Numerical simulation of aquifer detection using low frequency pulsed radar

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Abstract— We describe two numerical models of the detection of aquifers under limestone using low frequency pulsed radar which we use for experimental design, depth range estimations, and testing data analysis methods. The first model implements a 1D FDTD scheme for Maxwell's equations coupled to a ground model incorporating dielectric permittivity, conductivity, and a Debye polarization model. The material parameters of the model were obtained from in situ measurements through limestone pillars performed underground in a mine [2]. The input to the simulation is the measured output of a low frequency pulsed radar system manufactured by Adrok Ltd. The complicated radar pulse produced by the transmitter contains frequencies from 3 to 65MHz and the low frequency component allows for deep penetration in suitable materials, see for example [1], where a similar simulation for deep surface probing on Mars is described.

The simulated pulse propagates through the limestone with a relative permittivity avaraging $\epsilon_r = 6$ and is reflected by an aquifer which we model as a layer with $\epsilon_r = 40$. After reflecting off the wet layer the pulse travels back up and is measured on the surface as a time domain trace. Synthetic noise calibrated to match measurements from the actual equipment is added to the computed result. In normal operation mode (STARE), 8000 traces are stacked, and the reflection is detected from the data using either visual identification of the return or, when the return signal is very weak, by analysing the correlations between stacked traces. Results indicate the aquifer is detectable up to about 350m depth and that extending the range to 500m depth is achievable by increasing the stacking by a factor 25. Detecting a reflection from 650m would require stacking 2000×8000 traces, and down to 800m would require 100000×8000 traces. Assuming a trace length of 20μs, suitable for detecting reflections up to 1km for $\epsilon_r \leq 9$, the latter would require a theoretical minimum acquisition time of about 5 hours, which is probably close to what is practical.

In order to convert the reflection time of the pulse to depth we need to know the velocity which is governed by the relative permittivity ϵ. In some practical applications this may be known from geology, but if it is not it can be obtained from a WARR scan, where measurements are taken with transmitter and receiver at increasing separations and using a normal moveout method or a velocity spectrum (as used in seismic) to estimate velocity and ϵ_r. Because of the high frequency components in the pulse and the high accuracy required of the FDTD simulator (due to the large dynamic range that needs to be simulated) the required grid spacing is about 5cm and large computational resources would be required for a full 2D FDTD simulation which is why we model the WARR scan with a raytracing method. Simulated data is rendered by propagating the measured input pulse through all rays that reach the surface using computed reflection/transmission coefficients and an attenuation filter derived from the FDFT model. The ground is modeled as a layer with mean $\epsilon_r = 6$ with random fluctuations with standard deviation 0.5 at intervals which are distributed exponentially with a mean of 5m. This models irregularities and causes complicated backscatter similar to what is observed in practice. From a velocity spectrum analysis (suitably modified to incorporate radar specific losses) it appears that the velocity can be estimated from the backscatter up to about 150m down and from the stronger aquifer reflection at 350m with about 5% accuracy leading to a similar accuracy in depth estimation.

REFERENCES

1. V. Ciarletti, B. Martinat, A. Reineix, J. J. Berthelier, and R. Ney. Numerical simulation of the operation of the gpr experiment on netlander. *JOURNAL OF GEOPHYSICAL RESEARCH*, 108(E4, 8028):doi:10.1029/2002JE00186, 2003.
2. K. van den Doel, J. Jansen, M. Robinson, G. C. Stove, and G. D. C. Stove. Ground penetrating abilities of broadband pulsed radar in the 1-70MHz range. In *SEG Technical Program Expanded Abstracts 2014, Denver*, pages 1770–1774, 2014.

NUMERICAL SIMULATION OF AQUIFER DETECTION USING LOW FREQUENCY PULSED RADAR

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MOTIVATION

- Explore capabilities of low frequency subsurface radar
- Model commercial 3MHz system built by Adrok Inc.
- Low frequency radar systems (1-5MHz) used for km range imaging:
  - Mars
  - Antarctica
- How far can we see through rock with such a system?

SIMULATED EXPERIMENTS

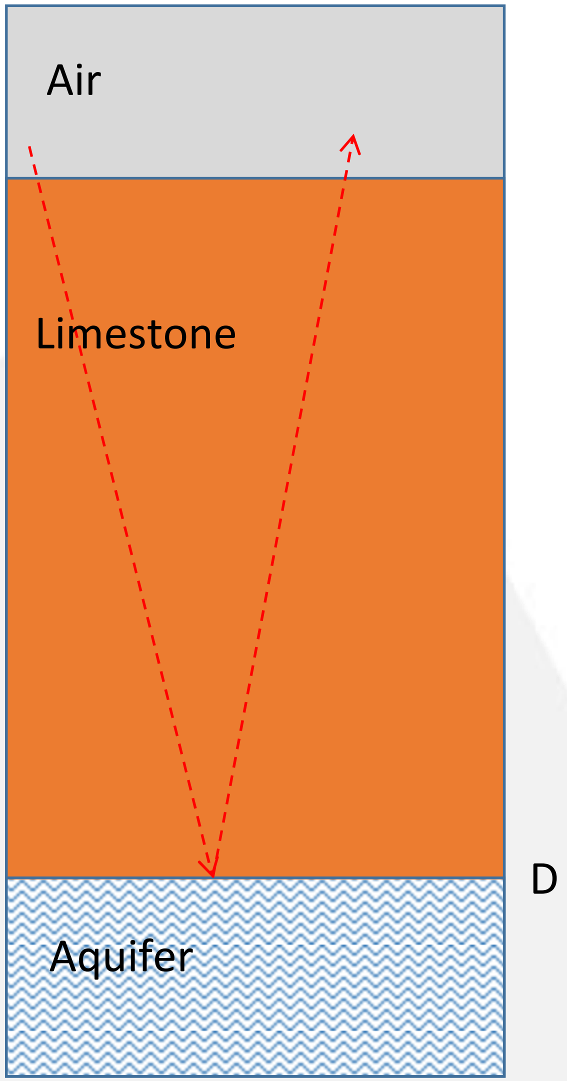
- Measure sensor sensitivities and noise levels
- Measure ground parameters in-situ through limestone
- Physical model: Sensors + ground + Maxwell equations
- Implement numerical simulator:
  - FDTD Maxwell + ground model in 1D
  - Raytracing in 2D
  - FDTD 2D/3D under development
- Insert measured sensor + ground parameters into model
- Perform virtual experiments + data analysis

CASE STUDY

- Goal is to detect aquifer depth D=350m and further down
- Aquifer under limestone
- At depth D can we
  - Detect round trip time of reflection from aquifer?
  - Measure velocity in medium? (CMP/WARR triangulation)
- How much stacking needed?
  - How deep can we see with a 1 day long scan?
- How long should the CMP/WARR line be?
  - How many points need to be sampled on scan line?
- What's the best signal processing method? (Not covered here.)

MODEL PARAMETERS

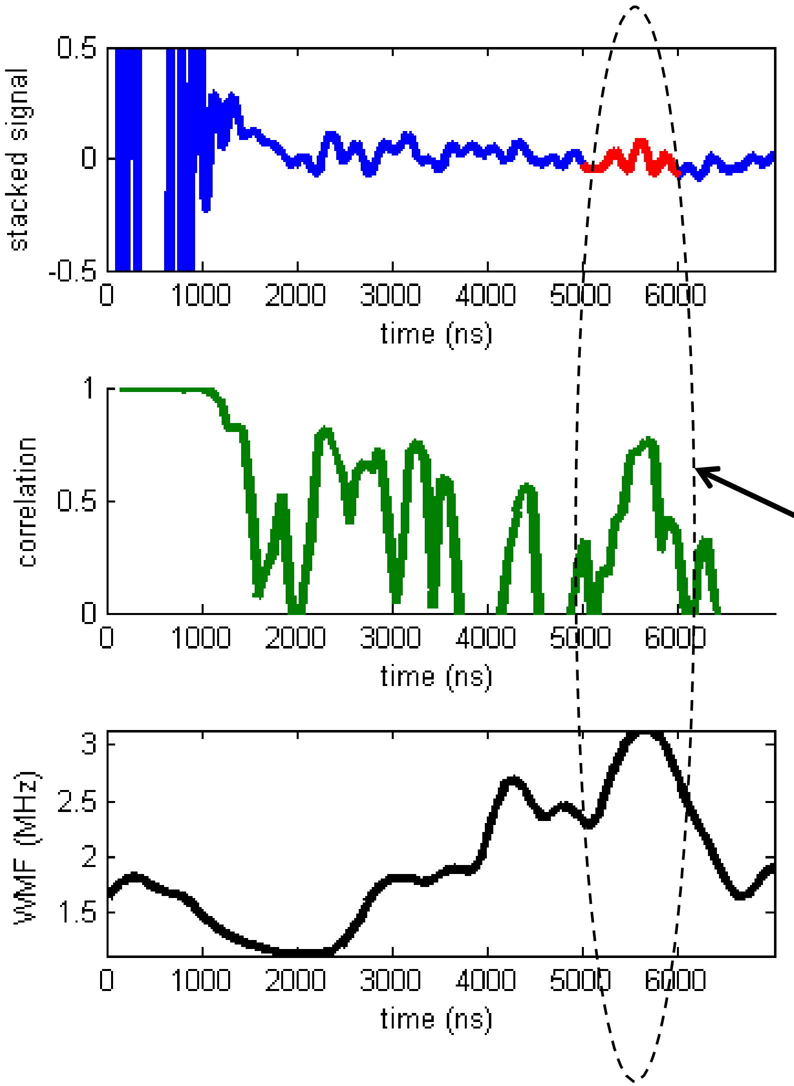
- Up to depth D:
  - Limestone: dielectric ϵ_r=6 + random fluctuations (std 0.25)
  - Conductivity σ=0.075mS/m
  - Debye relaxation time 0.4ns
- Aquifer at depth D:
  - ϵ_r=40, σ = 0.1S/m
- Noise level 1% of peak radar pulse maximum
- All except random fluctuations measured parameters



DATA PROCESSING

- Detect time of reflection from STARE scan
  - Transmitter/Receiver stationary, scan repeatedly and stack
  - 10000 scans/min
- Measure velocity for time→depth conversion
  - CMP or WARR line, Transmitter/Receiver at varying distances (e.g., 1-100m)

STARE SIGNAL PROCESSING



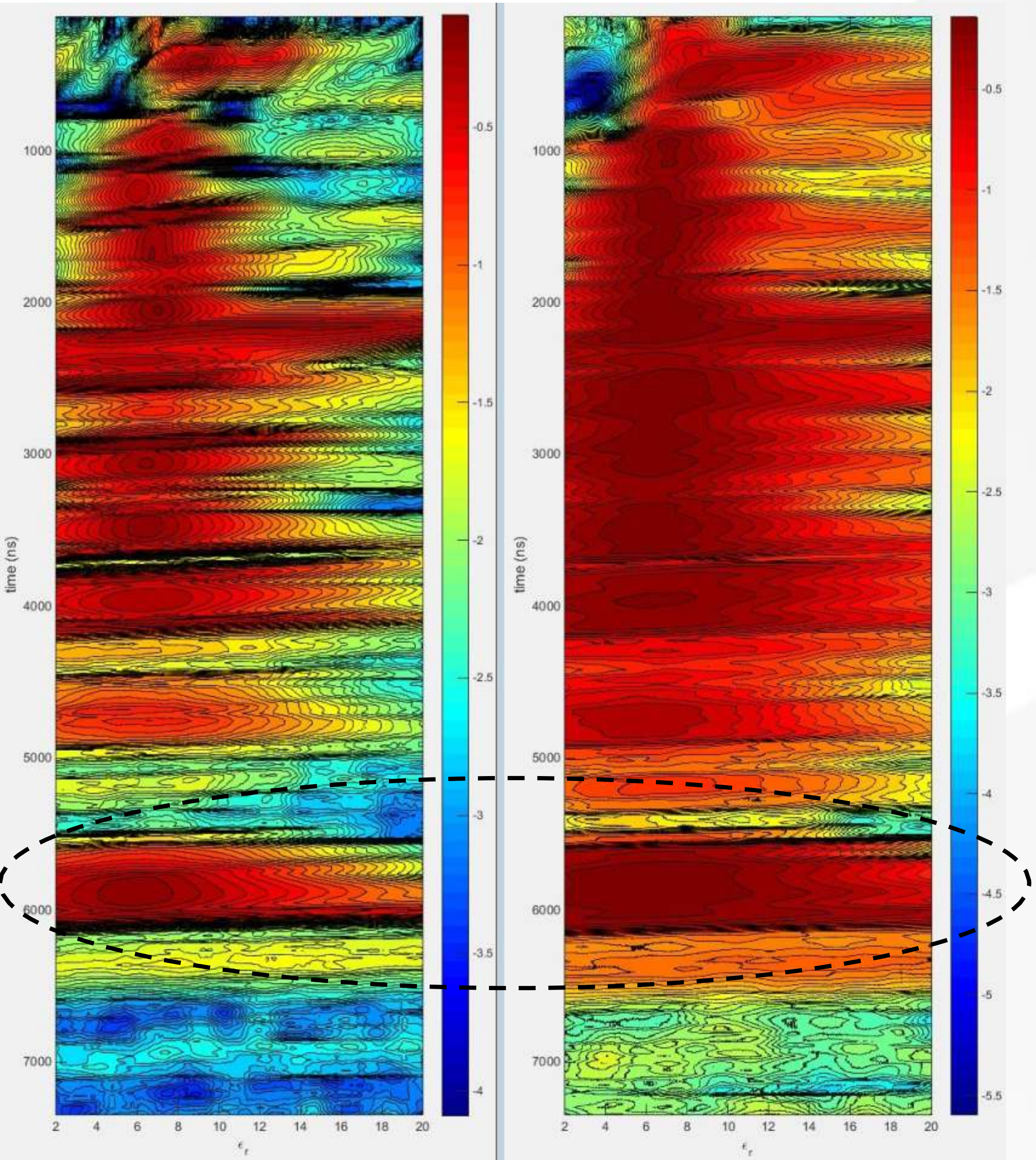
To identify strong reflectors.

Traces in stack (500 traces) highly correlated near reflection.

Frequency content consistent with return from 3MHz component of pulse.

(This is from real experiment, water reflector at known distance of 350m.)

VELOCITY SPECTRUM ANALYSIS TO DETERMINE VELOCITY



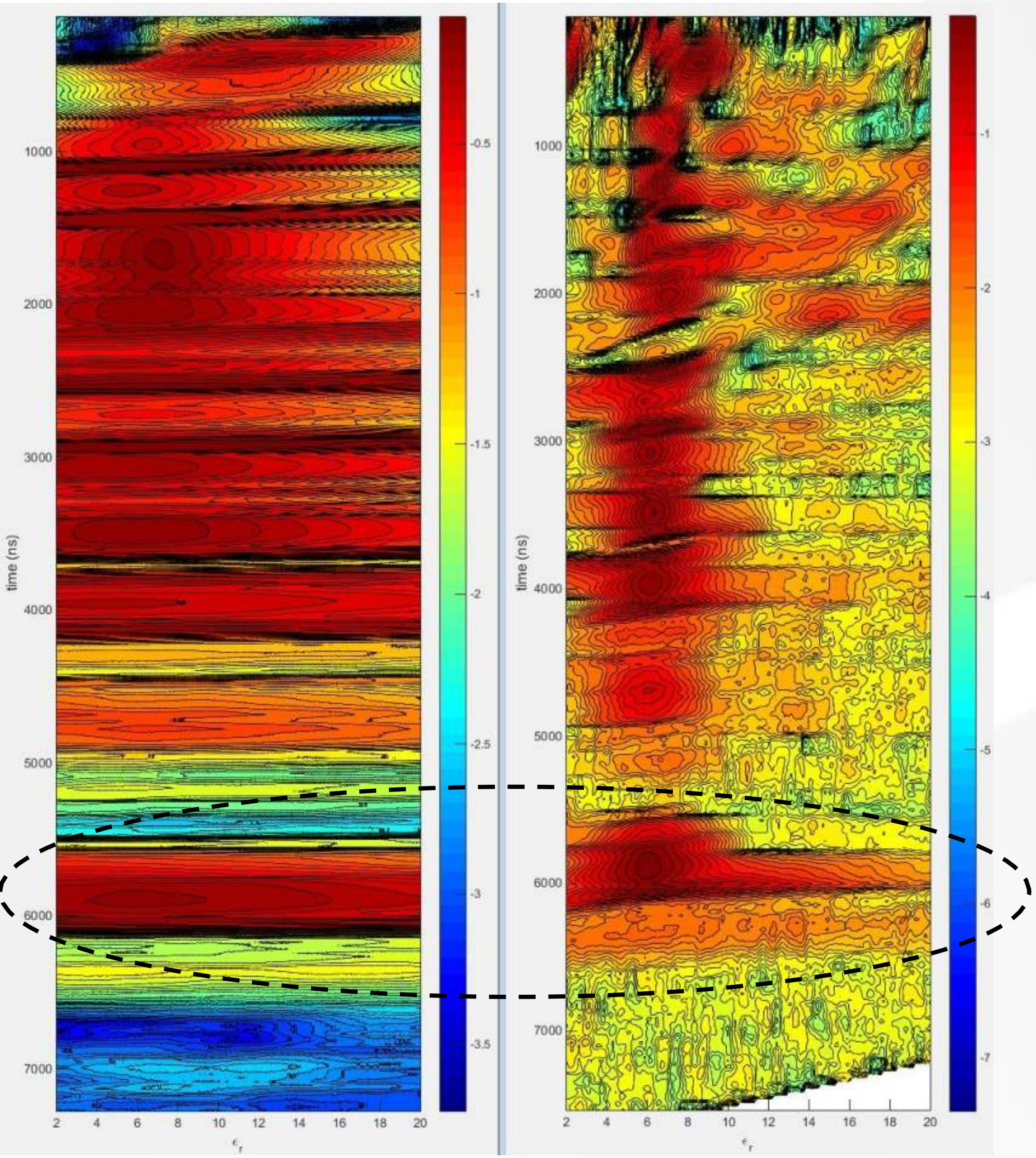
Semblance based velocity spectrum displays, translated to dielectric. Read off dielectric visually.

In example aquifer at t=5800ns, ϵ=6, gives D=355m (350m actual depth). 100m scan line.

Right: standard semblance

Left: improved resolution by extracting phase with Hilbert transform

EFFECT OF SCAN LINE LENGTH



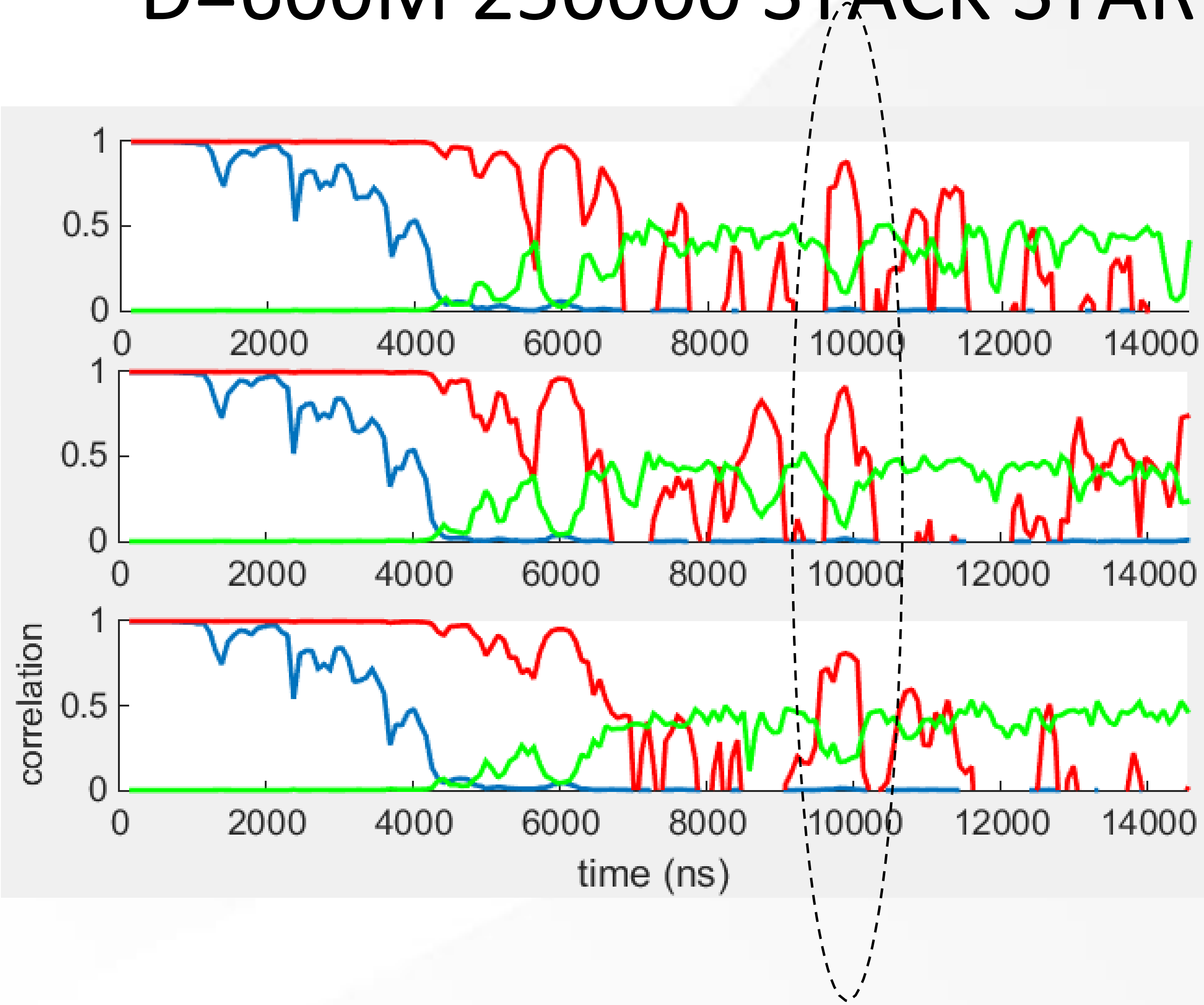
Same for 50m (left) and 200m (right) scan line.

Conclusion: 50m not enough, 200m near perfect, 100m good practical compromise for field experiment.

DEPTH LIMIT WITH A 1 DAY LONG SCAN

- Simulation results indicate 600m maximum depth
- STARE need 250000 stack to detect reflection time
- WARR needs a 200m line with 20 sampling points
    - 250000 stack at each sampling point
- Can be done in about 10 hours including setup
- Depth estimation error 5%

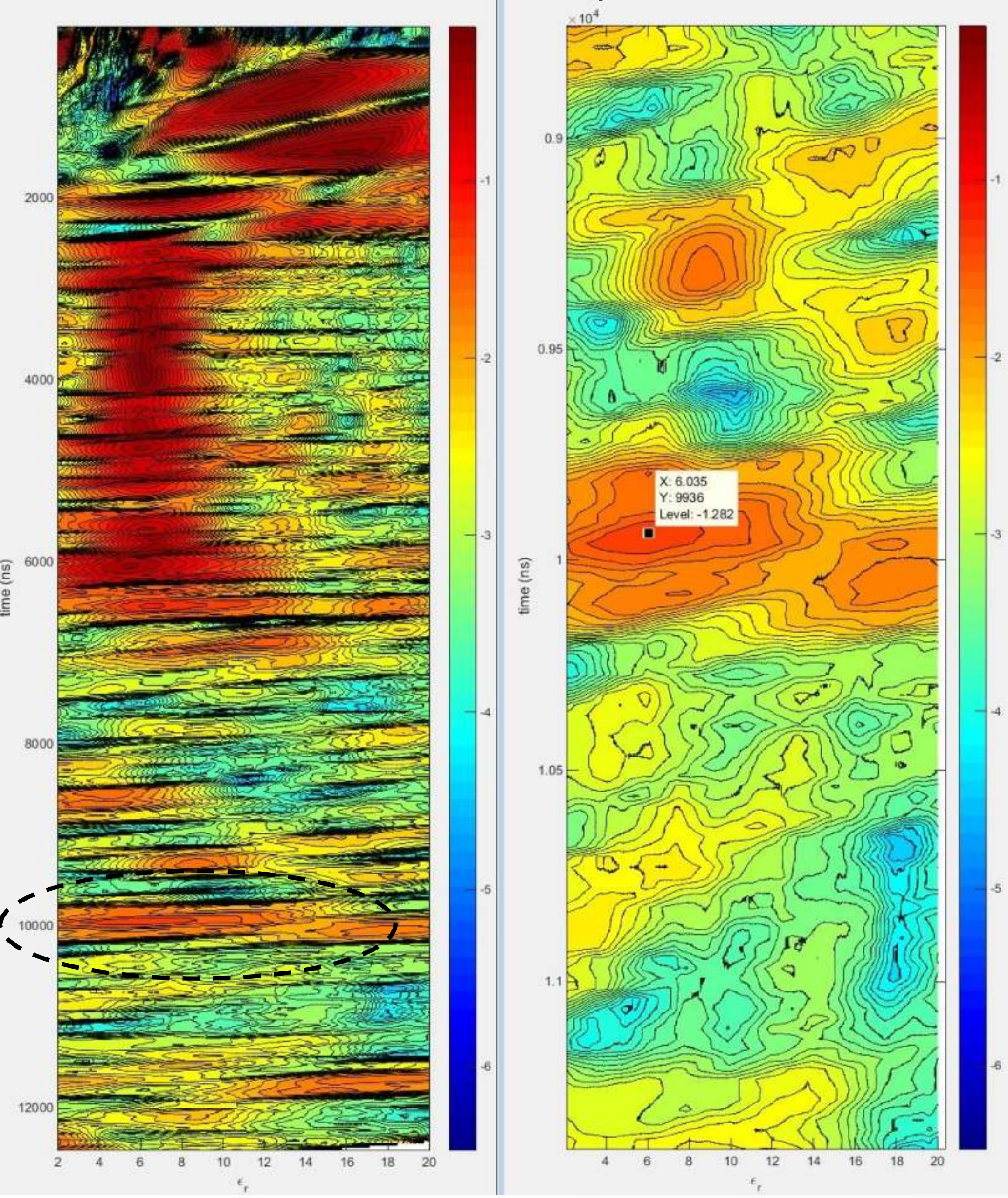
D=600M 250000 STACK STARE



Noise causes random correlations.

Replicate experiment, and look for persistent peaks.

D=600M WARR, 200M SCAN LINE, 20 SAMPLE POINTS



Lose signal at about 6000ns, peak at (10000ns, ϵ=6) faint but detectable.

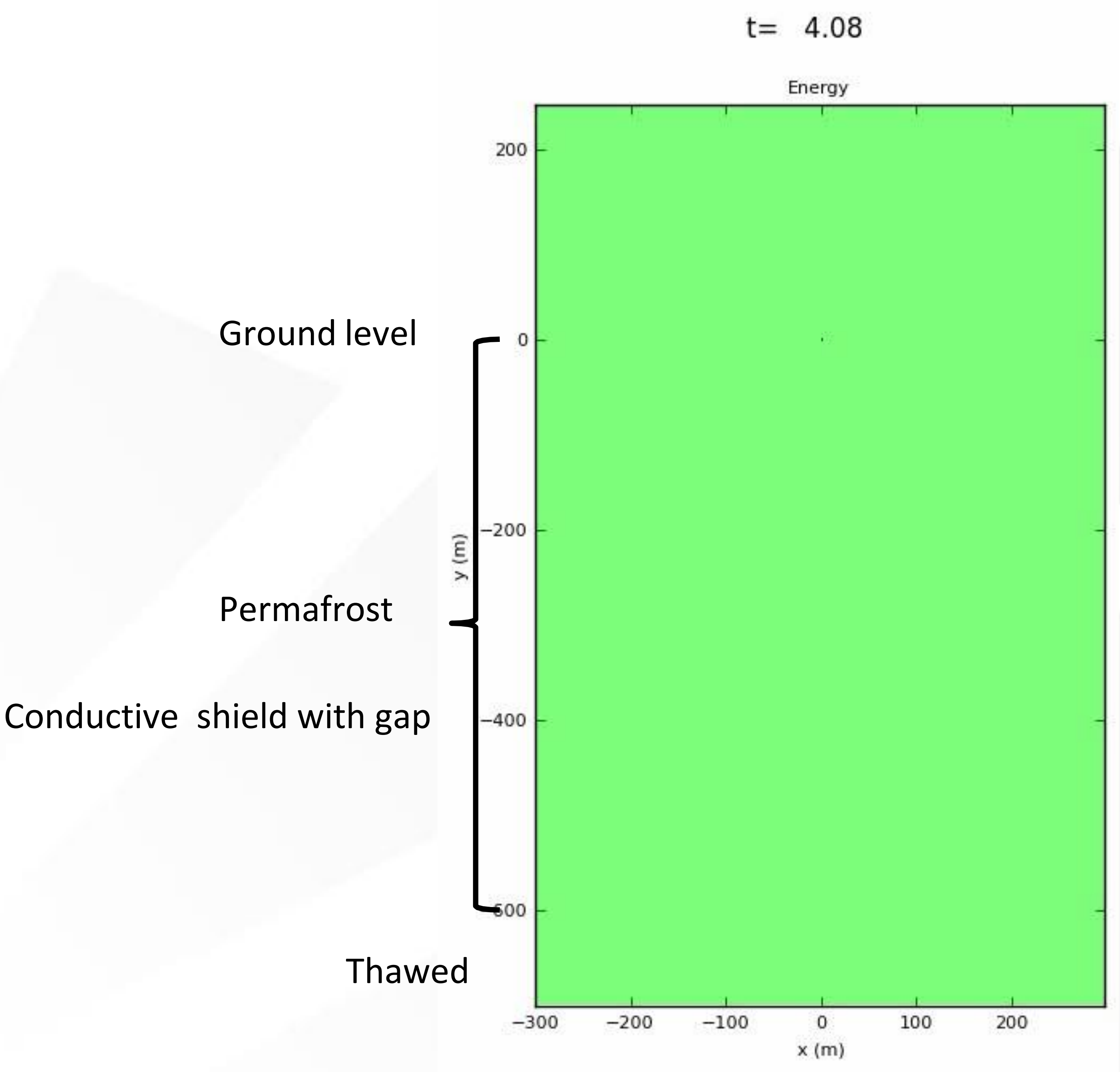
Some care required in interpretation due to spurious peaks caused by noise.

CONCLUSIONS

- Simulations useful for experimental design/feasibility study
- Prior to field work we can:
  - Determine amount of data needed
  - Determine WARR/CMP setup (scan length, sampling)
  - Determine if goal is achievable
  - Validate signal processing methods
  - Estimate expected interpretation errors
  - Suggest equipment improvements
- Example of aquifer detection under limestone: 600m practical limit

PEOPLE

Joel Jansen	**Teck Resources**
Michael Robinson	
Colin Stove	**Adrok**
Gordon Stove	
Staff at Pend Oreille mine	**Teck Washington**



Just for fun: A preview of current work on 2D FDTD simulation.