Friedrich-Alexander-Universität
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# Propagation of radio frequency signals in ice

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ARENA 2024 workshop

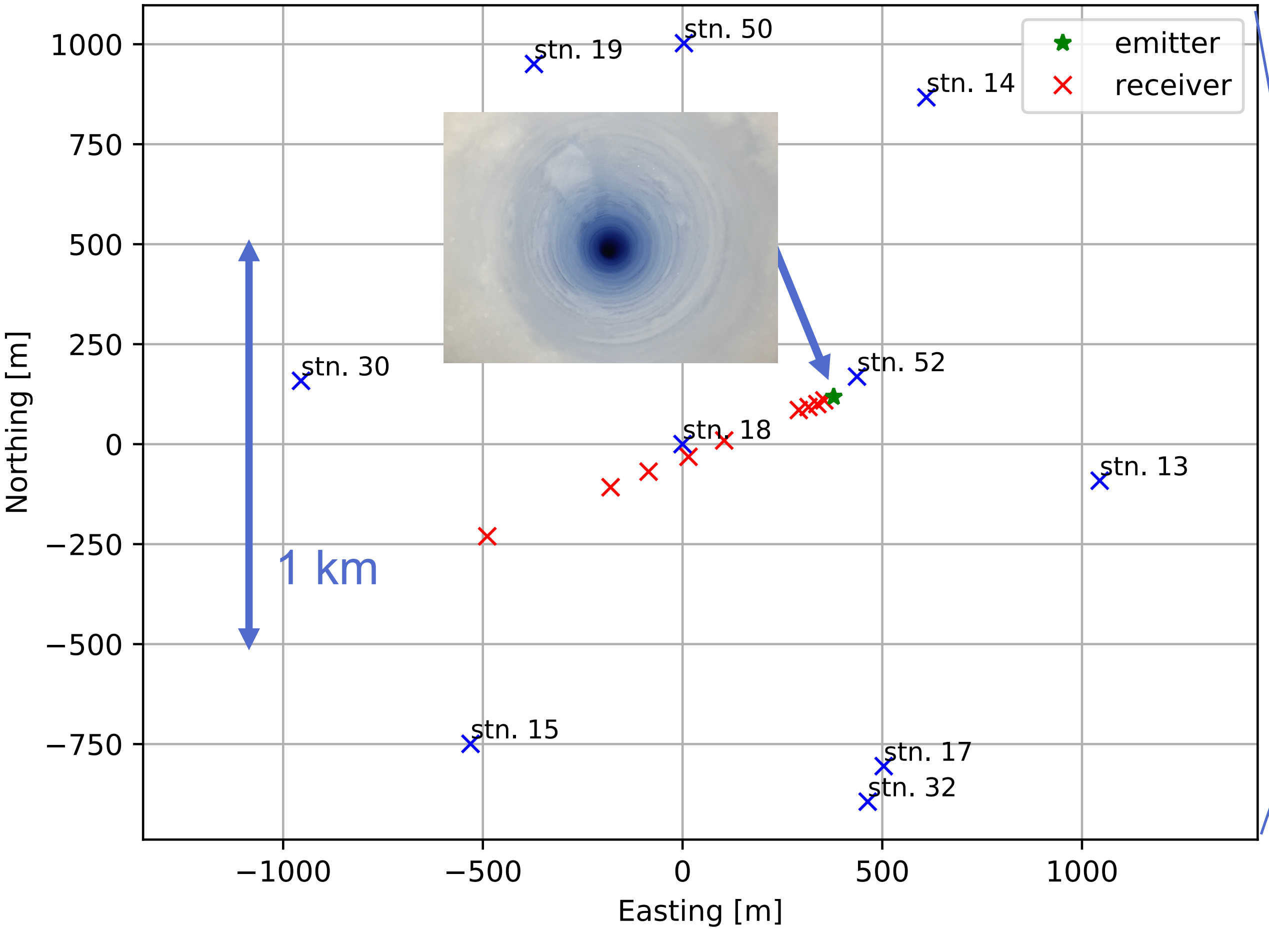
# Introduction

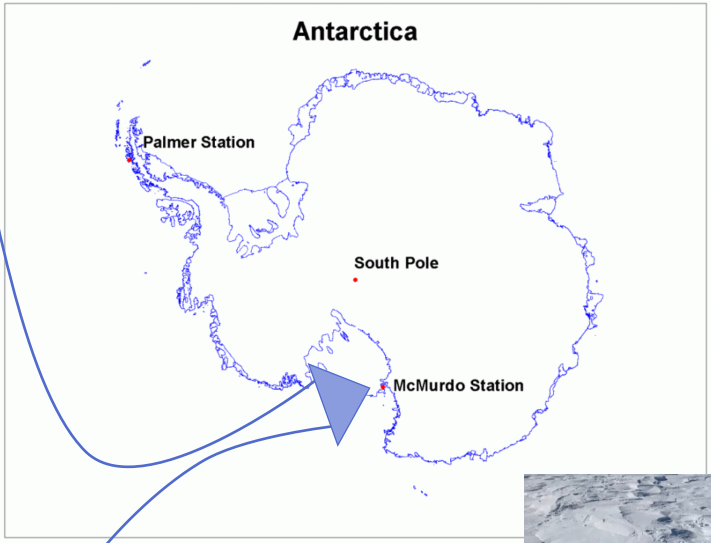
- This talk is concerned with the interpretation of RF signals in the ‘shadow zone’ that cannot be explained by geometric optics (ray tracing) in a medium with smoothly varying refractive index
- Starting point are test measurements made with ARIANNA and presented at the ICRC2019

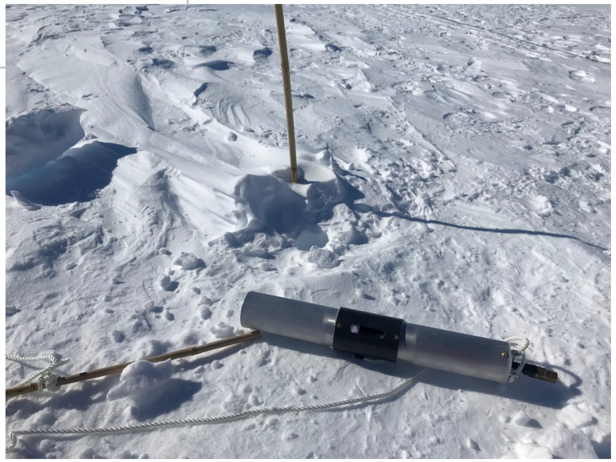
# Background

## Observations with test data from ARIANNA – Reported ICRC2019

2018/19 Antarctic season measurements: Dipole radio emitters and receivers arranged at distances from 25m to 1km



# Ray path definitions for arrival times

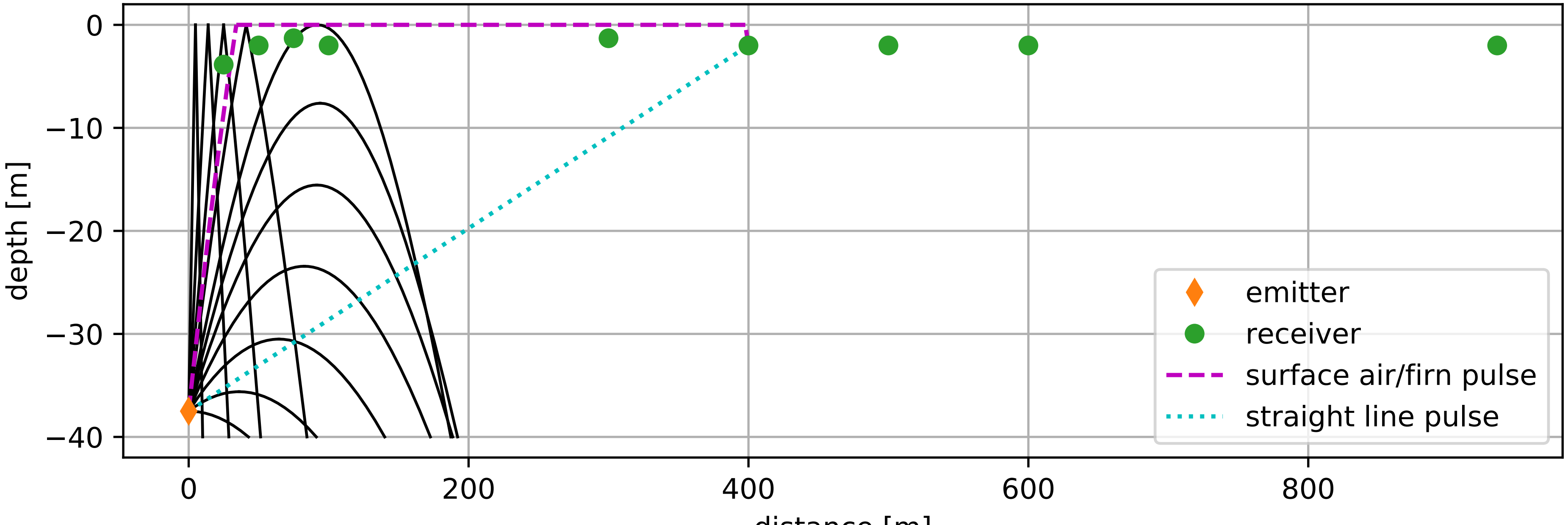
## Phenomenological description – Reported ICRC2019

Define three ray paths for signals observed in the 'shadow zone'

'surface air pulse': ray reaching surface at critical angle, travelling in a straight line through the air, entering the firn at the critical angle such that it reaches the position of the receiver.

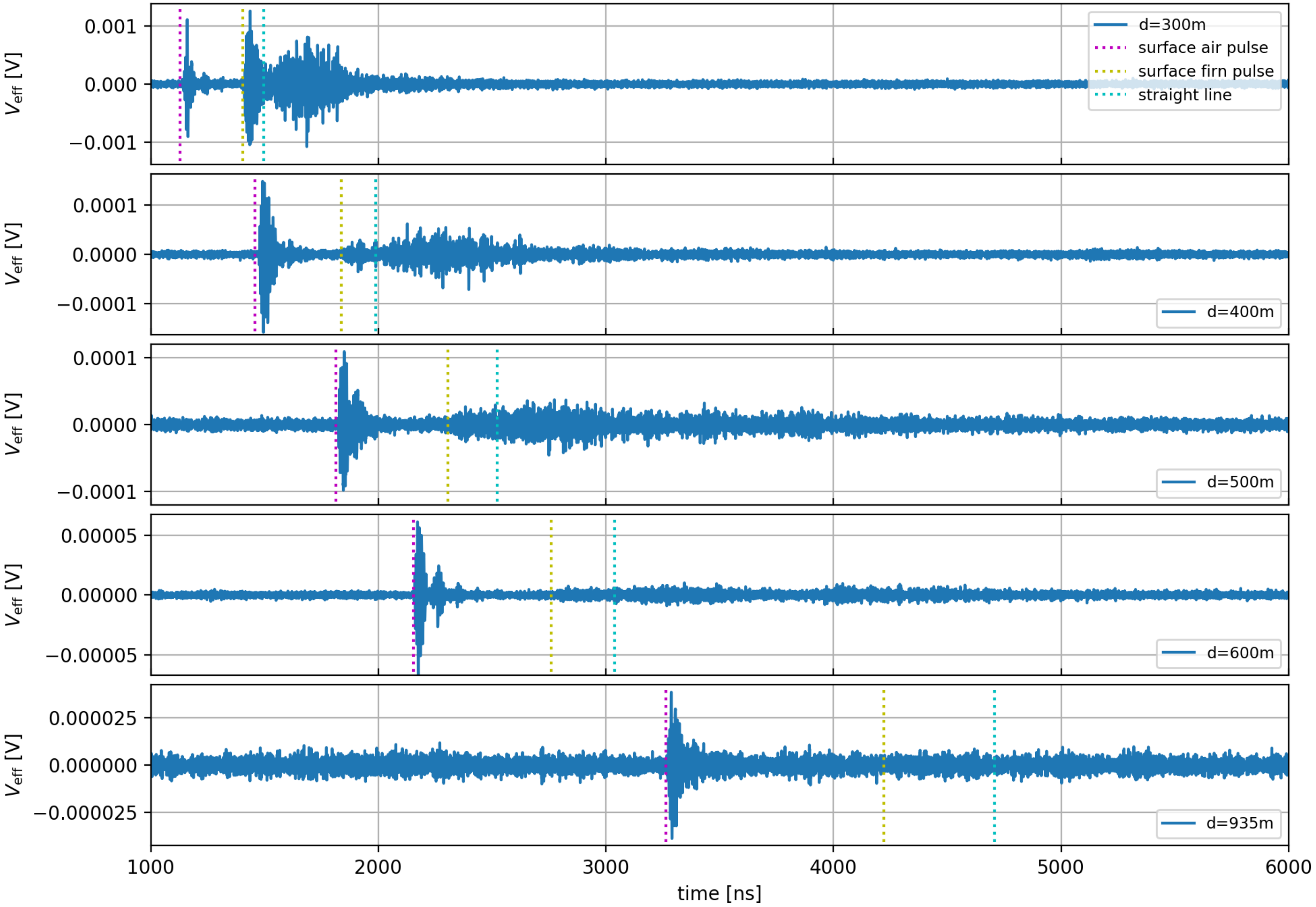
'surface firn pulse': As above, traveling in firn along surface

'straight line pulse': TOA consistent with $\int n(z) c_0^{-1}\, ds$ along straight line



# Time Traces with Calculated Pulse Times

Reported ICRC2019




- Surface air pulse
  Covered in books on EM waves in layered media, mostly called lateral wave
- Straight line pulse
  Scattering at layers in ice/firn? Investigated in M.Sc. thesis of Karen Terveer
- Surface firn pulse
  Not investigated so far

# Straight line pulse

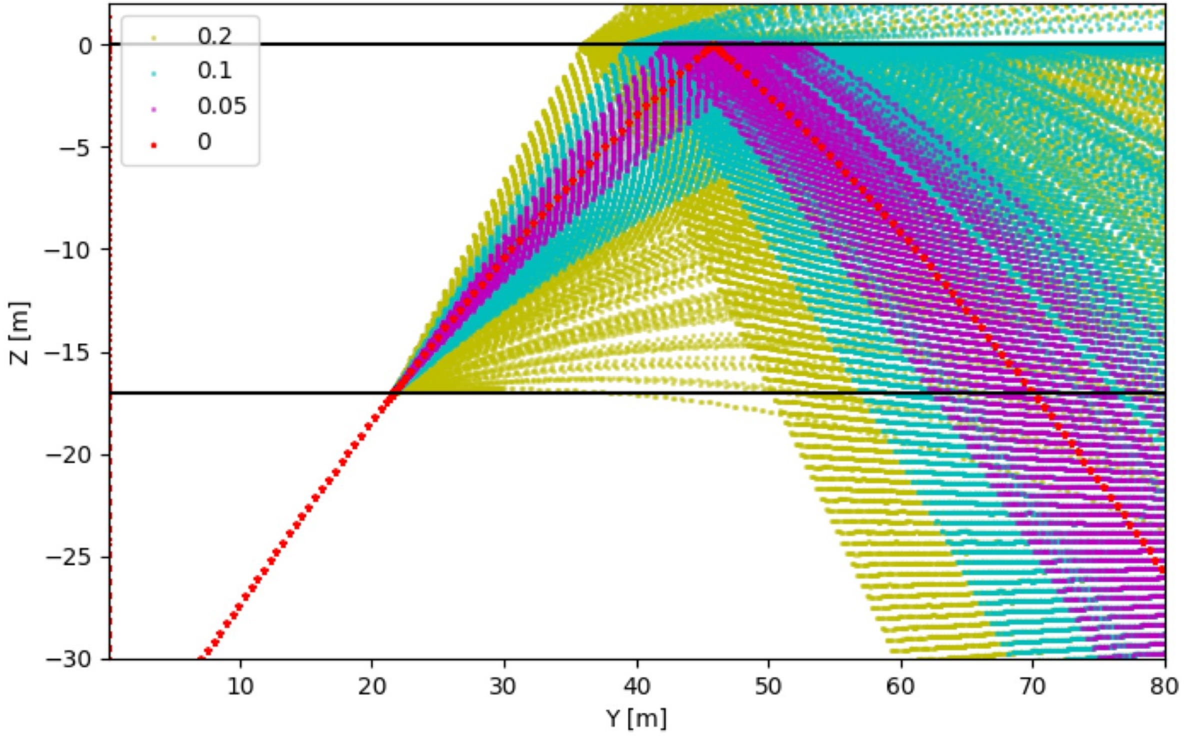
## M.Sc. thesis Karen Terveer

Assumption:

Scattering at boundaries of layers in ice leads to signal with properties of ‘straight line signal’

Simulation procedure:

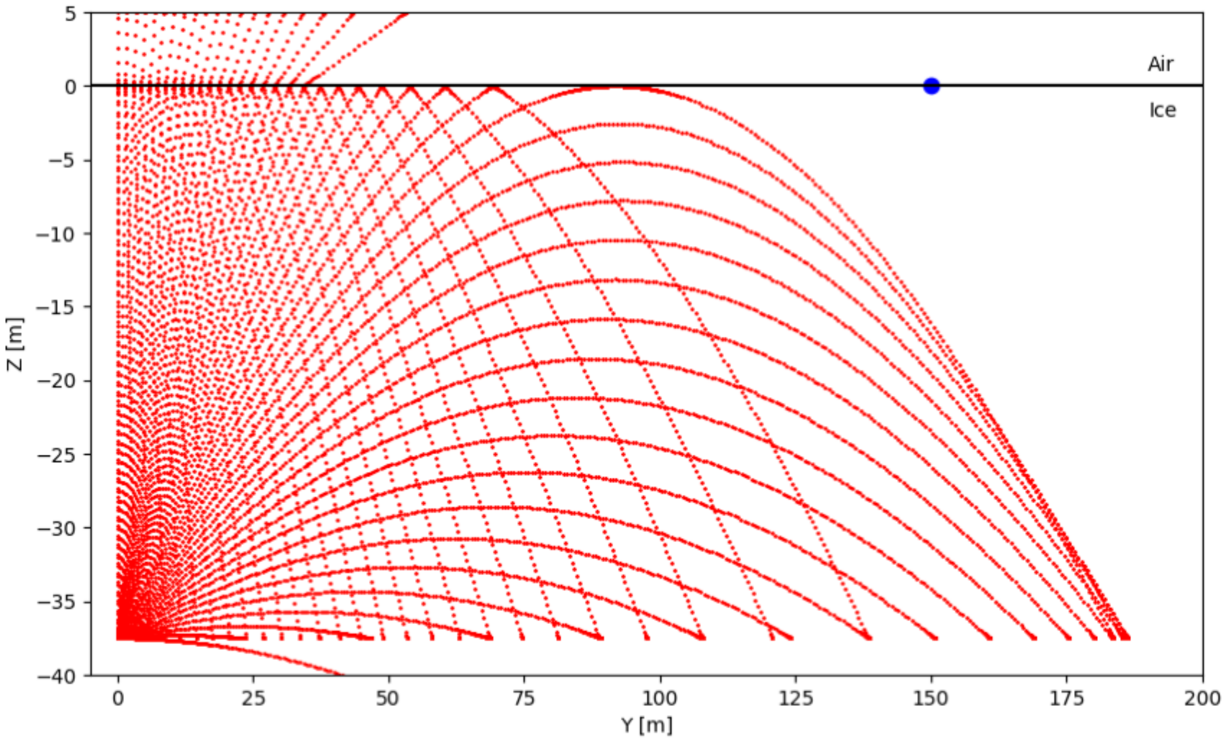
- Take smooth z-dependence of refractive index
  $n(z) = n_{ice} - \Delta_n e^{z/z_0}$
- At predefined layers introduce scattering according to normal distribution of *n*-values with predefined standard deviation
- Apply Snell’s law at boundary of $n(z)$ and $n(z) + n_{scat}$
- Ray tracing: step through emission angles, random scattering at layers; get high statistics

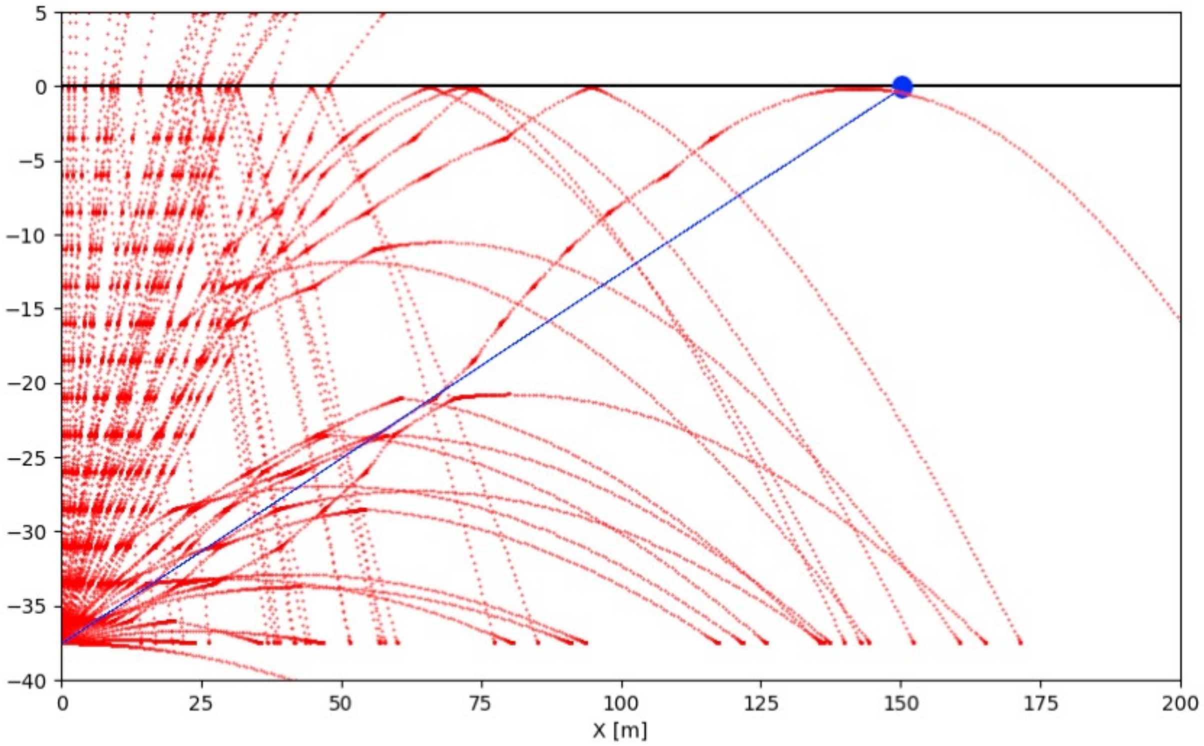



Plot from https://ecap.nat.fau.de/wp-content/uploads/2023/01/Master_Thesis__V2.pdf

# Straight Line Pulse

## Demonstration



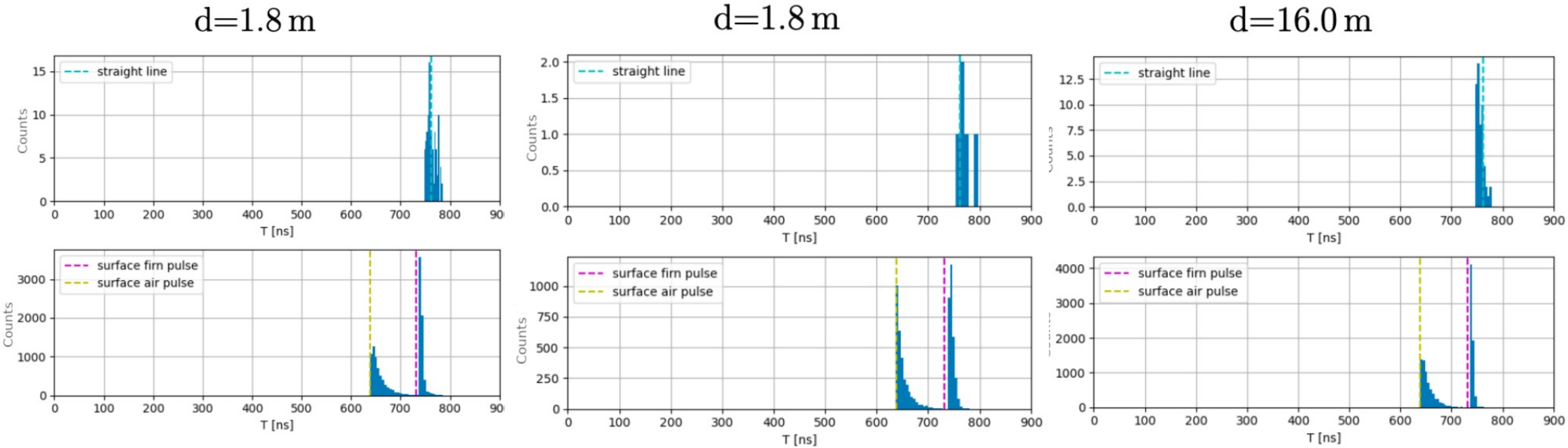




Plots from https://ecap.nat.fau.de/wp-content/uploads/2023/01/Master_Thesis__V2.pdf

# Straight line pulse

## Results of simulation

- Many combinations of layer distances *(d)* and standard deviation of scattering
- Arrival times in decent agreement with ARIANNA and calculations for all three pulses
- Signal strength difficult to reconcile with observation; no simulation of wave patterns
- Possibly an ‘effective layer distance’ can be tuned to observation




$\sigma_n$ = 0.05, D=150m, $z_0$ = –37.5 m

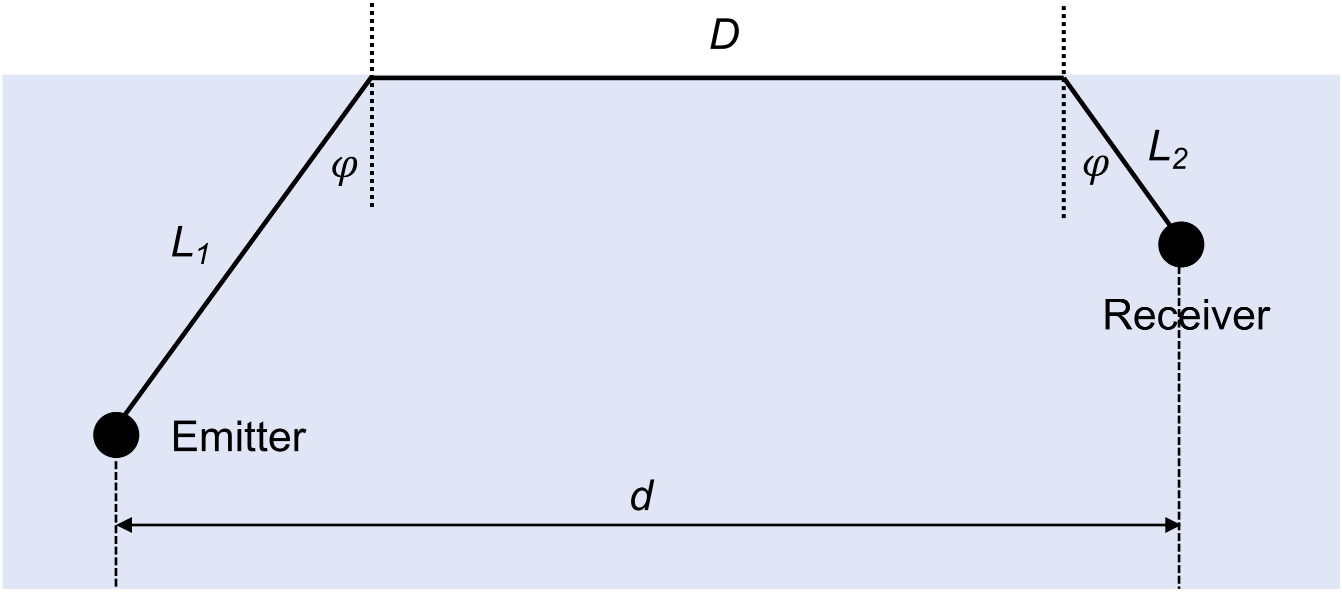
$\sigma_n$ = 0.1, D=150m, $z_0$ = –37.5 m

# Surface air pulse

Described e.g. in Tamir (line source) and in particular in Brekhovskikh (case of a dipole without attenuation):

Vertical component: $$E \propto \frac{2i}{kn(n^2-1)\sqrt{d}D^{3/2}} \exp(ik(L_1+L_2)+ik_{\mathrm{air}}D)$$

$\varphi$ = critical angle



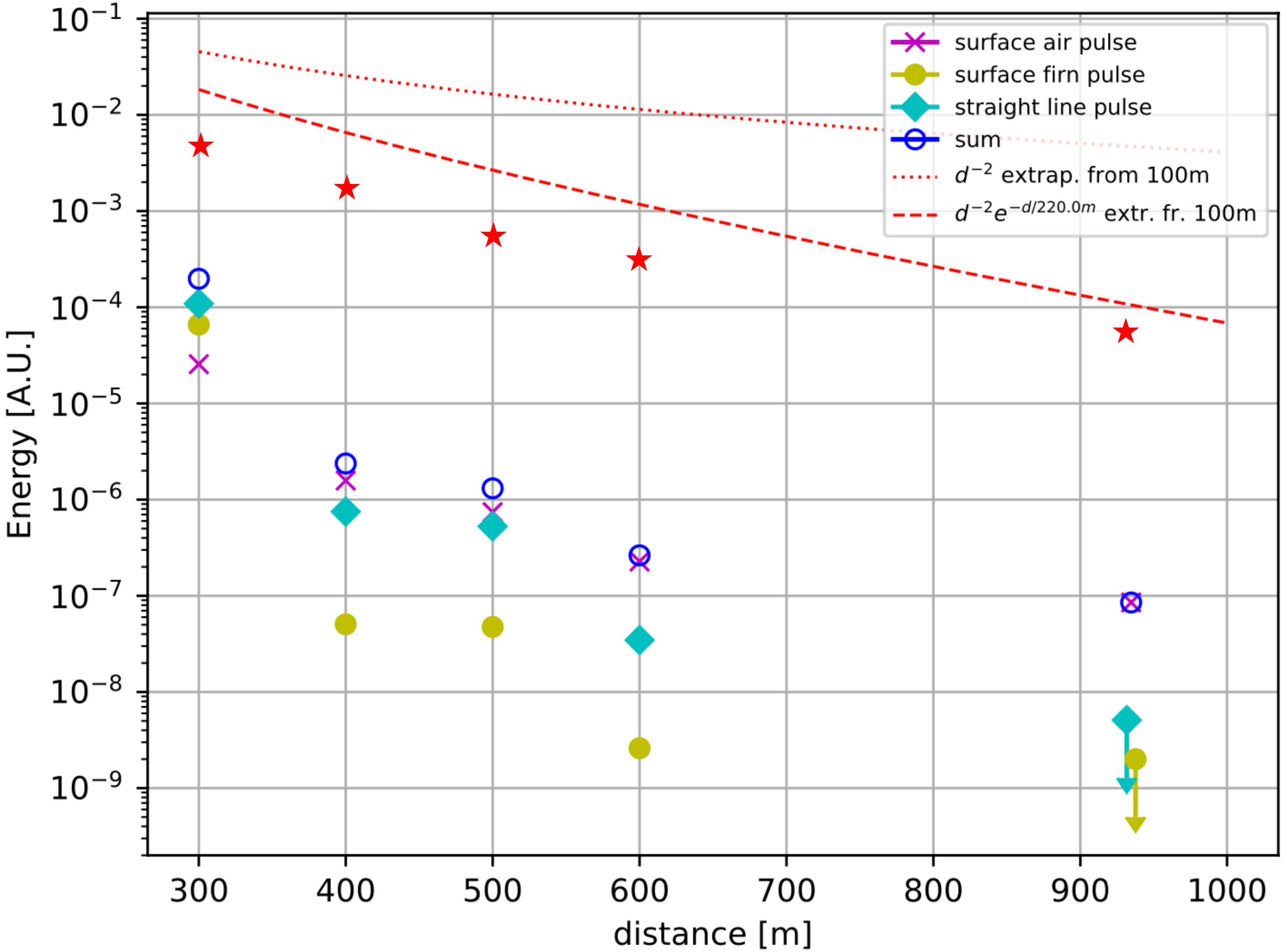

Power for large distances $d$ : $P \propto d^{-4}$

# Energy vs. distance

## Observations with test data from ARIANNA – Reported ICRC2019

Observation in ARIANNA:

Energy falls off steeper than $d^{-4}$ ★



# References

R. King, M. Owens, T. T. Wu: *Lateral electromagnetic waves* , Springer 1992, ISBN 0 387 97679 5

T. Tamir: *Lateral waves* in A.D. Boardman: *Electromagnetic surface modes* , John Wiley & Sons 1982,
ISBN 0 47 110077 3
(ask me for a PDF scan if you are interested)

L. M. Brekhovskikh: *Waves in layered media*, Academic Press Inc., 1980, ISBN 0 12 130560 0

# Summary and conclusions

- Signals in the 'shadow zone' of geometric optics were investigated
- Some qualitative understanding of processes, quantitative description much more challenging
- Investigation of shadow zone signals at other sites would provide further insights
- Maybe some workable balance between wave optics (solving Maxwell's equations – computationally expensive) and parametrization (simplification) can be found to include shadow zone signals in MC

# Thank you for your attention!