Validation of Sensor Systems in an Analogue Scenario for Icy Moon Exploration

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1. Project description

The Explorer Initiatives of the German Space Agency at the German Aerospace Center (DLR) comprise a collection of research projects focused on the exploration of celestial bodies. One area of focus is the exploration of icy moons in our Solar System, such as the Enceladus Explorer (EnEx) initiative and the TRIPLE (Technologies for Rapid Ice Penetration and subglacial Lake Exploration) initiative, which aim to explore Saturn's moon Enceladus and Jupiter's moon Europa, respectively. To simulate the environments of these moons, tests are conducted in terrestrial analogue scenarios. In March/April 2022, the projects EnEx-AsGAr and TRIPLE-FRS conducted measurements at the Jungfraufirn. The projects, their scientific objectives, and findings are described below.

The EnEx-AsGAr project, led by the University of Erlangen-Nürnberg, the University of Wuppertal, and DLR, is part of the EnEx initiative and focuses on researching radar technology for the exploration of structures in the icy crust of Enceladus. A key aspect of EnEx is probing a subglacial water reservoir with a melting probe, and EnEx-AsGAr aims to provide navigational support for such a probe. Therefore, the project's main challenge is to locate the probe with sufficient precision while concurrently mapping its environment in the ice and detecting potential points of interest. To accomplish this, several sensor systems are used:

1. Airborne synthetic aperture radar (SAR) system, namely F-SAR from DLR
2. UAV based radar system for the mapping of the upper firn layers
3. Borehole radar for determination of the permittivity distribution.

The main goal of the measurements using the F-SAR is to investigate the feasibility of locating an active radar transponder inside a borehole in the glacier, simulating a melting probe which is equipped with such a transponder. The tests were conducted with the transponder lowered to depths between 0 and 30 m into the glacier. The transponder works by delaying the radar signal and transmitting it after a strong amplification. As a result of the intrinsic delay, it appears defocused in a SAR image with standard processing, as shown in Figure 1 on the left. In the right panel, the transponder delay is considered during image focusing. The signature focuses to an almost perfect point target, proving the potential of this technology for more advanced signal processing of the acquired data and its applicability for subglacial exploration.

The processing of the data is not yet completed entirely.

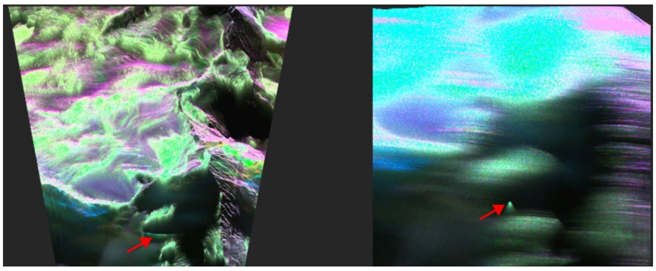

Figure 1. SAR image of the Jungfraufirn with the transponder lowered to 17,5m with standard reconstruction (left) and reconstructed image with incorporated transponder delay (right).

Figure 2. Flight-ready UAV at the Jungfraufirn.

For the UAV radar, a custom-made UWB FMCW radar was mounted on a drone along with an RTK-based localization solution, as shown in Figure 2. The drone was used to conduct a survey of the upper firn layers close to the snow farm below the Sphinx Observatory, simulating the precise mapping of the upper layers of the ice/firn crust of Enceladus. Figure 3 shows an example B-scan. The flight path followed multiple parallel lines perpendicular to the lines of the snow farm, resulting in the wave-like structure in the scan. Different layers corresponding to different seasons throughout the years are clearly visible. Furthermore, the distance between the radar system and the surface, as well as the high resolution of the radar, allows for a second very sharp layer to be visible close to the surface, which is likely caused by Sahara dust. Together with high radiation during the day and low temperatures during the night, this layer resulted in a small layer of ice inside the snow cover.

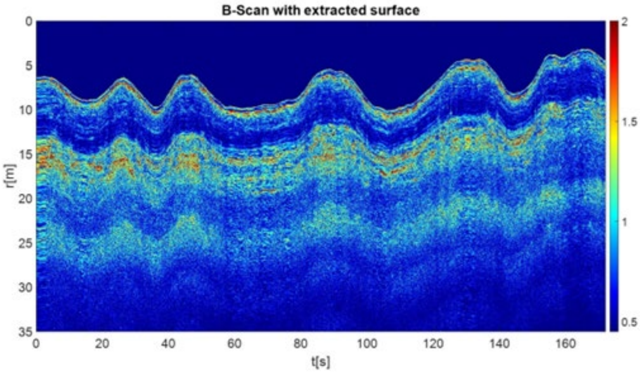

Figure 3. B-Scan of the firn layer at the snowfarm.

The permittivity radar is used to determine the permittivity distribution inside the glacier to correct the range assignment of both airborne and UAV based radar systems. With this, more accurate localization results can be achieved. For this, the transmitter and receiver were lowered into two different boreholes with predefined spacing between them. From the difference in measured signal travel time compared to the idealized speed of light, one can determine the average permittivity between the antennas. These tests were conducted for varying depths of both, the receiver and transmitter as well as for various distances between the boreholes. A schematic of the measurement setup is shown in Figure 4 on the left. On the right, two permittivity profiles derived from different borehole measurements are displayed, with two different borehole separations (25 m and 42 m) being used.

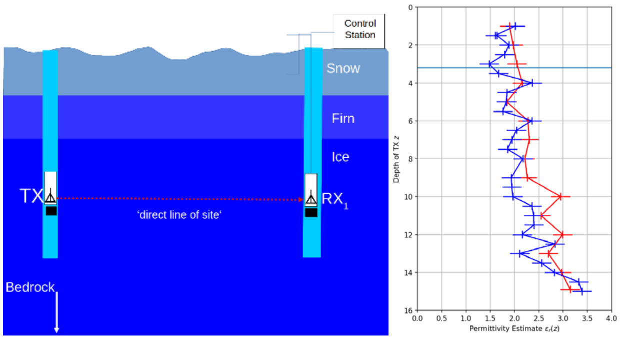

Figure 4. Measurement setup for borehole permittivity radar (left) and preliminary permittivity profile derived from two different borehole setups. The blue corresponds to two boreholes separated by 25 m, and the red corresponds to 42 m separation.

The goal of the TRIPLE project line is to demonstrate the feasibility of probing a subglacial water reservoir with a miniaturized autonomous underwater vehicle (nanoAUV). For this, a melting probe is used as the carrier system and needs to safely navigate its way to such a reservoir. That challenge is tackled by the TRIPLE-FRS project, which focuses on the development of a forefield reconnaissance system (FRS) for such a melting probe. The main idea behind that system is the identification of hazardous regions in the trajectory of the melting probe such as crevasses, rocks etc. With the knowledge about obstacles in the planned trajectory, the melting probe could potentially adapt its planned path and, hence, continue with its survey. Furthermore, the probe must be capable of identifying the ice-water interface at the subglacial water reservoir so that melting probe can anchor itself and the nanoAUV survey can be prepared. The system consists of a hybrid approach of radar and sonar system integrated into the tip of the melting probe. A permittivity sensor is included into the melting probe to generate scientific data as well as to determine the correct propagation speed of electromagnetic waves for the range assignment of the radar systems. At the Jungfraufirn, the tests were focused on the validation of measurement concepts of both sonar system and permittivity sensors without being fully integrated into the final FRS melting probe.

The permittivity sensor, for the melting probe comprises an open coaxial head that is pressed onto the ice. For the field test, this was done by mounting the coaxial head to an extendable cylinder. This cylinder was lowered into the ice and extended before the measurements were conducted, as shown in Figure 5 on the left.

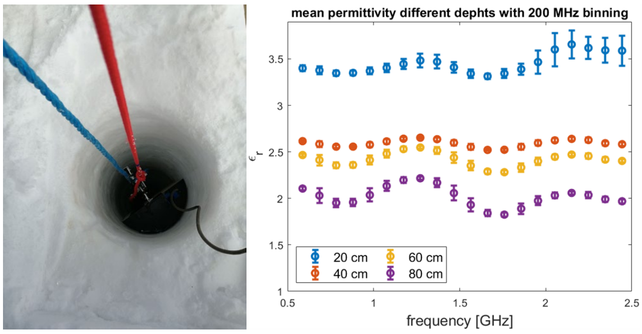

Figure 5. View onto the lowered permittivity sensor (left) and permittivity derived over frequency at various depths (right).

The ice in the surrounding of the open coaxial head has an influence on the electrical impedance of said head, which can be measured with a vector network analyser. From the reflection, the permittivity can be derived with an equivalent circuit approximation. Several permittivity profiles along frequency for different depths are shown in Figure 5 on the right.

For the sonar measurements, melting probes instrumented with acoustic systems were used. One of the so-called Autonomous Pinger Units (APU) is shown in Figure 6. The sound is generated using an acoustic transducer integrated in the melting head. On site, multiple measurement scenarios were carried out to measure the transfer function between the probes in snow and firn and to validate the form of the emitted signal.

Figure 6. Acoustic equipped melting probe used for the sonar measurements (melting head on the left).

Figure 7. Birdseye view of the area probed with three acoustic melting probes.

Figure 7 shows an example of two different on-site triangular setups including three melting probes - one emitter and two receivers. For reasons of redundancy, both receivers were placed at the same distance of 5 meters from the emitter in case of the larger triangle. While keeping the emitting probe at one fixed depth, the receivers were melted down in steps of 1 m to collect data in a reasonable time. At each stop, a series of different waveforms (frequency sweeps, barker codes) were sent by the emitter to the receivers. The study of the correlation between the emitted and received signals enables the identification of the arrival time of the direct signals and possible reflections created by the surroundings. This is used to create a solid knowledge base for the further waveform design for the final melting probe in the FRS project. The speed of sounds in the first layers of firn could be derived from the measurements and further dedicated analyses are still ongoing.

All in all, the tests conducted at the Jungfraufirn were a success for all participants even if not all data has been fully processed yet. The data showed great potential for the developed technologies which will be further evaluated in future field campaigns.

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Scientific publications and public outreach 2022

Several publications related to the conducted tests are planned but not published yet.

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