Modelling of induced polarization effects in time-domain electromagnetic data from a glacier in Svalbard, Norway

Heather A. Burgi and Colin G. Farquharson

Department of Earth & Ocean Sciences,
University of British Columbia;

Inco Innovation Centre, and
Department of Earth Sciences,
Memorial University of Newfoundland.

Memorial
University of Newfoundland

Acknowledgments

★ Prof. Tavi Murray, Swansea University.

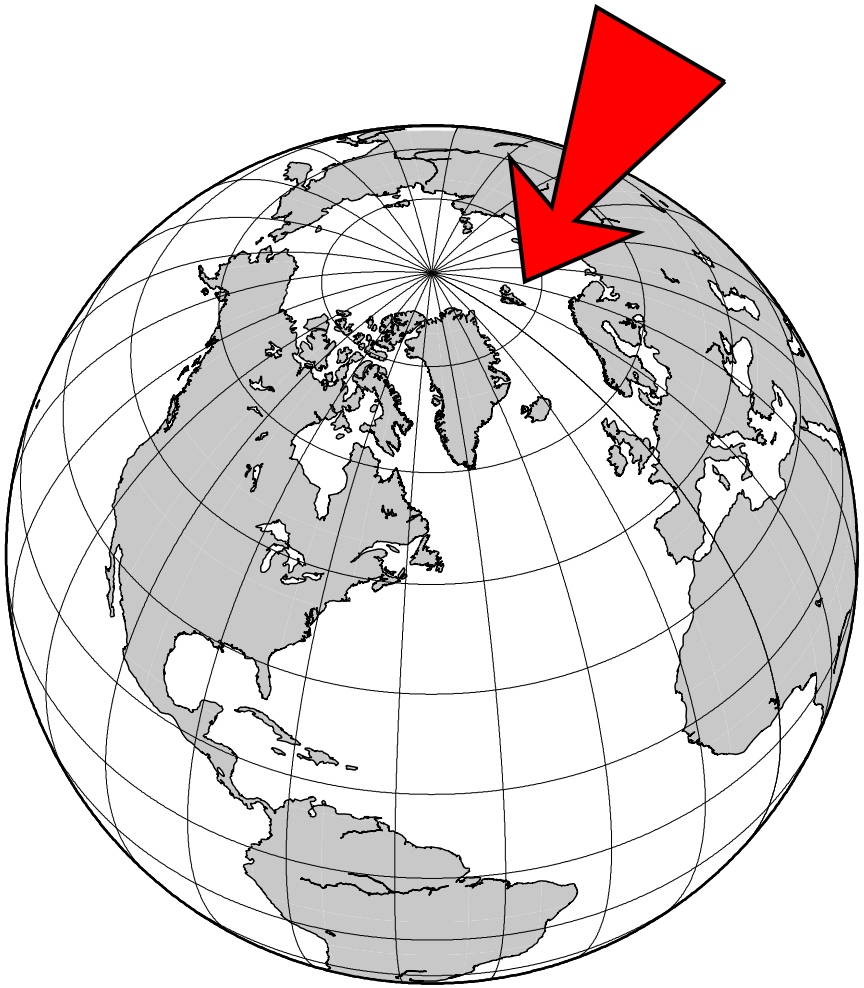
Outline

- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

Outline

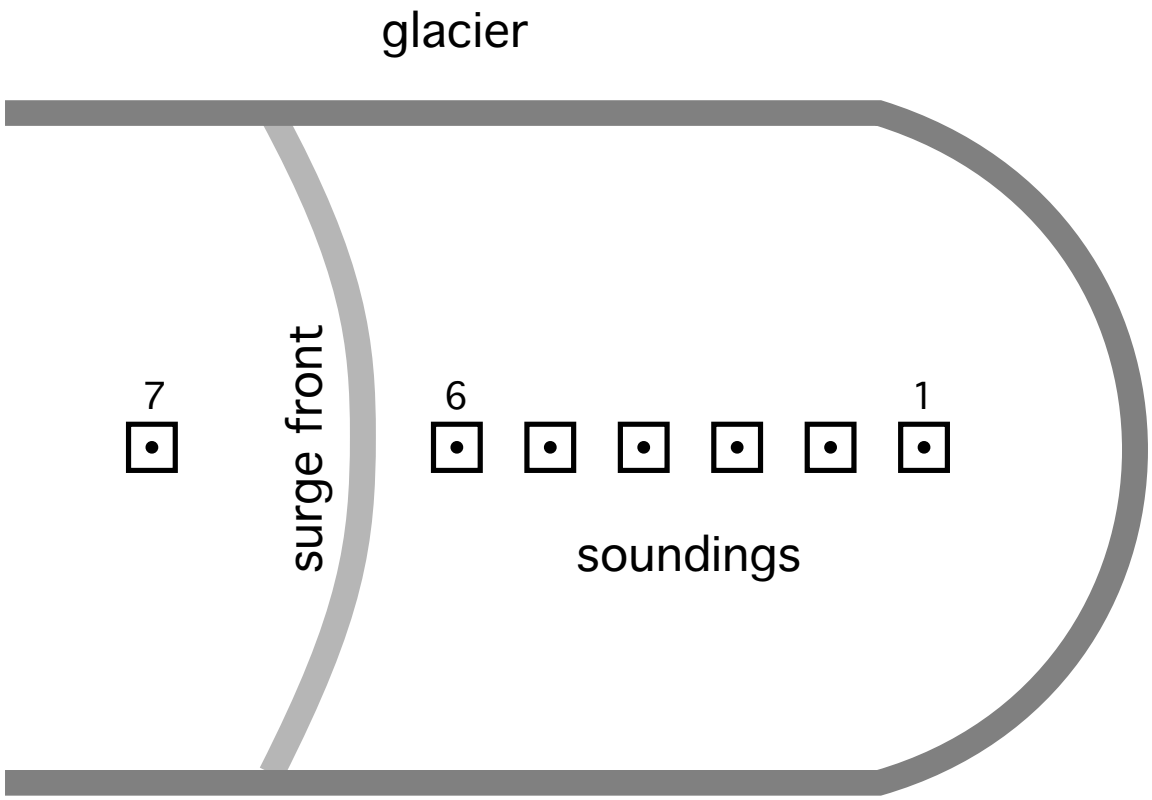
- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

Svalbard



The glacier in Svalbard: Bakaninbreen

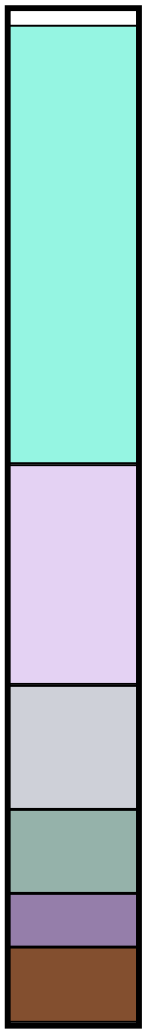
The glacier



The glacier

above surge front

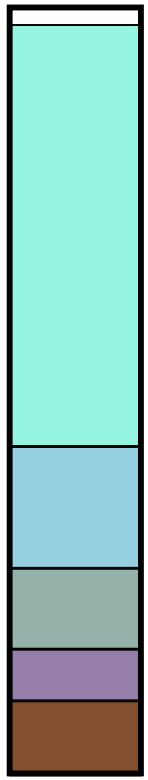
thickness (m)



2	snow
75 - 100	cold, clean ice
30 - 60	warm, clean ice
5 - 25	warm, sediment-rich ice
~ 10	permafrost
?	unfrozen sediment
?	bedrock (shales, mudstones)

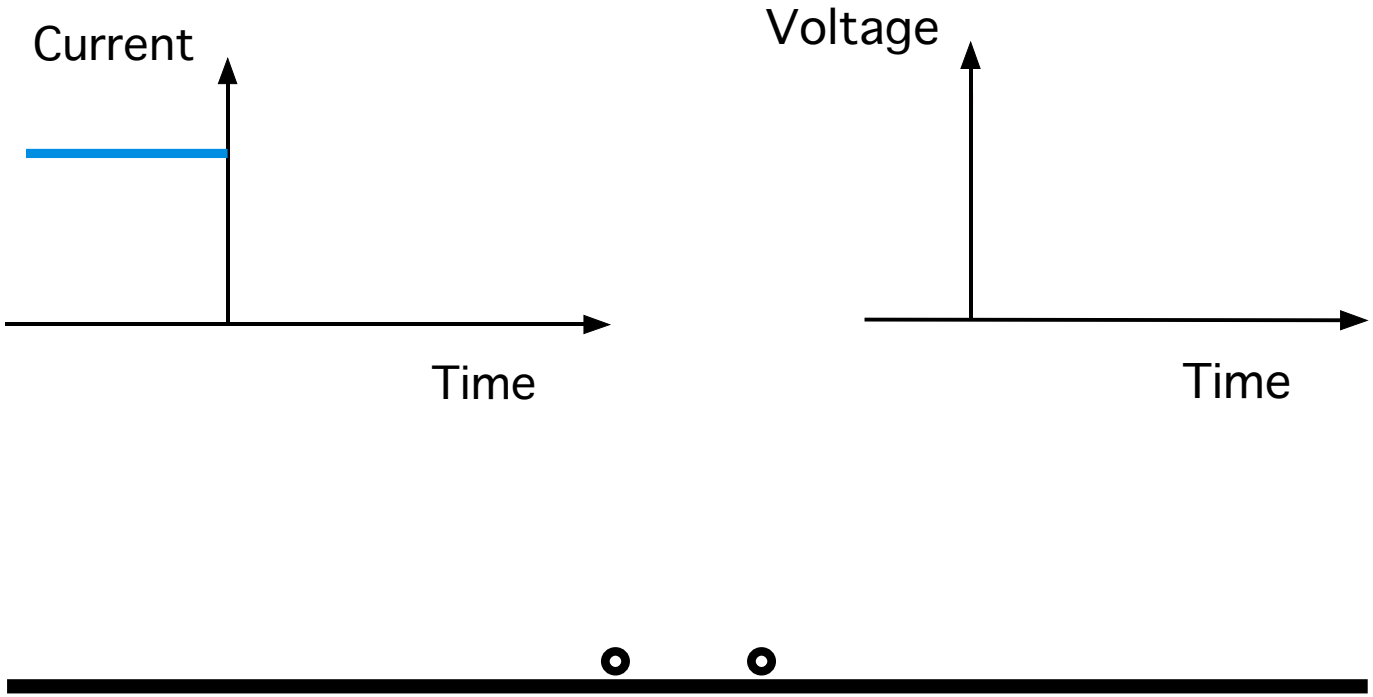
below surge front

thickness (m)

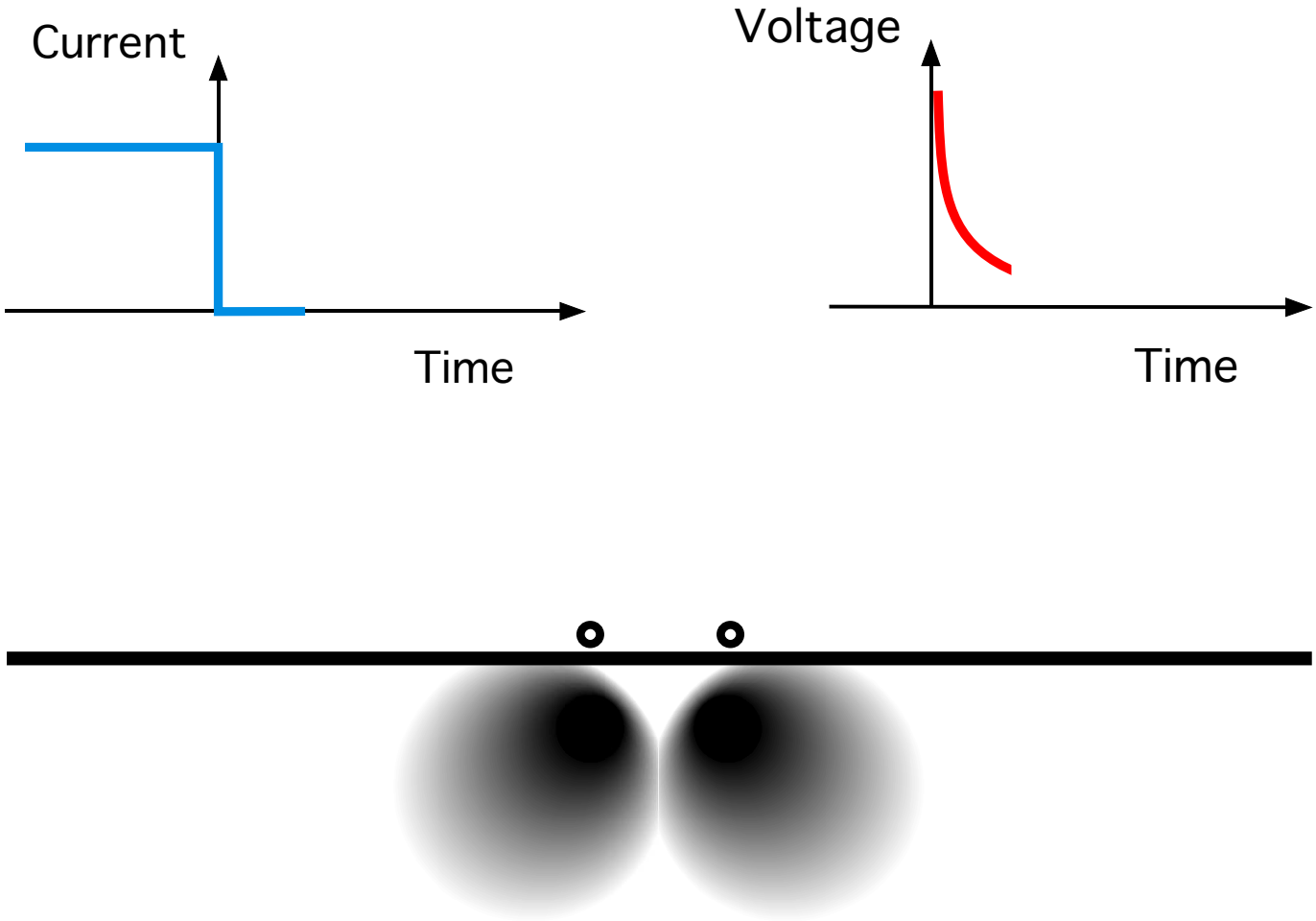


2	snow
50 - 60	cold, clean ice
5 - 20	cold, sediment-rich ice
~ 10	permafrost
?	unfrozen sediment
?	bedrock (shales, mudstones)

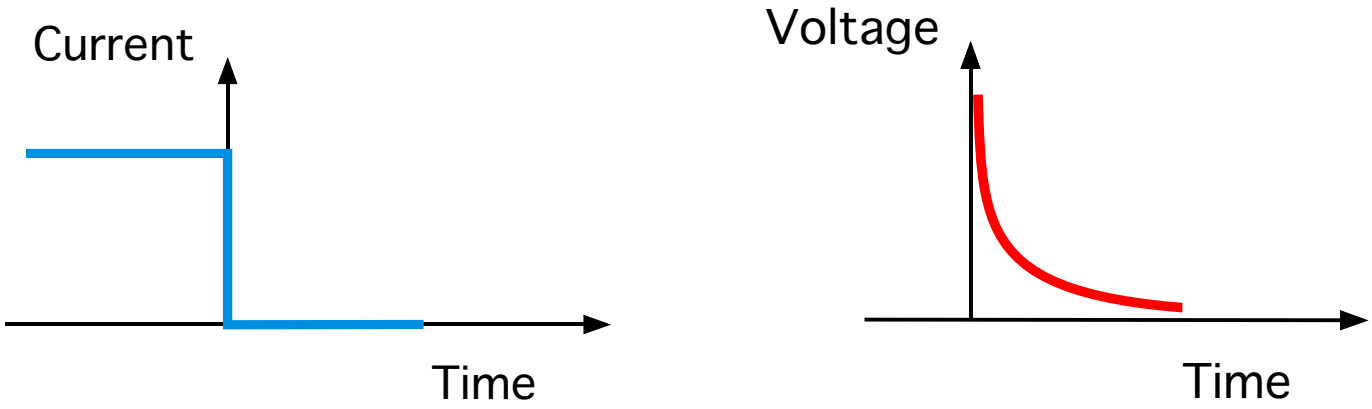
Time-domain EM soundings

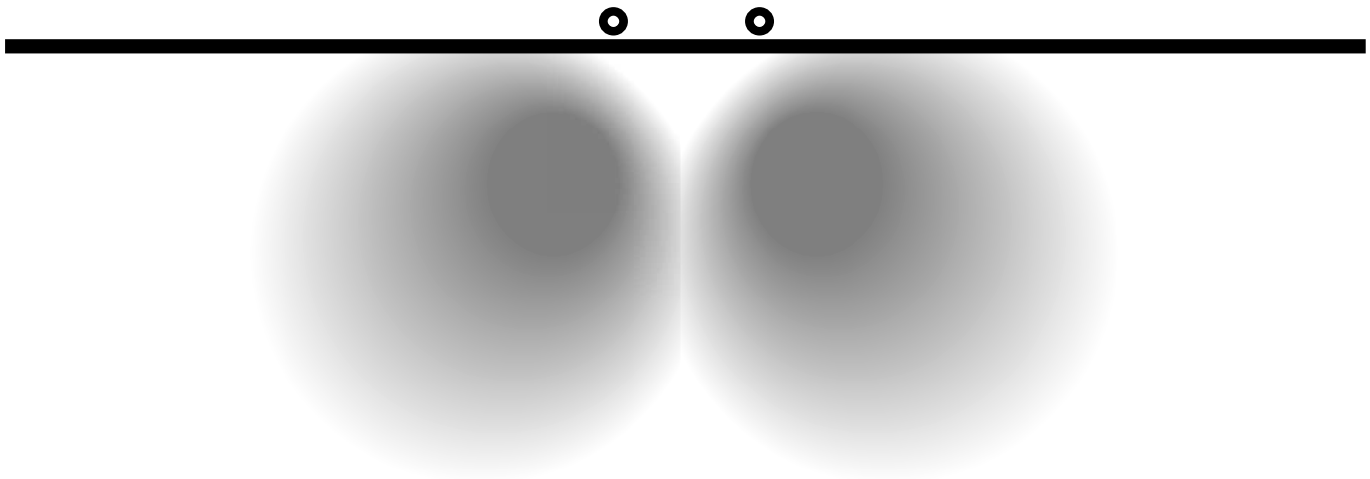


Time-domain EM soundings

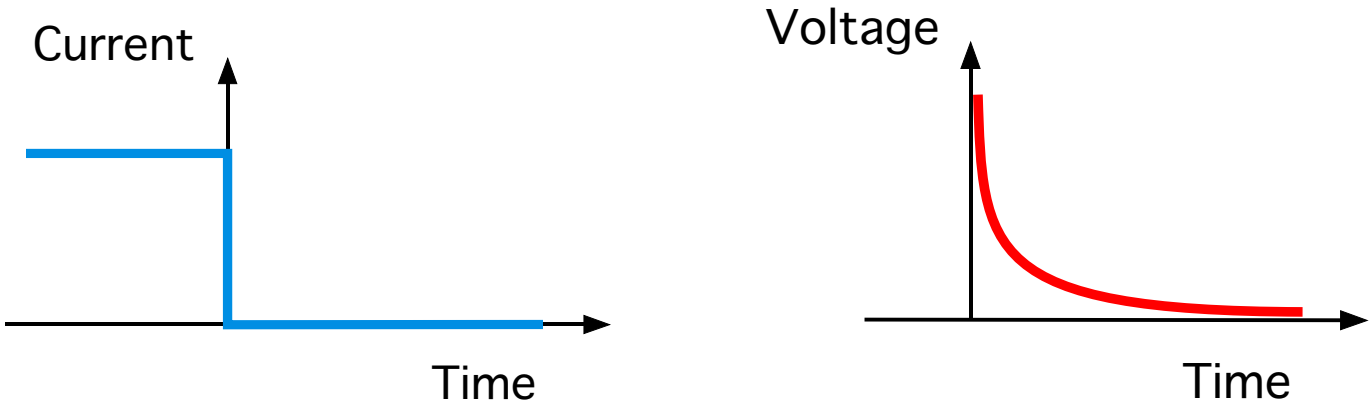


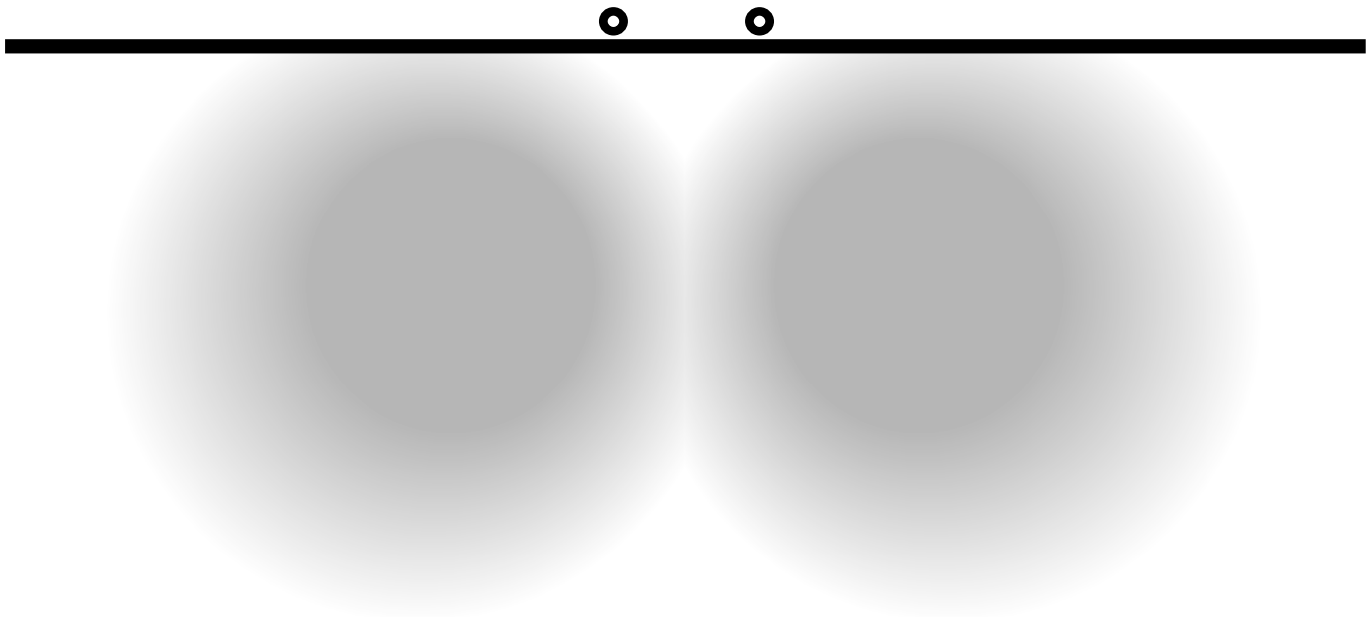
Time-domain EM soundings

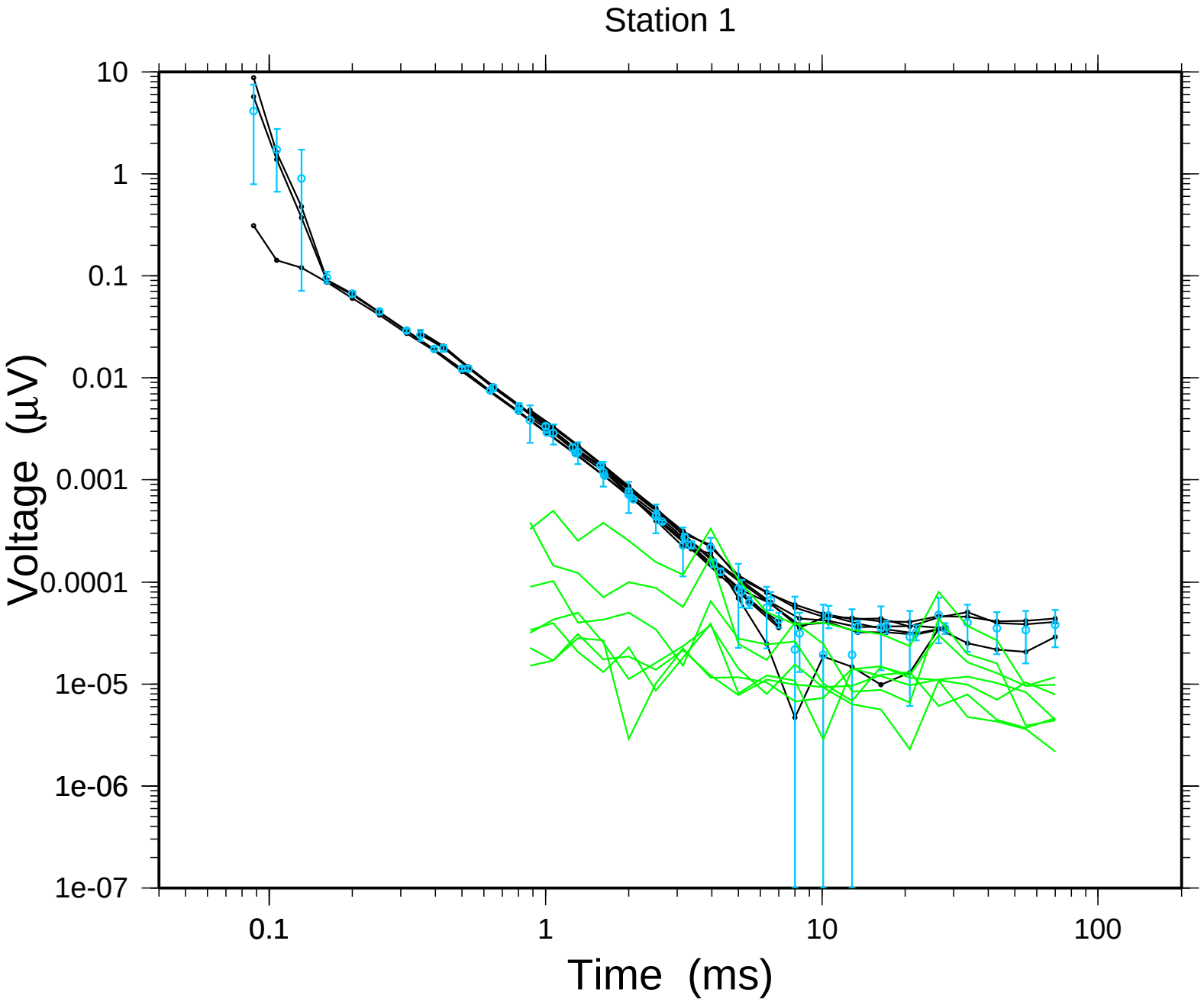


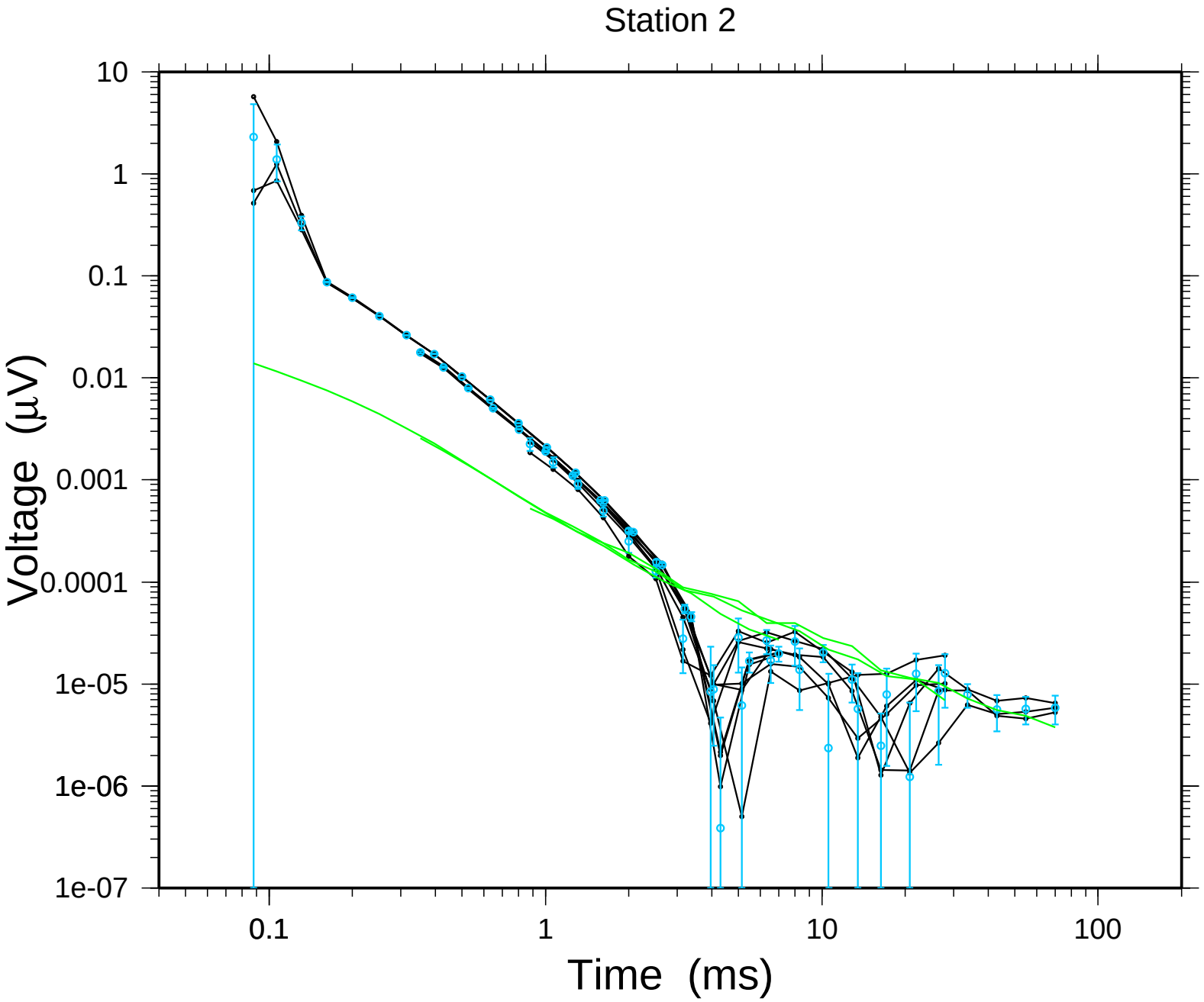


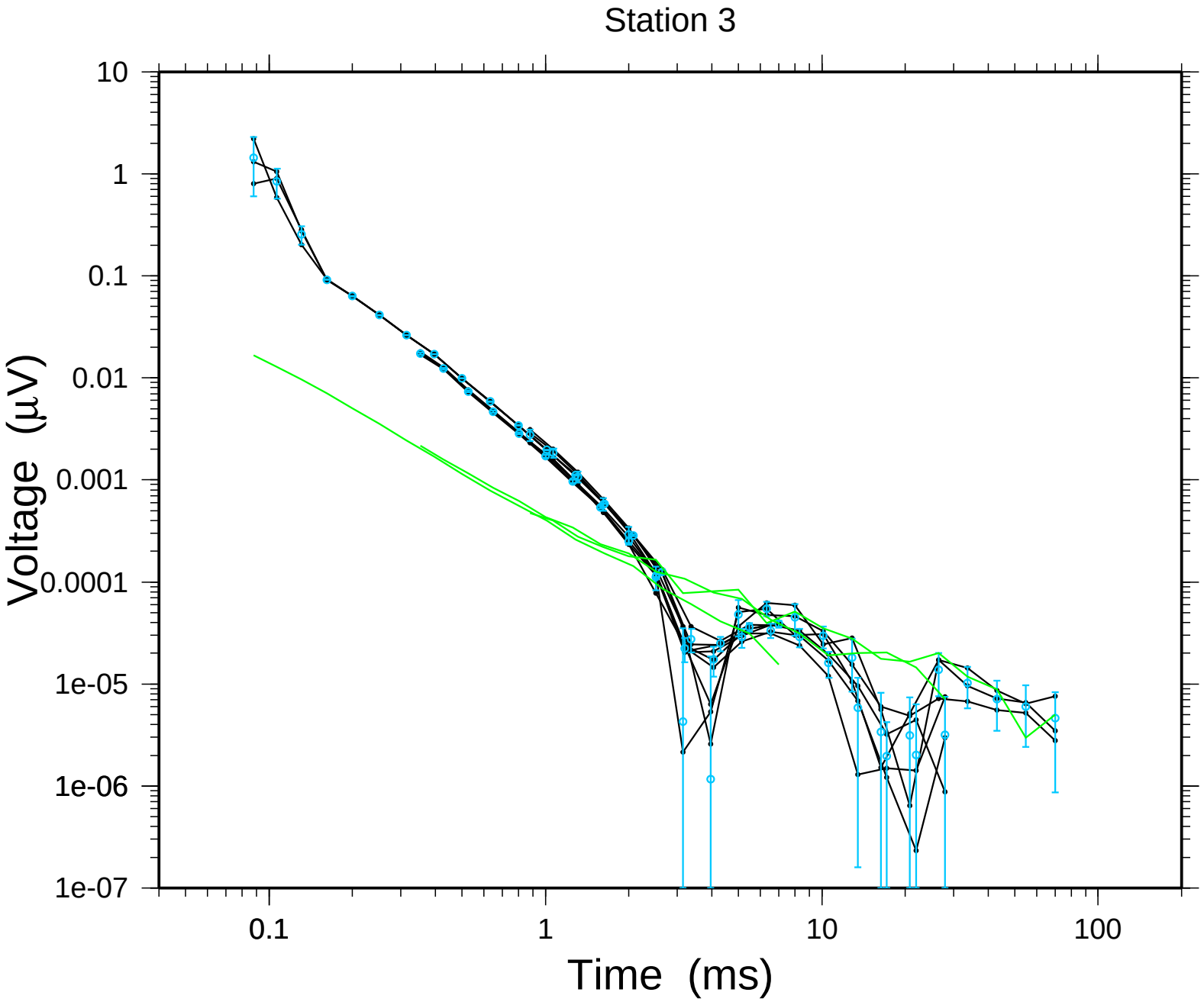
Time-domain EM soundings

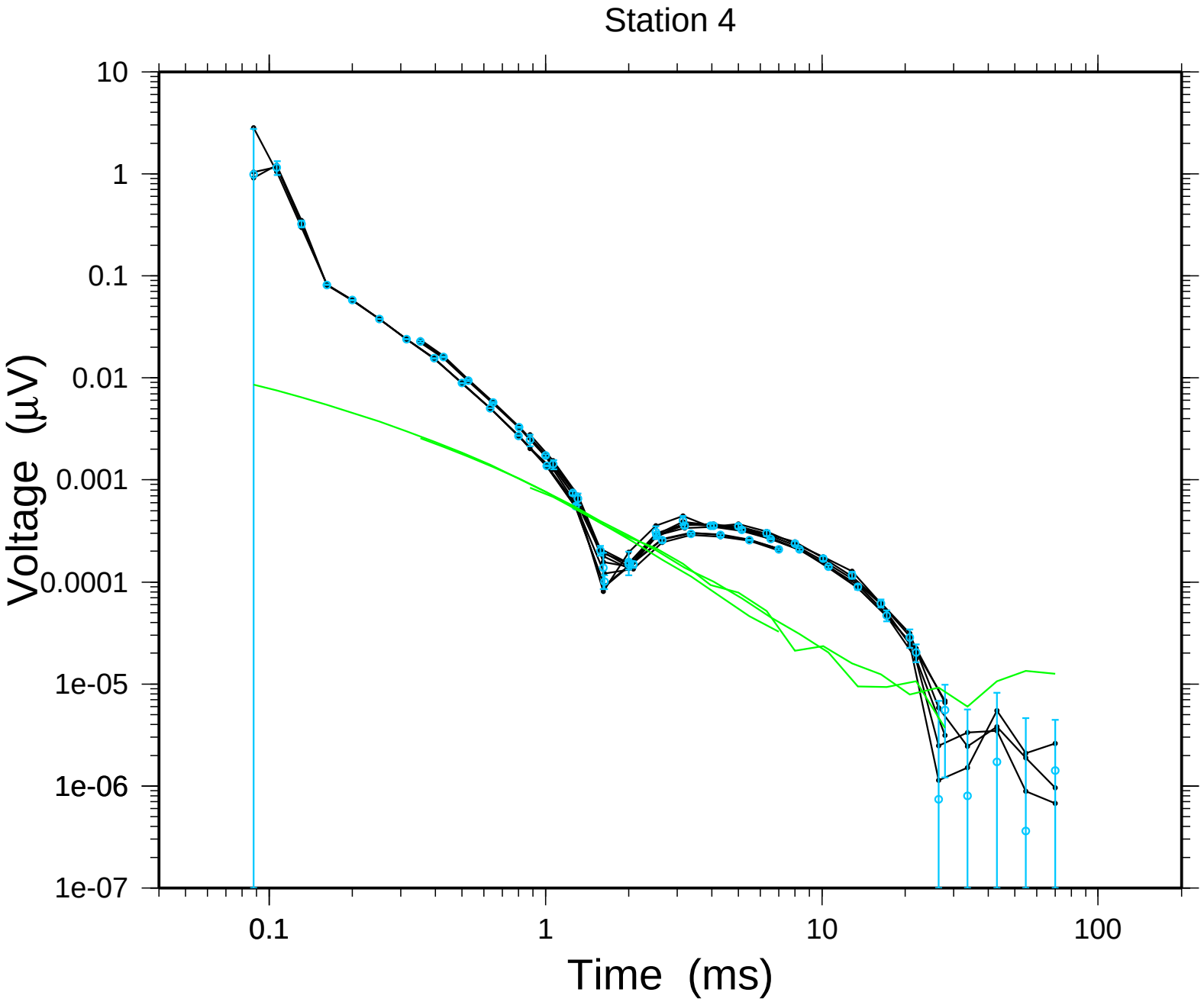


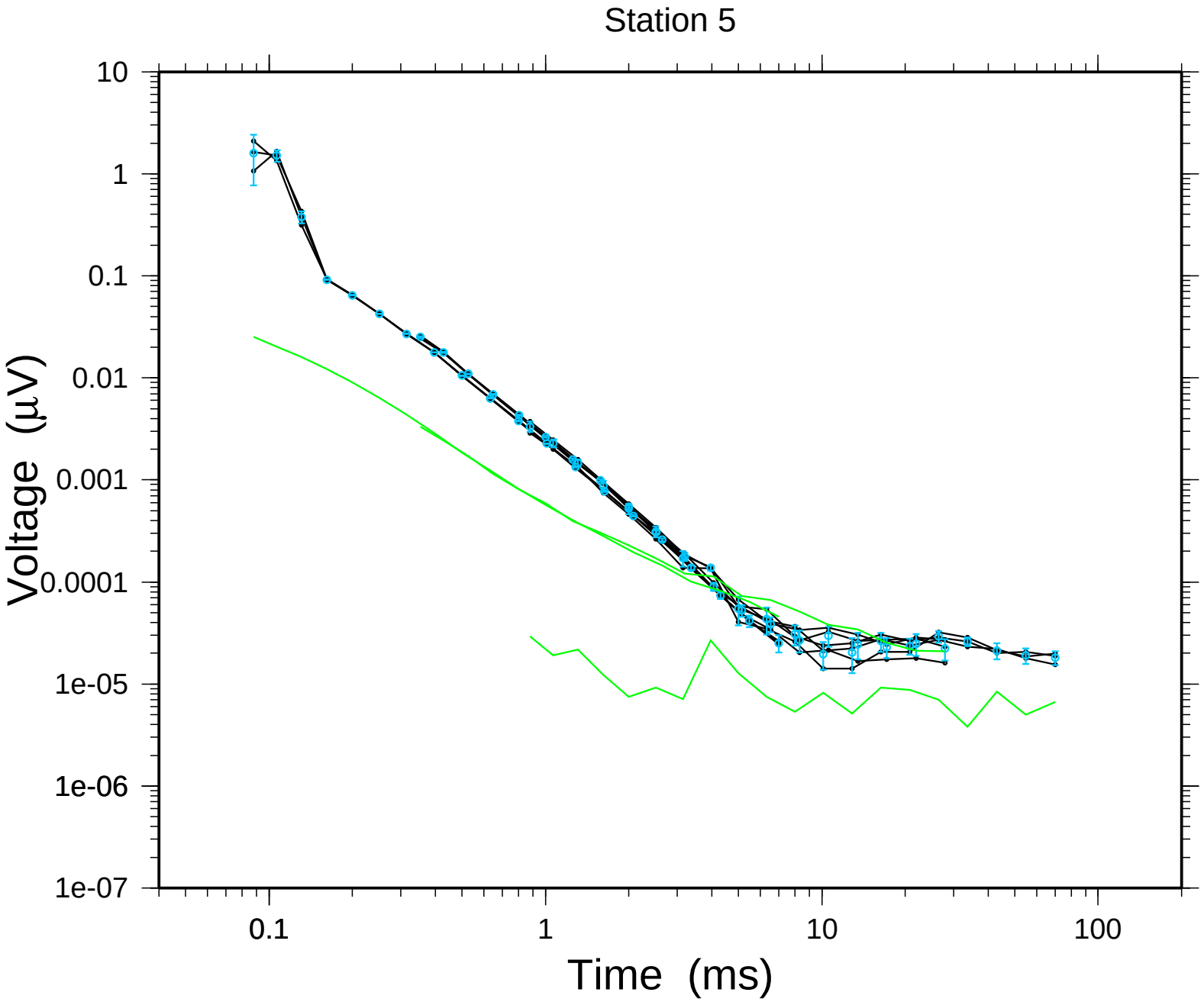


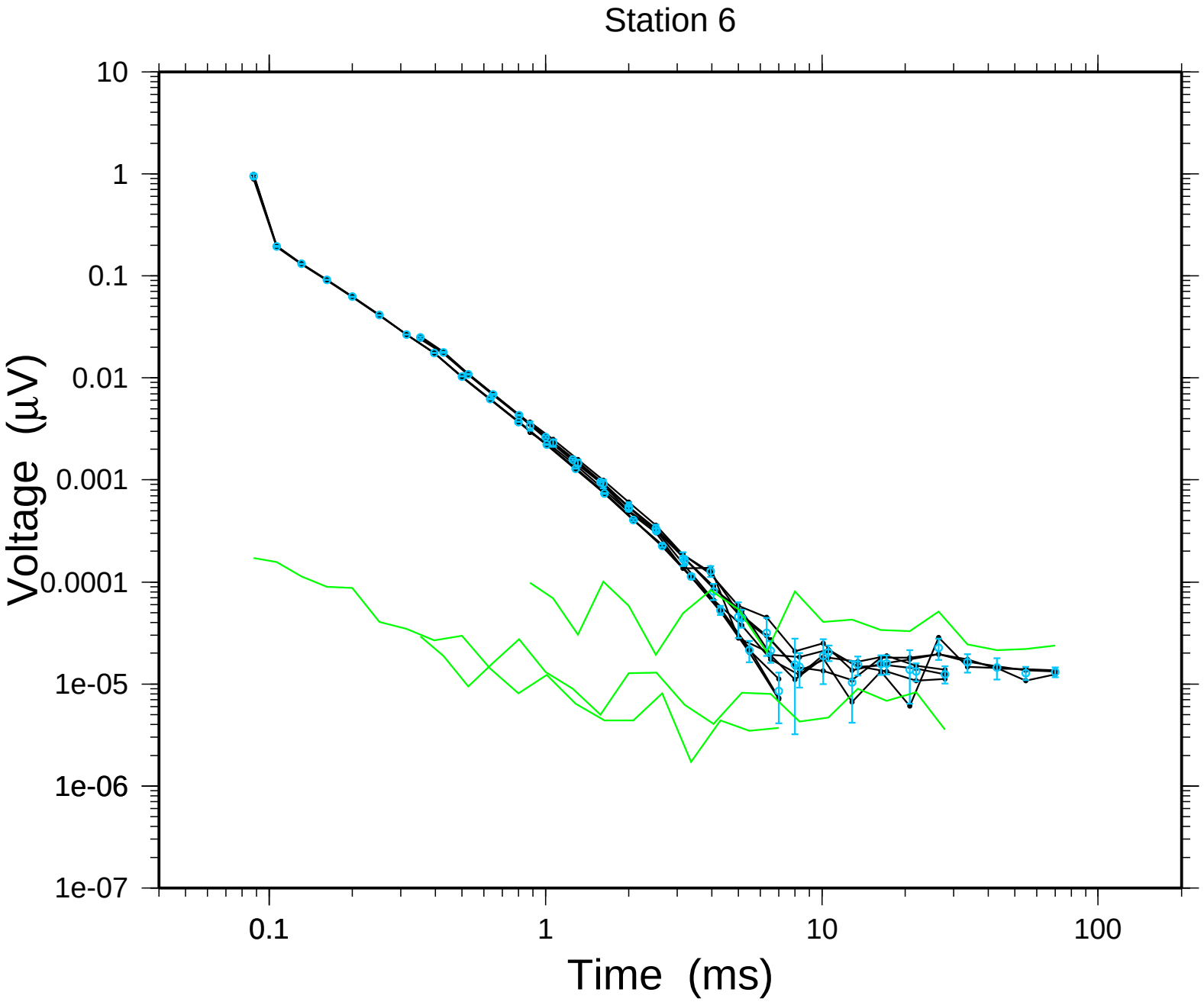

Station 1
Voltage (µV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)

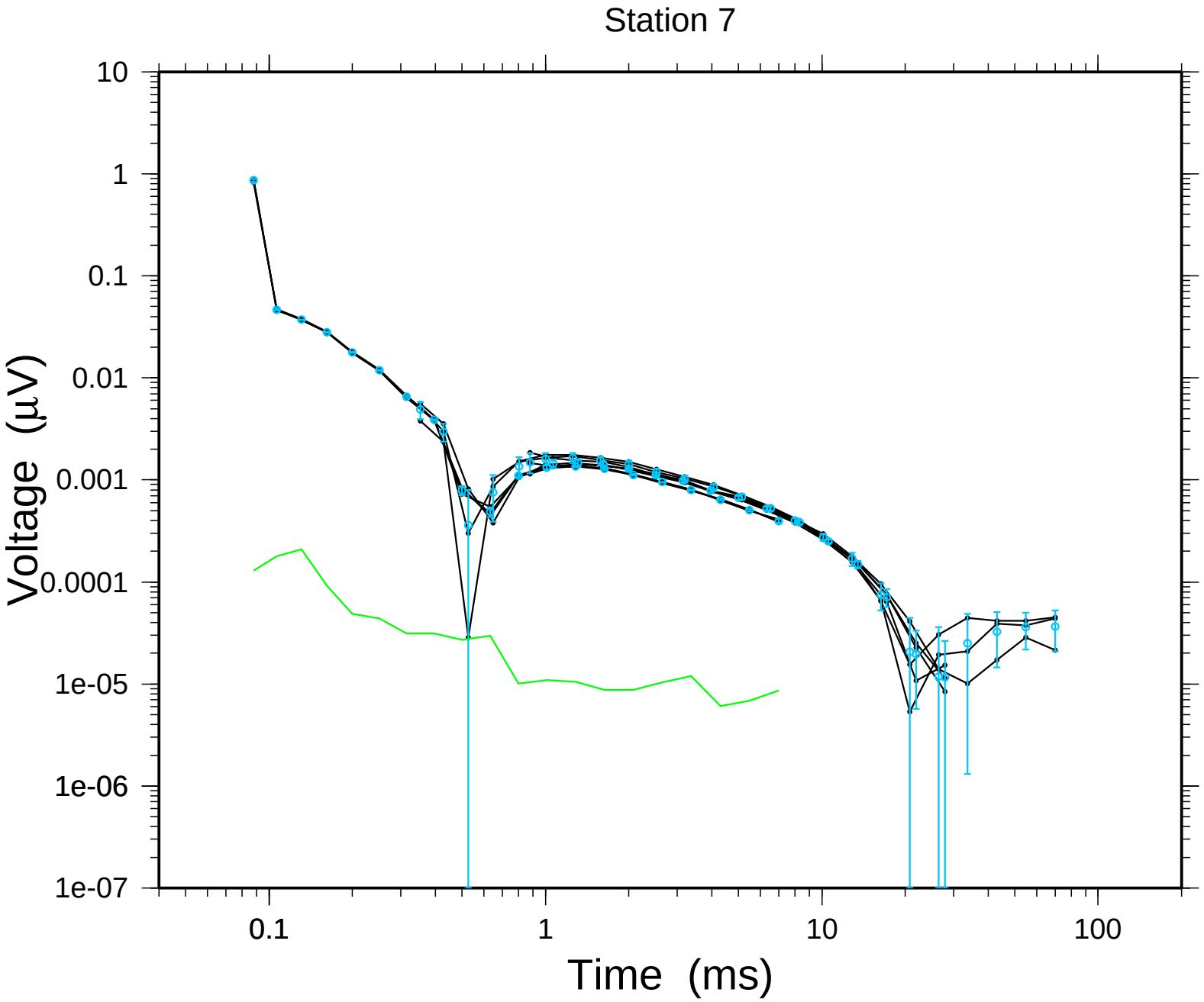

Station 2
Voltage (µV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)


Station 3
Voltage (μV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)


Station 4
Voltage (μV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)


Station 5
Voltage (µV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)

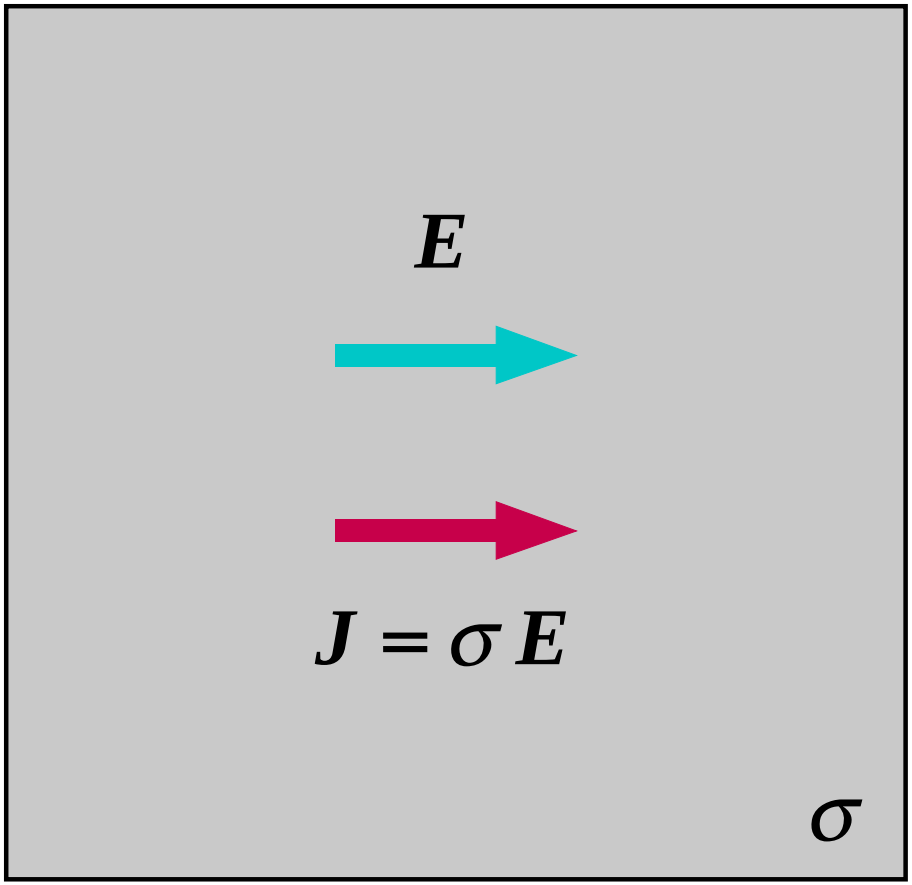

Station 6
Voltage (µV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)


Station 7
Voltage (µV)
10
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
Time (ms)

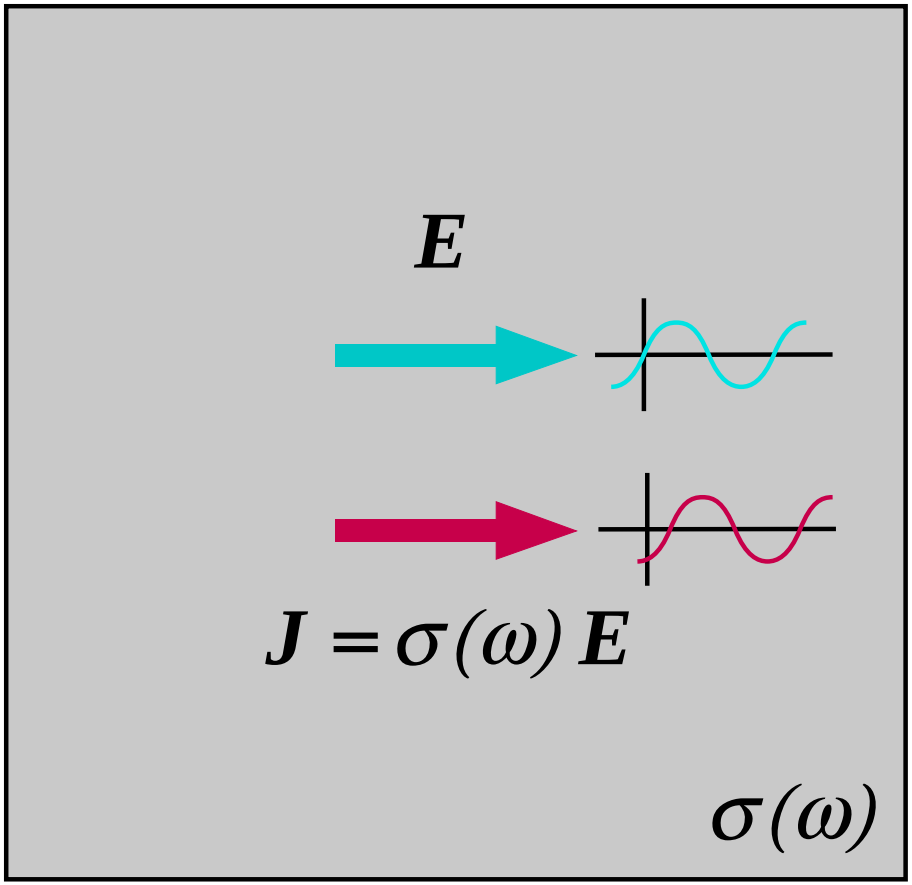
Outline

- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

Ohm's law



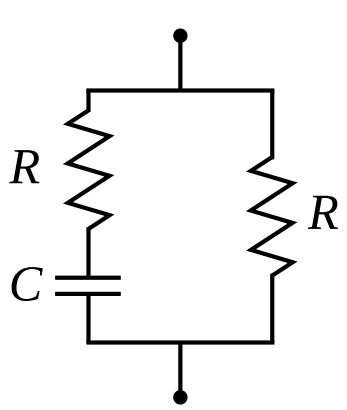
Ohm's law

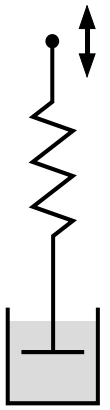


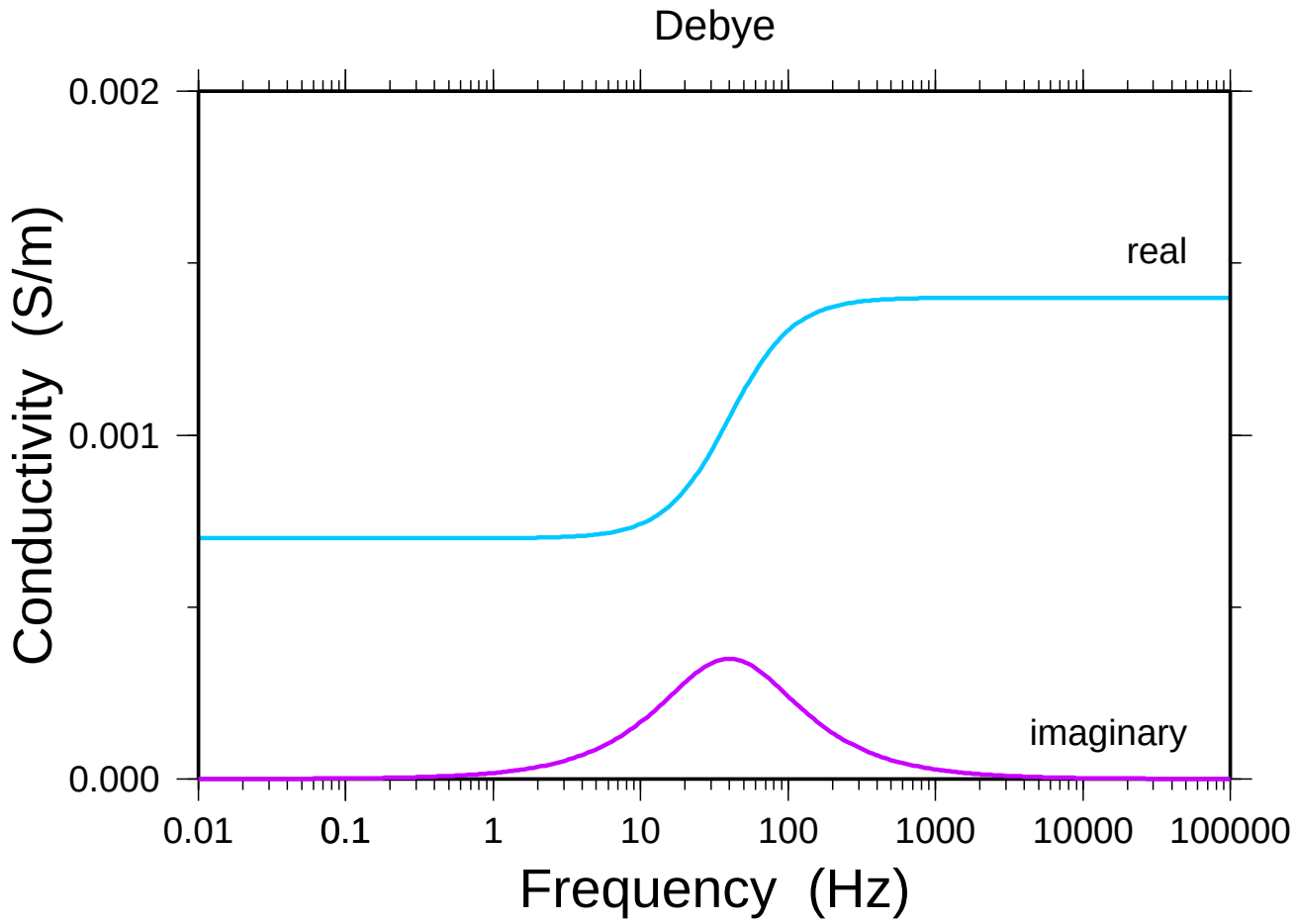
Debye and Cole-Cole models

$$\sigma(\omega) \;=\; \sigma_0 \,\frac{1+(i\omega\tau)^c}{1+(1-m)(i\omega\tau)^c}$$

σ_0	DC conductivity (S/m),
τ	relaxation time (s),
m	chargeability,
c	frequency parameter.





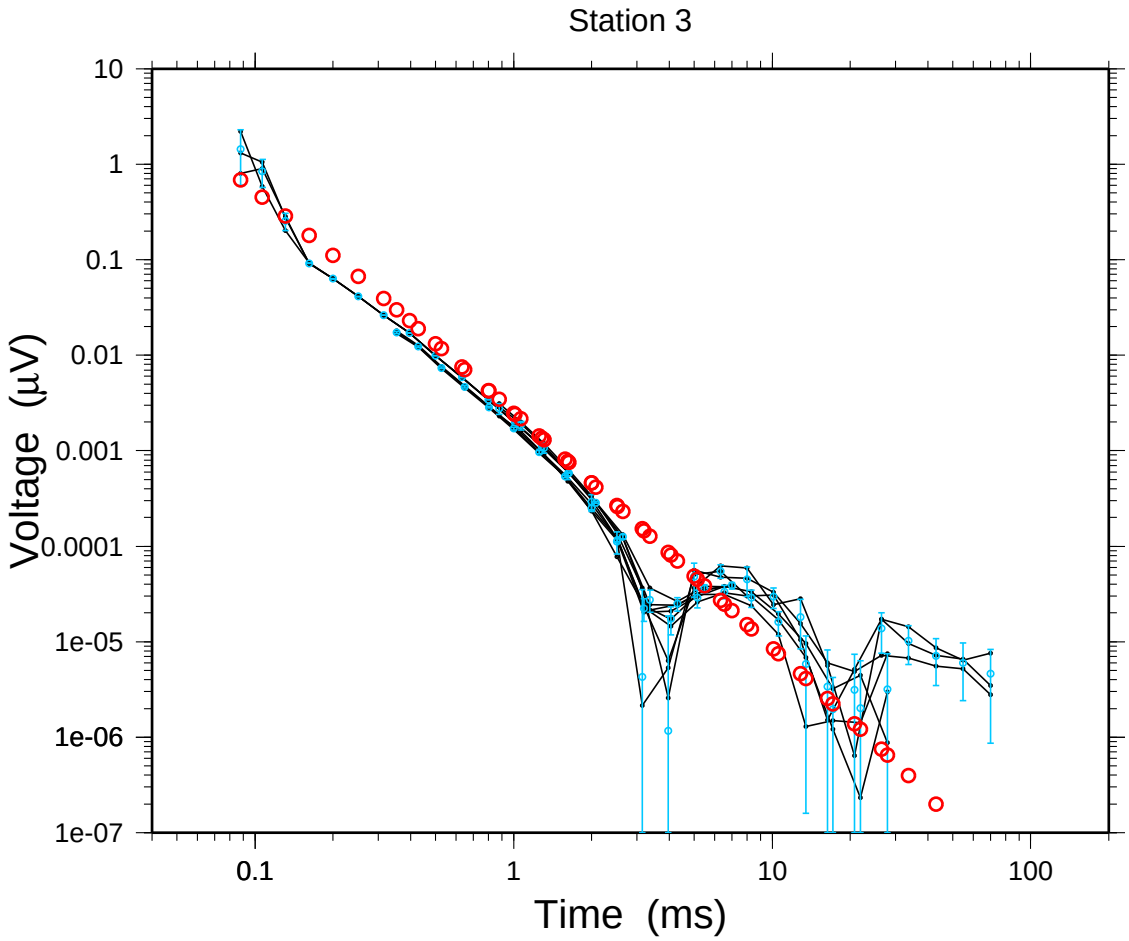


$$\sigma_0: \quad 7 \times 10^{-4}\,\mathrm{S/m}, \quad \tau: \quad 8 \times 10^{-3}\,\mathrm{s}, \quad m: \quad 0.5$$

Outline

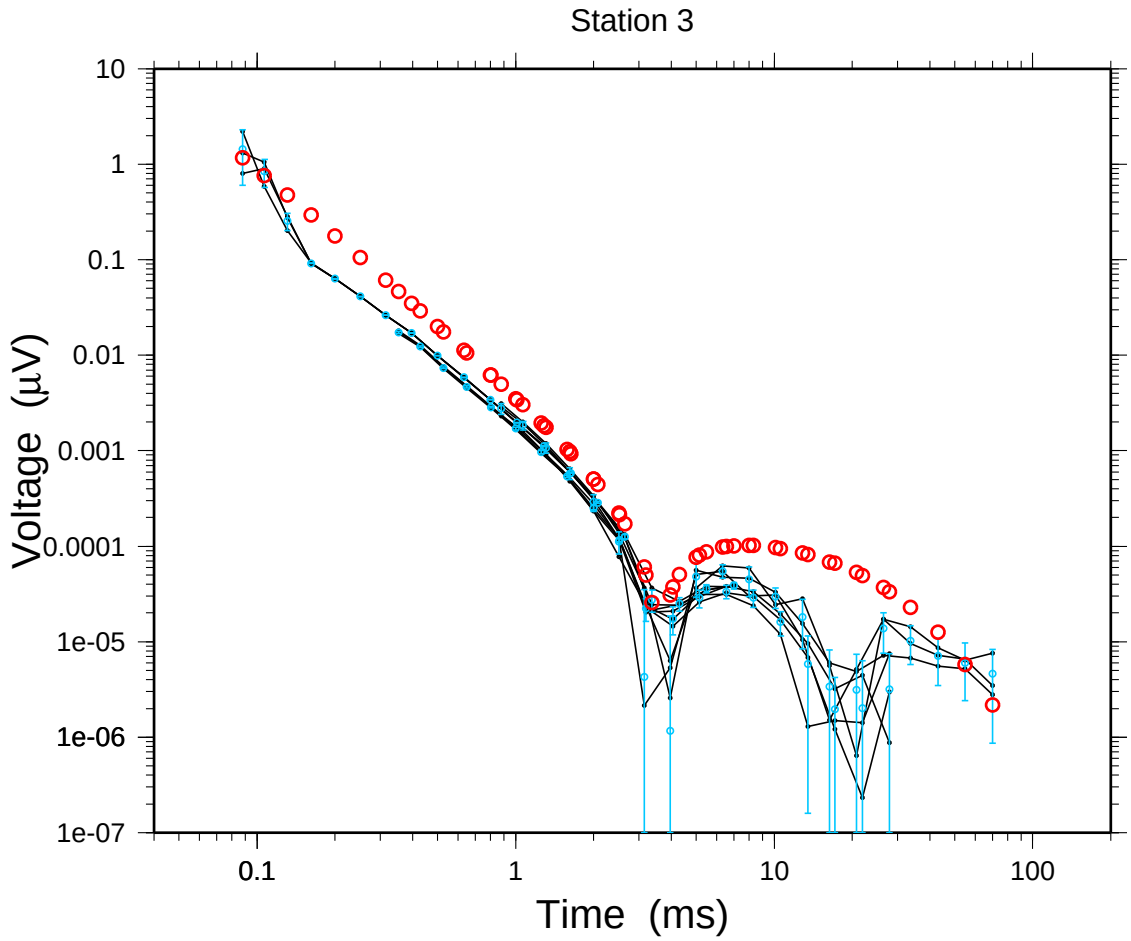
- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

Non-polarizable halfspace



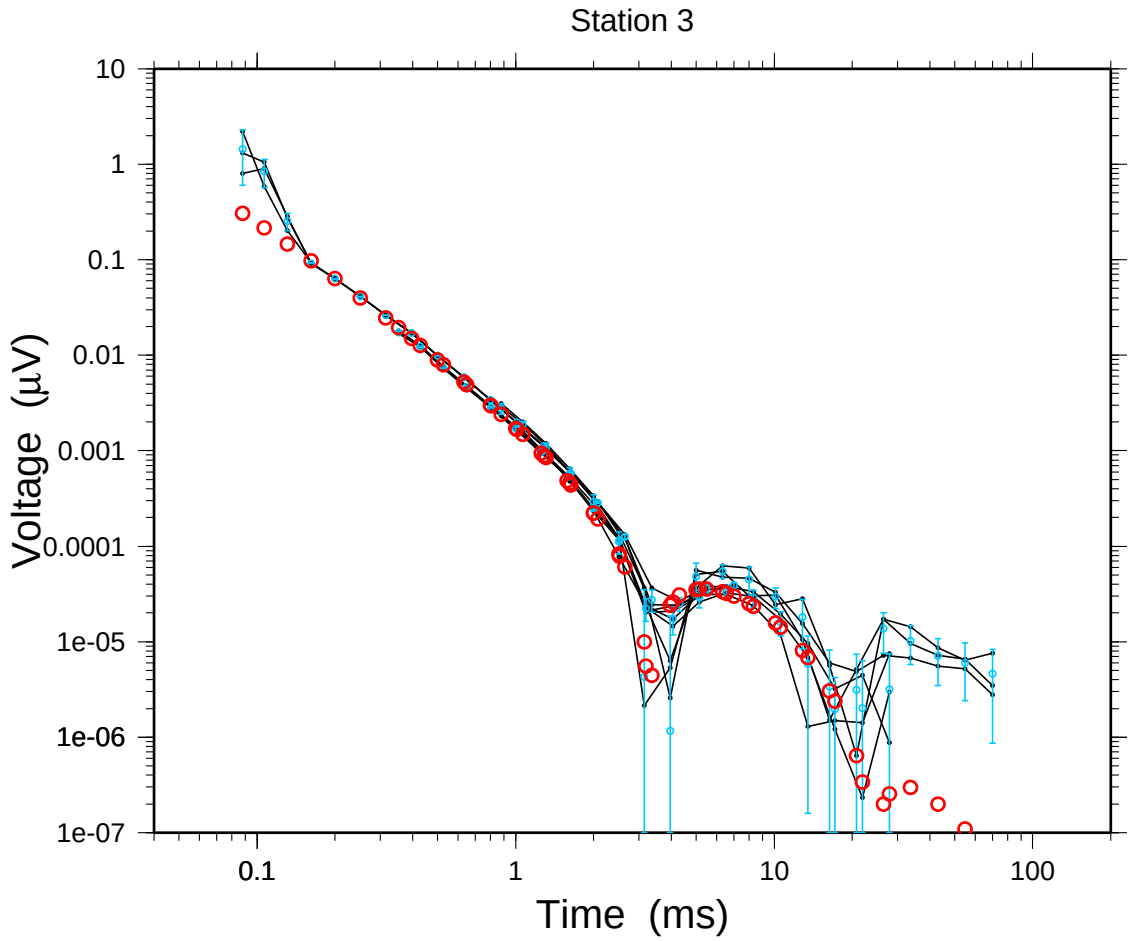
thickness (m)	σ_0 (S/m)	τ (s)	m
∞	8×10^{-3}	0	0

Polarizable halfspace



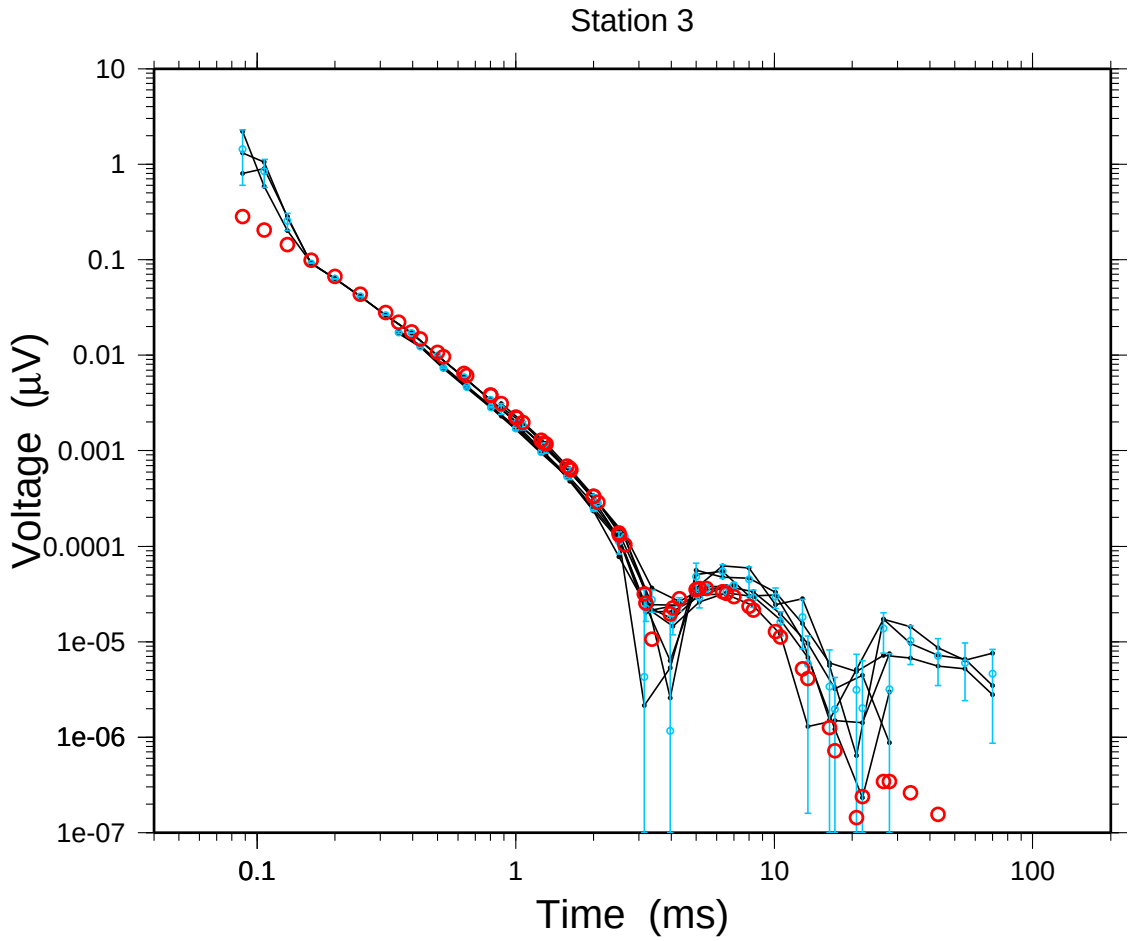
thickness (m)	σ_0 (S/m)	τ (s)	m
∞	6×10^{-3}	3×10^{-2}	0.5

Two-layer model, polarizable over non-polarizable



thickness (m)	σ_0 (S/m)	τ (s)	m
55	6.8×10^{-4}	8.5×10^{-3}	0.5
∞	1.0×10^{-2}	0	0

Two-layer model, non-polarizable over polarizable



thickness (m)	σ_0 (S/m)	τ (s)	m
62	5.0×10^{-5}	0	0
∞	9.0×10^{-3}	4.2×10^{-3}	0.29

Conclusions from numerical modelling

- ⋆ Double sign change can be easily mimicked using a simple complex-valued, frequency-dependent model of conductivity (i.e., Debye).

- ⋆ Slight preference for a two-layer Earth model, rather than a homogeneous polarizable halfspace.

Outline

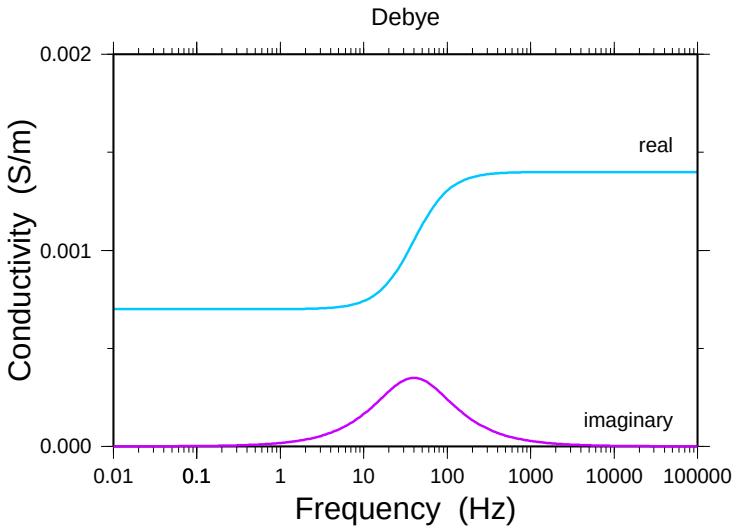
- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

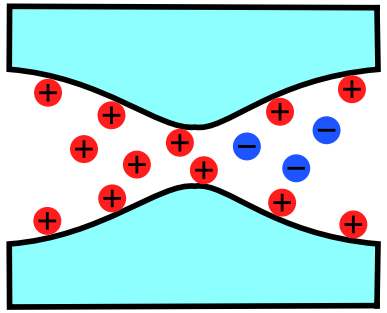
What is the physical mechanism?

- Traditional explanations for polarization effects in exploration geophysics:
  - *electrode polarization* – disseminated sulphides;
  - *membrane polarization* – clays.

What is the physical mechanism?

- But what about an explanation that's relevant here ...
  - the ice itself;
  - *membrane polarization* – ice–sediment mixture;
  - *membrane polarization* – ice–water mixture?





Outline

- Introduction.
- Context.
  - Svalbard.
  - The glacier.
  - Time-domain EM soundings.
  - The data.
- Complex-valued, frequency-dependent conductivity.
  - Mathematical model.
- Fitting the observations.
- The physical mechanism?
- Summary.

Summary

- Double sign changes have been observed in time-domain EM sounding data from a glacier.

- These sign changes can be easily reproduced mathematically with a complex-valued, frequency-dependent model of conductivity, such as the Debye model.

- The physical mechanism responsible for the polarization effects is unknown. It might be a consequence of an ice–water mixture, an ice–sediment mixture, or a property of the ice itself.