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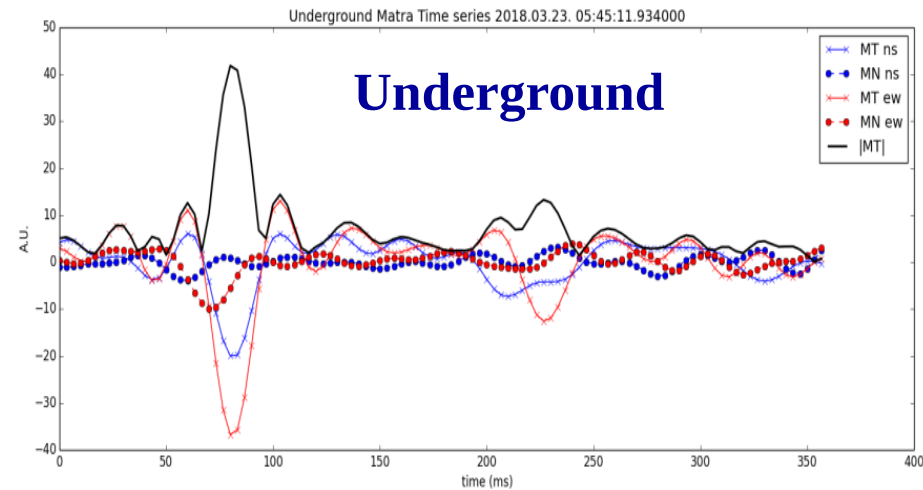
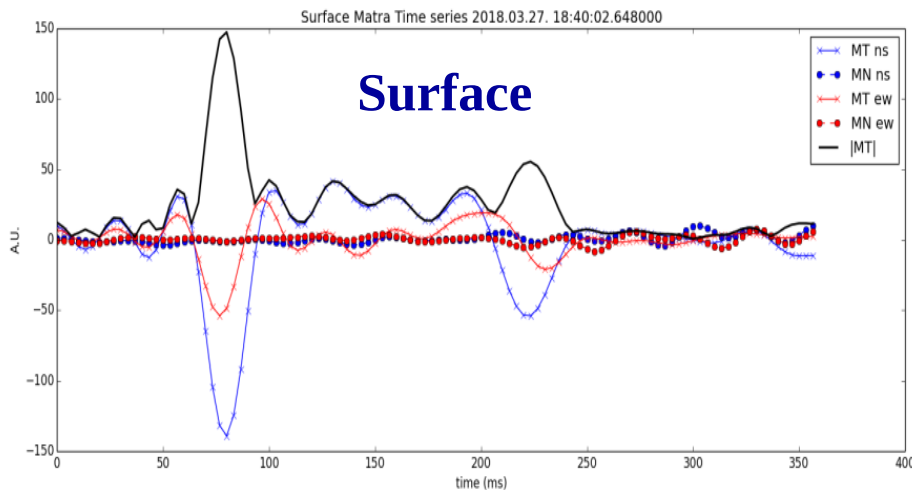
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Comparison of Q-bursts detected near the Earth's surface and 140 m below ground level



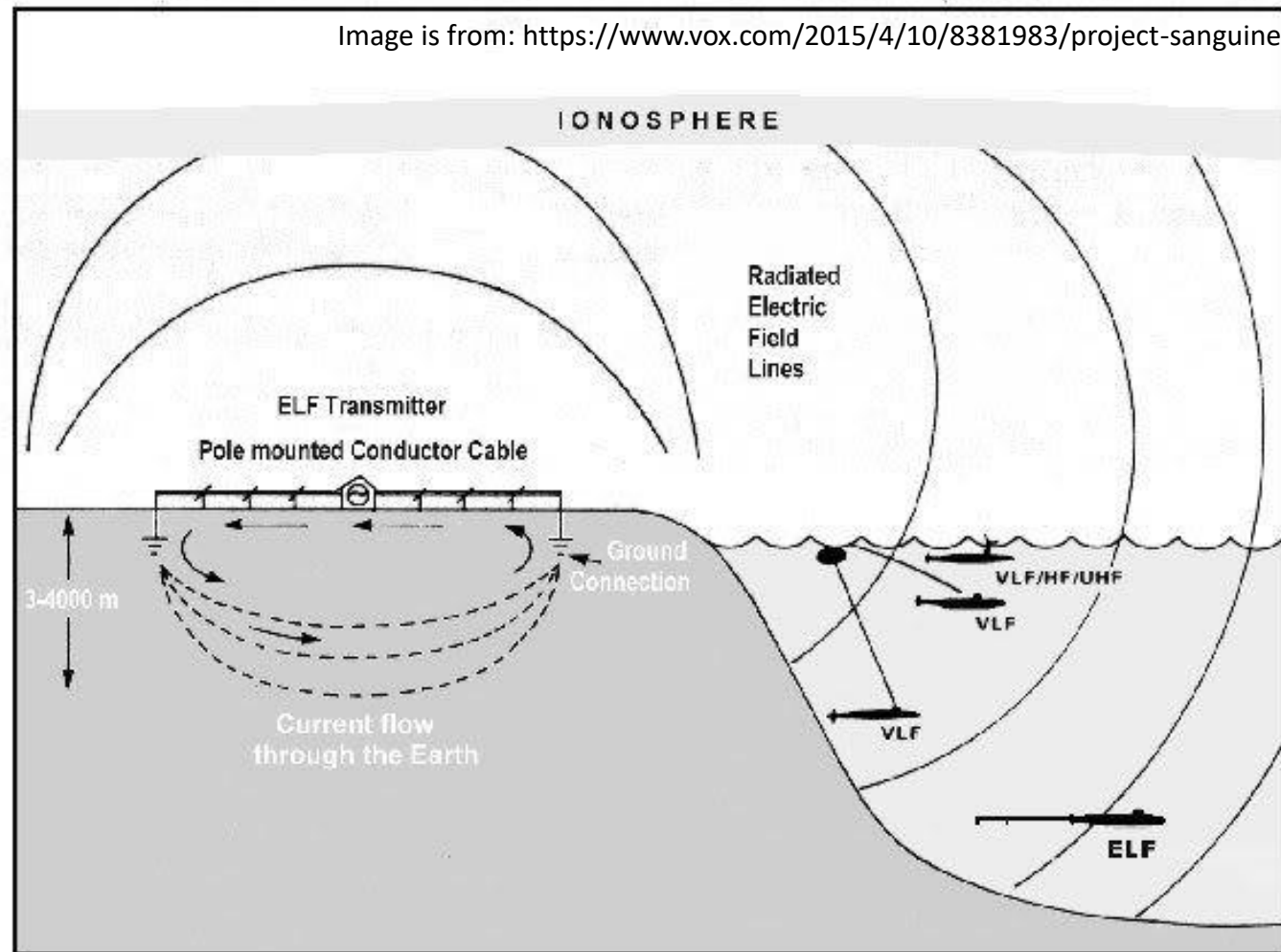
Skin effect

Image is from: <https://www.vox.com/2015/4/10/8381983/project-sanguine>

$$A_{\text{INSIDE}} / A_{\text{OUTSIDE}} \approx$$

$$e^{\left(- \frac{\text{depth}}{503 \cdot \sqrt{1/f \cdot \sigma}} \right)}$$

$$\text{or } e^{\left(- \frac{\text{depth}}{503 \cdot \sqrt{\rho/f}} \right)}$$



f: frequency; σ : conductivity; ρ : resistivity

(Assuming quasi-static conditions

$(2\pi f \cdot \epsilon \ll \sigma)$ and that the material is non magnetic ($\mu_r=1$)).

Objectives and Questions

- Can the effect of the Earth's crust on ELF-band radio waves be characterized by making measurements near the surface and underground?
- Can such measurements be used to determine the conductivity of the Earth's crust at the location of such measurements?

The measurements

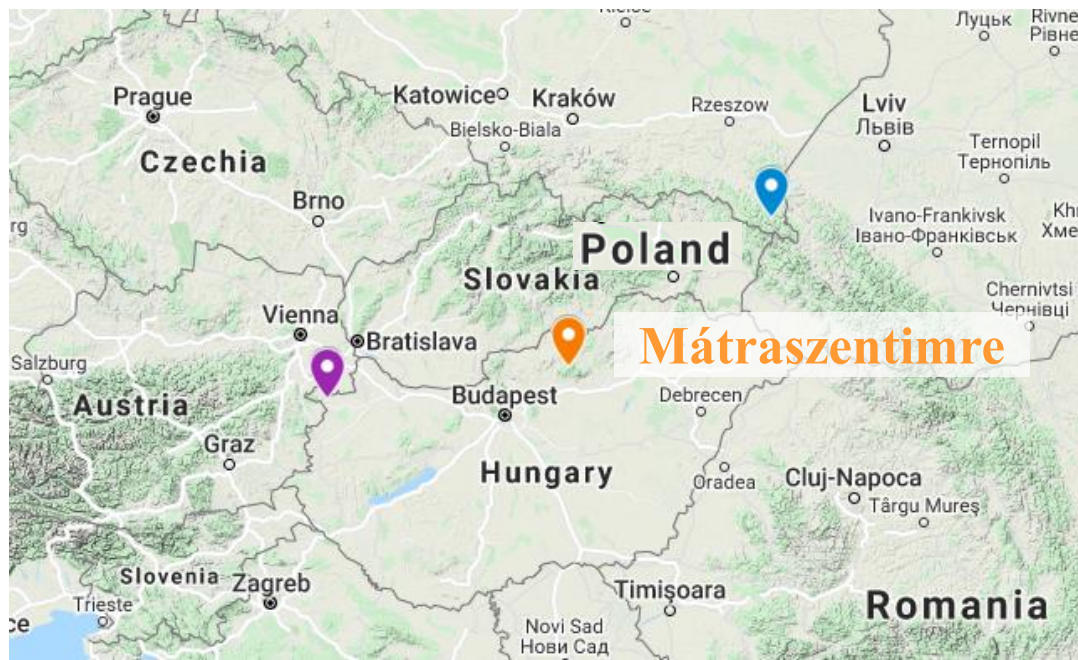
Two horizontal magnetic components of the atmospheric EM field was measured by a LEMI-423 magnetotelluric recording system in the 0.001-2000 Hz frequency range (sampling rate was 4 kHz) at Mátraszentimre, in the Mátra Mountains, Hungary in two not overlapping time periods.

Surface observations:

27-30 March, 2018. The magnetic observation site has been set up about 200 m away from the surface projection of the underground site.

Underground observations:

22-25 March, 2018 in the Matra Gravitational and Geophysical Laboratory in a mine shaft at a depth of 140 m.



Methodology

Use Q-bursts: natural, high SNR transient test signals produced by intense lightning.

- Calculate the amplitude transfer function between records from a reference ELF station and the records in Matra for the measurements both on the surface and underground. Do this for each Q-burst, then average. But first subtract the noise!

Amplitude spectra of a measured signal for any Q-burst :

$$A_{\text{Matra_Surf}}(f) = M_I(f) \cdot P(f, D) \cdot \text{Sys}_{\text{Matra}}(f)$$

$$A_{\text{RefSt}}(f) = M_I(f) \cdot P(f, D) \cdot \text{Sys}_{\text{RefSt}}(f)$$

$$A_{\text{Matra_Udg}}(f) = M_I(f) \cdot P(f, D) \cdot \text{Sys}_{\text{Matra}}(f) \cdot L_{\text{Matra}}(f)$$

$$+ N_{\text{Matra_Surf}}(f) \cdot \text{Sys}_{\text{Matra}}(f)$$

$$+ N_{\text{RefSt}}(f) \cdot \text{Sys}_{\text{RefSt}}(f)$$

$$+ N_{\text{Matra_Udg}}(f) \cdot \text{Sys}_{\text{Matra}}(f)$$

Current
moment of
the source
lightning
stroke

Propagation
term, D is the
source-observer
distance

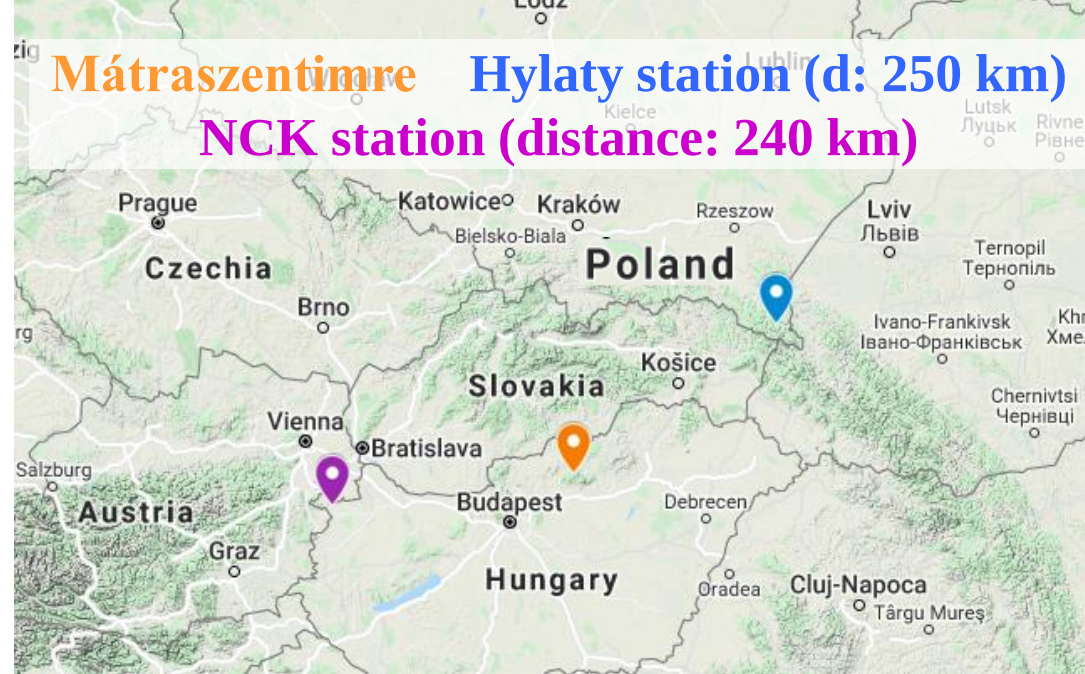
Response
function of the
measuring
system

Loss term:
Transfer
function of the
Earth's crust

Noise
(including SR)
**Must be
subtracted!**

- The ratio of the surface and underground amplitude transfer functions yields the „loss term”, i.e., the amplitude transfer function of the Earth's crust in the Matra.
- The conductivity/resistivity of the Earth's crust can be obtained from the amplitude transfer function of the Earth's crust via fitting the model of the skin effect.

Reference measurements



Hylaty Station

Continuous measurements

H_{NS} and H_{EW} components

$f_s = 887.784 \text{ Hz}$

Effective bandwidth up to $\sim 400 \text{ Hz}$

NCK station, Continuous measurements

E_z , H_{NS} and H_{EW} components

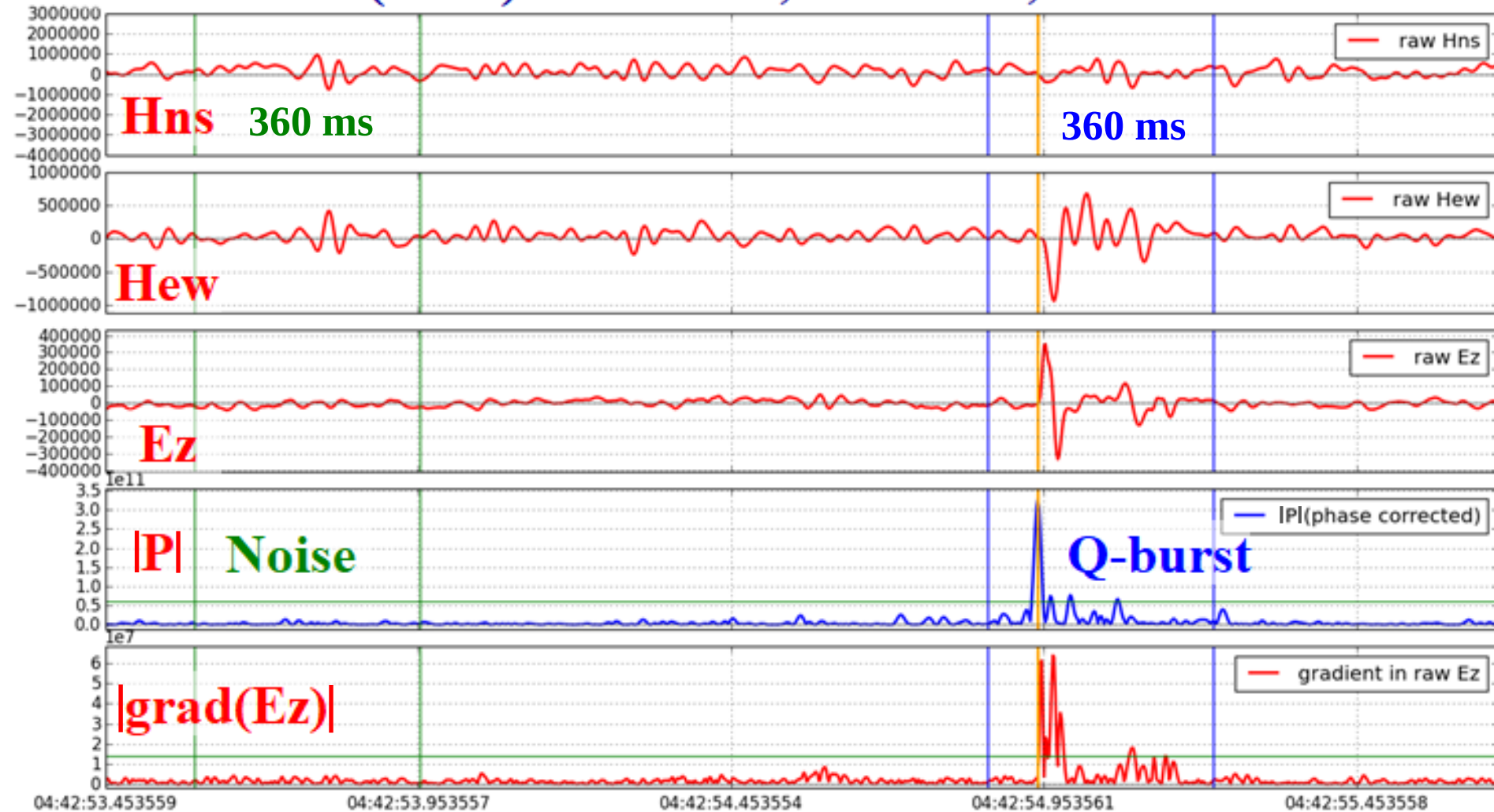
$f_s = 500 \text{ Hz}$, Effective bandwidth 5-35 Hz

Identification of Q-bursts

Example event from NCK

Identification is based on outstanding values of the Poynting vector and signal gradient in the E_z time series.

Time series (UTC) from NCK, 23 March, 2018.

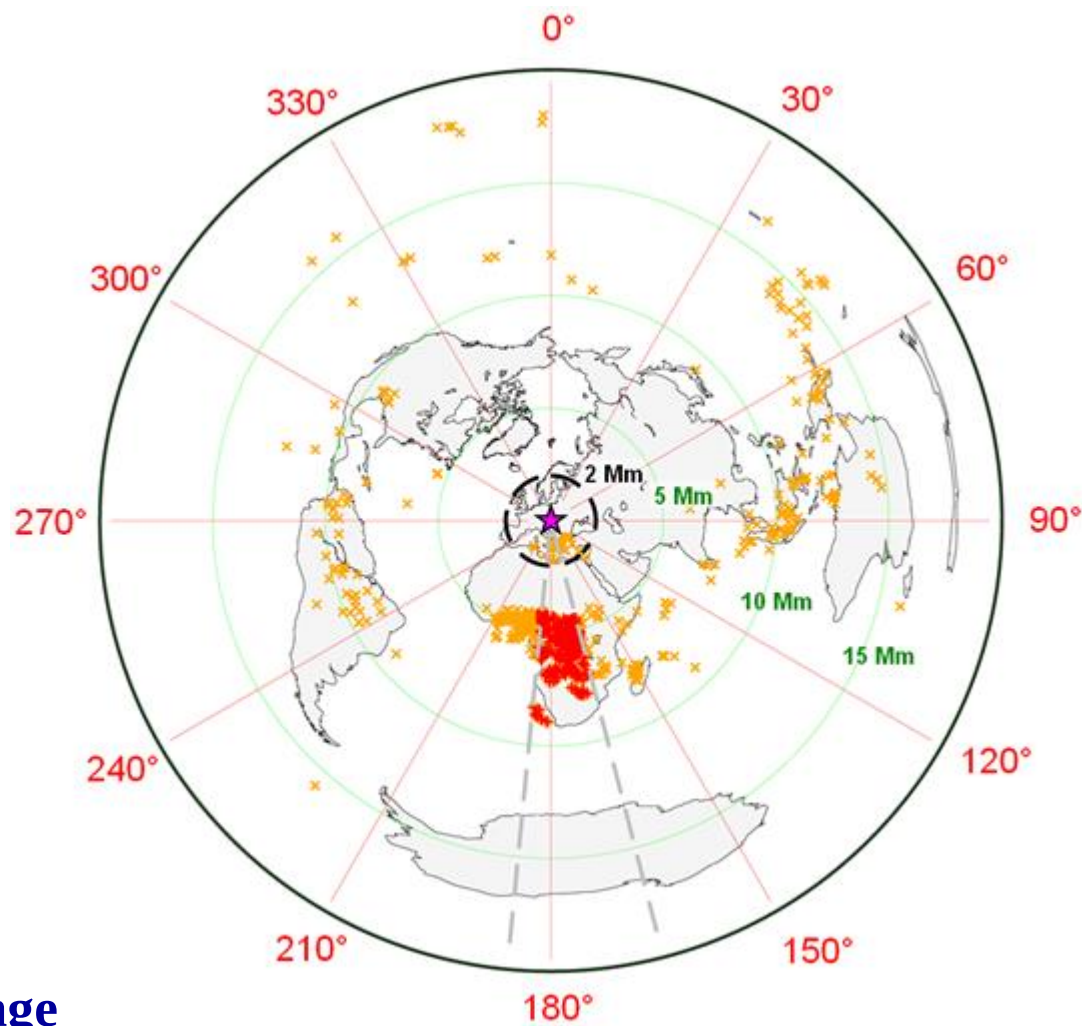


Selection of Q-bursts

Location of source lightning strokes of Q-bursts, detected in NCK on 22-23 & 27-28 March, 2018. WWLLN data were used, event times were matched.

Selected events were produced by sources which were farther from the ROI (specifically from NCK) more than 2000 km (2 Mm), along the shortest GCP path.

Additional condition when the reference station was NCK:
azimuth in the $165.5^\circ - 185.5^\circ$ range
(to use only the H_{EW} coil $\leq$ reduces noise)

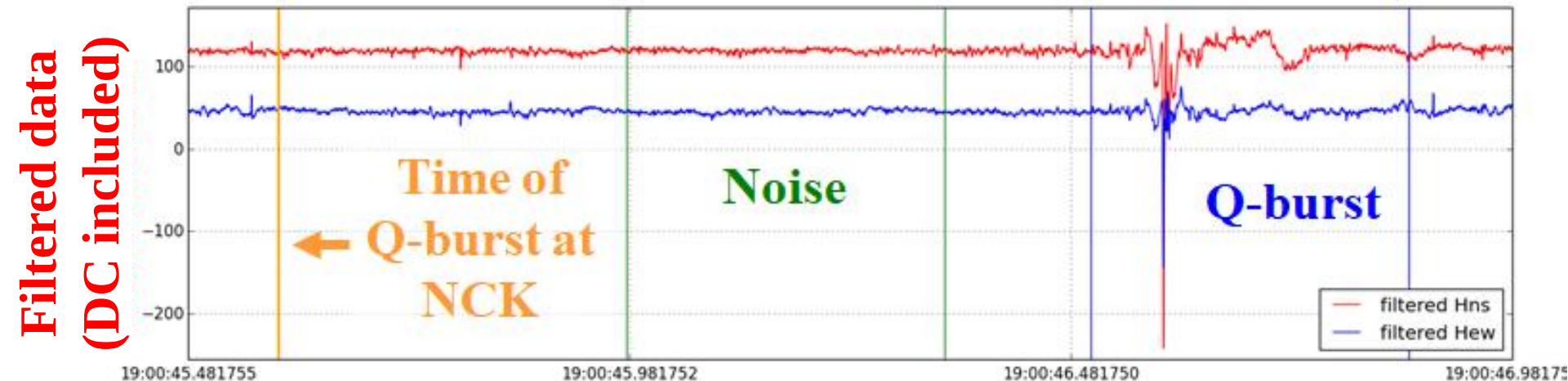
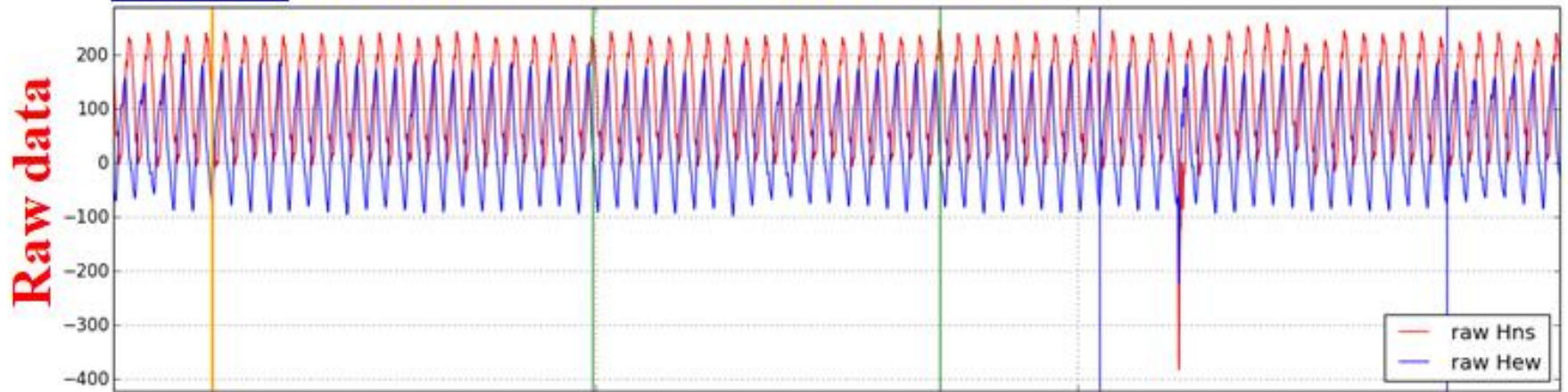


Number of Q-bursts taken from	NCK as reference	Hylaty as reference
Surface measurements	152	181
Underground measurements	85	269

Example event from Mátra, surface measurements

Mind the noise and time offset! (GPS hardware issue?)

**Time series (UTC) from Mátra Mountains
surface measurements, 27 March, 2018**



19:00:45.481755

19:00:45.981752

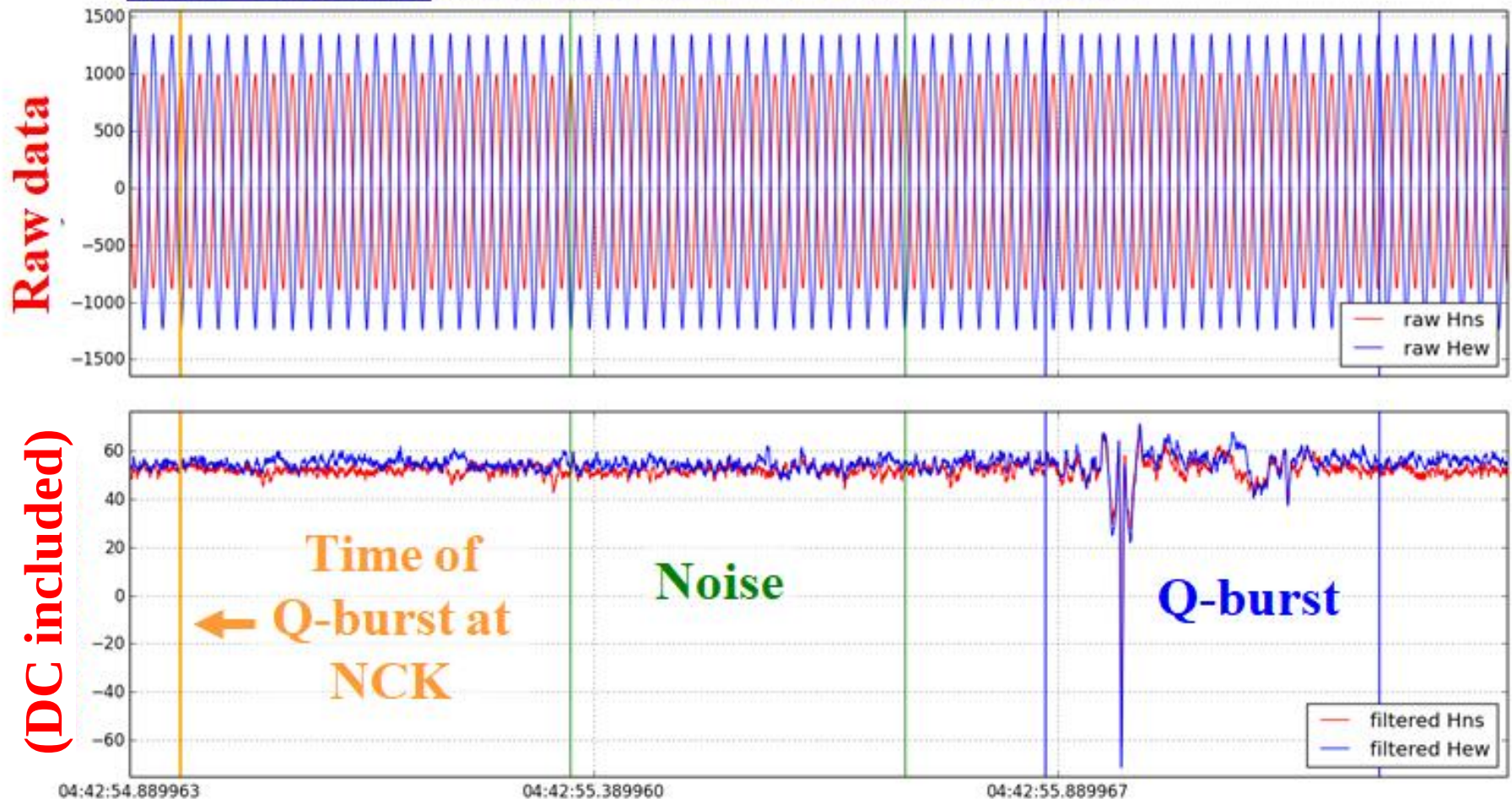
19:00:46.481750

19:00:46.981753

Example event from Mátra, underground measurements

Mind the noise and time offset! (GPS hardware issue?)

**Time series (UTC) from Mátra Mountains
underground measurements, 23 March, 2018**



Pre-processing the data → Homogenization of the time series

- Application of low-pass/band-pass digital filters of the same passband on the time series both from Matra and the actually used Reference station:
NCK as the reference station: FIR filter of 2-34 Hz passband
Hylaty as the reference station: FIR filter with three passbands:
2-34 Hz, 71-95 Hz, 105-140 Hz
(to avoid the 50 Hz, 100 Hz, and 150 Hz power line noise)
- Down sampling all time series to a common same sampling rate
300 Hz in our case
- Using the same time window length for both Q-burst and noise data:
360 ms.

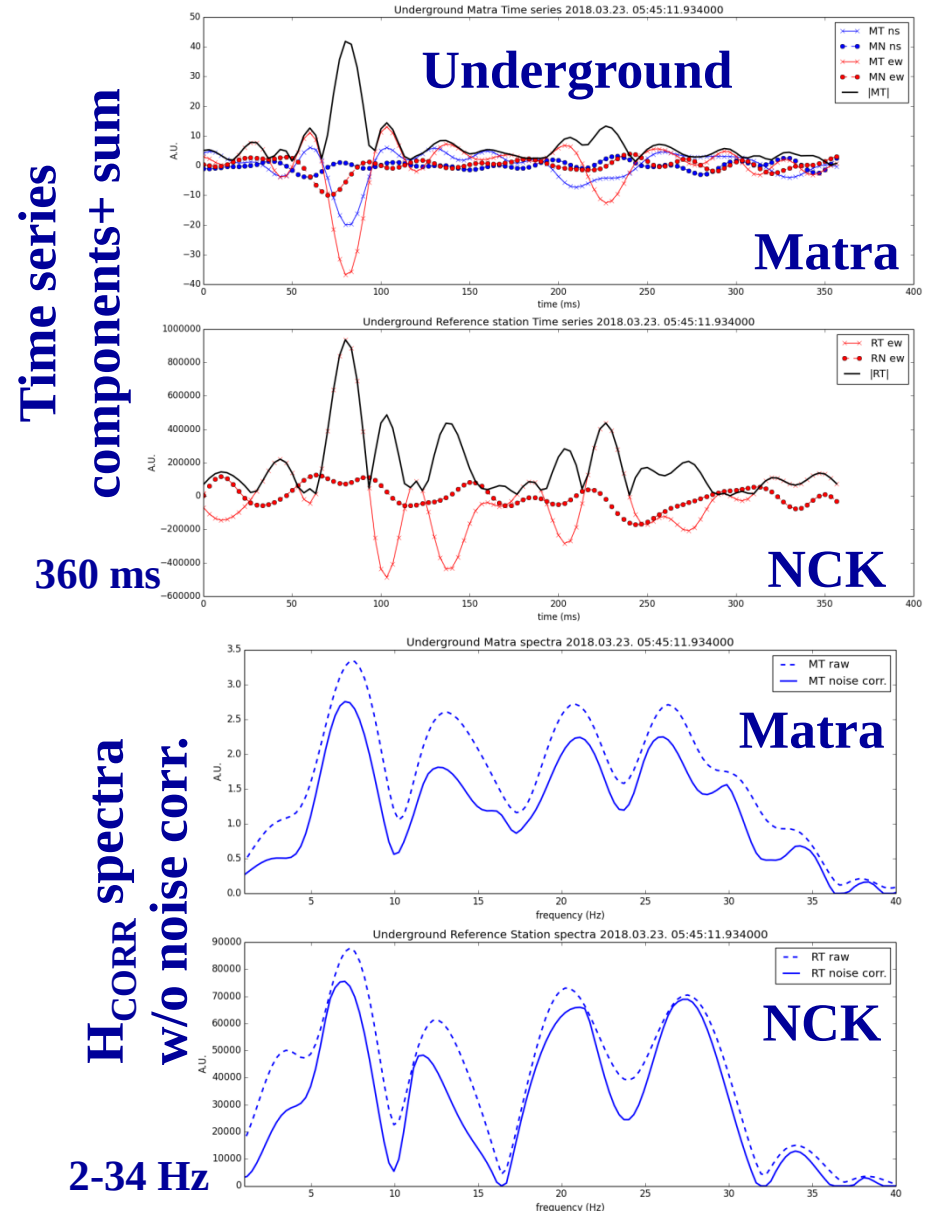
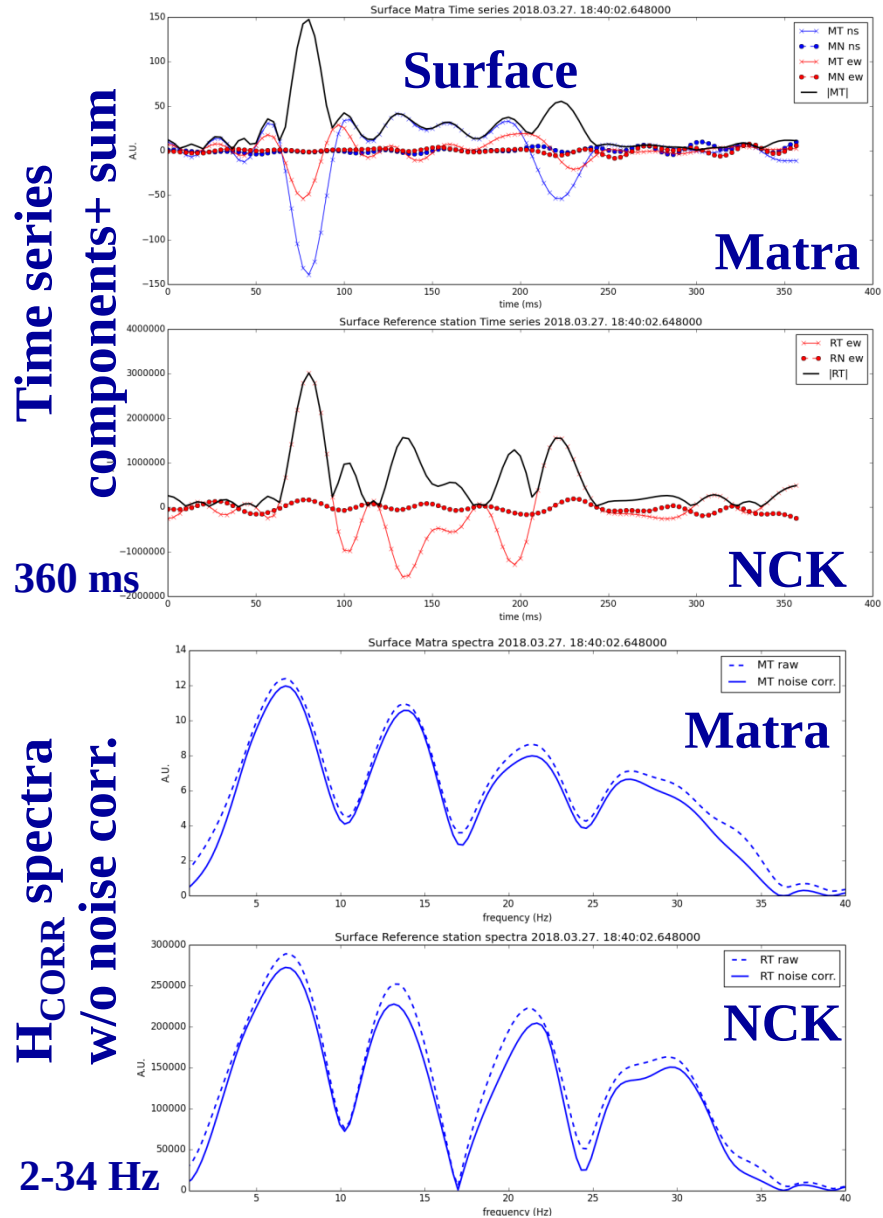
In case of Q-bursts: -50 ms and +250 ms relative to event time, extended by a 30-30 ms head and tail for tapering by a Hanning window function.

The time window of the corresponding noise immediately precedes the time window of the event in automatic data processing mode.

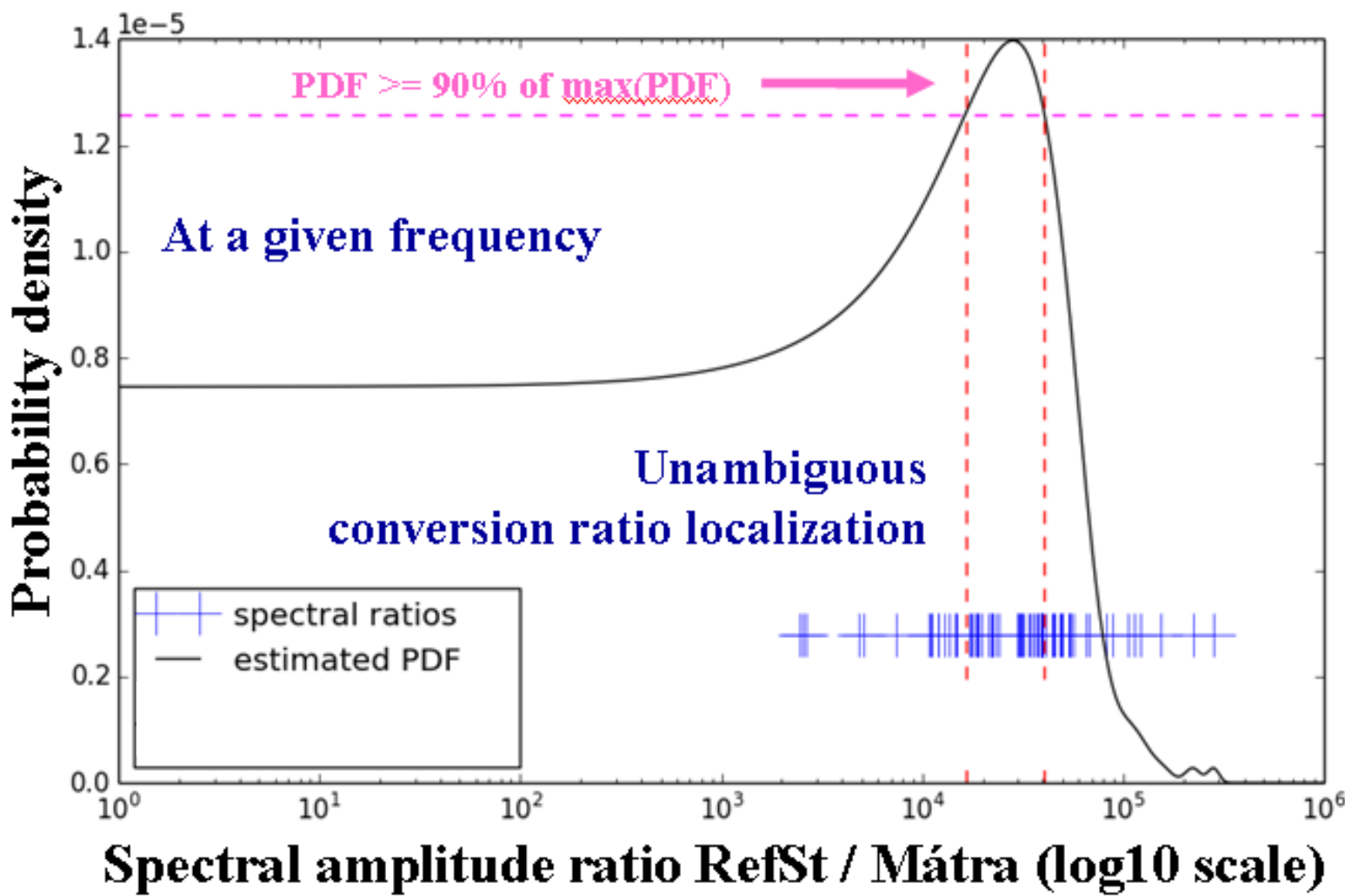
Spectral noise example

correction NCK as RefSt

$$H_{CORR}^{Q-burst} = \sqrt{\left(H_{EW}^{Q-burst} - H_{EW}^{noise}\right)^2 + \left(H_{NS}^{Q-burst} - H_{NS}^{noise}\right)^2}$$

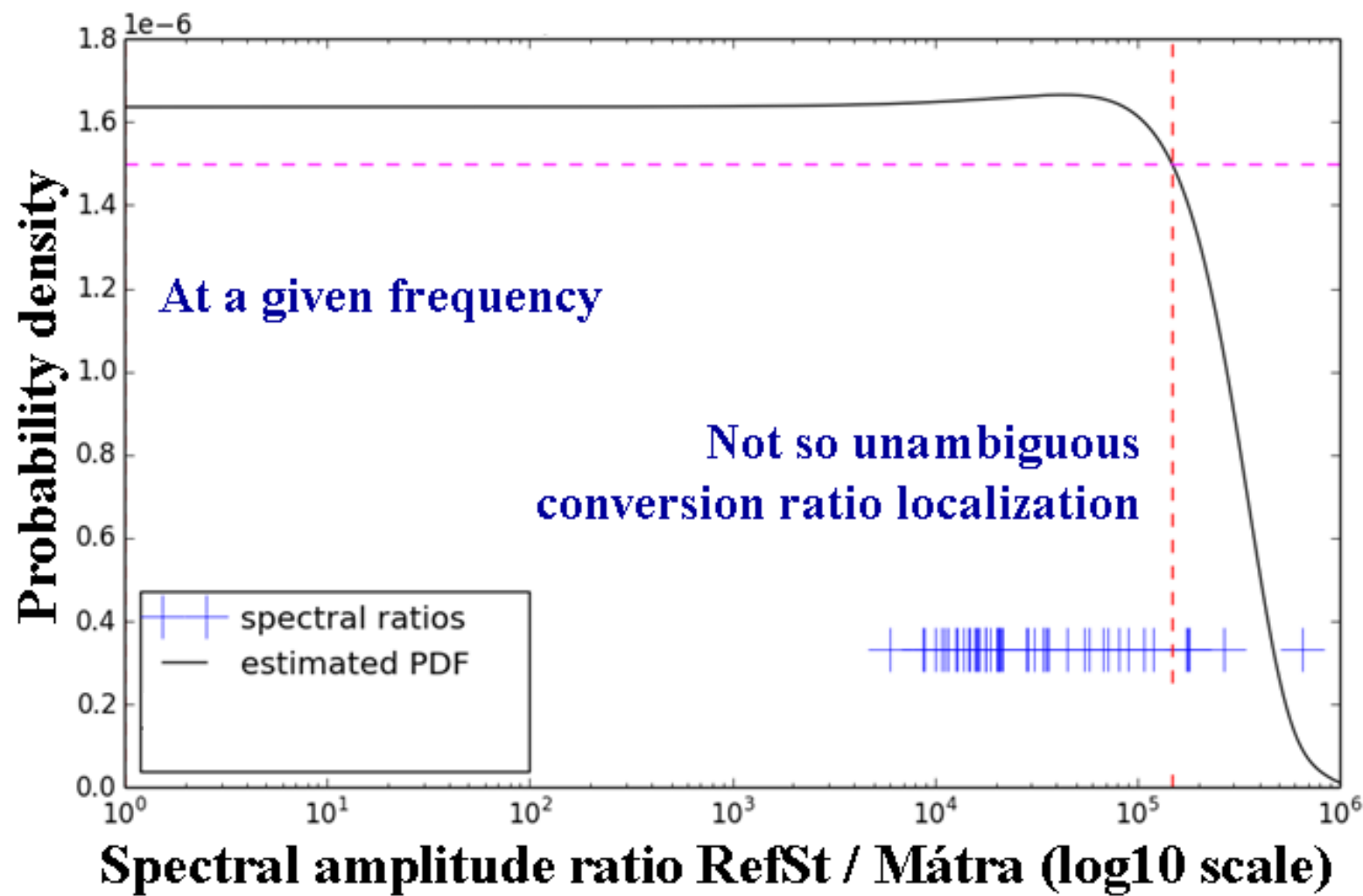


Spectral conversion ratios for each freq. – a good case



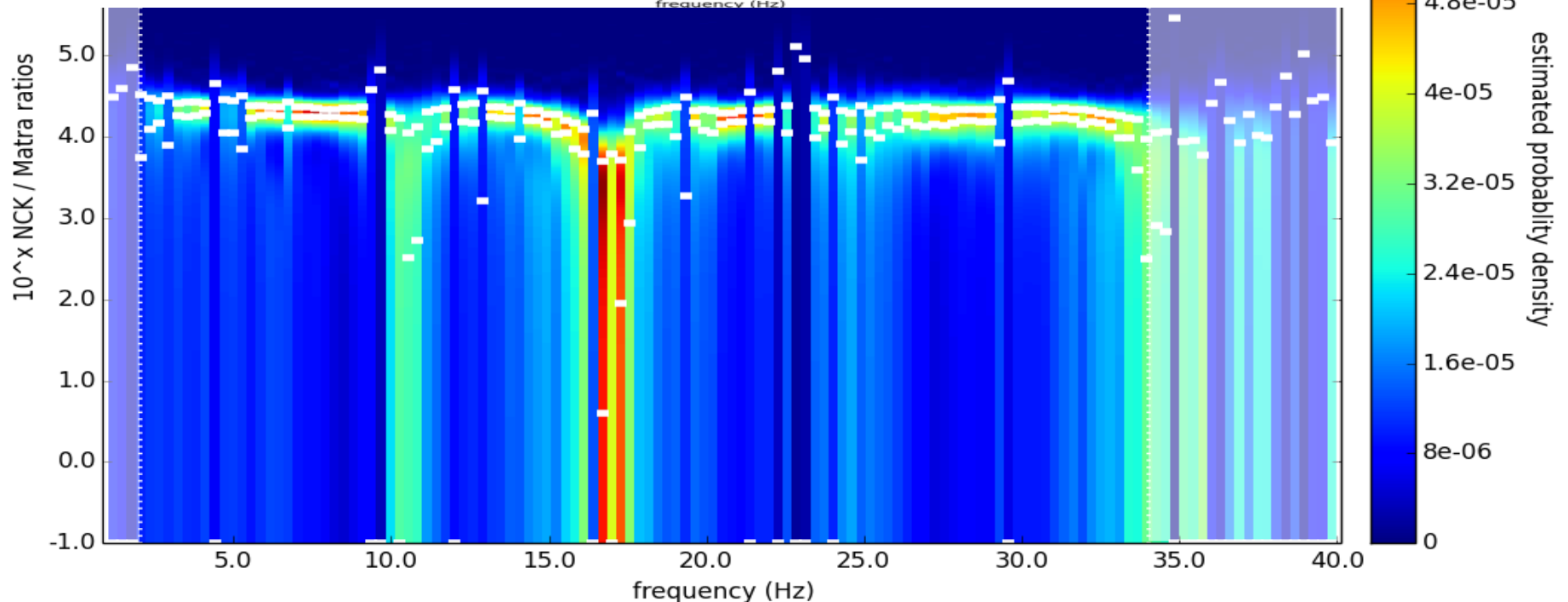
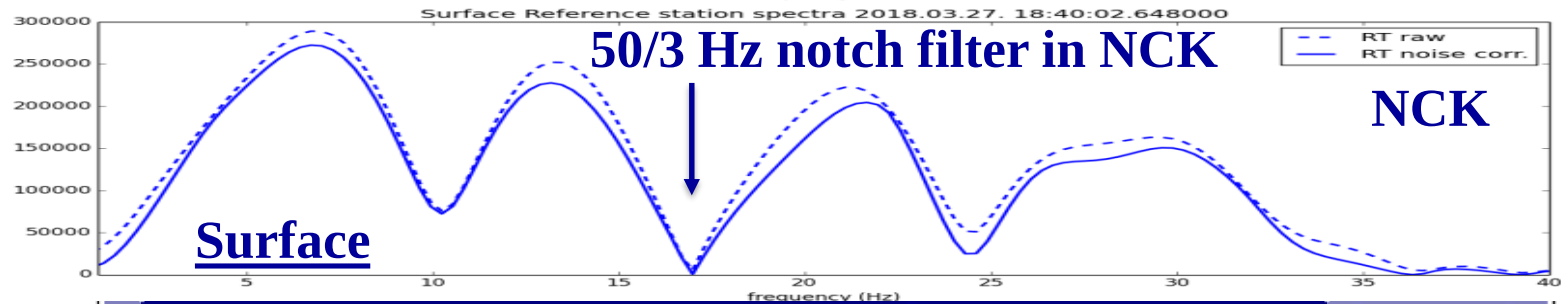
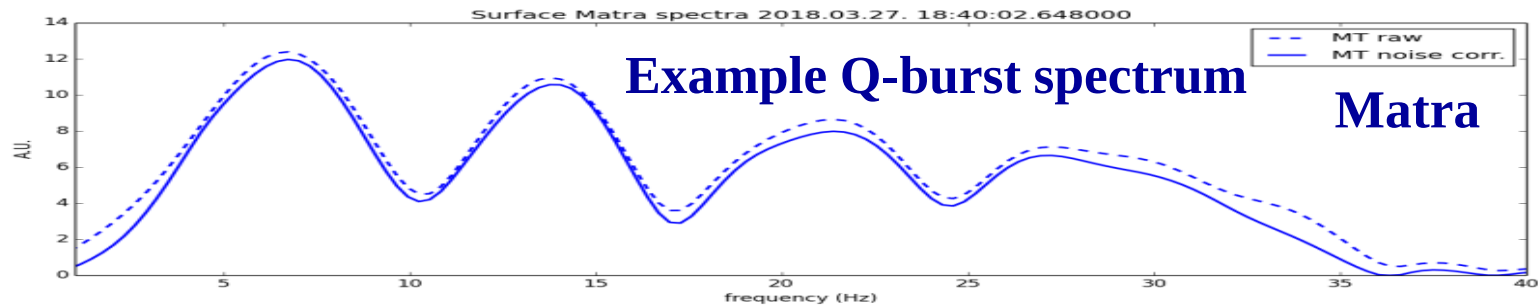
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Spectral conversion ratios for each freq. – a poor case

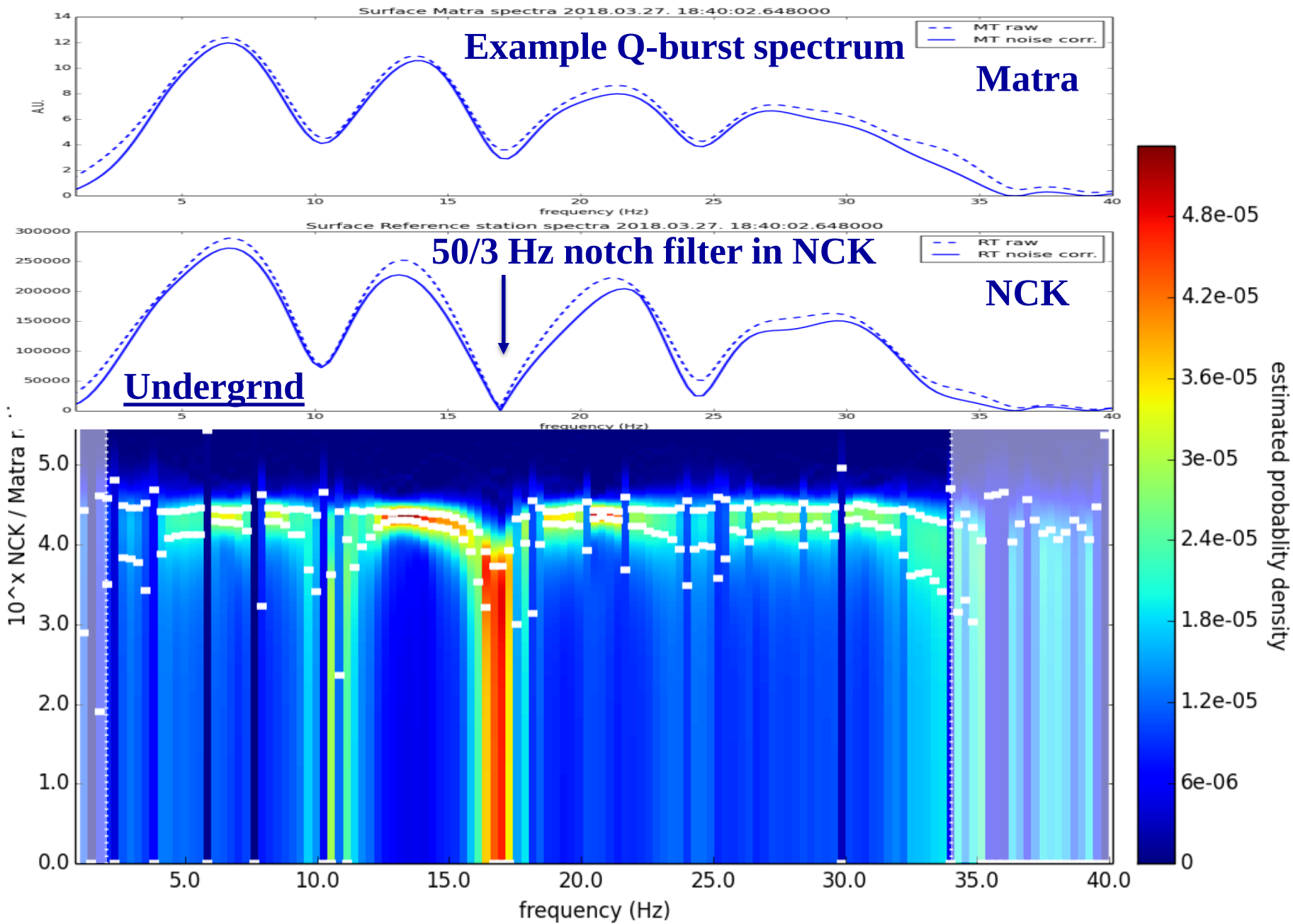


Number of Q-bursts used in	NCK as reference	Hylaty as reference
Surface measurements	152	181
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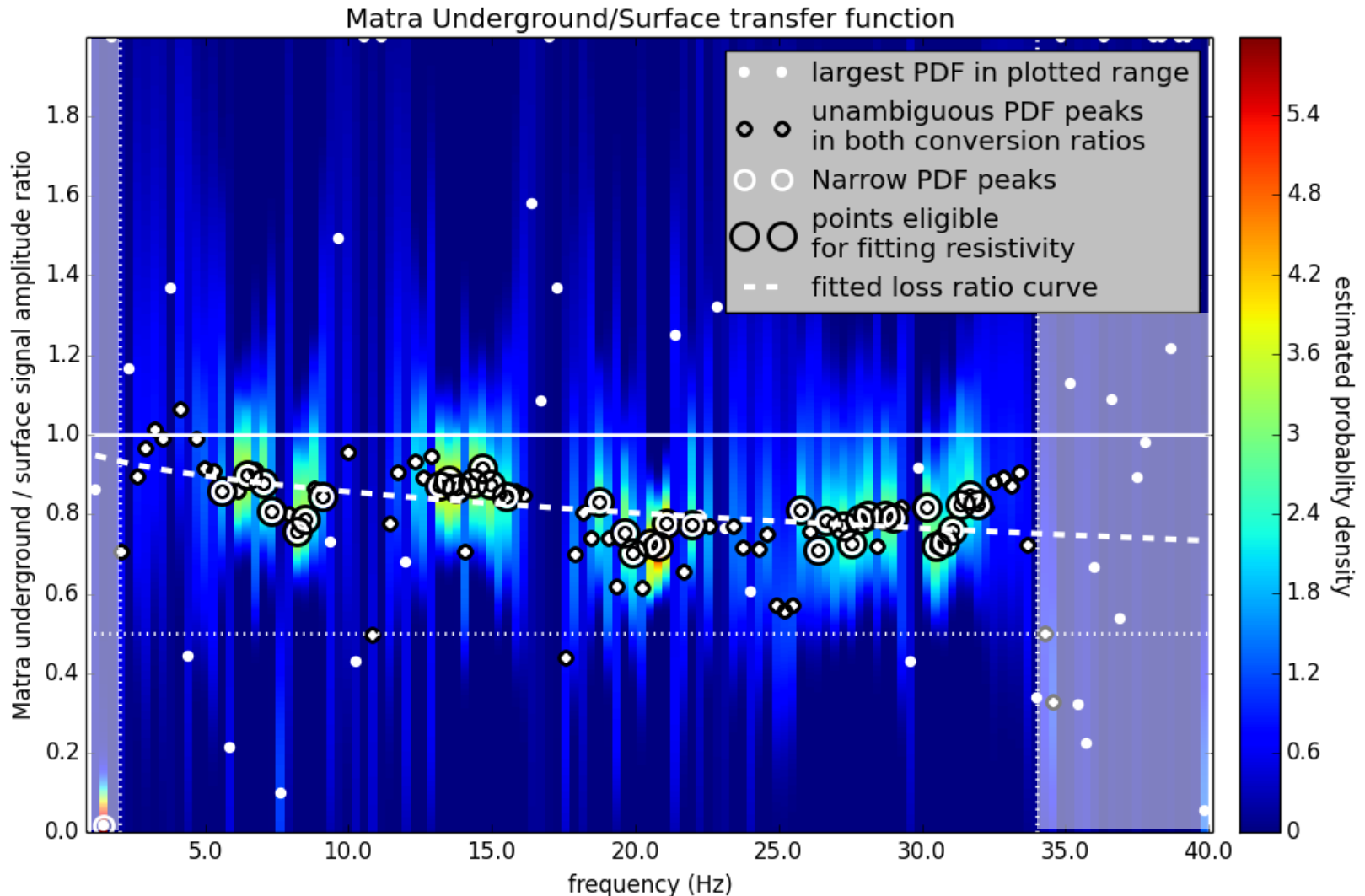
Spectral conversion ratios: between Matra and NCK, 2-34 Hz



Spectral conversion ratios: between Matra and NCK, 2-34 Hz



Amplitude loss spectrum Reference station: NCK, 2-34 Hz



Requirements for points accepted for fitting: (1) Well defined peaks in PDFs in both surface and underground transfer ratio distributions, (2) Narrow peak in the loss ratio distribution (peak width at 90% < 0.15), (3) Reasonable value: between 0.5 and 1.

Fitted parameters: $\sigma = 0.031 \text{ S/m}$, $\rho = 32.28 \Omega\text{m}$

Spectral noise example

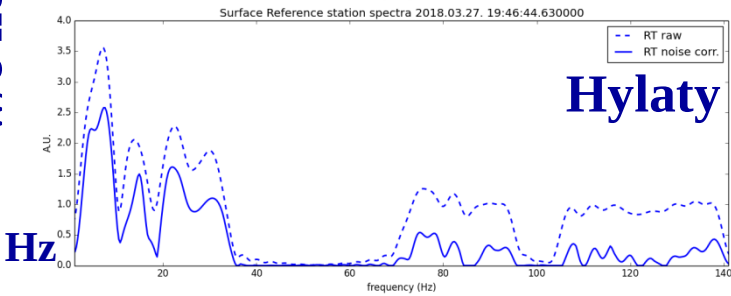
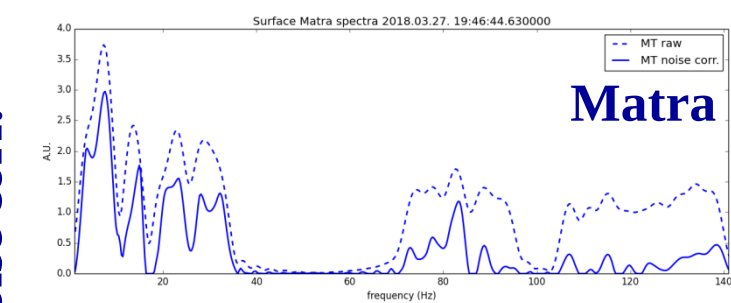
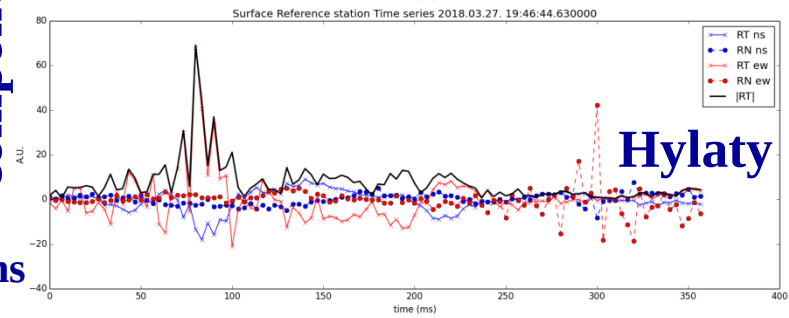
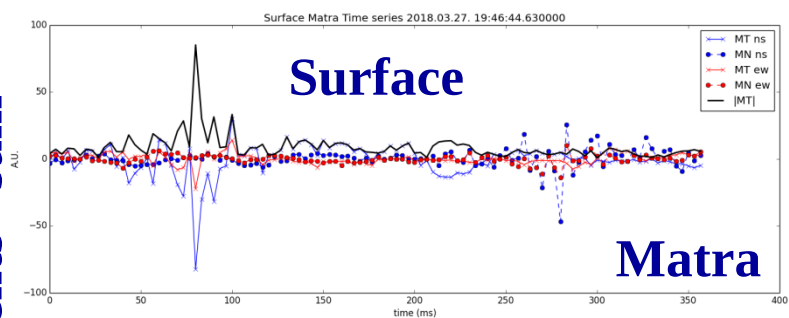
correction: Hylaty as RefSt

$$H_{CORR}^{Q-burst} = \sqrt{\left(H_{EW}^{Q-burst} - H_{EW}^{noise}\right)^2 + \left(H_{NS}^{Q-burst} - H_{NS}^{noise}\right)^2}$$

Time series
components+ sum

360 ms

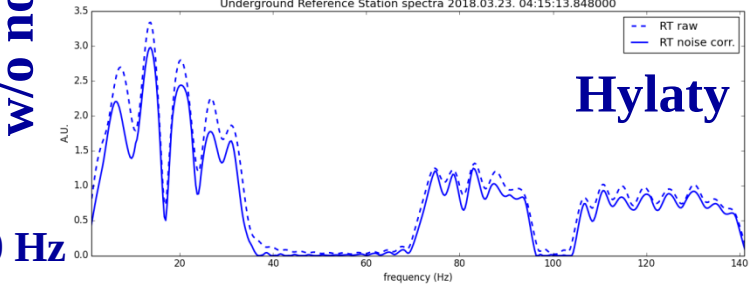
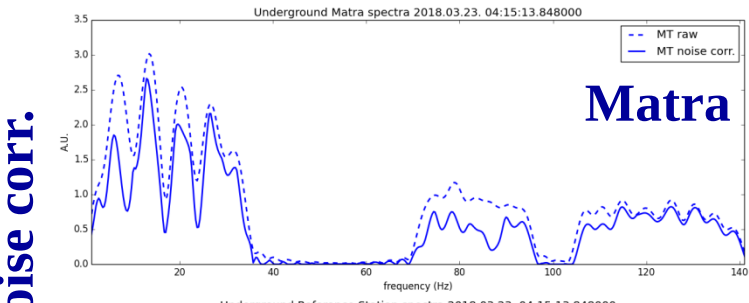
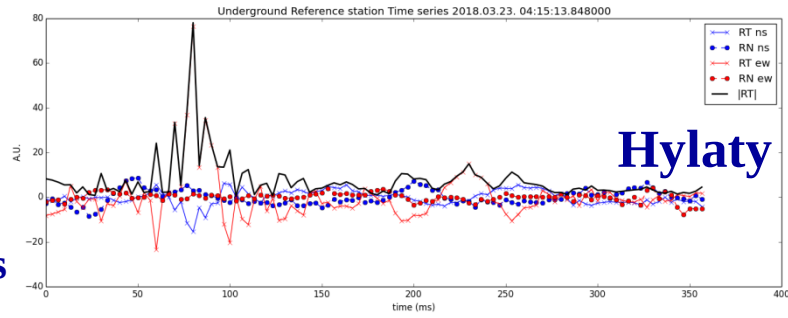
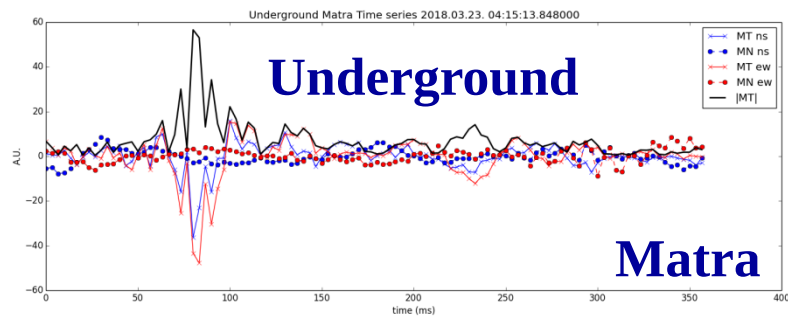
H_{CORR} spectra
w/o noise corr.
2-140 Hz



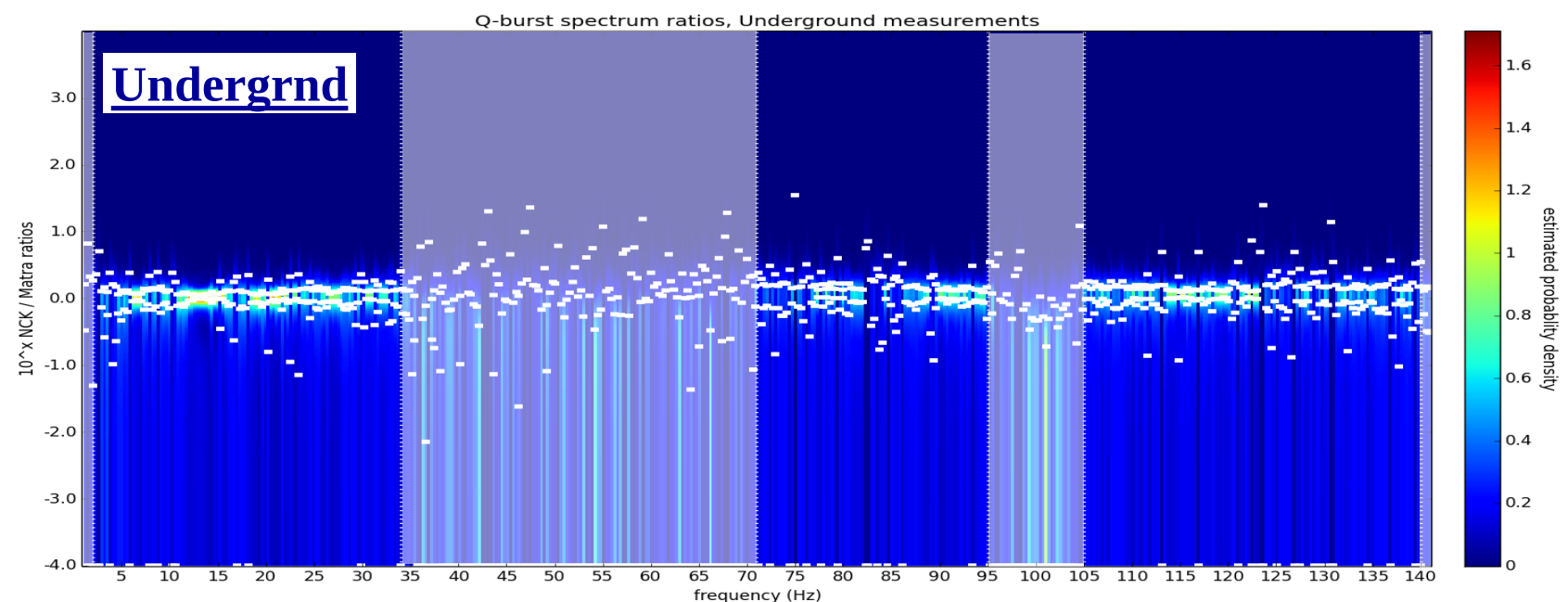
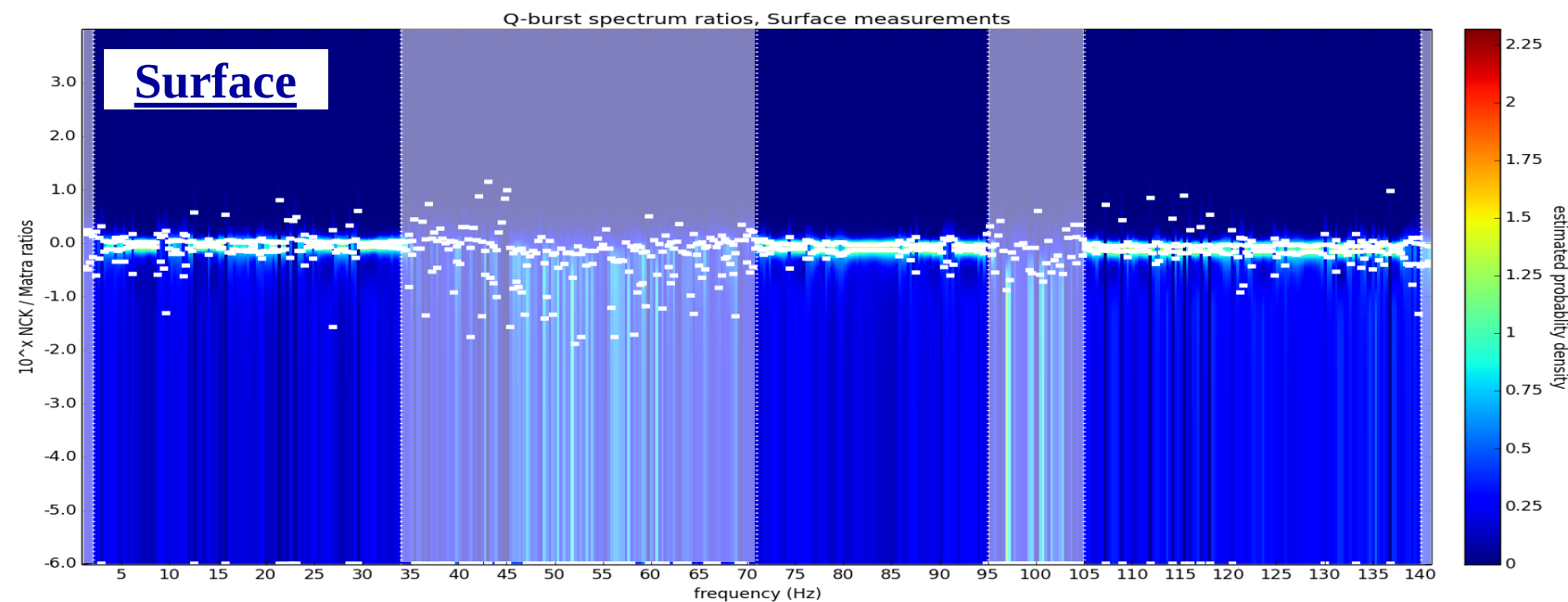
Time series
components+ sum

360 ms

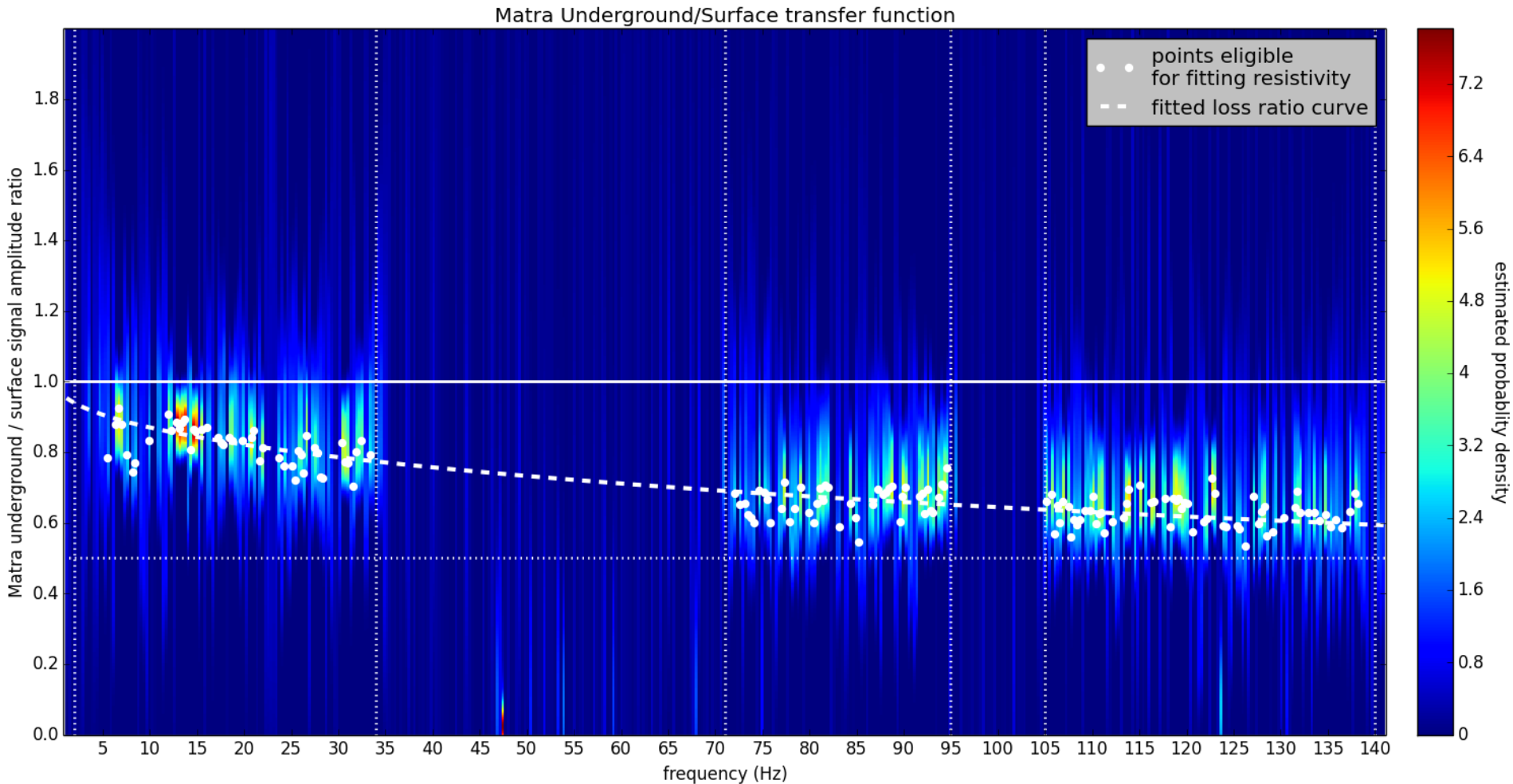
H_{CORR} spectra
w/o noise corr.
2-140 Hz



Spectral conversion ratios: between Matra and Hylaty, 2-140 Hz



Amplitude loss spectrum Reference station: Hylaty, 2-140 Hz



Requirements for points accepted for fitting: (1) Well defined peaks in PDFs in both surface and underground transfer ratio distributions, (2) Narrow peak in the loss ratio distribution (peak width at 90% < 0.15), (3) Reasonable value: between 0.5 and 1.

Fitted parameters: $\sigma = 0.026 \text{ S/m}$, $\rho = 39.06 \text{ } \Omega\text{m}$

Before the conclusions ...

Acknowledgements

This work was supported by the National Research, Development and Innovation Office, Hungary-NKFIH, K115836.

The Authors also acknowledge the support of COST, and the Action CA15211, ELECTRONET as a whole.



... and the Conclusions

- Dielectric properties of the Earth's within its 140 m deep uppermost layer were successfully estimated at the Matra Gravitational and Geophysical Laboratory, Hungary, using Q-bursts occurring worldwide.
- The success of the applied method requires a statistical approach, proper pre-processing, and careful correction of the data for (the rather variable) local noise.
- From the ratio of signal amplitudes measured at the surface and inside a mine shaft, conductivity (resistivity) of the ground layer above the measuring point under ground was estimated using ELF band records from independent reference stations.

With data from NCK, Hungary: $\sim 0.031 \text{ S/m}$ ($\sim 32 \text{ }\Omega\text{m}$).

With data from Hylaty, Poland: $\sim 0.026 \text{ S/m}$ ($\sim 39 \text{ }\Omega\text{m}$).

- Fair agreement of the results from independent measurements confirm the validity of the applied method and the values of the obtained parameters.
- The obtained resistivity is somewhat lower than the values known for highly moist ground (50-200 Ωm), which matches the conditions of the surface measurements in the Matra: clearing in a woodland in spring, shortly after the snow has melted. (TAI Inc Consuletter International, Vol. 6, No. 5, Earth Constants by Peter N Saveskie)
- The results suggest that the soil may play dominant role in the attenuation of ELF band electromagnetic waves in the uppermost layer of the Earth's crust .