Electromagnetic geophysical measurements using SQUID sensors in low noise unshielded environment

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Plan of talk

1. **Introduction to TDEM/TEM technique**
2. **Multi-loop SQUID sensors and laboratory characterization**
3. **Experiments within the DAE campus**
4. **Field experiment outside campus**
5. **Challenges yet to be overcome**

Exploration of conductive targets

Electrical Conductivity
(mineral, groundwater, UXO, archaeological objects)

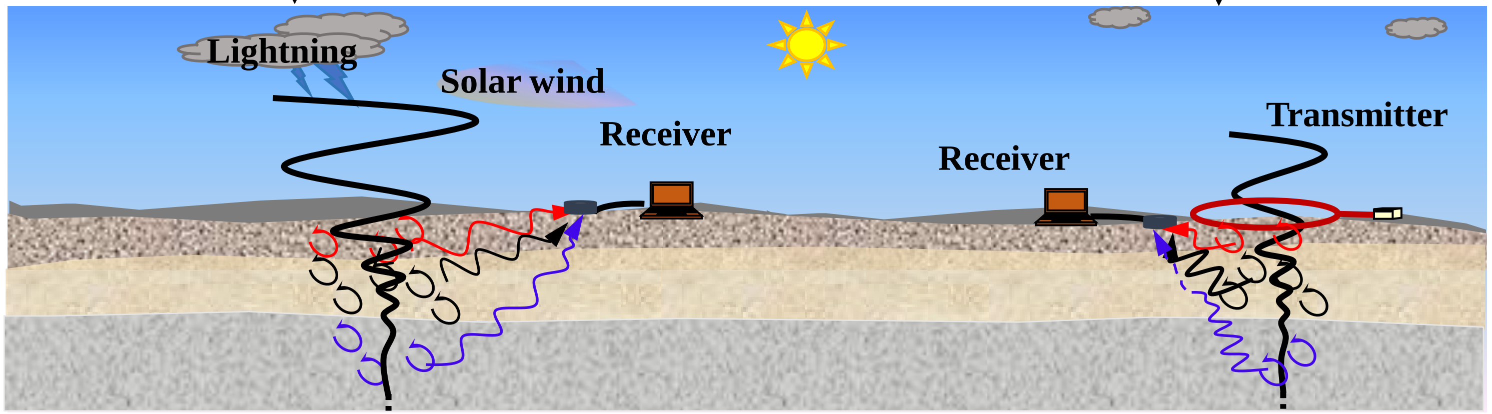
PASSIVE

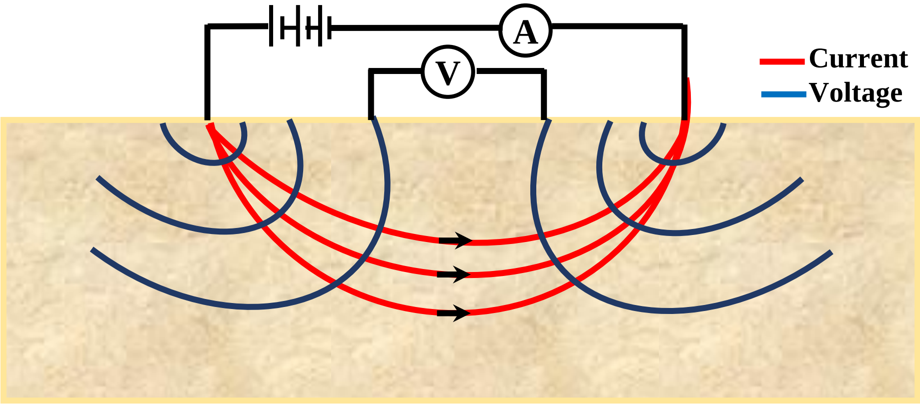
ACTIVE

Magnetotelluric
(uncontrolled)

FDEM/TDEM (controlled)

DC resistivity
(controlled)

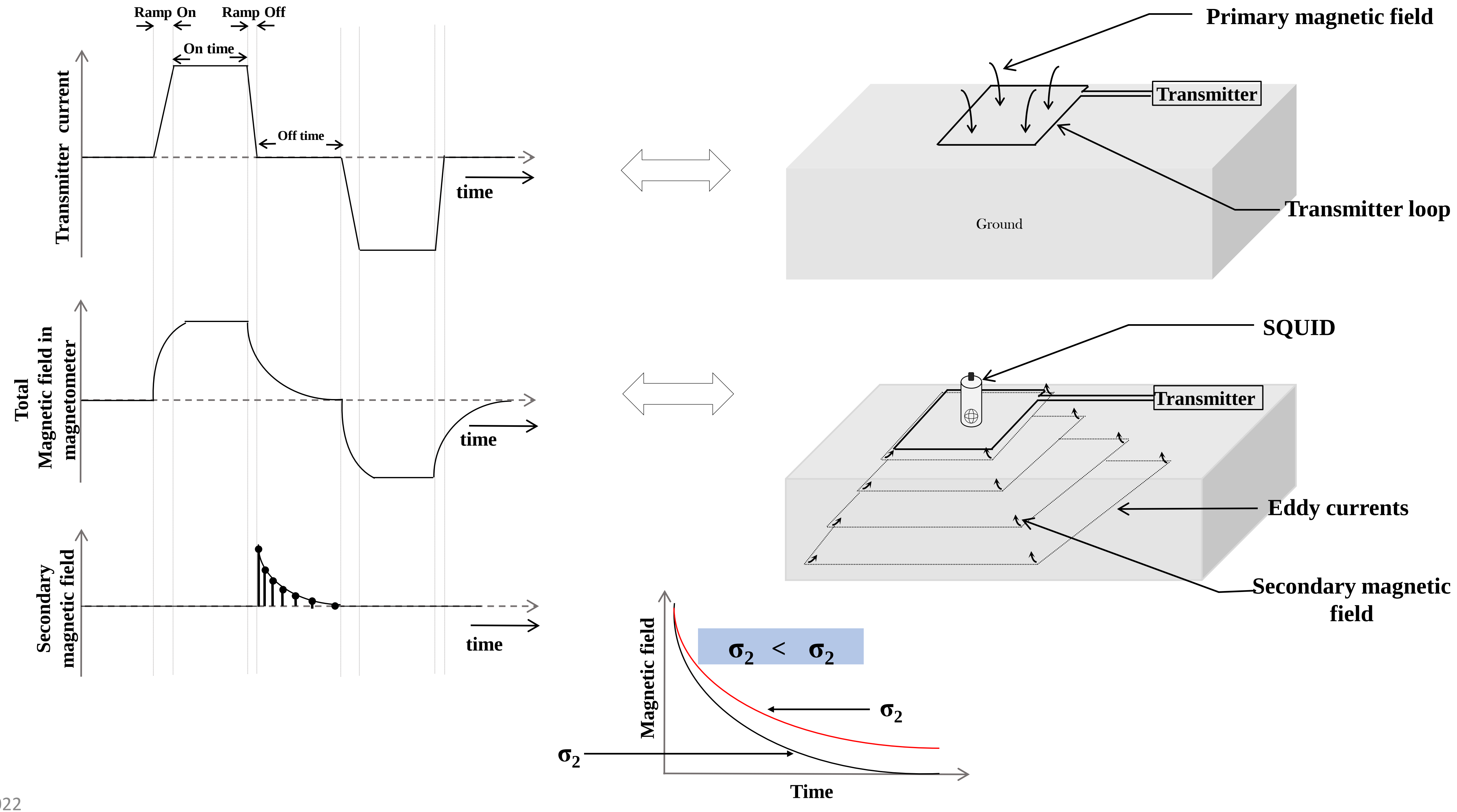




Static shift due to near-surface resistivity close to receiver cause false interpretation of conductivity-depth.

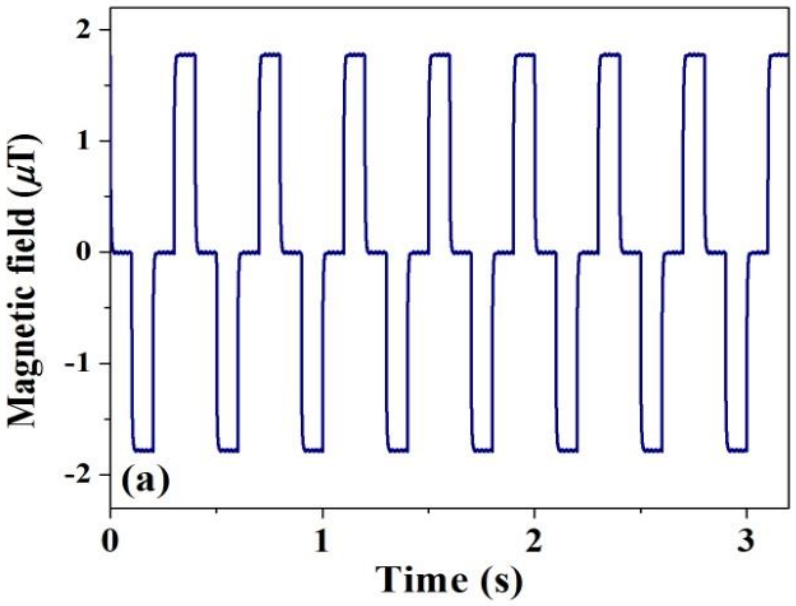
Transmission of current difficult in resistive terrains and measurements are also highly affected by lateral variations

Transient electromagnetic geophysical exploration

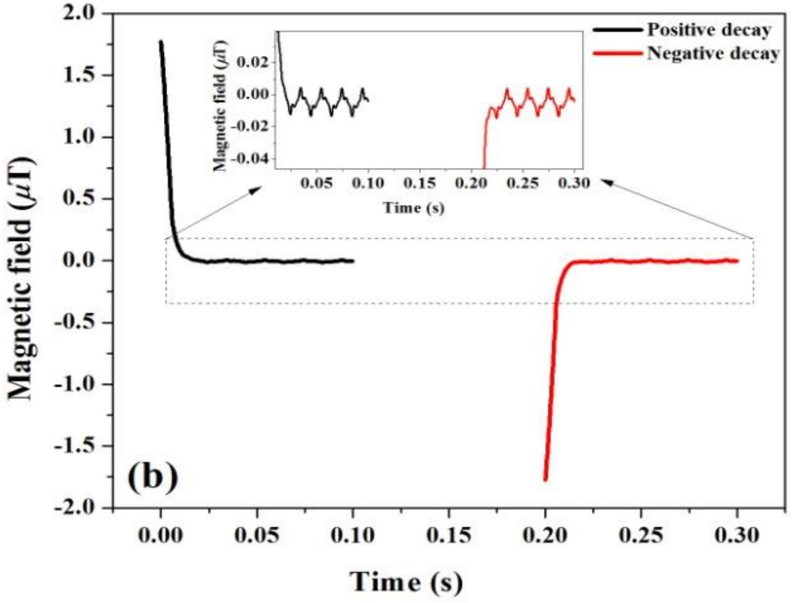


Example of data processing in the TDEM technique

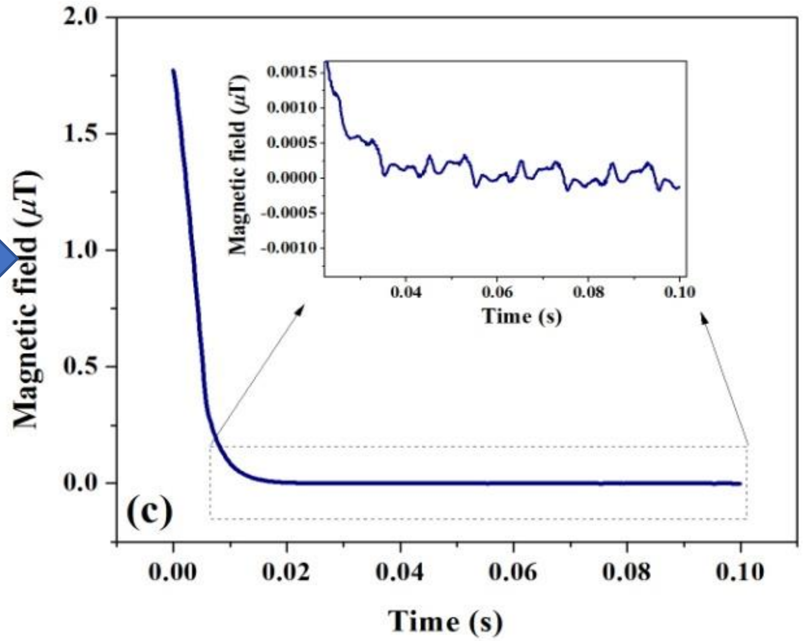
Raw data with 8 stacks



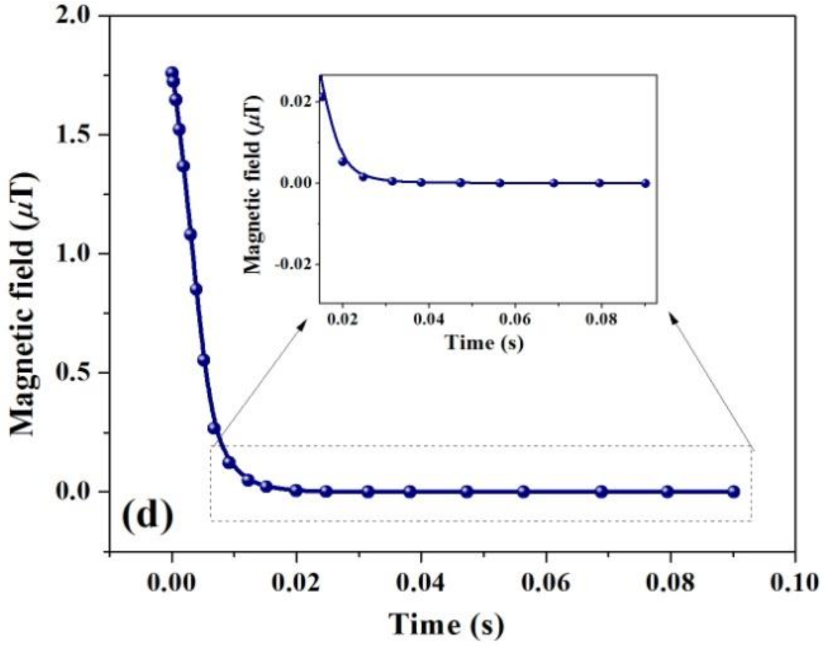
Averaging of transients



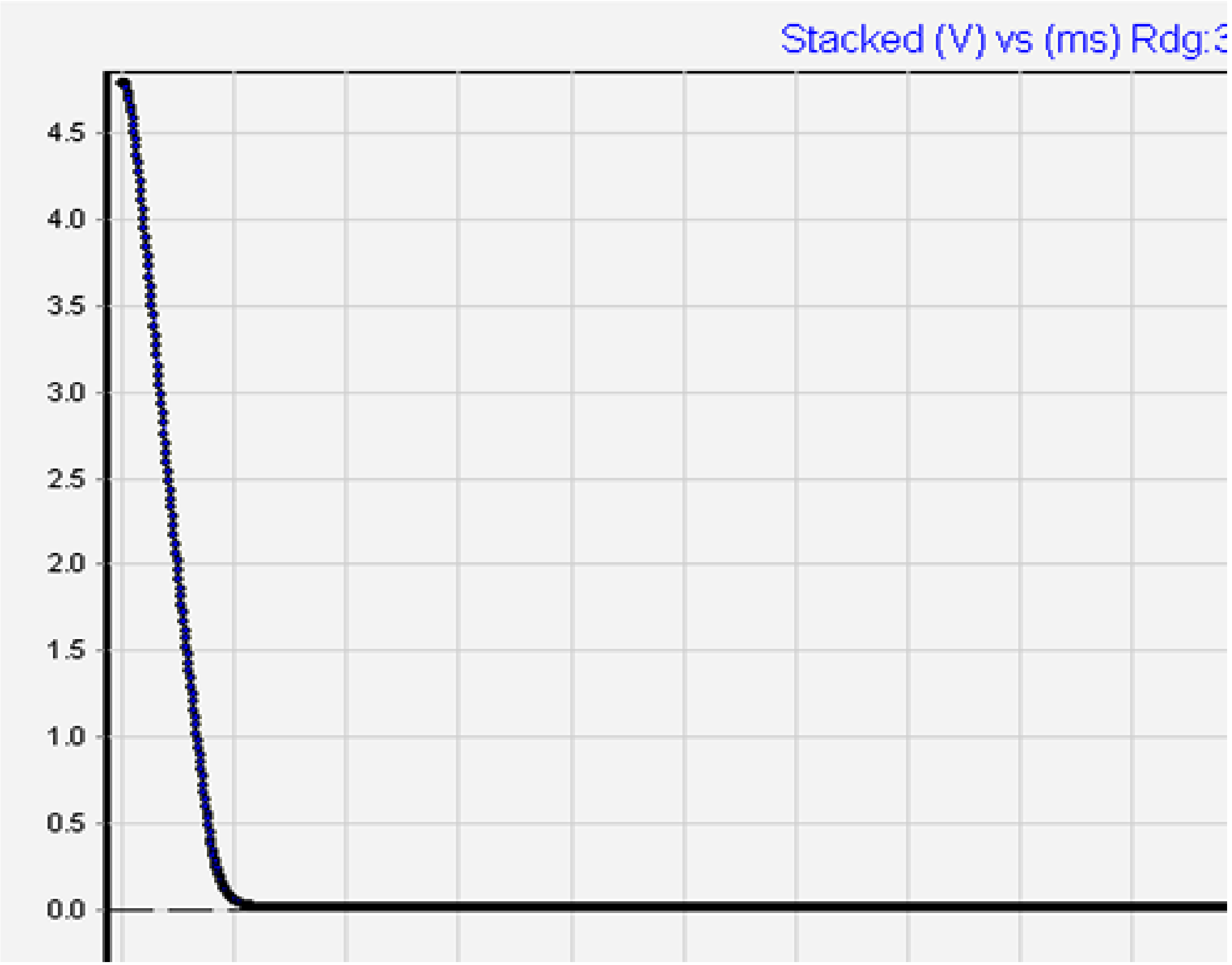
Inversion and averaging

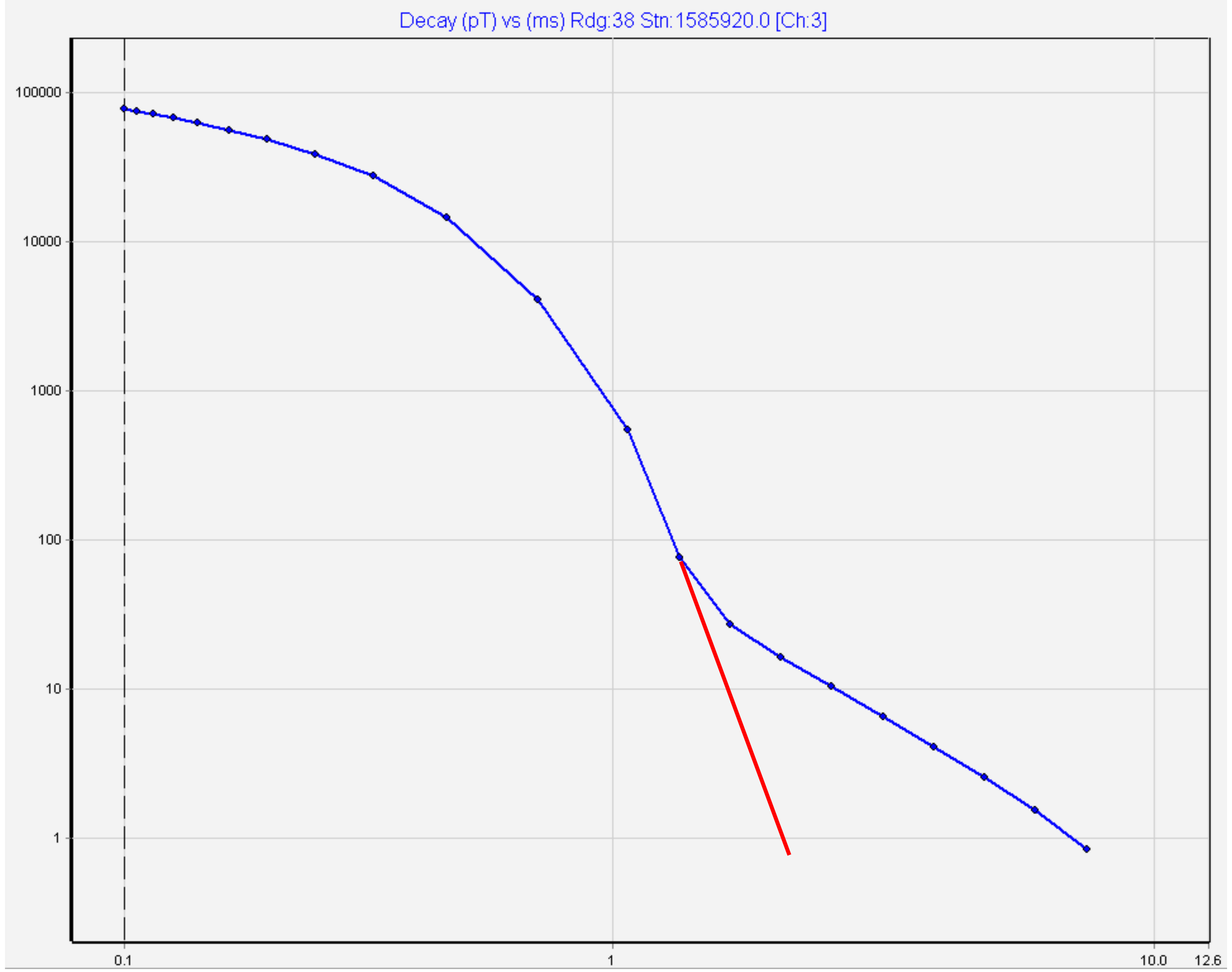


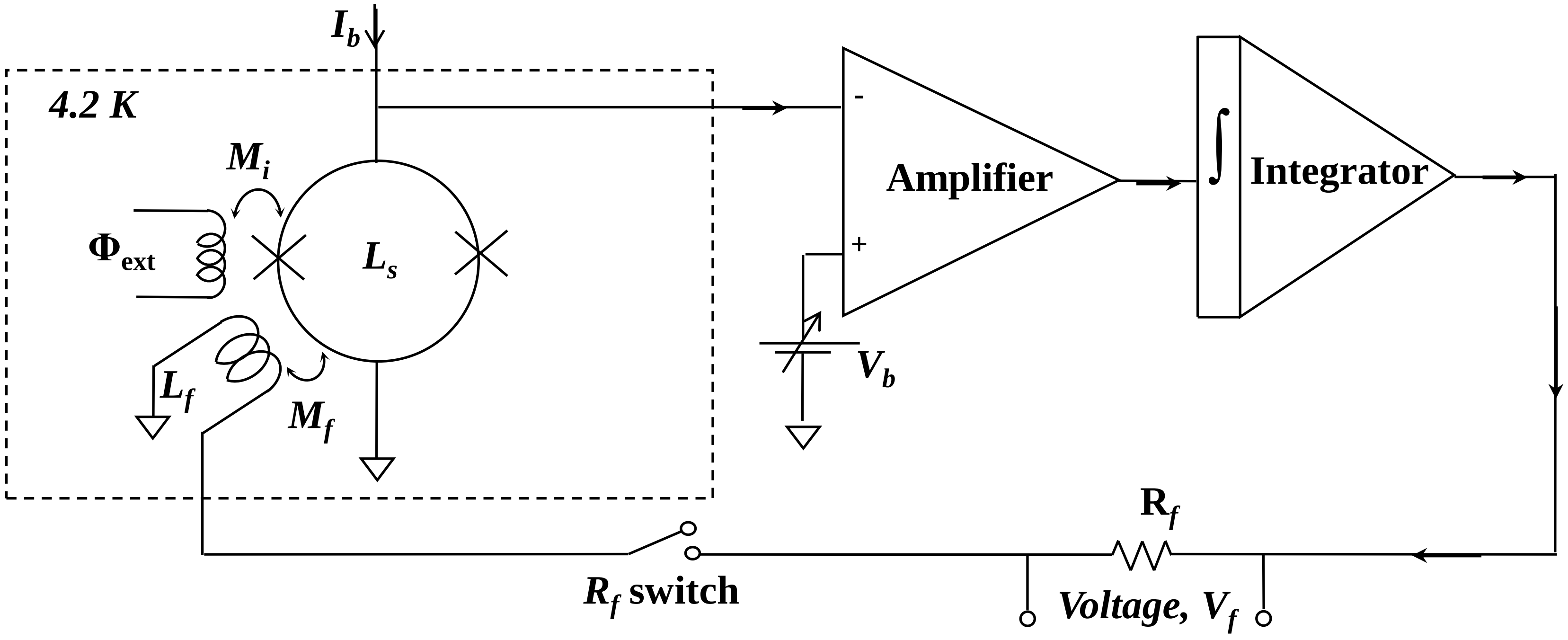
Final decay

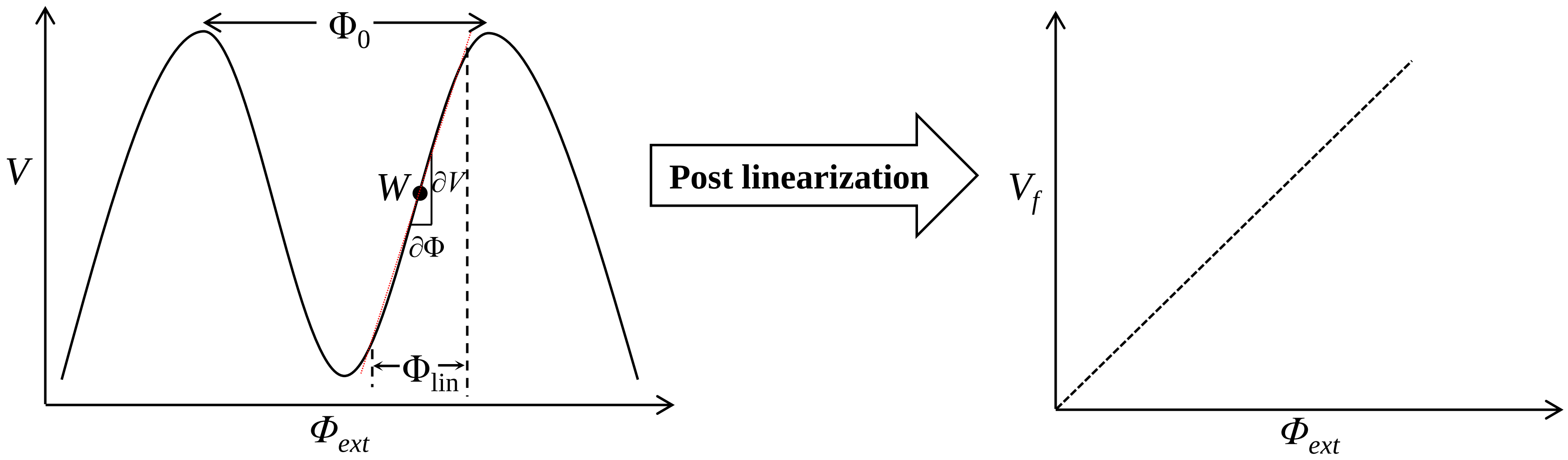


Processed magnetic field decay plots-linear and logarithmic scales



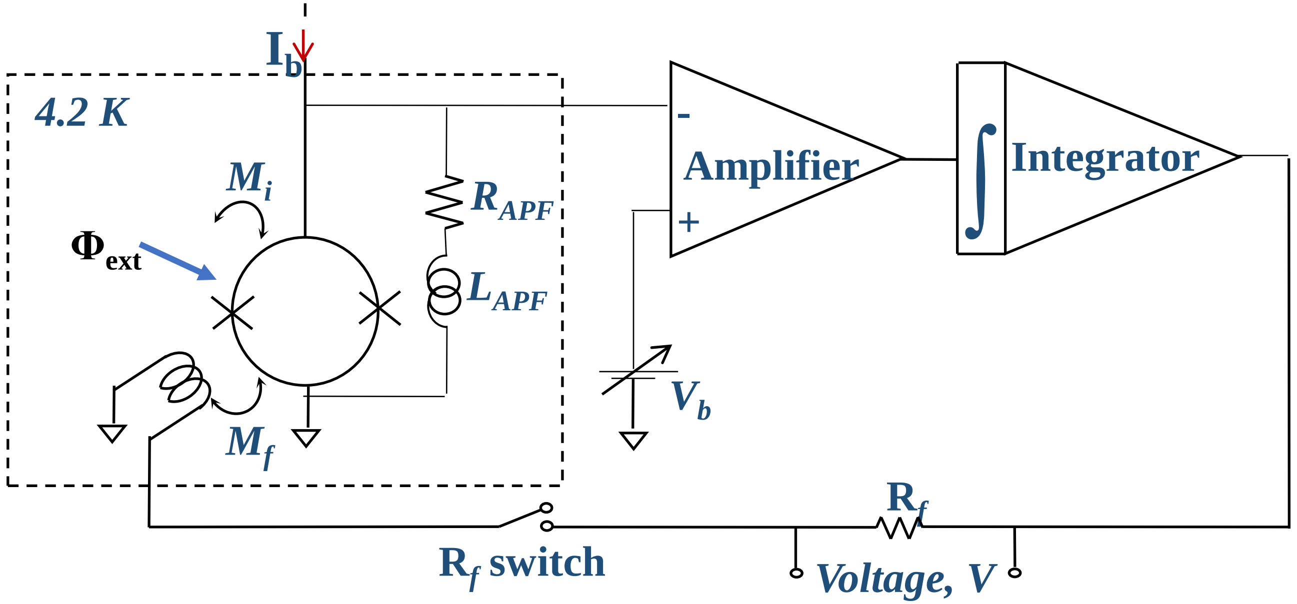




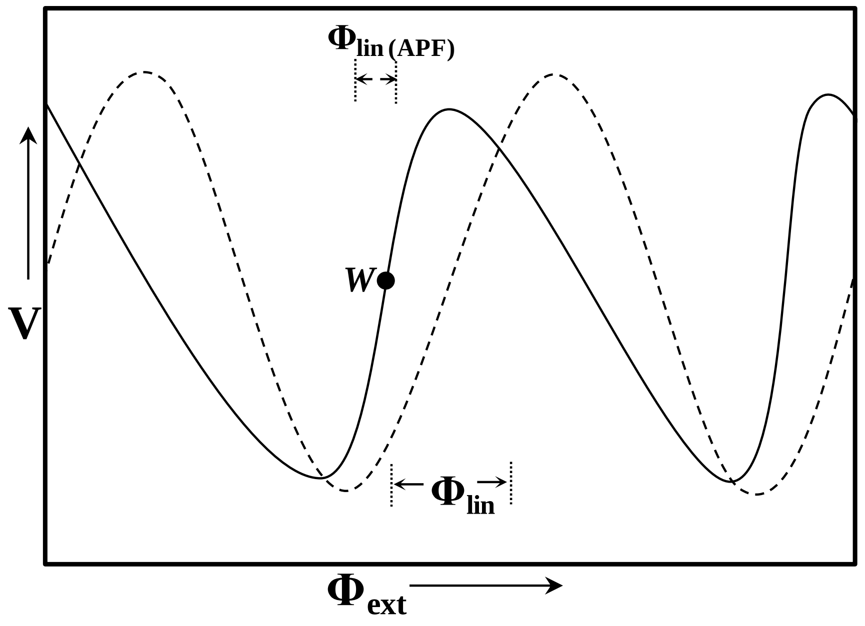


$1\ \Phi_0 = 2.07 \times 10^{-15}$ Wb

Superconducting Quantum Interference Device is a flux-to-voltage transducer.



Circuit diagram showing FLL operation in SQUID with APF scheme.

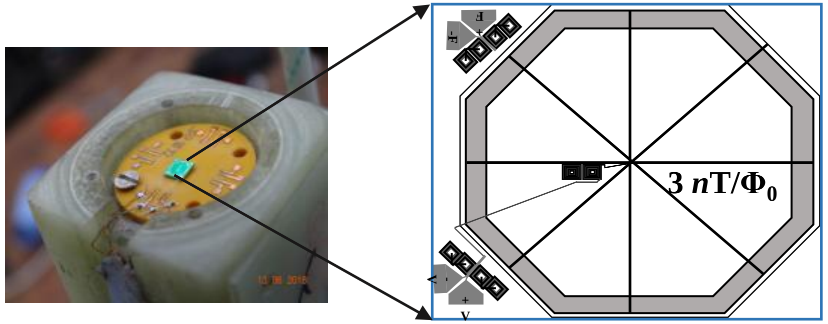


Typical open-loop output of the conventional SQUID (dashed) and the multi-loop SQUID with APF (solid)

ADVANTAGES

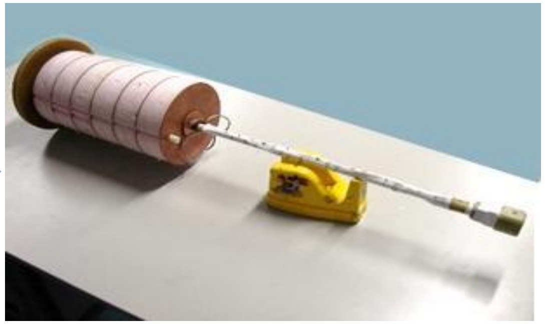
- higher effective area
- enhanced flux-to-voltage transfer coefficient $(\partial V/\partial\Phi)_{I_b}$
- higher slew rate

Characterization of the sensor in Magnetic shielded room



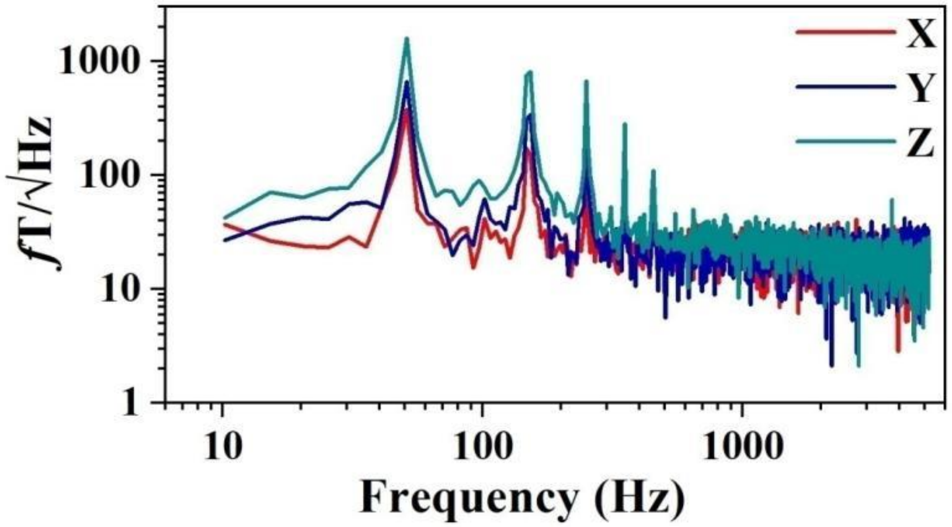
SQUID magnetometer from Magnicon

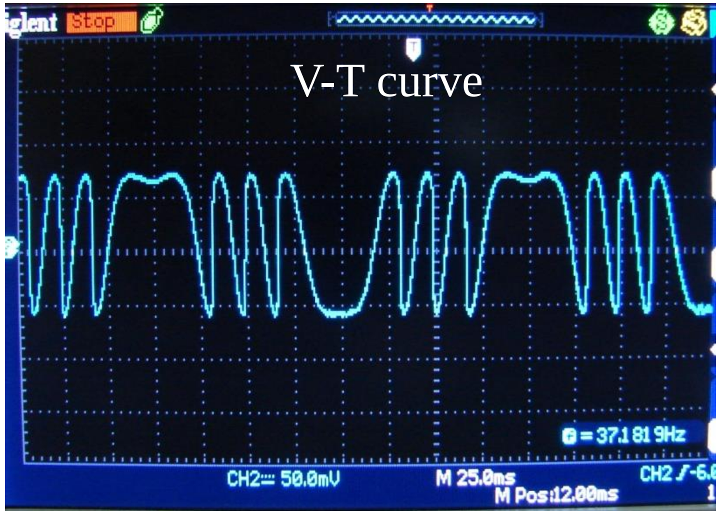
3 SQUIDs mounted on FRP in 3 orthogonal directions

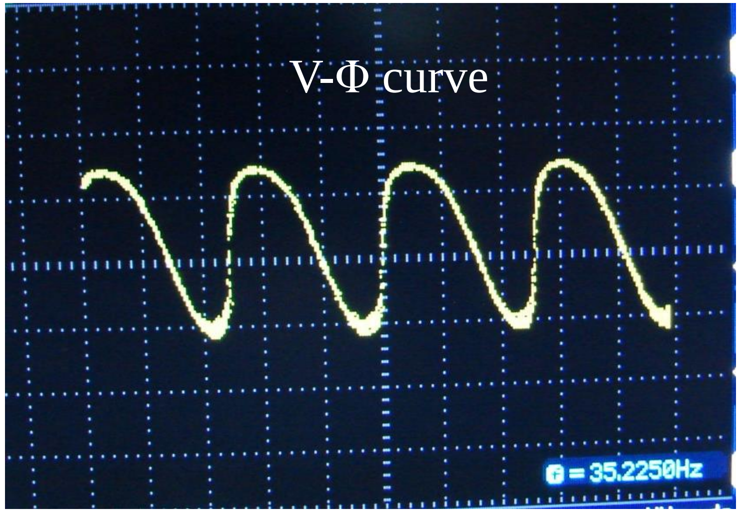


SQUID probe

Cryostat with the probe inserted

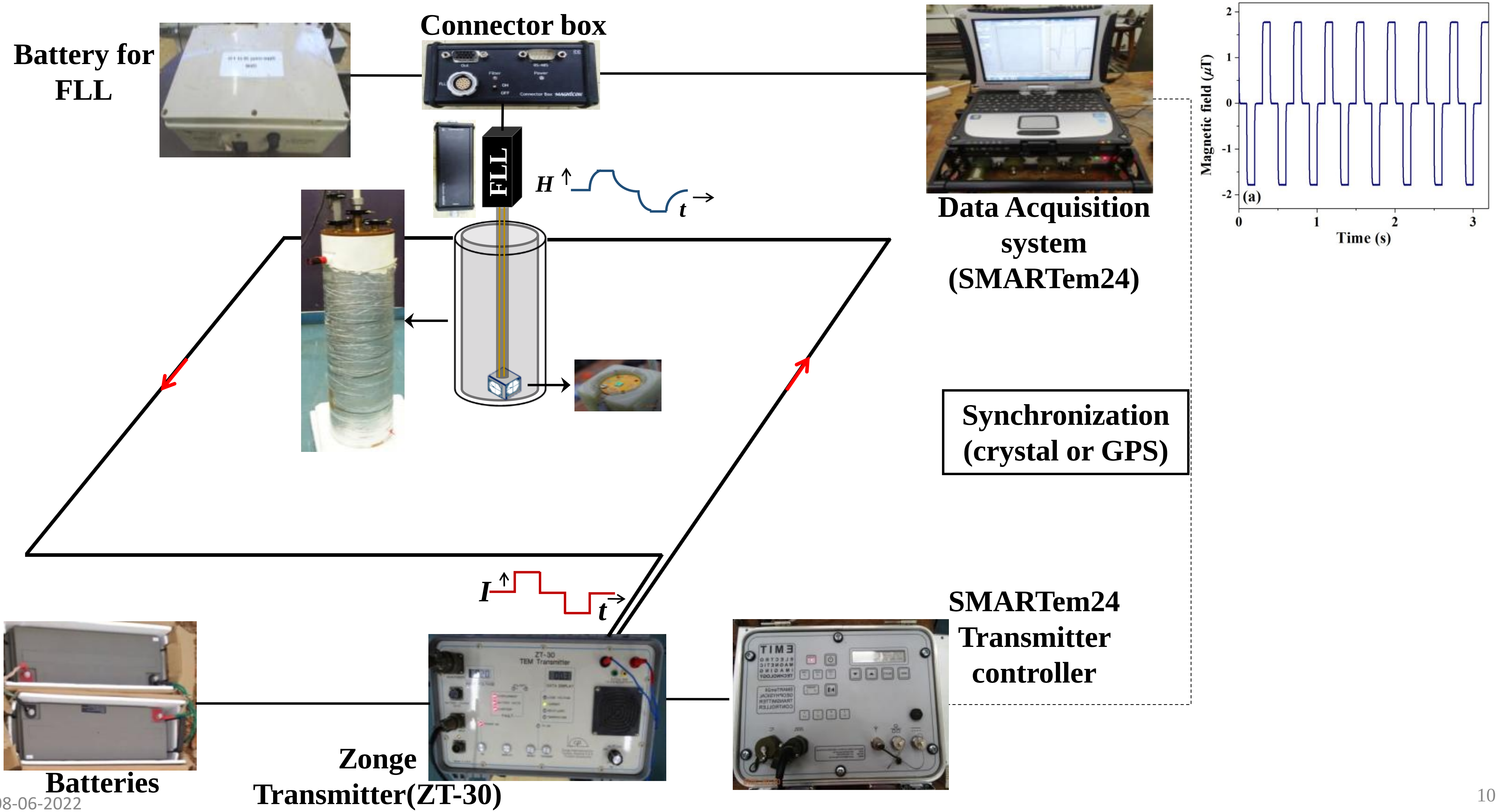




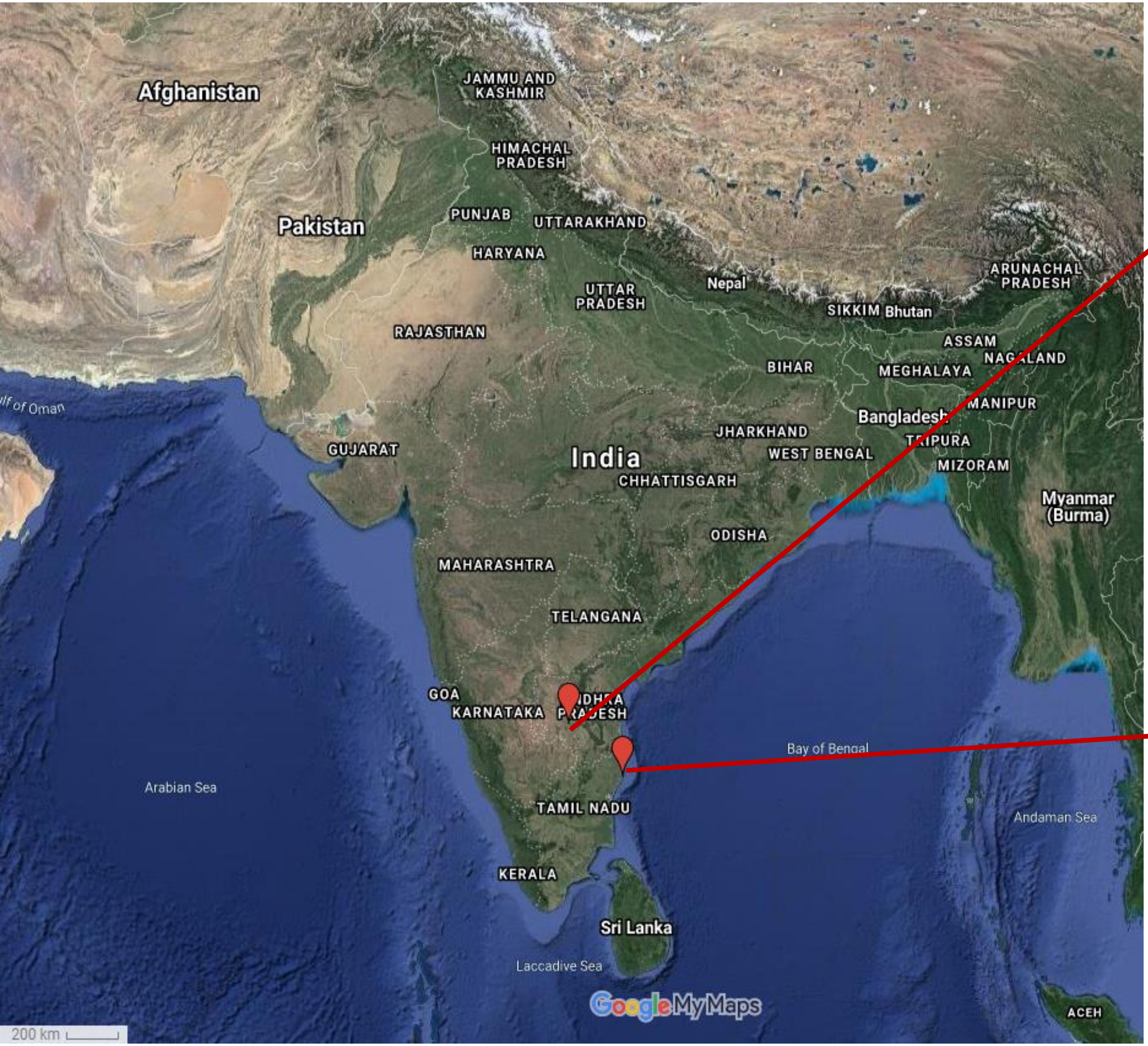


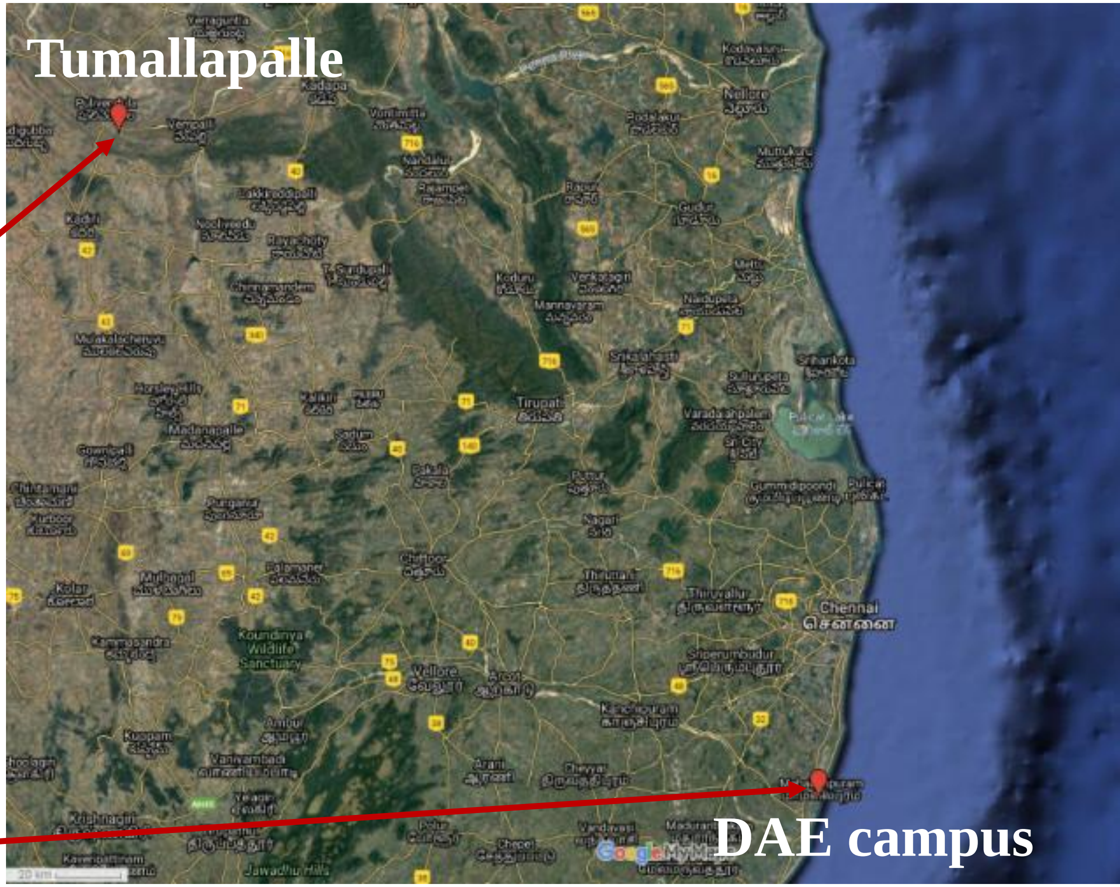
- Inverse effective area : 3nT/Φ_0
- Slew rate: 3 mT/s or 10^6 Φ_0/s at R_f = 10 kΩ
- Spectral density of the field noise in the white noise regime : 25 fT/√Hz

Central loop TDEM experimental setup

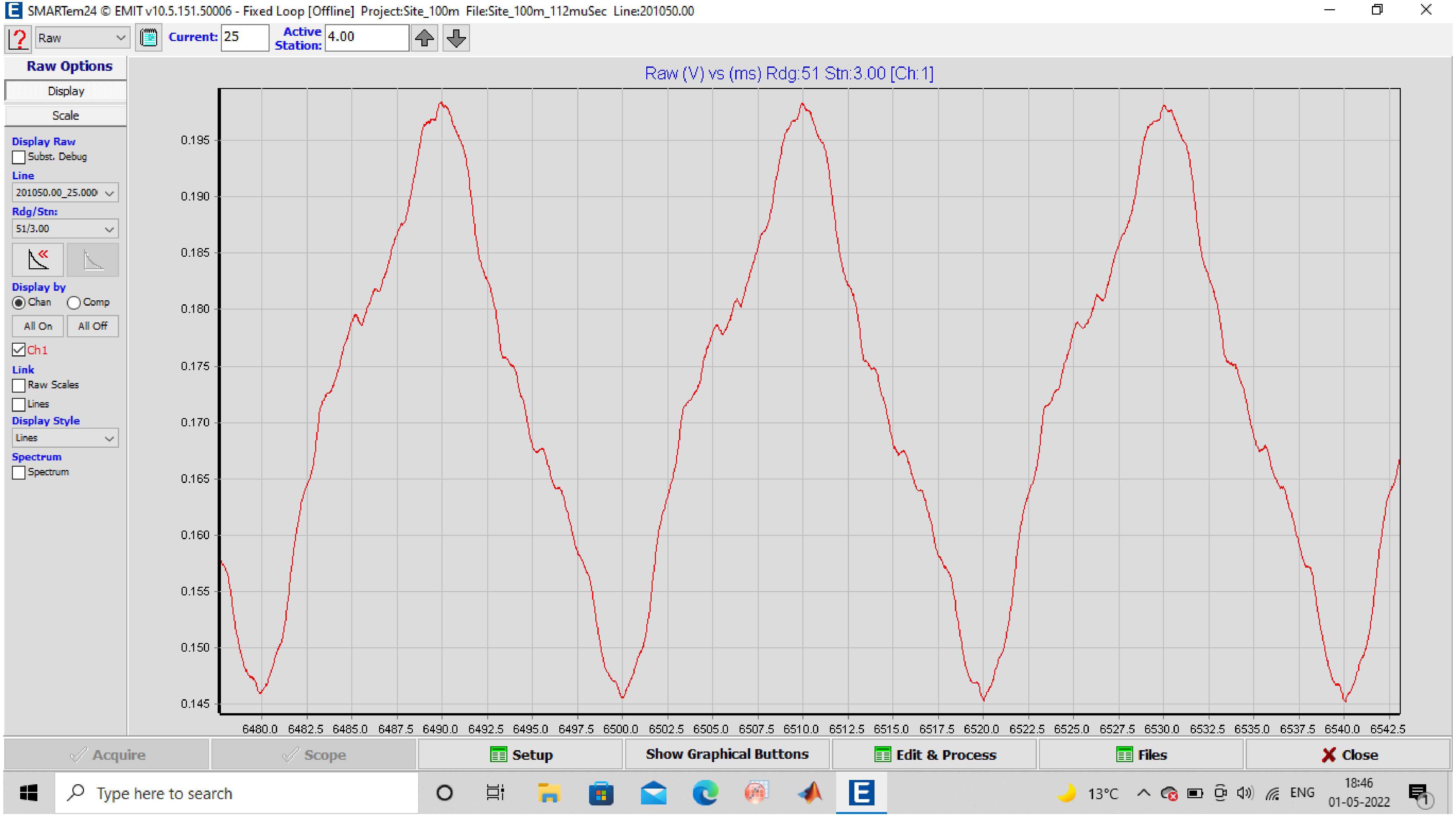


Two sites where TDEM sounding were performed



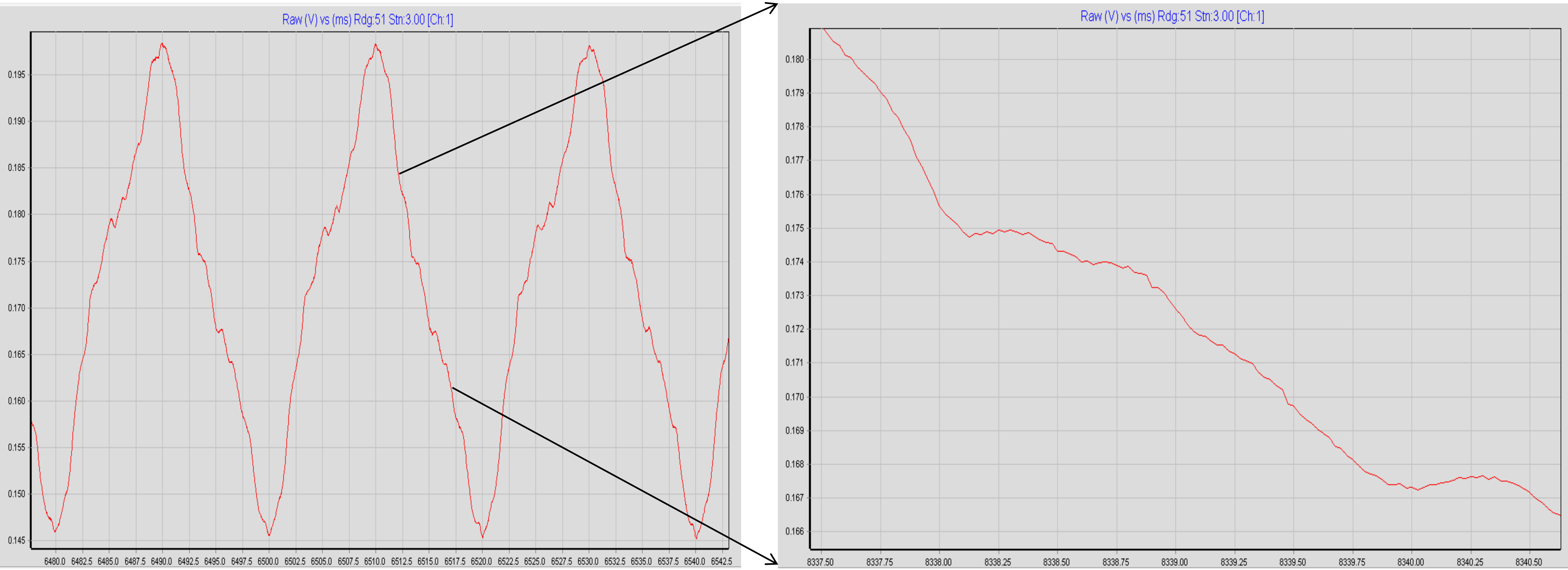


Powerline noise of 50 Hz in time domain DAE campus



Strength of the 50 Hz ~ 1.05 Φ_0 ~3.15 nT

High frequency background noise

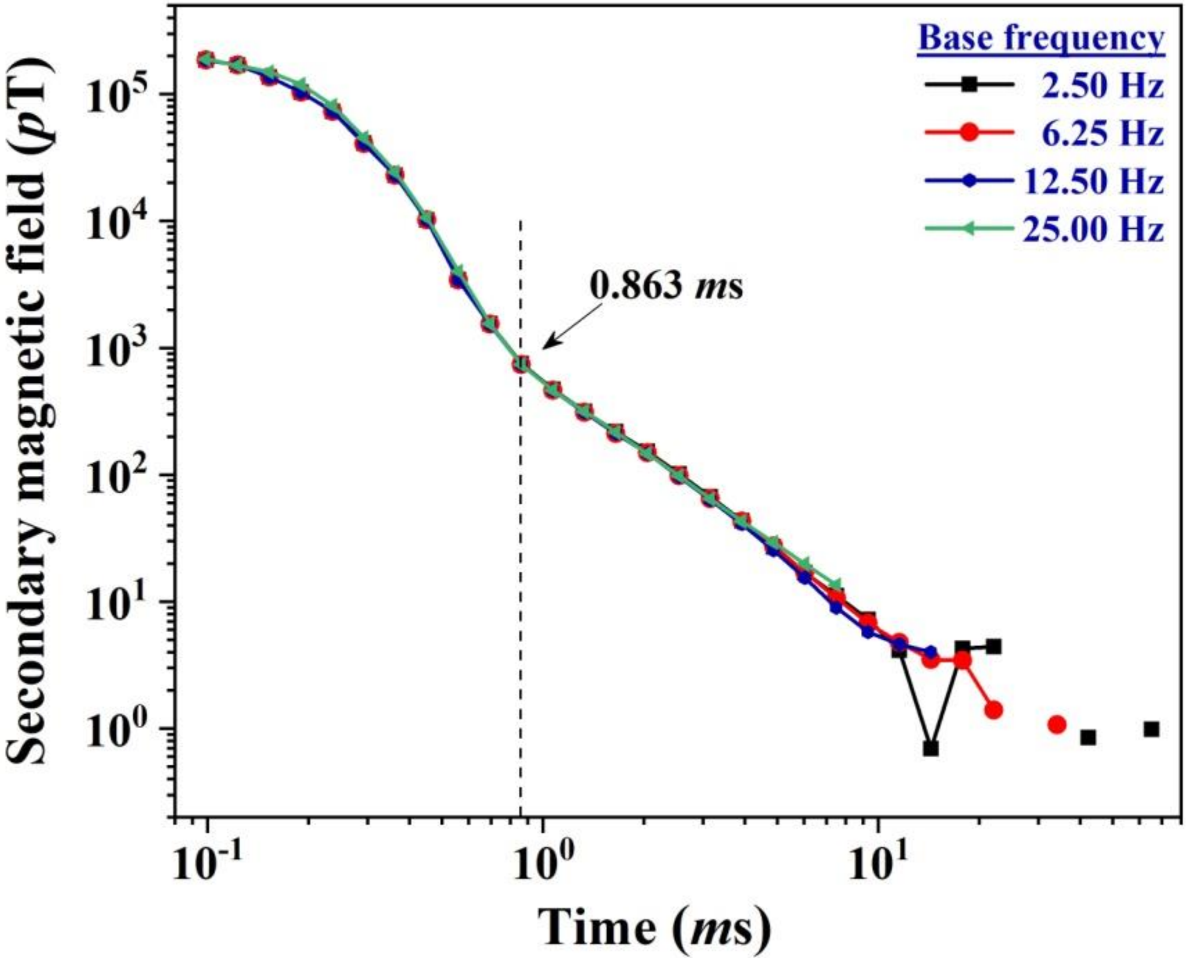


Strength of the 50 Hz ~ 1.05 Φ_0 ~3.15 nT

Predicted high-frequency noise 0.03 Φ_0 ~ 90 pT

Experiments with SQUID at Kalpakkam, Tamil Nadu

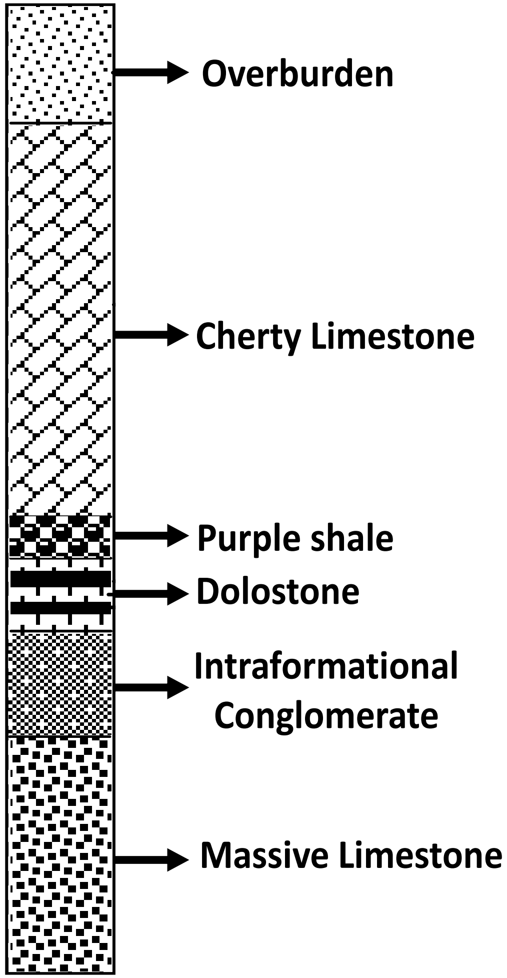
Loop size (m^2)	Resistance (Ω)	No. of 12V batteries used (series)	Current (A)	Central Magnetic field (*n*T)	Magnetic moment(Am^2)
100 X 100	0.6	2	25	283	2.5 X 10^5

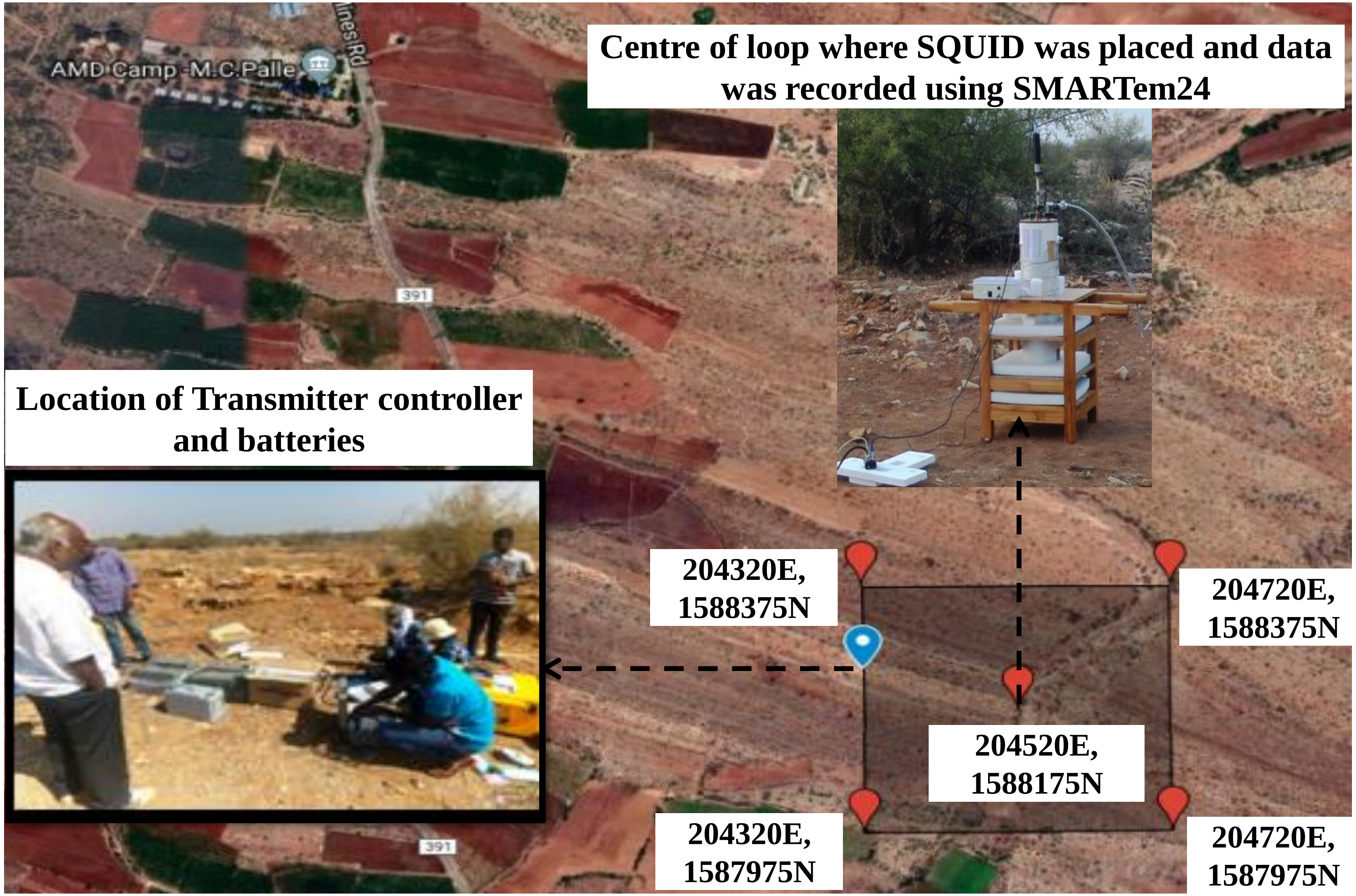


Experiments with SQUID at Tumalapalle, Andhra Pradesh, INDIA

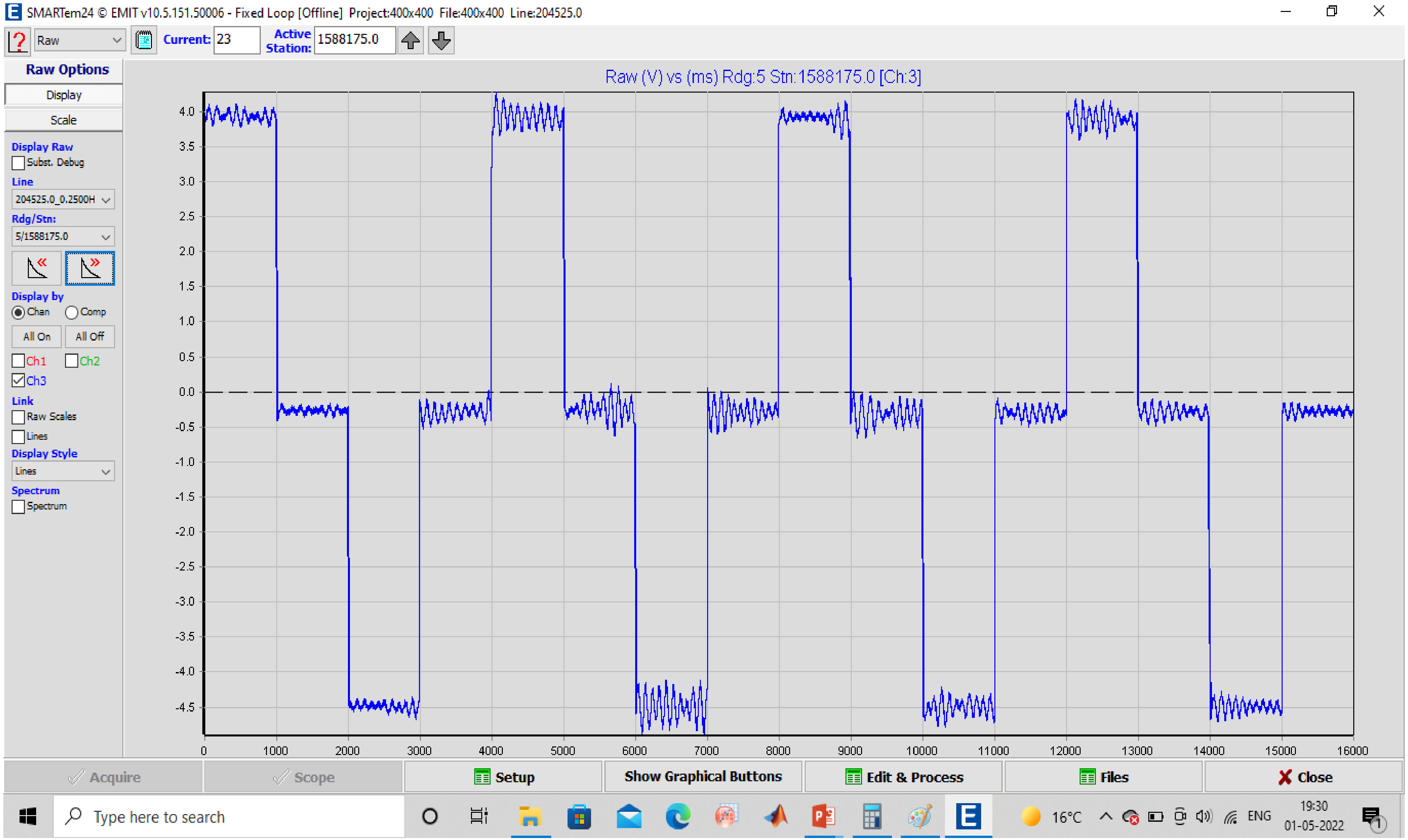
Loop size (m^2)	Resistance (Ω)	Current (A)	Central Magnetic field (*n*T)	Magnetic moment(Am^2)
400 X 400	2.4	27	81	4.32×10^6

Stratigraphy of site 2

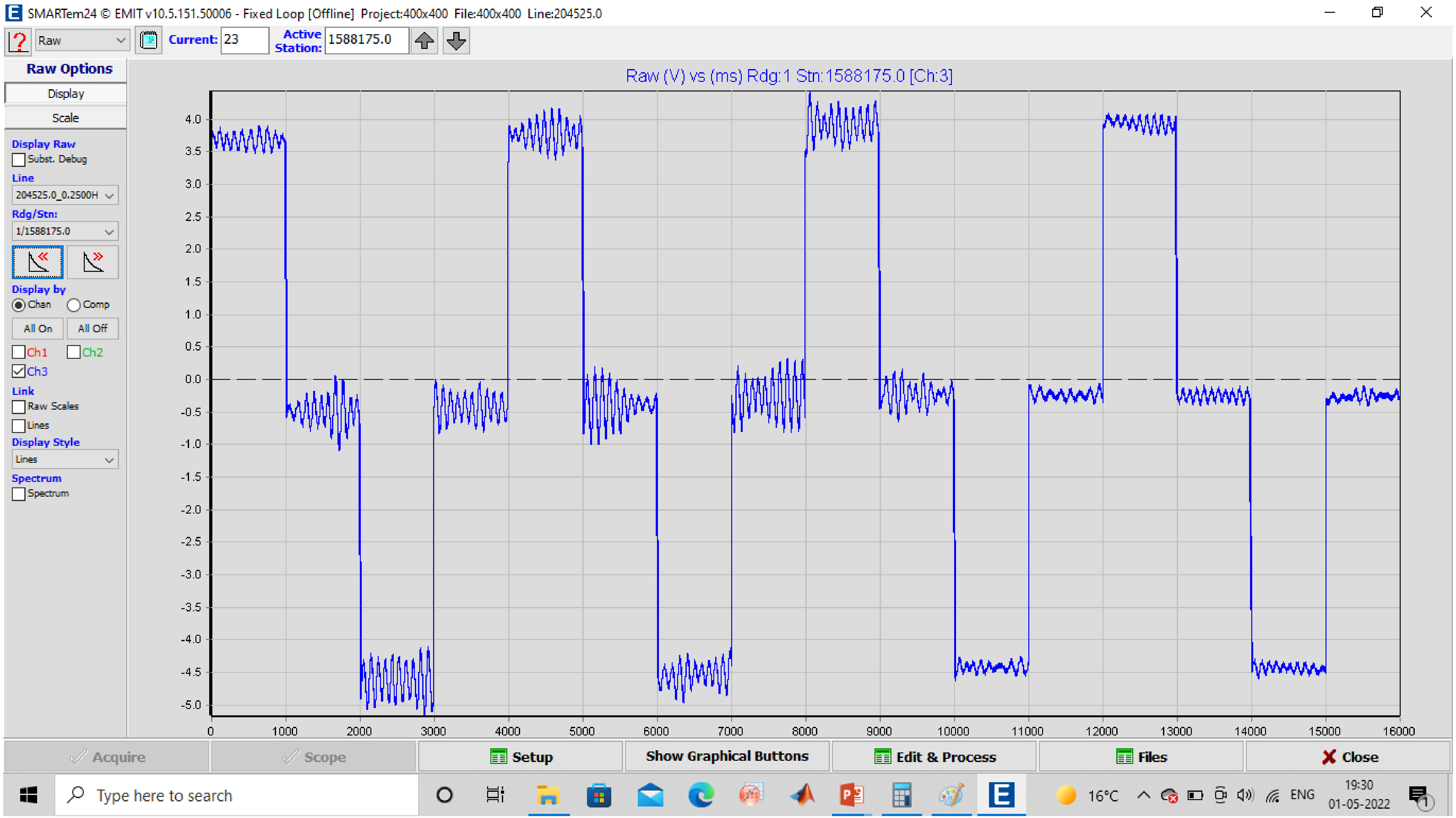




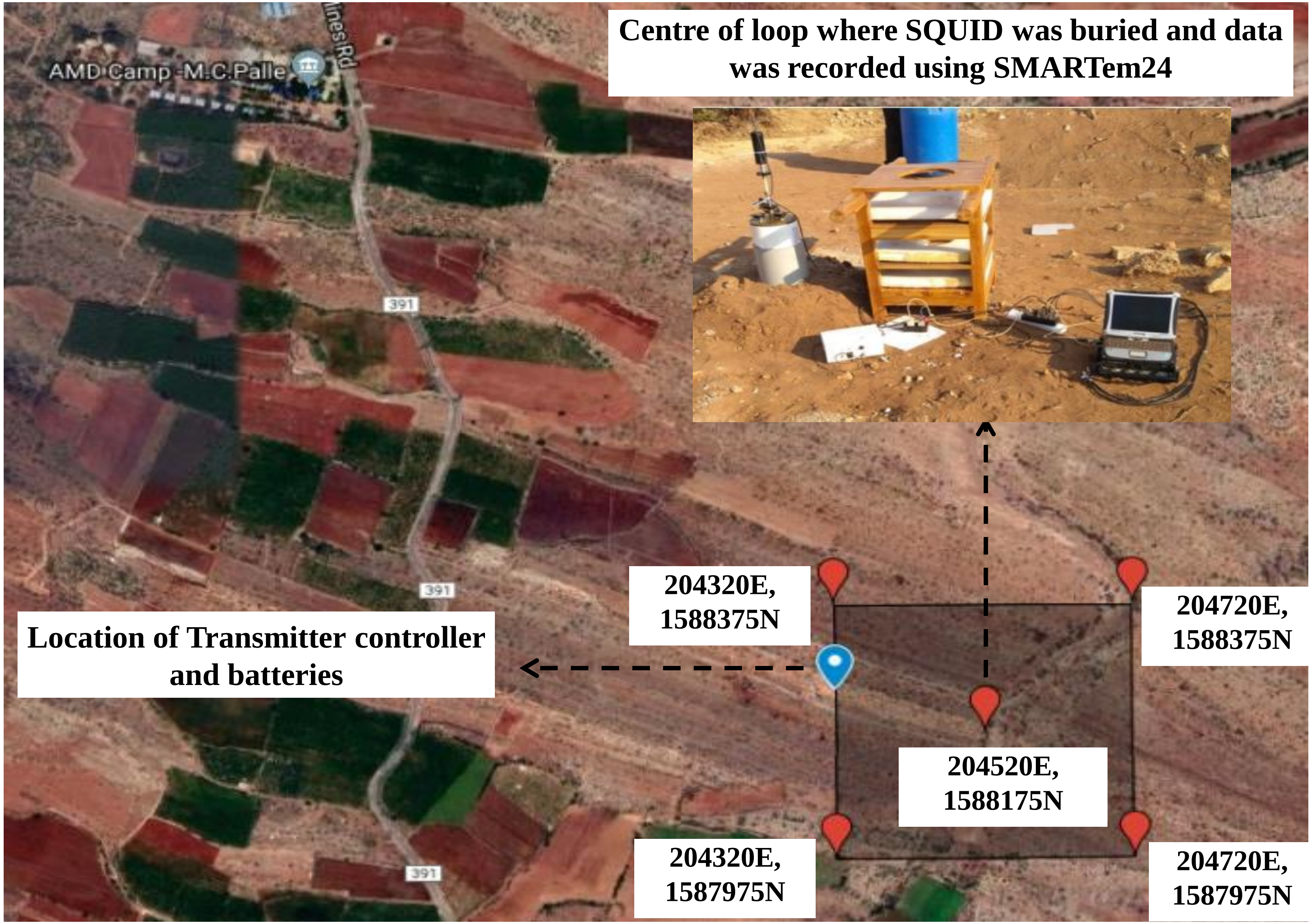
Magnetic field as recorded by the SQUID sensor



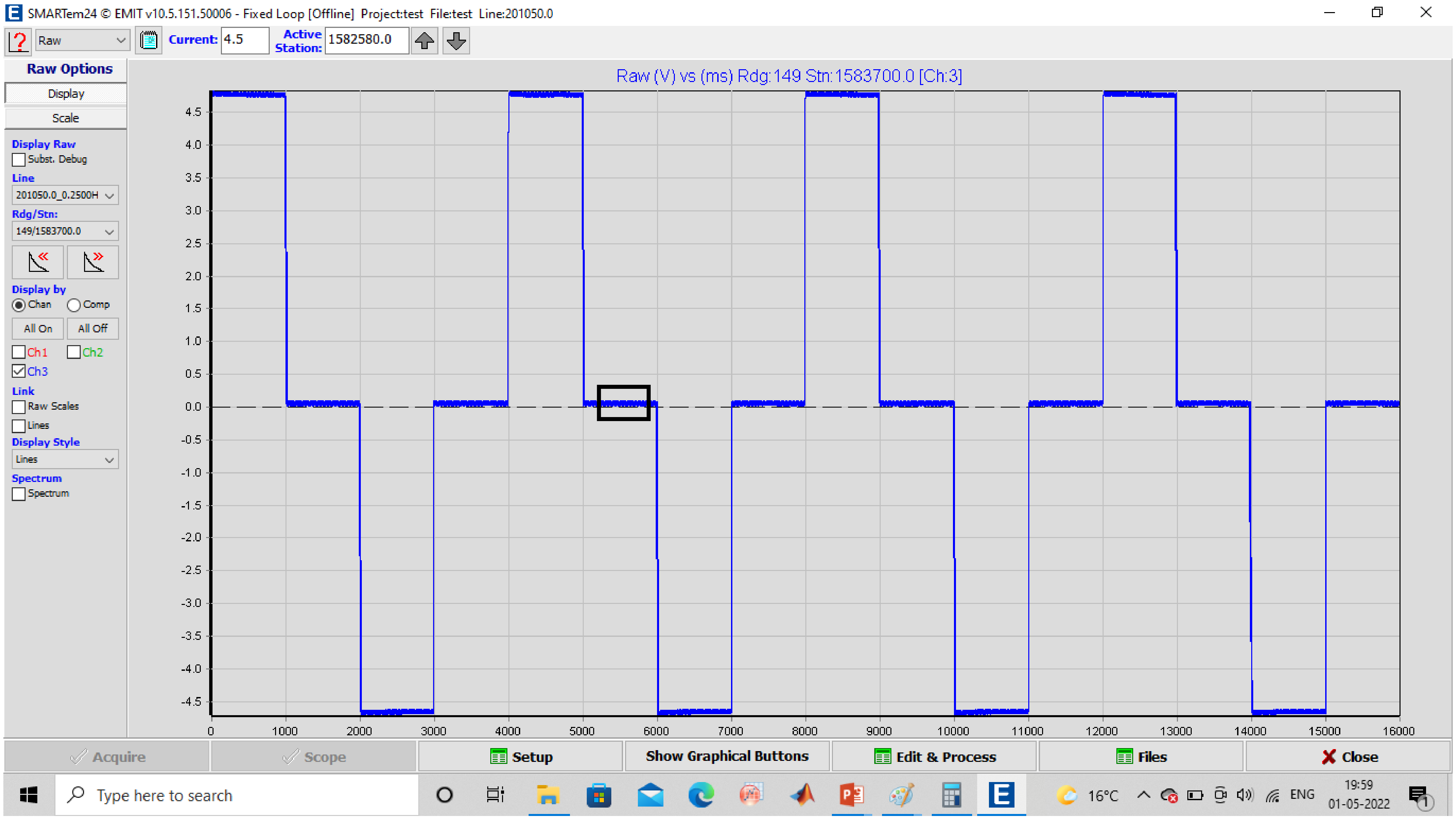
Magnetic field as recorded by the SQUID sensor



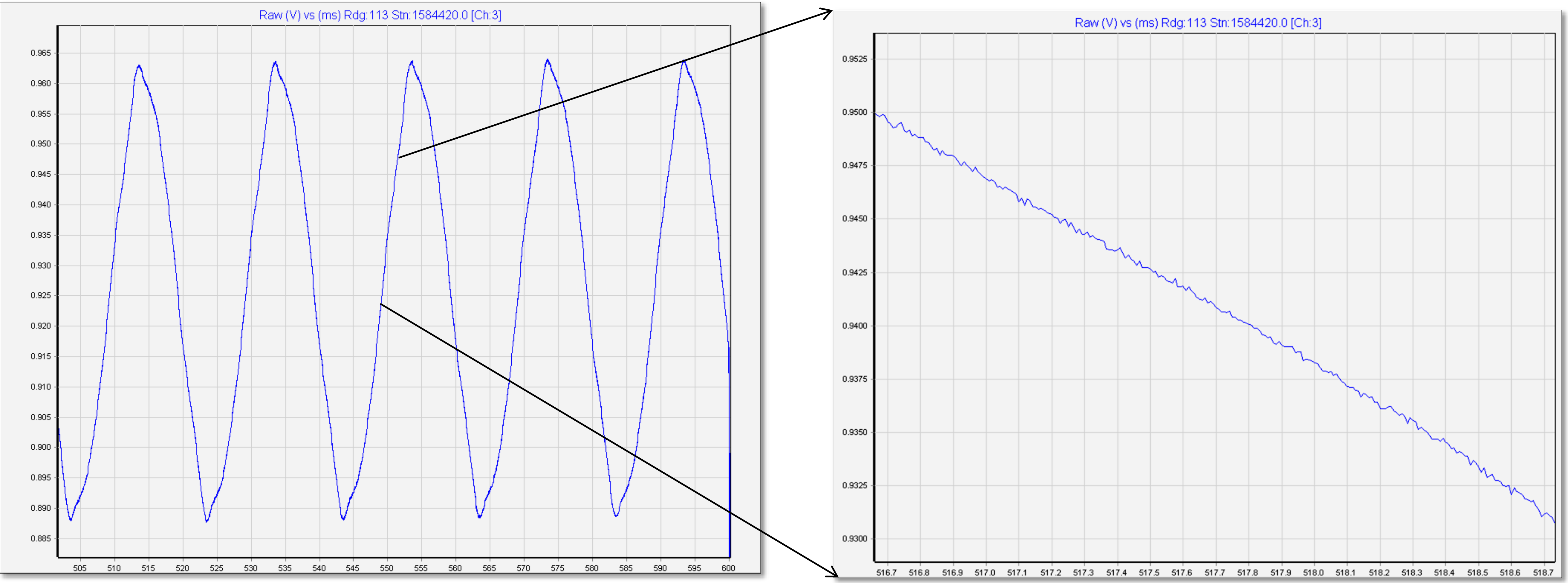
Experiments with SQUID semi-buried



Magnetic field as recorded by the SQUID sensor



High-frequency noise



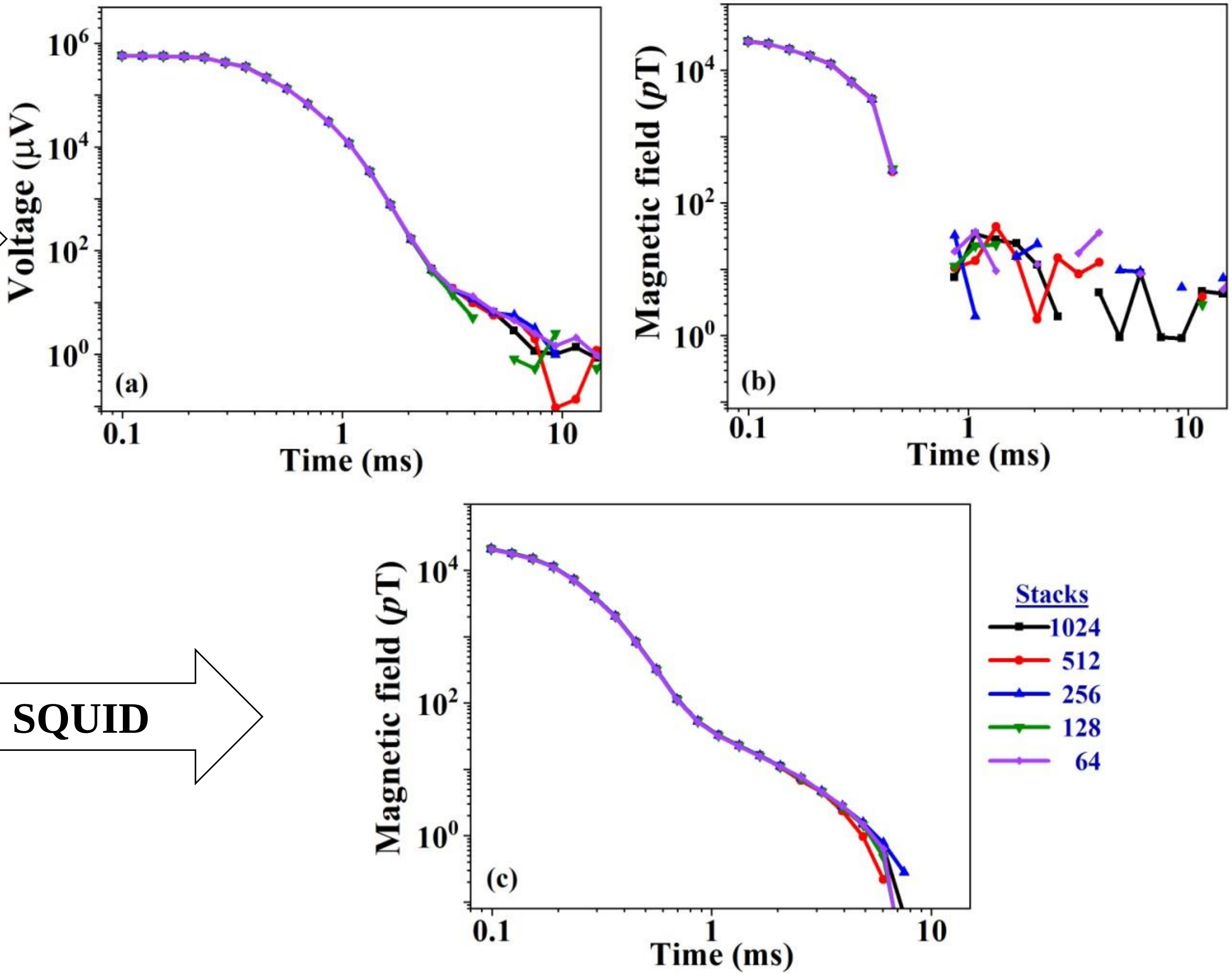
Strength of the 50 Hz ~ 75 *m*V ~ 0.4 Φ_0 ~1.2 *n*T (@ 175 *m*V = 1 Φ_0 = 3 *n*T)

Predicted high-frequency noise 0.0028 Φ_0 ~ 8.4 pT

Decays recorded using coil, fluxgate and SQUID

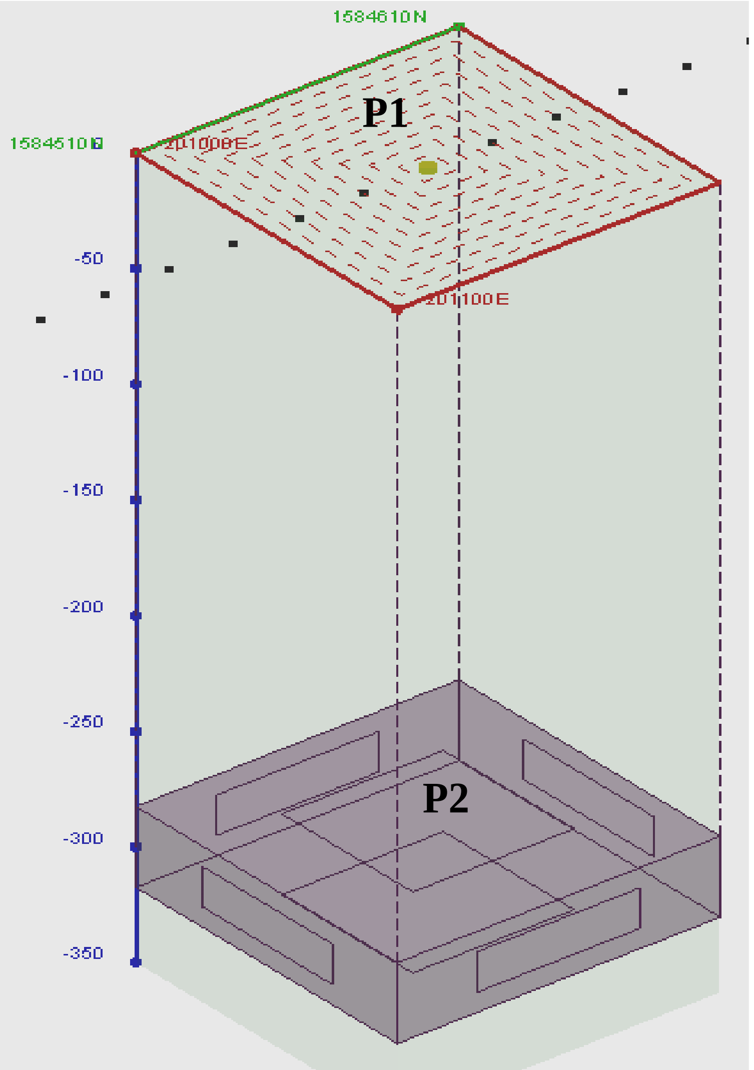
Induction coil

Fluxgate



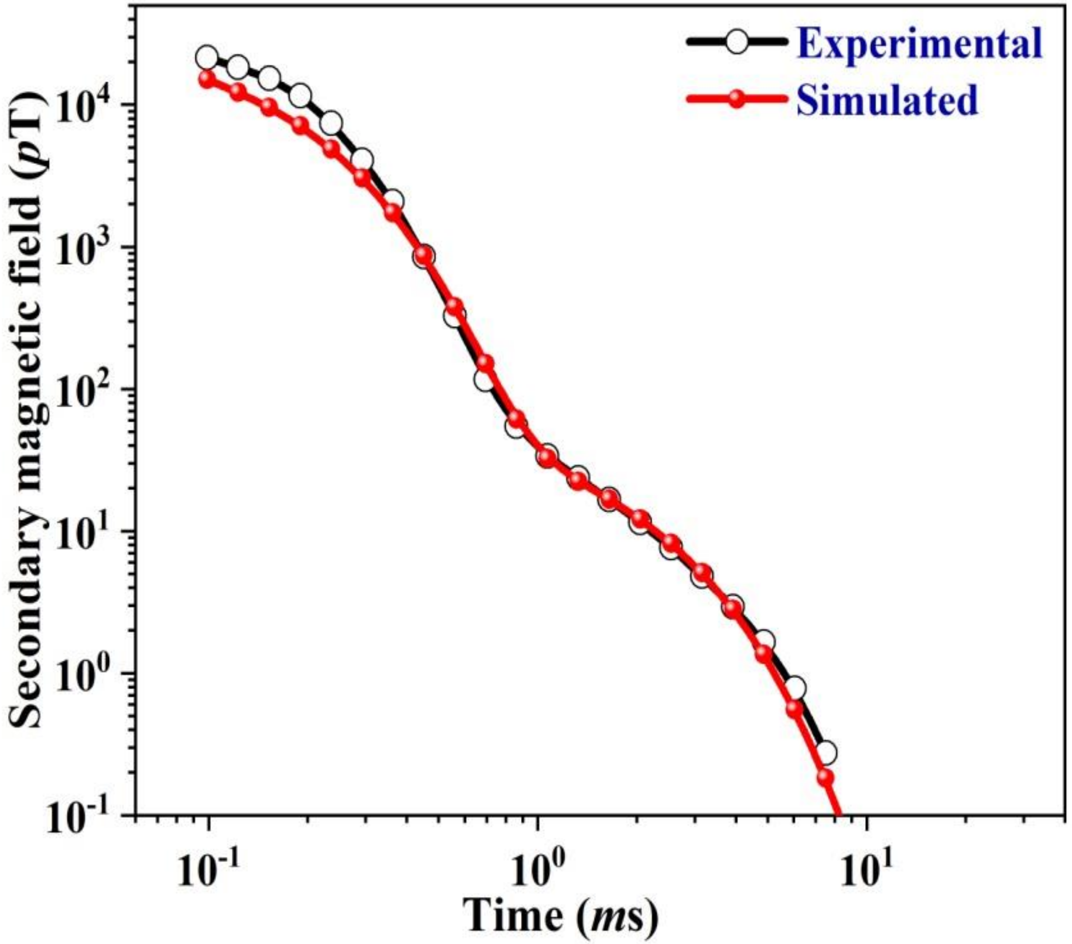
SQUID

A forward model for the TDEM results

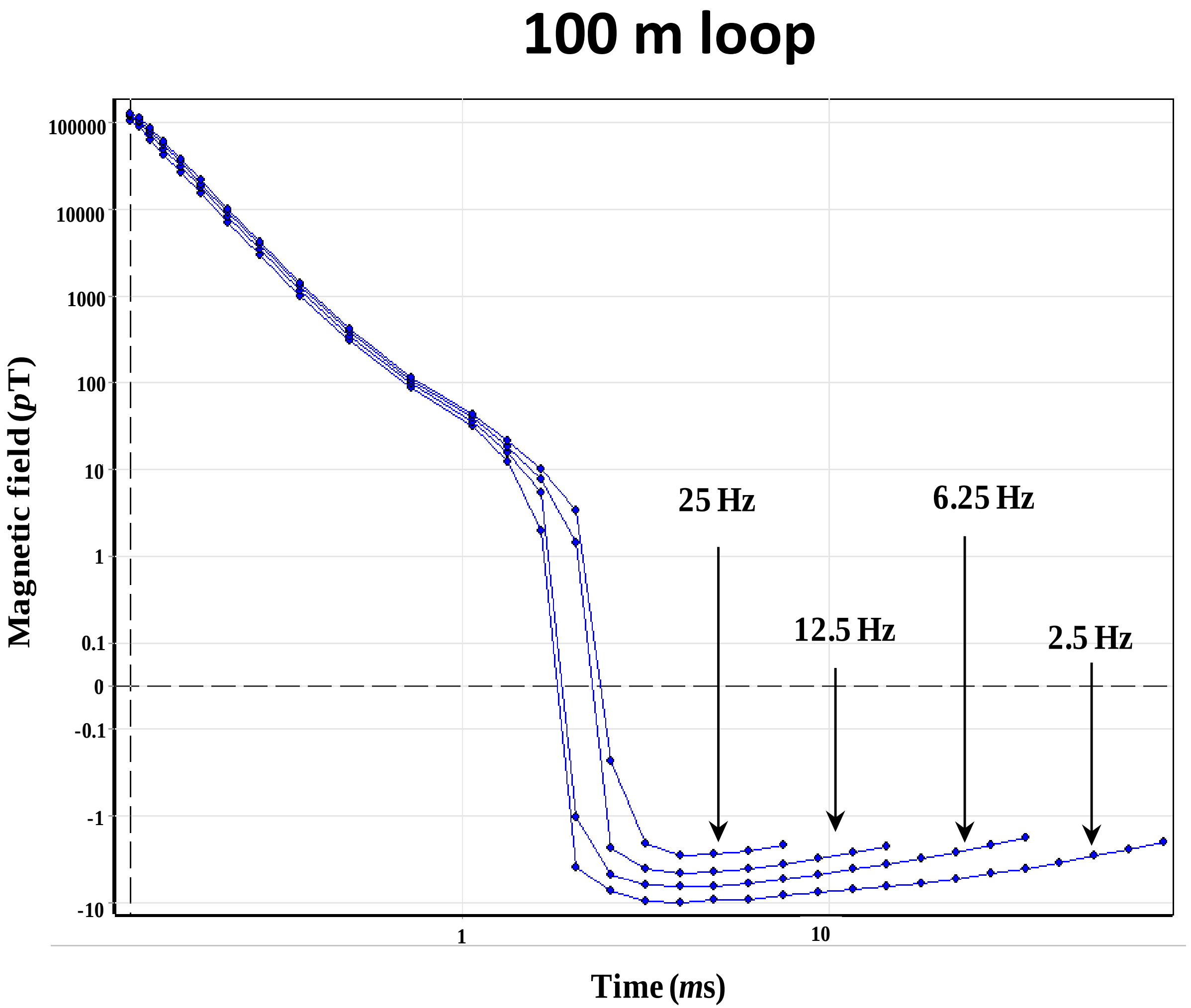


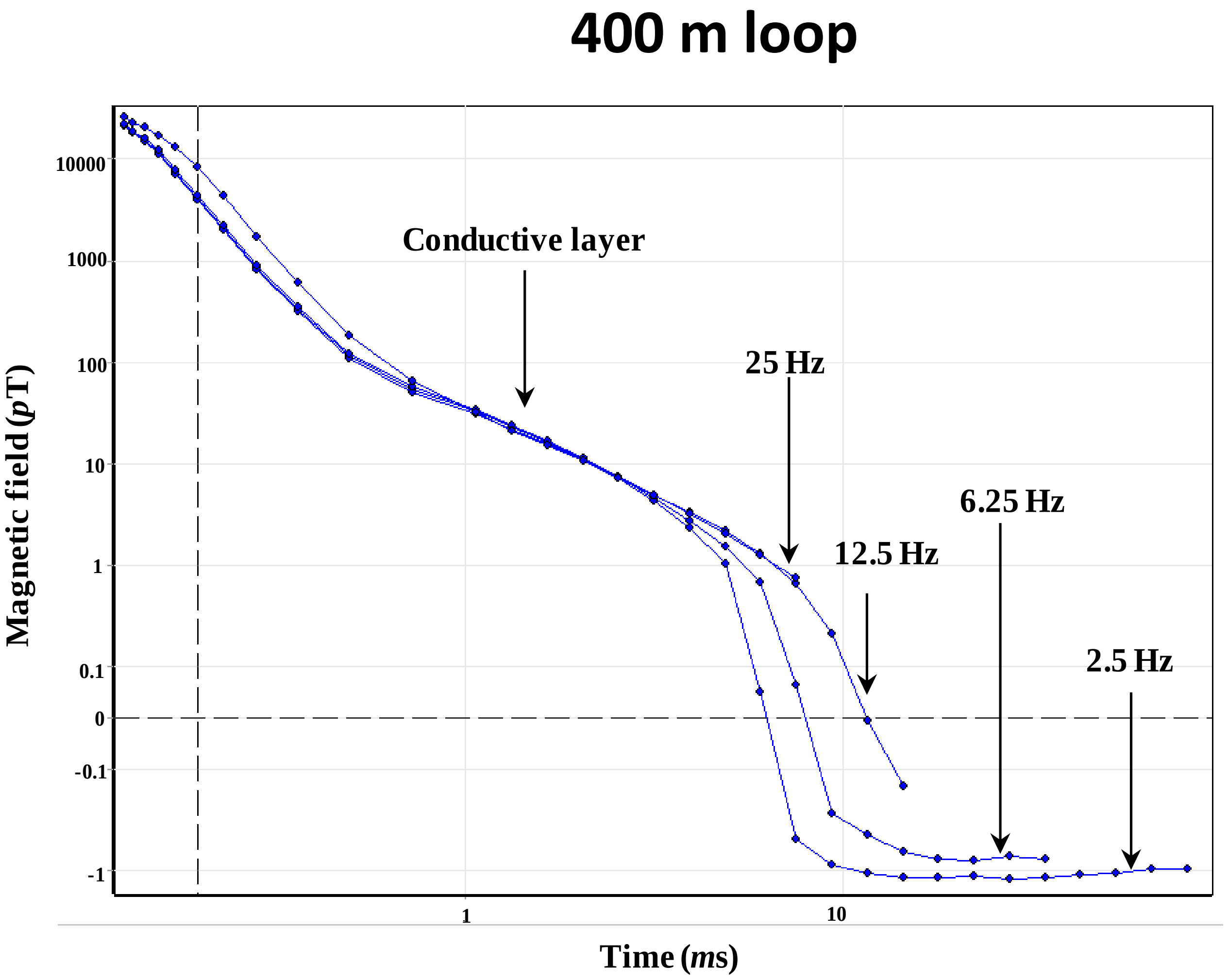
Layered plate model showing top and bottom layers

Plate	Depth of center of plate from surface (m)	Thickness (m)	Conductivity (S/m)
P1	0	0	14
P2	300	35	0.175



Challenges yet to be overcome!





- Why the negative part in decay?
- Why is it dependent on the base frequency?
- Why is it dependent on the size of transmitter loop (magnetic moment of loop)?

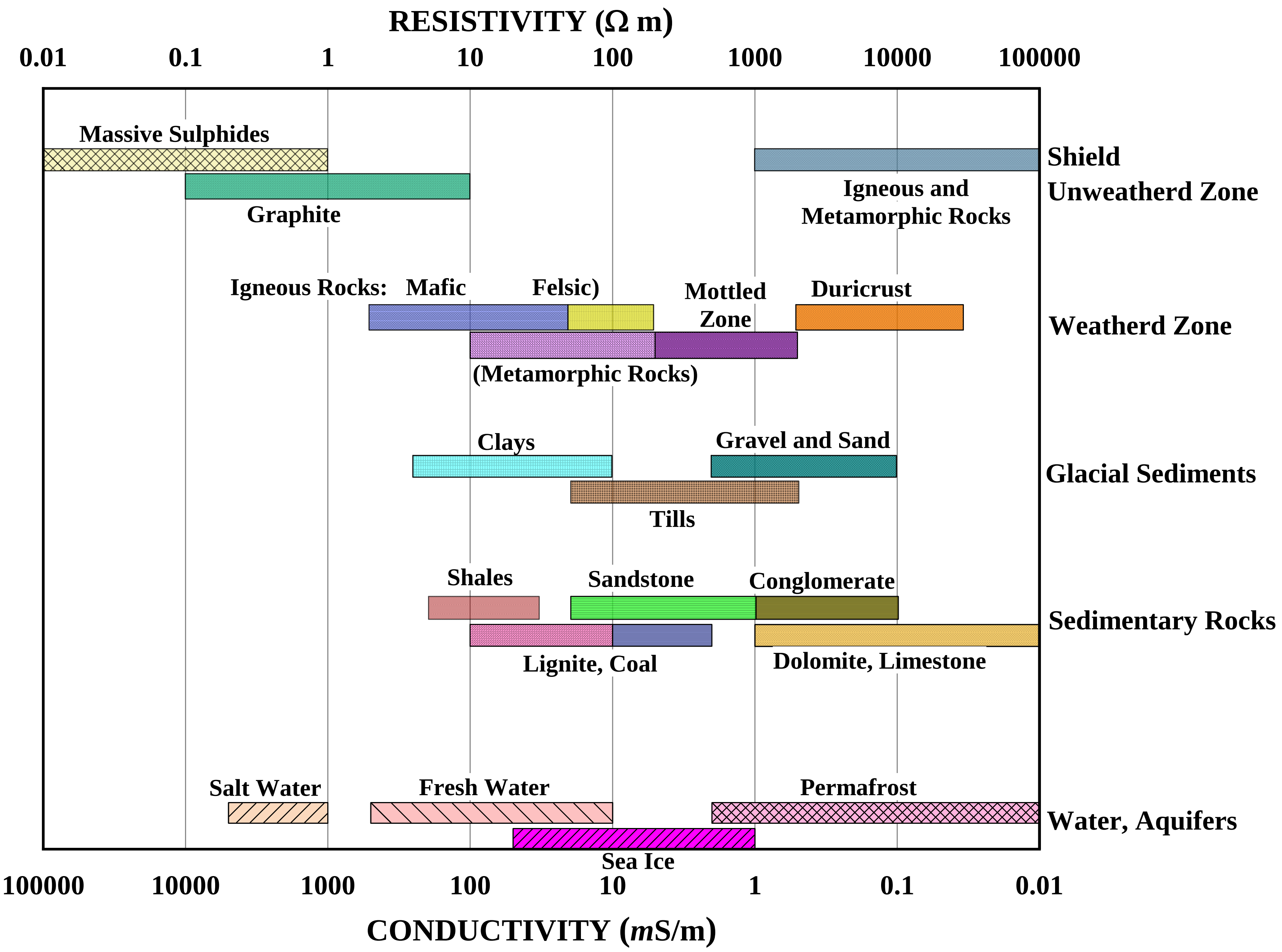




Thank you

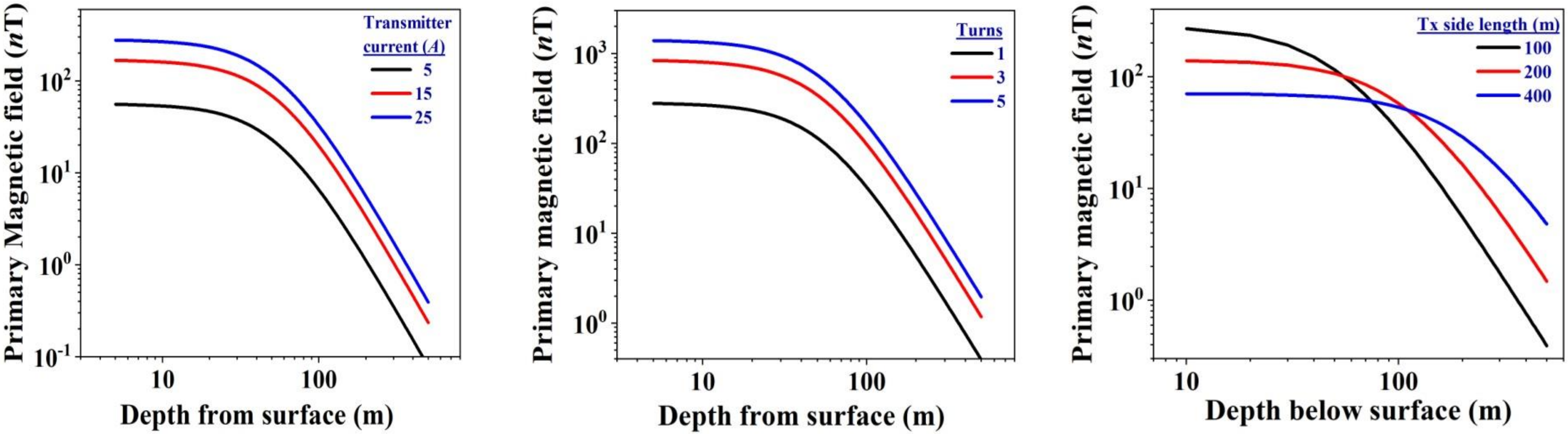


Resistivity Table



Magnetic field along the central axis of square loop carrying current I:

$$B_z = \frac{2_0 I a^2}{\pi\, r}\left(\frac{1}{z^2 + a^2}\right)$$



Martin Misakian, J. Res. Natl. Inst. Stand. Technol. 105, 557 (2000)

- The signal amplitude at times when the second layer is detected is given by the late-time asymptotic expression:

Vertical magnetic field response

$$B_z = \frac{Ia^2\sigma^{3/2}\mu_0^{5/2}}{30\sqrt{\pi}\,t^{3/2}}$$

Voltage response corresponding to B_z

$$V_z = \frac{Ia^2\sigma^{3/2}\mu_0^{5/2}}{20\sqrt{\pi}\,t^{5/2}}$$

- Maximum depth of investigation, *d*, for a single layer homogeneous half space geophysical model

Magnetic field sensor

$$d = 2.8\times 10^{-3}\left({}^{M}/_{\eta_B}\right)^{1/3}$$

Voltage sensor

$$d = 0.55\left({}^{M}/_{\sigma\eta_V}\right)^{1/5}$$

Parameters

I = Current through the circular transmitter loop

A = Area of the transmitter loop

M = *Magnetic moment = I A*

t = *sampling time*

η_B = *system noise level of magnetic field sensor*

η_V = *system noise level of voltage sensor*

σ = *conductivity of the upper layer*

μ = *permeability of half-space*

Spies, B.R. Depth of investigation in electromagnetic sounding methods. *GEOPHYSICS* **1989**, *54*, 872–888.