

Enceladus Explorer

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



Participant Talk for Astroparticle School, Obertrubach-Bärnfels

9th of October, 2018



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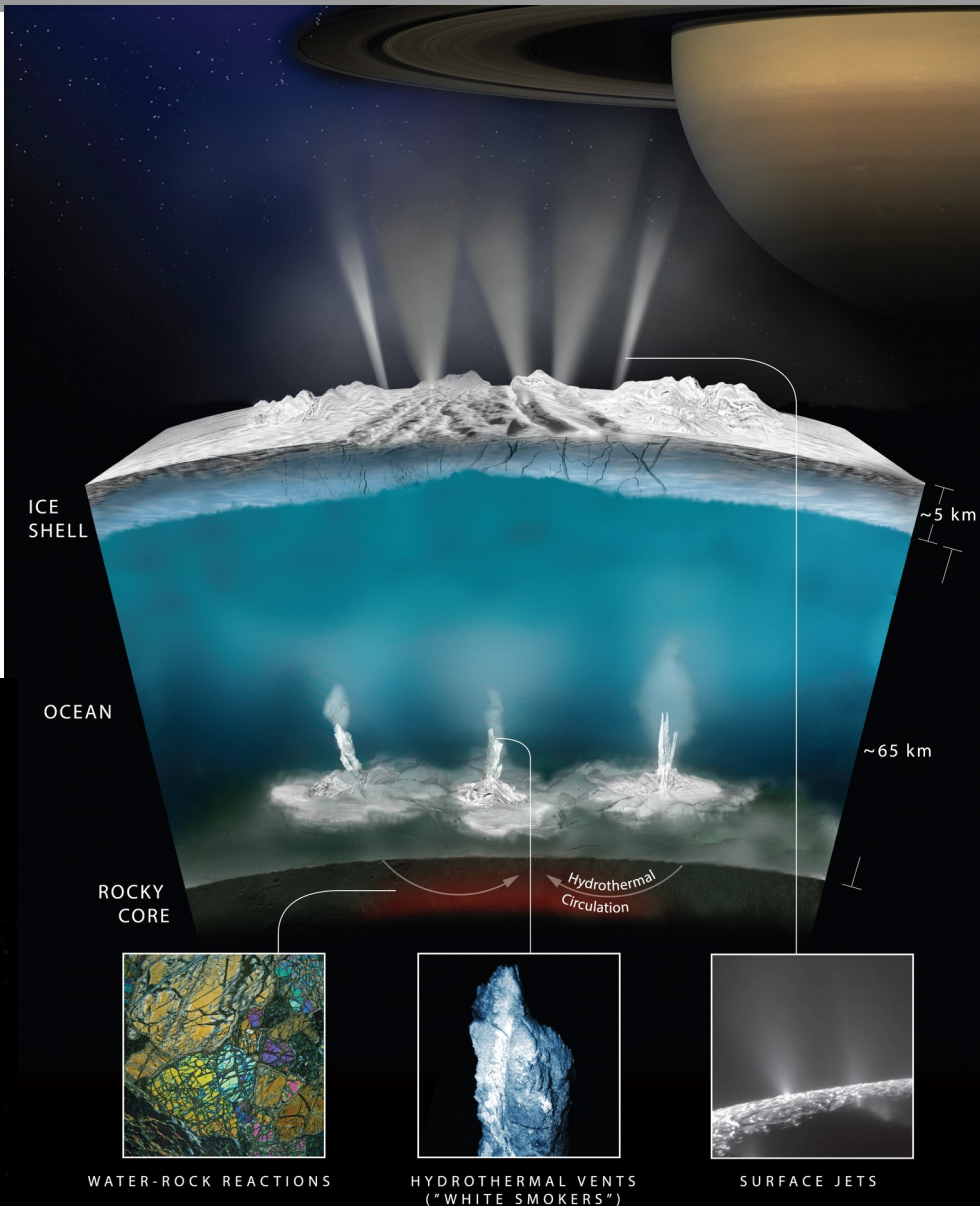
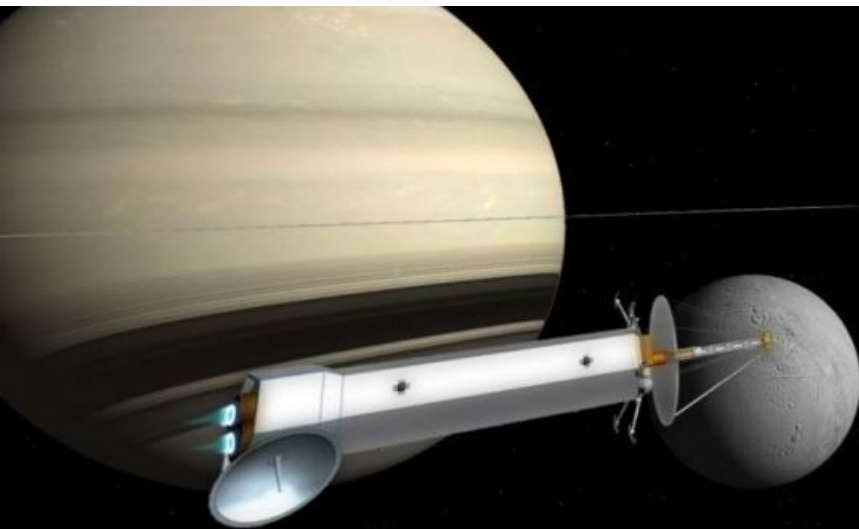
Enceladus Explorer

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'

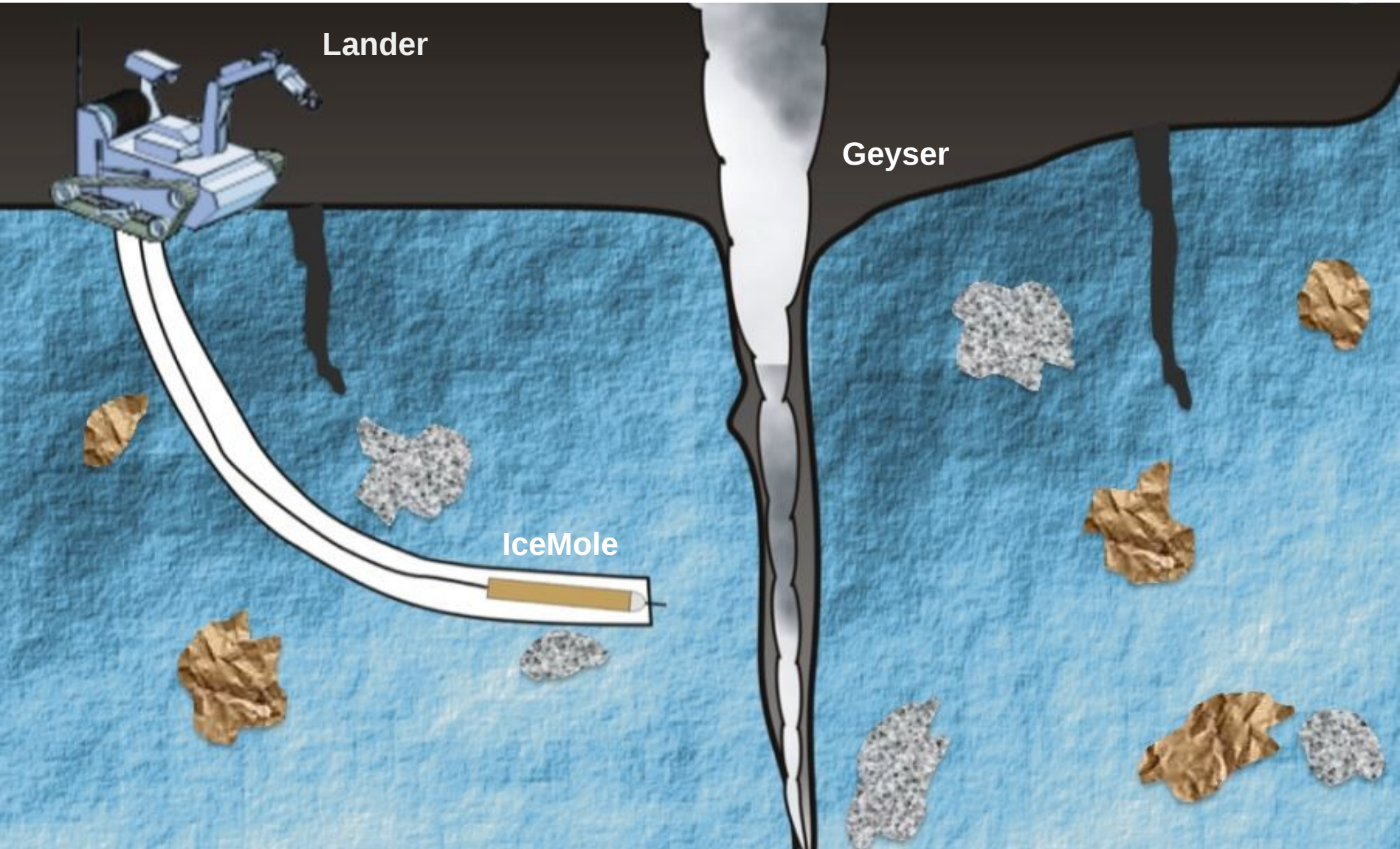
The IceMole would melt through ~100 metres of ice towards a pocket of liquid water

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



ENCELADUS

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:

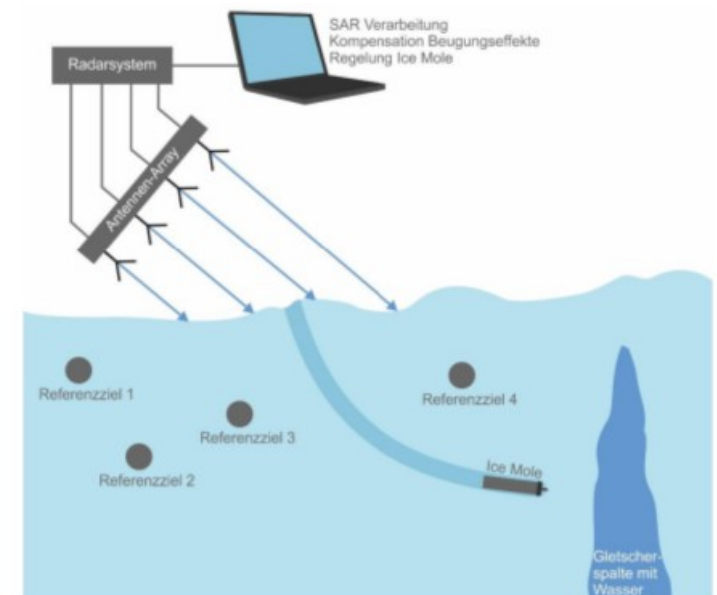
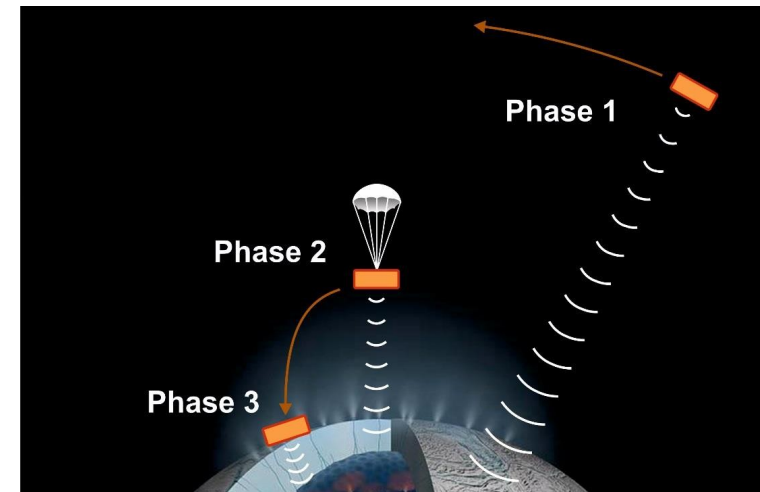
The development of ice-penetrating radar systems for orbiter, lander and IceMole to achieve:

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)

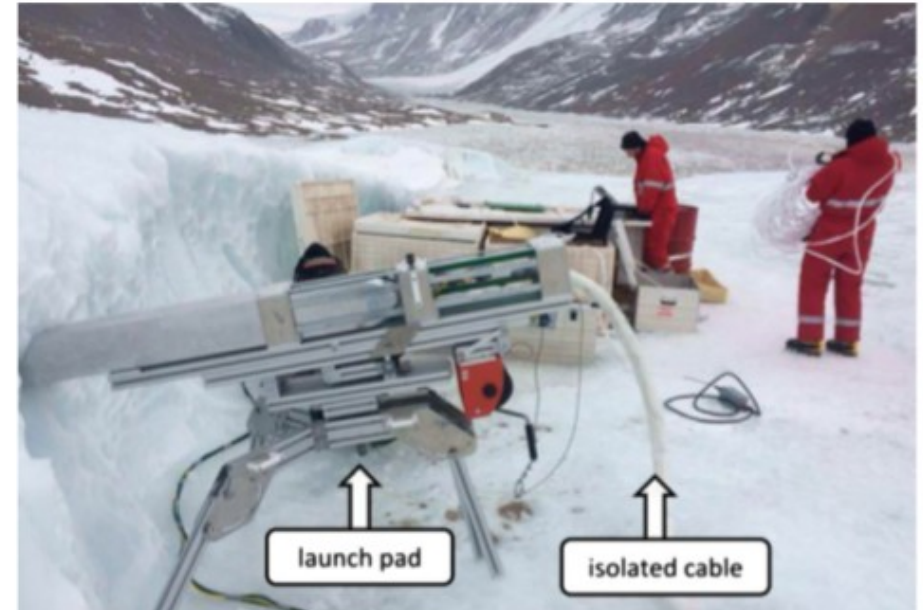
- Identification of obstacles: meteorites, crevasses, thick soil belts
- SAR based positioning of IceMole relative to lander
- Identification of Water Pocket from IceMole



IceMole Prototype

Current Prototype:

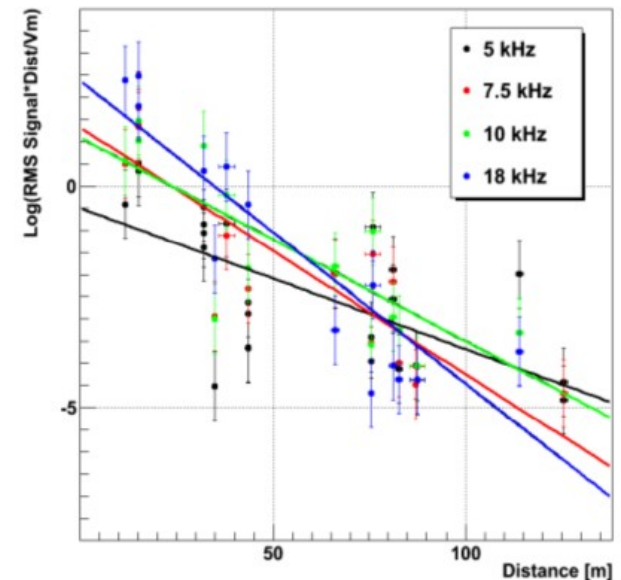
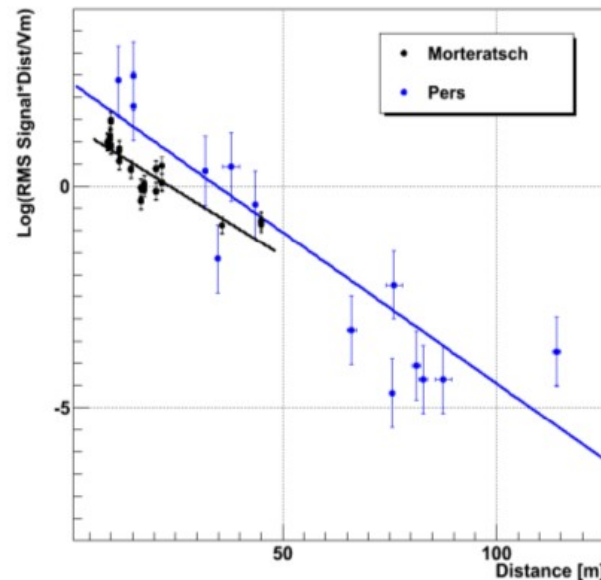
- Geometry: 15cm x 15 cm x 200 cm (prototype)
- Weight: 60 kg
- Melting Power: 1 kW (to be supplied by RTG on lander)
- Melting Speed: 1 metre/hour



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

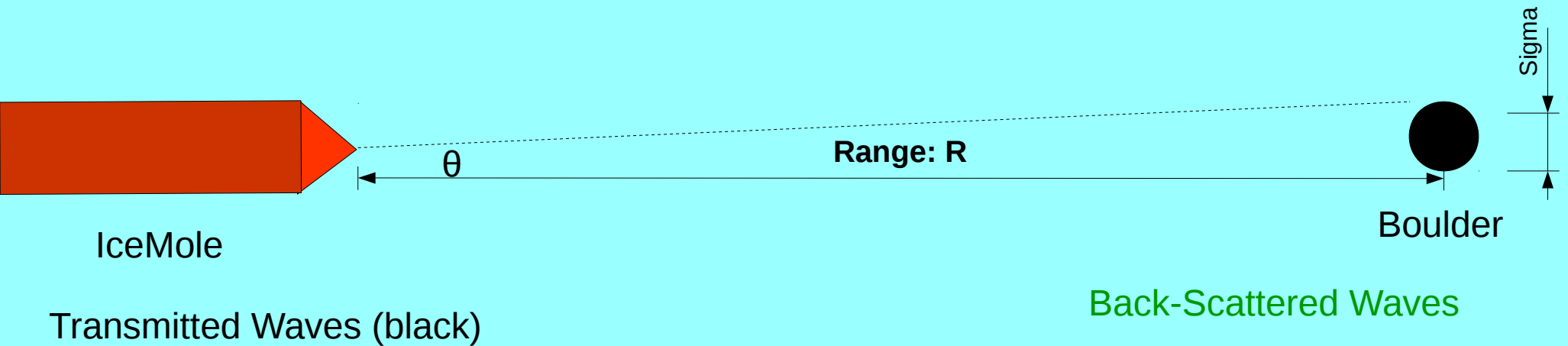
$$P_R = \frac{P_T G^2 \lambda^2 \sigma L}{(4\pi R^2)^2} \propto \frac{1}{R^4}$$

- 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

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

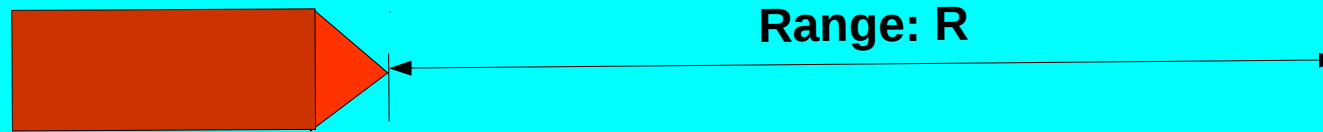


Identification of Water Pocket

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

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

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



IceMole

Range: R

Ice $\epsilon_r = 3.1$

Salt Water $\epsilon_r \sim 80$

Dielectric Properties of Ice

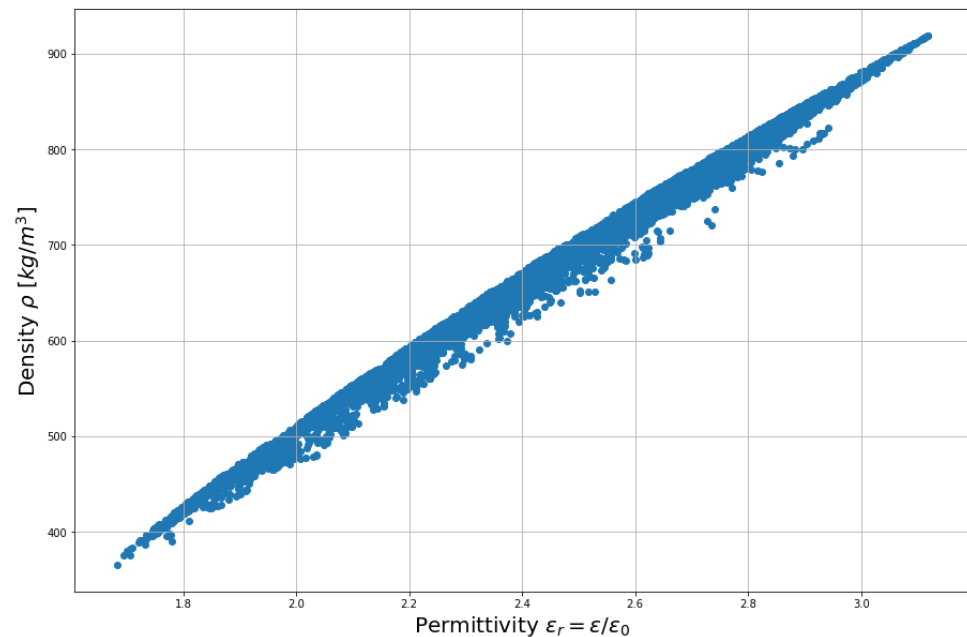
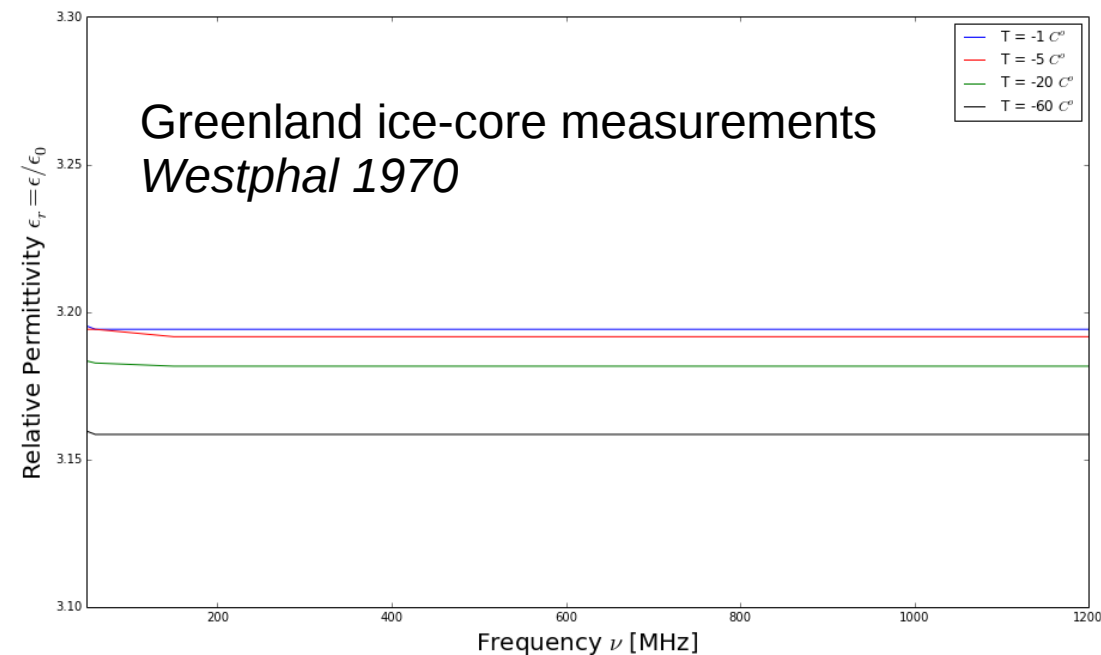
To gauge distance to obstacle with radar (amplitude or frequency modulated) requires knowledge of relative permittivity ϵ_r across the used bandwidth

Permittivity ϵ_r is strongly linear with ice density - *Wilhelms & Frank (2018)*

Should not vary much across radio frequencies

Moderate temperature dependence

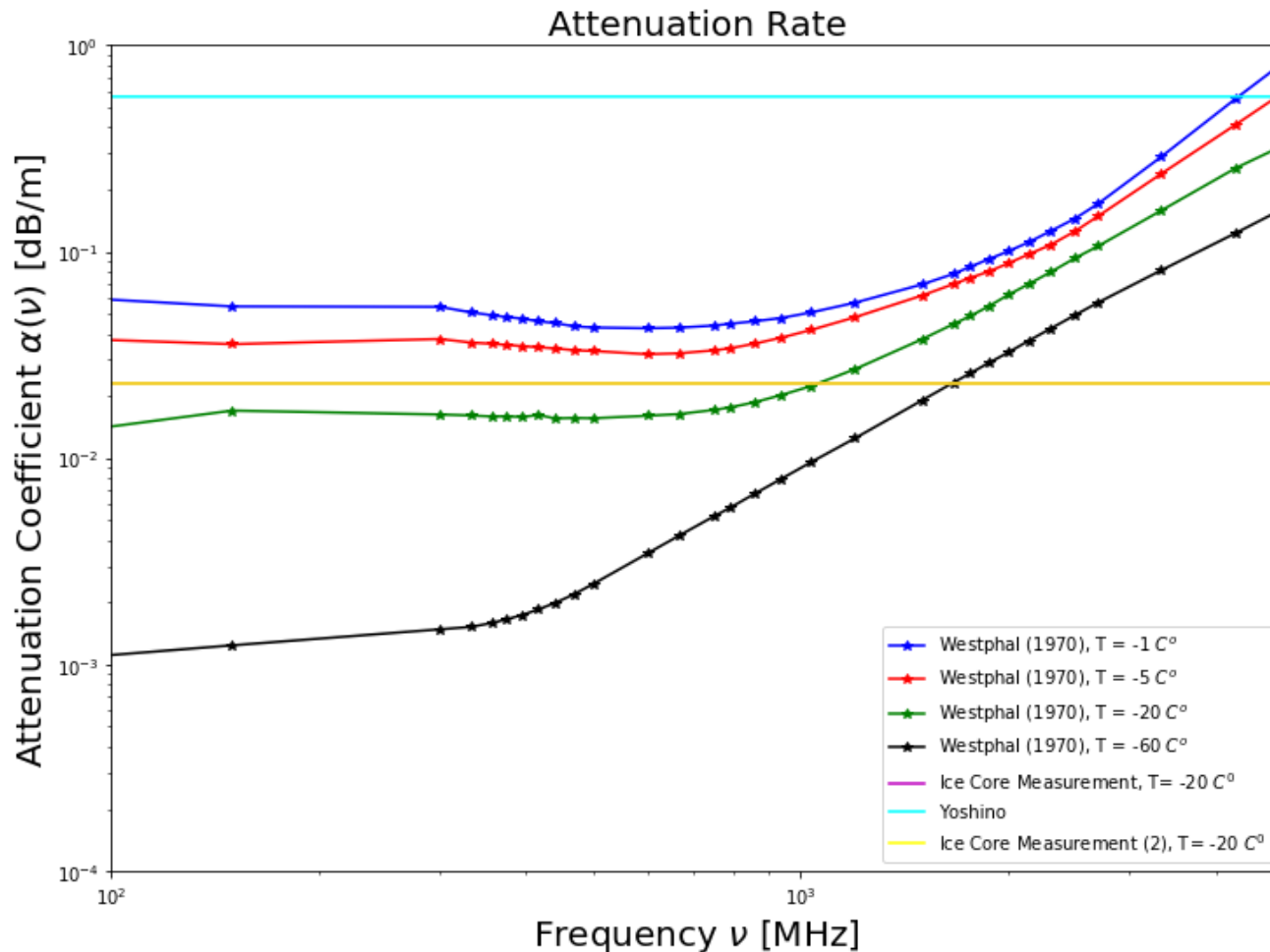
At solid ice density $\rho_{ice} = 920 \text{ kg/m}^3 \rightarrow \epsilon_{r,ice} \sim 3.2$



Dielectric Properties of Ice

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

At solid ice density $\rho_{ice} = 920 \text{ kg/m}^3 \rightarrow \epsilon_{r,ice} \sim 3.2 \rightarrow$ relatively constant across radio frequencies



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

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*)

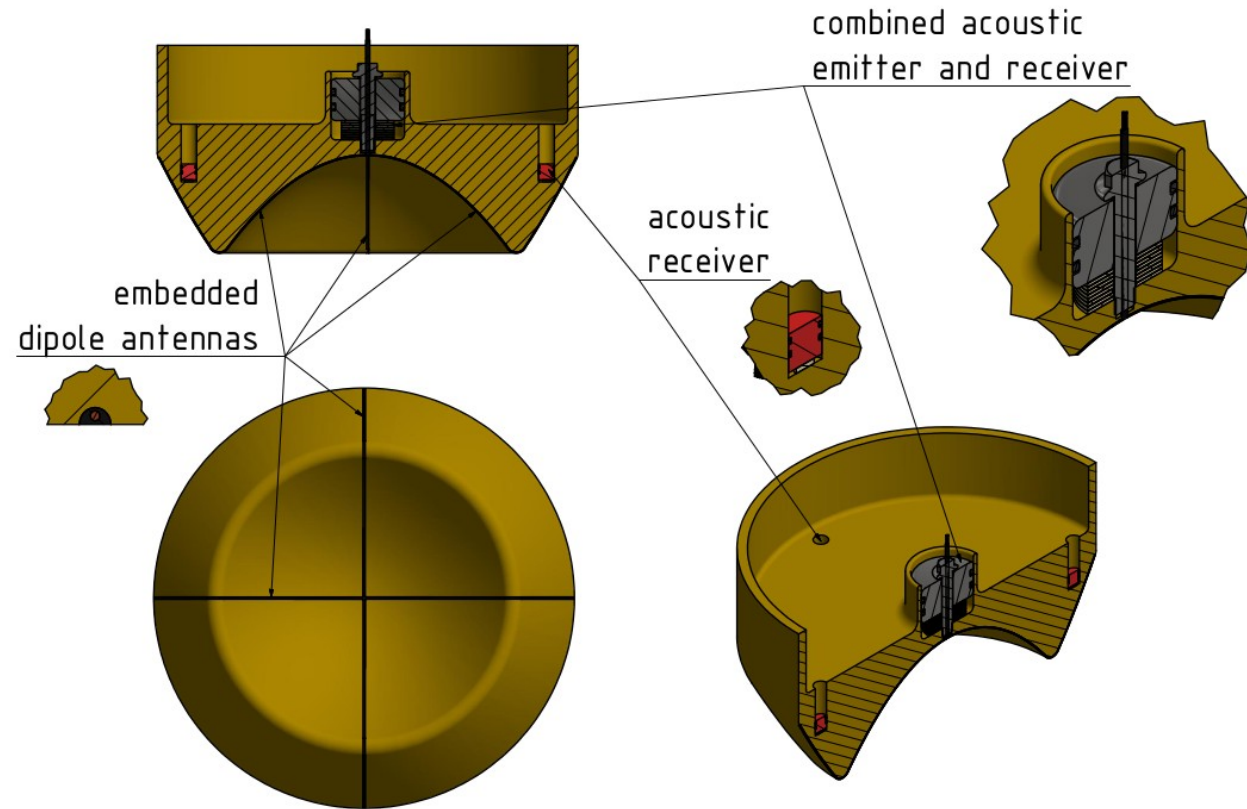
Challenges for Radar Sounding

Dimensions of IceMole require use of high frequency waves: ($\lambda \sim 30$ cm, $f \sim 1$ 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

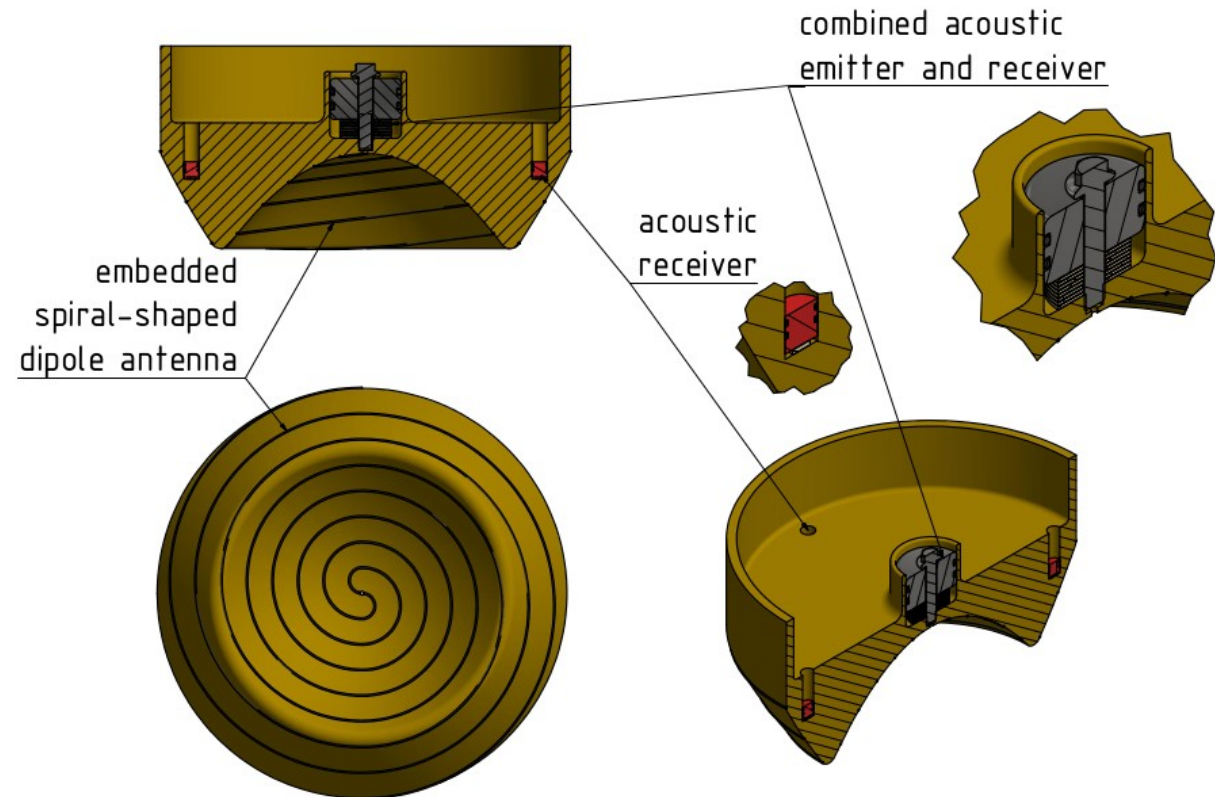
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Proposed design (spiral antenna)

Aachen University

Glacier vs Enceladus

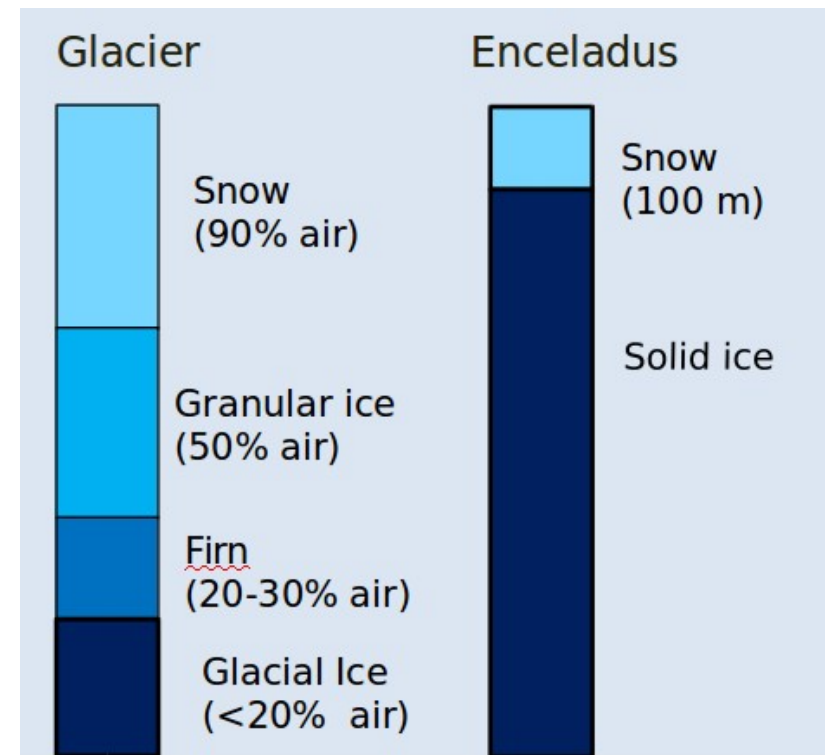
Much colder temperatures on Enceladus than anywhere on Earth

Unlikely to have water content

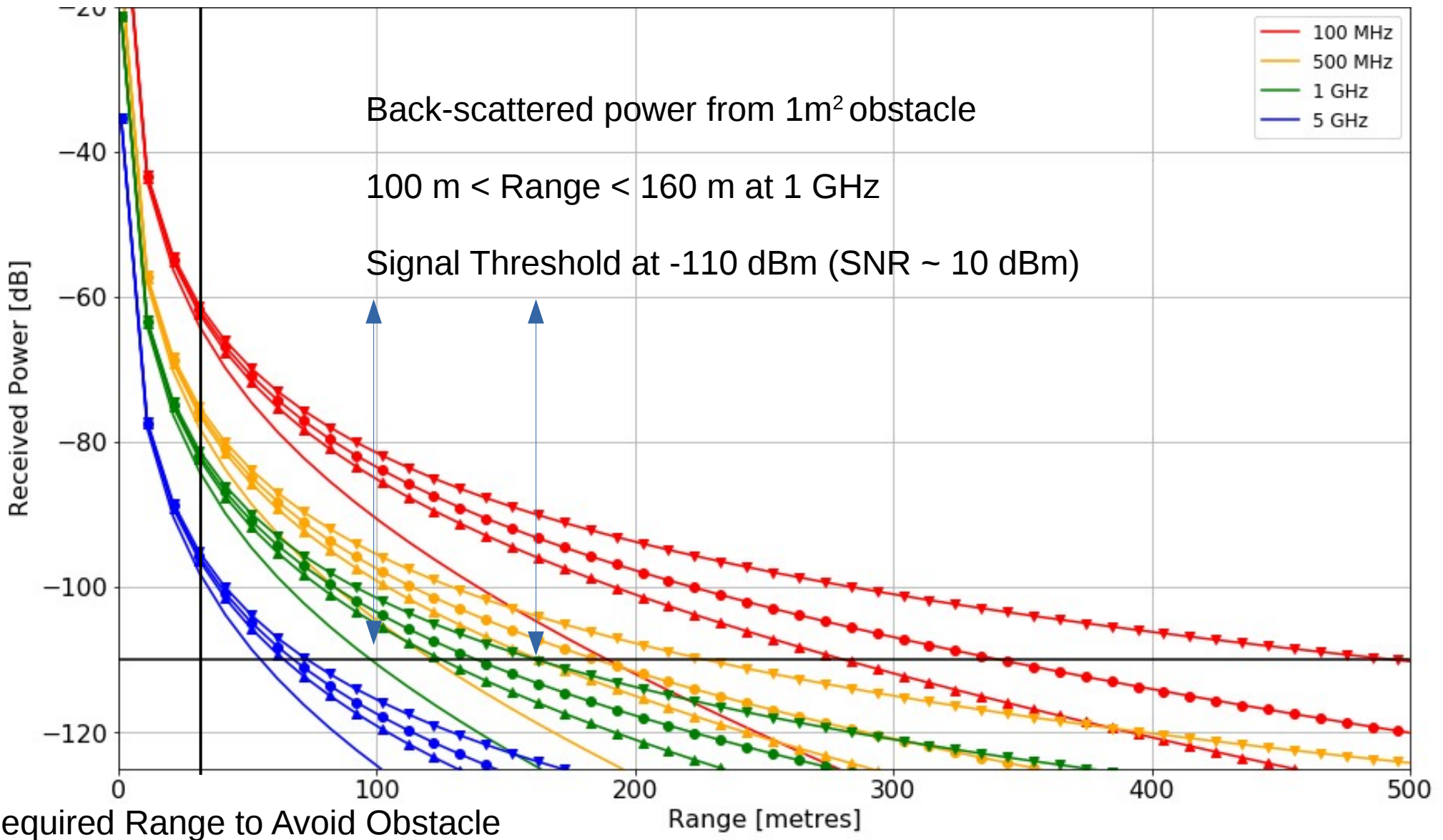
Ice suspected to be much purer ($\sigma < 1 \mu\text{Sm}^{-1}$) than on Earth

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

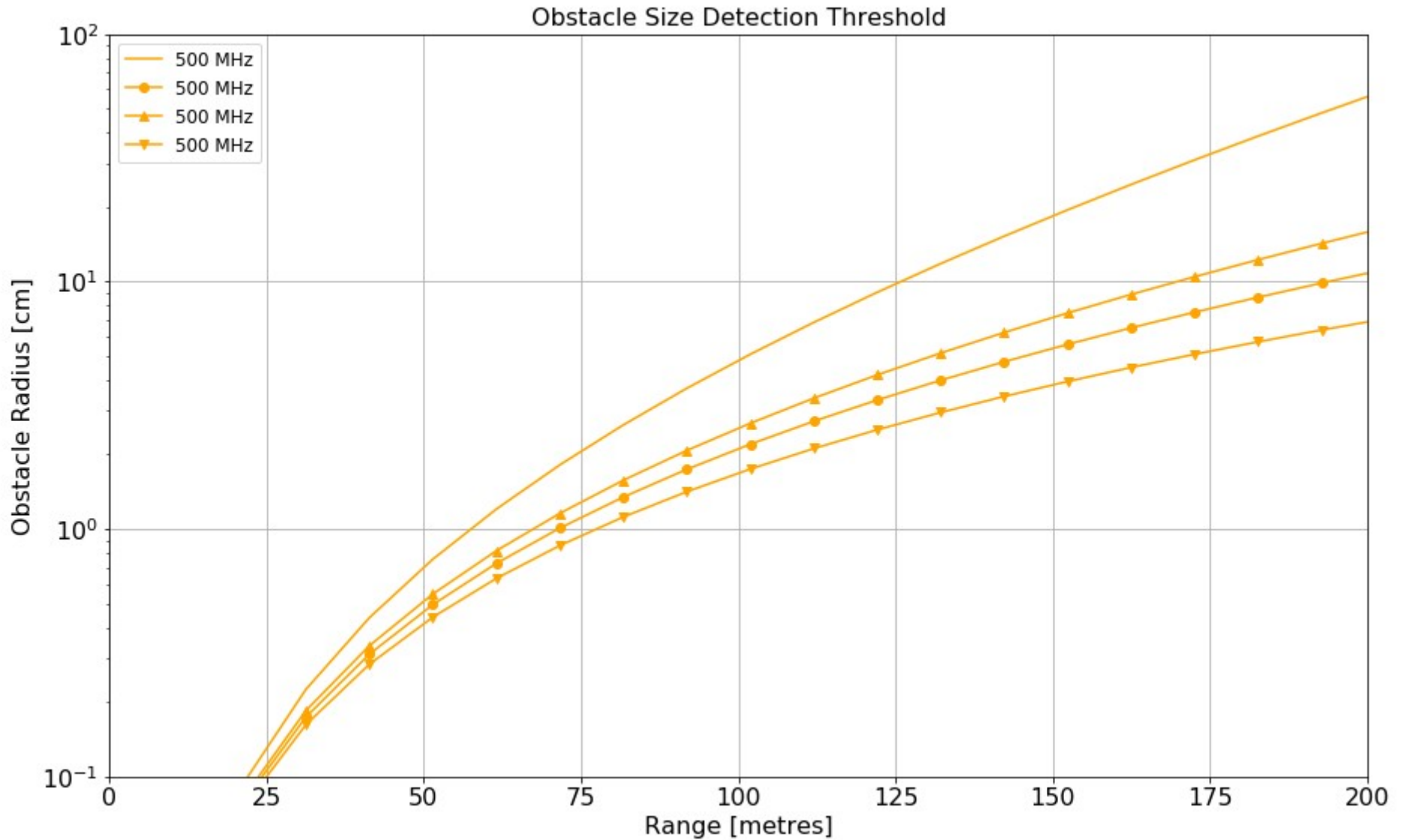
Ice properties:	Alpine Glacier	Enceladus
Phase	Hexagonal crystals (I_h)	Hexagonal crystals (I_h)
Temperature	-10 °C	-200 °C
Density	30 - 900 kg/m ³	mainly 920 kg/m ³
Layering	Complex stratification	2 layers
Water content	Yes	No
Purity	Impure water ice	Pure water ice



Radar Range



Radar Range



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

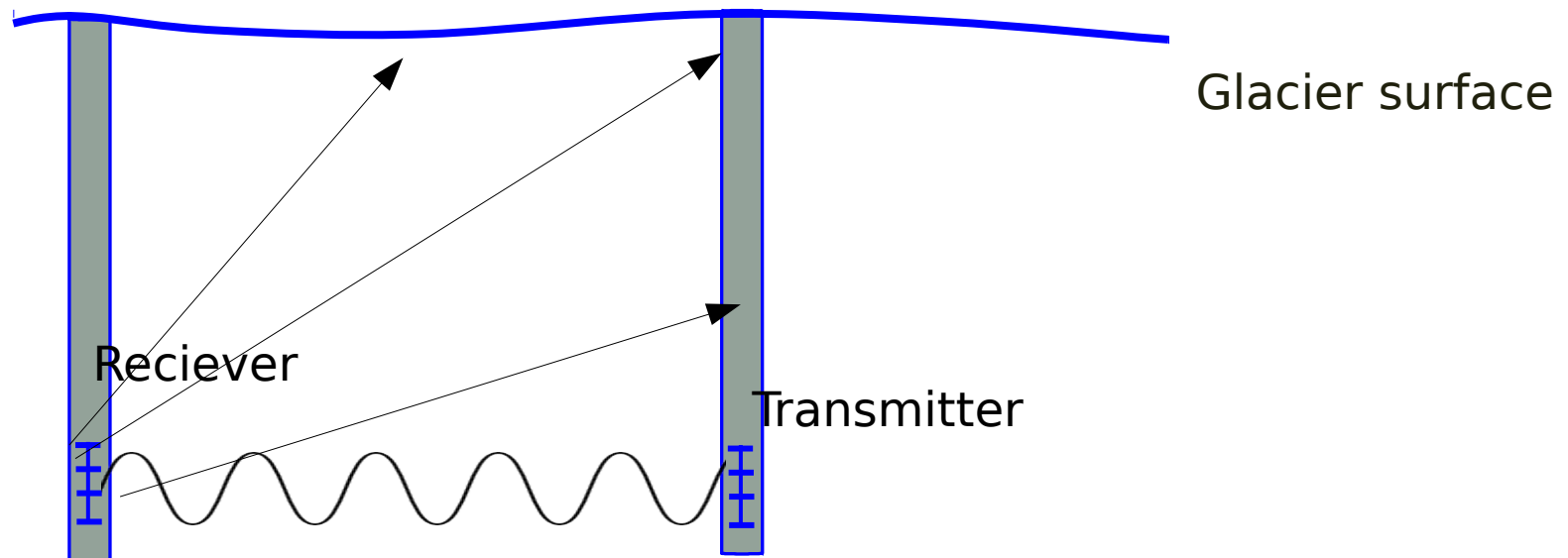
Method:

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



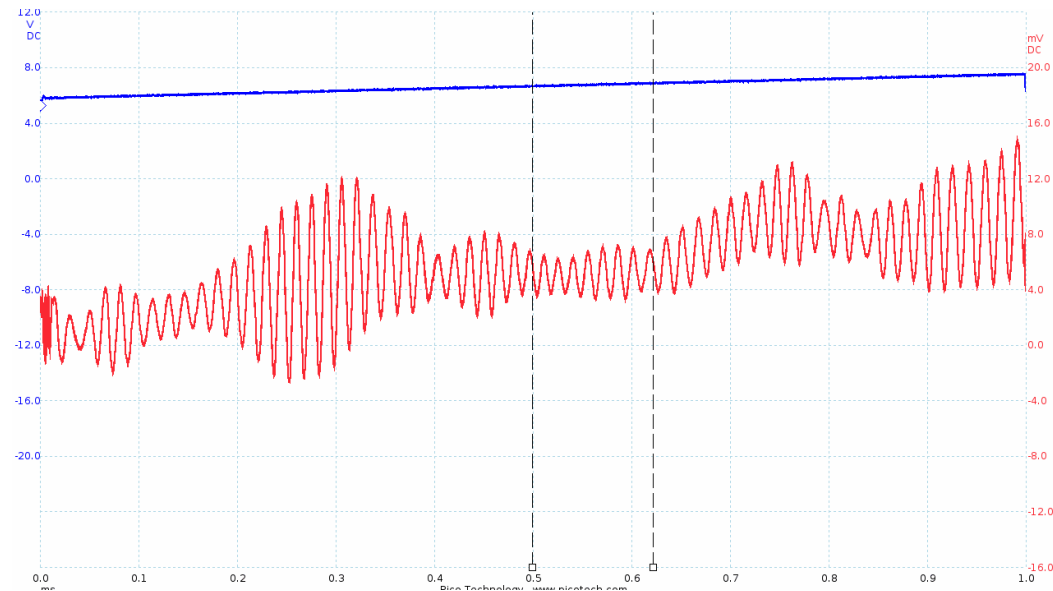
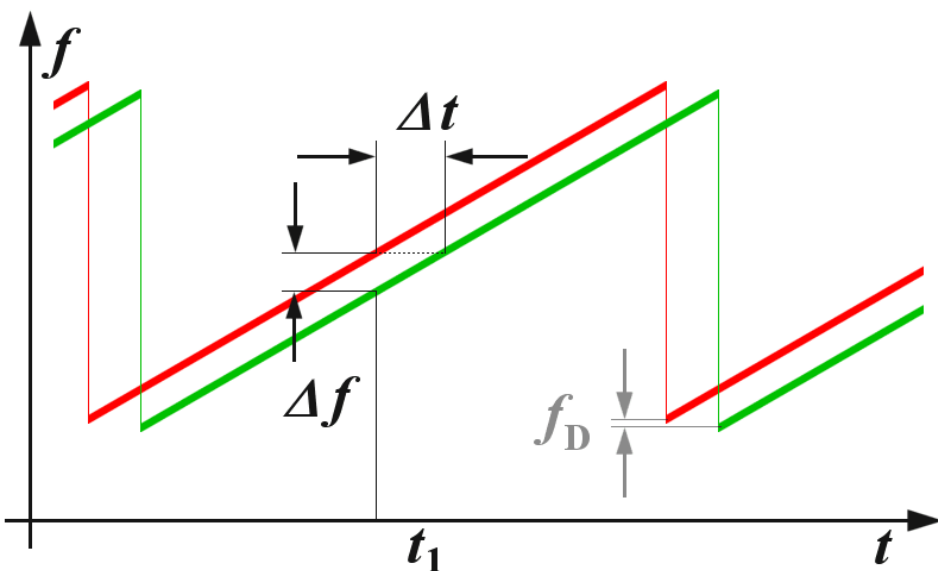
FMCW Method

Frequency-Modulated Continuous Wave Radar:

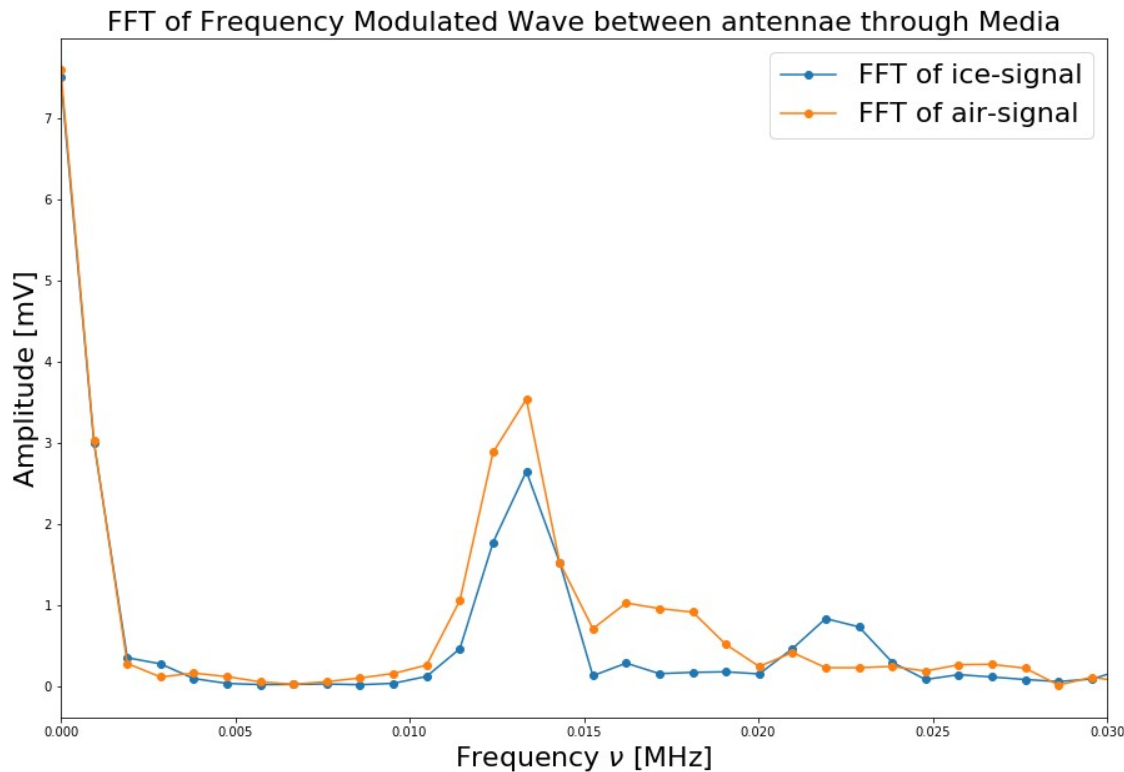
$$\Delta f = \frac{T c R}{n B} \quad R = \frac{n B}{T c} \Delta f \quad \Delta R = \frac{c}{2 n B}$$

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



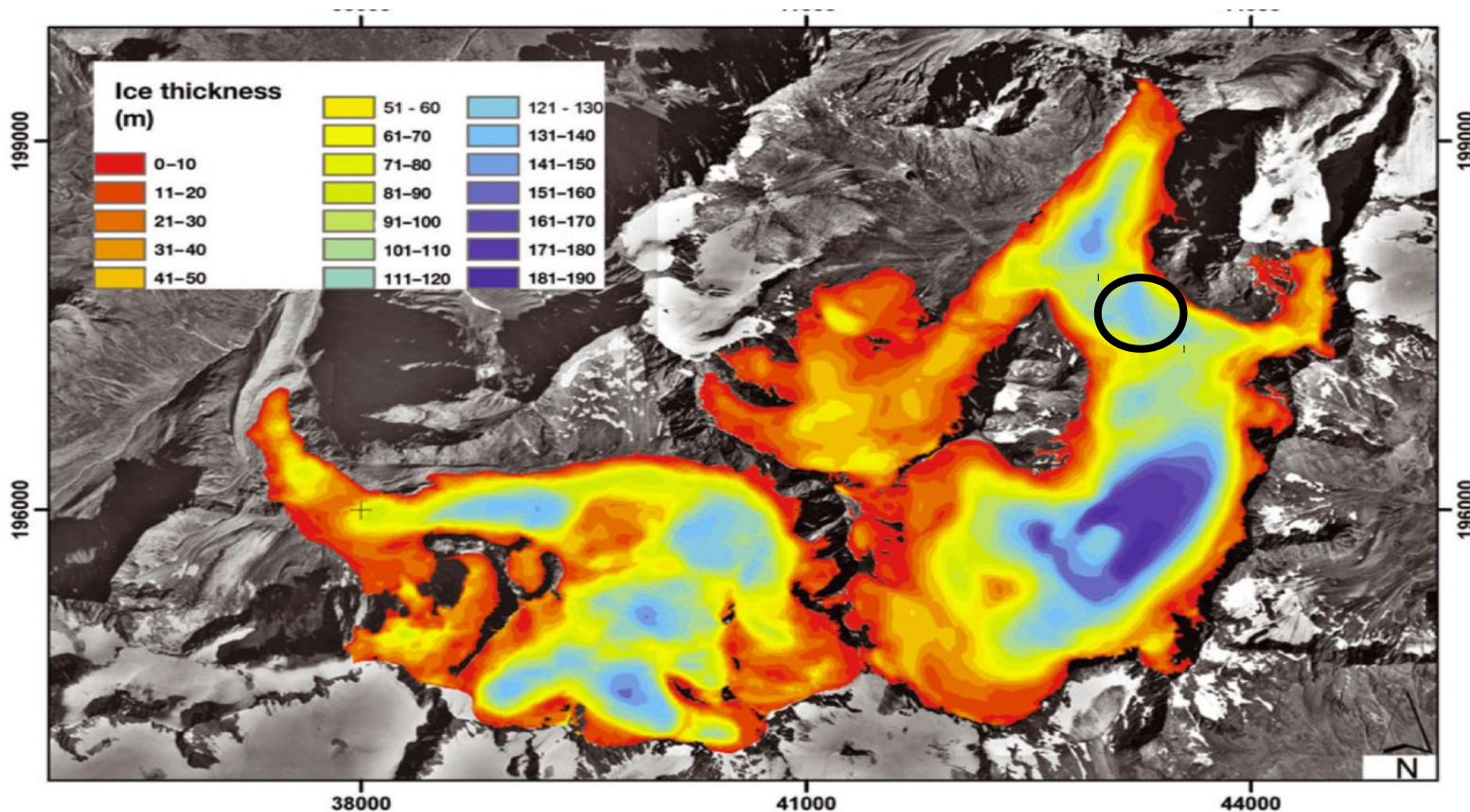
Bandwidth: 50 MHz
Distance: 10 metres

Refractive Index measured with frequency shift
 $n \sim 1.8$

Attenuation Coefficient measured from peak
difference: $\alpha \sim 0.01$ dB/m



Field Test Location

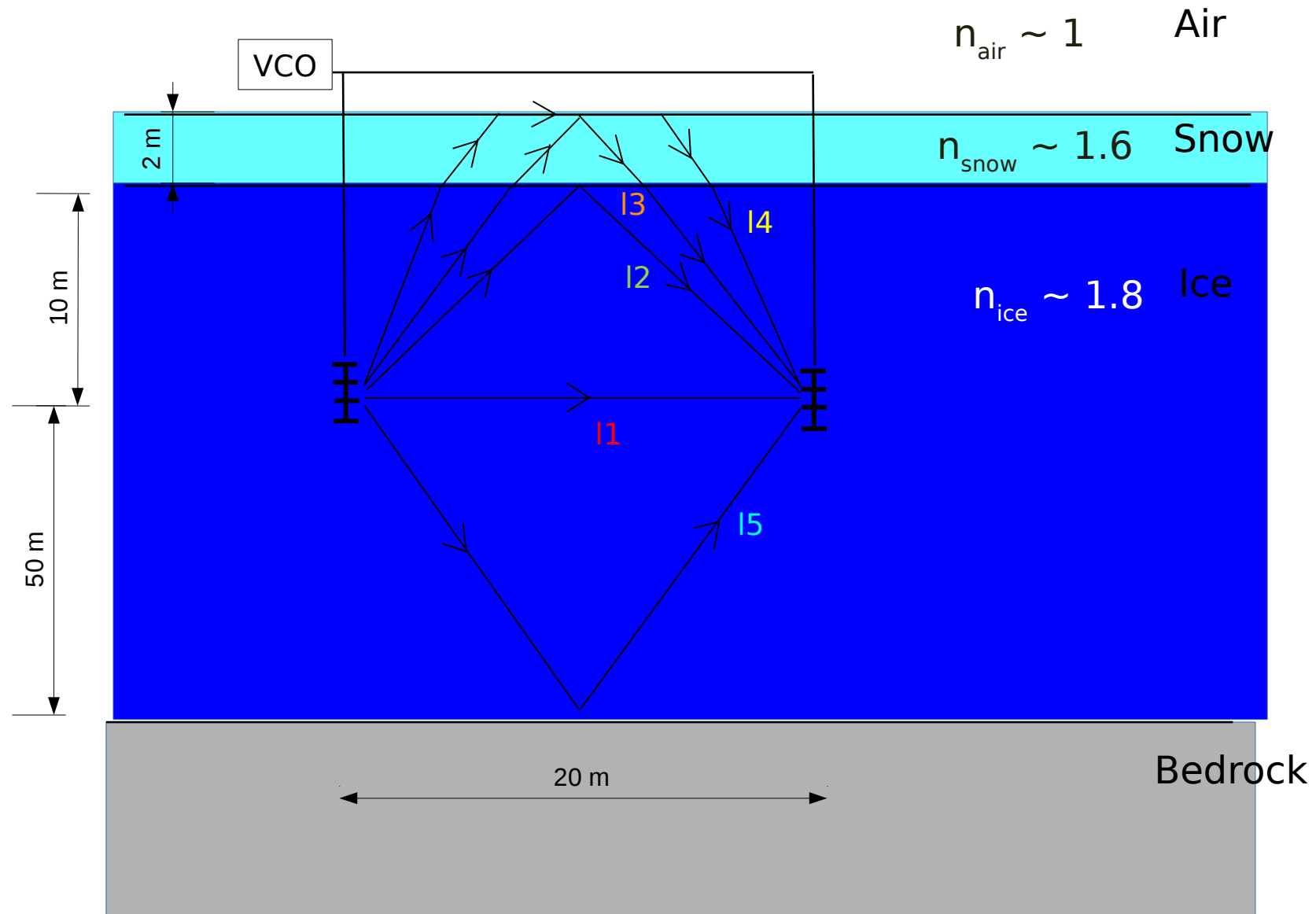


Fischer and Kuhn, 2013

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

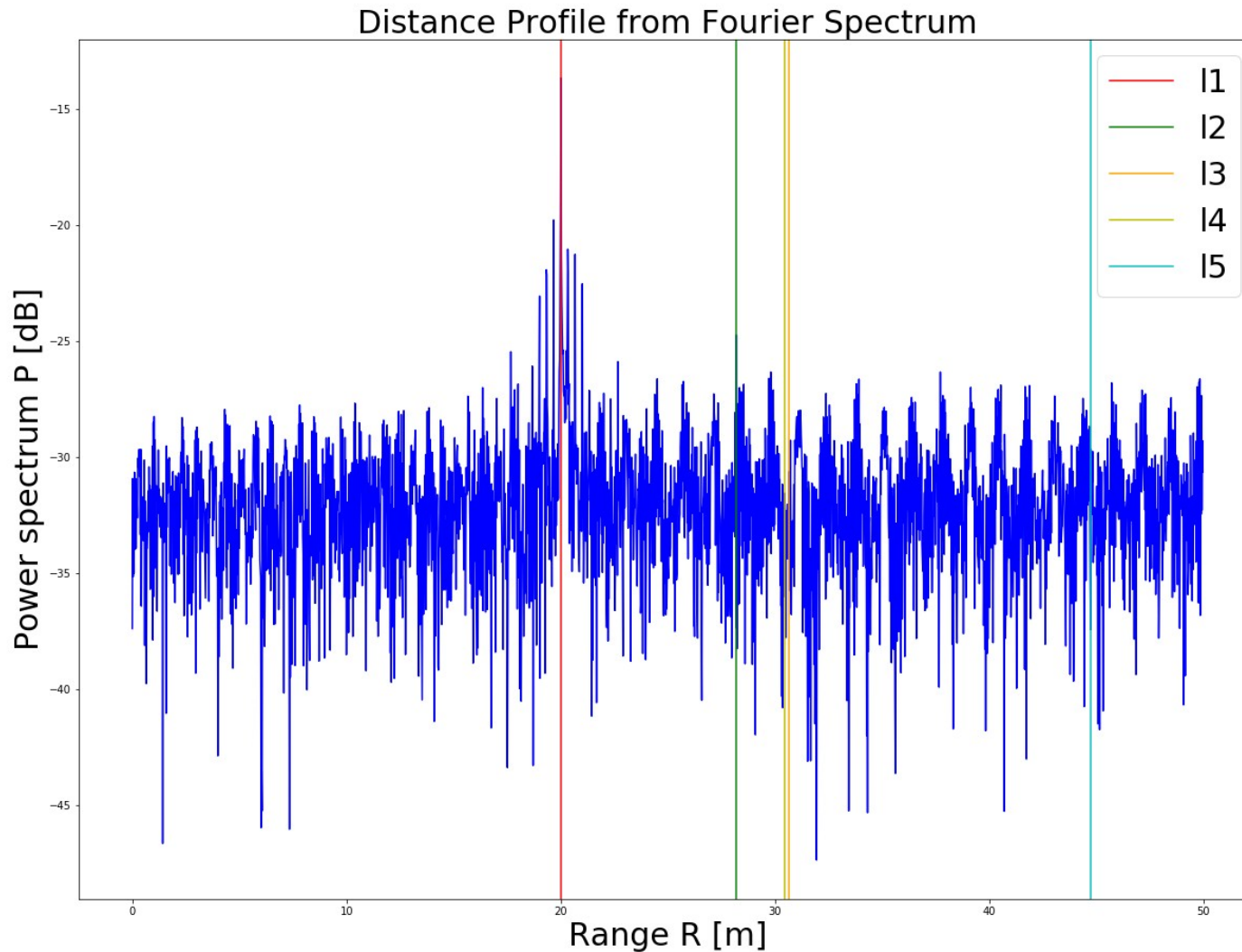
Simulations for Field Test



Modulations

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

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



Direct transmission peak
easily distinguishable

Reflection peaks
significantly weaker

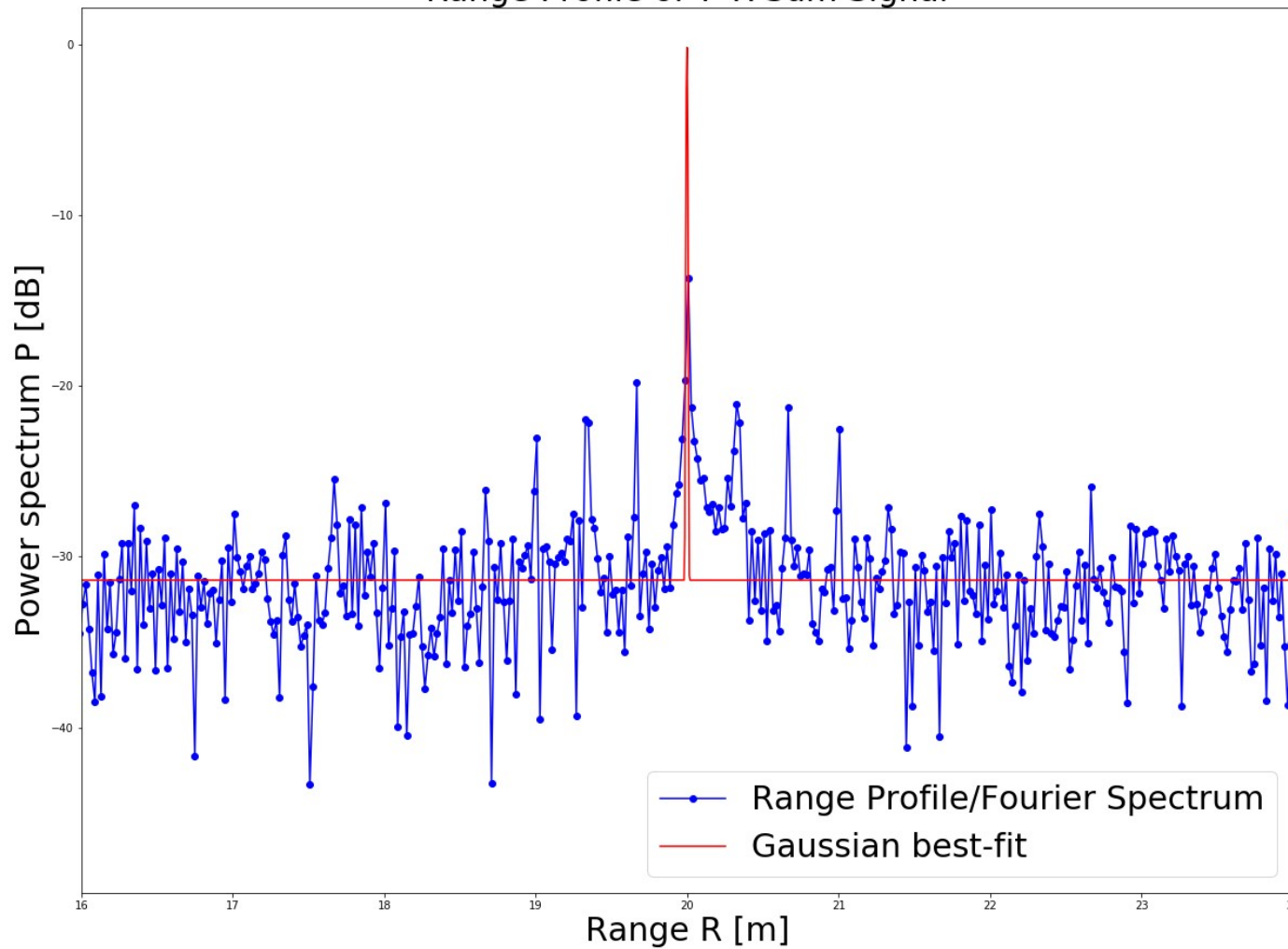
I3, I4 and I5
indistinguishable from
background

Modulations

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

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

Range Profile of T*R Sum Signal



Distance resolution
within 10 %

Summary

Knowledge of Ice Permittivity and Attenuation essential for IceMole

Detectable range of 1m² 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:

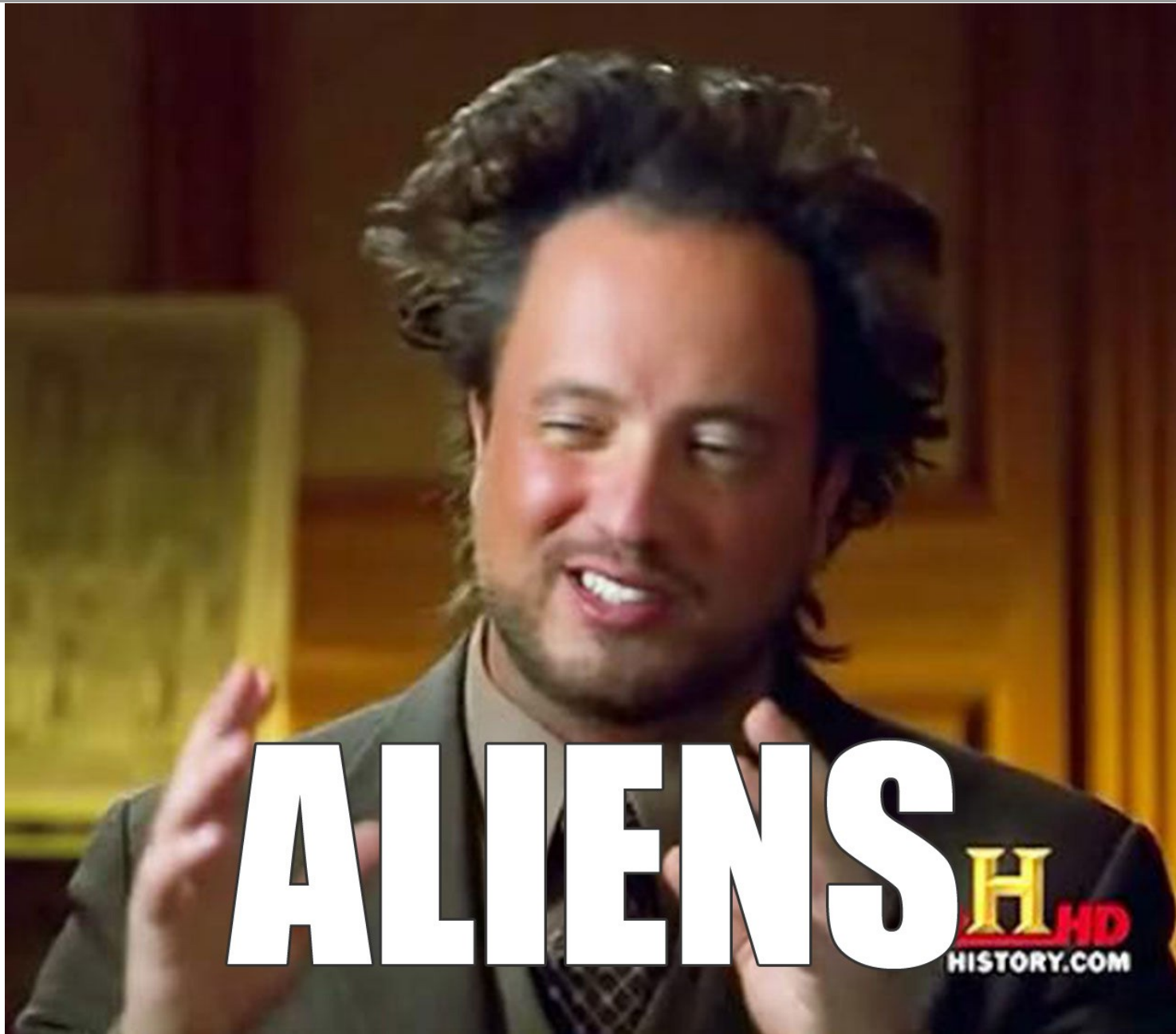
- 400 – 800 m at 500 MHz
- 300 – 600 m at 1 GHz

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 Slides: Distance Measurements

