EGU General Assembly 2022

BERGISCHE UNIVERSITÄT WUPPERTAL

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

EnEx ENCELADUS EXPLORER
an initiative of DLR Space Administration

Simulating radio propagation in ice with the Parabolic Equation method:

Applications to terrestrial glaciers and ice moons (Enceladus)

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EGU22 CR3.1, 24.05.2022

Enceladus Explorer (EnEx)

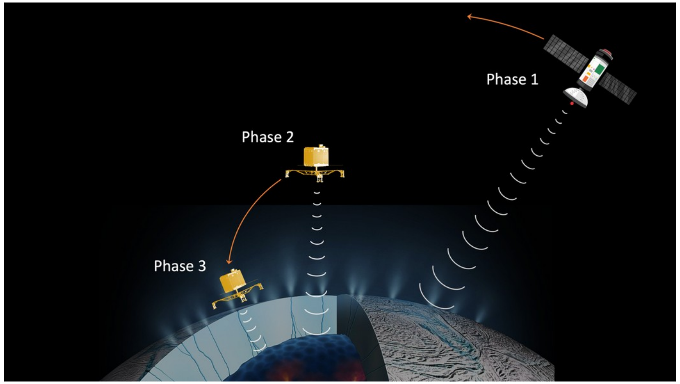
Project Objectives:
- Develop an autonomous melting probe to land safely near an active geyser on Enceladus‘ south polar region (Tiger Stripes) [4]
- Locate and navigate towards near surface aquifer
- Probe water for microbes

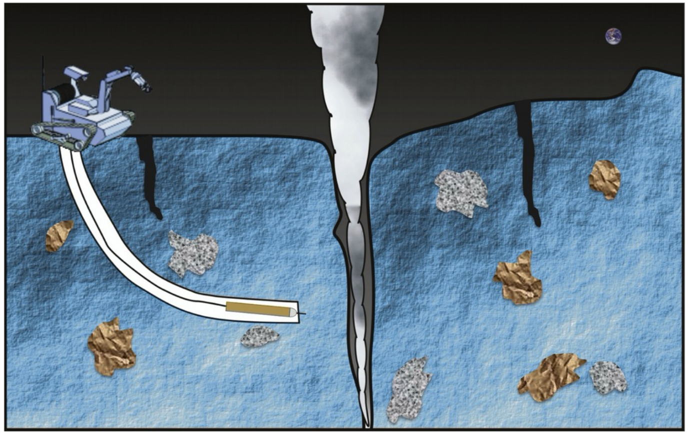
Ice is relatively transparent at Microwave frequencies (0.3 to 2 GHz)

Radar imaging system:
- Map Enceladus’ surface and upper ice crust
- Identification of a safe landing site close to a geyser
- Identification of near-surface aquifers, crevasses and obstacles
- Tracking the melting-probes’ position through the ice relative to obstacles‘
- Learn about Enceladus’ geological history and geophysical processes

Time of radar echo from water pockets, aquifers depends on surface permittivity profile:

$$\nabla T(x,y,z) = \varepsilon_r(x,y,z) / c^2$$





Permittivity Model of Enceladus

South polar terrain is complex
Surface is covered by unconsolidated ice grains from the geyser plumes → ‘snow layer’

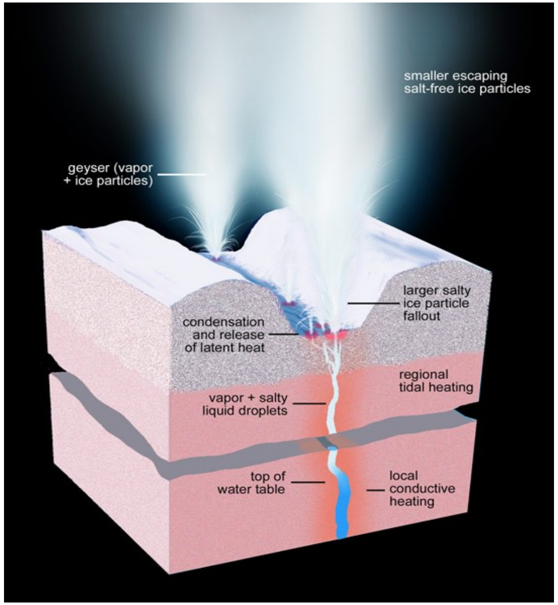
Depth of layer depends on how long South Polar region has been active (< 2 Myr)[5]

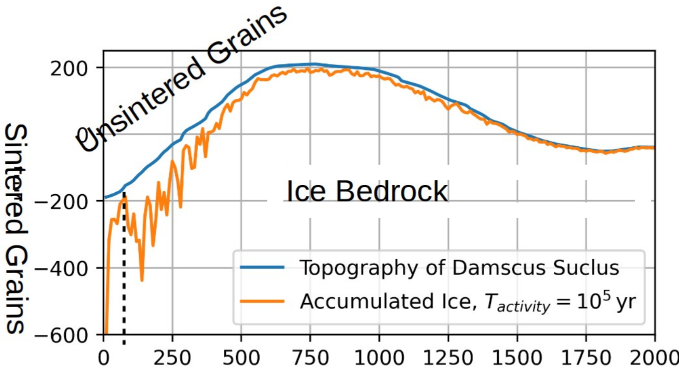
Surface temperature ~80 K on average , ~140 K within tiger stripes (near vents) [2]

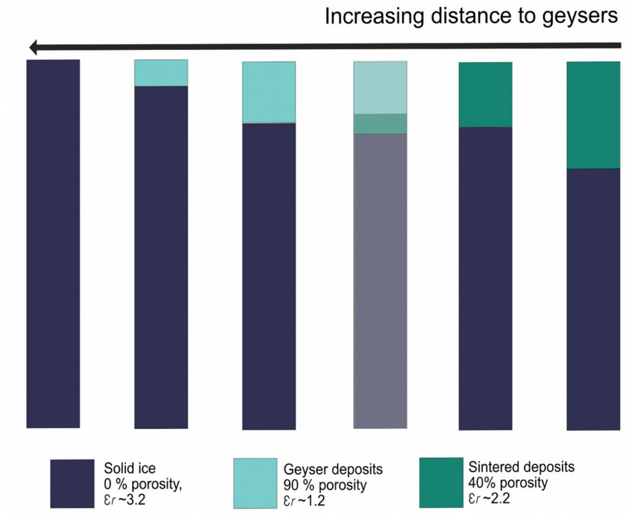
Ice grains undergo sintering → forming a denser layers

Ice grain types identified by Cassini [1]:
Type I – Salt poor
Type II – Organics rich & salt poor
Type III – Salt rich
Type III concentrated near Tiger Stripes → higher conductivity → high attenuation rate

Additional inhomogeneities:
Ice boulders (~10 m), crevasses, meteorites





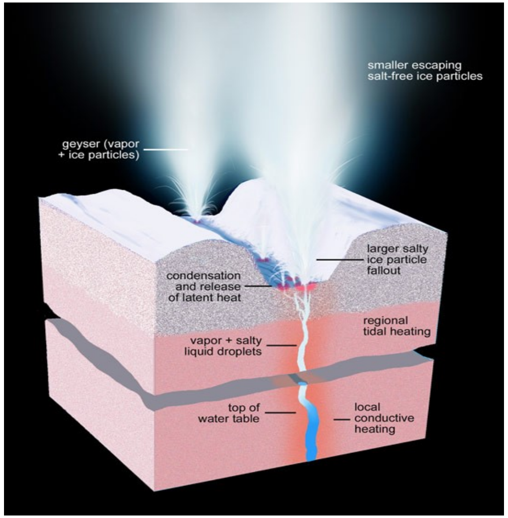


Simulating radar back-scatter

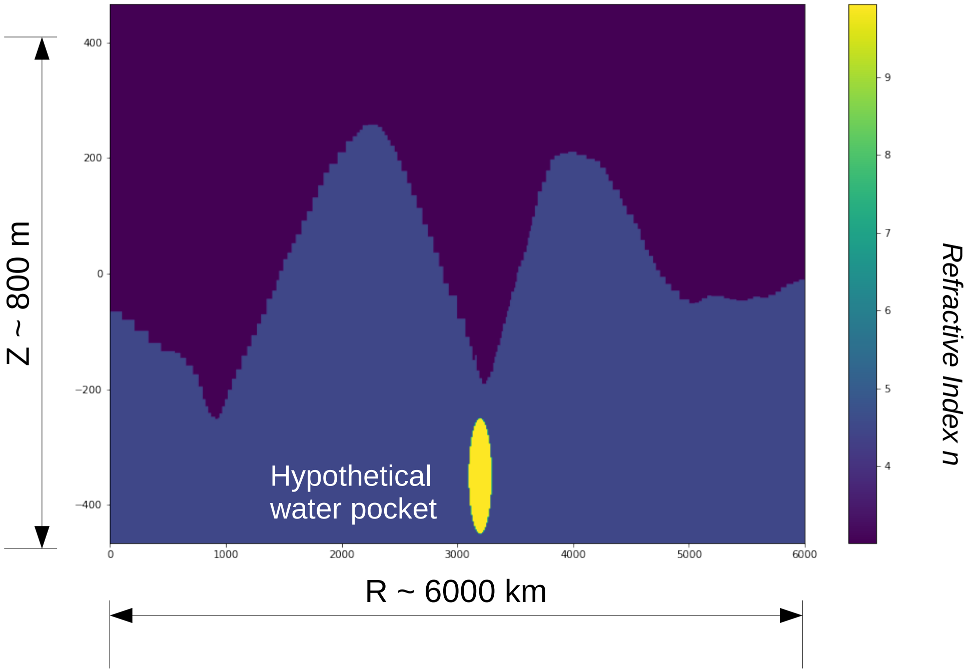
Accurate radio-propagation simulations needed to predict the radar signature of water pocket given likely Enceladus permittivity models

Enceladus water table at a depth ~10% of ice crust thickness [7] (5 km – 8 km deep at Enceladus South Pole [6]) → water pocket depth 500 m – 800 m

Frequency range: 100 MHz < ***f*** < 2000 MHz
Simulation Dimensions: ~ 6000 m x 1000 m



Permittivity + Topography [2] model



Parabolic Wave simulations

Approximation of Maxwell’s equations in ‘paraxial direction’ (within 90^o of propagation direction)]

PE solved using marching method → E-field at x + Δx solved from previous step x

More efficient than FDTD methods, more accurate than Ray Tracing (RT) methods

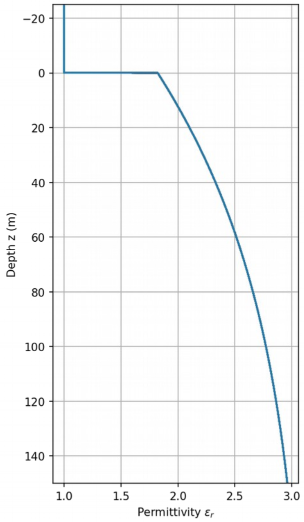
paraPropPython is a FOSS PE solver for ice environments written in python [3]
https://github.com/prchyr/paraPropPython.git

Procedure:
1. Set dimensions
2. Set complex permittivity profile
3. Set source (TX) depth
4. Define source as emitting continuous wave or a pulse
5. Solve PE across entire geometry
6. Sample amplitude at receivers → RX

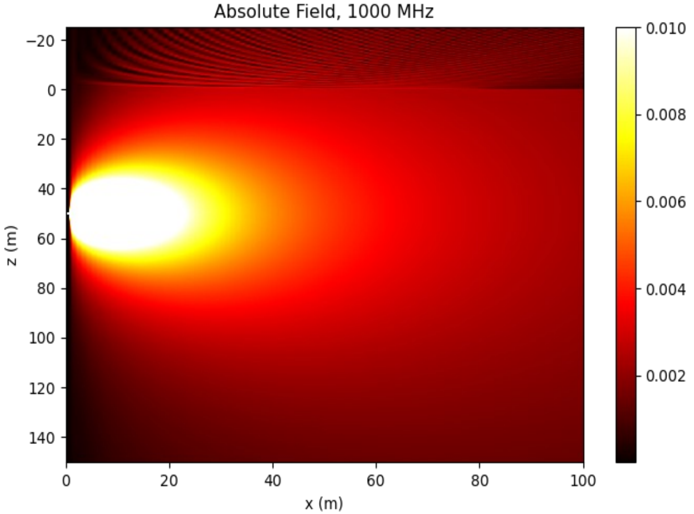
$$E(x+\Delta x)=\exp(-ik_0\Delta x(1-Q))E(x)$$

$$Q_{ice}=\sqrt{1+\left(\frac{\delta}{\delta z}\right)^2\frac{1}{k_0^2}}+n\sqrt{1+\frac{1}{n_0^2}}-\sqrt{1+\frac{n}{n_0}}$$

Terrestrial South Pole Ice (empirical)



$$\epsilon_r(z)=(A+Be^{-Cz})^2$$



Source z = 50 m, f = 1 GHz.

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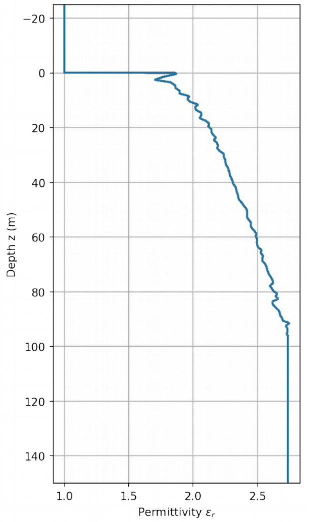

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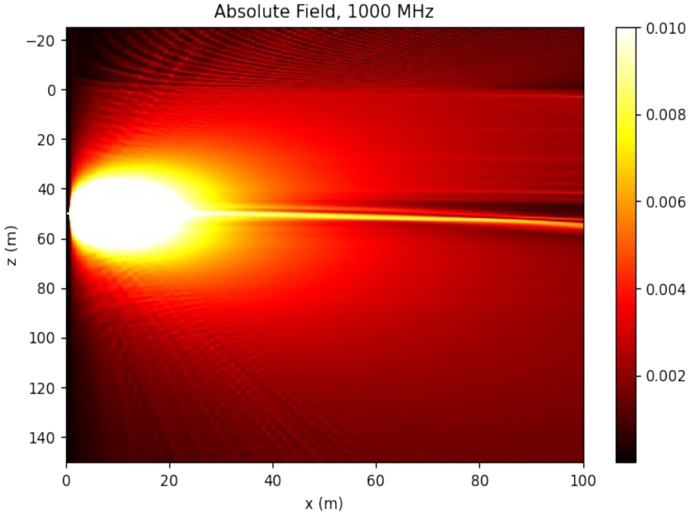
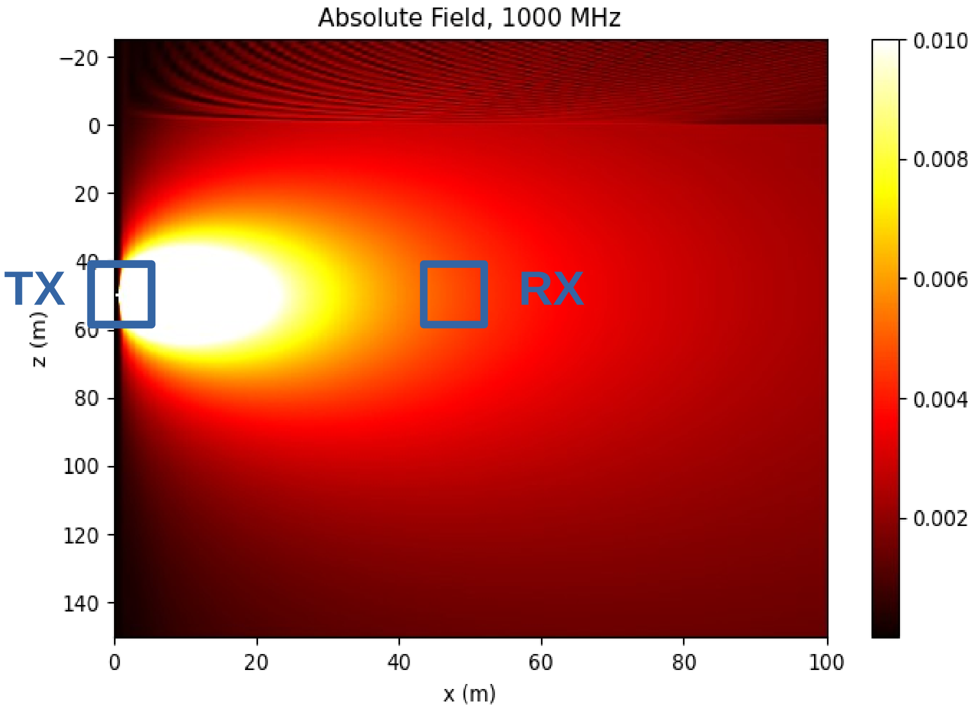
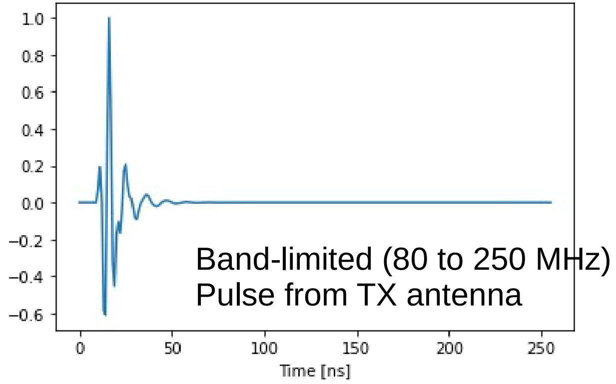


Source z = 50 m, f = 1 GHz.

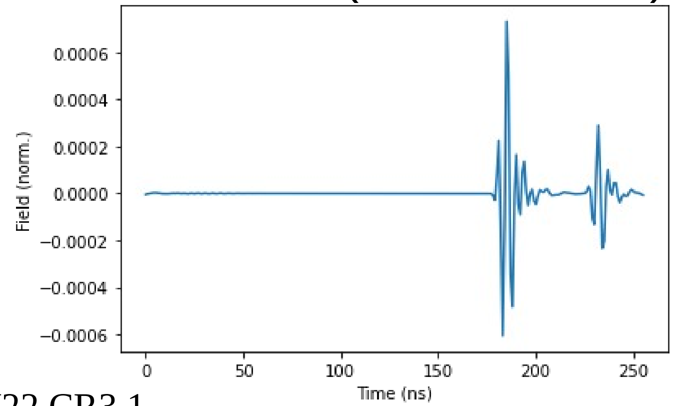
Parabolic Wave time-domain



Transmitter (x = 0, z = 50)



Receiver (x = 50, z = 50)

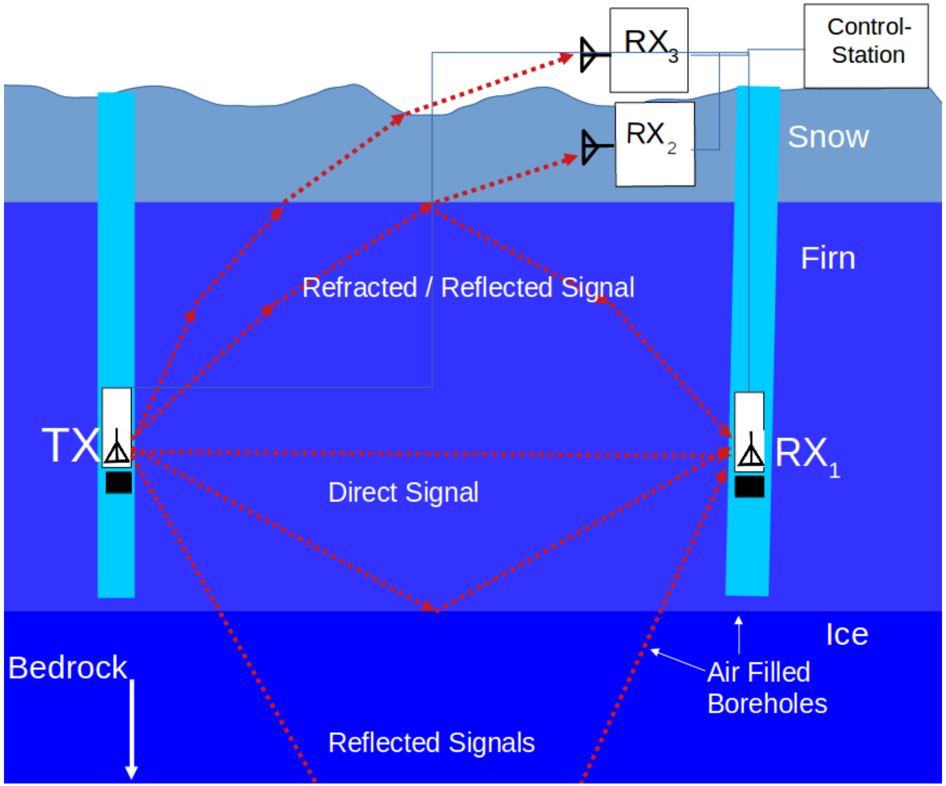


Applications to Enceladus

PE simulations may be used to radar response to subsurface water pocket

Example on the right → cross borehole transmission through Enceladus ice

-Snow Layer 10 m deep
-Sntetered Layer 20 m deep
-Water pocket 50 m deep



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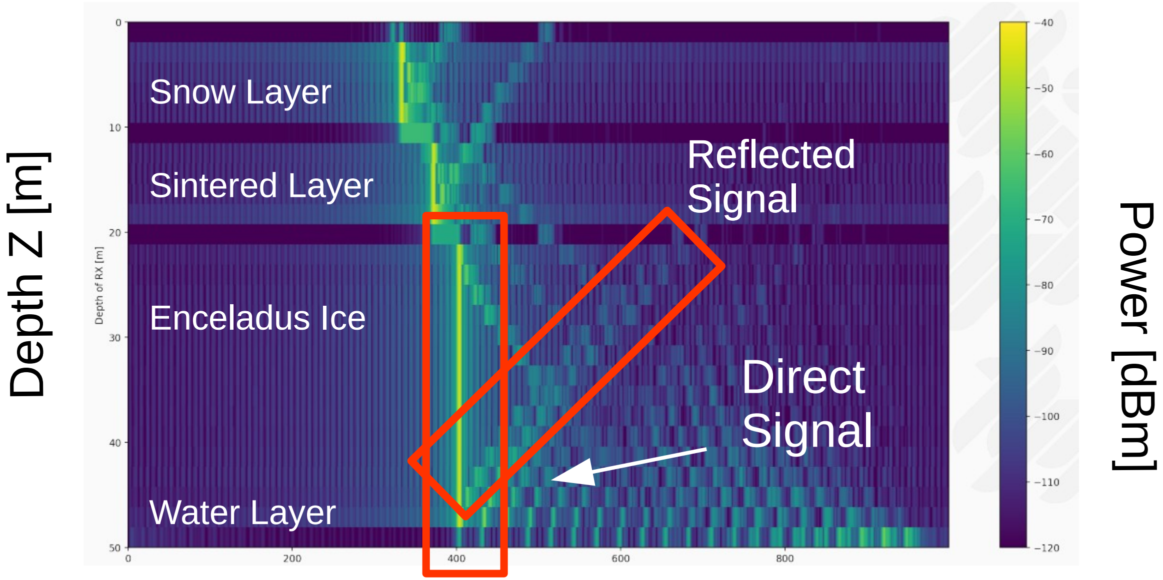
Results:
Simulations shows strong boundary layer reflections from snow-sinter, sinter-ice, ice-boundaries

Strong signal attenuation (assuming Type III particles dominate) $\boldsymbol{\alpha}$ ~ 0.8 dB/m (f = 1 GHz)

3-layer Enceladus model



Time of Flight t [ns]

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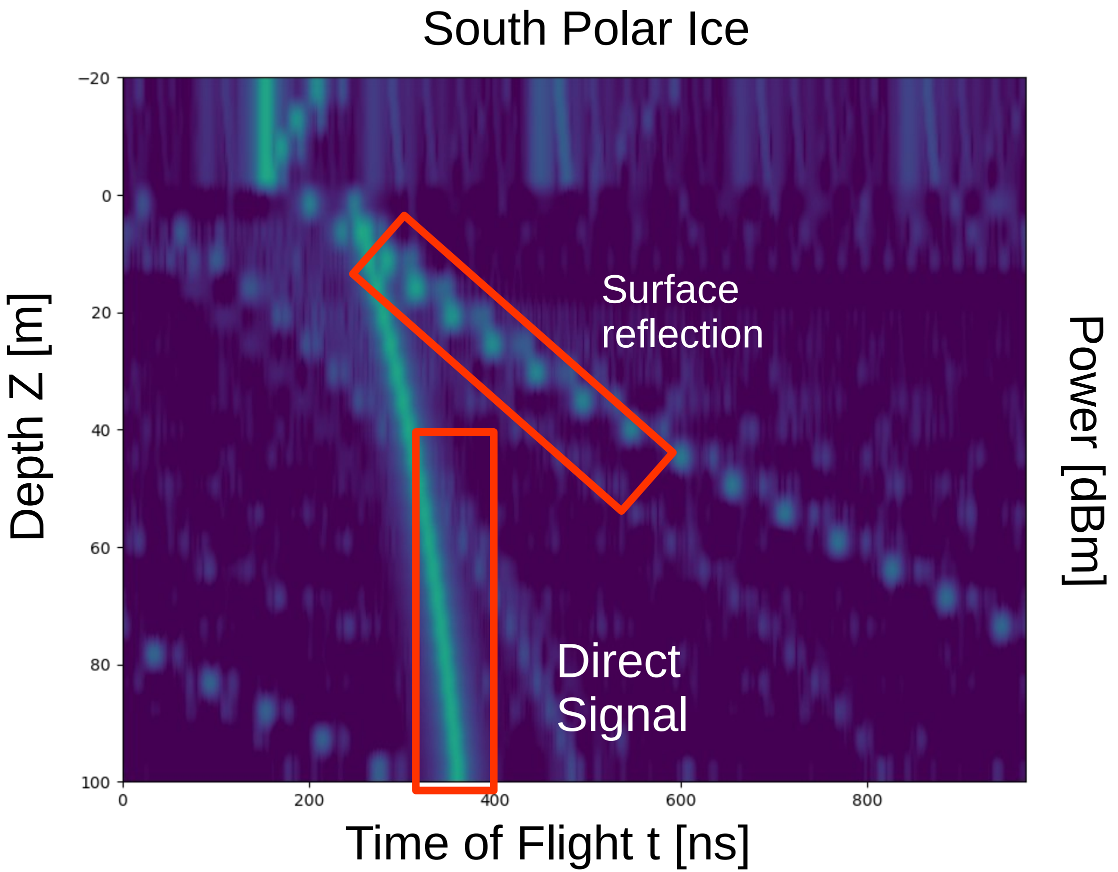


Summary

Enceladus ice model: Layer of deposited ice grains in Tiger Stripe region → sintering of ice grains within Tiger Stripes ($R < 100$ m from source), unconsolidated ice grains outside

Primordial ice beneath it → water pocket ~ 500 m – 1000 m beneath surface → should be accessible to melting probe mission

PE simulations may be used to simulate radar-echo of water pocket while accounting for different ice environment scenarios on icy bodies such as Europa, Mars and Enceladus

Also useful for modellling radio propagation through firn on terrestrial glaciers and ice sheets

Future work:
Verification of PE simulation technique using real-world data → EnEx field campaign in Aletsch Glacier, Switzerland March/April 2022

Perform a comprehensize analysis of radar echo signature of water pockets → using global topography, deposition and temperature data

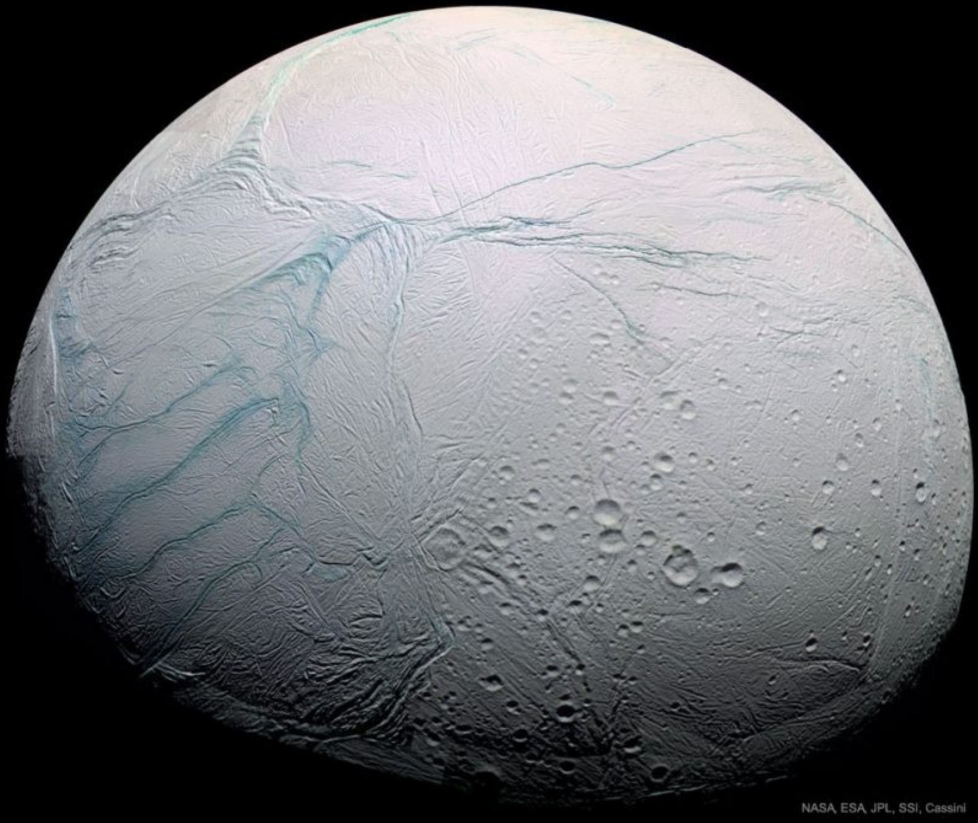
paraPropPython simulation code available at: https://github.com/prchyr/paraPropPython.git

Contact: kyriacou@uni-wuppertal.de

References:

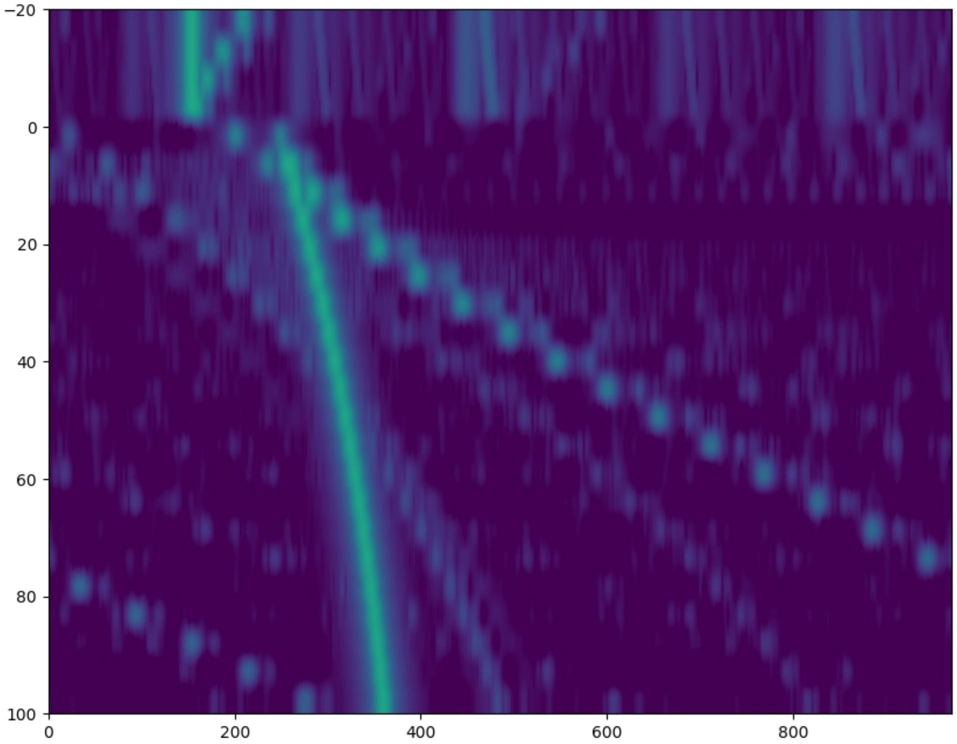
1. Postberg et al (2018b) ***Plume and Surface Composition of Enceladus, Enceladus and the Icy Moons of Saturn***
2. Abramov et al. (2015), ***Temperature of vents within Enceladus Tiger Stripes*****, LPSC 2015**
3. Prohira et al (2021) ***Modeling in-ice radio propagation with parabolic equation methods***
4. Konstantinides et.al. (2015), **'Enceladus explorer (ENEX): A lander mission to probe subglacial water pockets on Saturn's moon enceladus for life'**
5. Porco et al. (2006) ***Cassini Observes the Active South Pole of Enceladus***
6. Kang and Flierl ***Spontaneous formation of geysers at only one pole on Enceladus's ice shell***
7. Spencer (2018) ***Plume Origins and Plumbing (Ocean to Surface), Enceladus and the Icy Moons of Saturn***

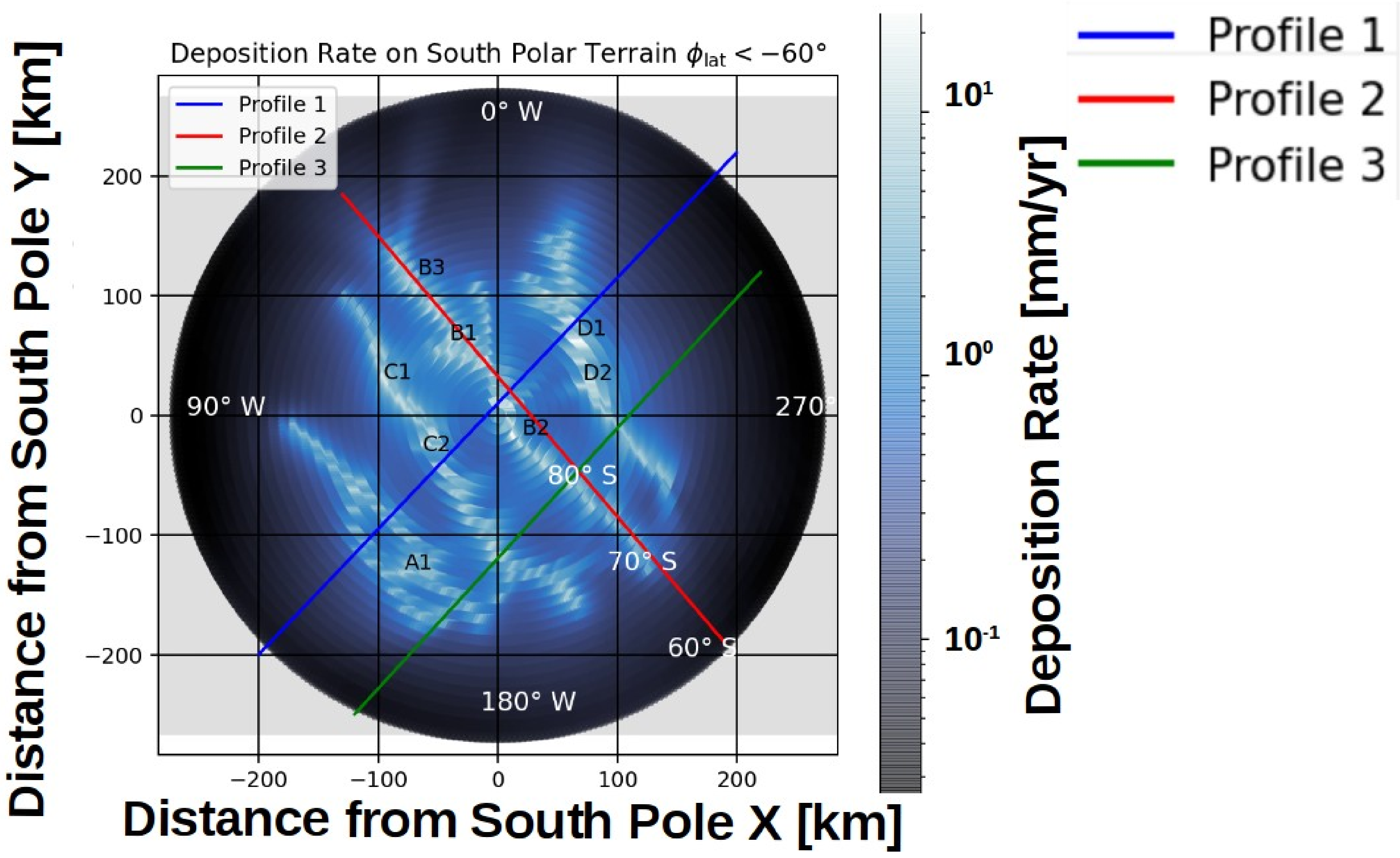
Backup Slides

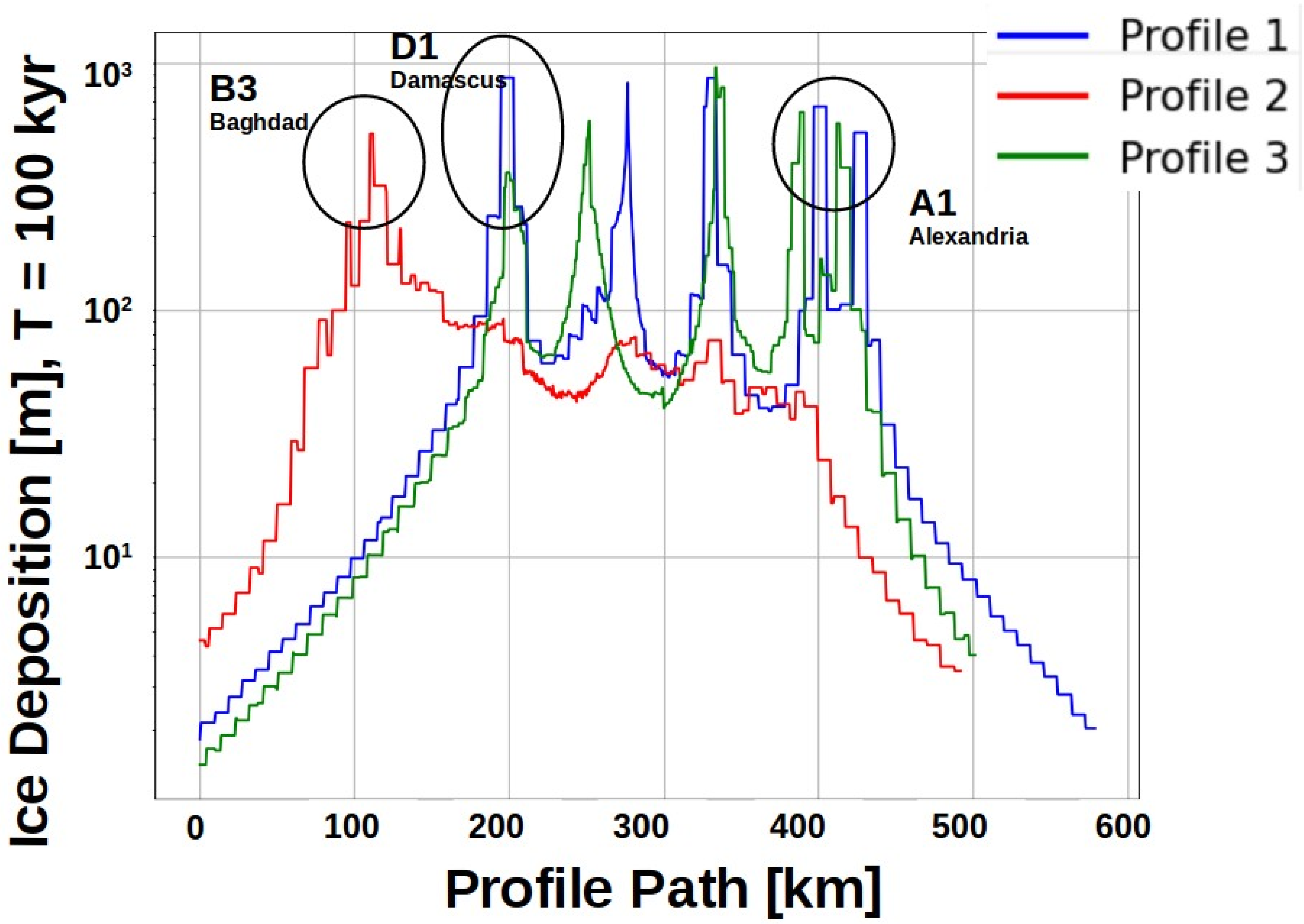


B-Scans – Example with South Poalr Ice

• A B-Scan is an image formed by combing signals measure at multiple different antenna positions
• Two antennas (TX and RX) at constant range R = 50 m move down through the ice
• TX produces a pulse recorded by RX
• Images shows two features, direct propagating signal, and a reflection signal (from the ice surface interface)

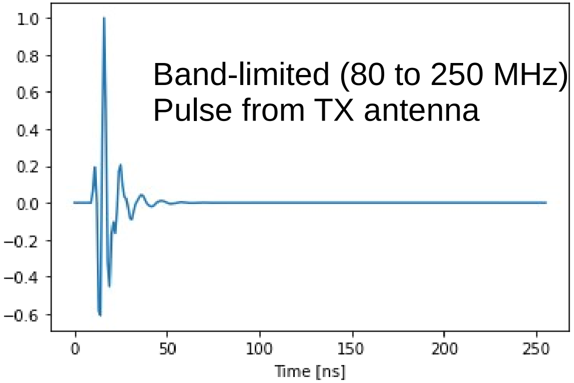


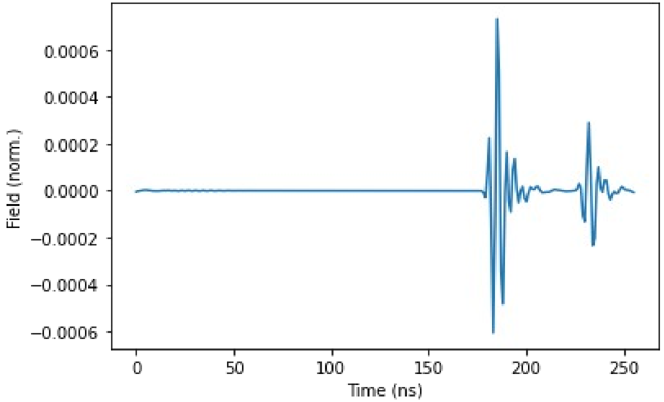

Deposition Rate on South Polar Terrain $\phi_{\mathrm{lat}} < -60°$
Profile 1
Profile 2
Profile 3
0° W
90° W
270°
180° W
80° S
70° S
60° S
B3
B1
B2
C1
C2
D1
D2
A1
200
100
0
−100
−200
−200
−100
0
100
200
Distance from South Pole Y [km]
Distance from South Pole X [km]
10^{1}
10^{0}
10^{-1}
Deposition Rate [mm/yr]
Profile 1
Profile 2
Profile 3


Ice Deposition [m], T = 100 kyr
10^3
10^2
10^1
0
100
200
300
400
500
600
Profile Path [km]
Profile 1
Profile 2
Profile 3
B3
Baghdad
D1
Damascus
A1
Alexandria

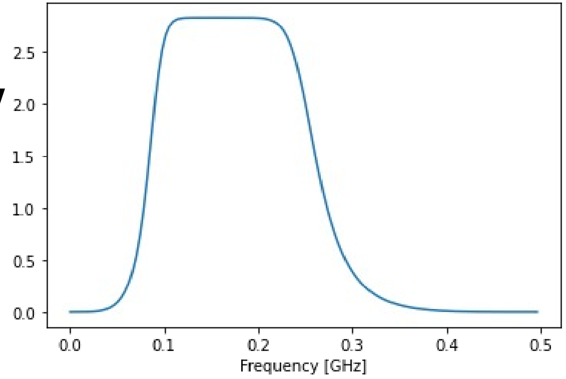
Transmitter (x = 0, z = 50)

Receiver (x = 20, z = 50)



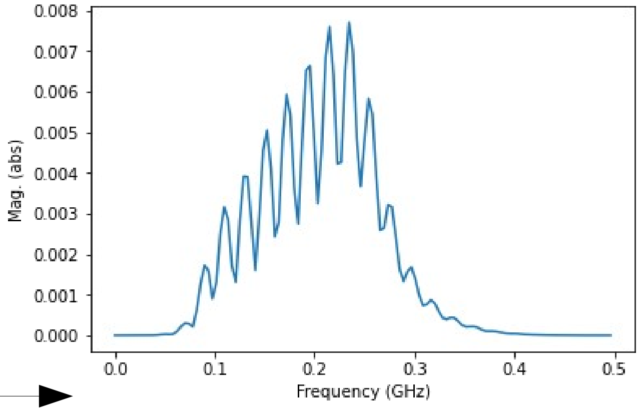


1. Fourier transform



2. Run PE solver Define source amplitude at each frequency using the pulse spectrum

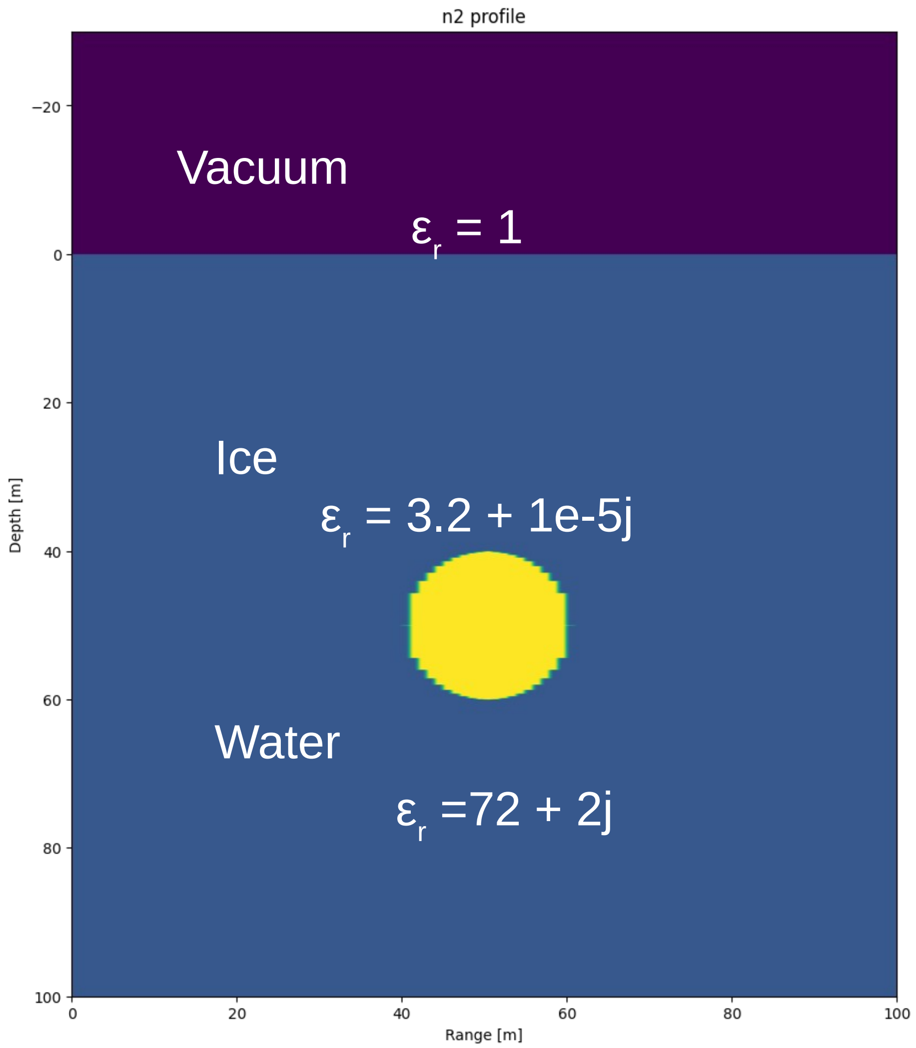
3. Sample field amplitude at RX for each frequency

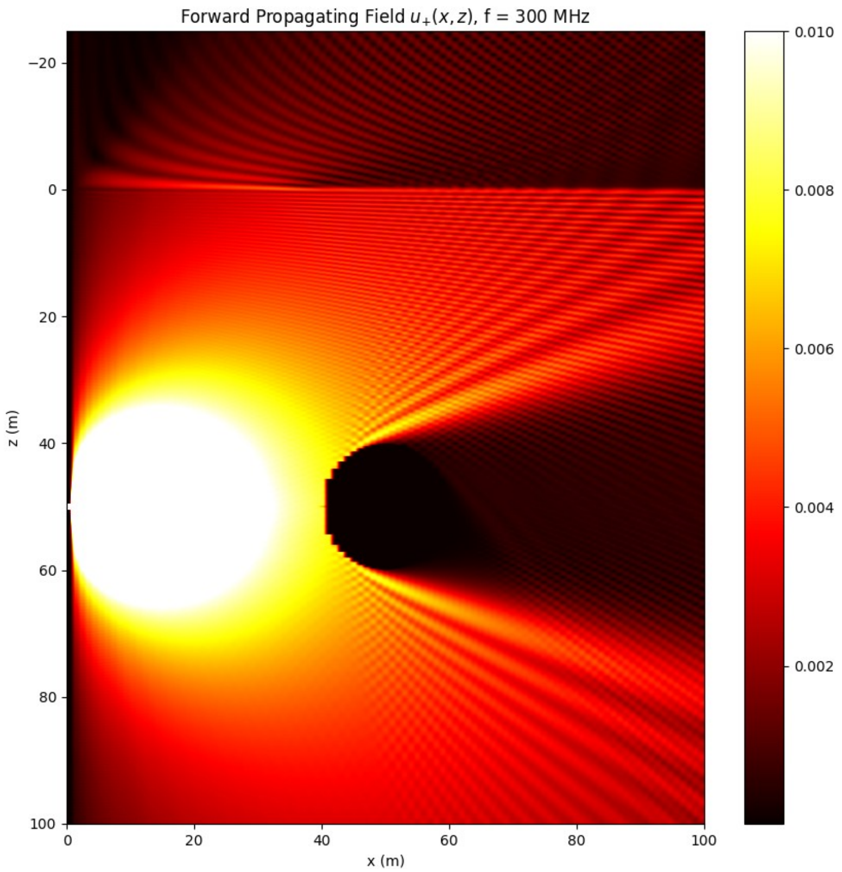


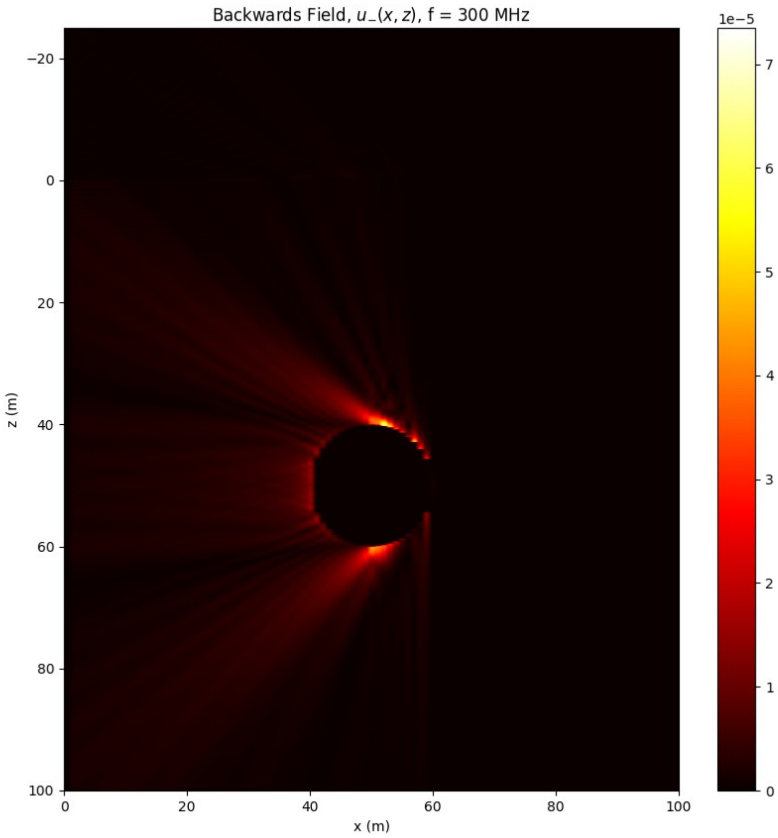
4. Inverse Fourier transform spectrum to reconstruct receiver wave-form

Single Frequency Simulation

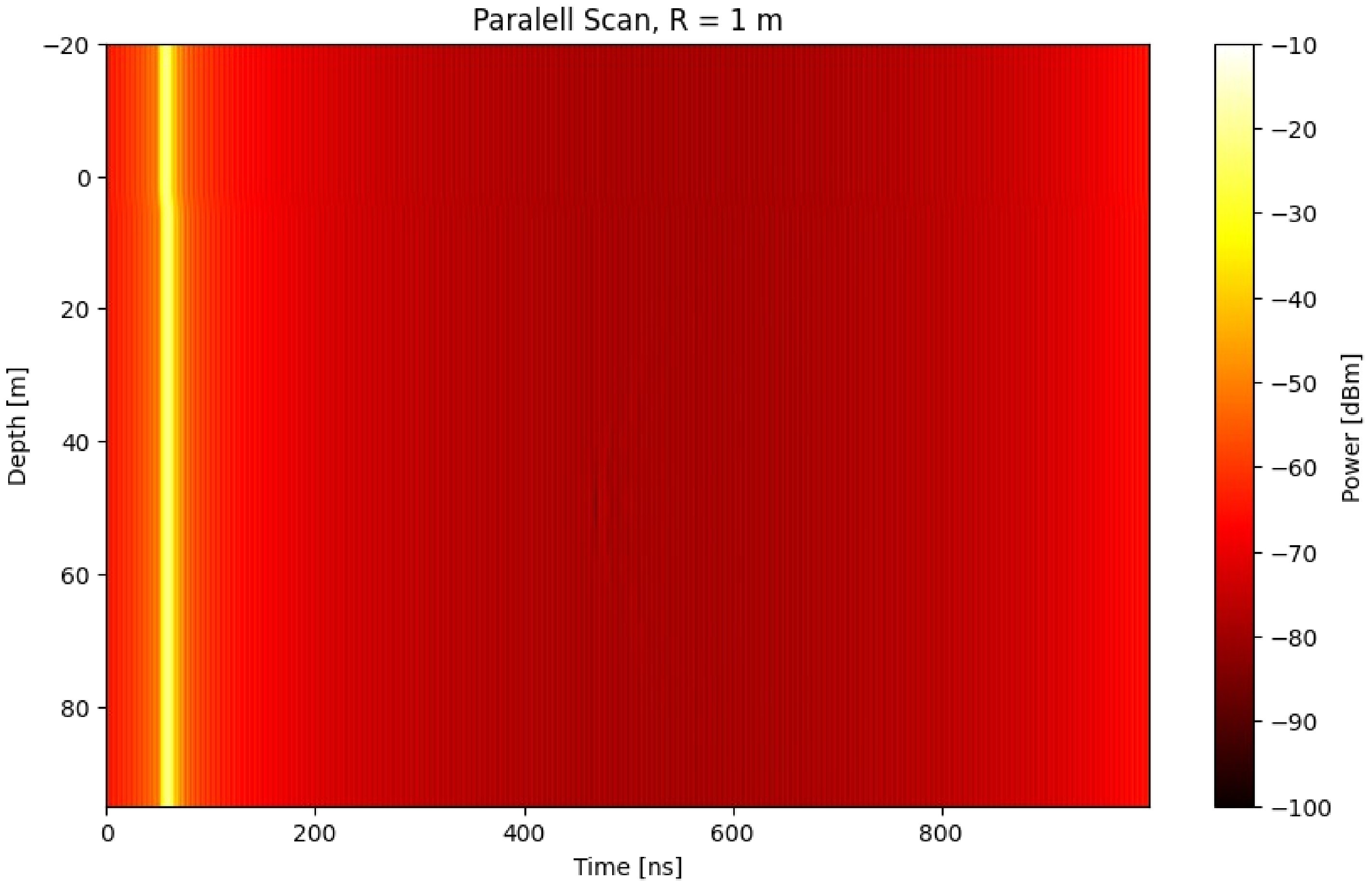
Simple example, with homogenous ice and a cicrcular water pocket (radius of 10 m)




Forward Propagating Field $u_+(x, z)$, f = 300 MHz
z (m)
x (m)
0.010
0.008
0.006
0.004
0.002

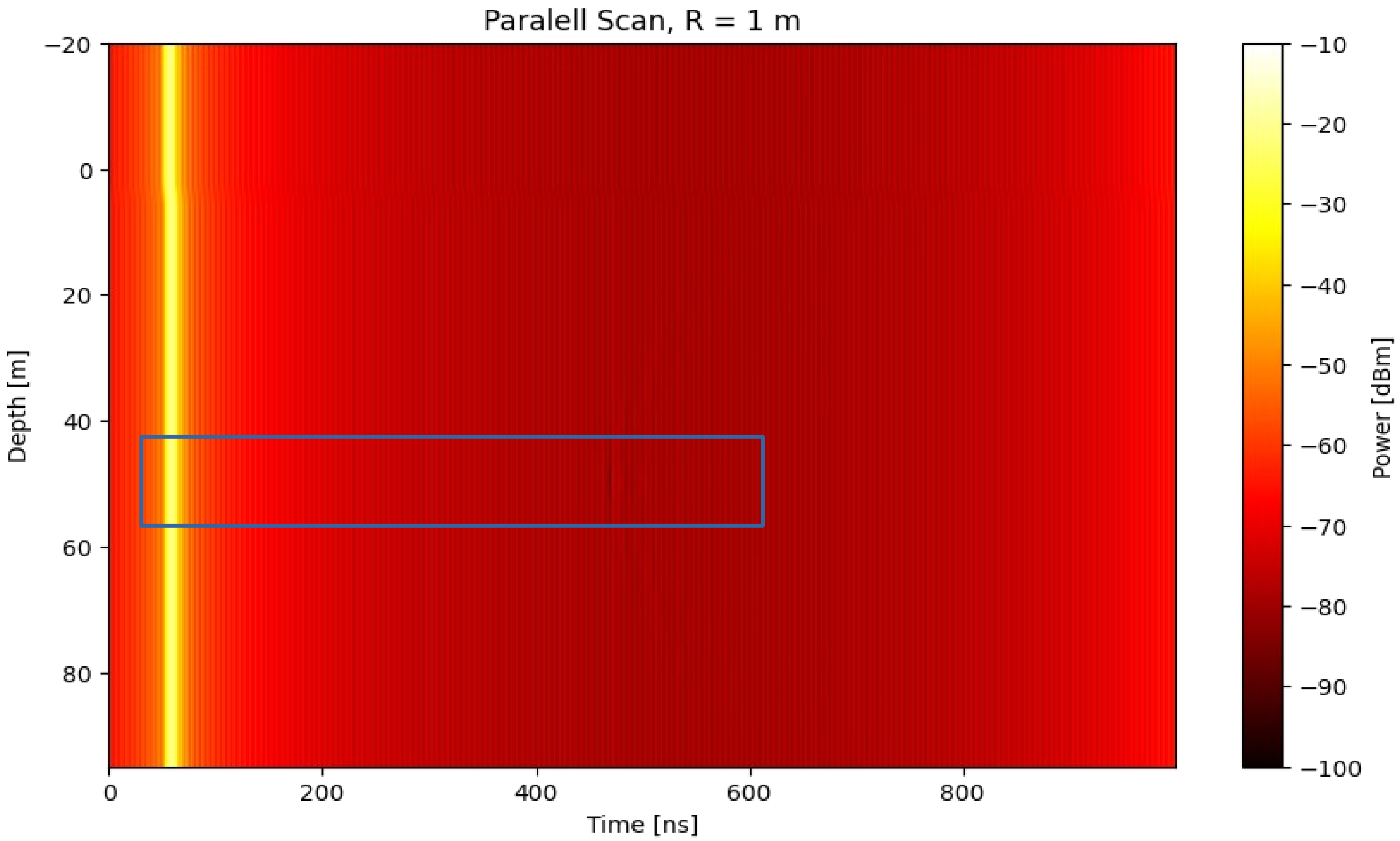

Backwards Field, $u_-(x, z)$, f = 300 MHz
z (m)
x (m)
1e−5

Result



Paralell Scan, R = 1 m
−20
0
20
40
60
80
Depth [m]
0
200
400
600
800
Time [ns]
−10
−20
−30
−40
−50
−60
−70
−80
−90
−100
Power [dBm]

Result



Examine at
50 m depth

Example:

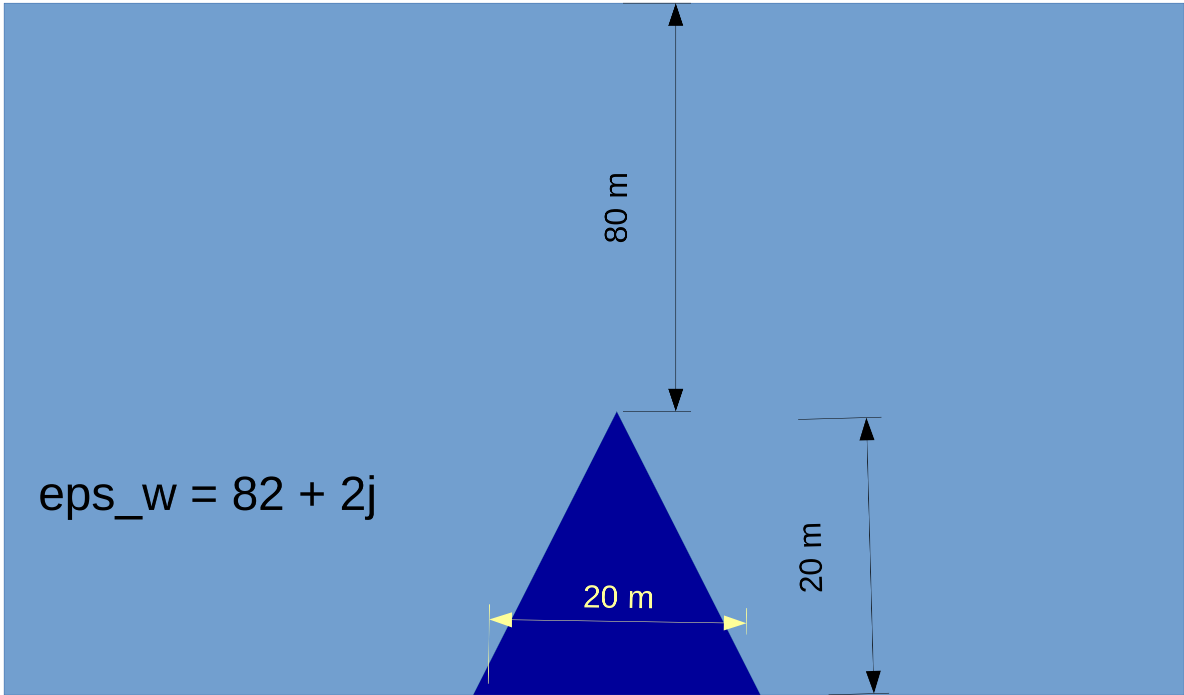
n-prof: South Pole analytical profile

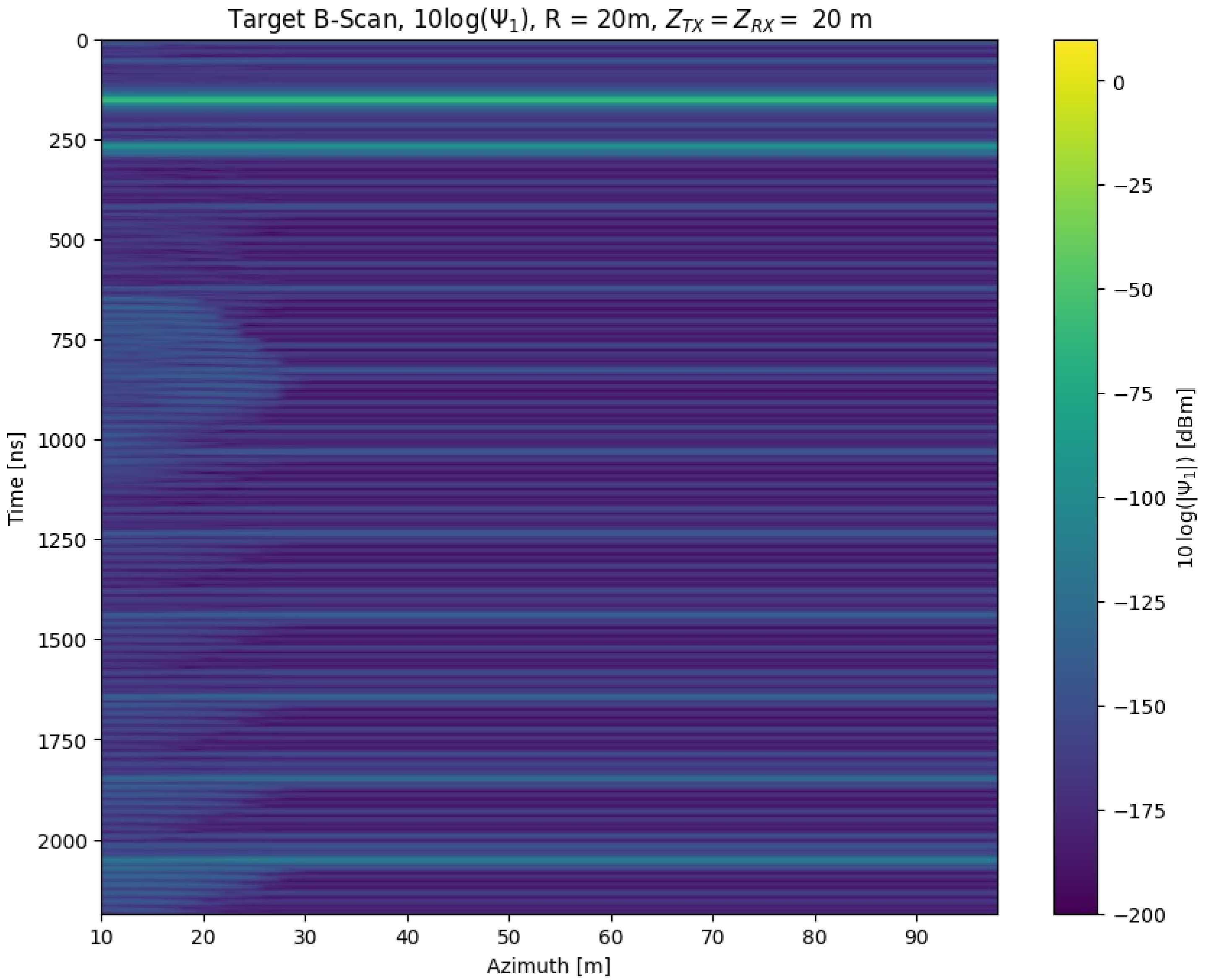
Single-source depth: 20 m

‚Mexican hat‘ pulse → central frequency 500 MHz

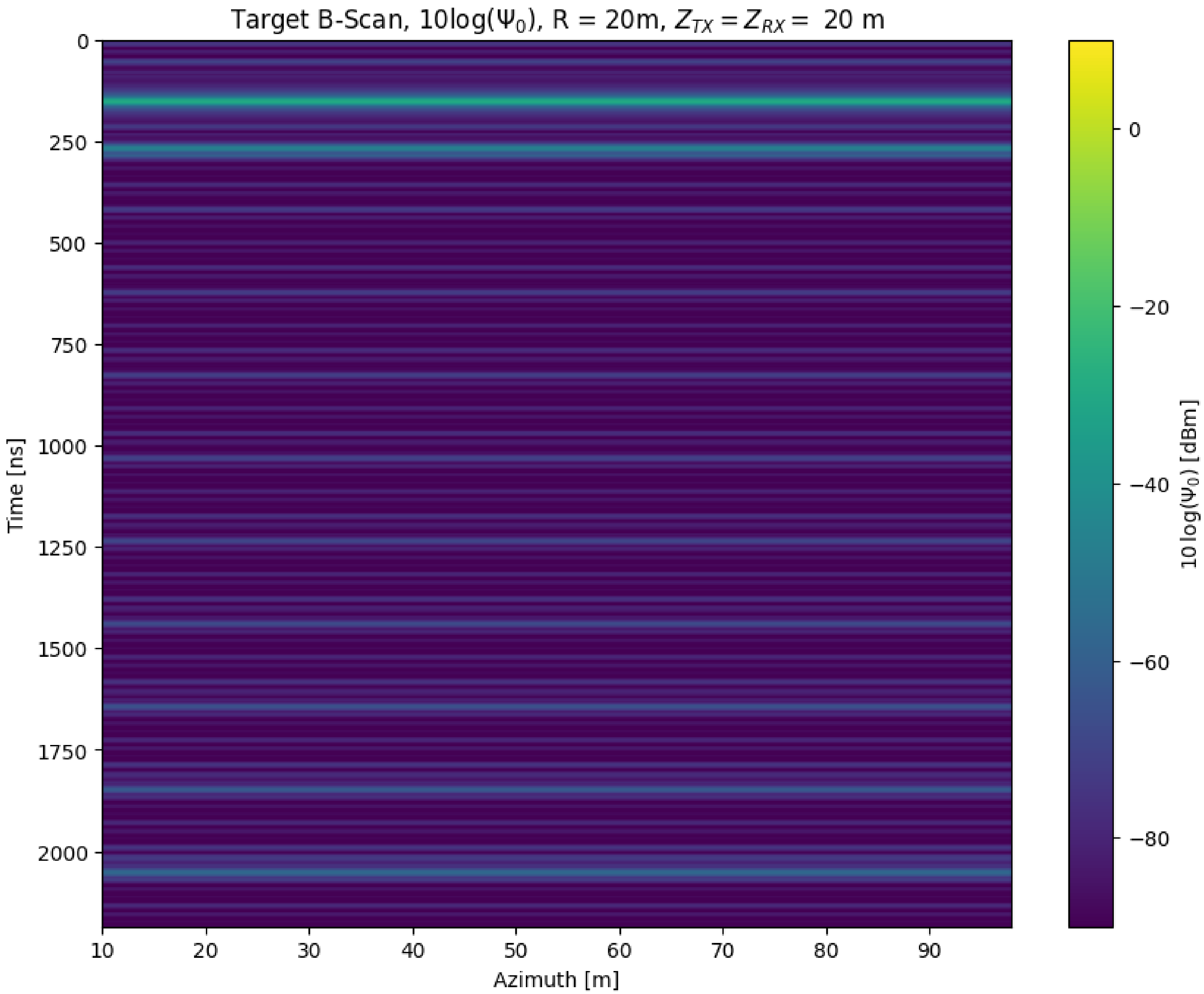
Ice dimensions: 100 m deep, 100 wide

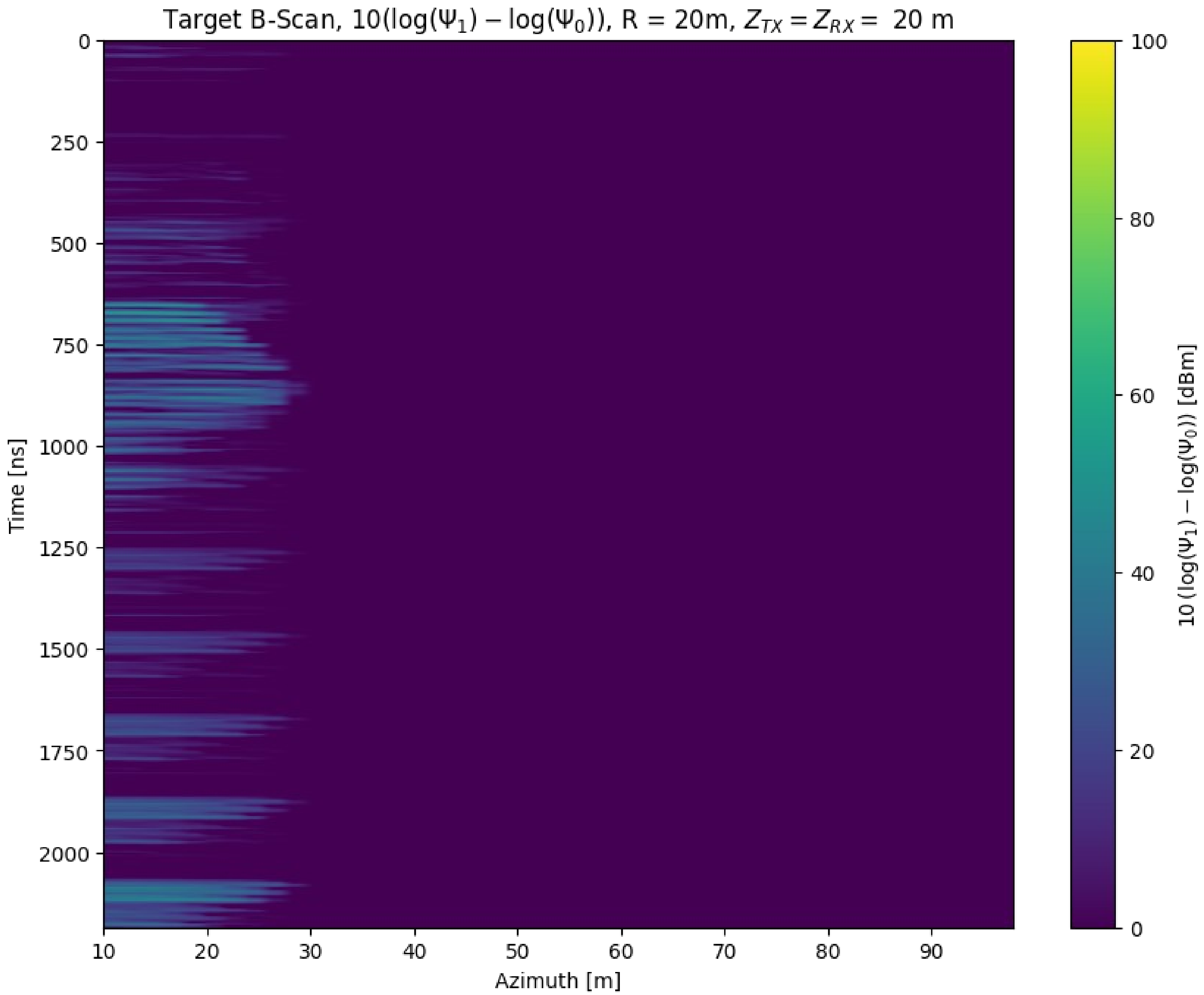
Aquifer dimensions:
80 m below surface

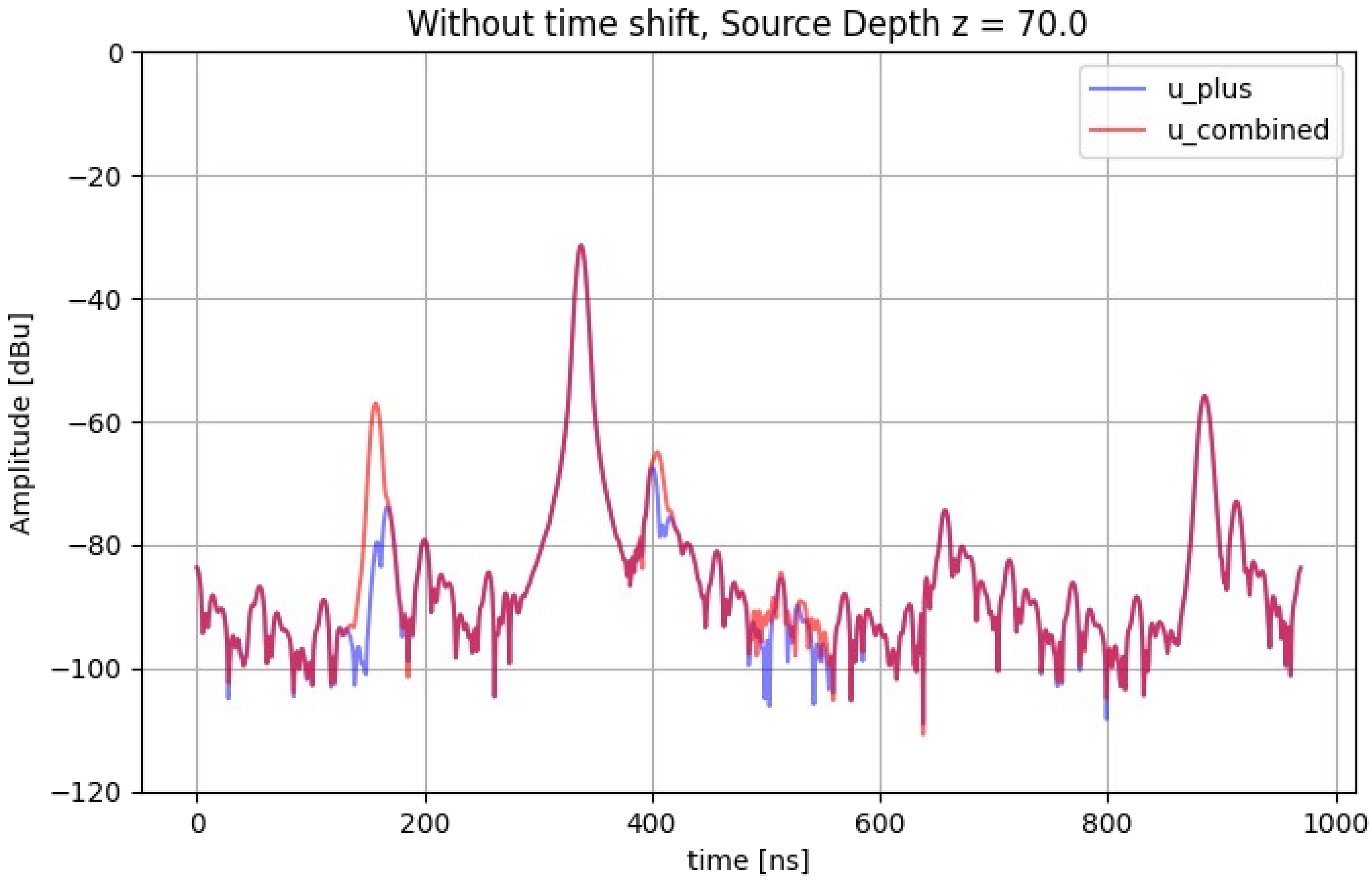


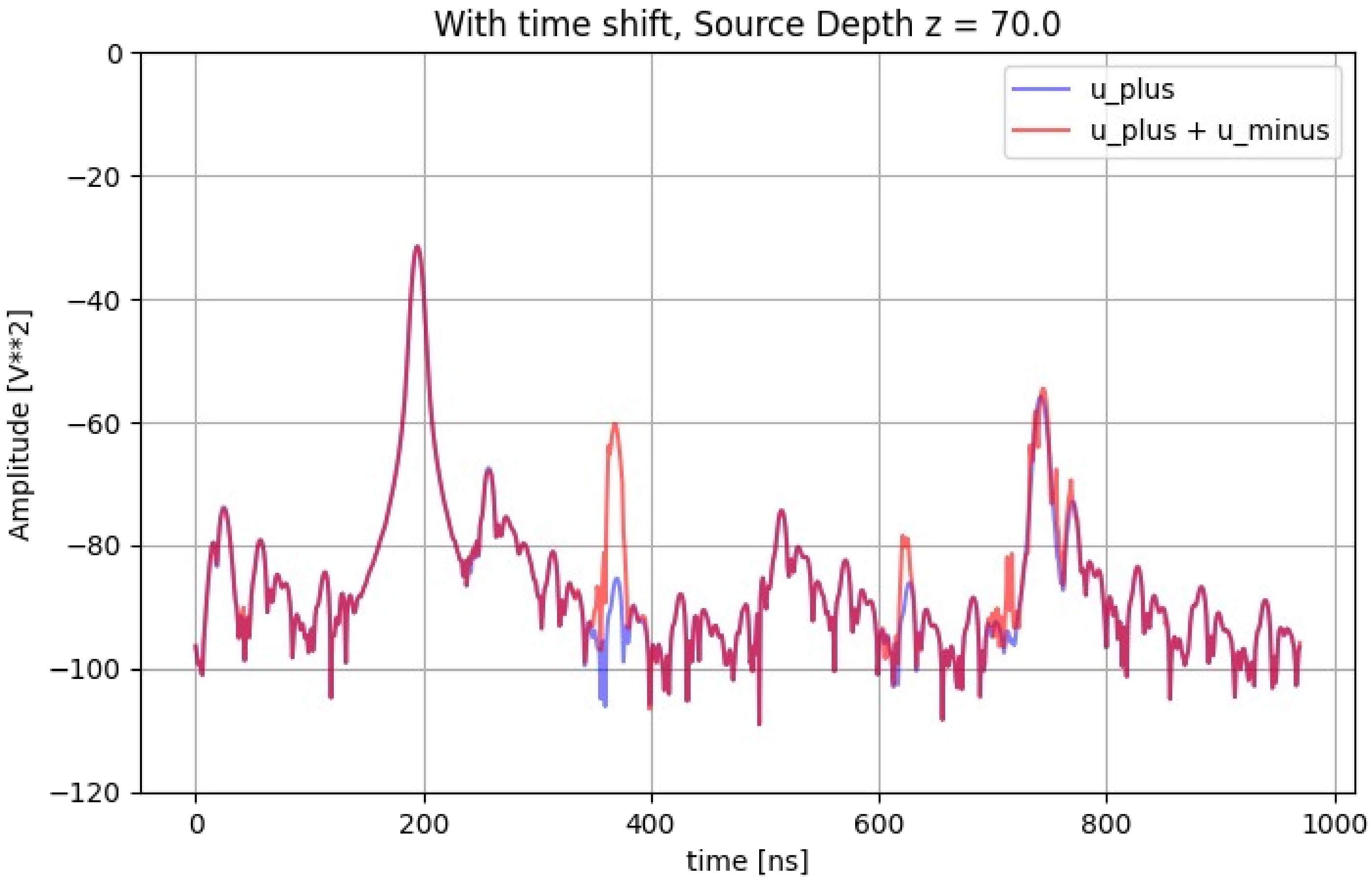


Target B-Scan, 10log(Ψ1), R = 20m, Z_TX = Z_RX = 20 m
Time [ns]
0
250
500
750
1000
1250
1500
1750
2000
Azimuth [m]
10
20
30
40
50
60
70
80
90
10log(|Ψ1|) [dBm]
0
−25
−50
−75
−100
−125
−150
−175
−200


Target B-Scan, $10\log(\Psi_0)$, R = 20m, $Z_{TX} = Z_{RX} =$ 20 m
Time [ns]
0
250
500
750
1000
1250
1500
1750
2000
Azimuth [m]
10
20
30
40
50
60
70
80
90
$10\log(\Psi_0)$ [dBm]
0
−20
−40
−60
−80


Target B-Scan, 10(log(Ψ1) − log(Ψ0)), R = 20m, ZTX = ZRX = 20 m
Time [ns]
0
250
500
750
1000
1250
1500
1750
2000
Azimuth [m]
10
20
30
40
50
60
70
80
90
10(log(Ψ1) − log(Ψ0)) [dBm]
0
20
40
60
80
100


Without time shift, Source Depth z = 70.0
u_plus
u_combined
Amplitude [dBu]
time [ns]
0
−20
−40
−60
−80
−100
−120
0
200
400
600
800
1000



With time shift, Source Depth z = 70.0
u_plus
u_plus + u_minus
Amplitude [V**2]
time [ns]
0
−20
−40
−60
−80
−100
−120
0
200
400
600
800
1000

Real World example: Aletsch Glacier

Field Test for the EnEx project in Aletsch Glacier
March-April 202

Measurement of permittivity profile upper 15 m of firn with bi-static FMCW radar
→direct signal component → the largest siggnal component
→Reflected signals may arrive earlier or later

Qualitative agreement between simulation and data