Development of a permittivity sensor for melting probes to explore terrestrial and extra-terrestrial cryospheres

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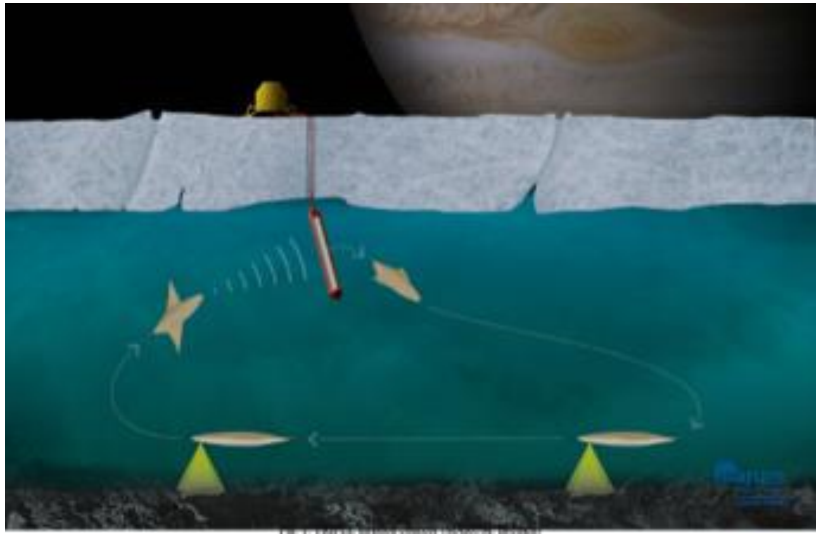
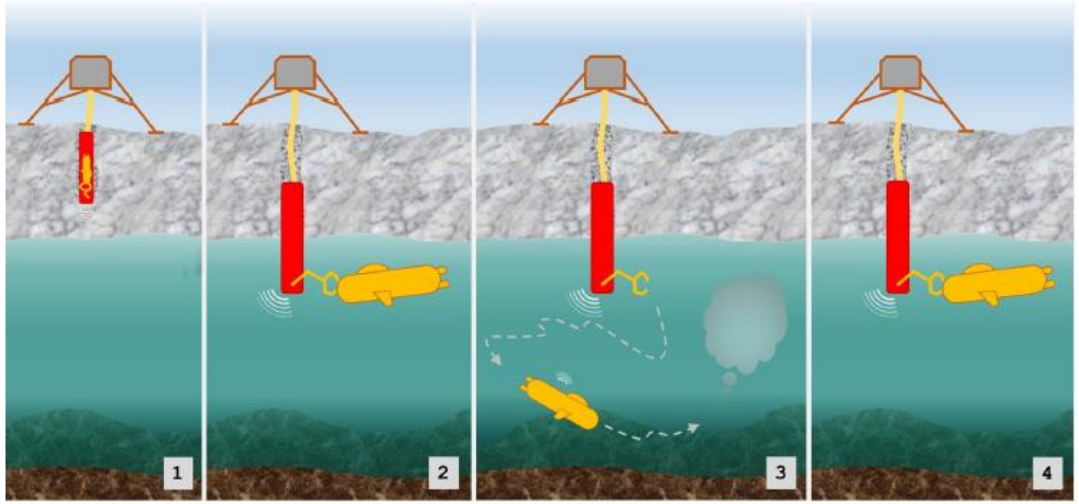
TRIPLE-Technologies for Rapid Ice Penetration and subglacial Lake Exploration

- Projects to develop technologies for a space mission to icy moons (Europa or Enceladus) in our solar system to search for extraterrestrial life
- The concept is based off three different components:
  - 1) melting probe
  - 2) nanoAUV
  - 3) AstroBioLab
- To demonstrate these technologies, a full test is planned in the Dome C region (Antarctica) with exploring a subglacial lake (Winter 26/27)
- Website: https://triple-project.net/
- BUW (Bergische Universität Wuppertal) is part of this research initiative in a subproject
  → TRIPLE-FRS



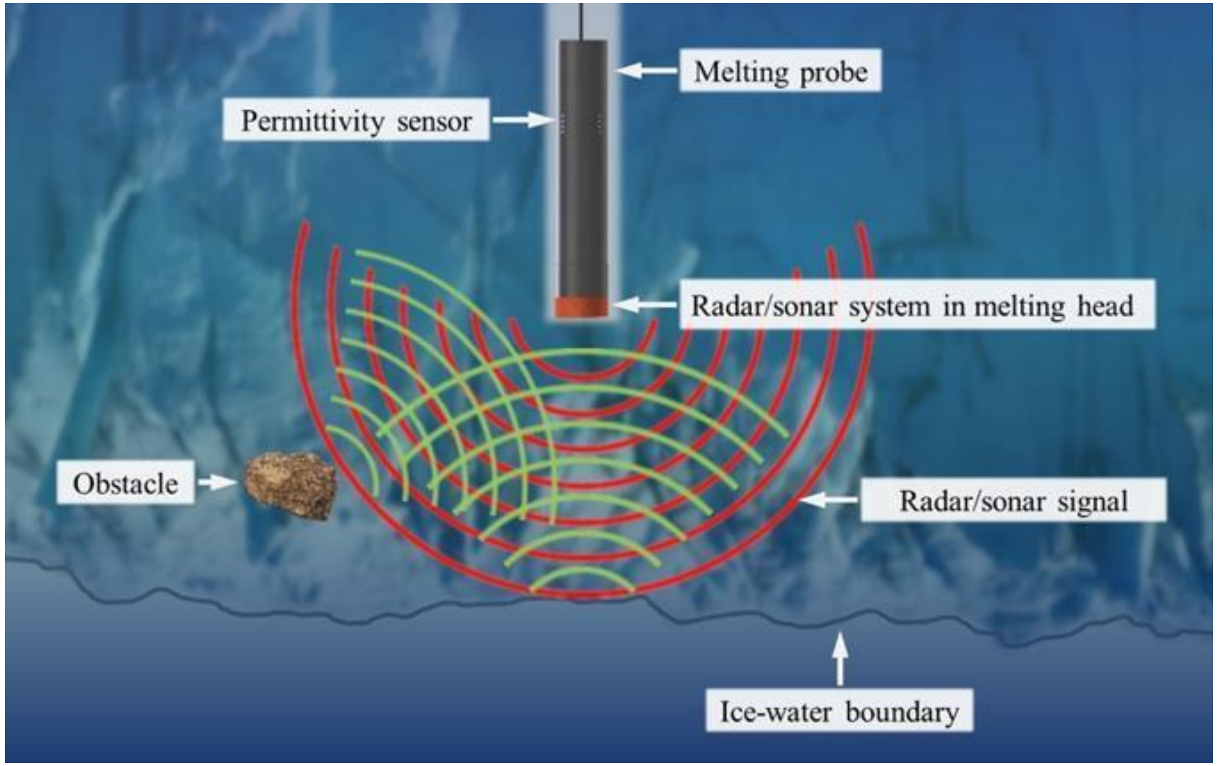
TRIPLE mission sketch [1]



TRIPLE mission sequence [2]

TRIPLE - Forefield Reconnaissance System (FRS)

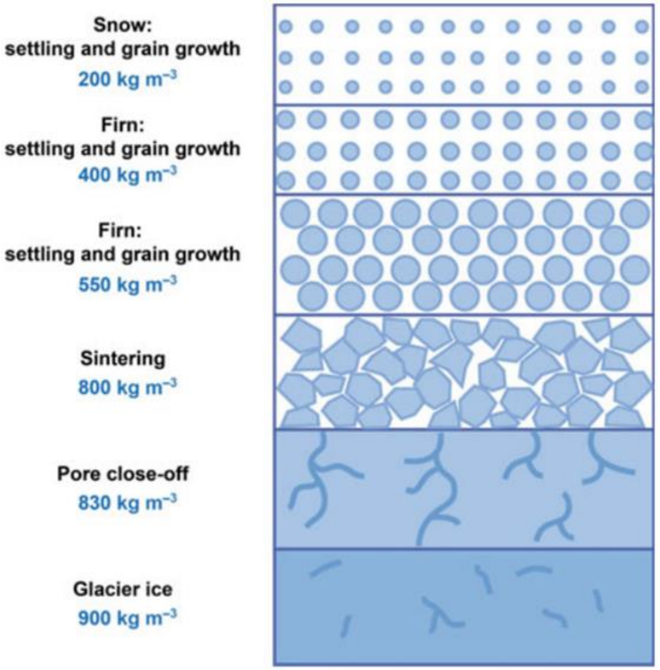
- Development of key technologies for the orientation of a melting probe in ice sheets from icy moons or in terrestrial ice
- Detection of obstacles in the trajectory of the probe and the water-ice boundary
- 4 partners in this project: RWTH Aachen, FAU Erlangen, GloMic and BUW
- Consists of sonar (RWTH Aachen) and radar (FAU Erlangen) for hybrid orientation
- A permittivity sensor (PS) to account for possible changes of the radio wave velocity in the ice
- With the help of the relationship between density and permittivity in ice, the wave velocity of acoustic waves can also be calculated



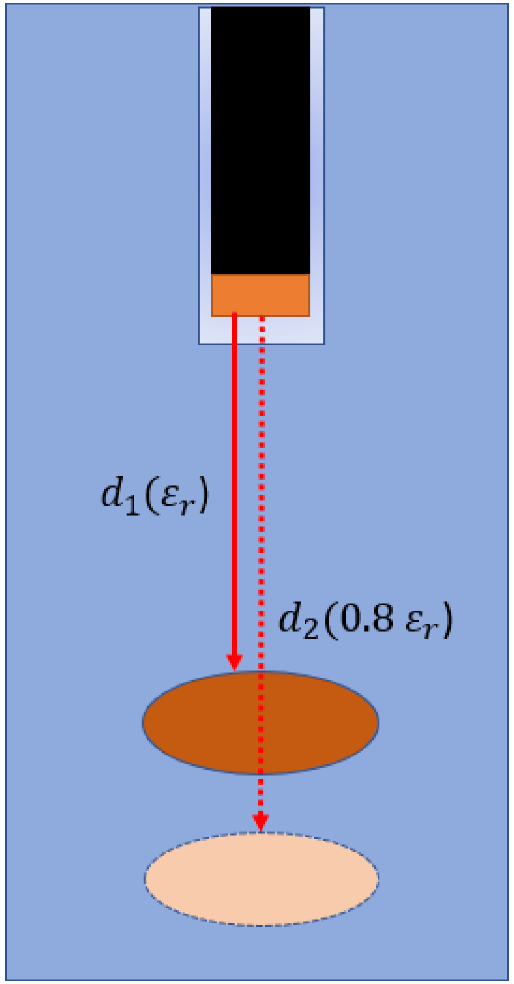
Function of the FRS

PS-Sensor Motivation

- The permittivity usually increases with depth due to the density increase in the ice layer
- The permittivity value/profile is different and unknown in all ice sheets + other anomalies in an ice body can also influence the permittivity (volcanic deposits, ice diapirs, meltwater channels)
- In order to measure these variations the PS is needed → transfer the radar image from time domain to space domain → The true distance (d_1) depends strongly on the permittivity, otherwise you skew the distance between melting probe and reflection (distance d_2)
- By accurate determination of reflection points, the melting probe can plan a trajectory
- The data of the PS can as well still be used for geophysical or glaciological research



Structure of a glacier with density increase [3]



Change of reflection point due to wrong permittivity assumption

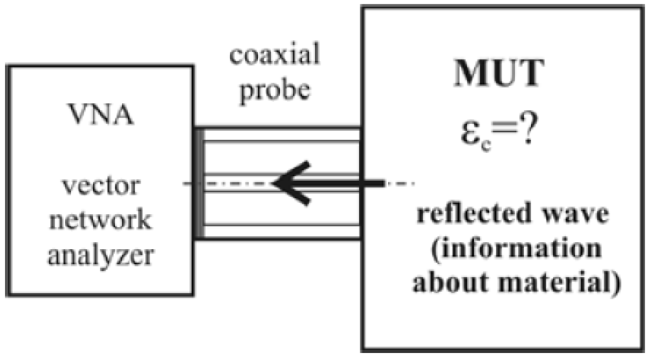
PS-measurements

PS-Sensor Concept

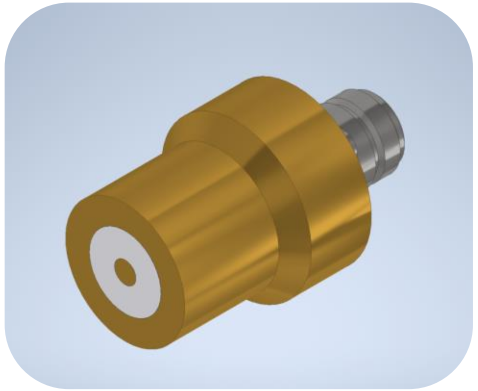
- **Coaxial probe** with inner and outer conductor is in contact with the material under test (MUT)
- Coaxial probe is connected to a **vector-network-analyser** (VNA) to determine the magnitude and phase of the S11-parameter (reflected wave)
- **S11-parameter** depends on the permittivity of the MUT
- Coaxial probe can be approximated with an **equivalent circuit** with 3 components (picture bottom right)
- This **approximation** leads to an equation
- For **calibration** and as an input information in the equation one need measurements from dielectrics with well-known permittivity

$$Y = \frac{1}{Z_0} \cdot \frac{1 - S_{11}}{1 + S_{11}}$$

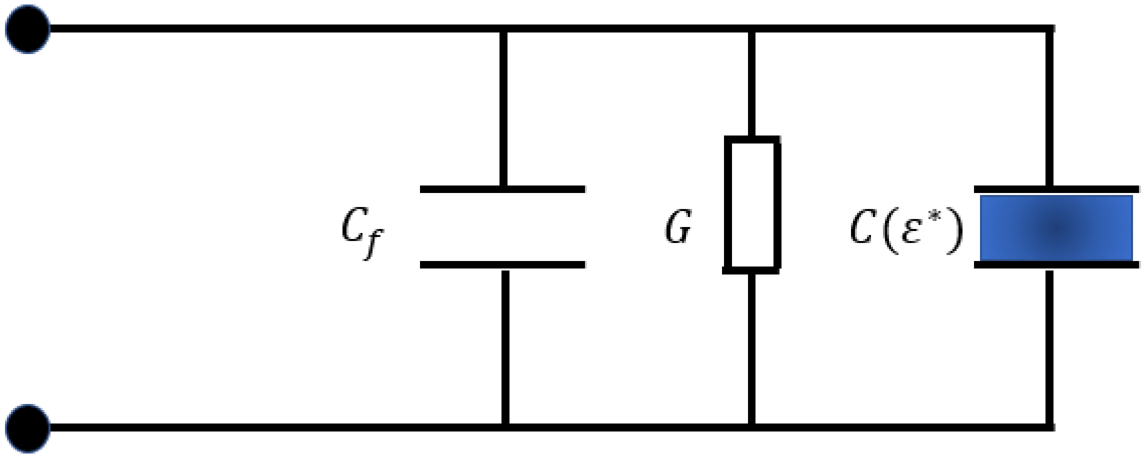
$$Y = i \cdot \omega (C_f + \varepsilon_r^* \cdot \chi) + G \cdot (\varepsilon_r^*)^{2.5}$$



Concept of the permittivity measurement [4]

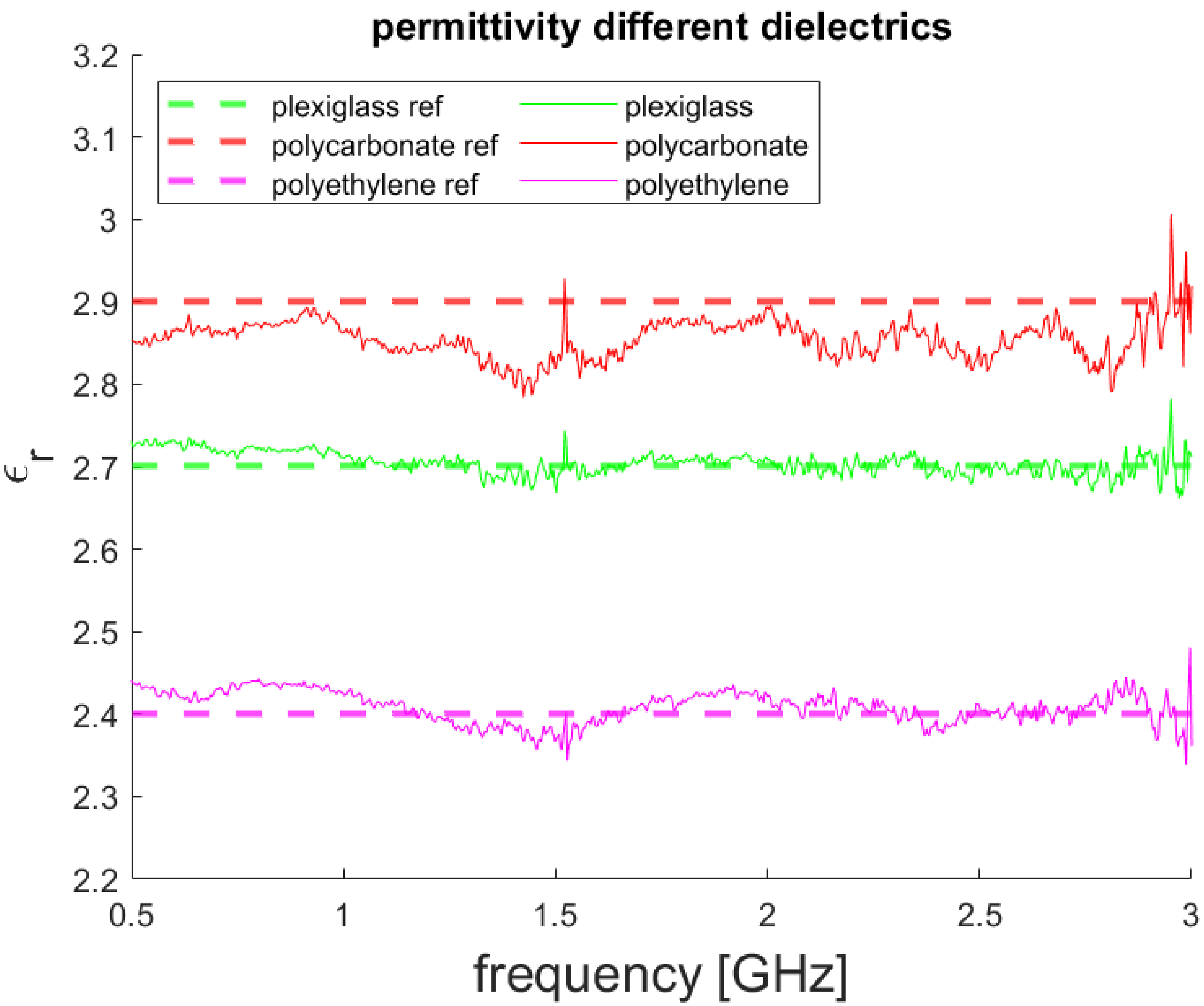


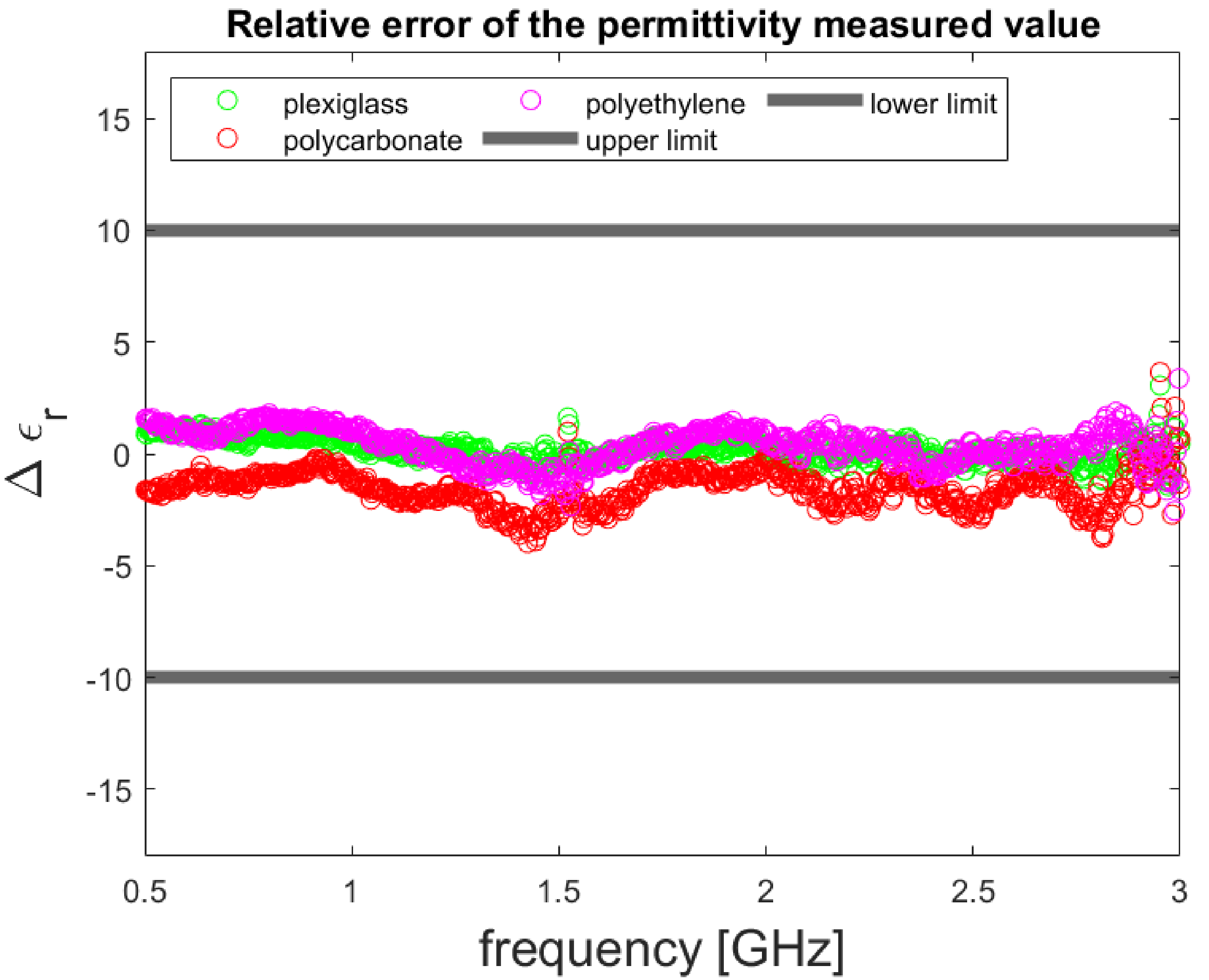
CAD image of an open coaxial head



Equivalent circuit from the open coaxial head

Permittivity measurements of dielectrics ➔ Required accuracy of 10 % achieved





PS-Sensor Test Setup on the Glacier

Scenario in a snow pit on the Jungfraufirn in Switzerland:

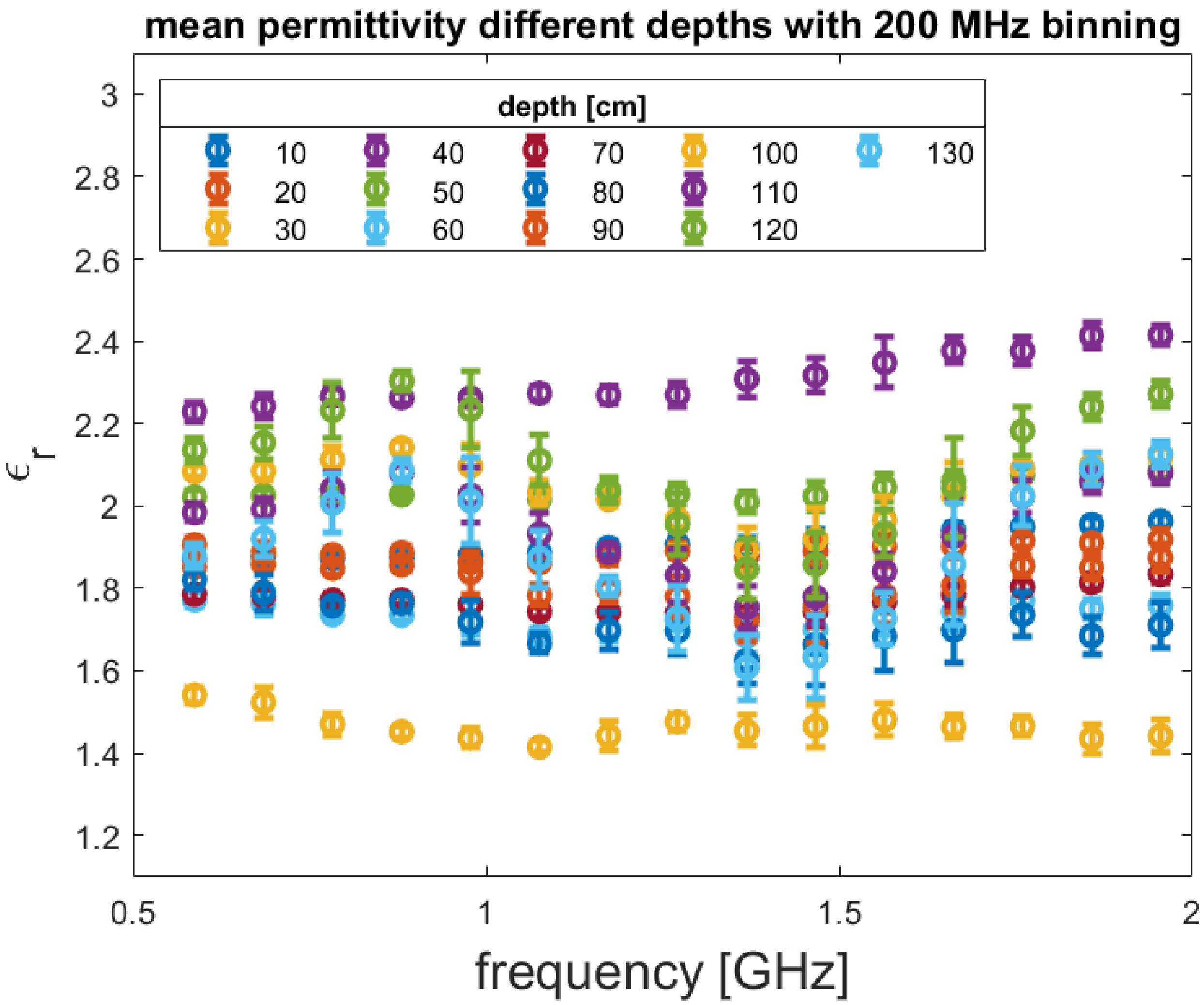
- Snow pit excavated to measure at several depths
- Recognize stratification of the glacier in permittivity profile (increase of density ⇒ increase of permittivity)
- Coaxial head pressed directly against the glacier at different depths and measured there
- It is possible to find layering or deposition or even layers with meltwater ➔ Profile anomalies
- First test of the measuring method, but without being integrated into the melting probe

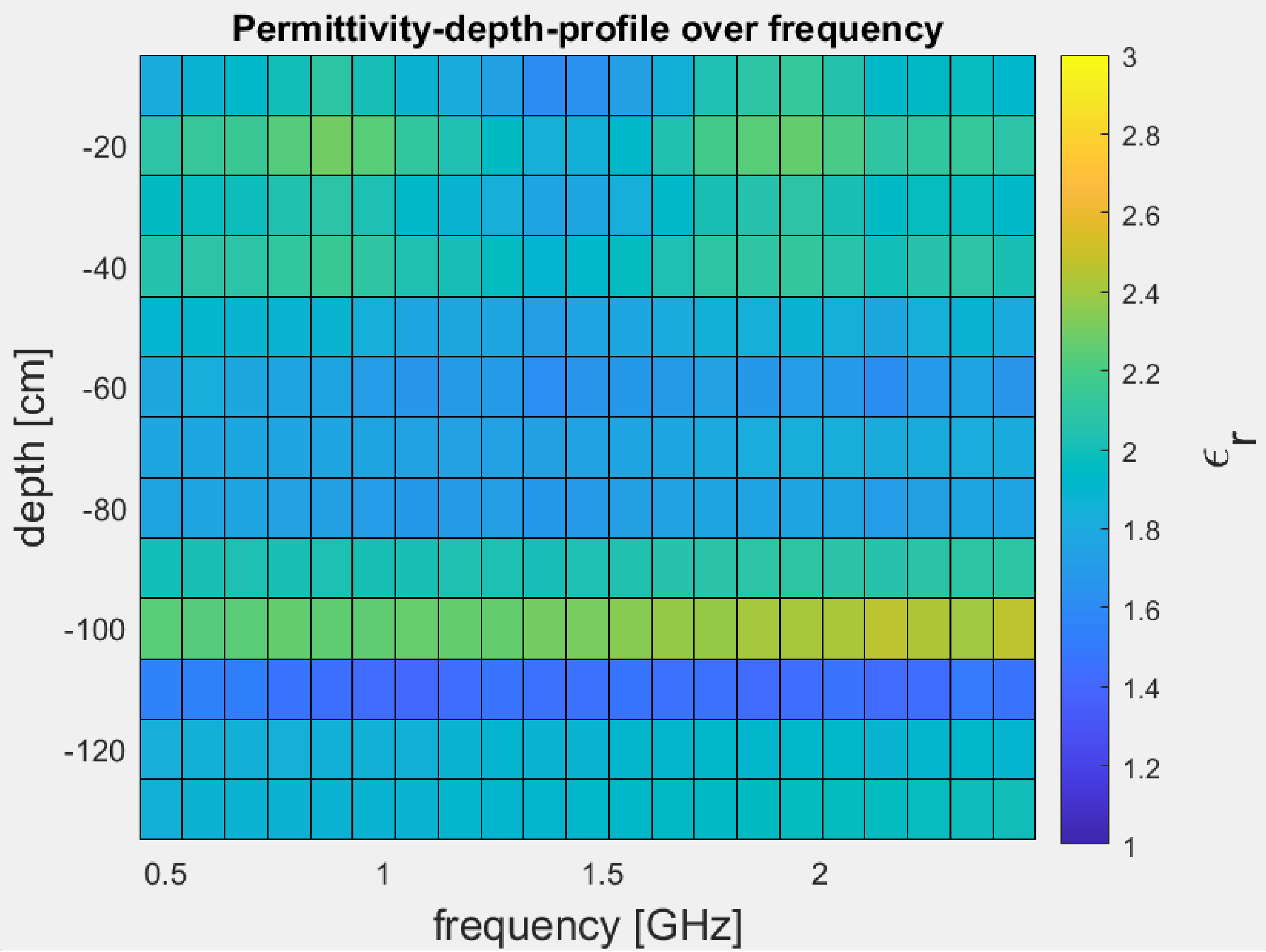
View to the Jungfraufirn and the Aletschglacier with our camp

Snow pit

Coaxialhead pressed against the glacier

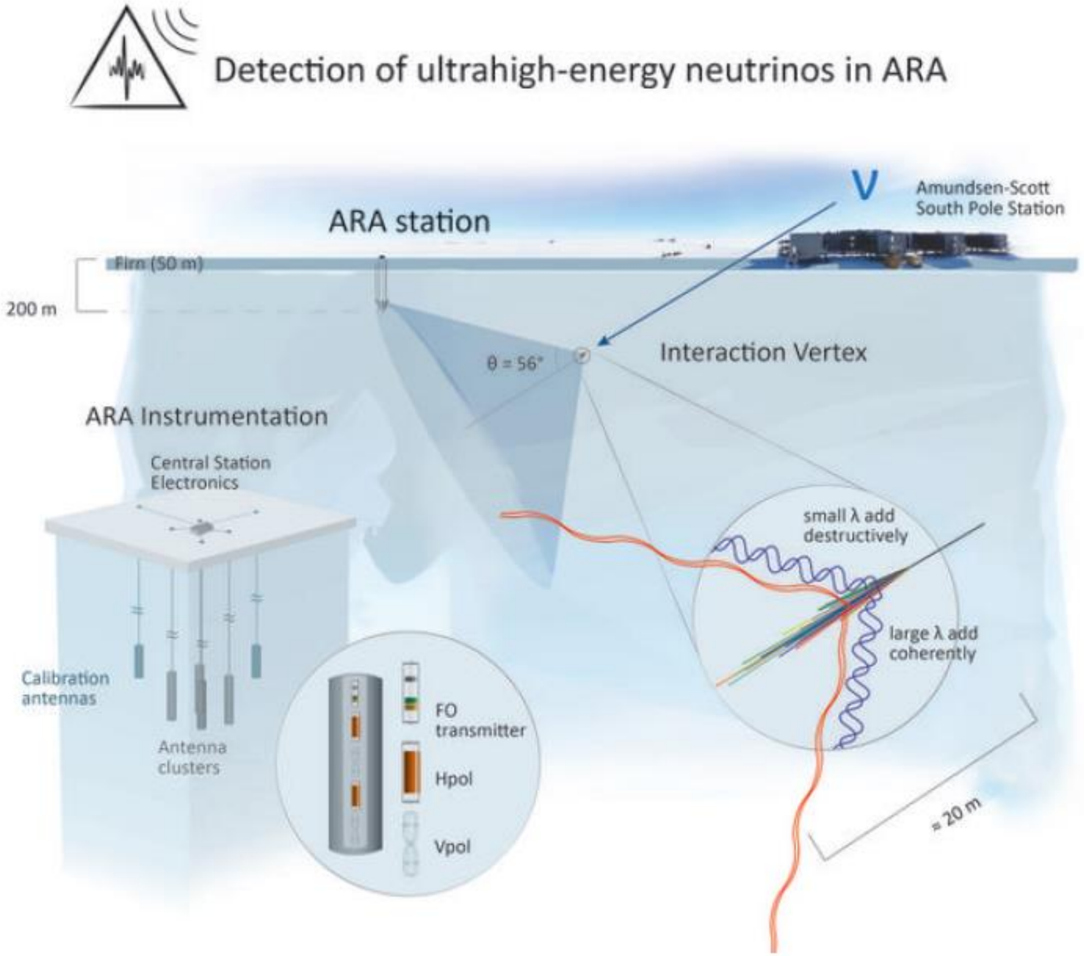
PS-FRS results from the first tests in a snow pit on a glacier ➔ Permittivity value increased with depth and anomalies indicating layer boundaries were measured





Experiments in ice to detect neutrinos

- The collision of ultra-high energy (UHE) neutrinos with ice molecules produces hadronic and electromagnetic showers
- For detection of UHE neutrinos it is possible to use these interaction in the Antarctic ice sheet
- Experiments like ARA or ARIANNA use the Askaryan effect which produce an electromagnetic signal in the radio wavelength scale
- With a large-scale radio antenna array in the ice of Antarctica one can measure these signals and construct the neutrino energy and the neutrino direction from them



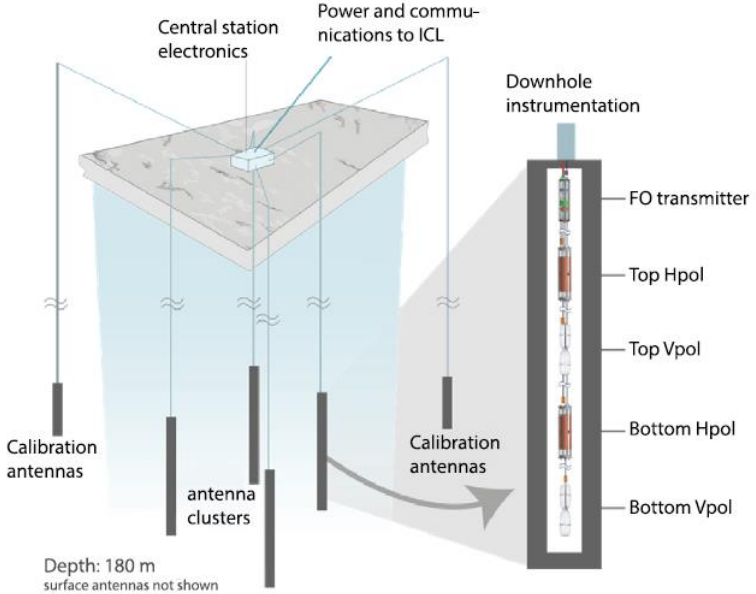
Schematic of the ARA neutrino detection [5]

Impact from PS-Sensor in a melting probe

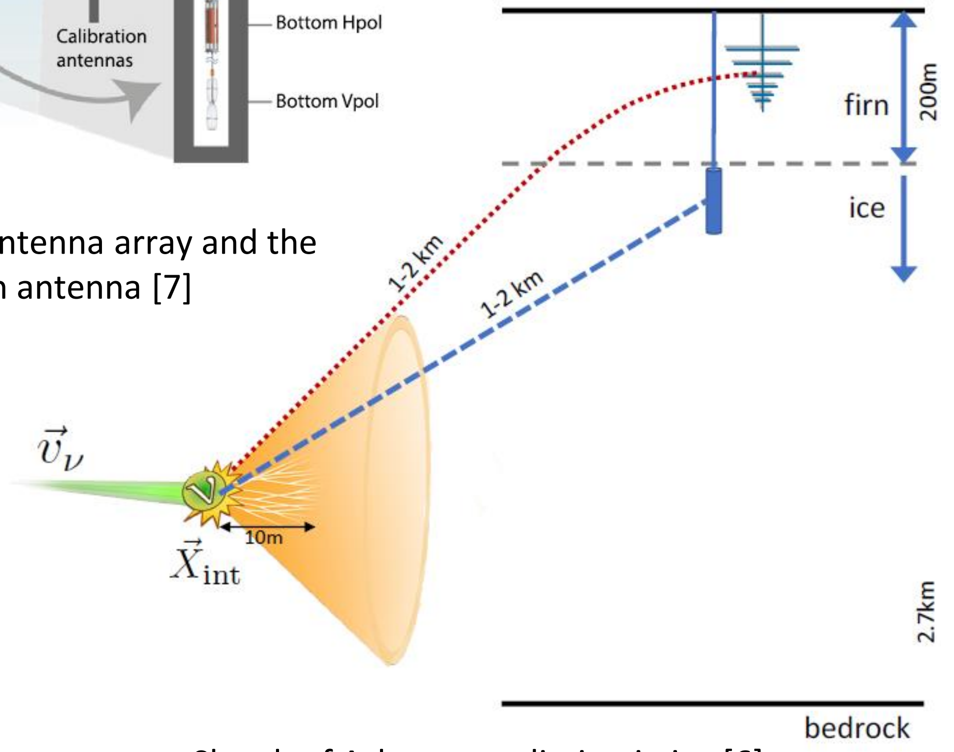
- Antennas are installed in the firn of the Antarctic glaciers → easy to transport to a 200 m depth with a melting probe
- Permittivity profile in Antarctica unclear → often used a depth (density)-dependent relation → melting probe with PS can create a very accurate profile of the permittivity
- Equipped melting probe can be reused and can measure already during the installation of the antennas

→ Very accurate model to reconstruct the traveling path of EM signals originating from UHE neutrino collision in ice

→ Pierre Auger group at BUW also uses permittivity measurements for radio based reconstruction of UHE Cosmic-rays



Structure of the ARA antenna array and the structure of an antenna [7]



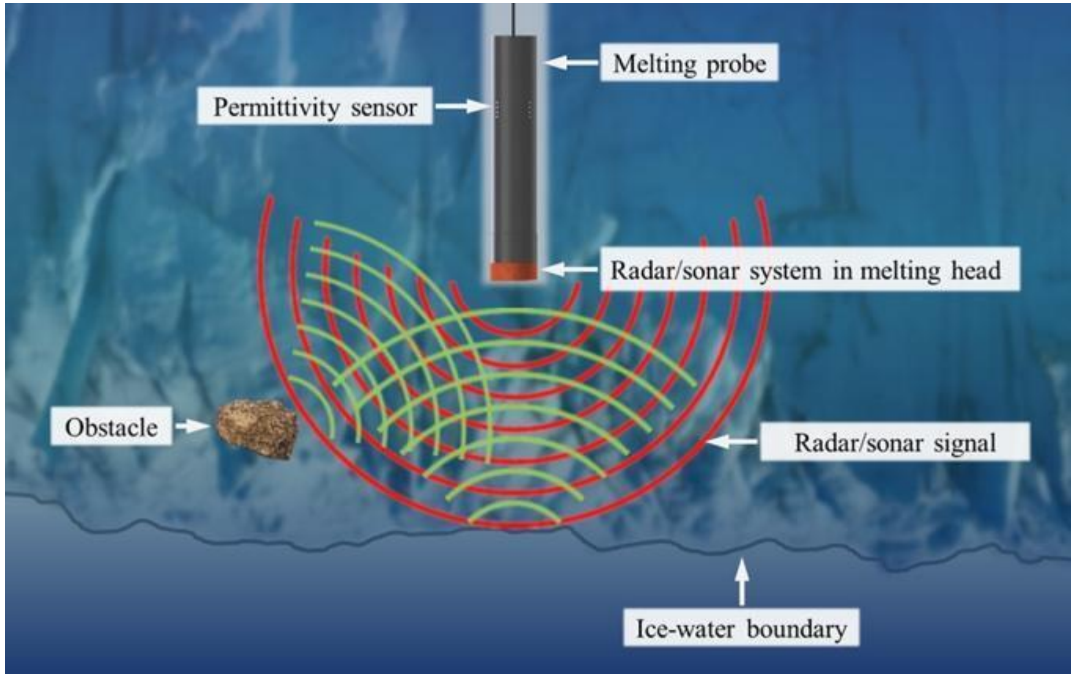
Sketch of Askaryan radiation in ice [6]

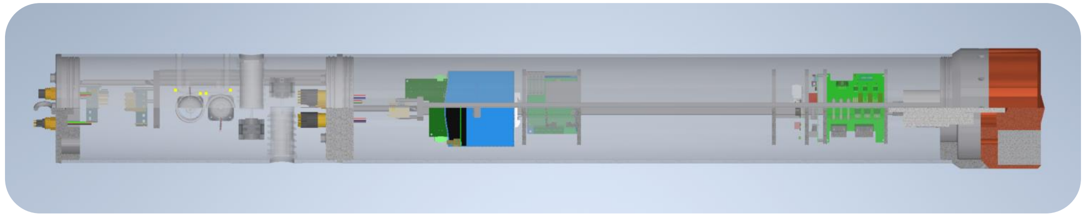
conclusion

- Permittivity sensor is developed for the desired application range and also already tested in ice and in a glacier
- The results show that in the needed frequency range the accuracy of 10 % required in the project TRIPLE-FRS was achieved

outlook

- Sensor will be installed in a melting probe, which will be tested next year on the Jungfraufirn (Switzerland)
- The TRIPLE initiative will probably carry out several Antarctica missions in the next 3 years, where the sensor will always be integrated in the melting probes used for this purpose
- A melting probe with the integrated PS can be of importance for the following radio arrays in ice sheets, which can be used for the detection of UHE neutrinos





Backup slides

Calculation of the permittivity

$$\varepsilon_r^*(f) = \frac{c_1^*(f) \cdot S_{11}^*(f) - c_2^*(f)}{c_3^*(f) - S_{11}^*(f)} \tag{1}$$

Calculation of parameters c_1^*, c_2^* and c_3^*

$$\underline{A} \cdot \vec{x} = \vec{b} \tag{2}$$

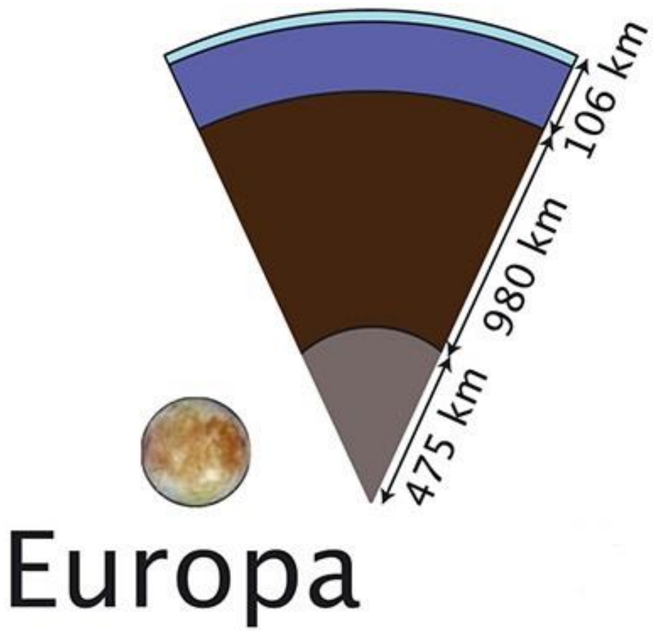
$$\underline{A} = \begin{bmatrix} S_{11,A}^* & -1 & -\varepsilon_{r,A}^* \\ S_{11,T}^* & -1 & -\varepsilon_{r,T}^* \\ S_{11,P}^* & -1 & -\varepsilon_{r,P}^* \end{bmatrix} ; \vec{x} = \begin{pmatrix} c_1^* \\ c_2^* \\ c_3^* \end{pmatrix} ; \vec{b} = \begin{pmatrix} -\varepsilon_{r,A}^* \cdot S_{11,A}^* \\ -\varepsilon_{r,T}^* \cdot S_{11,T}^* \\ -\varepsilon_{r,P}^* \cdot S_{11,P}^* \end{pmatrix}$$

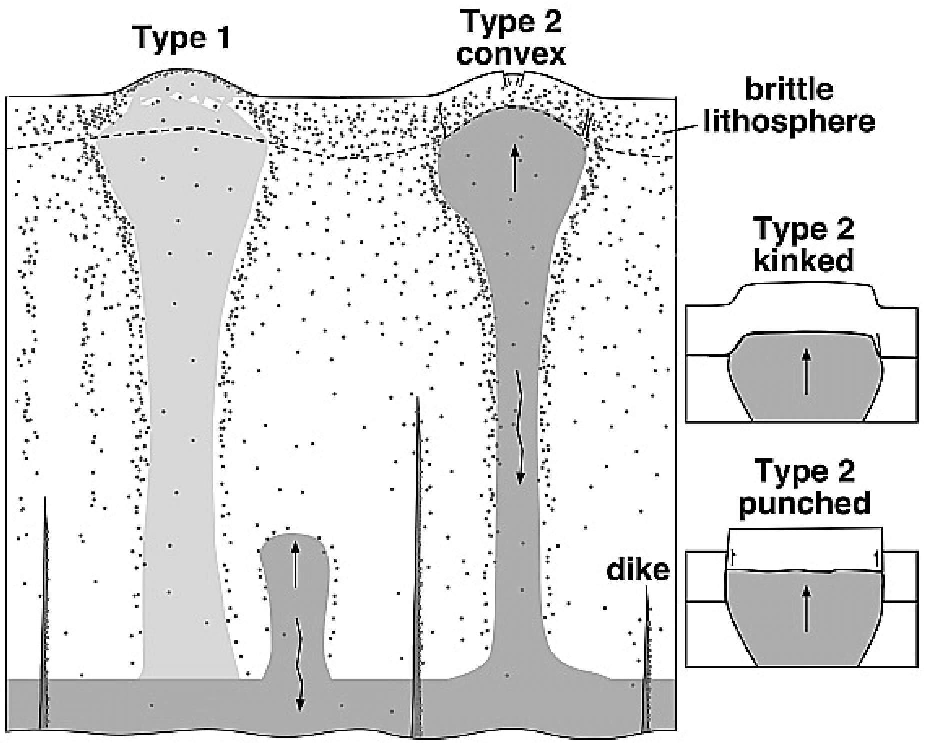
Meaning indices: A = air, T = Teflon, P = PLA

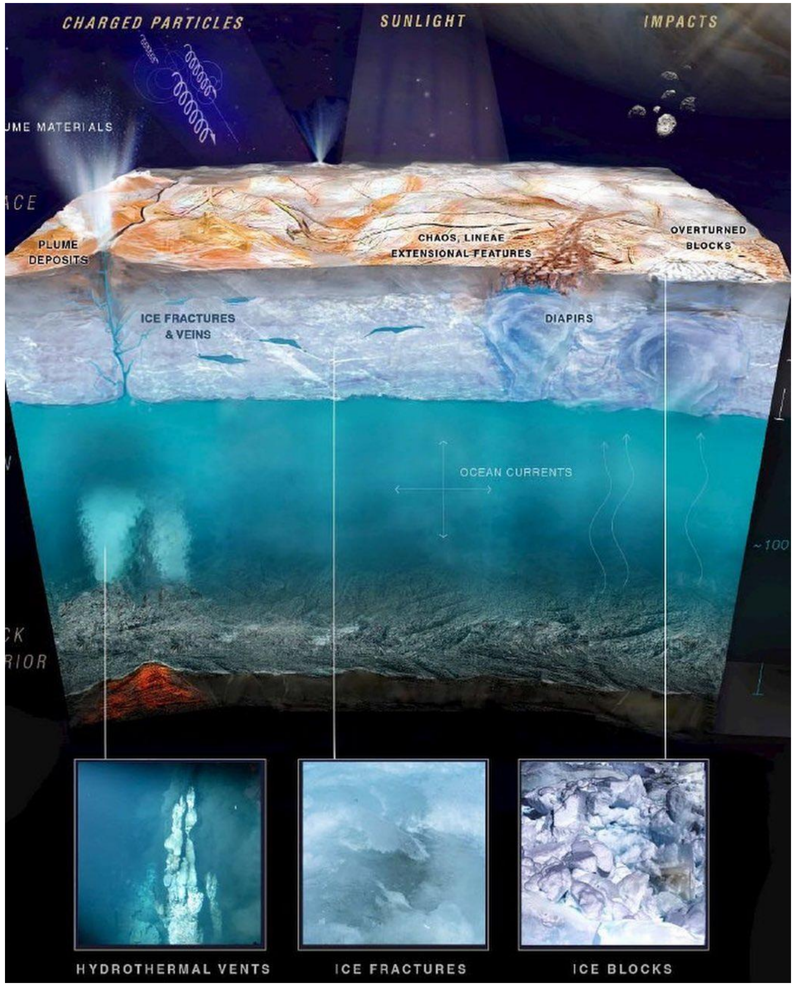
Solve Equation:

$$\vec{x} = \underline{A} \setminus \vec{b} \tag{3}$$

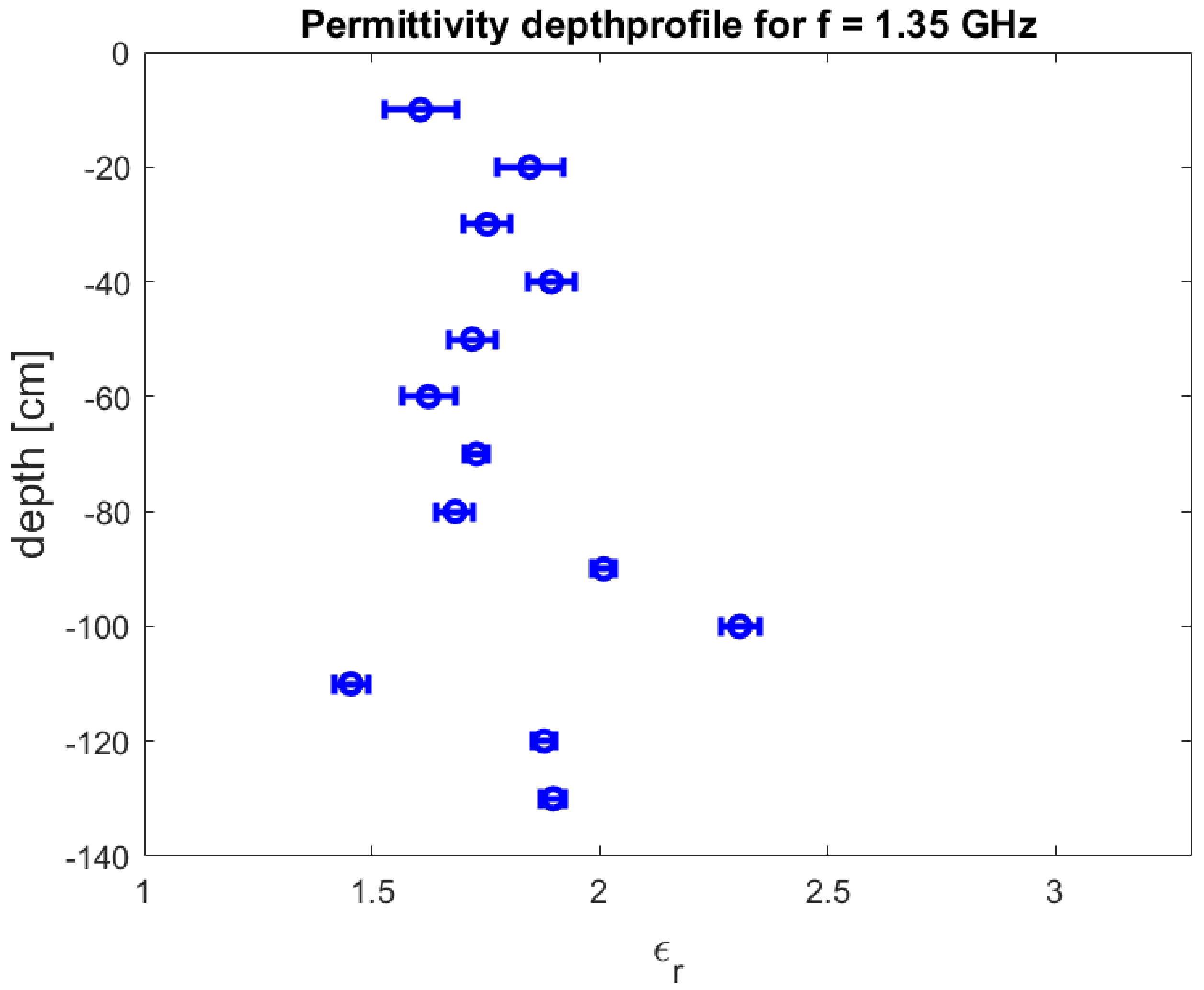
Ice Sheet on Europa

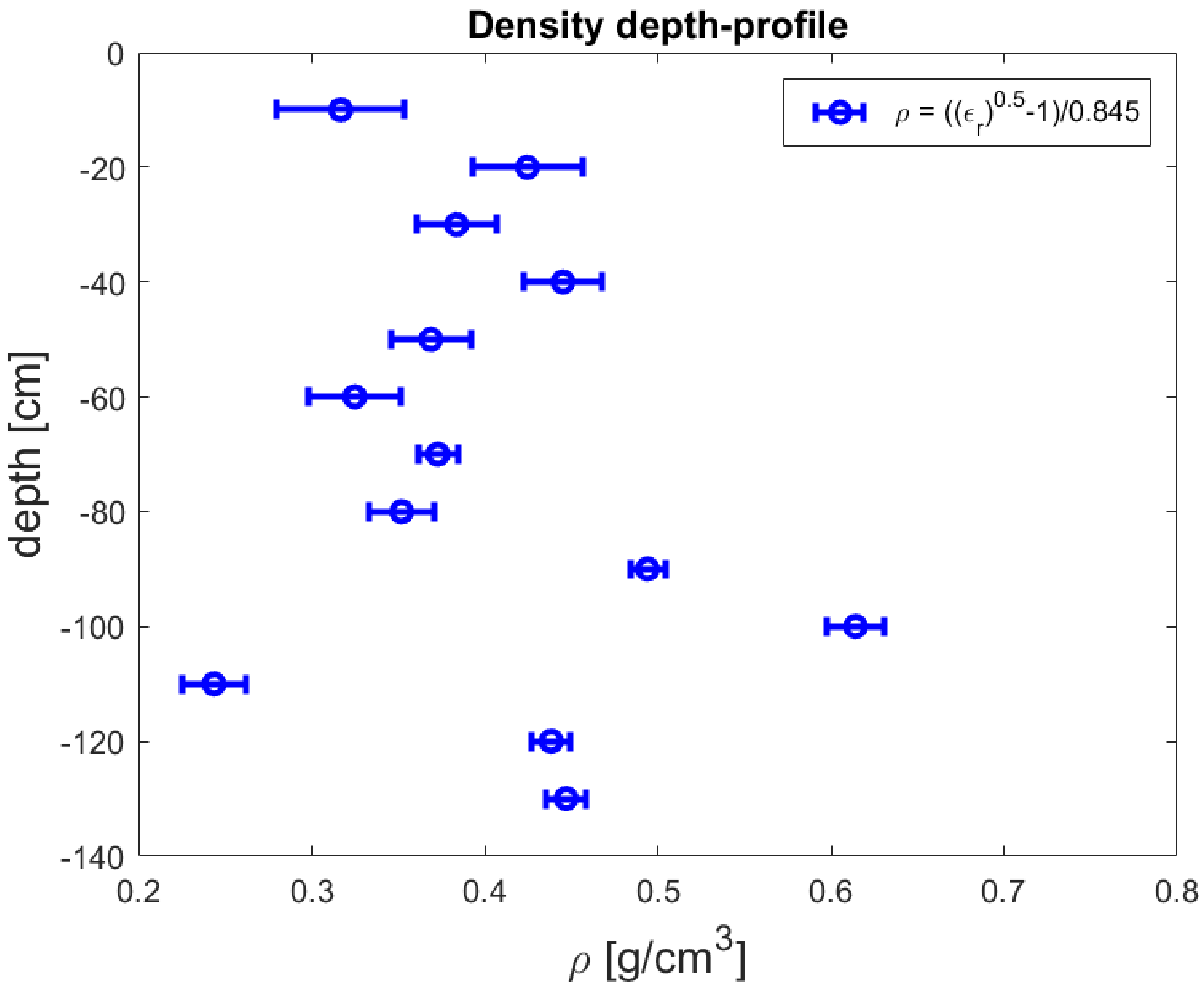






PS-FRS results - snow pit





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[1] https://triple-project.net/

[2] **Stenger**, David, Maximilian Nitsch, and Dirk Abel. "Joint Constrained Bayesian Optimization of Planning, Guidance, Control, and State Estimation of an Autonomous Underwater Vehicle." *arXiv preprint arXiv:2205.14669* (2022).

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[4] **Sheen**, N. I., and I. M. Woodhead. "An open-ended coaxial probe for broad-band permittivity measurement of agricultural products." *Journal of Agricultural Engineering Research* 74.2 (1999): 193-202.

[5] **Allison**, P., et al. "Measurement of the real dielectric permittivity ϵr of glacial ice." *Astroparticle Physics* 108 (2019): 63-73.

[6] **Barwick**, Steven, and Christian Glaser. "Radio Detection of High Energy Neutrinos in Ice." *arXiv preprint arXiv:2208.04971* (2022).

[7] **Allison**, Patrick, et al. "Performance of two Askaryan Radio Array stations and first results in the search for ultrahigh energy neutrinos." *Physical Review D* 93.8 (2016): 082003.