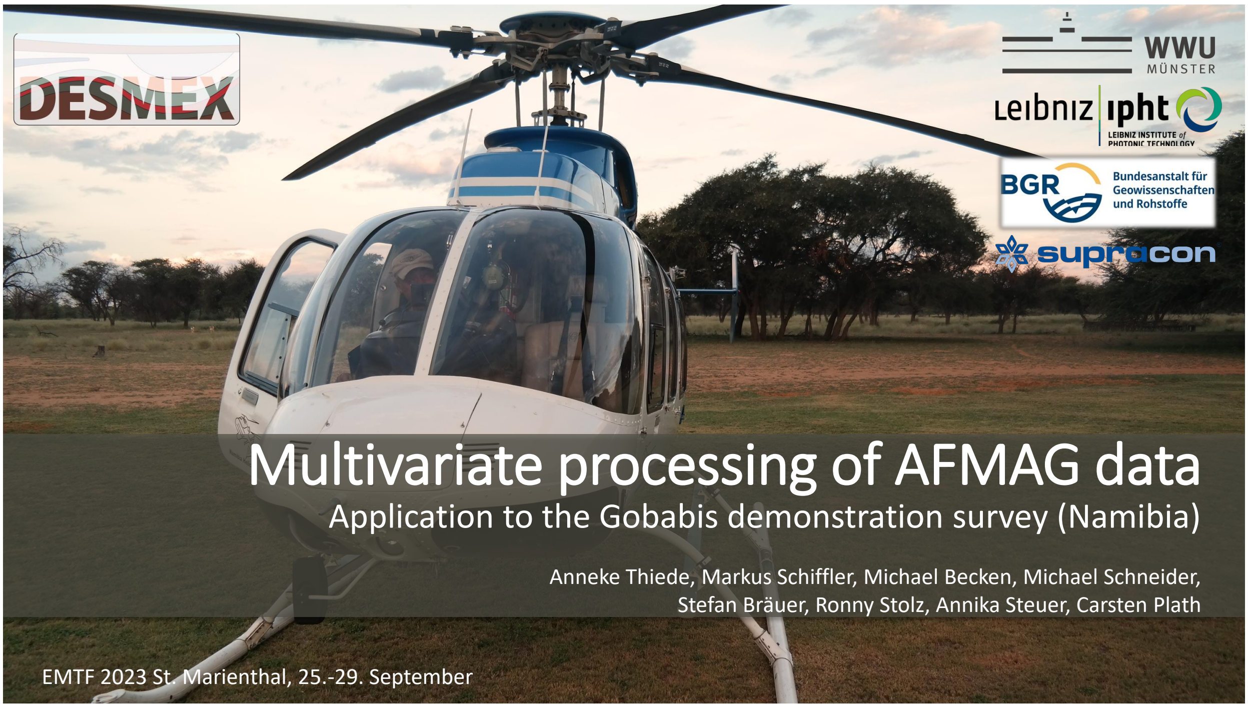
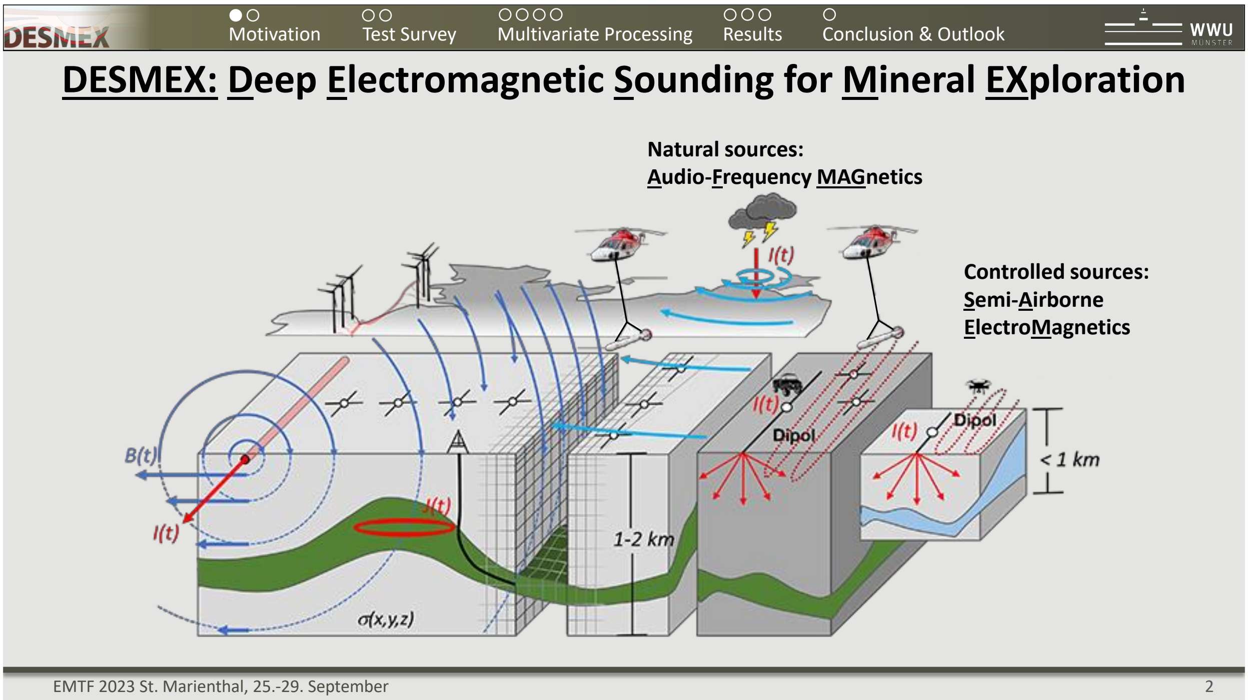

DESMEX
WWU MÜNSTER
Leibniz ipht
LEIBNIZ INSTITUTE of PHOTONIC TECHNOLOGY
BGR Bundesanstalt für Geowissenschaften und Rohstoffe
supracon
Multivariate processing of AFMAG data
Application to the Gobabis demonstration survey (Namibia)
Anneke Thiede, Markus Schiffler, Michael Becken, Michael Schneider,
Stefan Bräuer, Ronny Stolz, Annika Steuer, Carsten Plath
EMTF 2023 St. Marienthal, 25.-29. September


DESMEX
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
DESMEX: Deep Electromagnetic Sounding for Mineral EXploration
Natural sources:
Audio-Frequency MAGnetics
Controlled sources:
Semi-Airborne
ElectroMagnetics
I(t)
B(t)
I(t)
J(t)
σ(x,y,z)
1-2 km
Dipol
I(t)
Dipol
< 1 km
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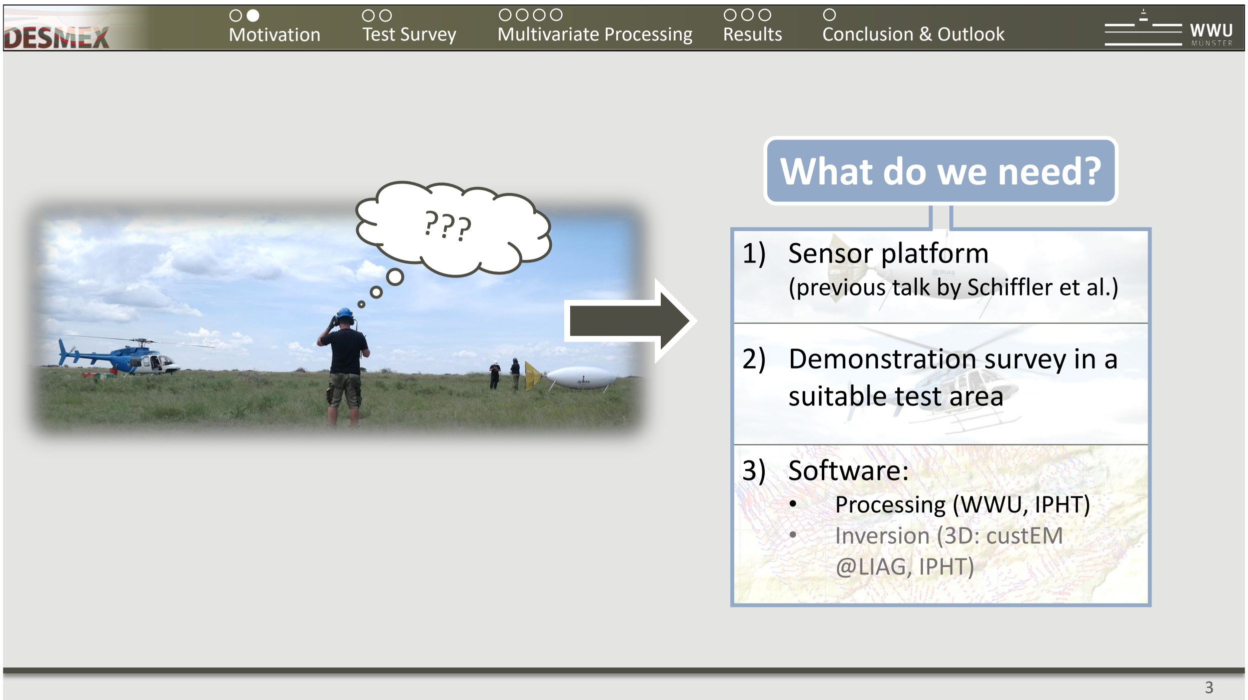
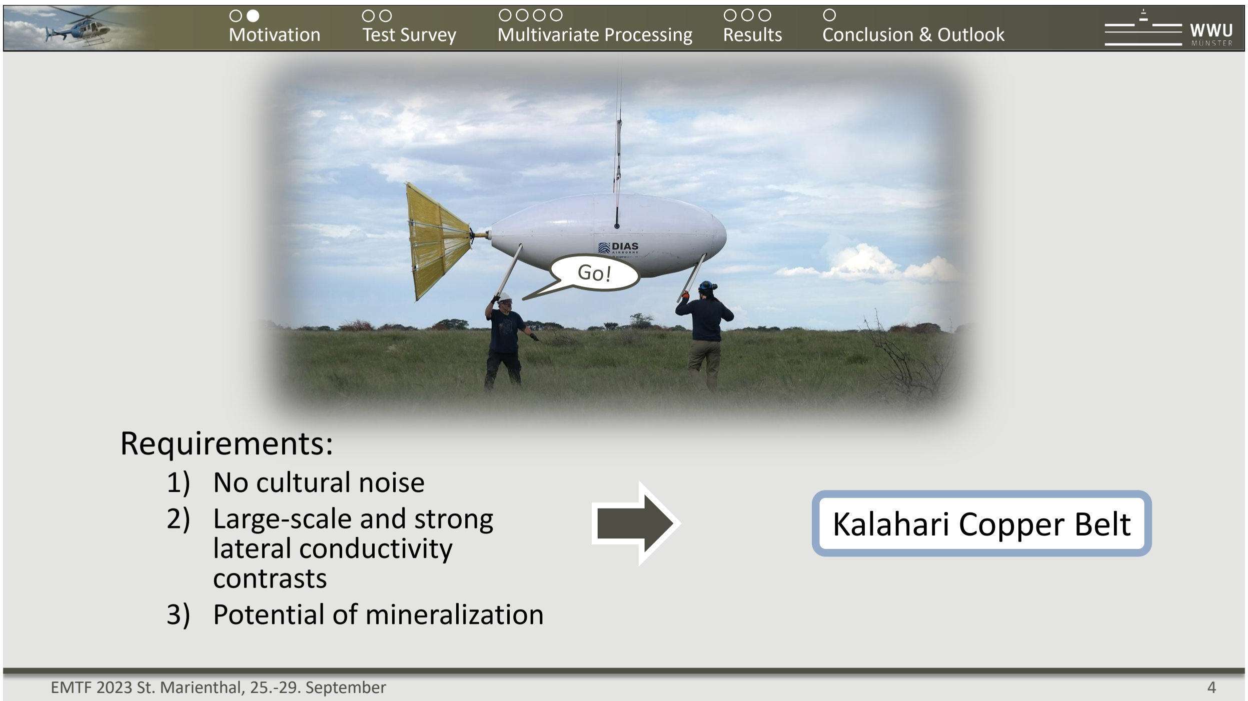
2


DESMEX
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
???
What do we need?
1) Sensor platform
(previous talk by Schiffler et al.)
2) Demonstration survey in a suitable test area
3) Software:
• Processing (WWU, IPHT)
• Inversion (3D: custEM @LIAG, IPHT)
3


Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
Go!
Requirements:
1) No cultural noise
2) Large-scale and strong lateral conductivity contrasts
3) Potential of mineralization
Kalahari Copper Belt
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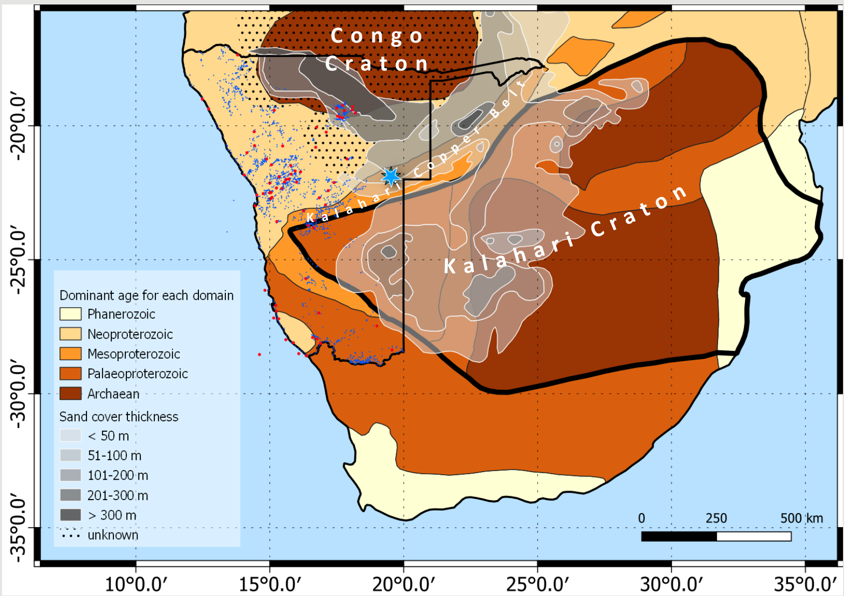
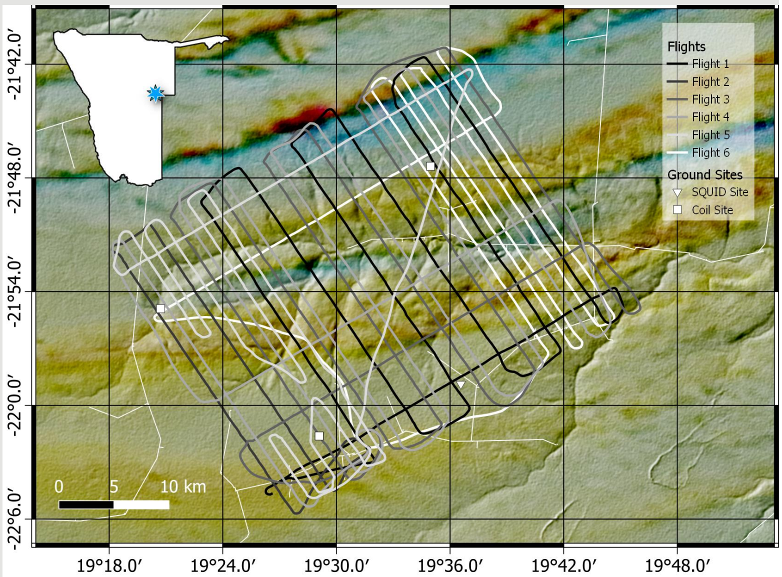
Tectonics

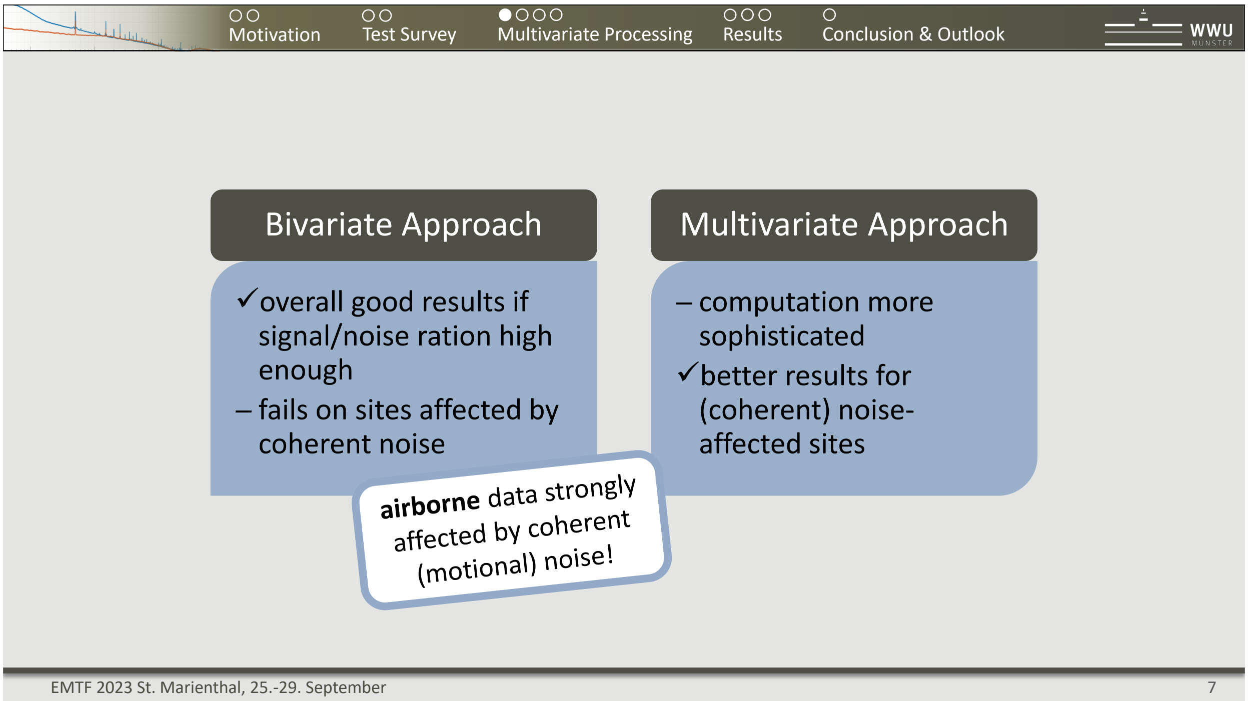
- KCB:
  - Cu, Ag, Pb, Zn, Fe sulphides
- Covered by Kalahari sands in NE part
- Mining activities at Klein Aub, Witvlei and Ghanzi Ridge



Survey

- Area: 30 x 36 km²
- Set up:
  - Flight lines: 31/37 (1 km spacing, 890.6 km)
  - Tie lines: 5/6 (5 km spacing, 176.8 km)
  - line spacing: 1km / 5km
- Ground stations ($\vec{E}$ and $\vec{B}$-field):
  - 1 SQUID base station
  - 3 induction coil stations




Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
Bivariate Approach
✓overall good results if signal/noise ration high enough
– fails on sites affected by coherent noise
Multivariate Approach
– computation more sophisticated
✓better results for (coherent) noise-affected sites
airborne data strongly affected by coherent (motional) noise!
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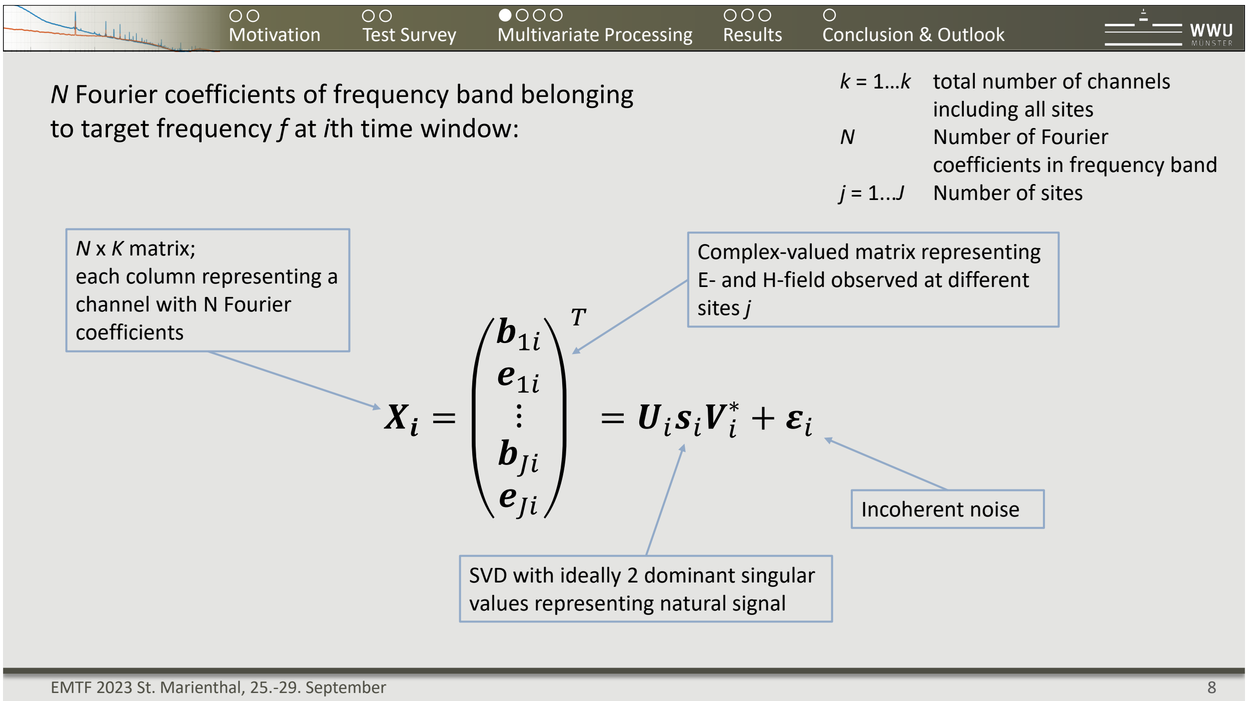
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
N Fourier coefficients of frequency band belonging to target frequency *f* at *i*th time window:
k = 1…*k* total number of channels including all sites
N Number of Fourier coefficients in frequency band
j = 1…*J* Number of sites
N x *K* matrix; each column representing a channel with N Fourier coefficients
Complex-valued matrix representing E- and H-field observed at different sites *j*
$\boldsymbol{X}_i = \begin{pmatrix} \boldsymbol{b}_{1i} \\ \boldsymbol{e}_{1i} \\ \vdots \\ \boldsymbol{b}_{Ji} \\ \boldsymbol{e}_{Ji} \end{pmatrix}^T = \boldsymbol{U}_i \boldsymbol{s}_i \boldsymbol{V}_i^* + \boldsymbol{\varepsilon}_i$
Incoherent noise
SVD with ideally 2 dominant singular values representing natural signal
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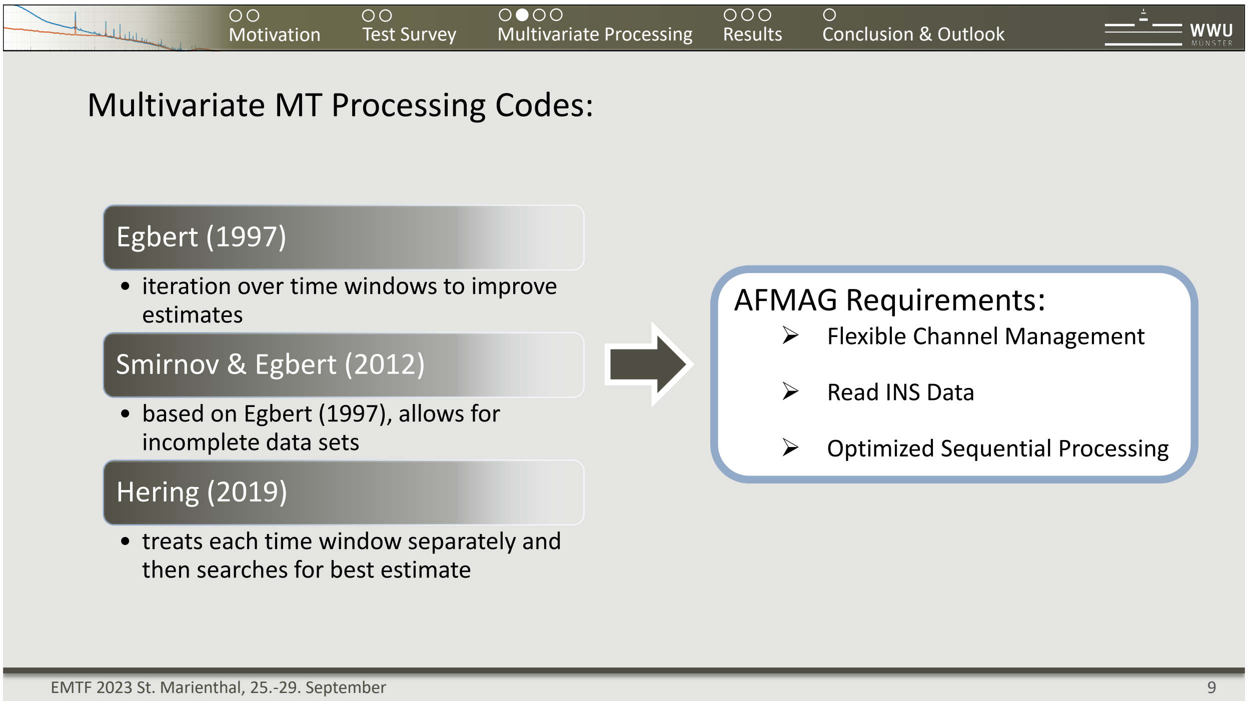
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Multivariate MT Processing Codes:
Egbert (1997)
• iteration over time windows to improve estimates
Smirnov & Egbert (2012)
• based on Egbert (1997), allows for incomplete data sets
Hering (2019)
• treats each time window separately and then searches for best estimate
AFMAG Requirements:
Flexible Channel Management
Read INS Data
Optimized Sequential Processing
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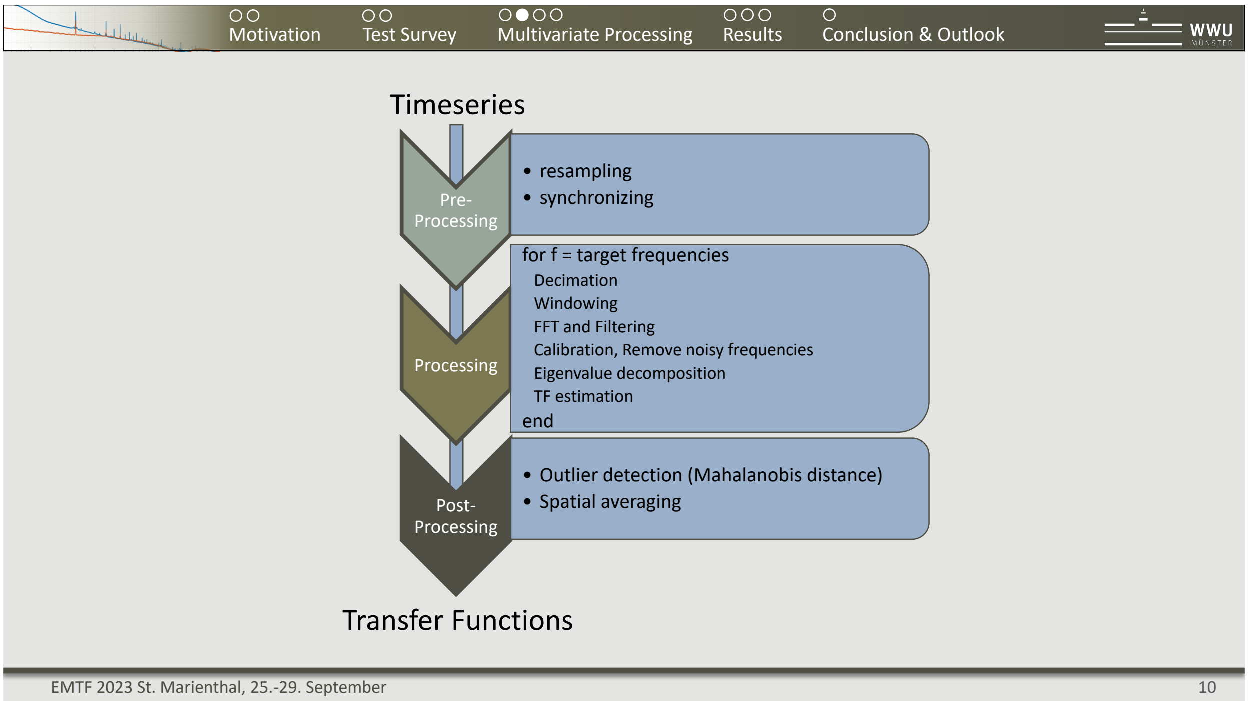
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Timeseries
Pre-Processing
• resampling
• synchronizing
Processing
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
Post-Processing
• Outlier detection (Mahalanobis distance)
• Spatial averaging
Transfer Functions
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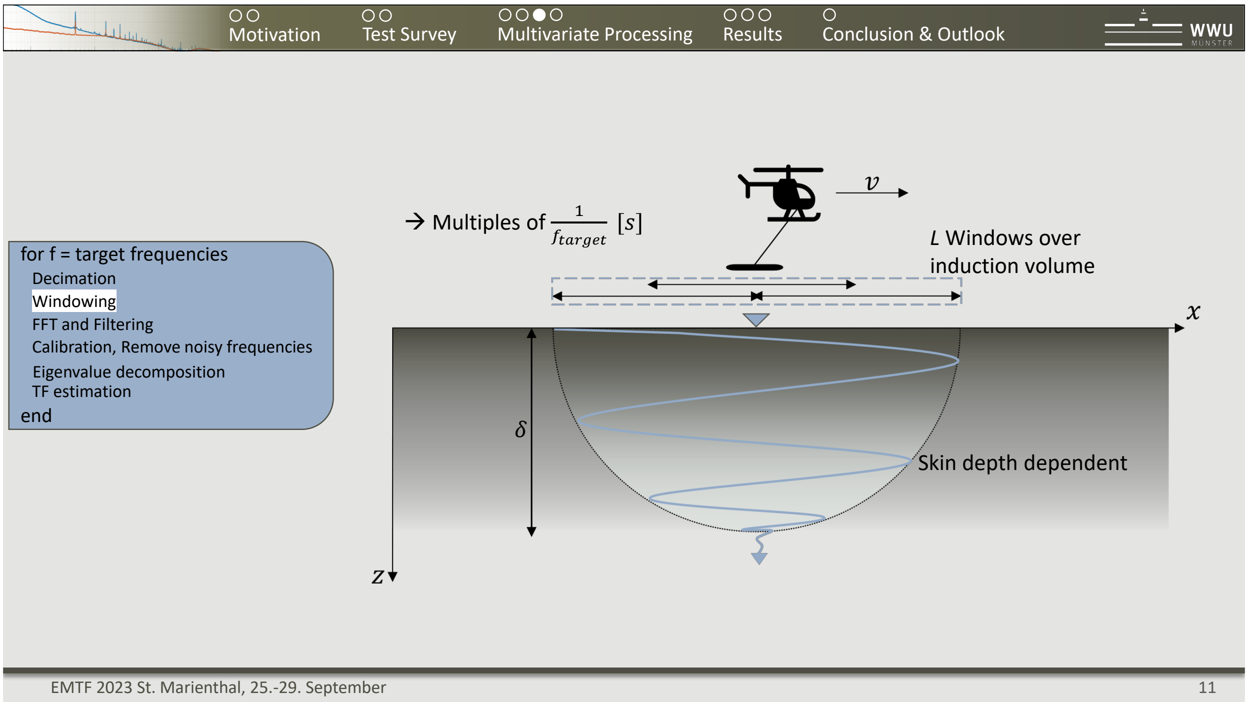
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
→ Multiples of $\frac{1}{f_{target}}$ $[s]$
v
L Windows over induction volume
x
δ
Skin depth dependent
z
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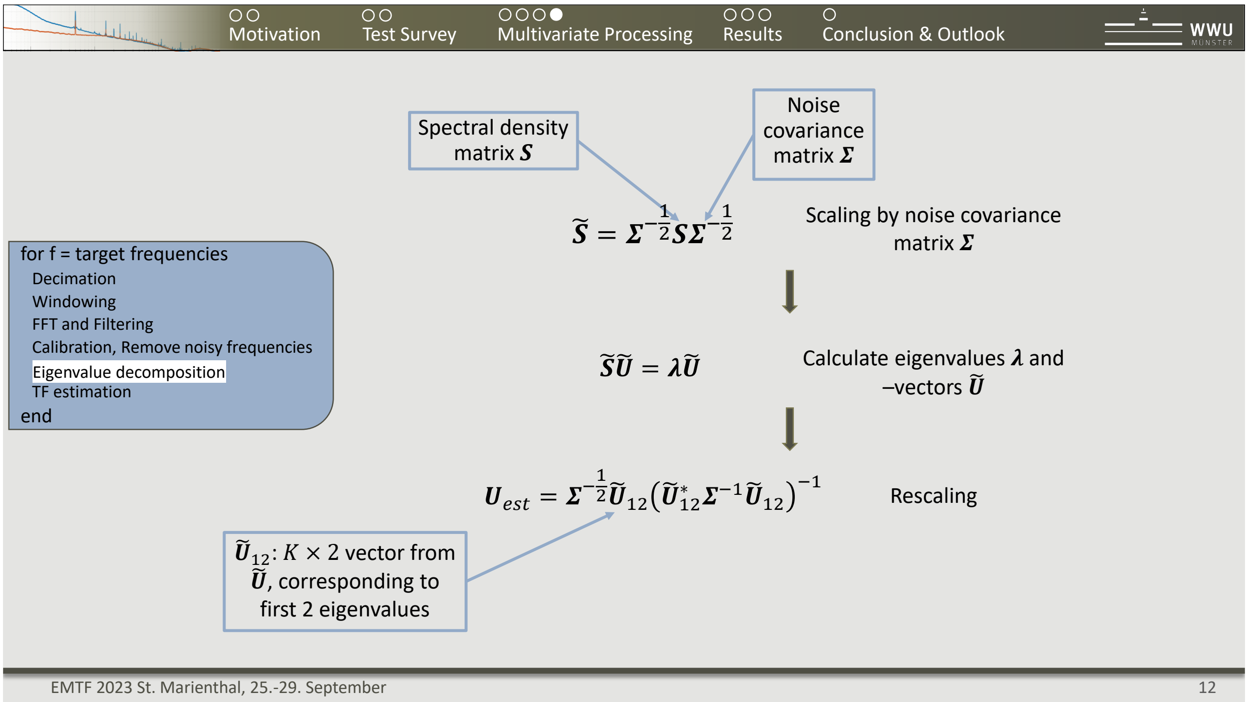
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Spectral density matrix $\boldsymbol{S}$
Noise covariance matrix $\boldsymbol{\Sigma}$
$\tilde{\boldsymbol{S}} = \boldsymbol{\Sigma}^{-\frac{1}{2}}\boldsymbol{S}\boldsymbol{\Sigma}^{-\frac{1}{2}}$
Scaling by noise covariance matrix $\boldsymbol{\Sigma}$
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
$\tilde{\boldsymbol{S}}\tilde{\boldsymbol{U}} = \boldsymbol{\lambda}\tilde{\boldsymbol{U}}$
Calculate eigenvalues $\boldsymbol{\lambda}$ and –vectors $\tilde{\boldsymbol{U}}$
$\boldsymbol{U}_{est} = \boldsymbol{\Sigma}^{-\frac{1}{2}}\tilde{\boldsymbol{U}}_{12}\left(\tilde{\boldsymbol{U}}_{12}^{*}\boldsymbol{\Sigma}^{-1}\tilde{\boldsymbol{U}}_{12}\right)^{-1}$
Rescaling
$\tilde{\boldsymbol{U}}_{12}$: $K \times 2$ vector from $\tilde{\boldsymbol{U}}$, corresponding to first 2 eigenvalues
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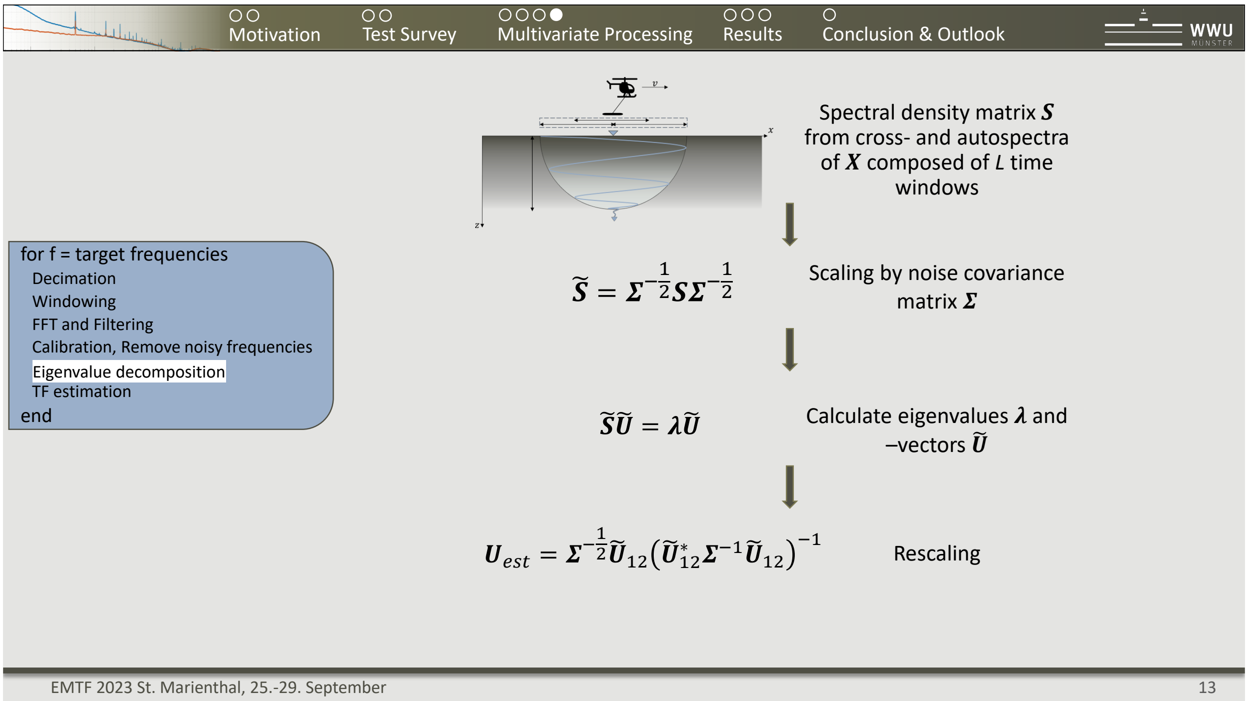
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
Spectral density matrix $\boldsymbol{S}$ from cross- and autospectra of $\boldsymbol{X}$ composed of L time windows
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
$\widetilde{\boldsymbol{S}} = \boldsymbol{\Sigma}^{-\frac{1}{2}}\boldsymbol{S}\boldsymbol{\Sigma}^{-\frac{1}{2}}$
Scaling by noise covariance matrix $\boldsymbol{\Sigma}$
$\widetilde{\boldsymbol{S}}\widetilde{\boldsymbol{U}} = \boldsymbol{\lambda}\widetilde{\boldsymbol{U}}$
Calculate eigenvalues $\boldsymbol{\lambda}$ and –vectors $\widetilde{\boldsymbol{U}}$
$\boldsymbol{U}_{est} = \boldsymbol{\Sigma}^{-\frac{1}{2}}\widetilde{\boldsymbol{U}}_{12}\left(\widetilde{\boldsymbol{U}}_{12}^{*}\boldsymbol{\Sigma}^{-1}\widetilde{\boldsymbol{U}}_{12}\right)^{-1}$
Rescaling
EMTF 2023 St. Marienthal, 25.-29. September
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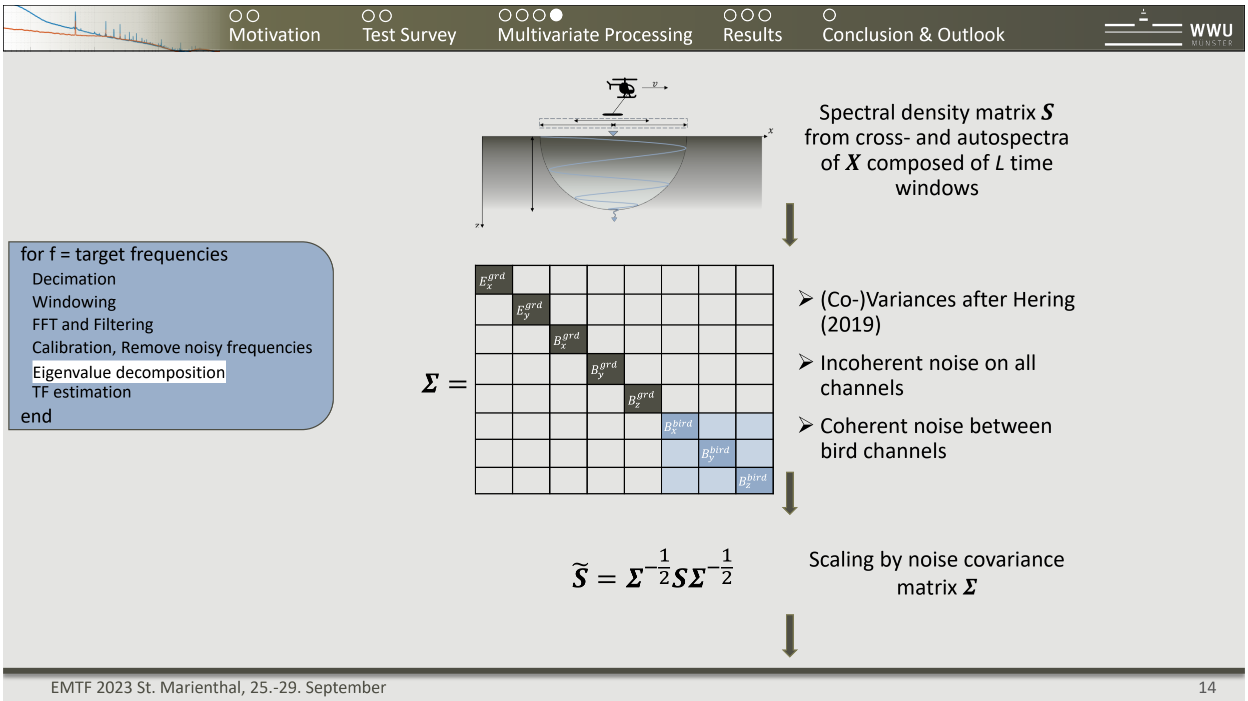
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
Spectral density matrix $\boldsymbol{S}$ from cross- and autospectra of $\boldsymbol{X}$ composed of L time windows
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
$\boldsymbol{\Sigma} =$
E_x^{grd}
E_y^{grd}
B_x^{grd}
B_y^{grd}
B_z^{grd}
B_x^{bird}
B_y^{bird}
B_z^{bird}
(Co-)Variances after Hering (2019)
Incoherent noise on all channels
Coherent noise between bird channels
$\widetilde{\boldsymbol{S}} = \boldsymbol{\Sigma}^{-\frac{1}{2}}\boldsymbol{S}\boldsymbol{\Sigma}^{-\frac{1}{2}}$
Scaling by noise covariance matrix $\boldsymbol{\Sigma}$
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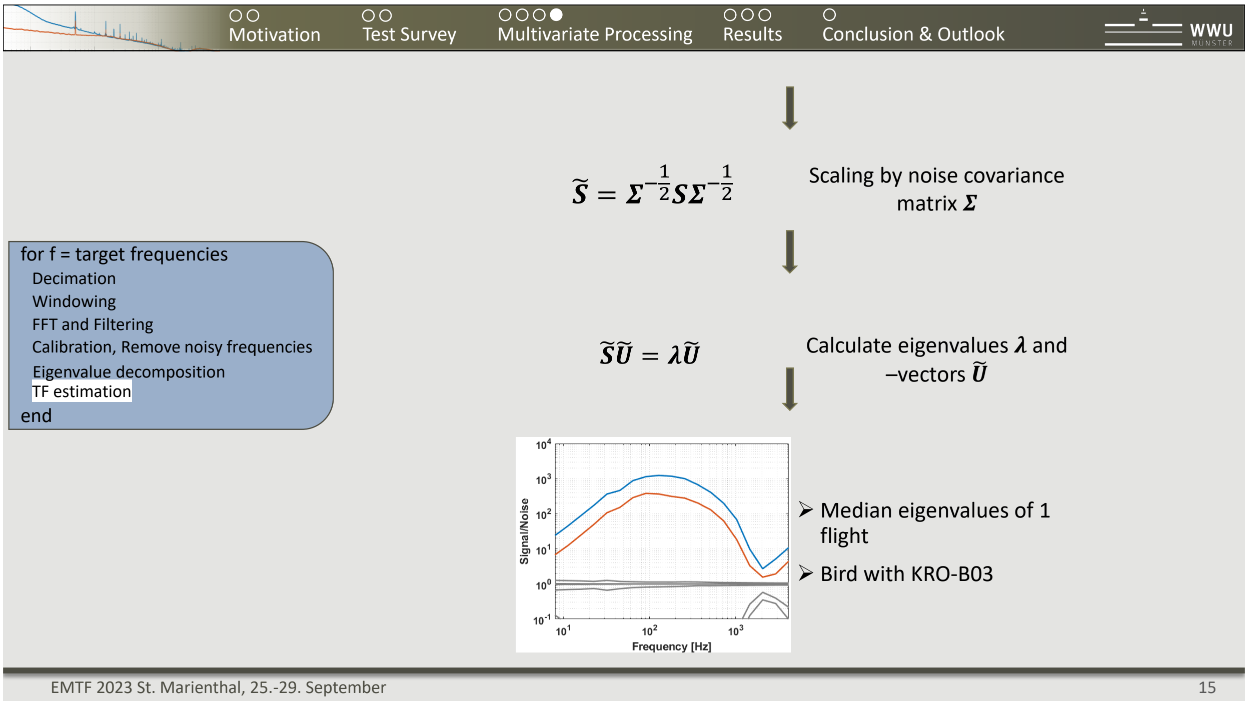
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
$\tilde{S} = \Sigma^{-\frac{1}{2}} S \Sigma^{-\frac{1}{2}}$
Scaling by noise covariance matrix Σ
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
$\tilde{S}\tilde{U} = \lambda\tilde{U}$
Calculate eigenvalues λ and –vectors $\tilde{U}$
Signal/Noise
Frequency [Hz]
Median eigenvalues of 1 flight
Bird with KRO-B03
EMTF 2023 St. Marienthal, 25.-29. September
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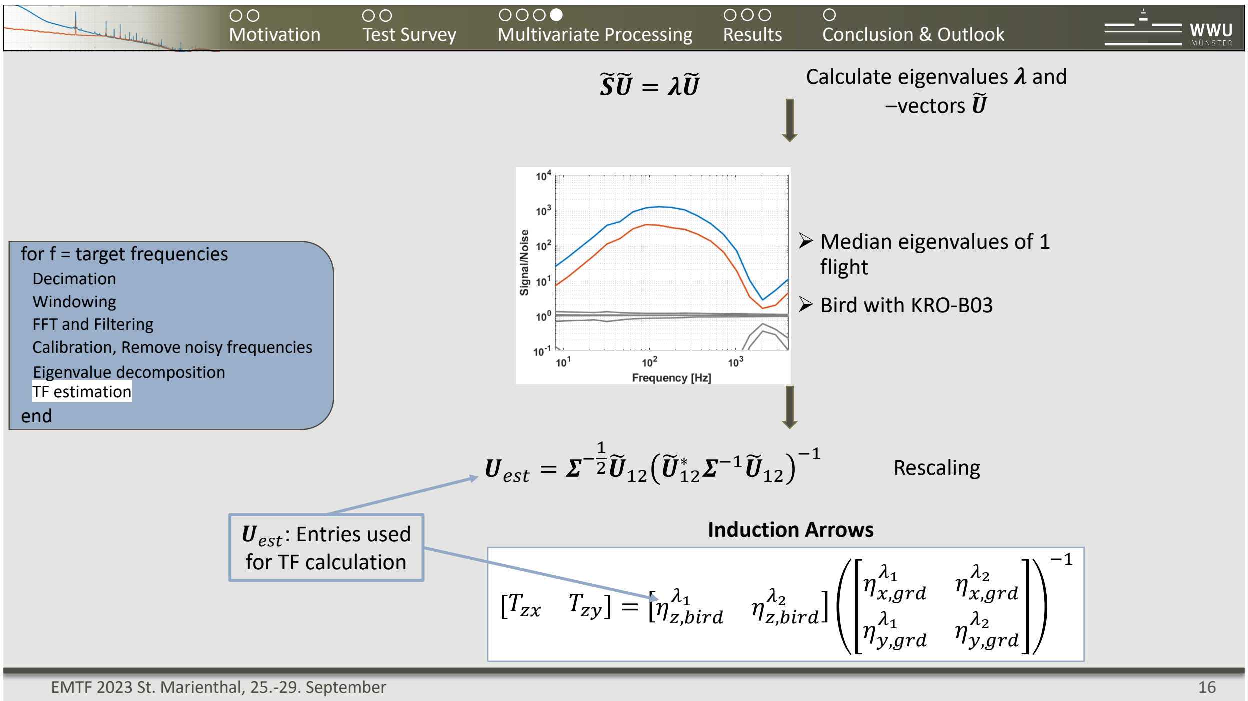
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU MÜNSTER
$\tilde{S}\tilde{U} = \lambda\tilde{U}$
Calculate eigenvalues λ and –vectors $\tilde{U}$
for f = target frequencies
Decimation
Windowing
FFT and Filtering
Calibration, Remove noisy frequencies
Eigenvalue decomposition
TF estimation
end
Signal/Noise
Frequency [Hz]
Median eigenvalues of 1 flight
Bird with KRO-B03
$U_{est} = \Sigma^{-\frac{1}{2}} \tilde{U}_{12} \left(\tilde{U}_{12}^{*} \Sigma^{-1} \tilde{U}_{12}\right)^{-1}$
Rescaling
U_{est}: Entries used for TF calculation
Induction Arrows
$[T_{zx} \quad T_{zy}] = [\eta_{z,bird}^{\lambda_1} \quad \eta_{z,bird}^{\lambda_2}] \left(\begin{bmatrix} \eta_{x,grd}^{\lambda_1} & \eta_{x,grd}^{\lambda_2} \\ \eta_{y,grd}^{\lambda_1} & \eta_{y,grd}^{\lambda_2} \end{bmatrix} \right)^{-1}$
EMTF 2023 St. Marienthal, 25.-29. September
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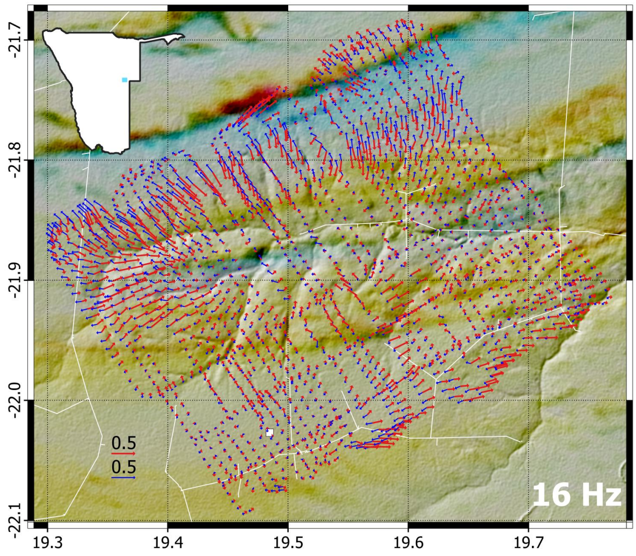
Processing settings

- $\rho_{bg} = 1000\ \Omega m$ for windowing
- $L = 11$ windows
- Reference: KRO-B03

- Problems:
  - Time drift (bird): F1, F2
  - Thunder storm activity: F1

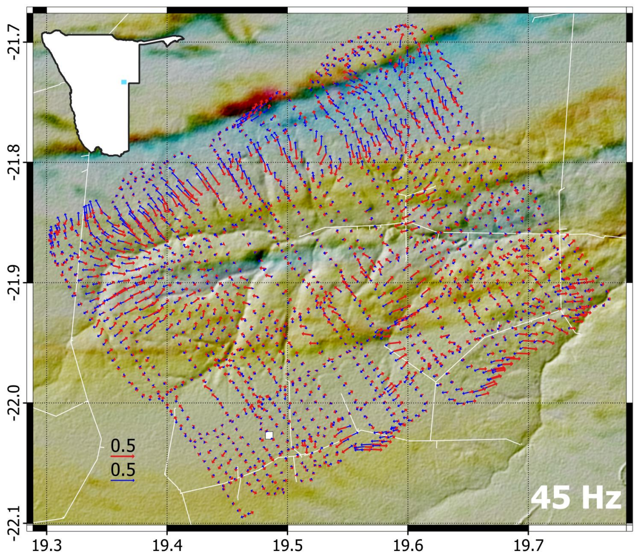


Motivation | Test Survey | Multivariate Processing | Results | Conclusion & Outlook | WWU MÜNSTER

Processing settings

- $\rho_{bg} = 1000\ \Omega m$ for windowing
- $L = 11$ windows
- Reference: KRO-B03

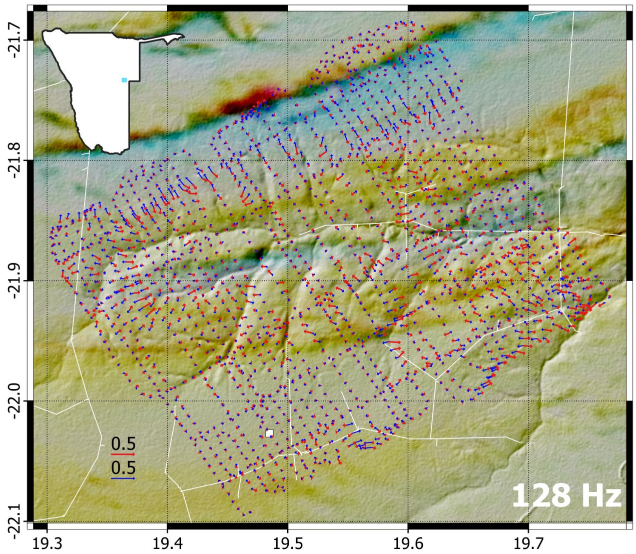
- Problems:
  - Time drift (bird): F1, F2
  - Thunder storm activity: F1



Processing settings

- $\rho_{bg} = 1000\ \Omega m$ for windowing
- $L = 11$ windows
- Reference: KRO-B03

- Problems:
  - Time drift (bird): F1, F2
  - Thunder storm activity: F1

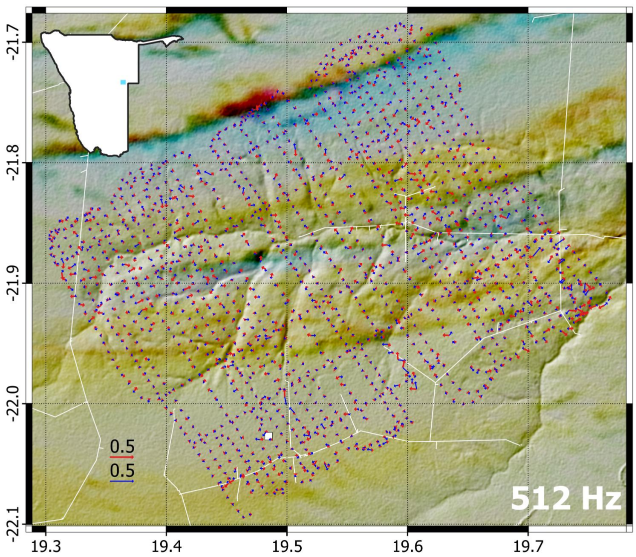


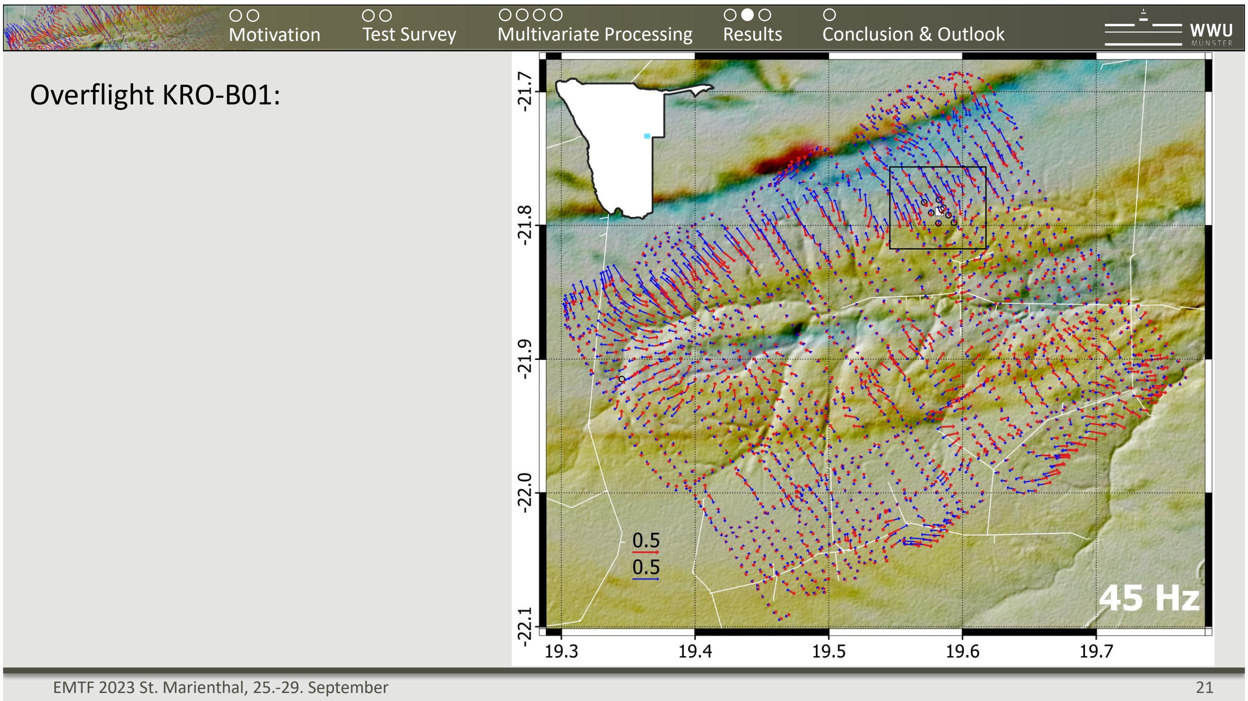
Motivation | Test Survey | Multivariate Processing | Results | Conclusion & Outlook | WWU MÜNSTER

Processing settings

- $\rho_{bg} = 1000\ \Omega m$ for windowing
- $L = 11$ windows
- Reference: KRO-B03

- Problems:
  - Time drift (bird): F1, F2
  - Thunder storm activity: F1




Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Overflight KRO-B01:
-21.7
-21.8
-21.9
-22.0
-22.1
19.3
19.4
19.5
19.6
19.7
0.5
0.5
45 Hz
EMTF 2023 St. Marienthal, 25.-29. September
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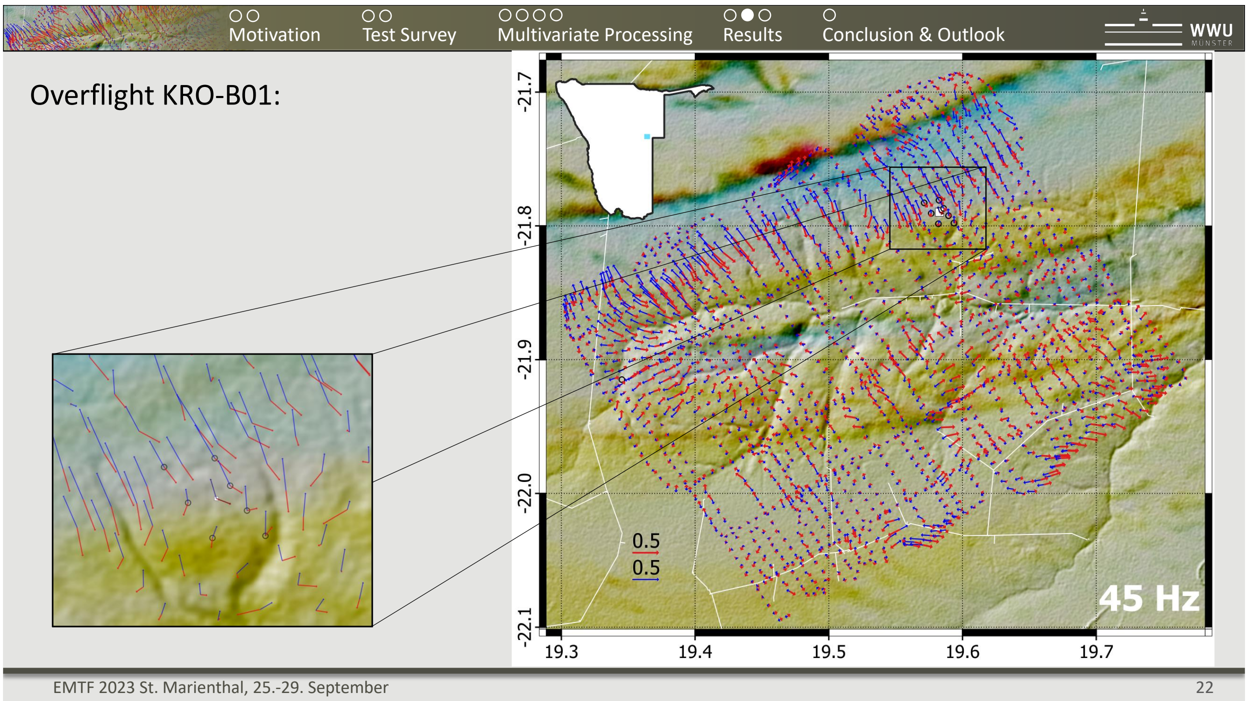
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Overflight KRO-B01:
-21.7
-21.8
-21.9
-22.0
-22.1
19.3
19.4
19.5
19.6
19.7
0.5
0.5
45 Hz
EMTF 2023 St. Marienthal, 25.-29. September
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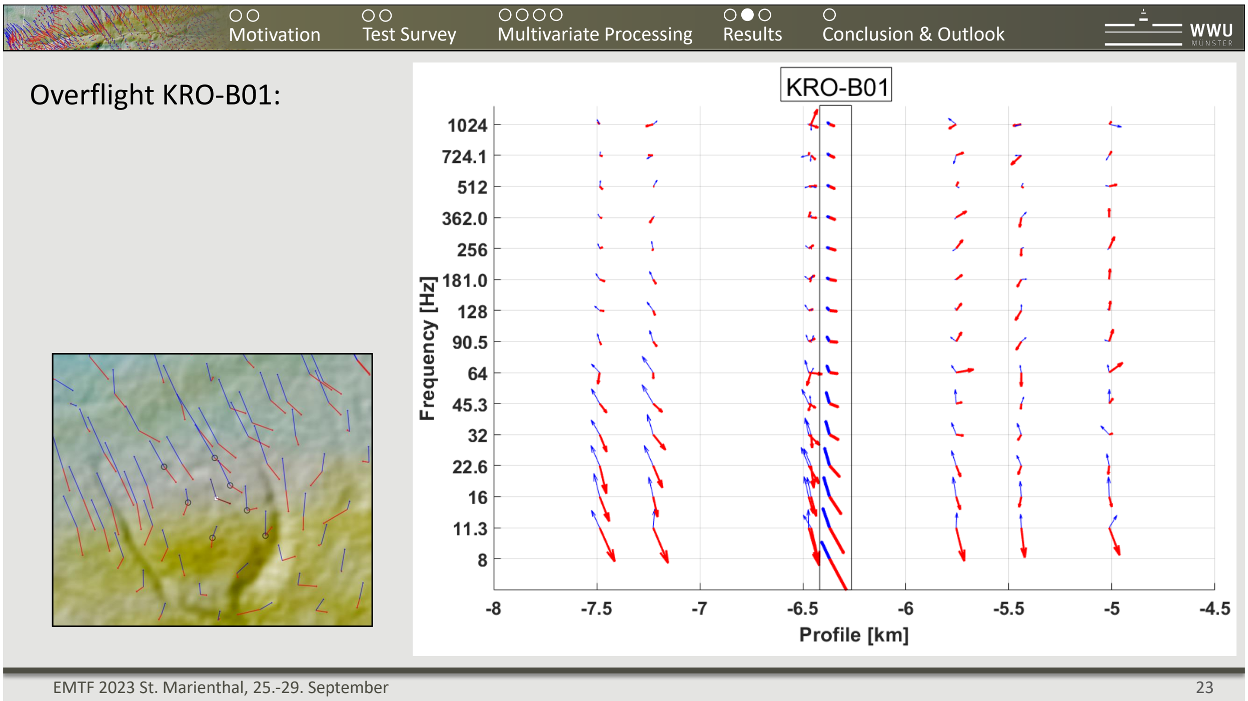
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
MÜNSTER
Overflight KRO-B01:
KRO-B01
1024
724.1
512
362.0
256
181.0
128
90.5
64
45.3
32
22.6
16
11.3
8
Frequency [Hz]
-8
-7.5
-7
-6.5
-6
-5.5
-5
-4.5
Profile [km]
EMTF 2023 St. Marienthal, 25.-29. September
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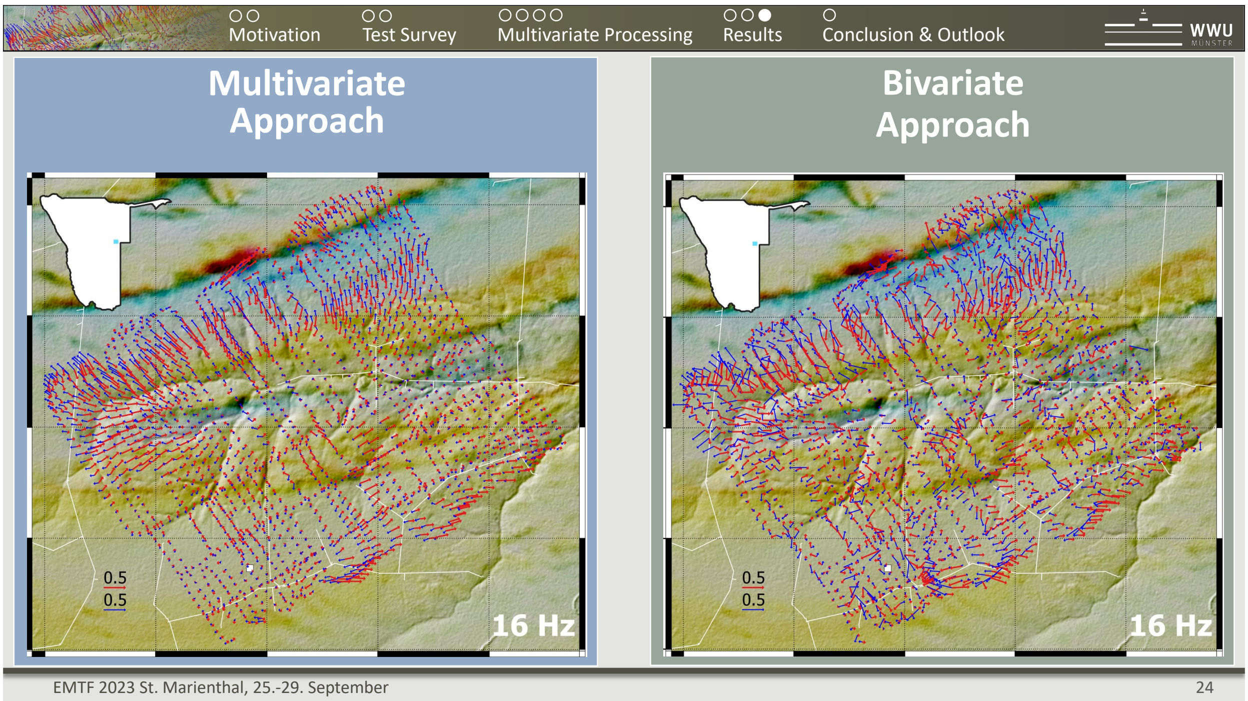
Motivation
Test Survey
Multivariate Processing
Results
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WWU
MÜNSTER
Multivariate Approach
Bivariate Approach
0.5
0.5
16 Hz
0.5
0.5
16 Hz
EMTF 2023 St. Marienthal, 25.-29. September
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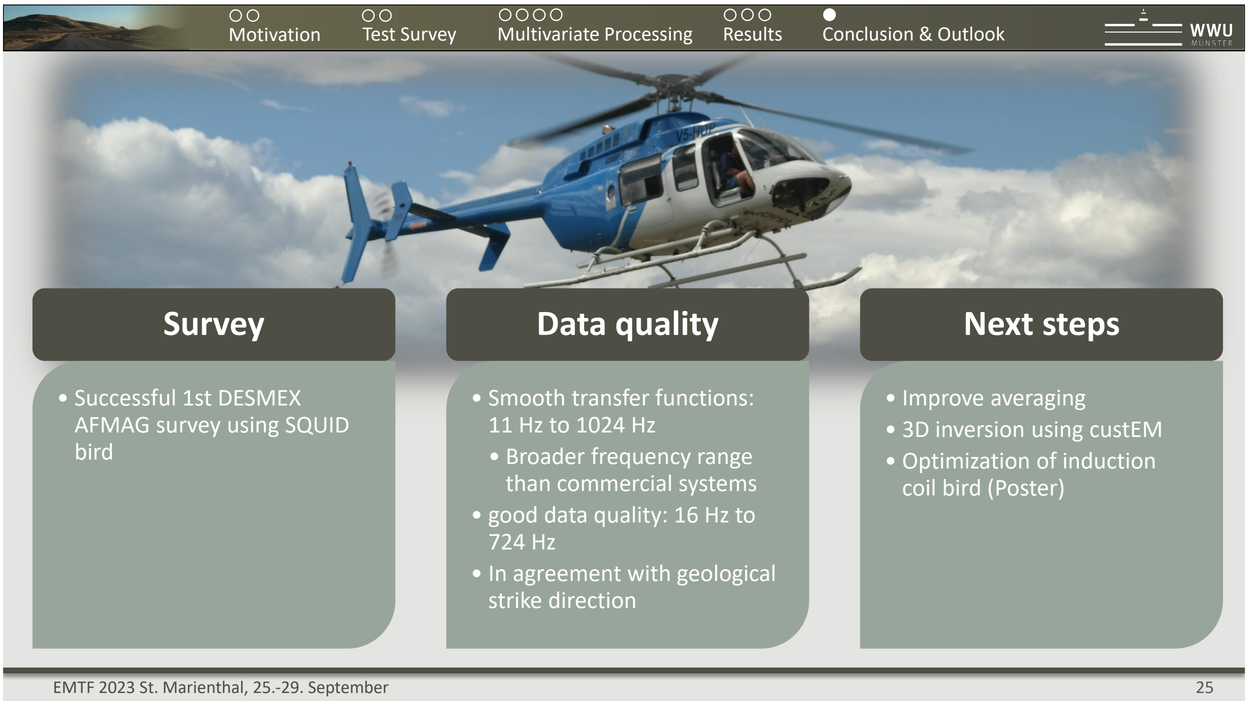
Motivation
Test Survey
Multivariate Processing
Results
Conclusion & Outlook
WWU
Survey
• Successful 1st DESMEX AFMAG survey using SQUID bird
Data quality
• Smooth transfer functions: 11 Hz to 1024 Hz
• Broader frequency range than commercial systems
• good data quality: 16 Hz to 724 Hz
• In agreement with geological strike direction
Next steps
• Improve averaging
• 3D inversion using custEM
• Optimization of induction coil bird (Poster)
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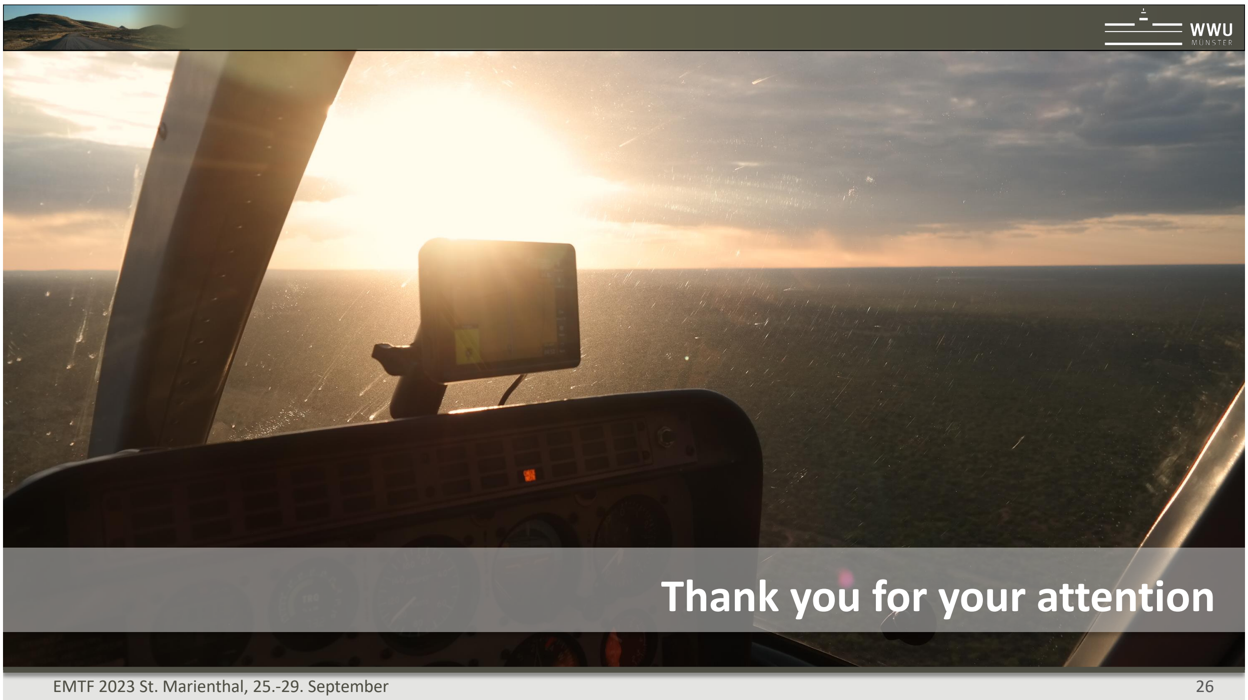
WWU
Thank you for your attention
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