Enceladus Explorer

Radar based sounding system and navigation for a melting probe to investigate the ocean of Enceladus for signs of life

Joe Bergeron ©2006

Participant Talk for Astroparticle School, Obertrubach-Bärnfels

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Contents

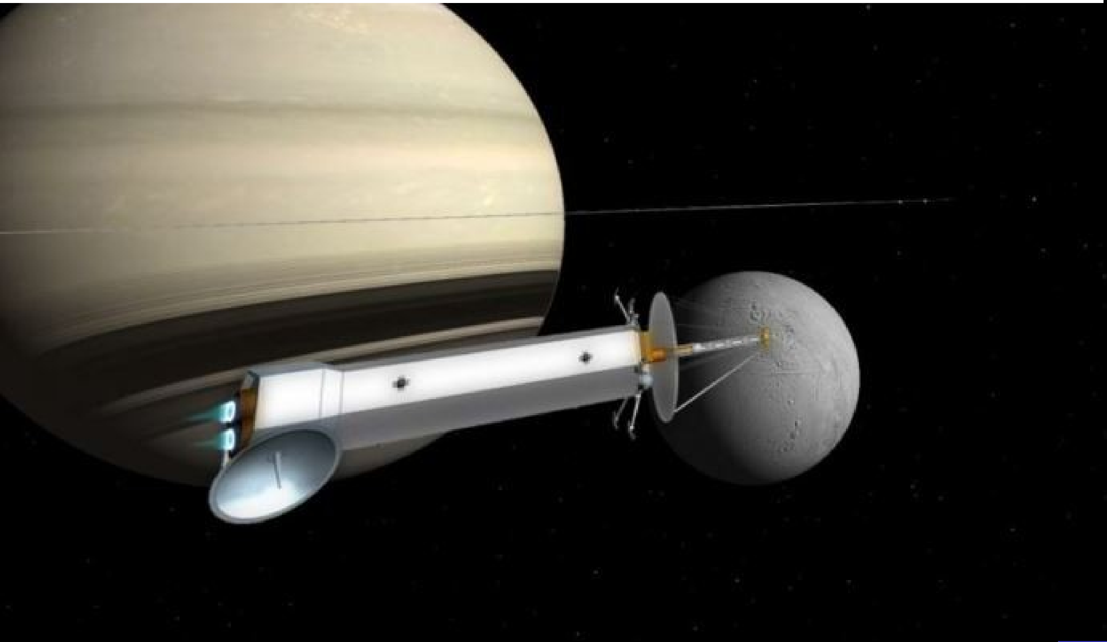
Enceladus Explorer

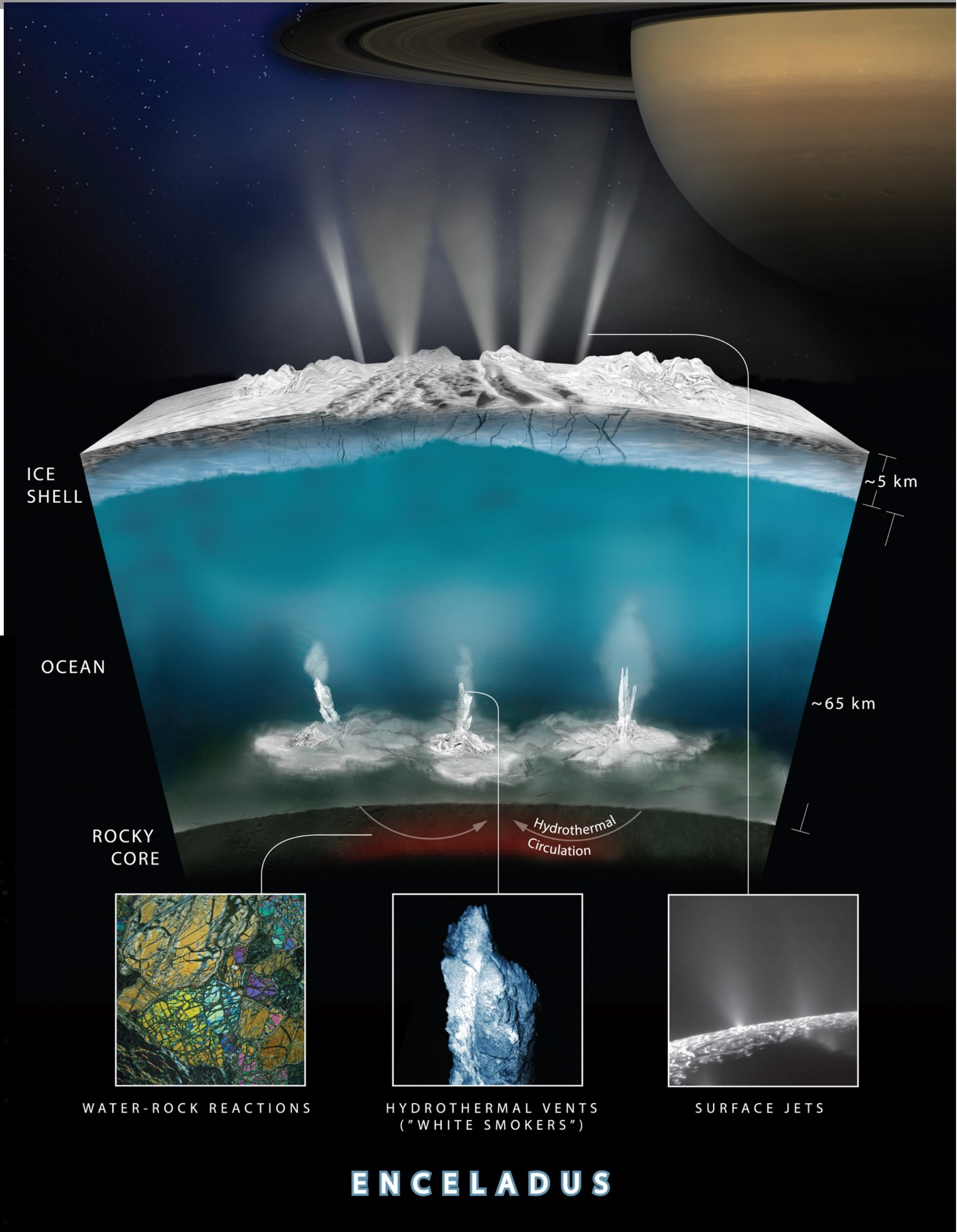
Enceladus Explorer (EnEx) is a proposed space probe to investigate Enceladus for signs of extraterrestrial life

The space probe consists of an orbiting bus and a lander which additionally carries a melting probe: 'IceMole'

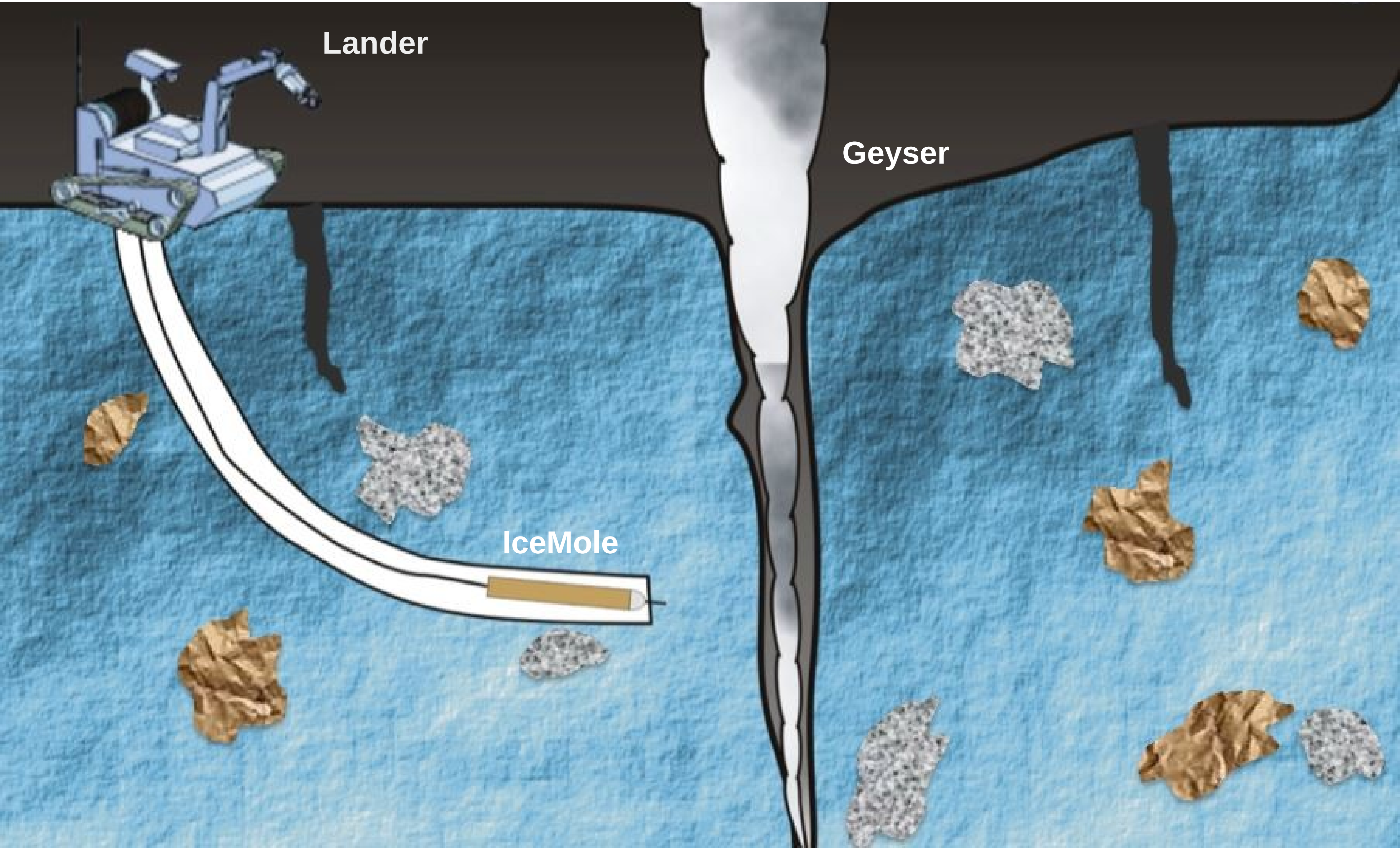
The IceMole would melt through ~100 metres of ice towards a pocket of liquid water

At the water pocket IceMole will conduct testing of water for biosignatures





Enceladus Explorer



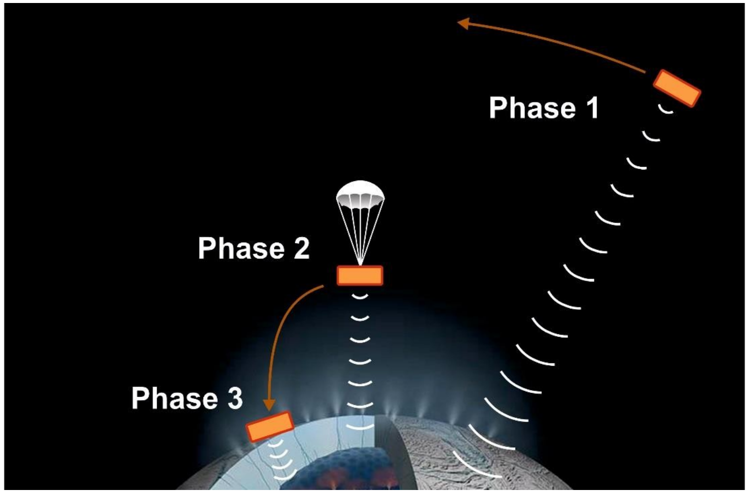
EnEx-AsGAr

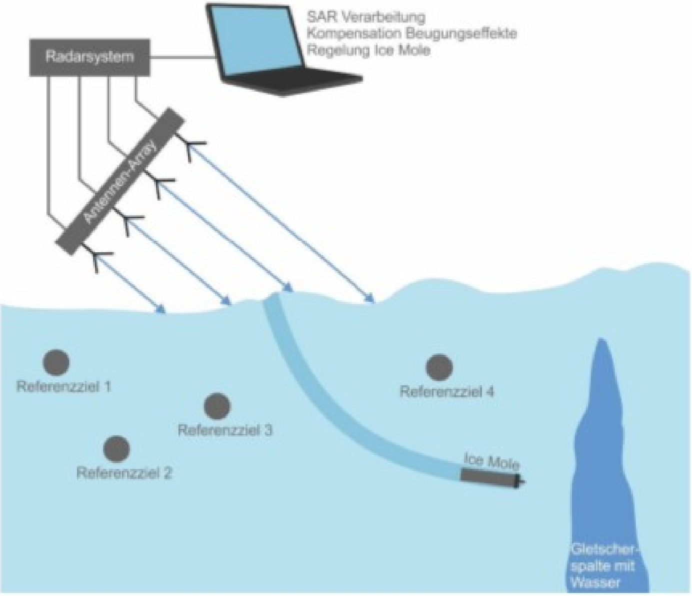
Deutsch: “Abbildungssystem für Gletscherspalten in der Astrobiologie zur roboterbasierten Eis-Exploration”
English: “Image system for crevasses in astrobiology for robot-based ice exploration”

Objectives:
The development of ice-penetrating radar systems for orbiter, lander and IceMole to achieve:

1. Long-Range Mapping of Surface Ice Structure from orbit and the surface (FAU)
    - Identification of landing spot
    - Gauge ice depth
    - Map internal structure of geyser cracks
    - Identify near-surface water pockets

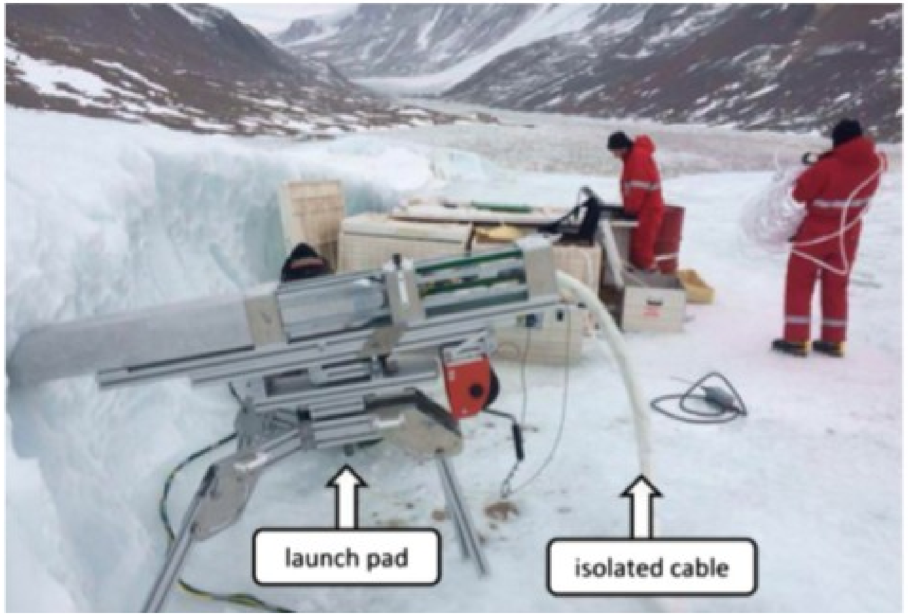
2. Short Range Ice Sounding and Navigation for the IceMole (BUW)
    - Identification of obstacles: meteorites, crevasses, thick soil belts
    - SAR based positioning of IceMole relative to lander
    - Identification of Water Pocket from IceMole





IceMole Prototype

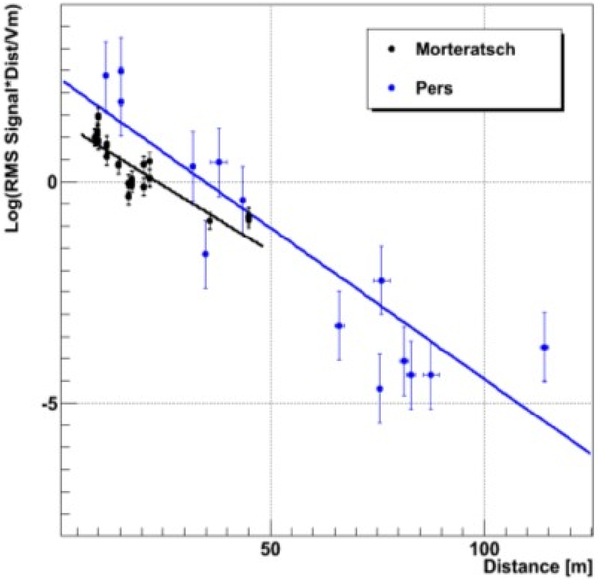
Current Prototype:
- Geometry: 15cm x 15 cm x 200 cm (prototype)
- Weight: 60 kg
- Melting Power: 1 kW (to be supplied by RTG on lander)
- Melting Speed: 1 metre/hour

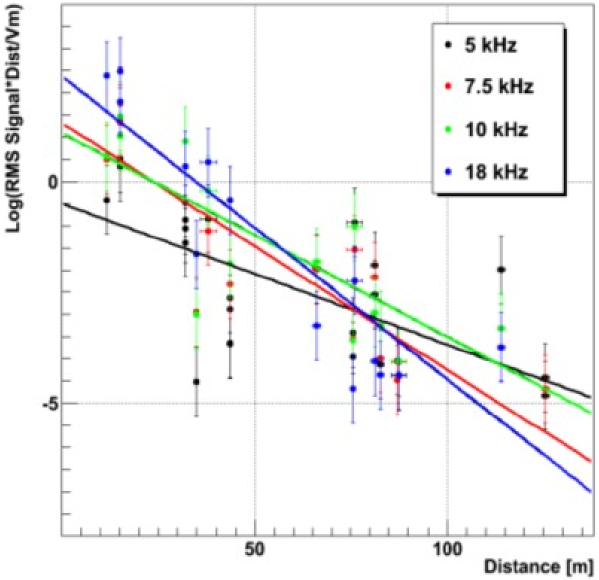


Current design includes pingers (in melting head to generate acoustic waves, the backscatter of which can be measured by acoustic sensors.

Low range of acoustic waves in glacial ice (~ 30 m - *Helbing et al (2016)*)

→ highlights the need for a hybrid positioning system incorporating radar





Identification of Obstacles

P_R: Received Power

$$P_R = \frac{P_T G^2 \lambda^2 \sigma L}{(4\pi R^2)^2} \propto \frac{1}{R^4}$$

P_T	Transmitted power
P_R	Reflected power
G	Antenna Gain
λ	Wave Length
σ	Target Cross Section
R	Range
L	Loss Factor ($L < 1$)

$$L \propto L_\alpha$$

Attenuation Loss

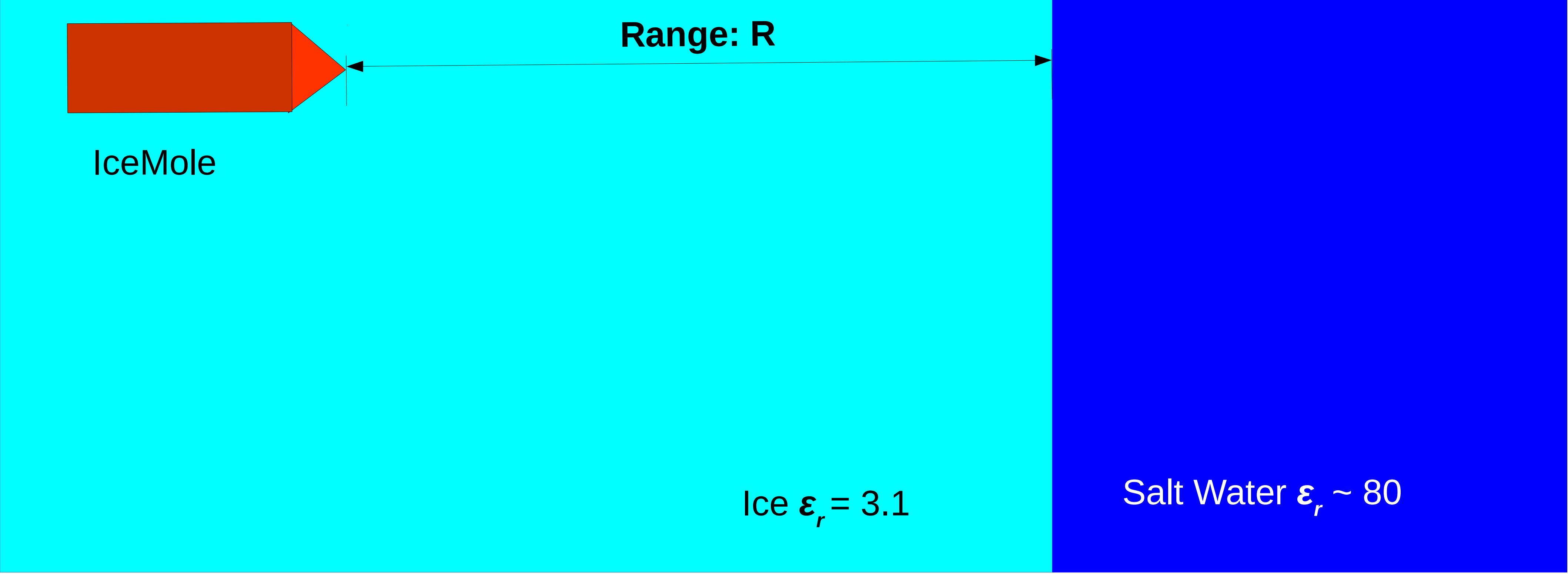
$$L_\alpha = e^{-2\alpha R}$$

Identification of Water Pocket

$$P_R = \frac{P_T G^2 \lambda L}{4 \pi R^2} \propto \frac{1}{R^2}$$

$$L = (1 - T_{ice \rightarrow water}) L_\alpha = (1 - T_{ice \rightarrow water}) e^{-\alpha R}$$

$$T_{ice \rightarrow water} = \frac{Z_{ice} - Z_{water}}{Z_{ice} + Z_{water}} = \frac{\sqrt{\epsilon_{r,water}} - \sqrt{\epsilon_{r,ice}}}{\sqrt{\epsilon_{r,water}} + \sqrt{\epsilon_{r,ice}}}$$



Dielectric Properties of Ice

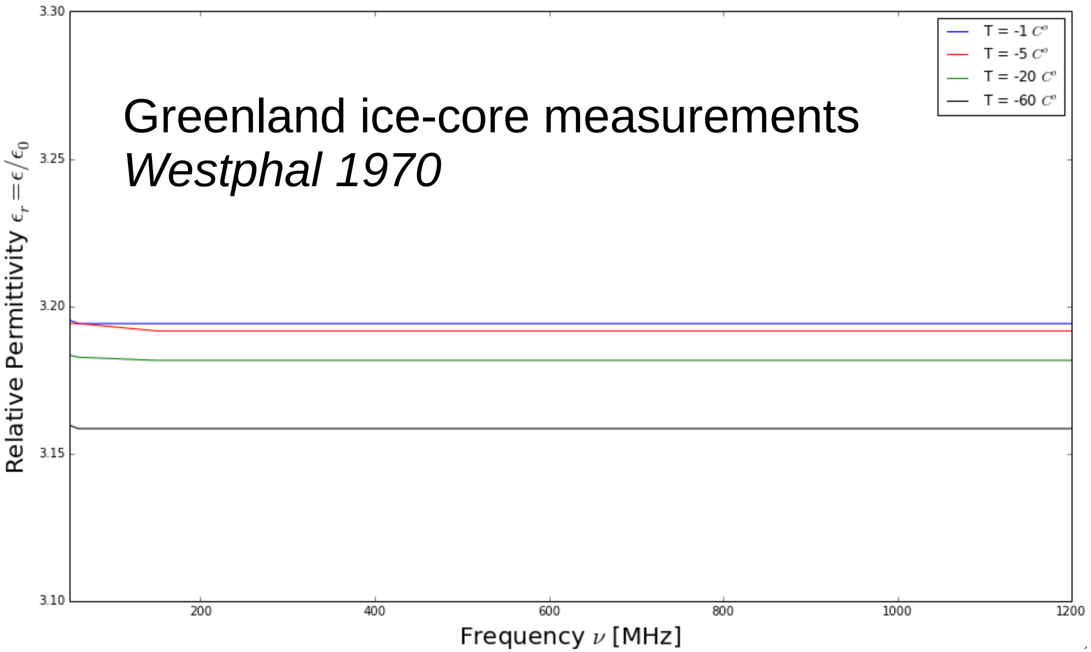
To gauge distance to obstacle with radar (amplitude or frequency modulated) requires knowledge of relative permittivity $\boldsymbol{\varepsilon_r}$ across the used bandwidth

Permittivity $\boldsymbol{\varepsilon_r}$ is strongly linear with ice density - *Wilhelms & Frank (2018)*

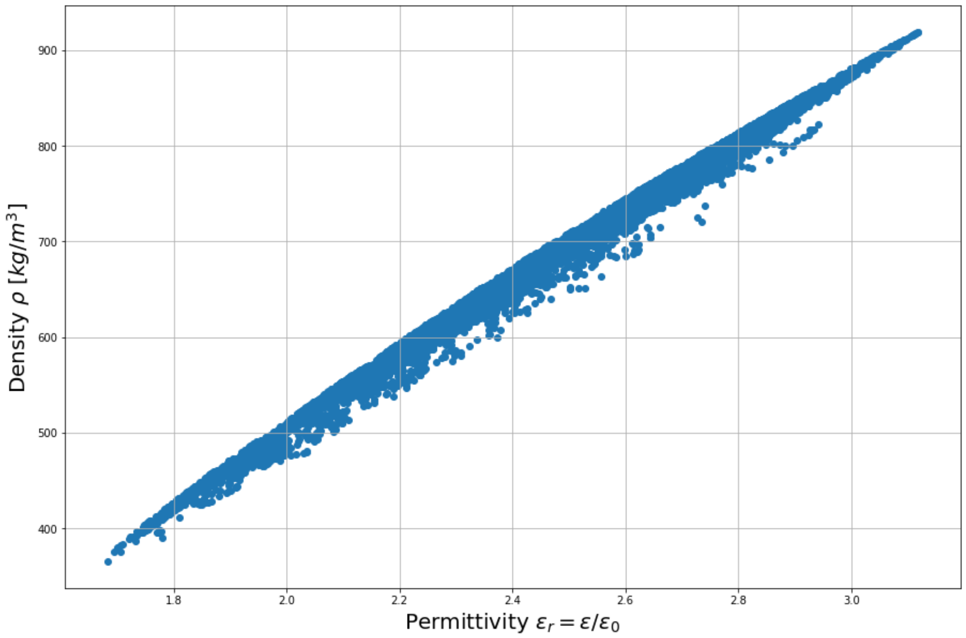
Should not vary much across radio frequencies

Moderate temperature dependence

At solid ice density $\boldsymbol{\rho_{ice}}$ = 920 kg/m^3 → $\boldsymbol{\varepsilon_{r,ice}}$ ~ 3.2



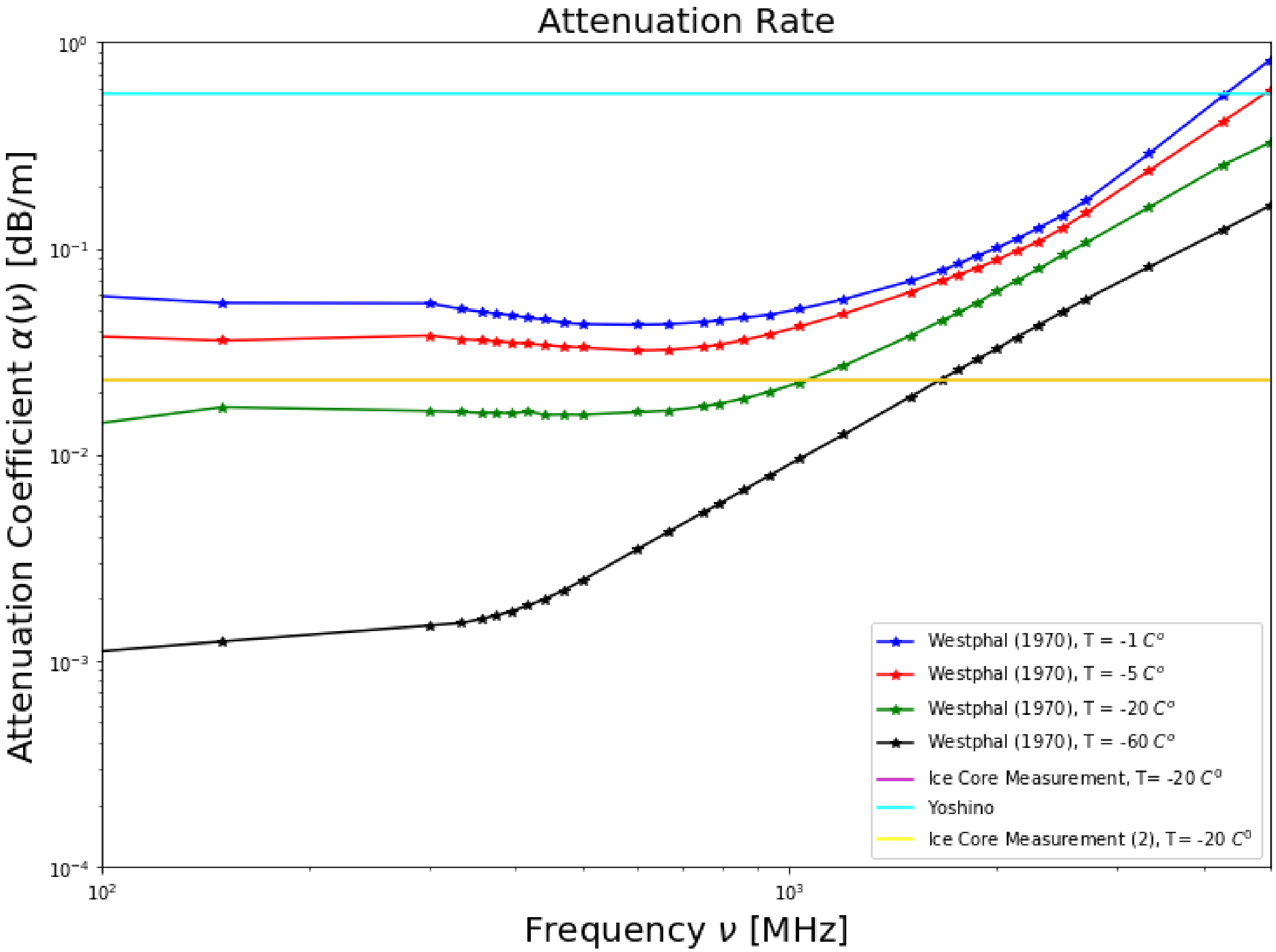
Greenland ice-core measurements
Westphal 1970



Dielectric Properties of Ice

Radio sounding requires accurate knowledge of the refractive index ***n* (= sqrt($\varepsilon_{r,ic}$))** and attenuation rate ***α***

At solid ice density ρ_{ice} = 920 kg/m^3 → $\varepsilon_{r,ice}$ ~ 3.2 → relatively constant across radio frequencies



Attenuation loss is dependent on the medium conductivity ***σ*** and permittivity $\varepsilon_{r,ice}$.

In ice attenuation is strongly dependent on liquid water content, temperature and presence of impurities

Attenuation increases sharply between 1 GHz and 10 GHz (*Westphal 1970*)

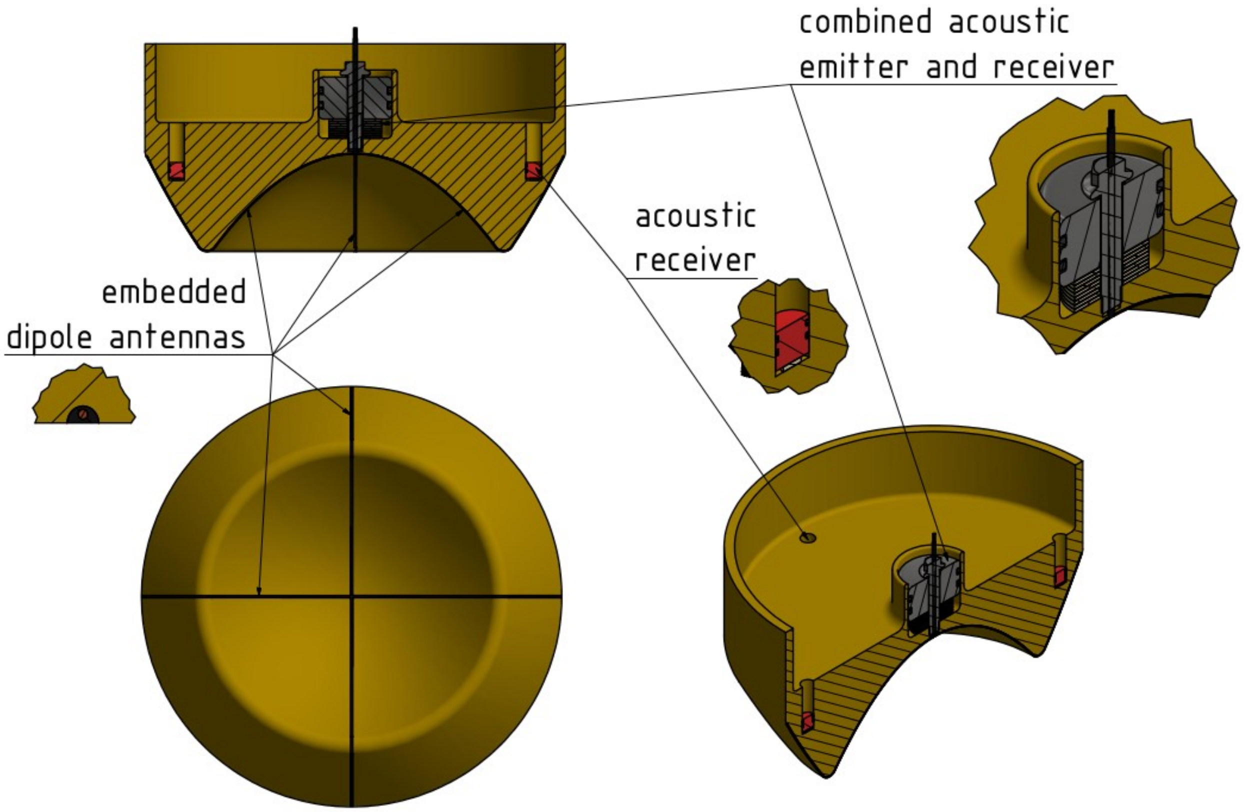
Challenges for Radar Sounding

Dimensions of IceMole require use of high frequency waves: (λ ~ 30 cm, ***f*** ~ 1 GHz)

Ice attenuation increases sharply from 1 GHz – 10 GHz → limits range of radar

Technically difficult to incorporate antenna into IceMole:

- Deployment in the 'front' (melting head) requires an antenna material that is thermally conductive and electrically conductive, and would result in a high noise level
- Deployment at the back creates a blind-spot in the front of the probe
- IceMole would be surrounded by a layer of water vapour (from the sublimating ice) → transmission losses



Proposed design → Dipole Antenna

Aachen University

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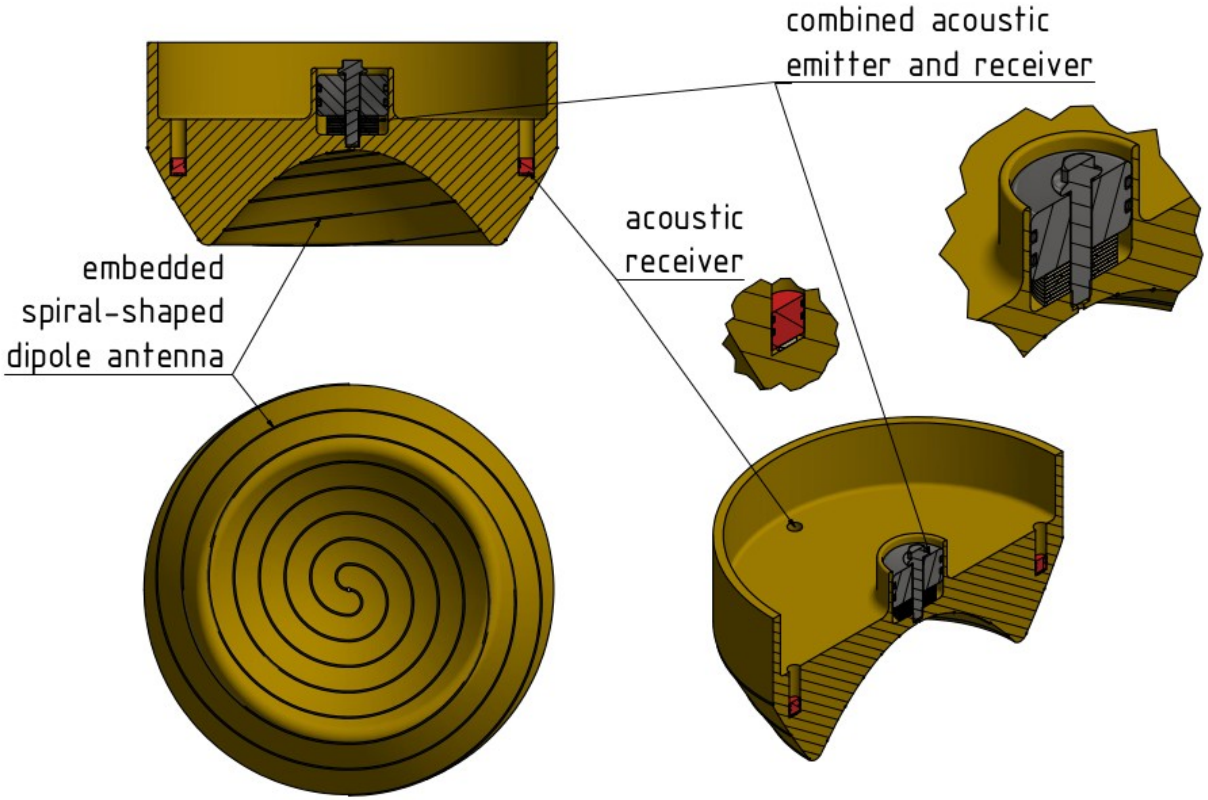
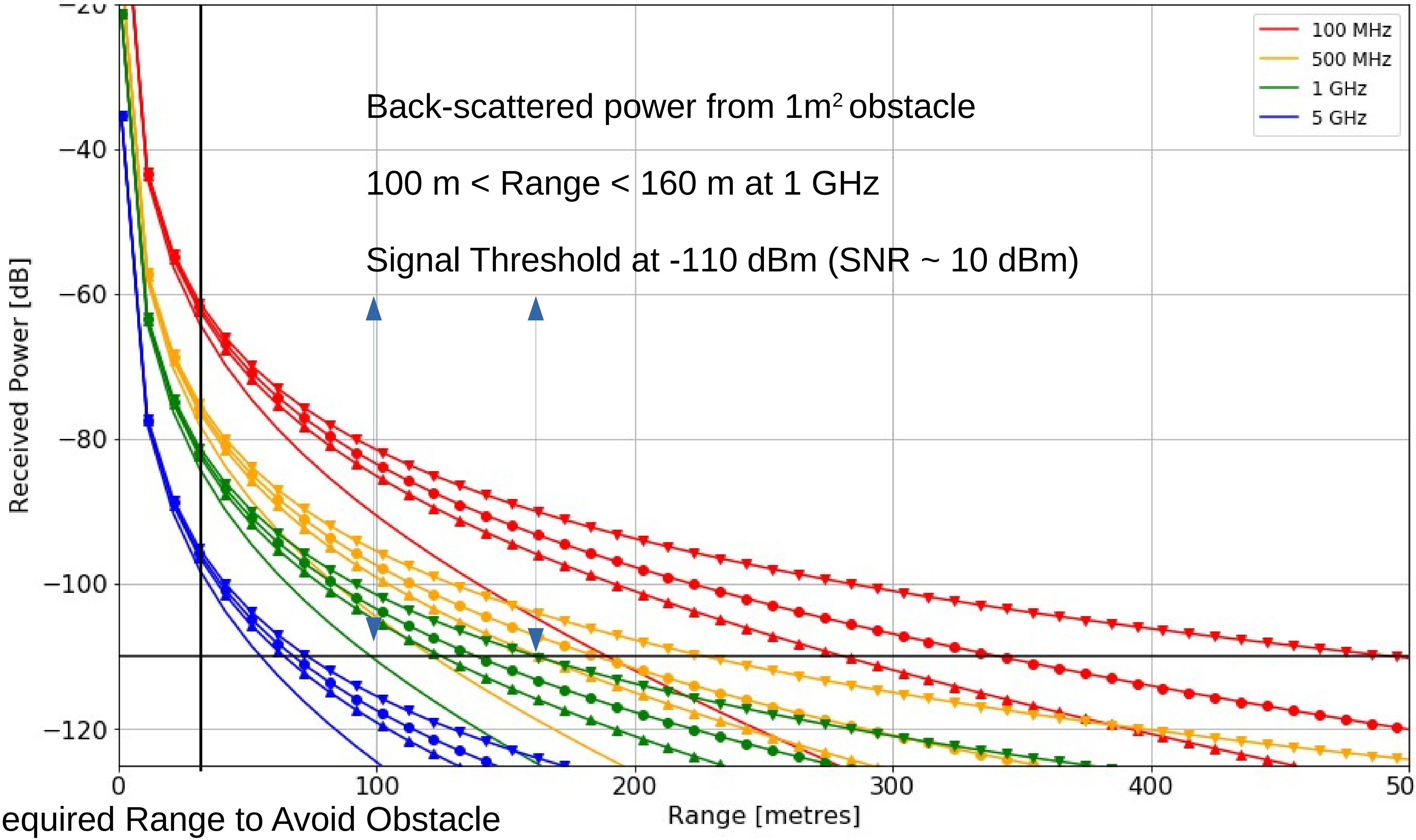


Proposed design (spiral antenna)

Aachen University

Radar Range



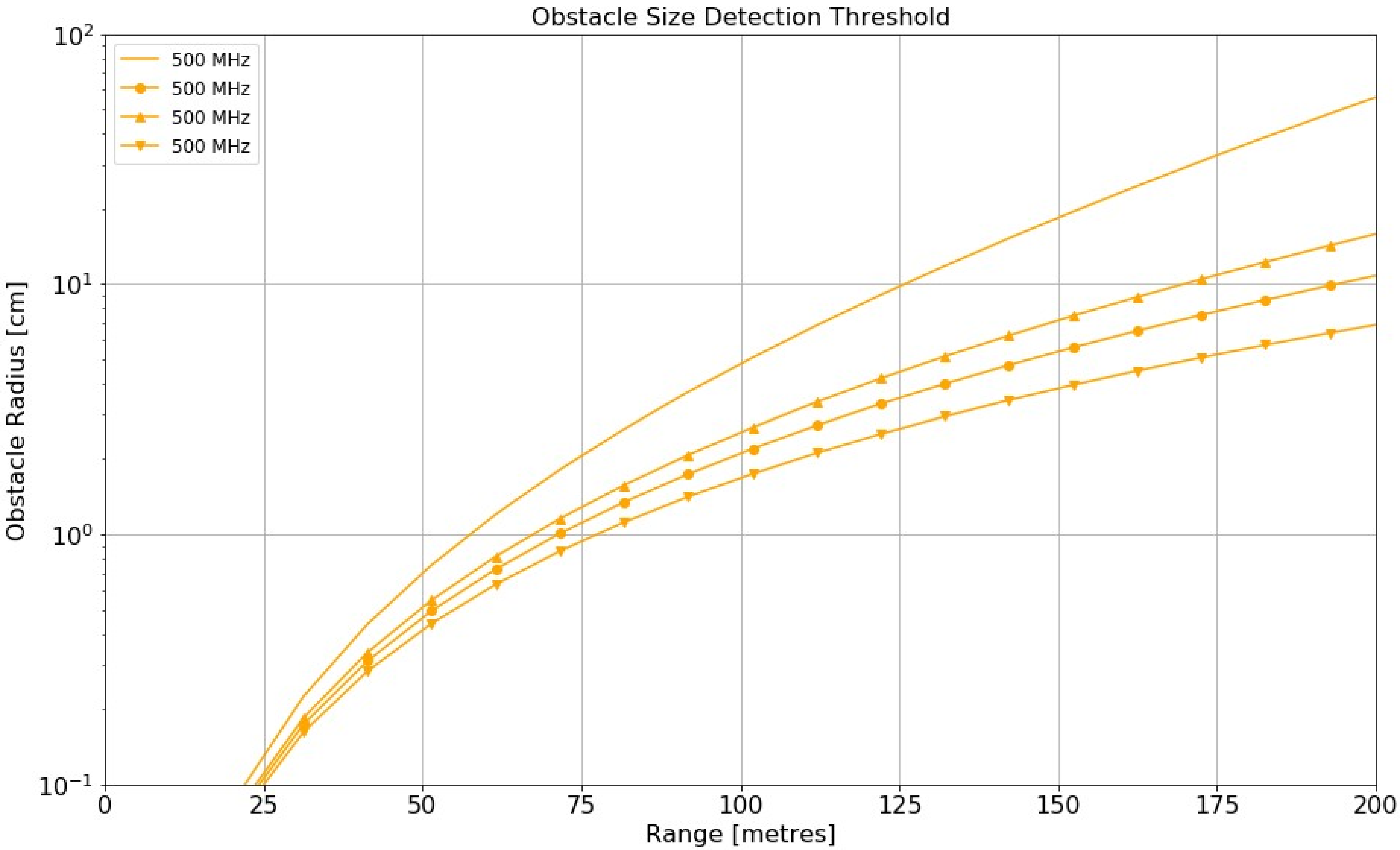
Back-scattered power from 1m^2 obstacle

100 m < Range < 160 m at 1 GHz

Signal Threshold at -110 dBm (SNR ~ 10 dBm)

Required Range to Avoid Obstacle

Radar Range

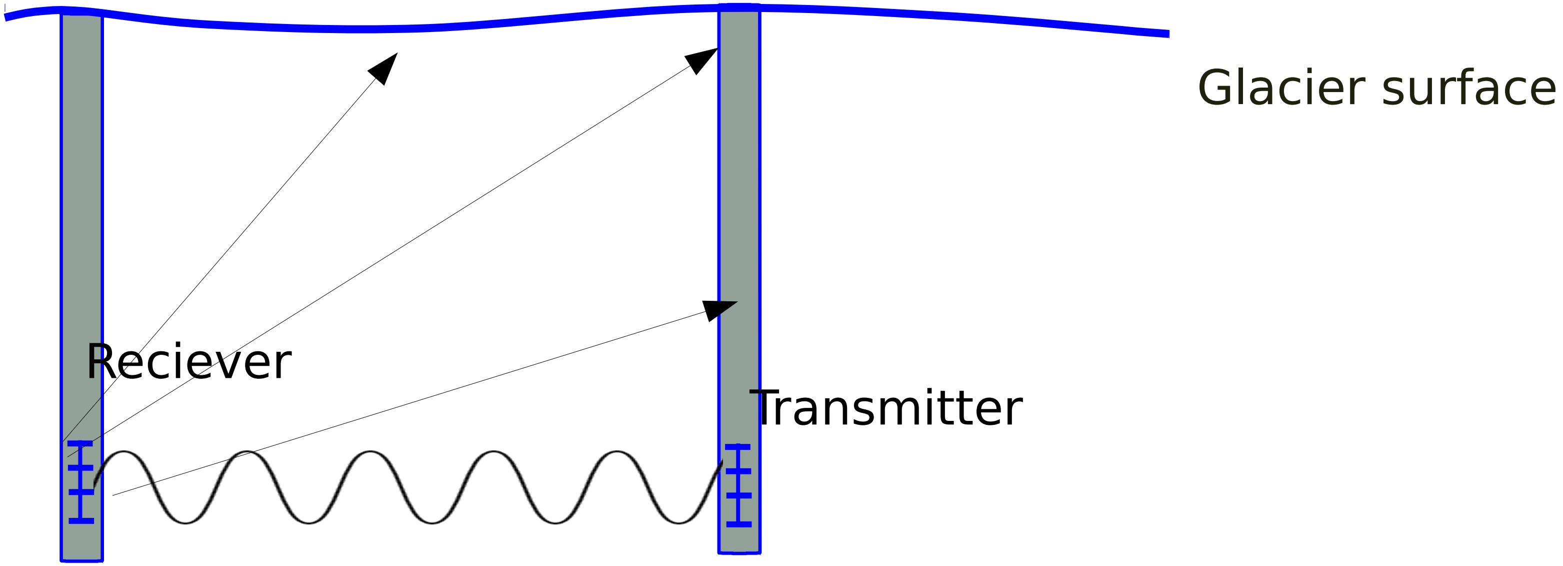

Obstacle Size Detection Threshold
500 MHz
500 MHz
500 MHz
500 MHz
Obstacle Radius [cm]
10^2
10^1
10^0
10^{-1}
0
25
50
75
100
125
150
175
200
Range [metres]

Field Test

First EnEx-AsGAr field test to be conducted at the Mittelbergferner glacier (Tyrol province, Austria)

Goals:
- Measurement of ice permittivity of the glacier as a function of depth (and density)
- Measurement of ice attenuation between 100 MHz and 2 GHz

Method:
Melting of boreholes into the ice (~ 10 m deep) at regular intervals
Placement of high-gain antennae
Transmission of FM signal between boreholes
Permittivity to be measured using FMCW method



FMCW Method

Frequency-Modulated Continous Wave Radar:

$$\Delta f = \frac{TcR}{nB} \qquad R = \frac{nB}{Tc}\Delta f \qquad \Delta R = \frac{c}{2nB}$$

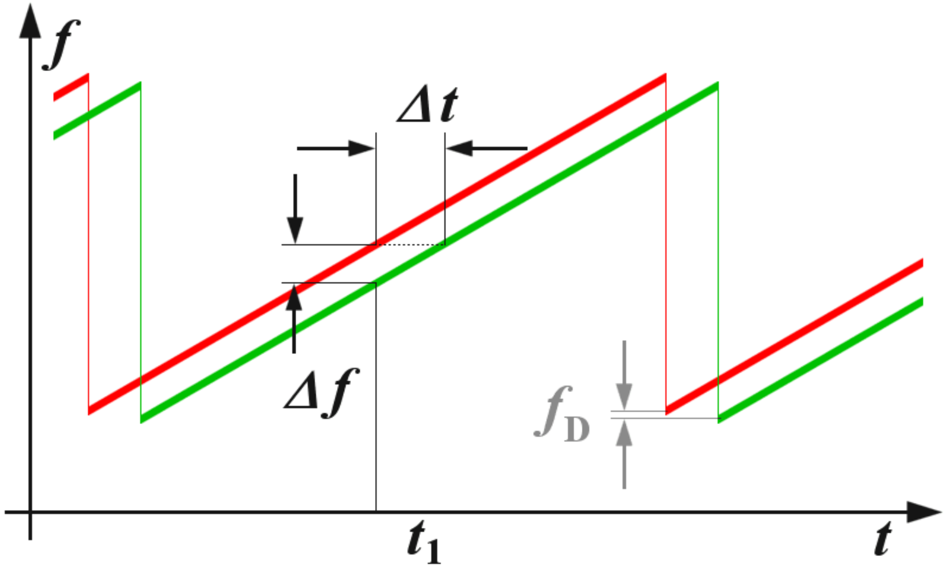
Steps:

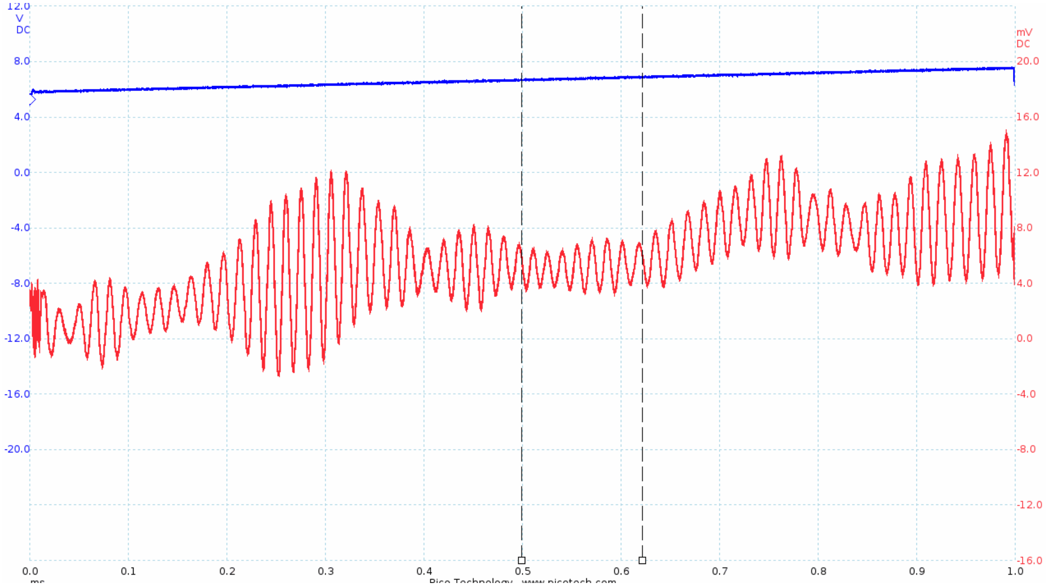
1. Generate a sine wave with a continuously increasing (ramped) frequency from T antenna

2. Measure signal (with time-delay phase) with R antenna

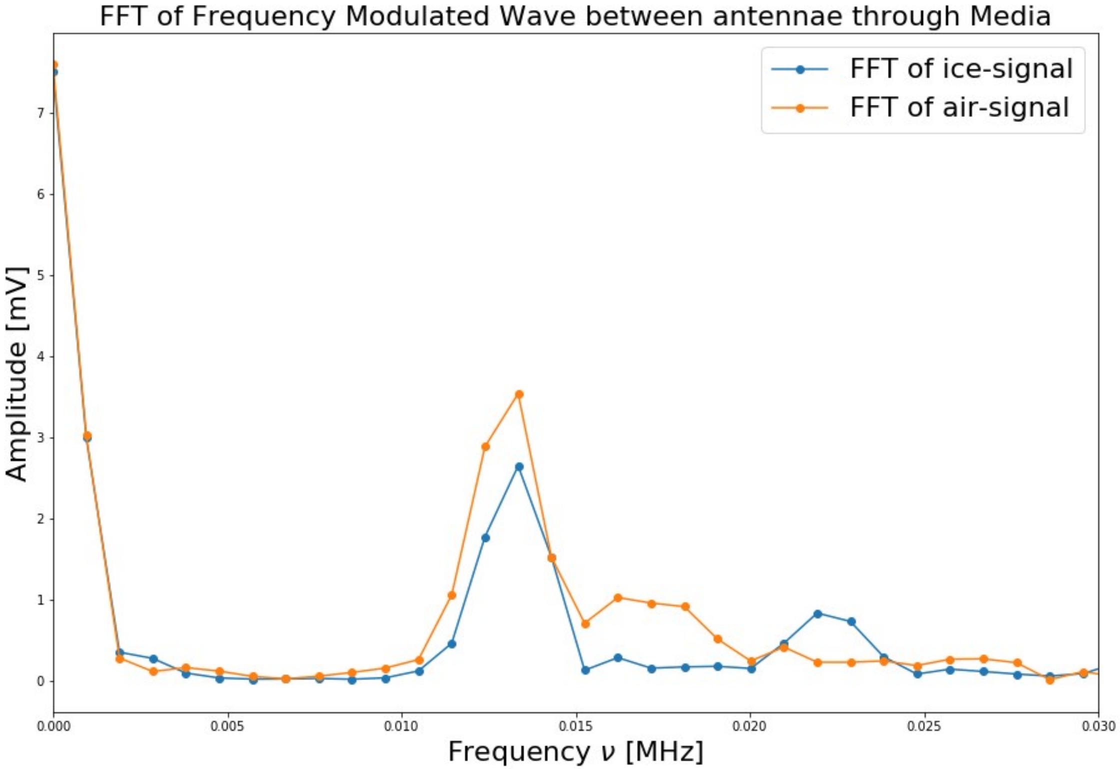
3. Mix received signal with control signal

4. Take Fourier spectrum of mixed signal → peak corresponds to antenna separation
→ can use known distance to calculate the permittivity





FMCW Method – Lab Measurements

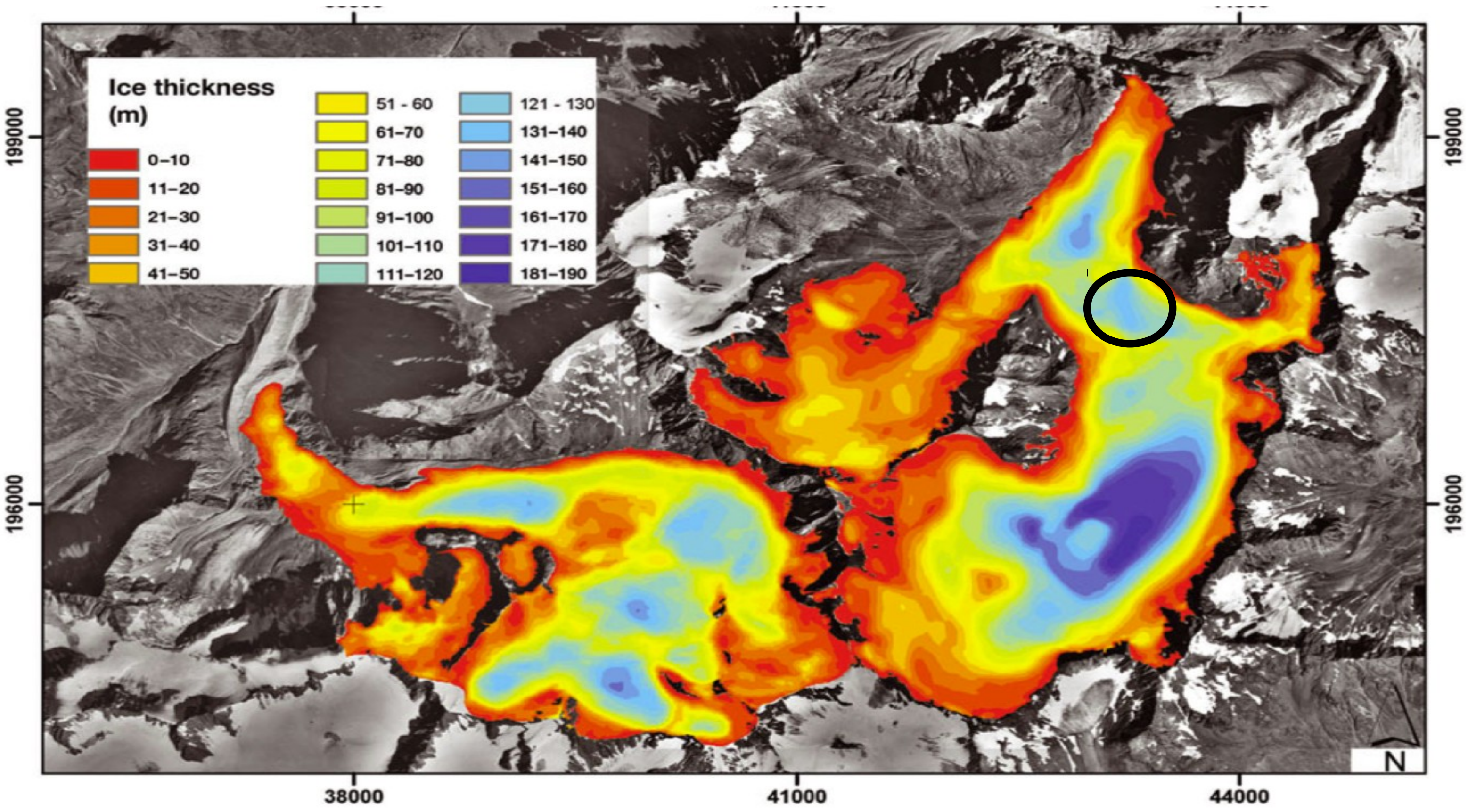


Bandwidth: 50 MHz
Distance: 10 metres

Refractive Index measured with frequency shift
n ~ 1.8

Attenuation Coefficient measured from peak difference: α ~ 0.01 dB/m

Field Test Location

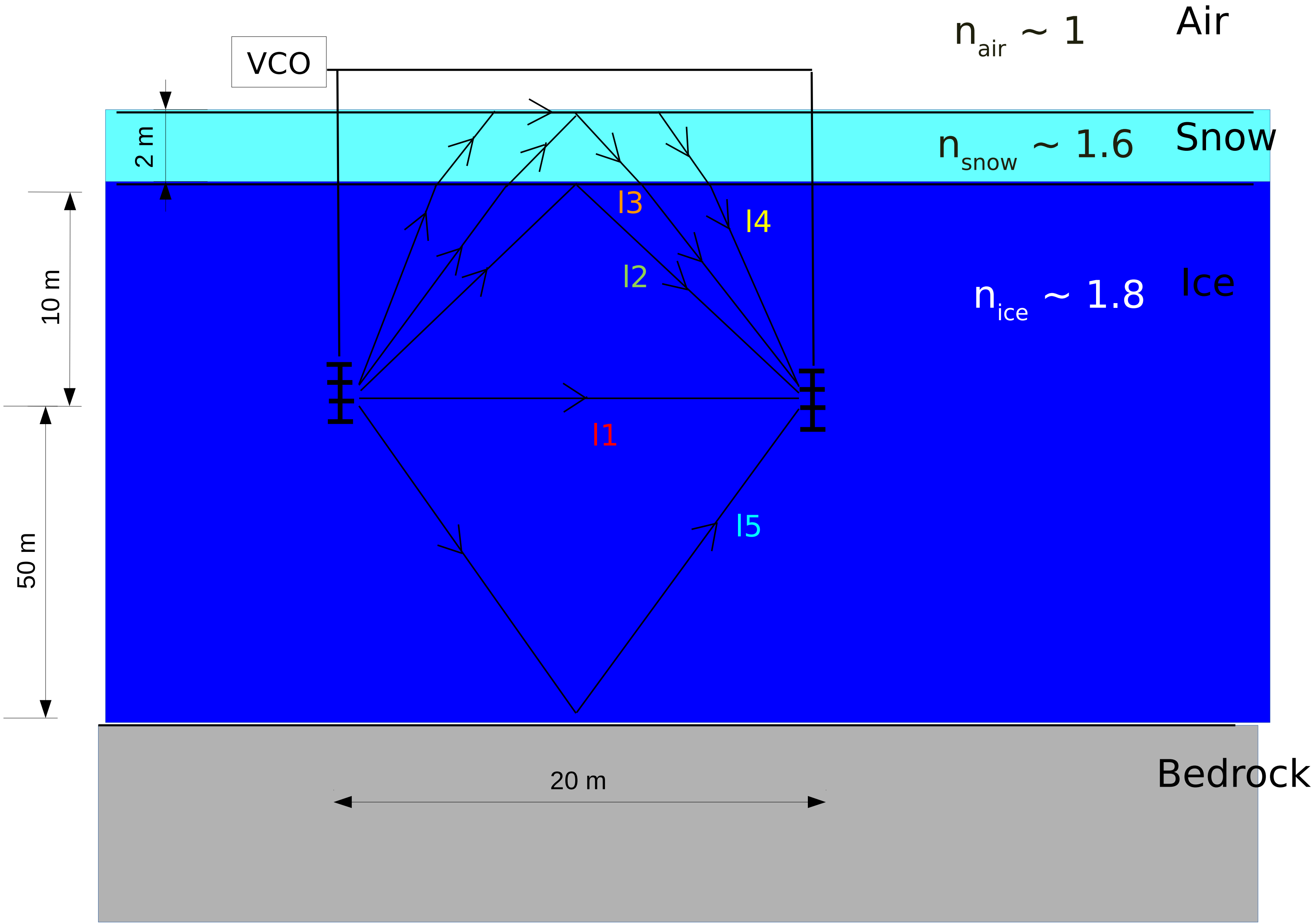


Fischer and Kuhn, 2013

First field test in February, 2019, Mittelbergferner Glacier, in the Austrian Tyrol

Glacier's depth has been mapped using low-frequency radar → 100 metres of depth is considered sufficient for our test

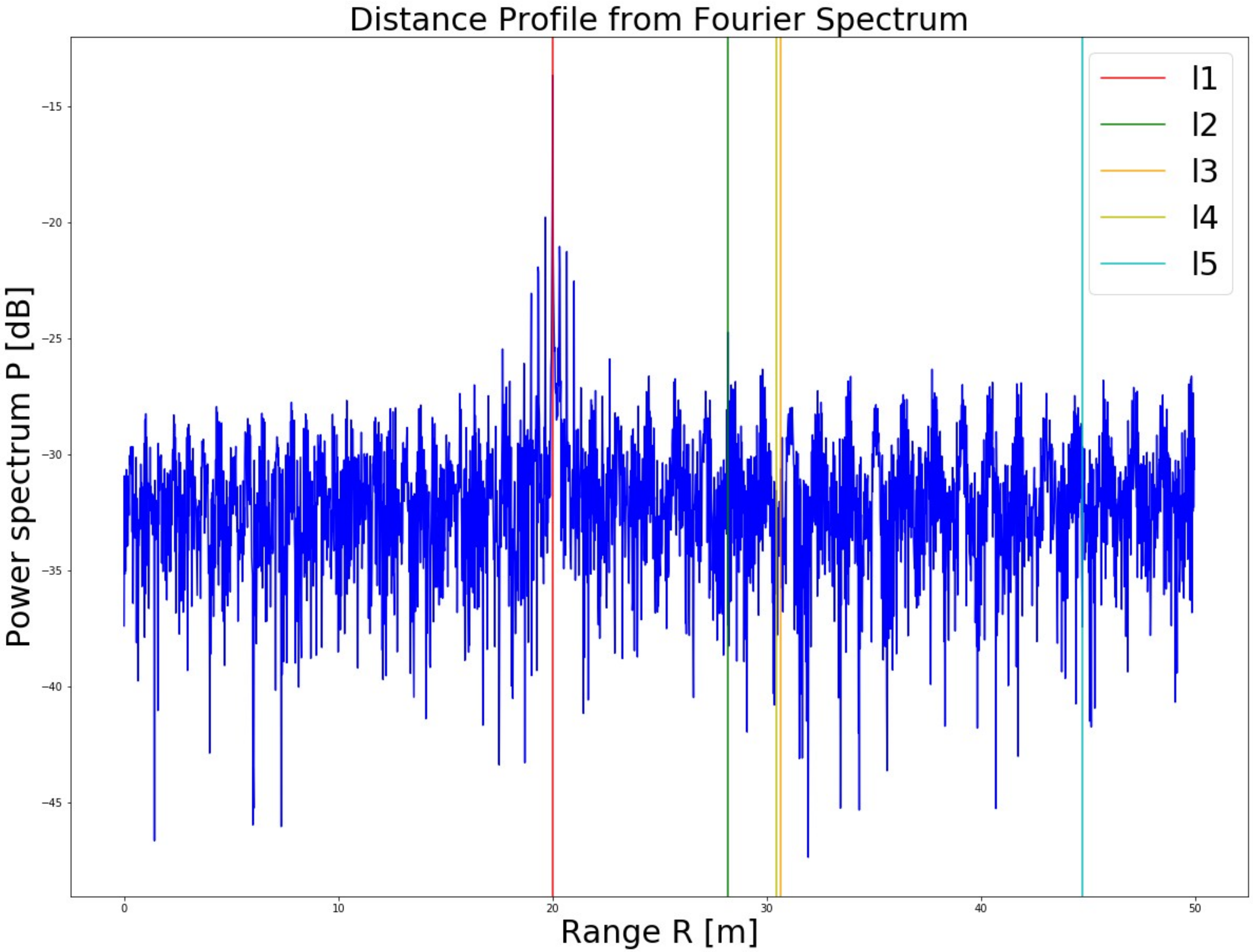
Simulations for Field Test



Modulations

f_{min} = 600 MHz, Bandwidth = 100 MHz, T = 1 ms

$$R = \frac{nB}{Tc} \Delta f$$



Direct transmission peak easily distinguishable

Reflection peaks significantly weaker

I3, I4 and I5 indistinguisable from background

Modulations

f_{min} = 600 MHz, Bandwidth = 100 MHz, T = 1 ms

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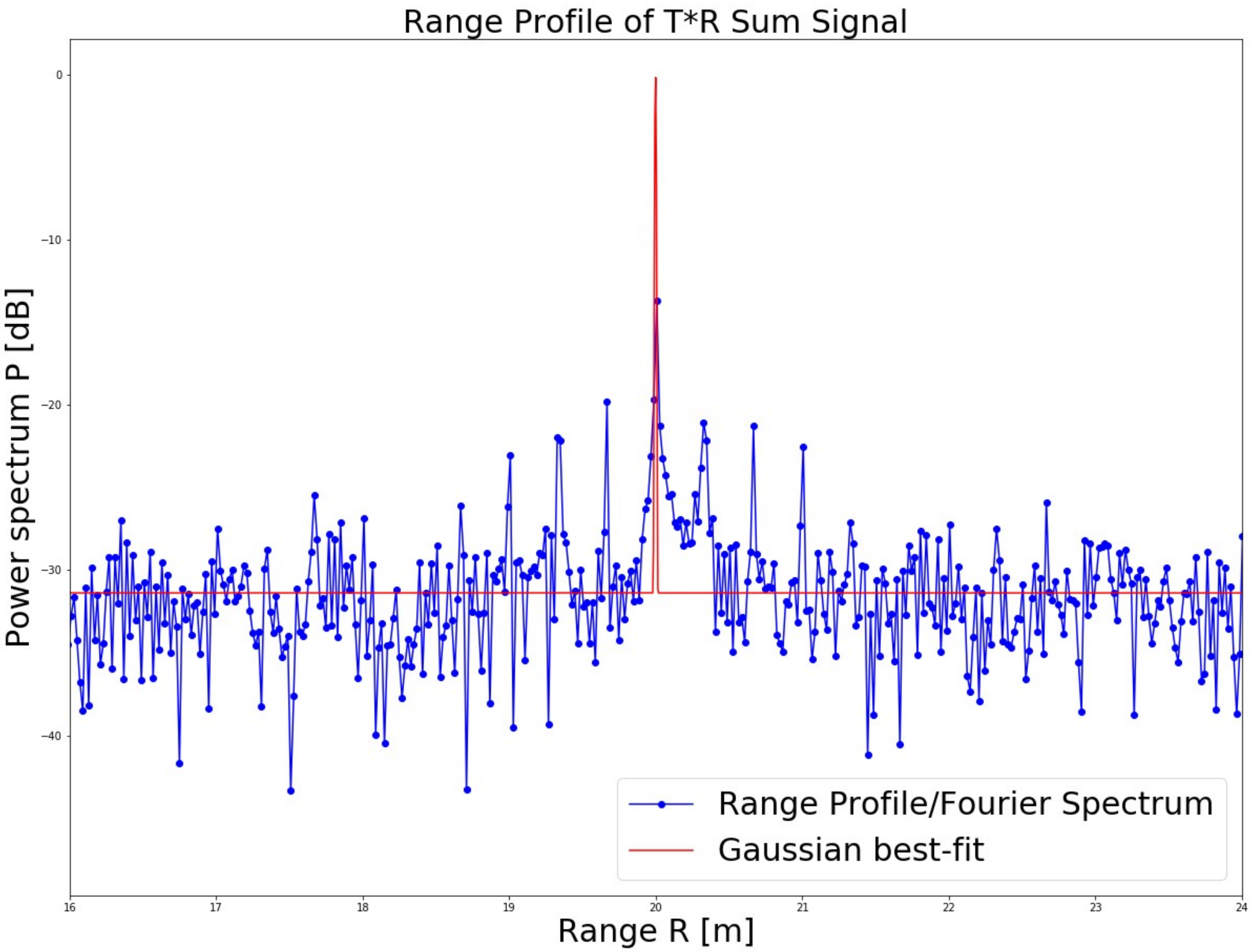


Distance resolution within 10 %

Summary

Knowledge of Ice Permittivity and Attenuation essential for IceMole

Detectable range of $1m^2$ obstacle using 100 mW spiral antenna:

- 120 – 220 m at 500 MHz (30 cm diameter)
- 100 – 160 m at 1 GHz (15 cm diameter)

Detectable range of water pocket:

- 400 – 800 m at 500 MHz
- 300 – 600 m at 1 GHz

FMCW to be used to measure permittivity and attenuation across depth and frequencies

In-ice reflections and scattering unlikely to cause problems for February field test

Many technical challenges lie ahead

Questions?

Backup: Glacier vs Enceladus

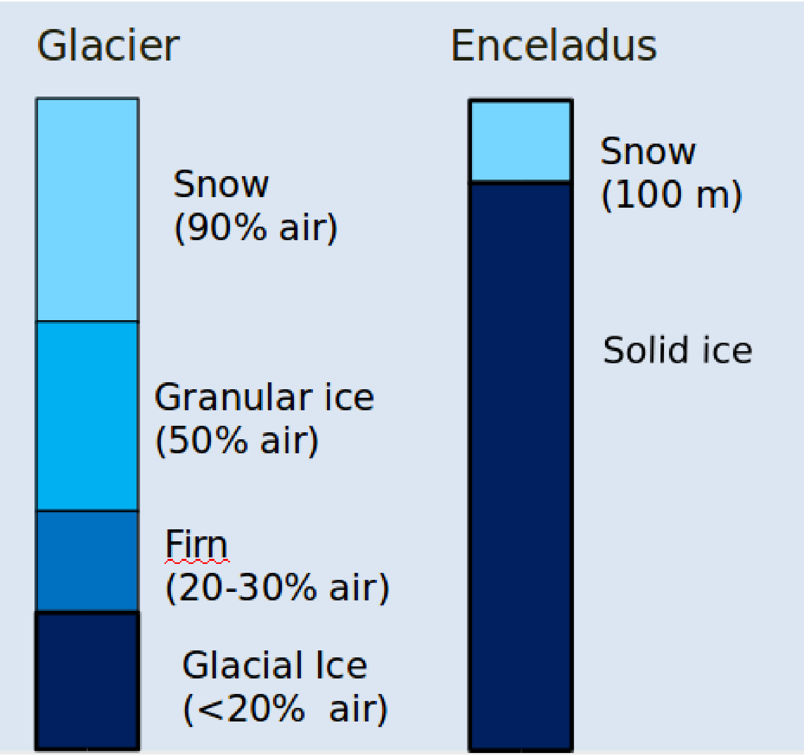
Much colder temperatures on Enceladus than anywhere on Earth

Unlikely to have water content

Ice suspected to be much purer($\sigma < 1\ \mu\mathrm{Sm}^{-1}$) than on Earth

Homogenous (expect for surface layer of geyser 'snow')

Ice properties:	Alpine Glacier	Enceladus
Phase	Hexagonal crystals (I_h)	Hexagonal crystals (I_h)
Temperature	-10 °C	-200 °C
Density	30 - 900 kg/m³	mainly 920 kg/m³
Layering	Complex stratification	2 layers
Water content	Yes	No
Purity	Impure water ice	Pure water ice



Backup Slides: Distance Measurements