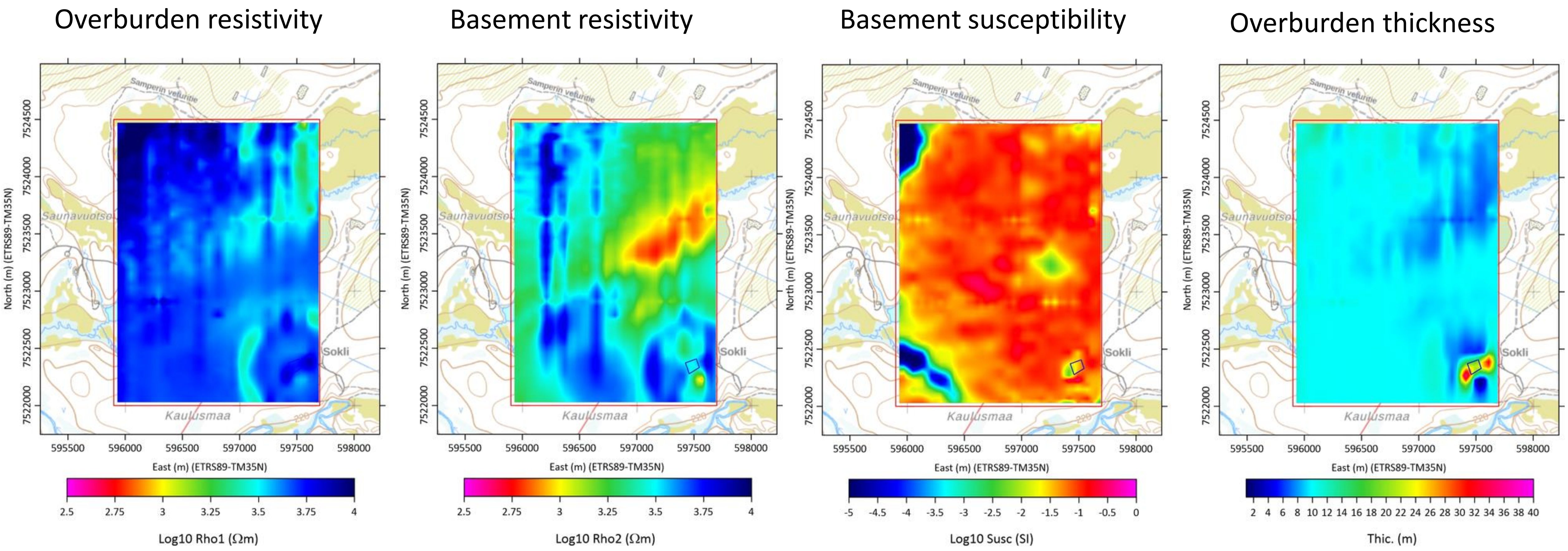
TMI



Altitude

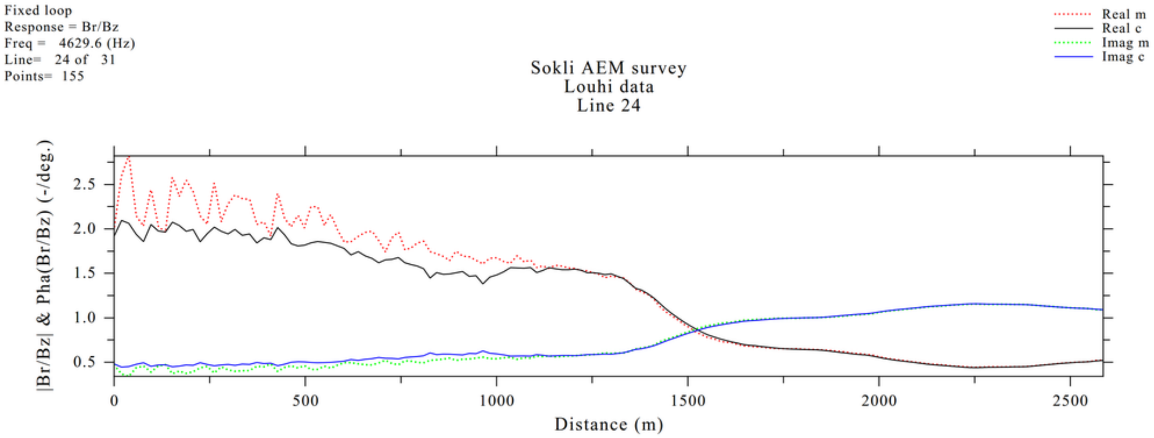


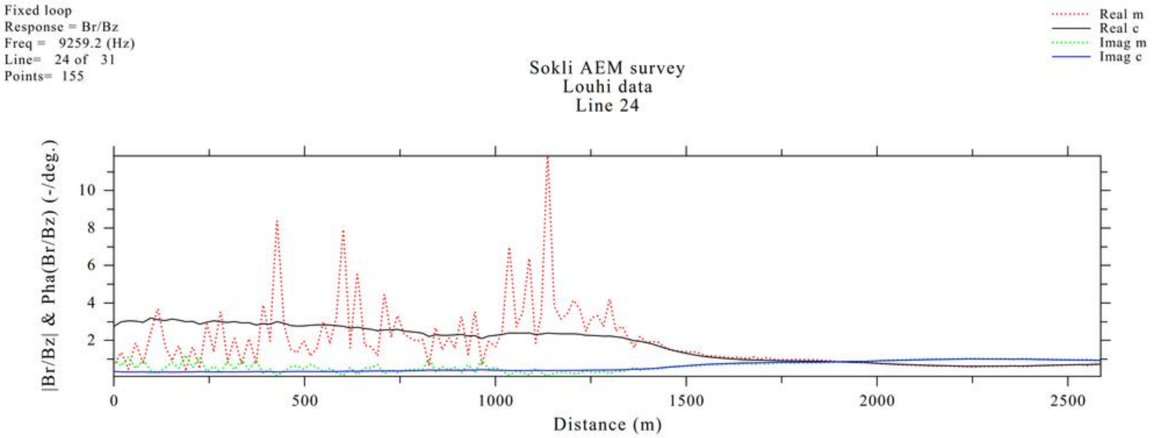
Sokli EM survey: 1D inversion by 2-layer model



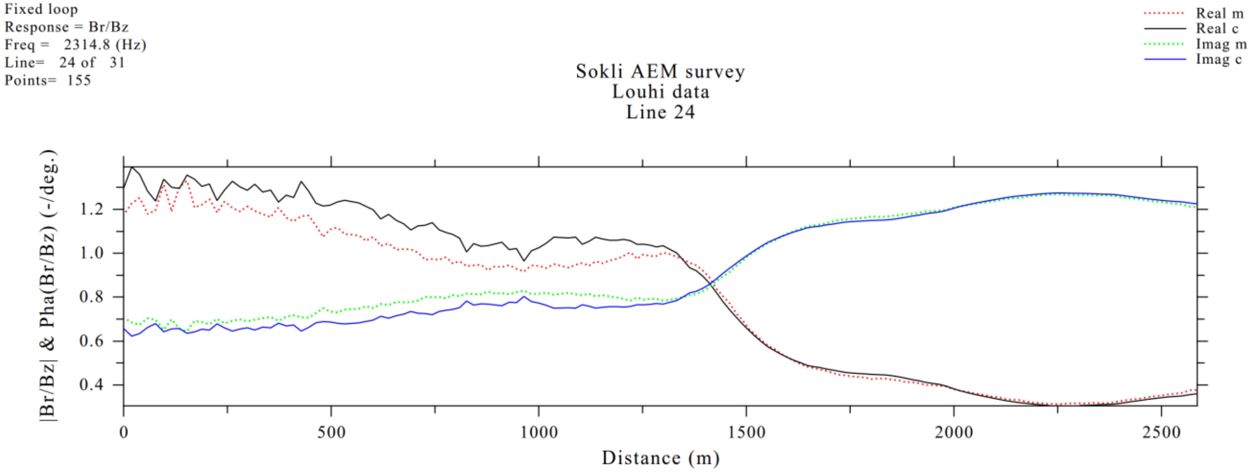
Sokli EM survey: Data fit example, Line #24

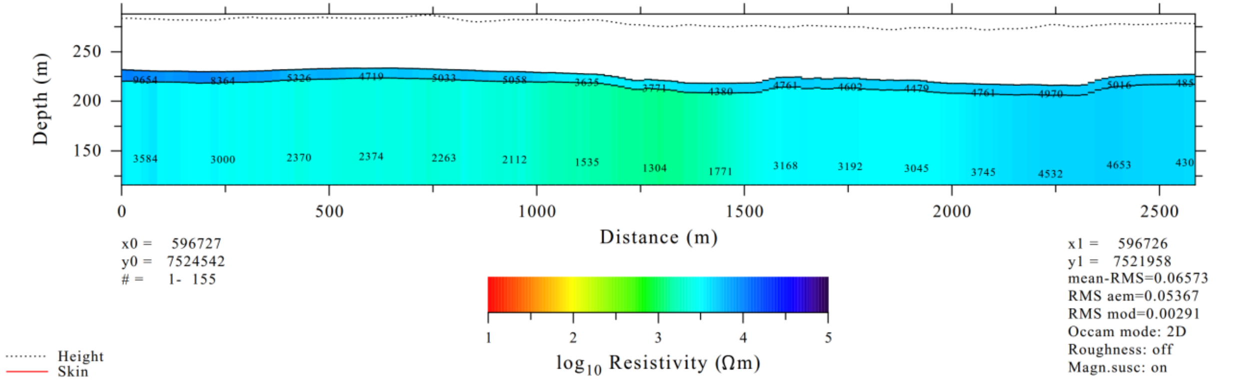
4 kHz & 9 kHz





2 kHz & pseudo-section





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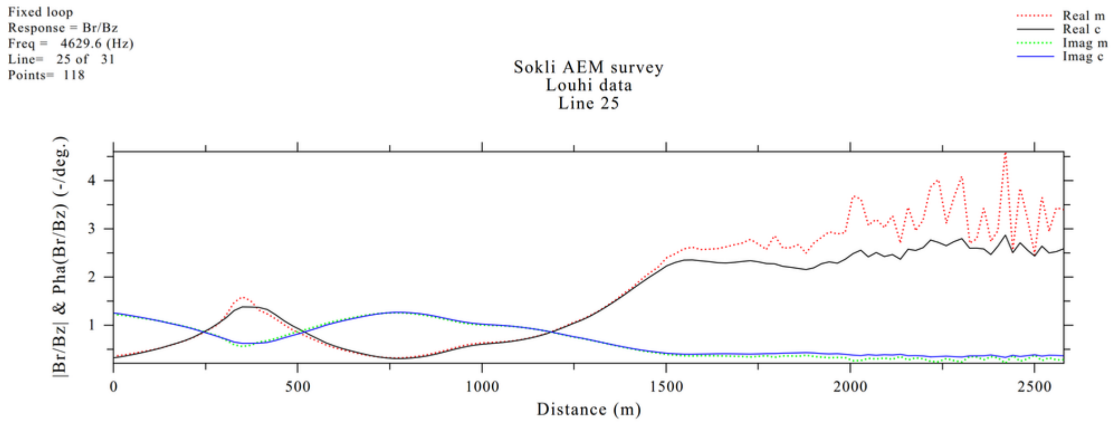
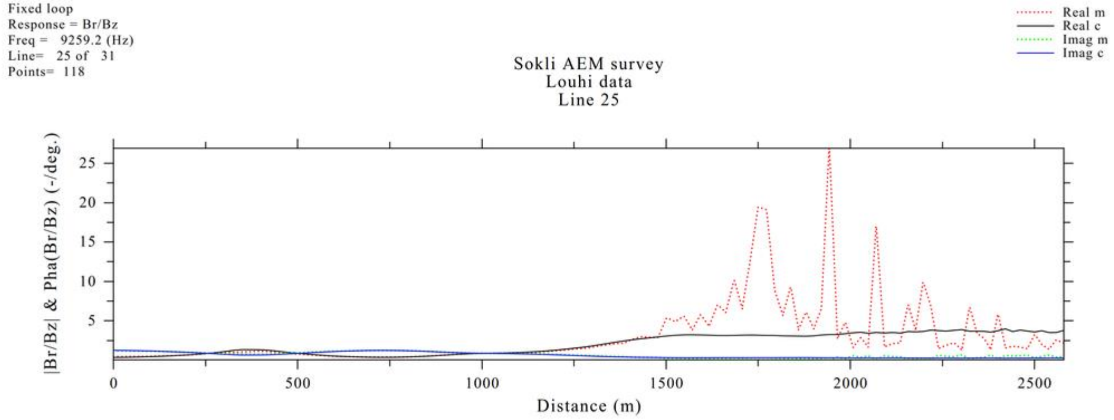
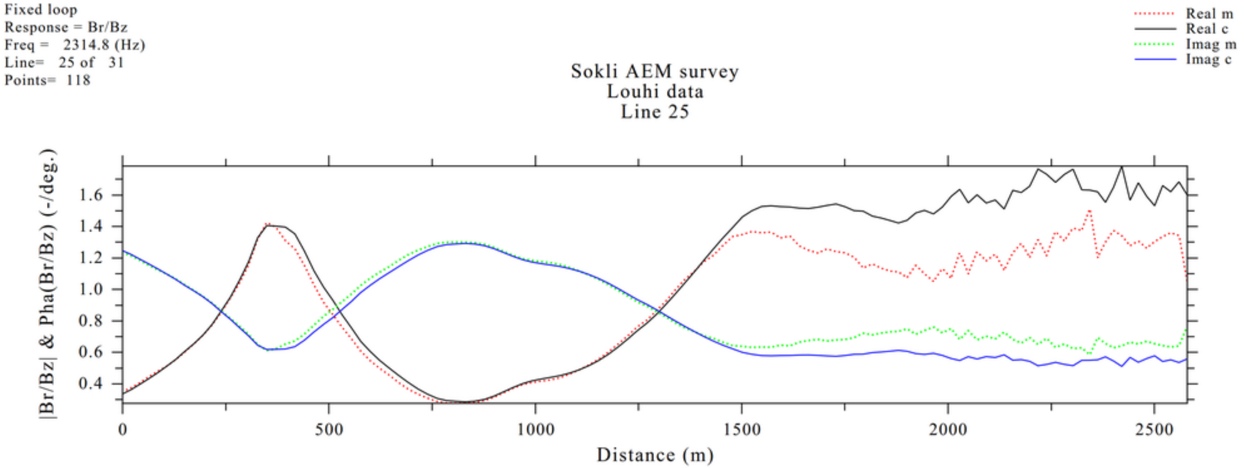
Sokli EM survey: Data fit example, Line #25

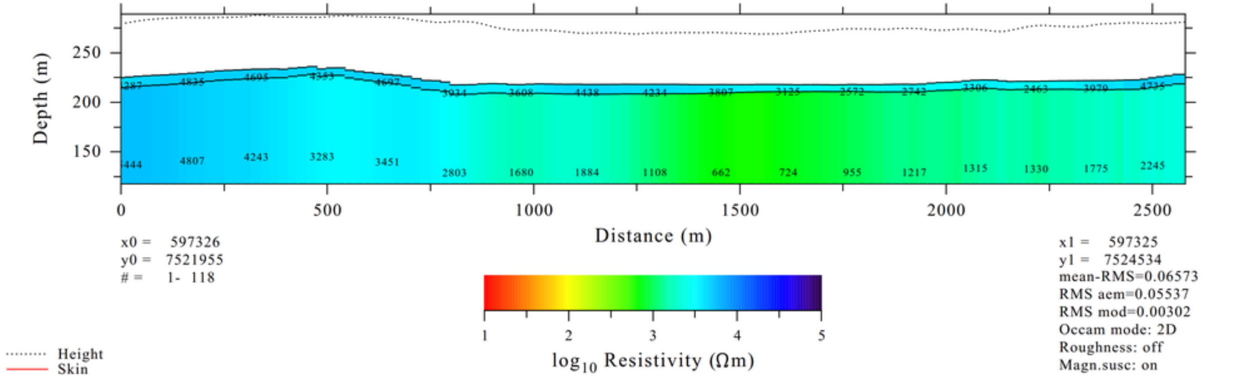
4 kHz & 9 kHz





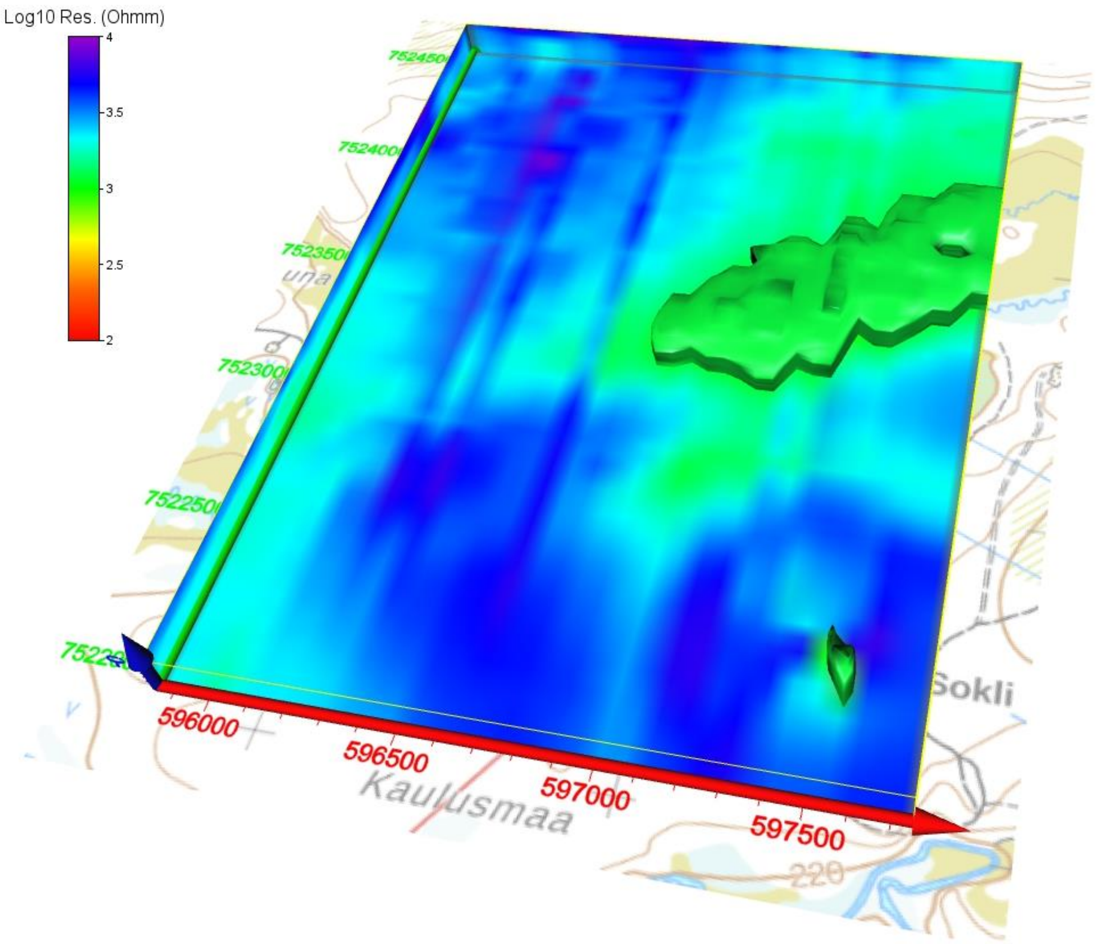
2 kHz & pseudo-section





Sokli EM survey: 3D model from 2-layer inversion

- The results from 1D inversion can be shown as a 3D resistivity mesh
- Important: 1D inversion of fixed loop data is not practical in general!
- That is because any 2D/3D conductivity target alters the EM fields in a manner that 1D model is incapable of modelling



Conclusions & Road ahead

- Fixed-loop (frequency-domain) EM system
  - Single drone (Slingram) system in 2024
- Three simultaneous frequencies (2,4 & 9 kHz)
  - Different set of frequencies for different applications
  - 2-3 different receivers in 2025?
- 1D combined inversion of AEM and magnetic data
  - Approximate 3D piece-wise layer model in 2024
- Louhi EM system is still under development
  - More field tests in 2024
  - More about 3D EM modelling and inversion later this afternoon by Dr. Xiao Longying!

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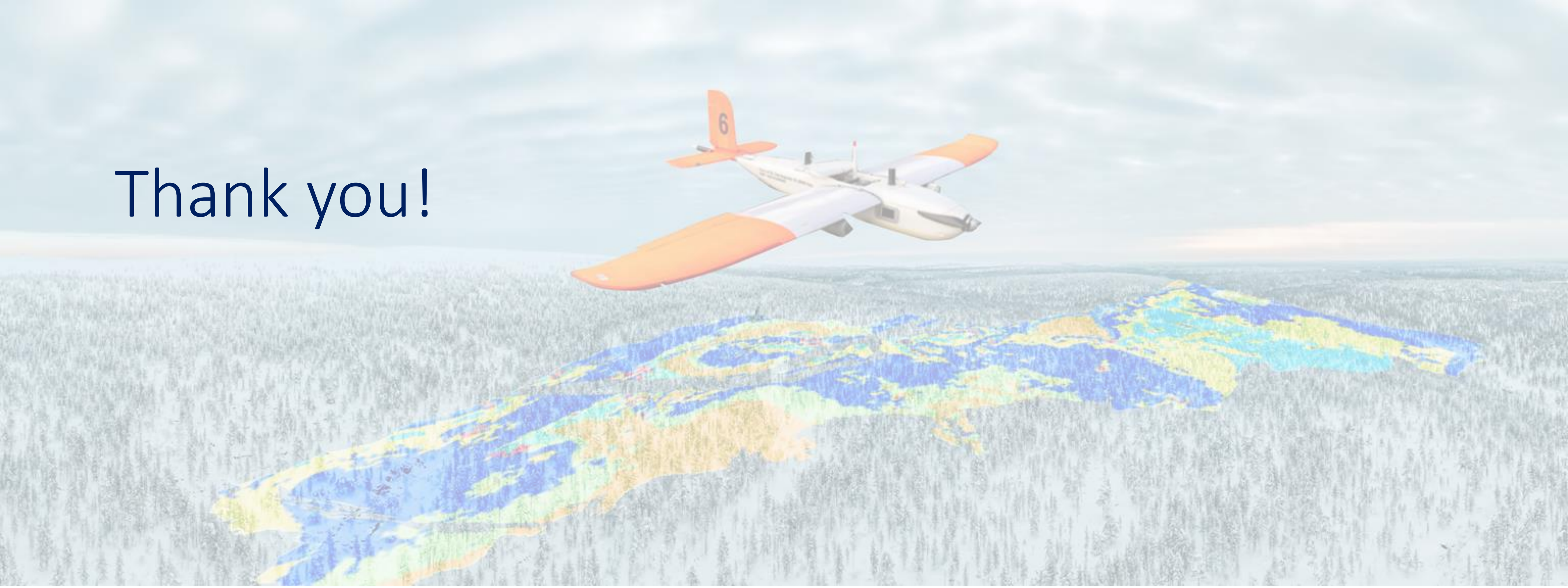

Thank you!

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