Adrok®

Optimal noise levels for the detection of conductive lenses in permafrost with low frequency pulsed radar scans

Dr Kees van den Doel
kdoel@adrokgroup.com

Gordon Stove
gstove@adrokgroup.com

Adrok
Edinburgh, Scotland

July 2019

PIERS
Photonics & Electromagnetics Research Symposium
also known as **Progress In Electromagnetics Research Symposium**
PIERS 2019 in Rome, Italy, 17-20 June, 2019

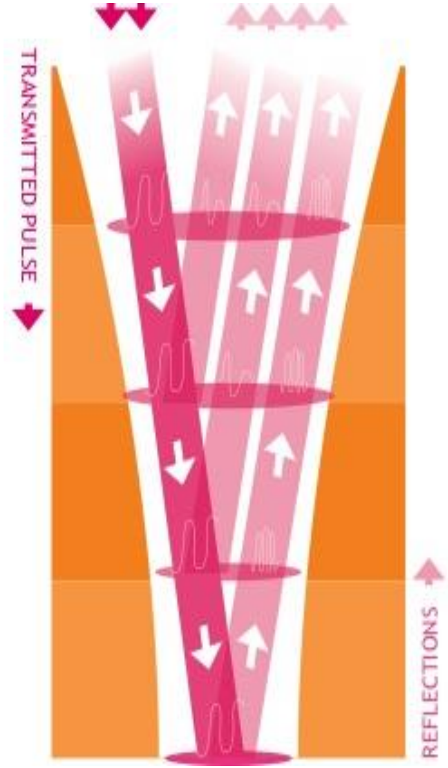
Overview

- Technology and methodology
- Motivation for this experimentation
- Case Study
- Conclusions

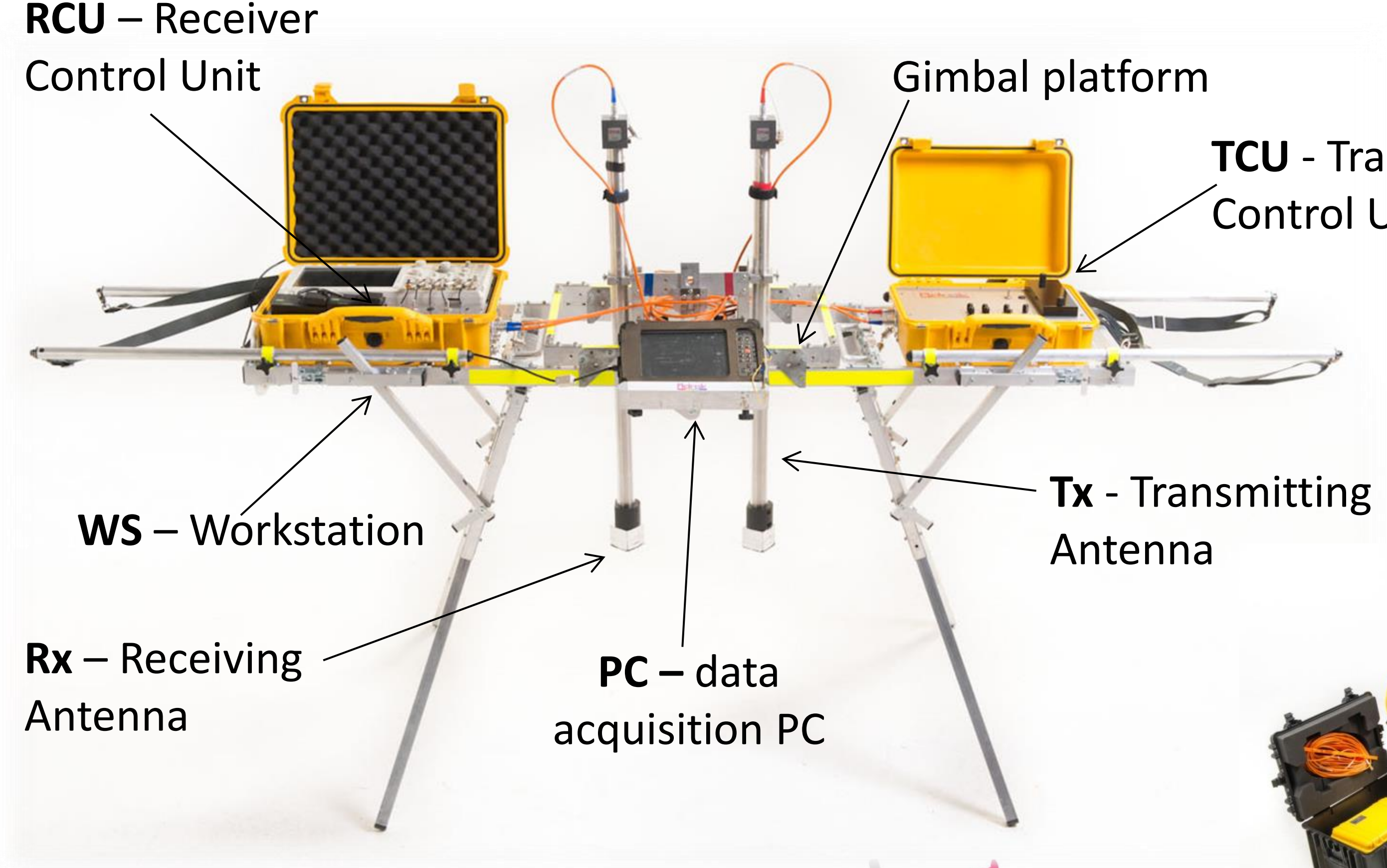
Technology and methodology

Atomic Dielectric Resonance (ADR)

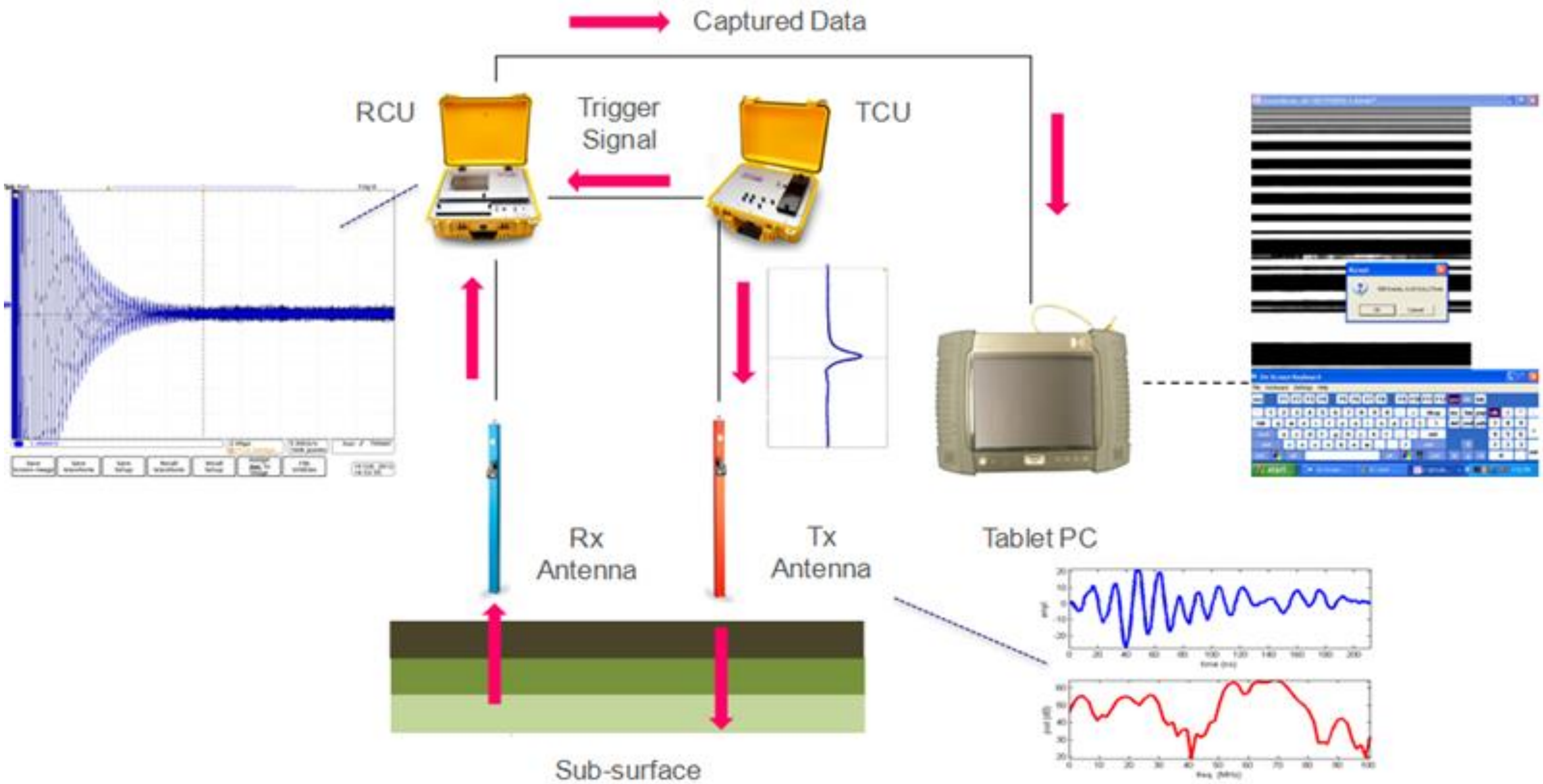
- RAdio Detection And Ranging in visually opaque materials
- ADR sends broadband pulses of radiowaves into the ground and detects the modulated reflections returned from the subsurface structures
- Transmit broad band pulses at a precisely determined Pulse Repetition Frequency (PRF) with low power (of the order of a few milliwatts, Mean Power)
- For large depth geo exploration typically transmit between 1MHz to 100MHz
- ADR measures dielectric permittivity & conductivity of material
- ADR also uses spectral content of the returns to help classify materials (energy, frequency, phase)



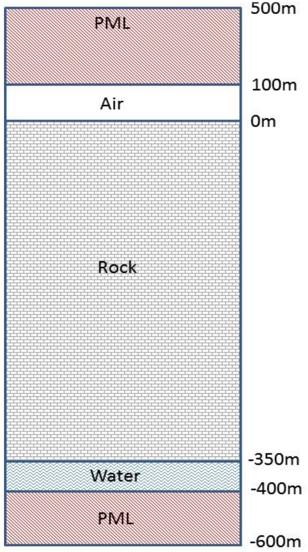
Field ADR Scanner

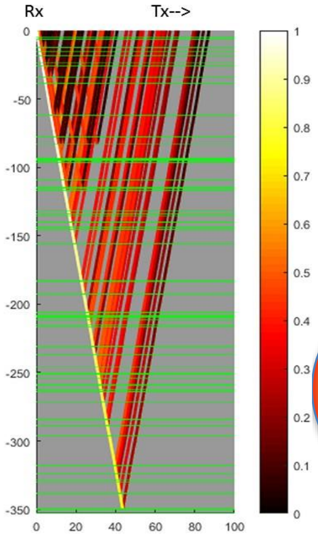


System Diagram



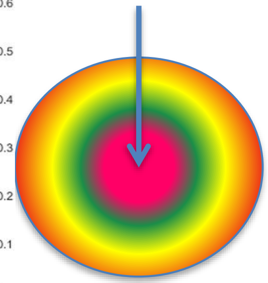
Wave propagation through measured radar beam cross sections





side view

Most intense part of the beam in centre, less intense at outer edge



end view

- The Beam Wavenumber (Bn) of the beam is:

$$Bn=kx\sqrt{|DC|}$$

Where: $k = 2\pi/\lambda$ and $\sqrt{|DC|}$ is the square root of the modulus of the dielectric constant, which is a measure of the electrical permittivity of the medium through which the beam is being propagated by transmission through the Radar Cross Section (RCA).

- Considering a two dimensional RCA where the x-direction is horizontal to the surface of the ground and the z-direction is vertical

$Bn=2\pi x/\lambda\sqrt{|DC|}$

$=2\pi x\sqrt{((1/\lambda_x)^2+(1/\lambda_z)^2)|DC|}$

- This formula clarifies the relationship between Bn, λ and DC

Field system specifications

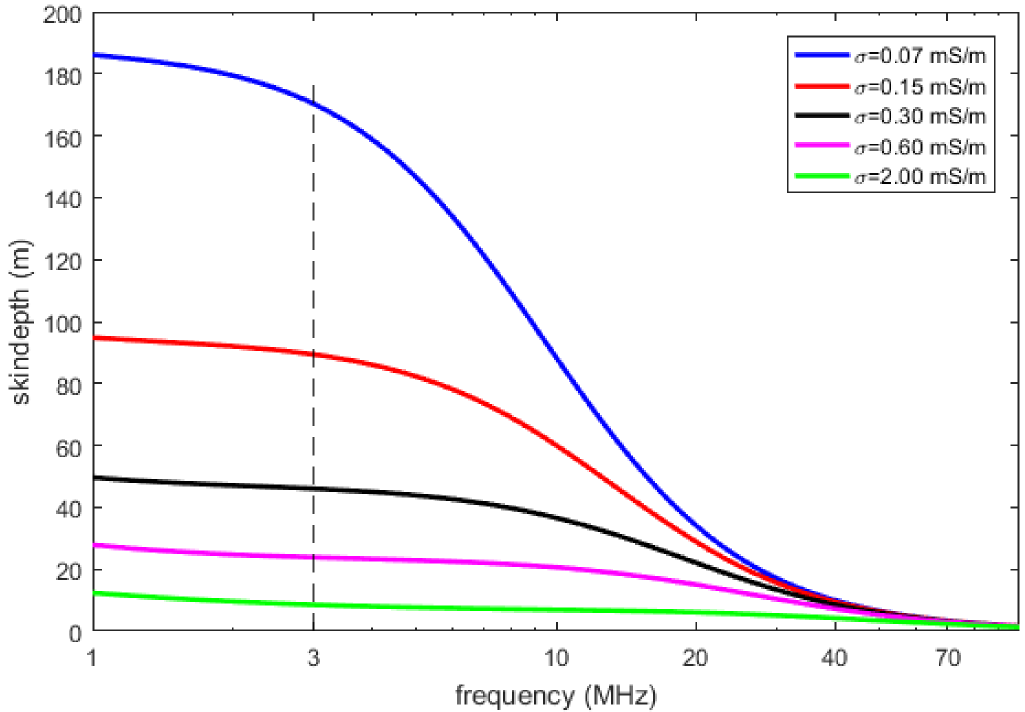
Sub-system	ADR Setting	Typical Range
TCU	Pulse width	~10ns
	Pulse repetition frequency	< 10 kHz
	Mean power	~ 5mW
	Power supply	1 off 15 Vdc Li-Ion battery
	Weight	7kg
Antenna	Tx pulse frequency	1 to 100 MHz
	Weight	5 kg
RCU:	Time Range (typical)	20,000ns, 40,000 & 100,000ns
	Number of samples/trace	100,000
	Power supply	4 off 30Vdc Li-Ion battery
	Power consumption	150W

- Pulsed based RF transmitter
- Proprietary antenna design
- High speed time domain sampling ~5GS/s
- Improvement in signal to noise through multiple waveform capture ~10,000 traces per recording station
- Effectively increase the ENOB of receiver from 8-bit to 16-bit.

Depth of subsurface penetration

- Losses are proportional to distance (in uniform material)
  - No matter what the mechanism is (for fixed frequency)
- Must be exponential exp(-d/sd)
  - d distance through medium
  - sd skindepth in meters
- Skindepth = distance where signal falls off by 1/e
- Skindepth generally decreases with frequency
  - Penetration depth proportional to skindepth
- Depends on conductivity
  - In-situ conductivity value is generally unknown (we measured ADR for limestone)
  - Value found lower than generally assumed but well within possible “book-range”

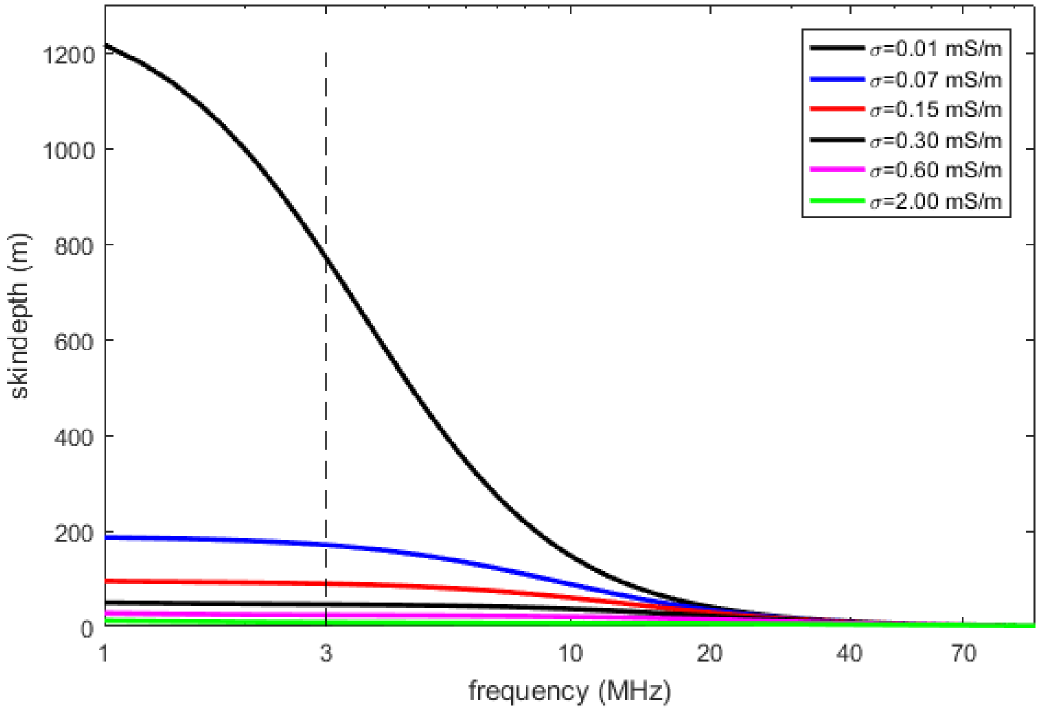
Skin depth versus frequency



- The blue curve is based on in-situ ADR measurement through limestone.
- The other curves represent various other book-values* for the conductivity, with the bottom one perhaps a reasonable guess from a geophysicist used to classical EM methods.
- ADR centre frequency for deep penetration indicated by dotted line (3MHz)

* Reynolds J.M. (2011); Jackson J.D. (1998)

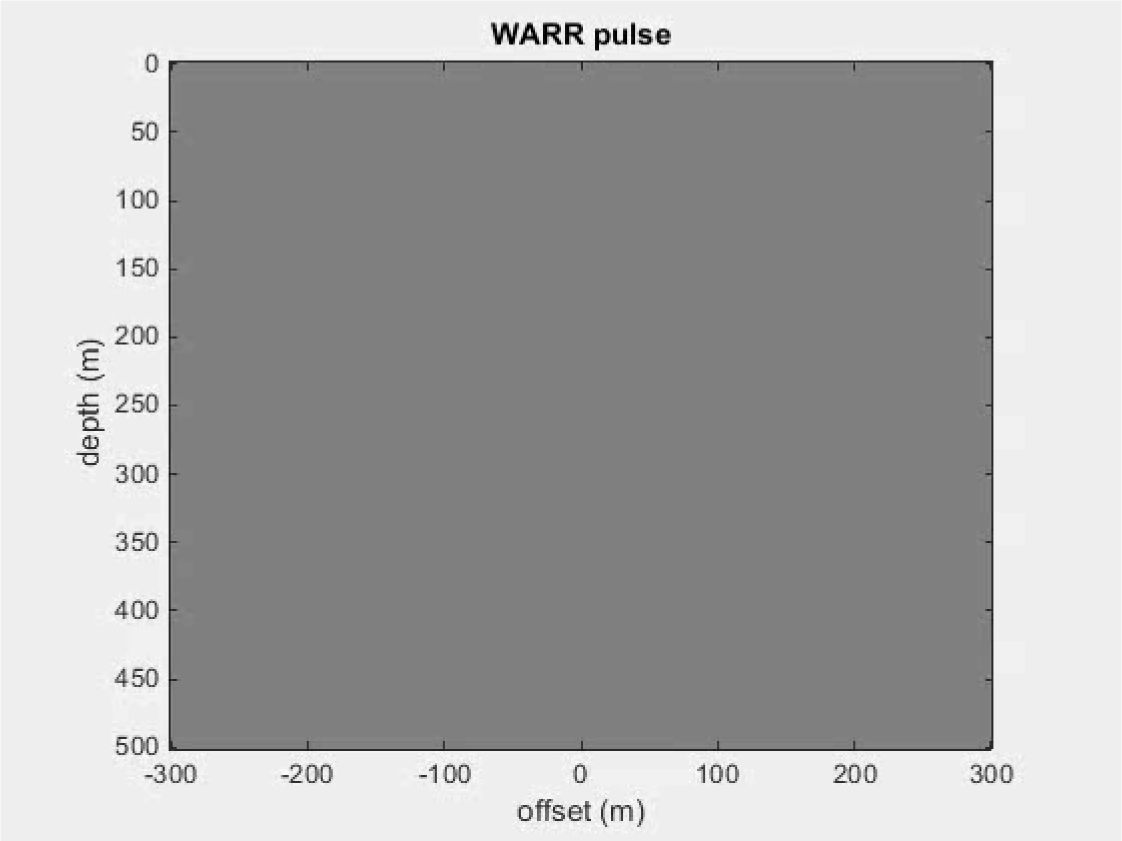
Skin depth versus frequency



- The blue curve is based on in-situ ADR measurement through limestone.
- The black curve based on book value in permafrost*.
- ADR centre frequency for deep penetration indicated by dotted line (3MHz)

* Vanhala et al, Geophysica (2009), 45(1-2), 103-118

Pulse transmission



- Line of transmitters in Wide Angle Reflection and Refraction (WARR) mode creates beam (Synthetic Aperture Radar, SAR)
- Note in animation pulse wavelet stays coherent

Forward model

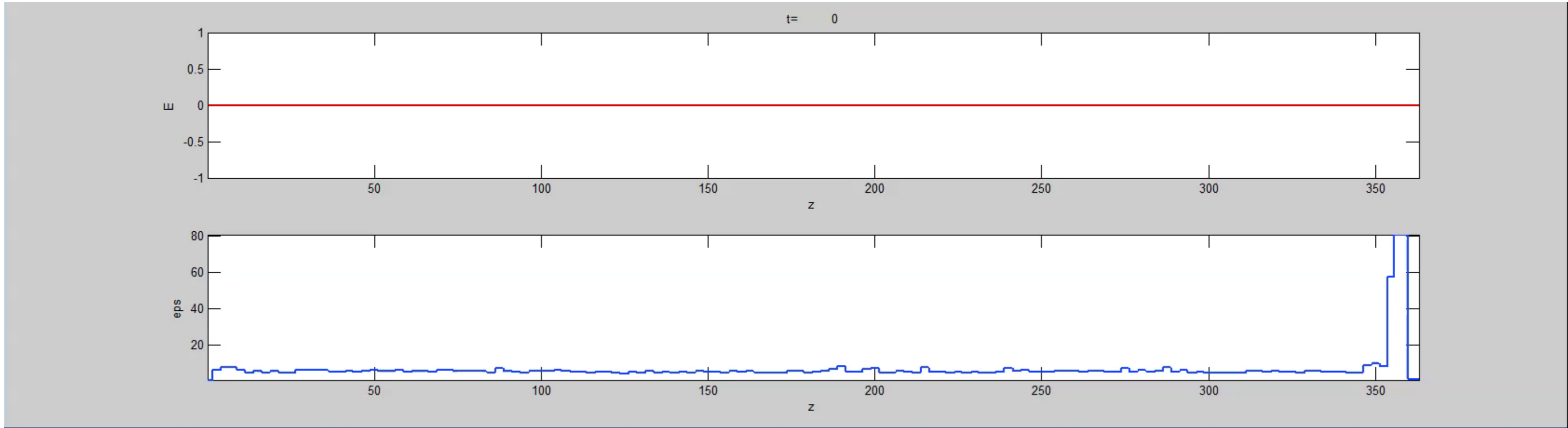
- Maxwell equations coupled to ground model
- Ground model: permittivity, conductivity and polarization (*P*)
  - E electric field, σ conductivity, τ Debye relaxation time, ε_r dielectric
- Resulting system of partial differential equations:

$$\epsilon_0 \frac{\partial^2 E(t,x)}{\partial t^2} + \sigma(x) \frac{\partial E(t,x)}{\partial t} + \frac{\partial^2 P(t,x)}{\partial t^2} - \frac{1}{\mu_0} \frac{\partial^2 E(t,x)}{\partial x^2} = 0, \tag{1}$$

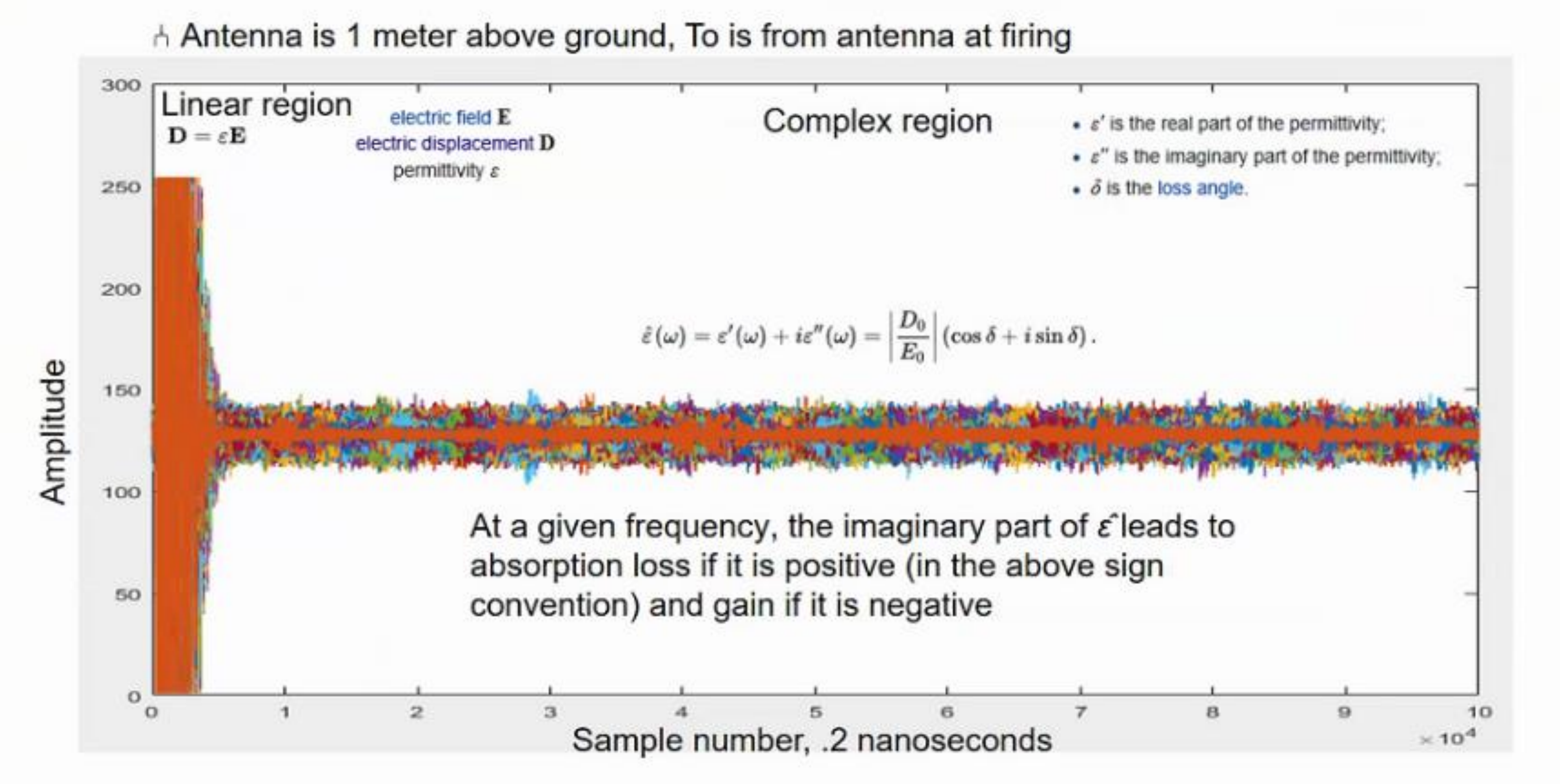
$$\tau(x) \frac{\partial P(t,x)}{\partial t} + P(t,x) = \epsilon_0(\epsilon_r(x) - 1))E(t,x). \tag{2}$$

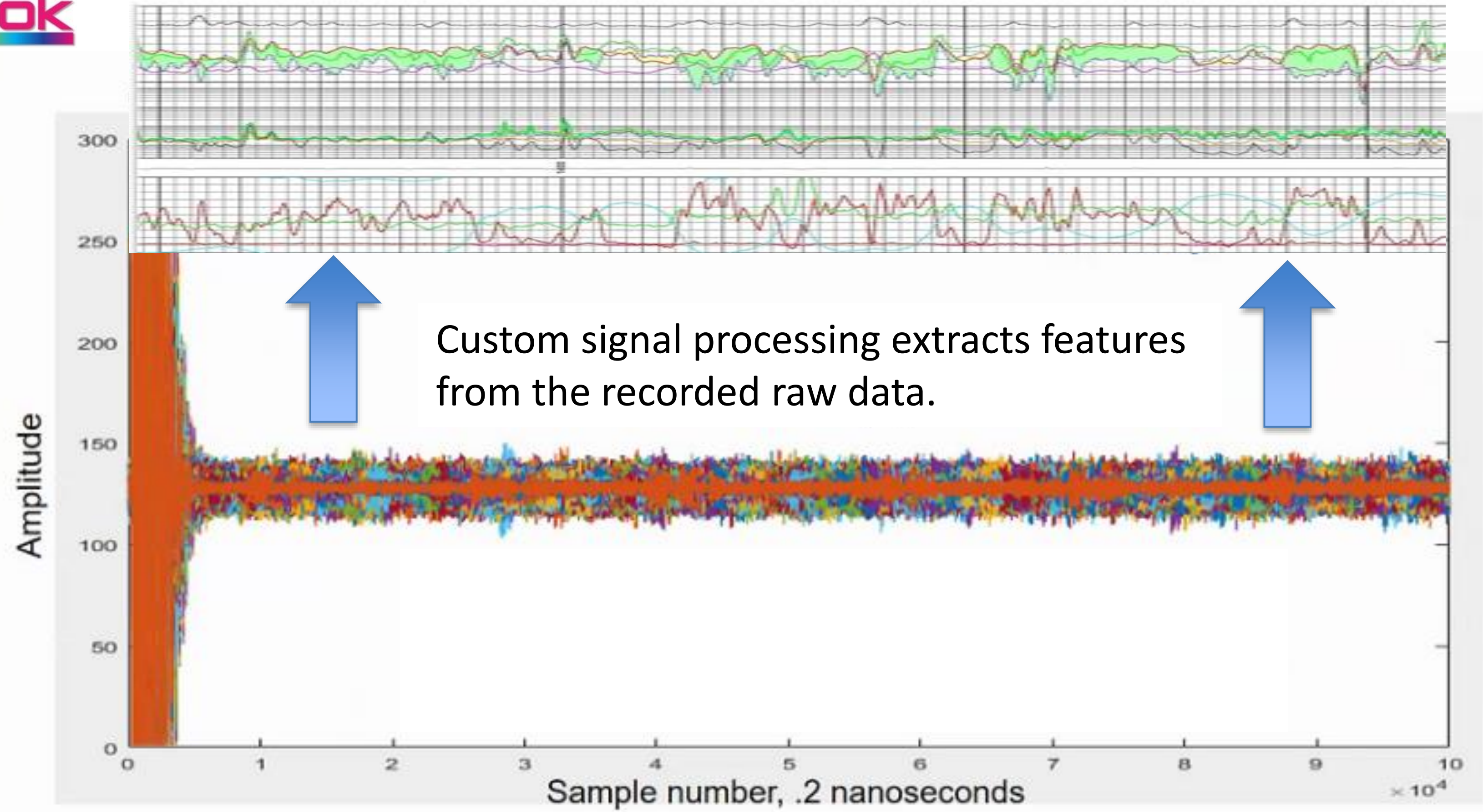
Simulation

- Dielectric Constant (DC) profile (bottom graph) take from WARR data
- Other parameters from transillumination experiments
- Peak in dielectric at 350m down represents a water body
- Electric field animated in top graph
  - We observe pulse traveling down (left to right)
  - Small irregularities in DC cause backscatter
  - Big reflection at jump in DC propagates back to surface



Received signals





Custom signal processing extracts features from the recorded raw data.

Motivation for this experimentation

Motivation

- Radar subsurface imaging (GPR) is cost-effective and non-destructive
- Most systems operate 50-100MHz range, limited to < 50m depth
- Low frequency radar systems (1-5MHz) used for km range imaging:
  - Mars
  - Antarctica
- Can we image through permafrost with such a system?
- Specifically detect conductive lenses in Canadian arctic
- Perform simulated scans to determine technical requirements

Simulated experiments

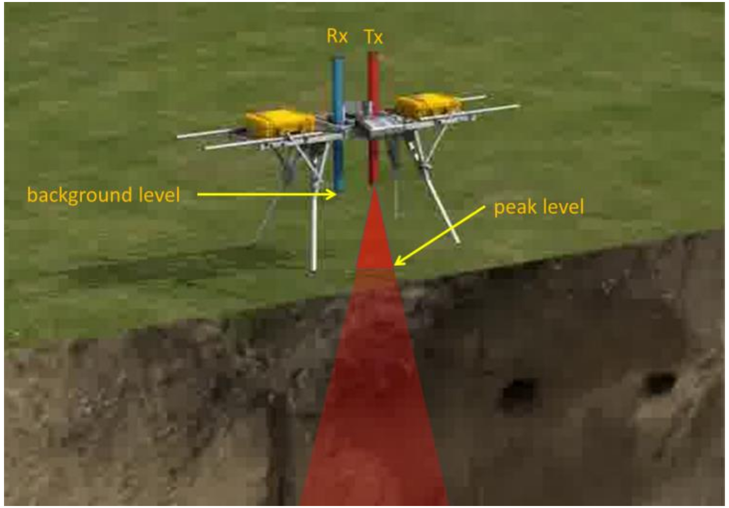
- Measure sensor sensitivities and noise levels
- Obtain ground parameters from borehole data (Canadian arctic)
- Physical model: Sensors + ground + Maxwell equations
- Implement numerical simulator:
  - FDTD Maxwell + ground model in 1D/2D
  - Raytracing in 2/3D
- Insert measured sensor + ground parameters into model
- Perform virtual experiments + data analysis
- Design optimal cost effective field acquisition based on results

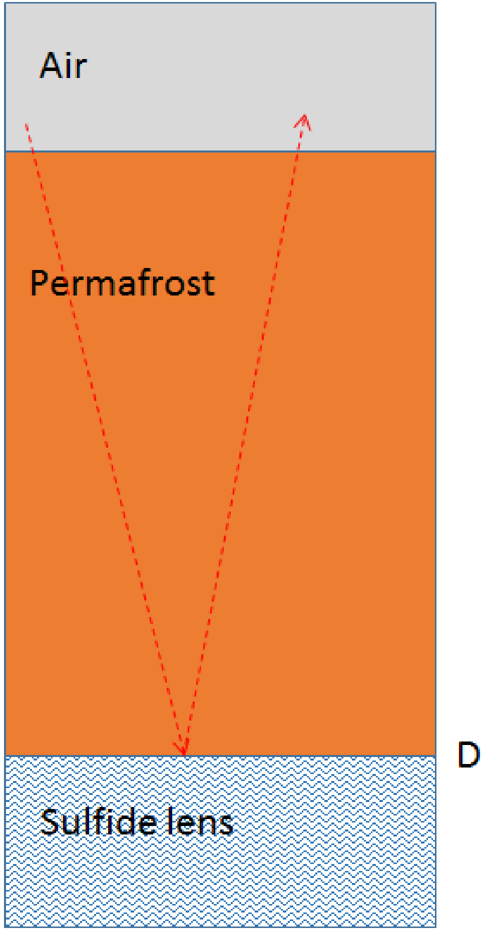
Case Study

Case study

- Goal is to detect conductive lens depth D=400-1500m in permafrost
- Permafrost resistive, R=50kΩm, mostly transparent to radio pulse
- Lenses contain metals
- At depths D determine largest noise level such that
  - we can detect lens using standard data analysis
  - repeat experiment 10 times with consistent results
- Determine size of stack needed (repeat measurements)
- Up to 1,000,000 repeat measurements can be done in 1hr

Model Parameters





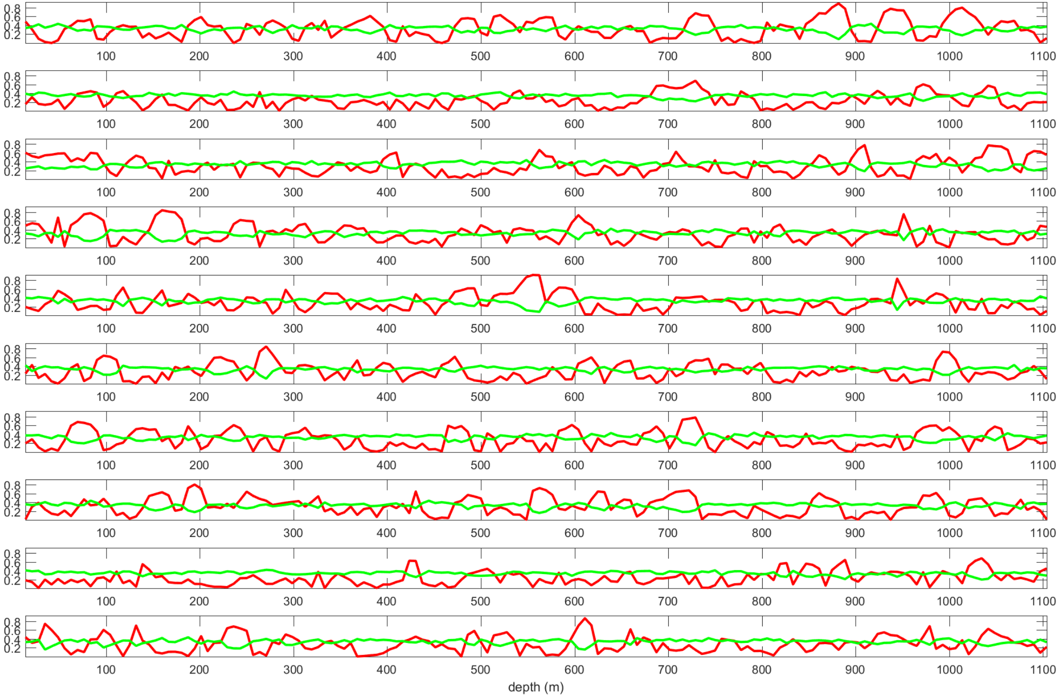
- Up to depth D:
  - Permafrost: dielectric ϵ_r=6 + random fluctuations (std 0.25)
  - Resistivity permafrost R=50kΩm
  - Resistivity sulfide lens R=1Ωm
  - Depths D=415,…,1600m simulated
- Noise level define as background signal divided by peak radar pulse power when entering ground

DATA processing

- Detect reflection in stack from correlation analysis
  - Measure local stack coherency on scale 0-1
  - Plot against depth, identify peaks as reflectors
  - Accept if can be repeated 10 times

- Run simulations with synthetic Gaussian noise added to data
  - Gradually increase noise
  - Detect when reflector no longer detected 10 times
  - That is our critical noise level to target in the field

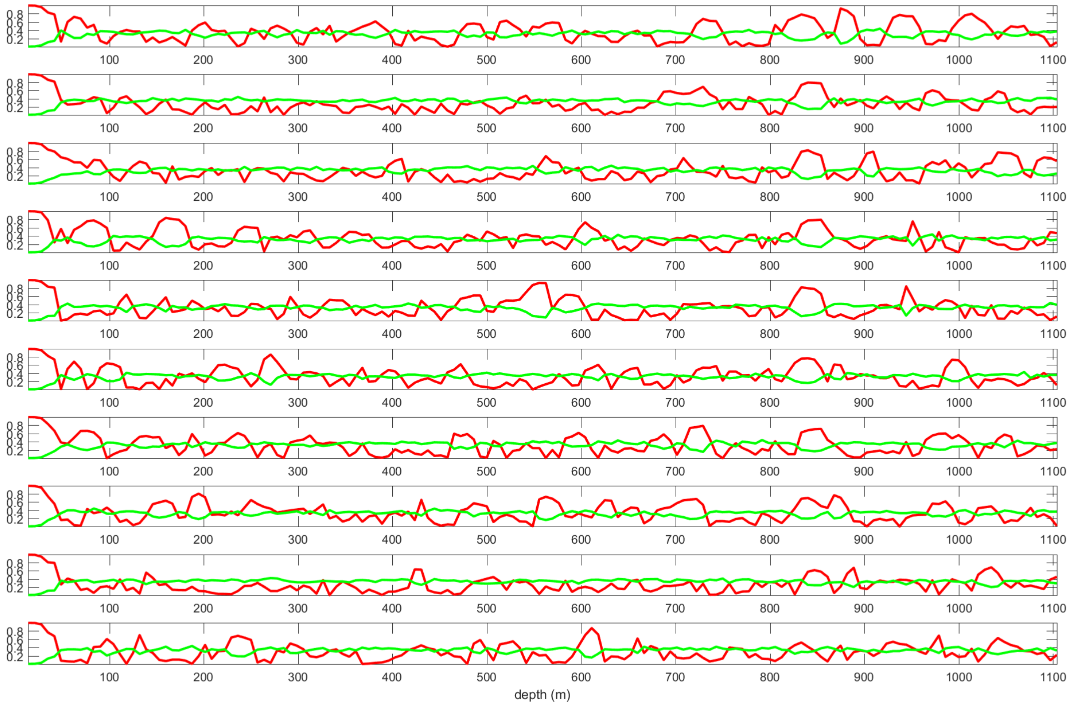
Result when Noise too high (lens at 830m)



No peak appears consistent over all 10 replicas, so we concluded noise level was too high to detect the target at 830m.

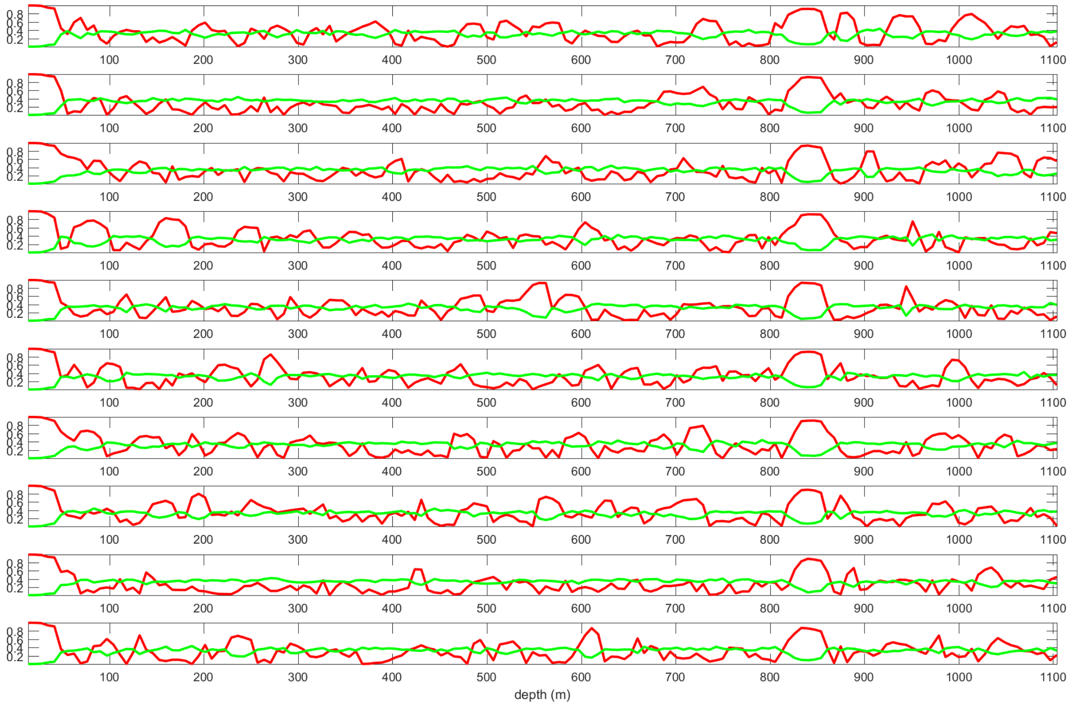
Adrok®

Result when Noise Near critical (lens at 830m)



Peaks appear in most plots at 830m, but not in the bottom one. Noise level is just a touch above optimal.

Result when Noise at critical (lens at 830m)



Peaks appear in all plots at correct location of 830m. Noise level is near (slightly below) optimal.

This is our target.

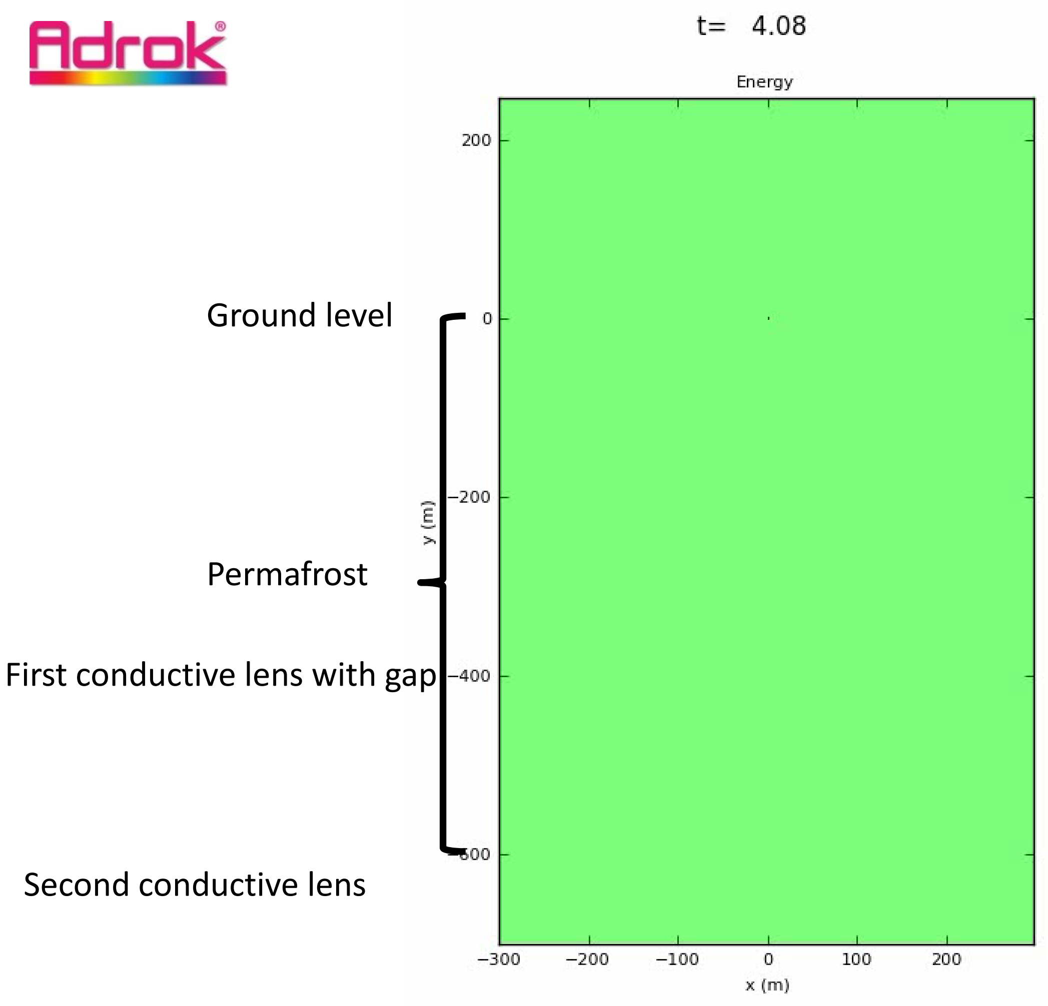
Conclusions

- Simulations useful for experimental design/feasibility study
- Critical noise levels (see table) when applied to our equipment indicate
  - Up to 830m a stack of 10,000 will do (3 mins acquisition)
  - Up to 1500m will require a stack of 6,000,000 (6hrs)
  - Noise reduction at hardware level another option
- Prior to field work we can:
  - Determine amount of data needed
  - Determine if goal is achievable
  - Validate signal processing methods
  - Estimate expected interpretation errors
  - Suggest equipment improvements
- This assists in determining most cost effective solution

Depth (m)	Noise level (%)
415	2.0
830	0.25
1245	0.04
1660	0.01

Maximum acceptable noise levels to detect the target as a function of target depth.

Future work



- Example of a more sophisticated simulation
  - Model a sulfide lens with “cracks”
  - Allows wave to diffract through it
  - Can we thus see multiple lenses?
- For now just a video…

Adrok®

Optimal noise levels for the detection of conductive lenses in permafrost with low frequency pulsed radar scans

Dr Kees van den Doel
kdoel@adrokgroup.com

Gordon Stove
gstove@adrokgroup.com

Adrok
Edinburgh, Scotland

July 2019

PIERS
Photonlcs & Electromagnetics Research Symposium
also known as **Progress In Electromagnetics Research Symposium**
PIERS 2019 in Rome, Italy, 17-20 June, 2019