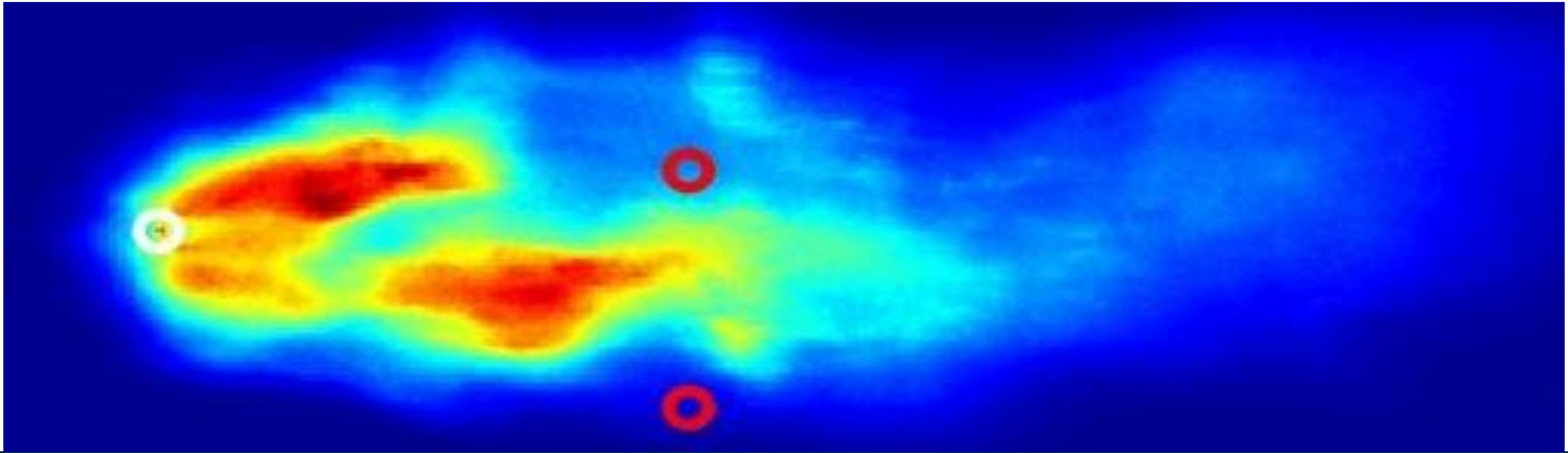


THE POTENTIAL OF TIME-LAPSE GPR FULL-WAVEFORM INVERSION AS HIGH RESOLUTION IMAGING TECHNIQUE FOR SALT AND ETHANOL TRANSPORT

P. HARUZI[1], J.SCHMÄCK[1], L.HAIN[1], Z. ZHOU[1], R. HOFFMANN[2], B. POULADI[3], J. DE LA BERNARDIE[3], H. VEREECKEN[1], J. VAN DER KRUK[1], **J. VANDERBORGHT[1]**, A. KLOTZSCHE[1]

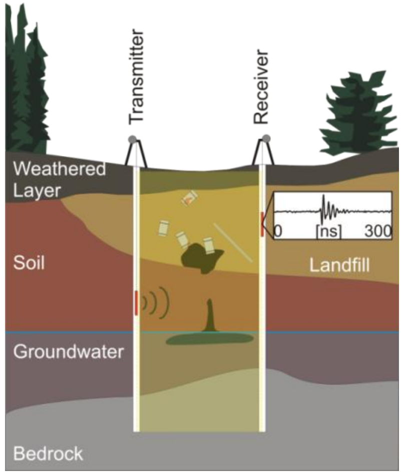
[1]Agrosphere (IBG-3), Forschungszentrum Jülich, Germany
[2]Urban Environmental Engineering Unit., Hydrogeology & Environmental Geology, Liège University, Belgium
[3]Univ Rennes, CNRS, Geociences Rennes, France

21 January 2021

Member of the Helmholtz Association

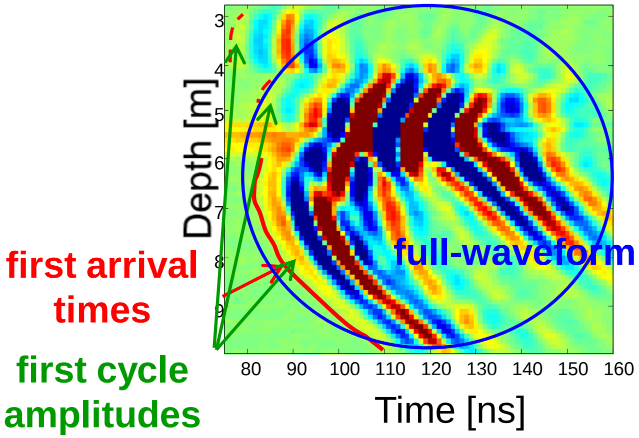
CROSSHOLE GPR FULL-WAVEFORM INVERSION

Mapping soil water content variability in the critical zone

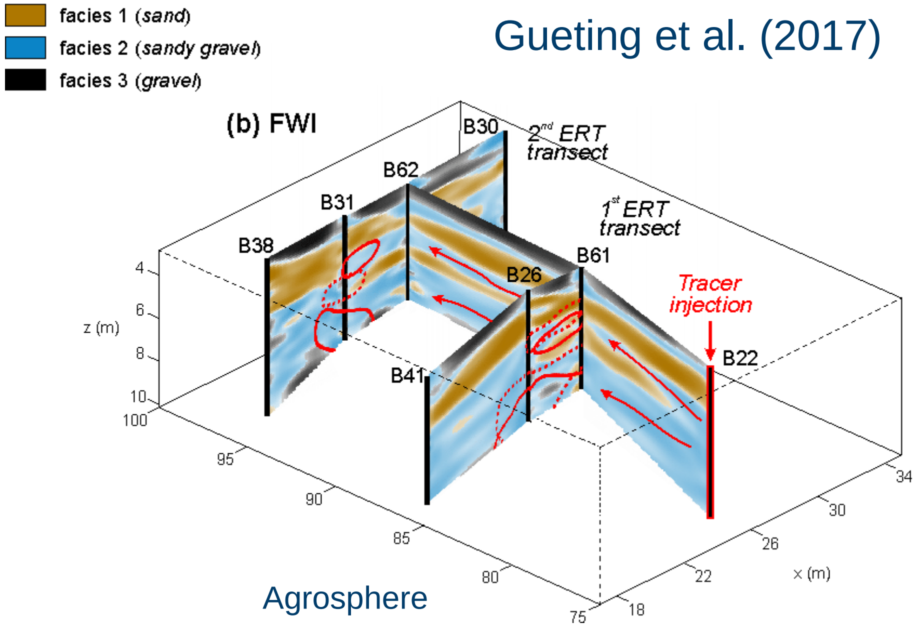


GPR is able to minimal-invasively investigate distributions of electromagnetic properties:

- dielectric permittivity ε_r / EM velocity:
  ➡ soil water content (SWC), porosity
- electrical conductivity σ/ EM attenuation:
  ➡ clay/silt content, salinity



Improved characterization compared to other non-invasive methods!



Gueting et al. (2017)

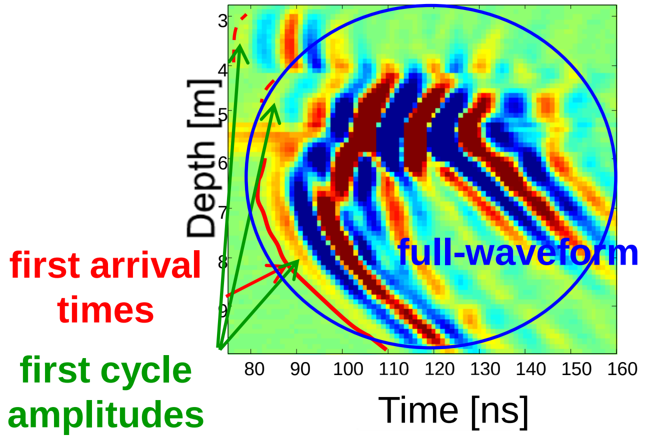
e.g., Ernst et al. (2007a, b); Virieux & Operto (2009); Meles et al. (2010); Klotzsche et al. (2010).

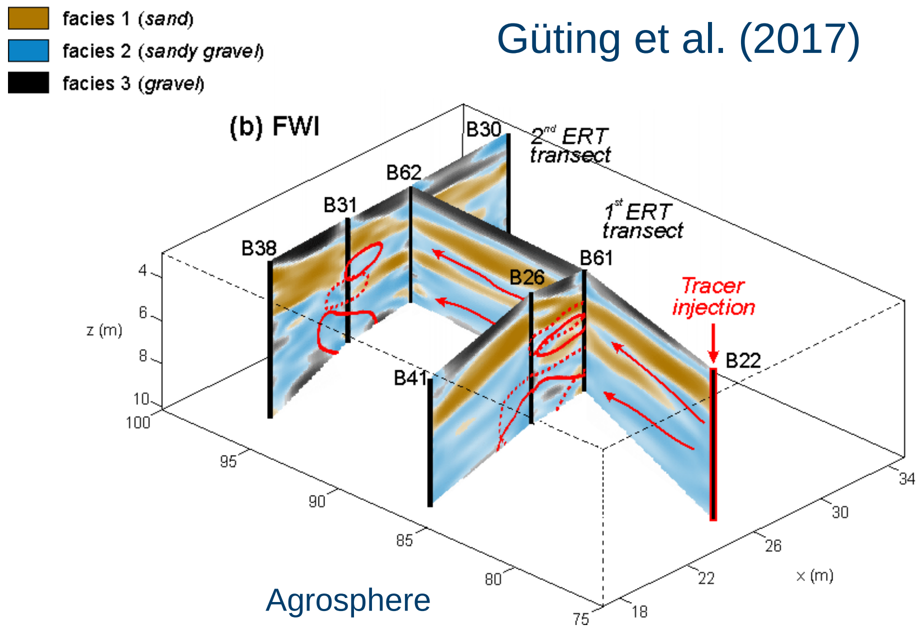
CROSSHOLE GPR FULL-WAVEFORM INVERSION

Mapping soil water content variability in the critical zone

To protect groundwater from pollution and to manage an aquifer, detailed knowledge of the flow and transport processes are necessary:

- No time-lapse data investigated using GPR FWI to obtain in-depth knowledge of tracer distribution within the aquifer.
- Investigate the potential of FWI to map monitor different tracer plumes (numerical study).
  - Positive electrical conductivity: saline, heat tracers
  - Negative electrical conductivity: deionized water.
  - Negative contrast in bulk permittivity and conductivity: ethanol tracer.
- Recently, saline and heat field tracer test was performed at the Krauthausen test site (Germany).





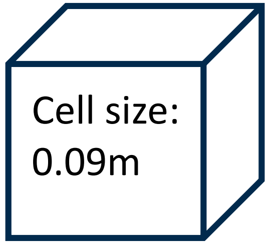
Güting et al. (2017)

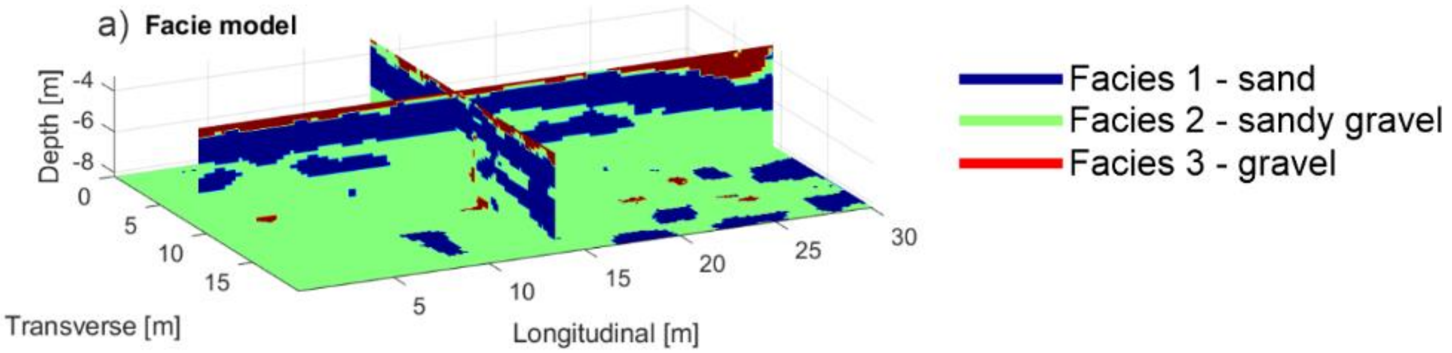
KRAUTHAUSEN AQUIFER MODEL

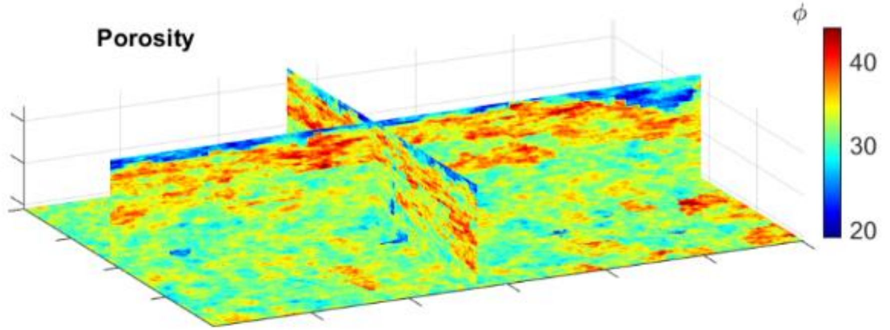
High resolution hydrological model:

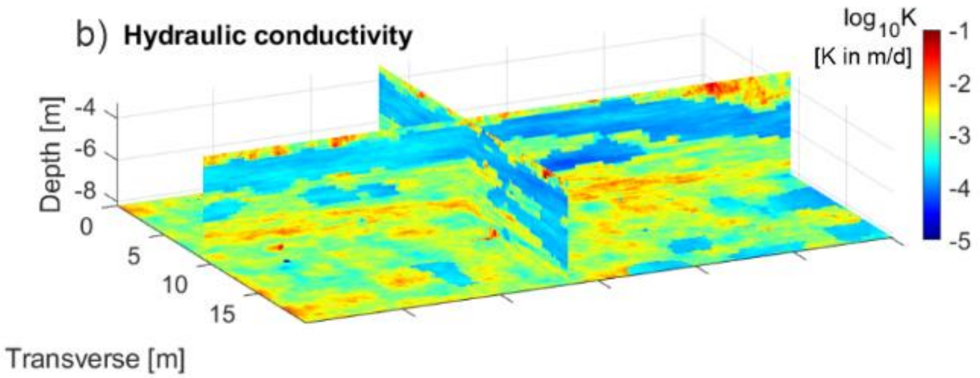
- 3D facies model was adopted, (Gueting et al., 2017, 2018)
- Hydraulic conductivity **K** (Velocity analysis (Englert, 2003), Tracer test (Mueller et al., 2010)).
- Porosity $\boldsymbol{\phi}$ (Cone penetration tests (Tillman et al., 2008), GPR FWI (Gueting et al., 2017).
- Dielectric permittivity ε_r from porosity using CRIM model (Birchak et al., 1974)).
- Electrical conductivity $\boldsymbol{\sigma_b}$ (*r=0.5* correlation between σ and ε_r of GPR FWI (Gueting et al., 2017)).

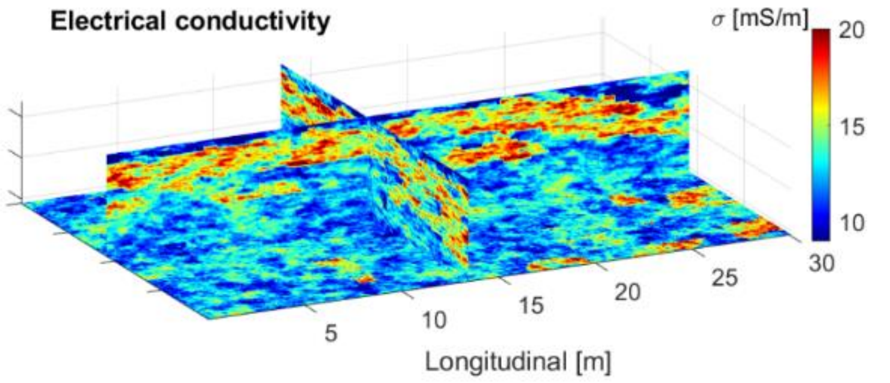
Variogram-based Sequential Gaussian Simulation (SGeMS software; Remy, et al., 2009)





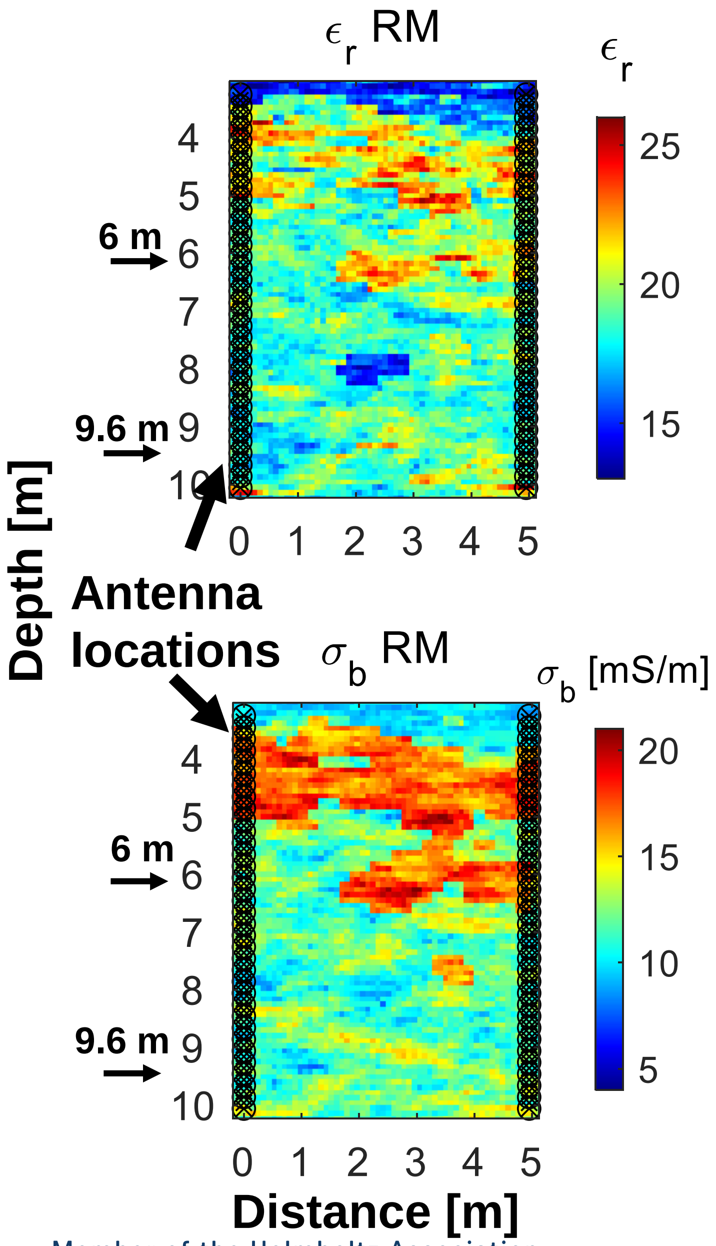




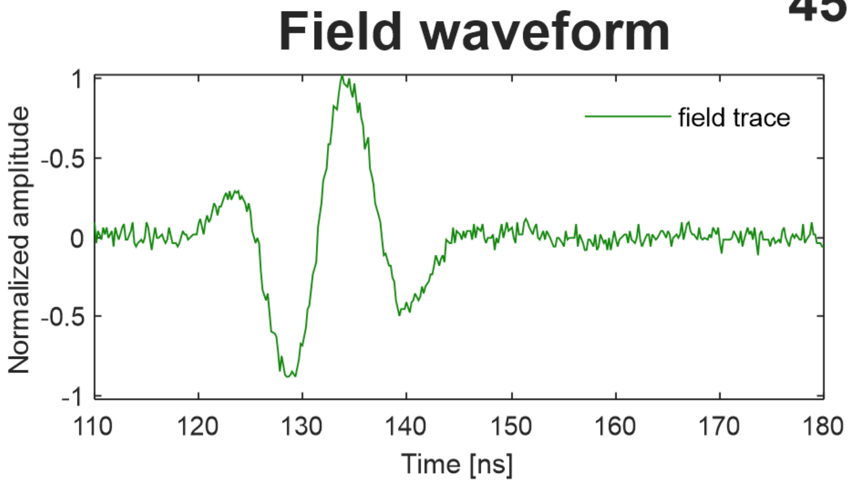


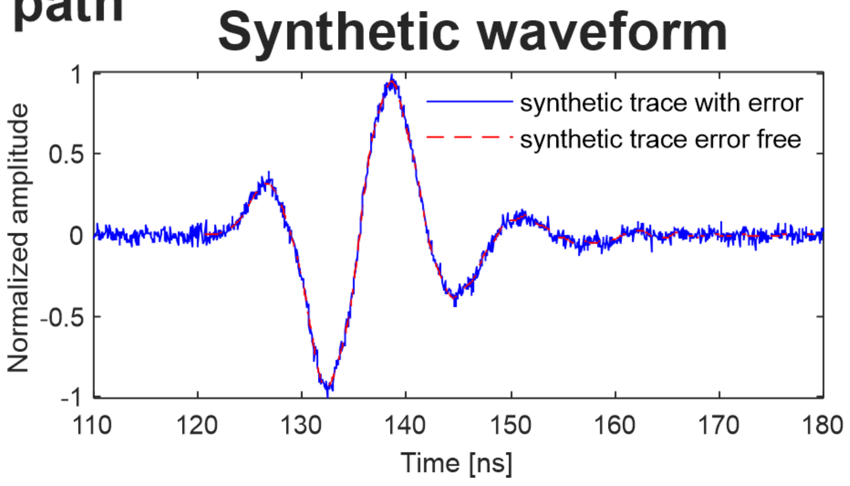
GPR DATA

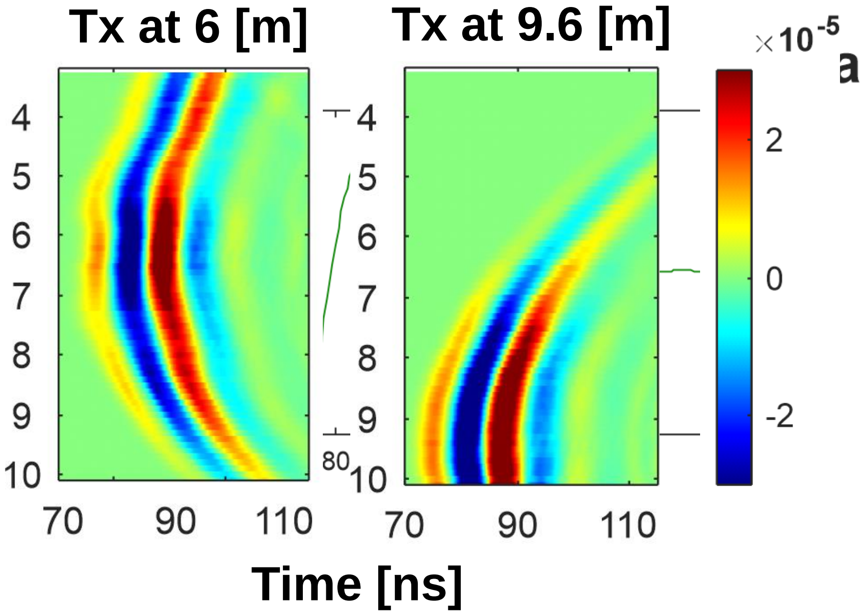
- GPR data was generated with 2D FDTD.
- Random noise was added to synthetic waveforms, with a level based on waveforms measured at the field.

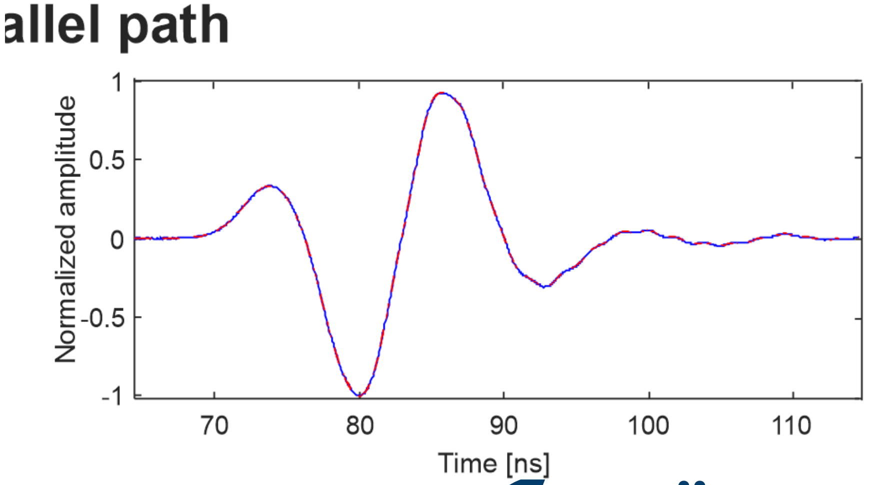


45° path

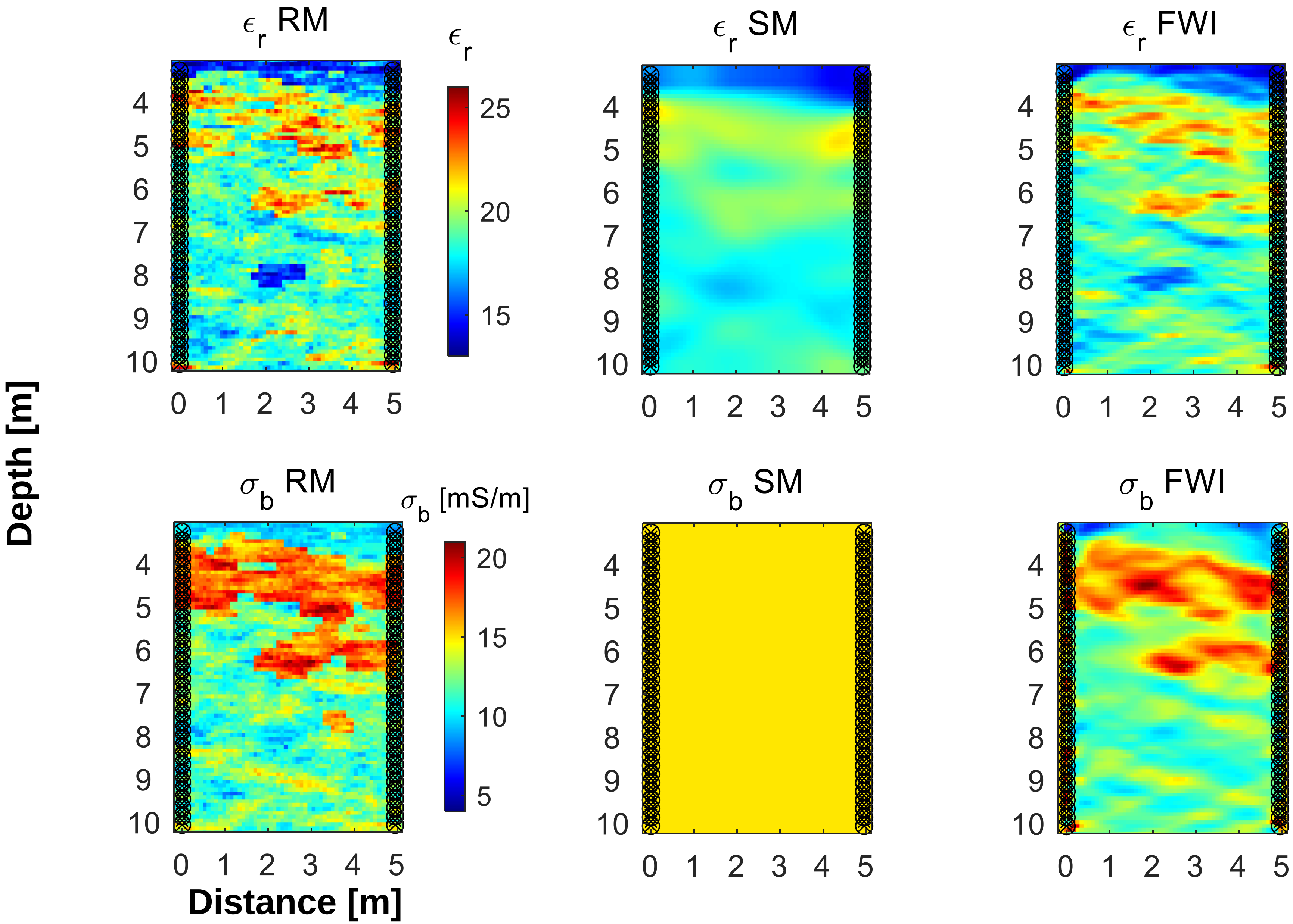




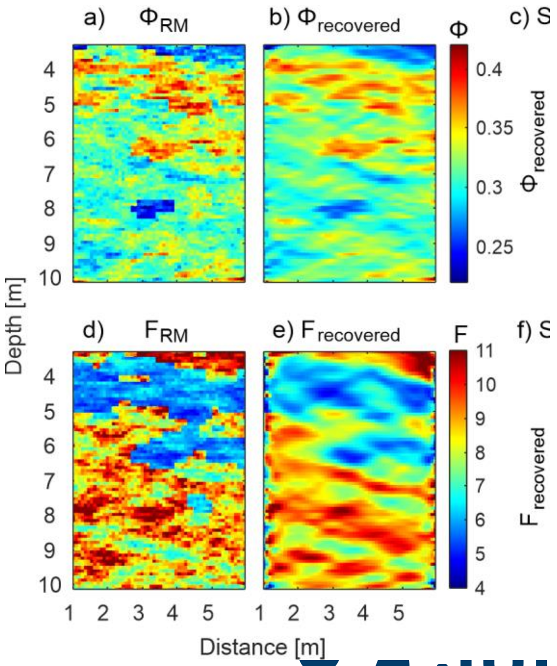




POROSITY AND FORMATION FACTOR



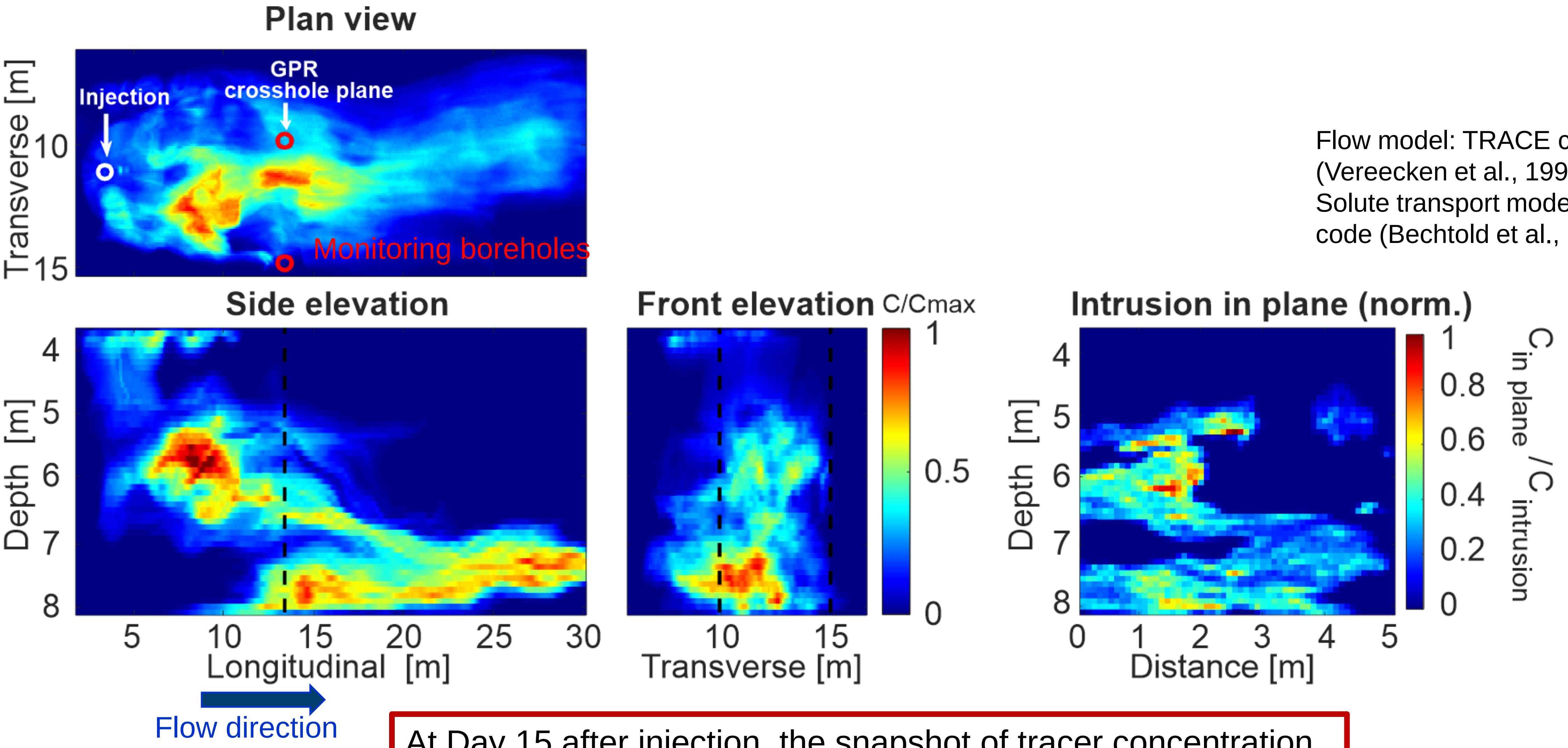
- The FWI recovery of permittivity is more accurate than electrical conductivity.
- Background FWI models will be used in petrophysical relations:
  - ε_r to calculate porosity.
  - σ_b to calculate the formation factor.



Porosity
r=0.85

Formation factor
r=0.75

FLOW AND SOLUTE TRANSPORT MODEL



Flow model: TRACE code (Vereecken et al., 1994)
Solute transport model: PARTRACE code (Bechtold et al., 2012)

At Day 15 after injection, the snapshot of tracer concentration between the boreholes is used to generate GPR data through petrophysical relations.

PETROPHSICAL RELATIONS FOR SALT TRACER

- No changes in ε_r (Sreenivas & Venkatarantan, 1975).
- σ_f increases with salinity. σ_b increases linearly with σ_f.
- → Concentrations from transport simulation were used to calculate σ_f.

Generation of petrophysical aquifer model from tracer changes

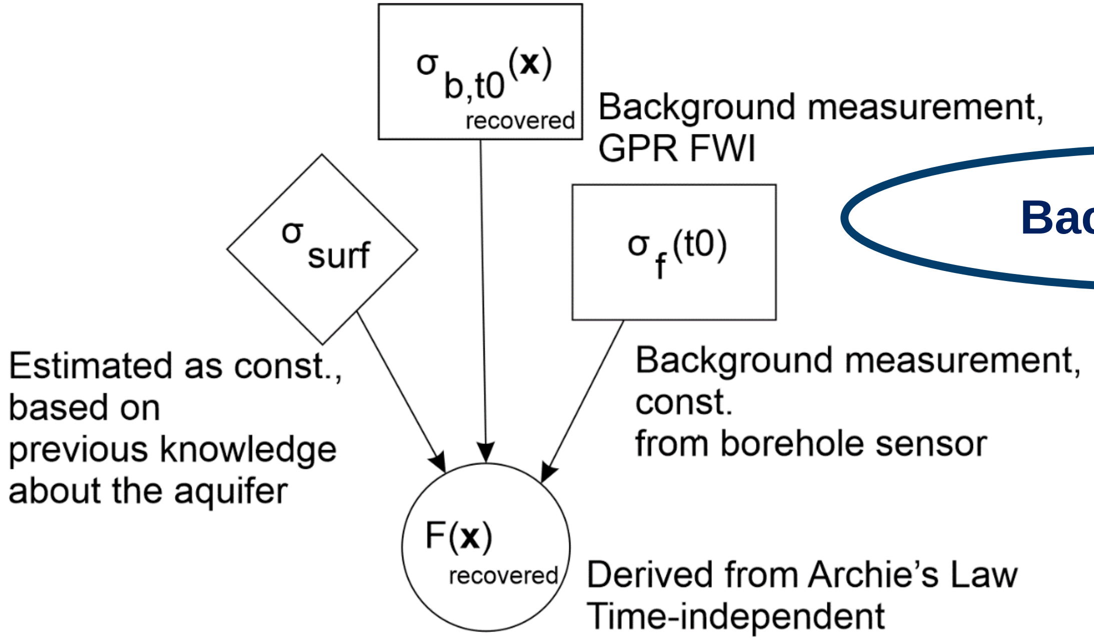
Archie's Law: $\sigma_b(\mathbf{x},t)=\sigma_f(\mathbf{x},t)/F(\mathbf{x})+\sigma_{surf}(\mathbf{x})$ Archie, 1942

$\sigma_{surf}(\mathbf{x})$ ~$N(1.2,0.3\text{^}2)$ mS/m with the same correlation lengths as σ_b.

$F(\mathbf{x})_{real}$ is calculated from $\sigma_{b real}$ and $\sigma_f(t0)_{real}$≈const.

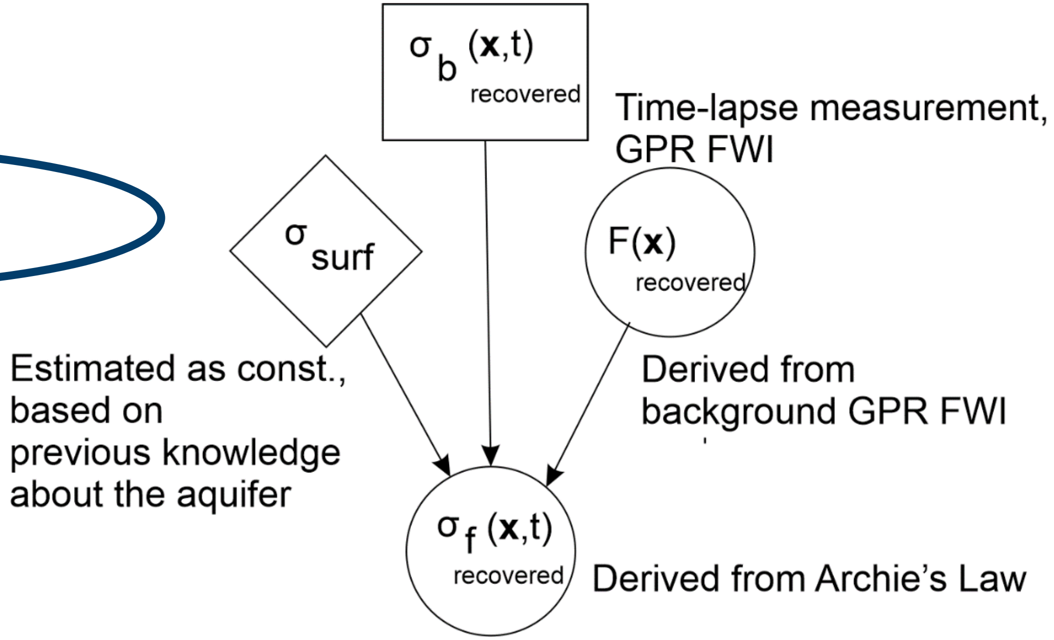
Forward processing

1. Derive $F(x)_{recovered}$ from background GPR FWI $\sigma_b(x,t0)_{recovered}$



Back processing

2. Derive $\sigma_f(x,t)_{recovered}$ from time-lapse GPR FWI $\sigma_b(x,t)_{recovered}$



PETROPHSICAL RELATIONS FOR ETHANOL TRACER

- ➢ ε_r and σ_b decrease with **ethanol volumetric concentration *S_{EtOH}*** in groundwater (Glaser et al., 2012).

→ Concentrations from transport simulation were used to calculate S_{EtOH}.

Forward processing

Generation of petrophysical aquifer model from tracer changes

ε_r model:

1. Empirical relation:

$$\varepsilon_{f\_mixture}(\mathbf{x},t) = 84.05 - 42.6 \cdot S_{EtOH}(\mathbf{x},t) - 15.7 \cdot S_{EtOH}(\mathbf{x},t)^2$$

2. CRIM mixing model (Birchak et al., 1974)

$$\varepsilon_{r\_eff}(\mathbf{x},t)=(\varepsilon_{f\_mixture}^{0.5} \cdot \boldsymbol{\phi}(\mathbf{x}) + \varepsilon_{matrix}^{0.5} \cdot (1-\boldsymbol{\phi}(x)))^2$$

$\boldsymbol{\phi}(x)_{real}$ *is calculated from* background GPR FWI, and $\sigma_f(t0)=const.$

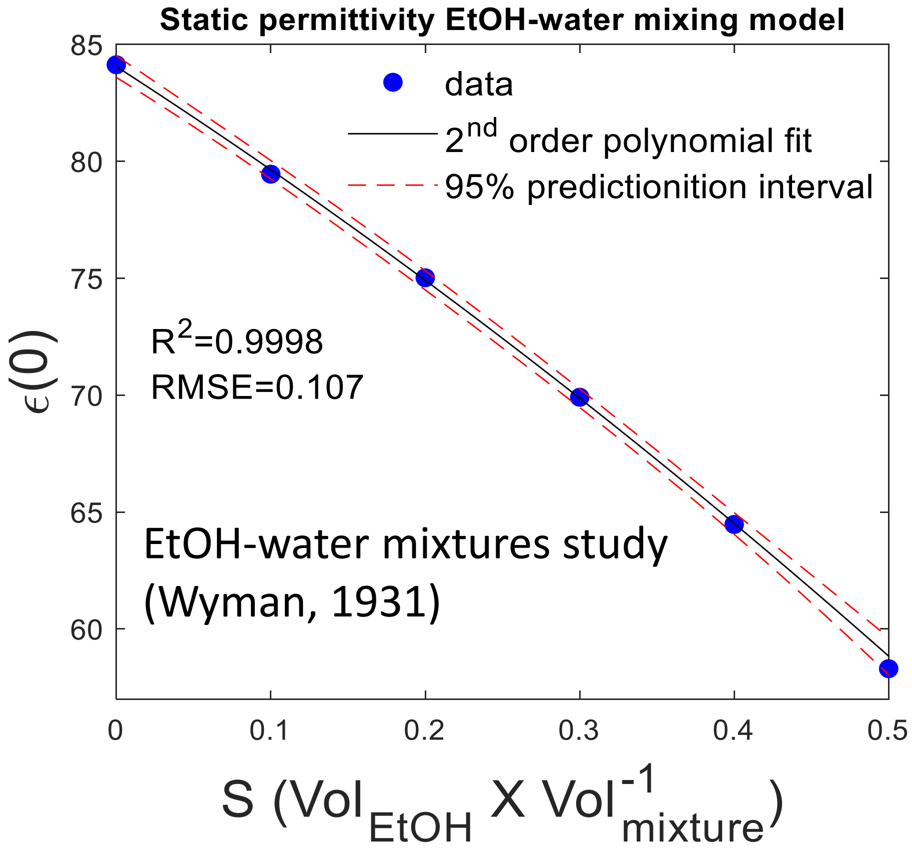
σ_b model:

1. Mixing model:

$$\sigma_{f\_mixture} = (S_{EtOH} \cdot \sigma_{EtOH}^{\alpha} + (1-S_{EtOH}) \cdot \sigma_{f,background}^{\alpha})^{1/\alpha}$$

With $\alpha = 0.3$ for $S_{EtOH} <= 0.4$.
(adopted from Personna et al., 2013)

2. $\sigma_{b,eff}$ is calculated using Archie's model:

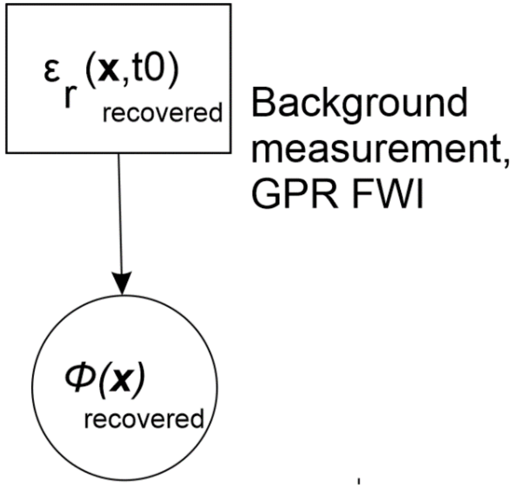


Agrosphere

JÜLICH Forschungszentrum

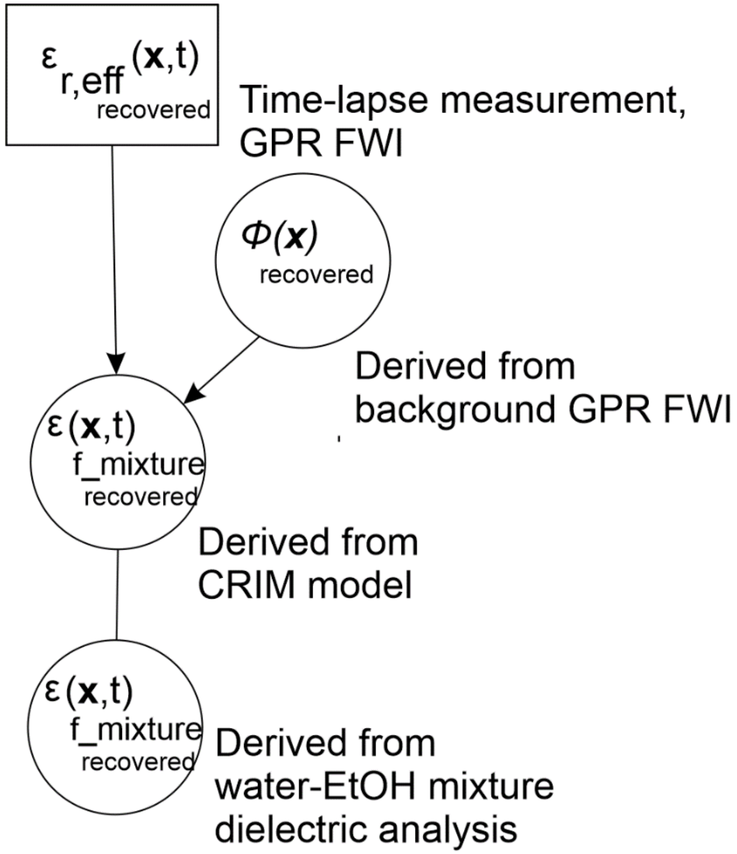
PETROPHSICAL RELATIONS FOR ETHANOL TRACER

1. Derive $\phi(x)_{recovered}$ from background GPR FWI $\varepsilon_r(x,t0)_{recovered}$



Back processing

2. Derive $S_{EtOH}(x,t)_{recovered}$ from time-lapse GPR FWI $\varepsilon_r(x,t)_{recovered}$

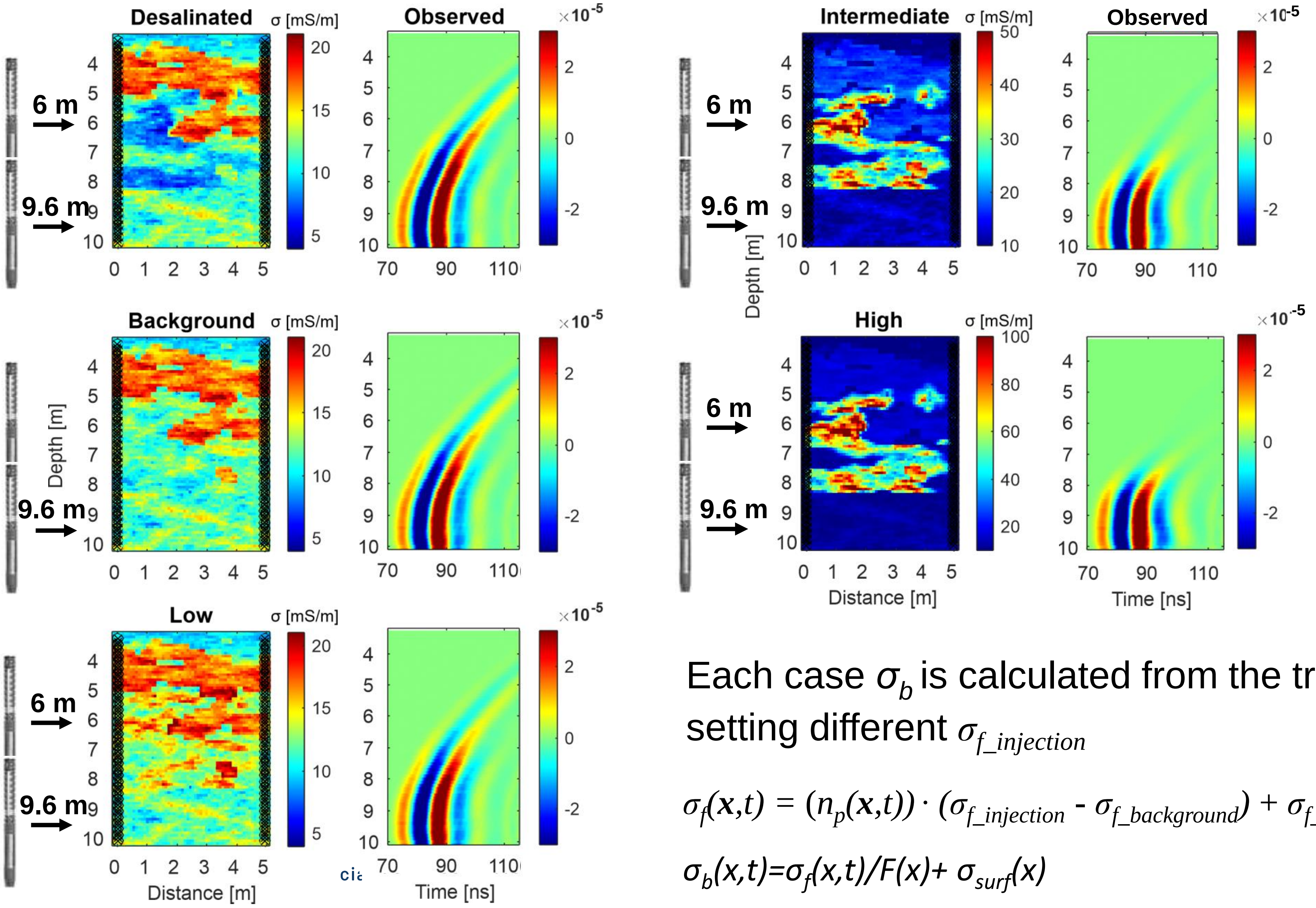


σ_b model:

Time-lapse GPR FWI σ_b enables deriving $\sigma_{f\_mixture}$, like for the salt tracer.

EFFECT OF SALT TRACER ON DATA

Amplitude scale is ten-fold lower.



- Five cases (including background) of changes in conductivity levels are tested.
- Amplitude decrease with increasing fluid conductivity.

Each case σ_b is calculated from the transport simulation by setting different $\sigma_{f\_injection}$

$$\sigma_f(\mathbf{x},t) = (n_p(\mathbf{x},t)) \cdot (\sigma_{f\_injection} - \sigma_{f\_background}) + \sigma_{f\_background}$$

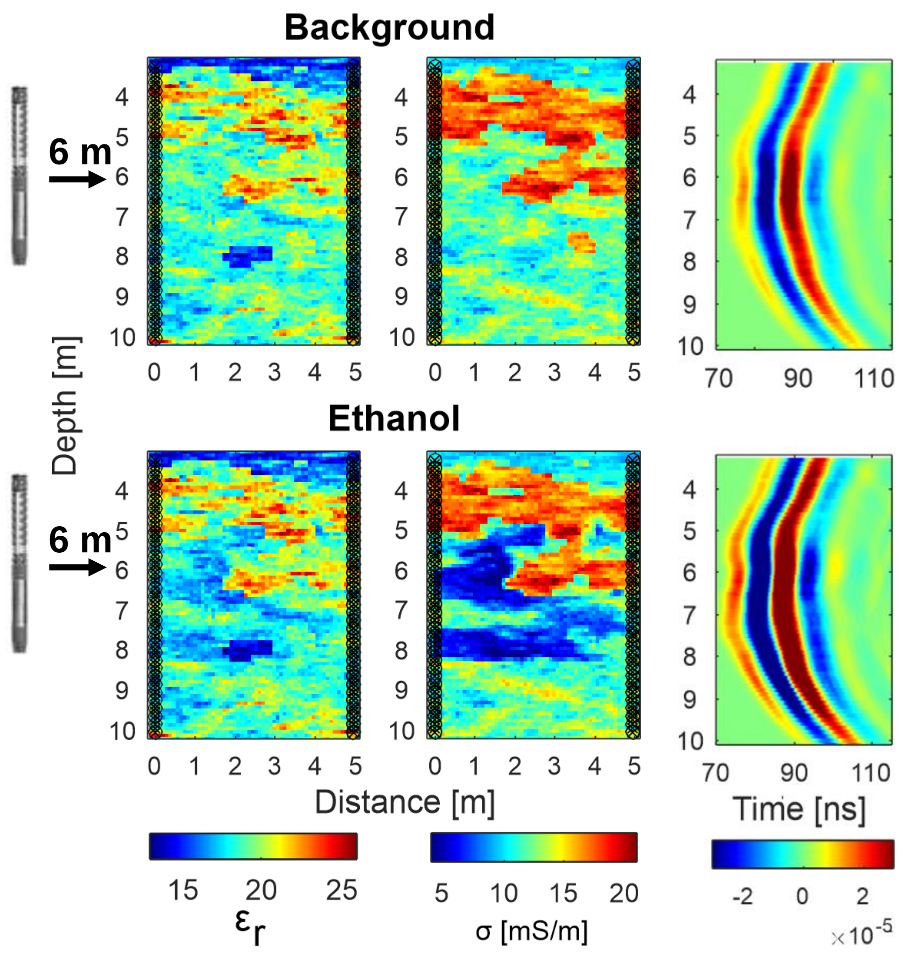
$$\sigma_b(x,t)=\sigma_f(x,t)/F(x)+ \sigma_{surf}(x)$$

Agrosphere

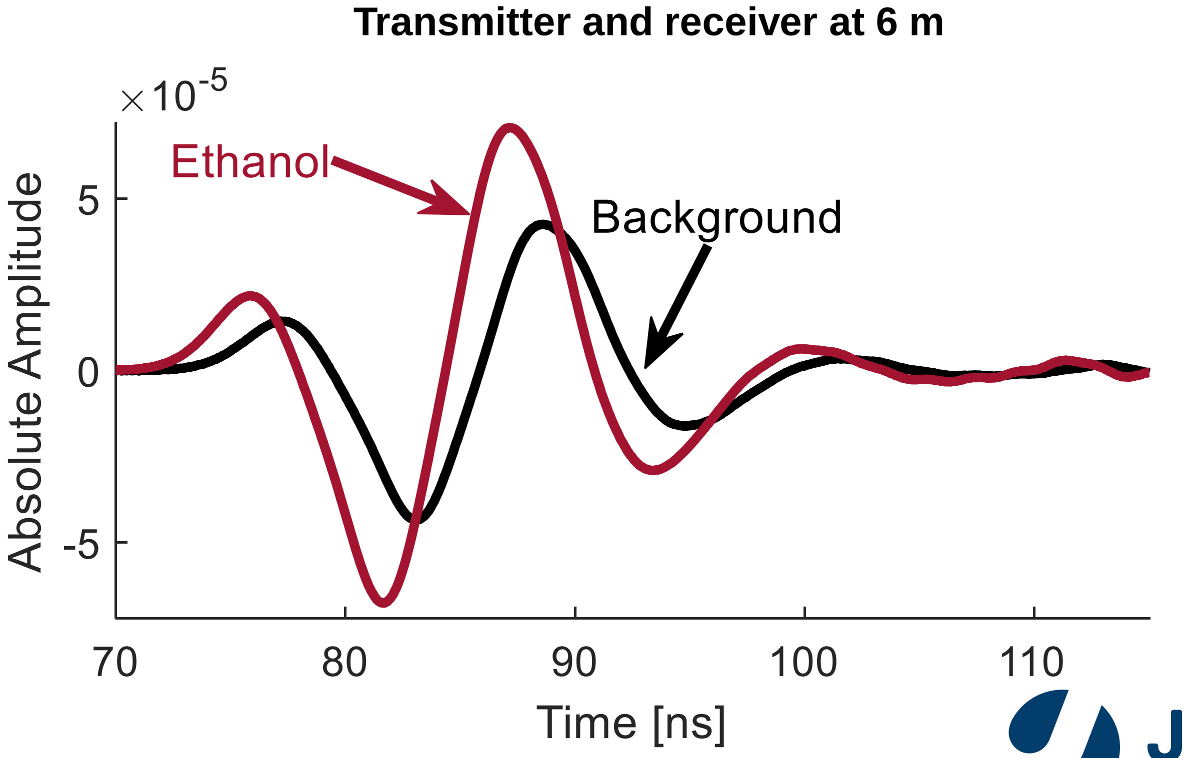
JÜLICH Forschungszentrum

EFFECT OF ETHANOL TRACER ON DATA

- ε_r and σ_b decrease with **ethanol volumetric concentration *S***



Maximal permittivity change of about Δεr=-4 between ethanol and background models lead to pahse shift of ~1.5 ns.

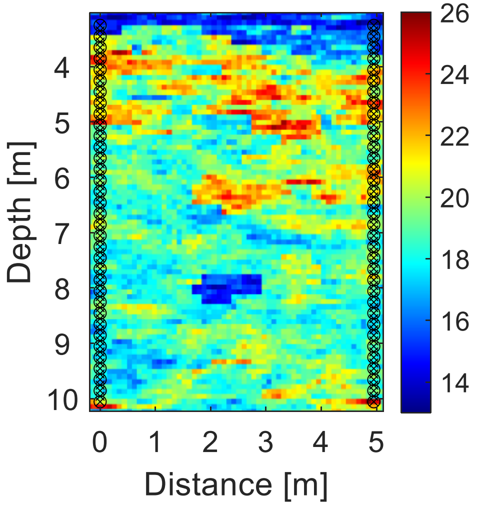


TIME-LAPSE STARTING MODEL INVERSION STRATEGIES

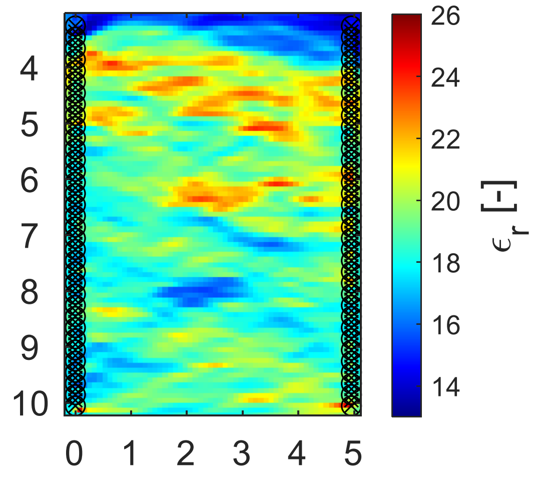
Strategy 1 – SM from background FWI recovered

Strategy 2 – SM of a previous day FWI recovered

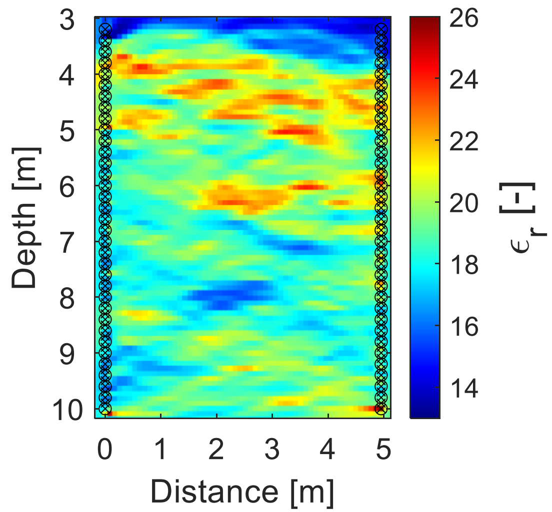
ε_r RM Day 15



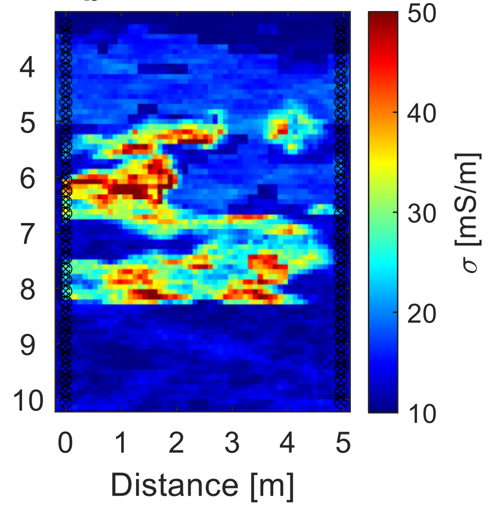
ε_r FWI background



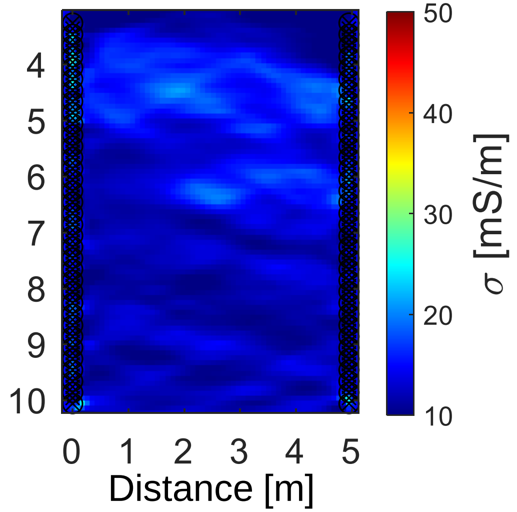
ε_r FWI of a previous day (13)



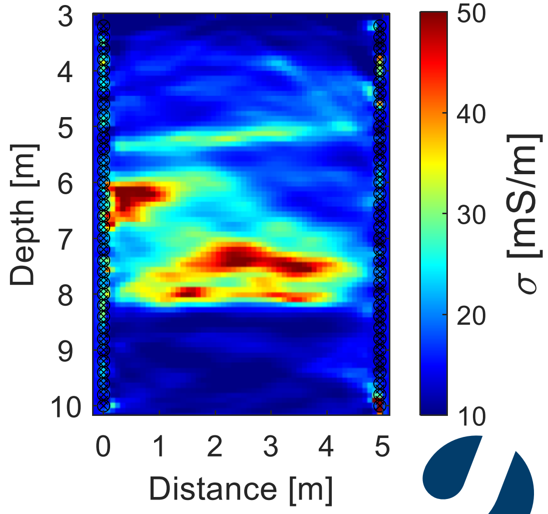
σ_b RM Day 15



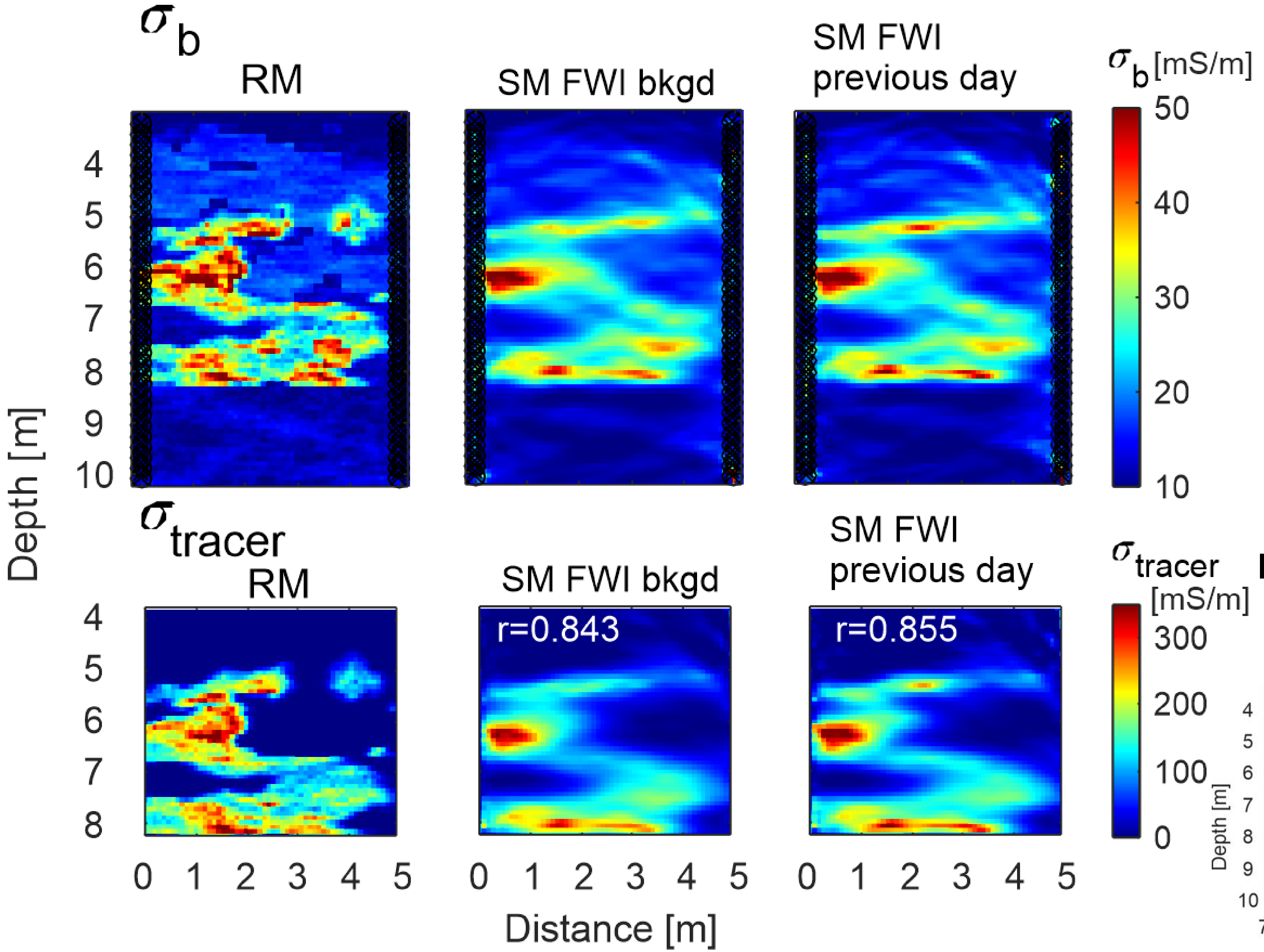
σ_b FWI background



σ_b FWI of a previous day (13)



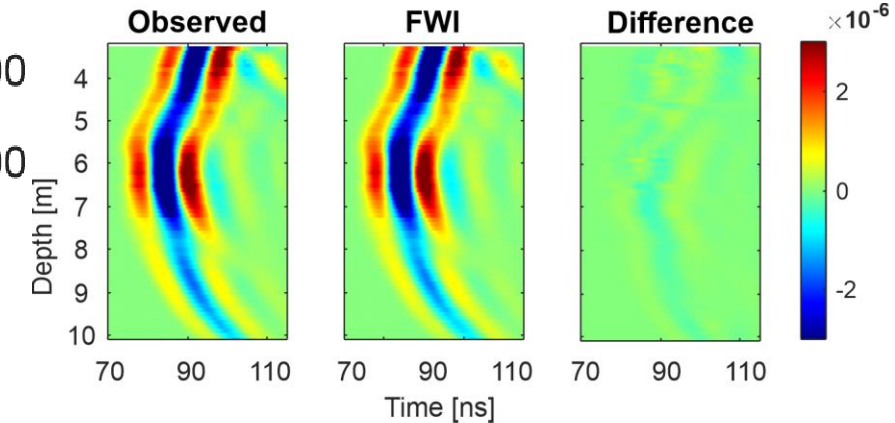
POSITIVE “INTERMEDIATE” ELECTRICAL CONDUCTIVITY TRACER



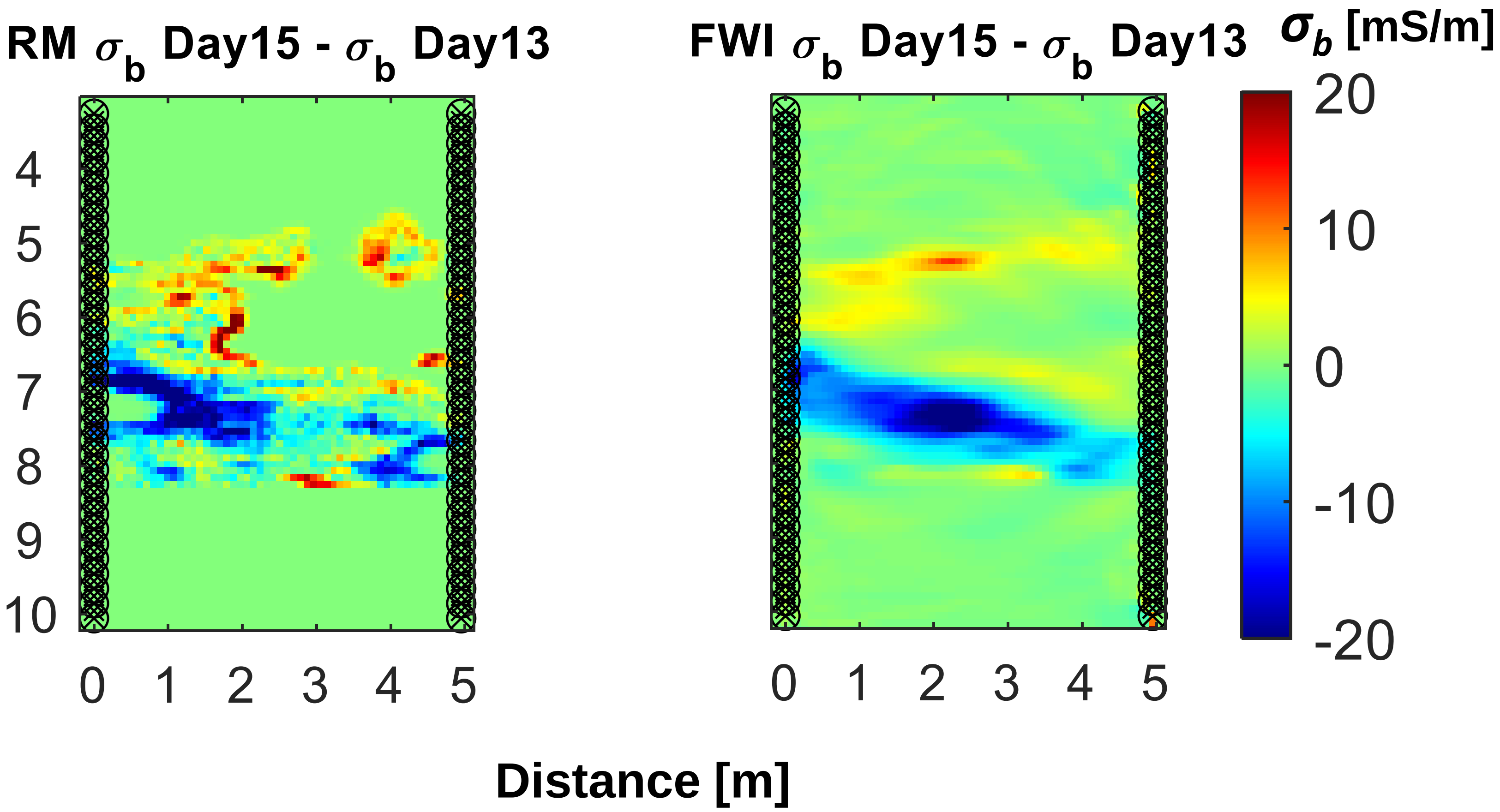
Starting model with FWI from the previous day results in better FWI model recovery (higher correlation with the RM σtracer).
However also SM from FWI background results in good recovery.

Intermediate case

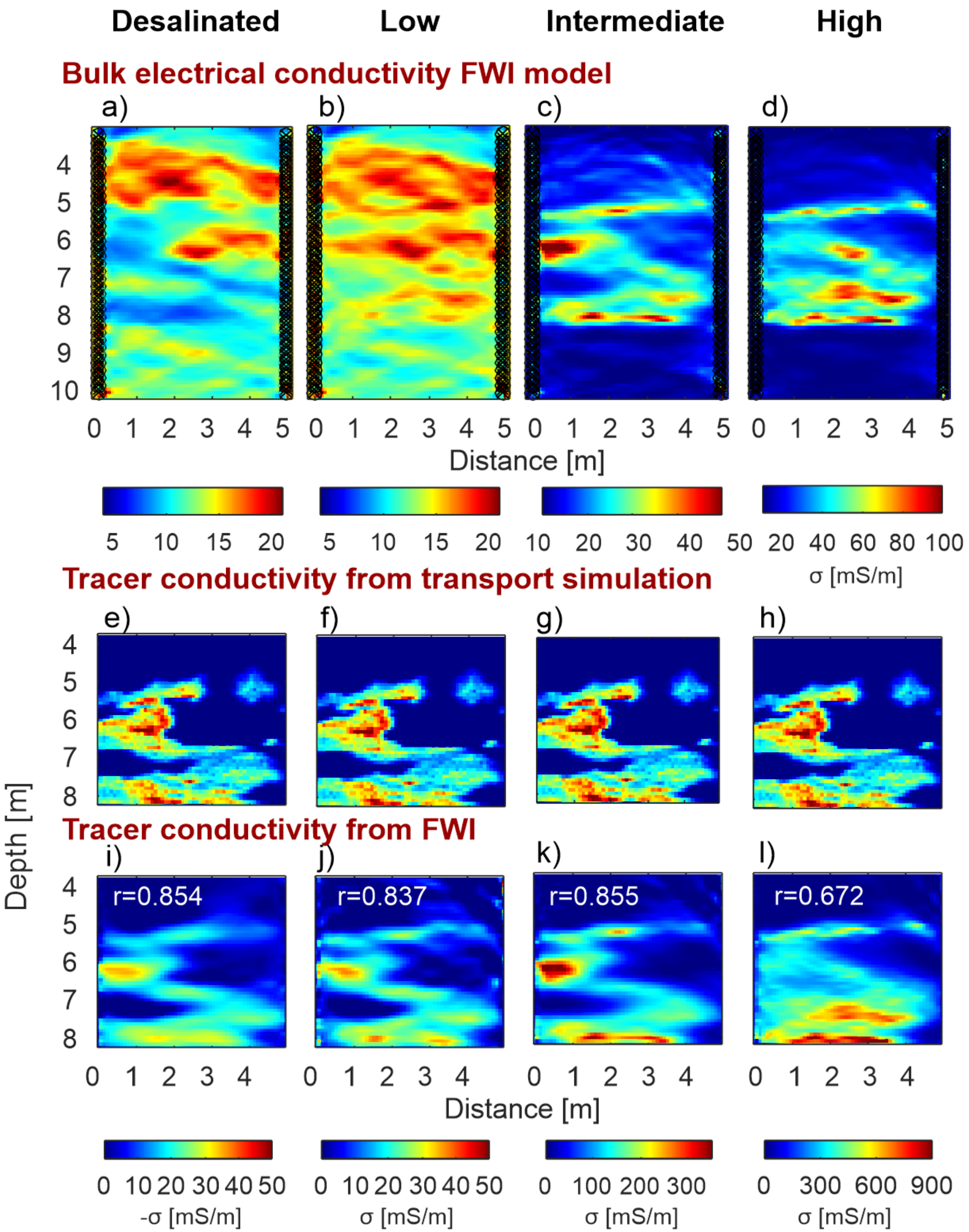
Good FWI data fit

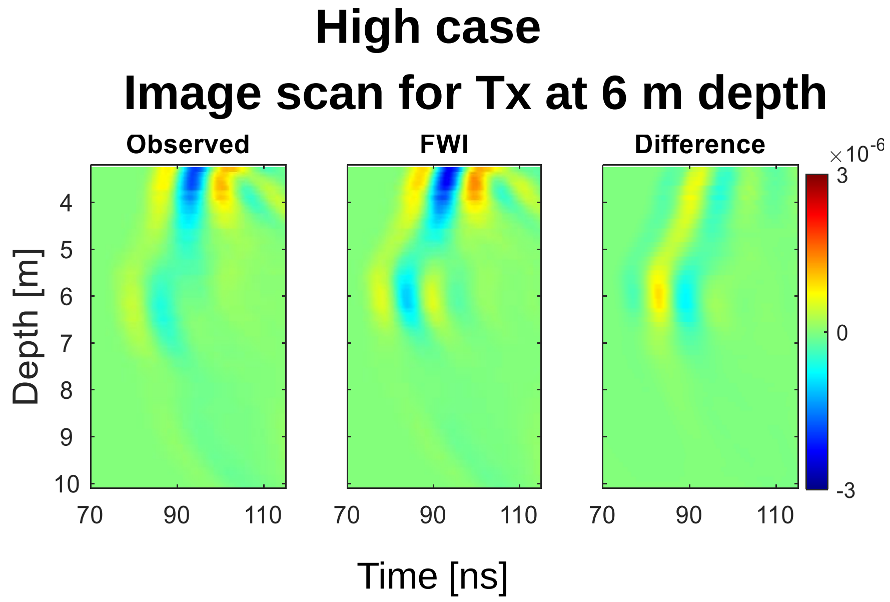


RECOVERY OF TIME-LAPSE FWI SALT CHANGES BETWEEN DAY 15 AND DAY 13



FLUID CONDUCTIVITY RECOVERY: COMPARISON OF SALT TRACER CASES





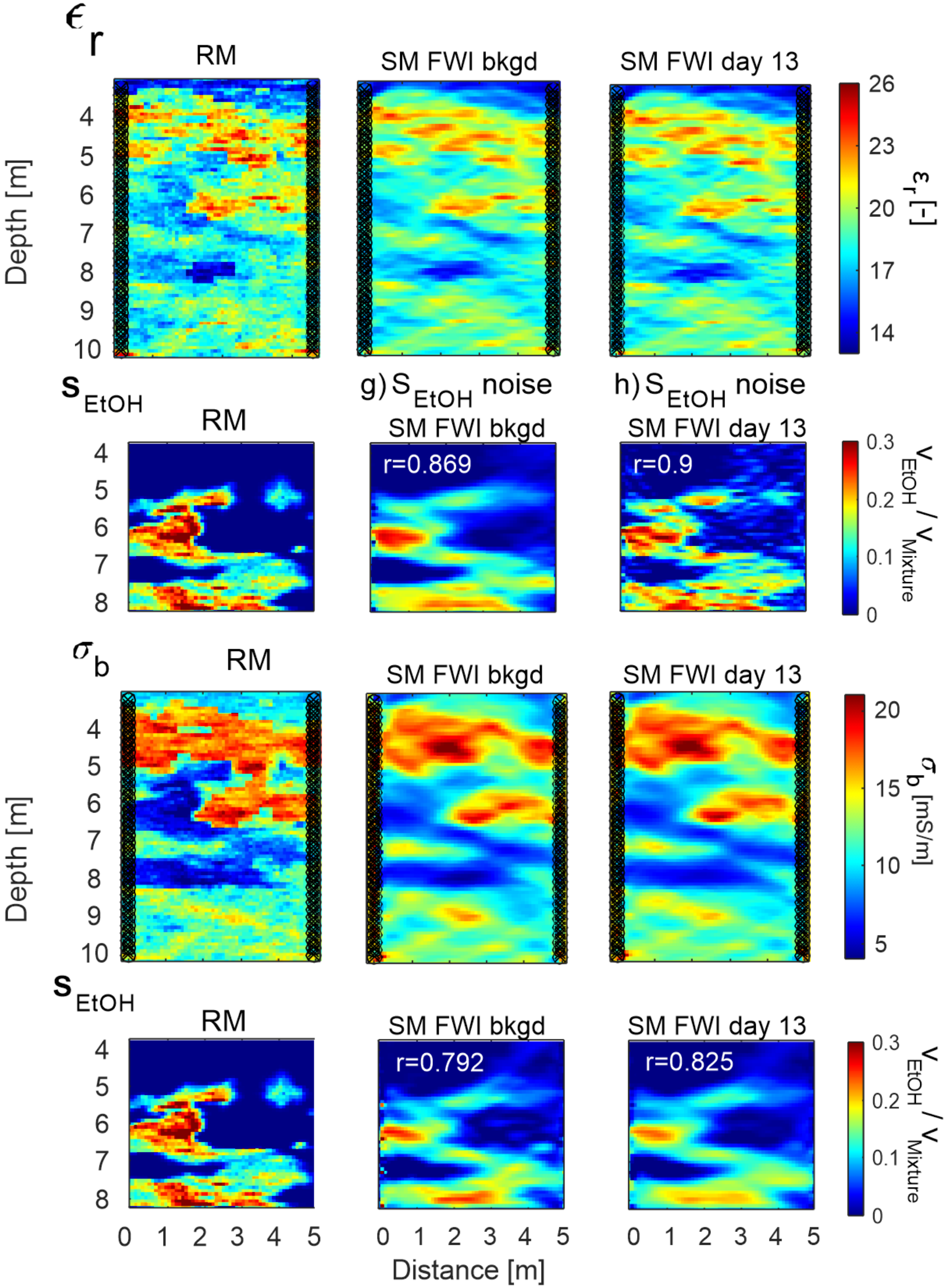
Difference in data is at the level of the observed/FWI data.

- Desalinated, Low and Intermediate recover σ_f well.
- Lower correlation in Desalinated, Low are not due to FWI bad fit but due to petrophysical relations, as the uncertainty in $F_{recovered}$ estimated from background FWI is propagated into σ_f, with a larger impact on low σ_b (*see* Archie's Law).
- In contrast, High case has lower correlation (r=0.672) because of bad fit of the data, as the high conductivity depressed the signal.

Agrosphere

JÜLICH Forschungszentrum

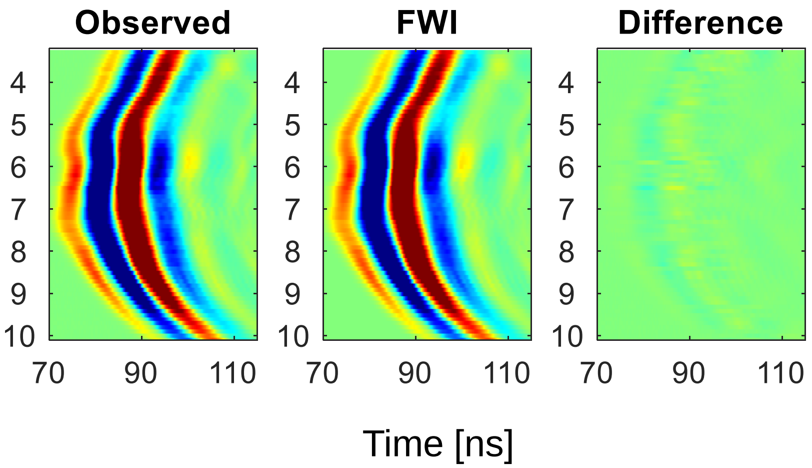
ETHANOL TRACER RECOVERY

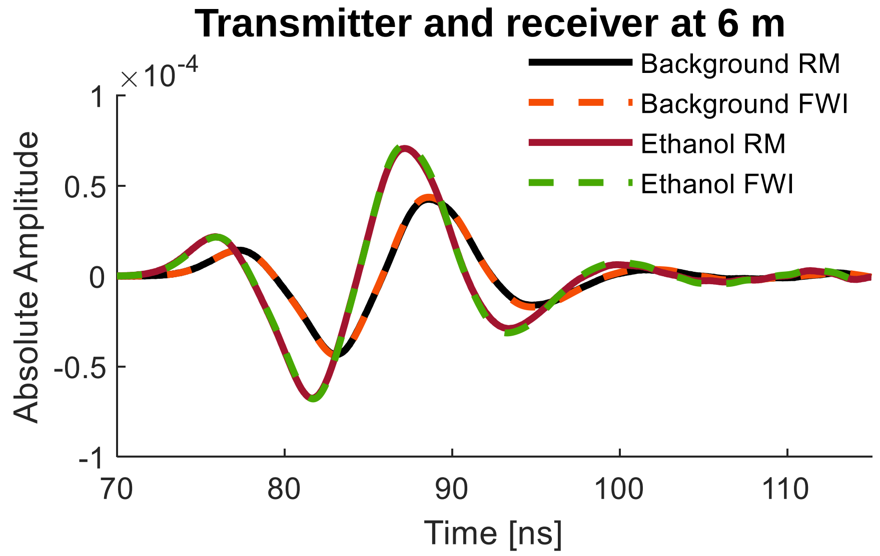


Starting model with FWI from the previous day results in better FWI model recovery.

Preferential paths from **permittivity** (r=0.9) are imaged in high-resolution.

In ethanol intrusion both the amplitude and the phase are fitted successfully.





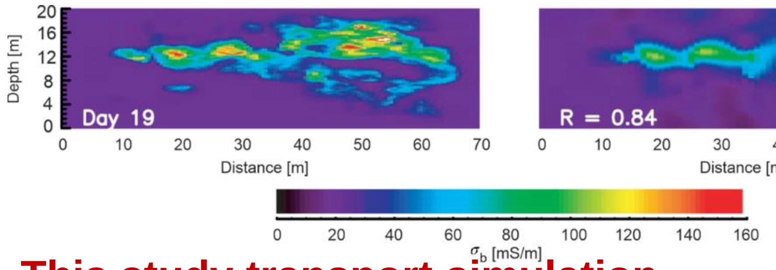
Agrosphere

JÜLICH Forschungszentrum

SPECTRAL ANALYSIS OF TRACER PLUME DISTRIBUTION

ERT study transport simulation

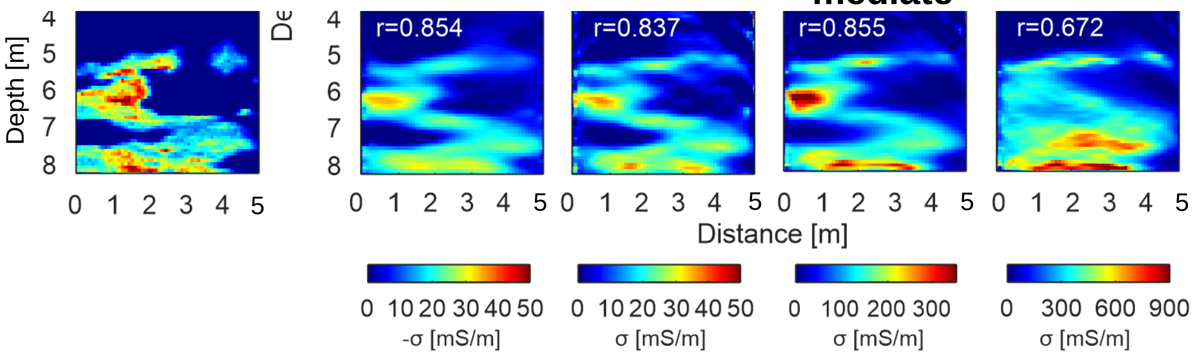
Real transport **ERT recovered**



Vanderborght et al., 2005

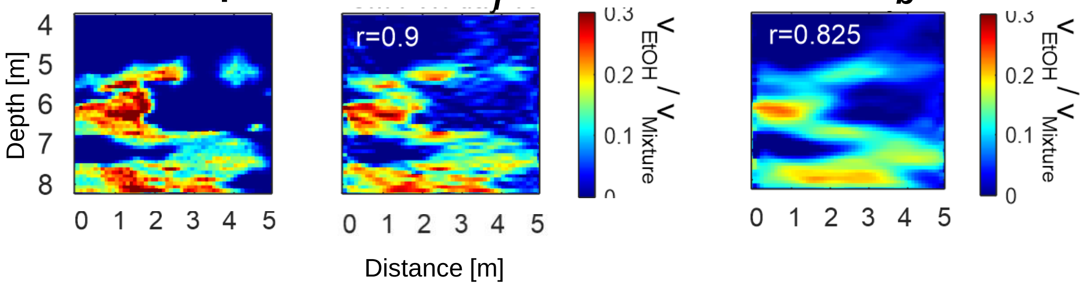
This study transport simulation – salt tracer (from σ_b changes)

Real transport **Desalinated** **Low** **Inter-mediate** **High**

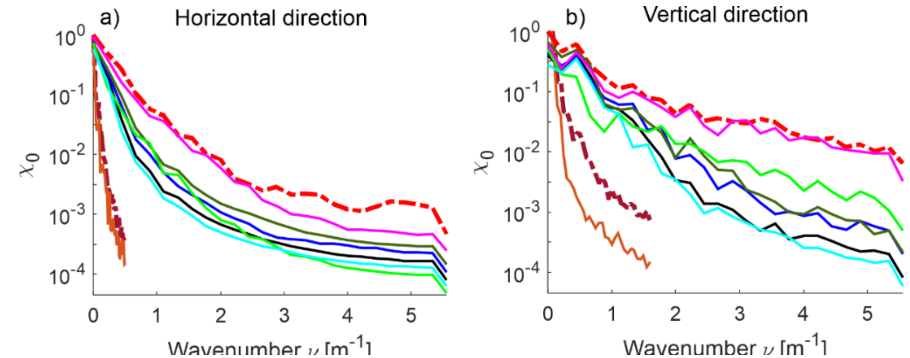


This study transport simulation – ethanol tracer (from ε_r and σ_b changes)

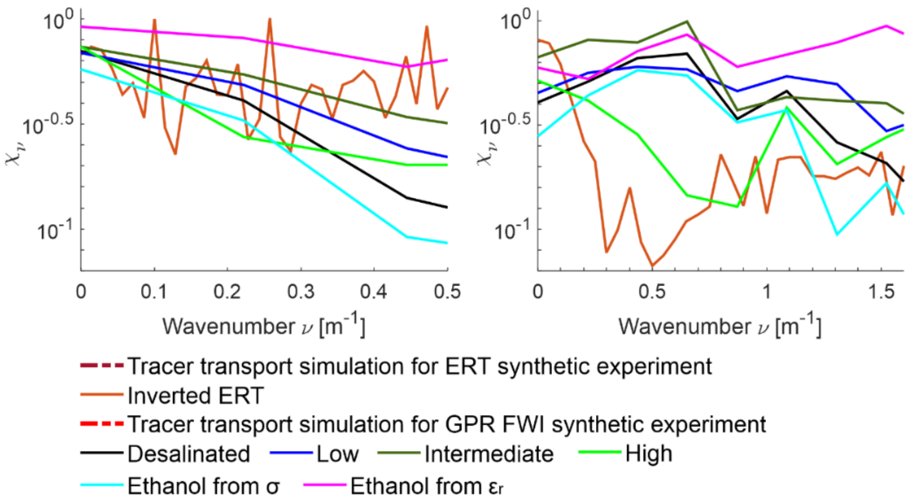
Real transport **From ε_r** **From σ_b**



$\chi_0(\upsilon) = PSD_{recovered}(\upsilon) / PSD_{transport}(\upsilon=0)$



$\chi_\upsilon(\upsilon) = PSD_{recovered}(\upsilon) / PSD_{transport}(\upsilon)$

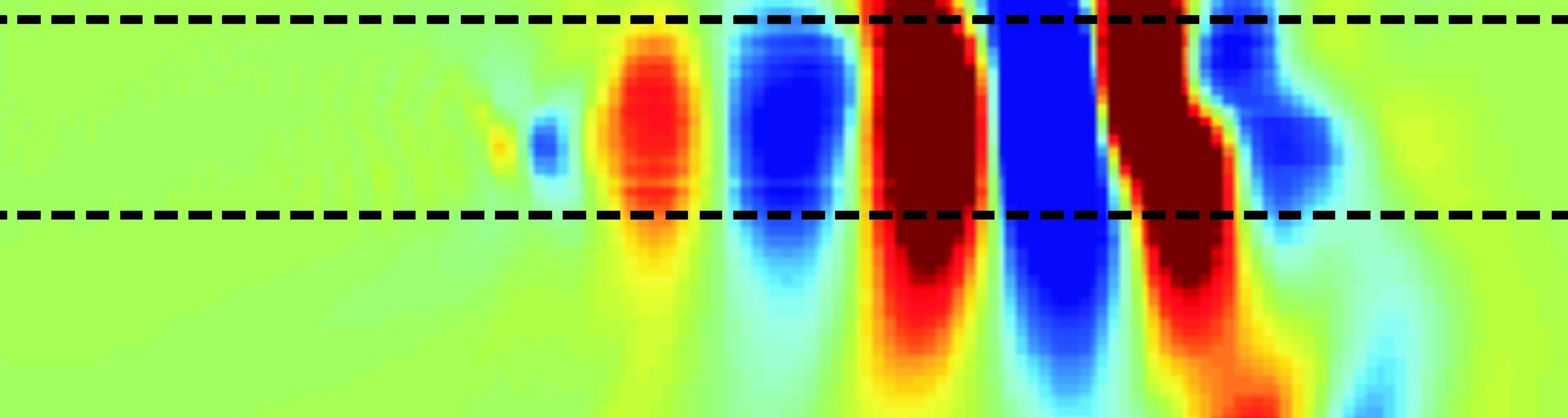


- Ethanol tracer distribution that is derived from the GPR FWI ε_r recovery is almost overlapping that of true tracer distribution transport.
- The Intermediate tracer conductivity case shows the best reconstruction amongst the saline tracer scenarios.
- More spectral information recovered in the vertical direction with GPR FWI. That may be related to higher sampling (tx 0.2 and rx 0.1 m receriver spacing; ERT 0.6 m electrode vertical seperation).

CONCLUSION

- A high resolution transport model of the Krauthausen aquifer has been built to investigate the potential of time-lapse GPR FWI.
- Synthetic time-lapse GPR FWI allowed to investigate different inversion strategies which showed that higher accuracy of tracer imaging can be achieved by using a previous fay FWI models as SM for the current day.
- Time-lapse GPR FWI has the potential for high resolution imaging of tracer tests that cause changes in electrical conductivity and/or permittivity, with better potential for pemittivity, to delinaite flow paths of about 0.1 m thickness.
- Resolution of permittivity changes is better than conductivity and have the potential to delineate flow paths of about 0.1 m thickness.
- First experimental data for saline and heat tracer experiments show an effect on the GPR data.

Thank you for your attention!



Acknowledgments:

- Helpers of the with infiltration experiment, GPR measurements data analysis: Rainer Harms, Yi Yu, Katalin Havas, Nasim Nassar, Nicole Höring, Tobias Ganther, Emil Shahnazaryan, Louisa Hain.
- This project is funded by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No 722028.

ITN Enigma