In-ice acoustic positioning system for the Enceladus Explorer

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Abstract. The IceMole, a combination of melting and drilling probe, which is able to move and steer through ice and take samples while doing so, can be used to install instruments in ice. In addition to the inertial navigation system, the ice-craft will be equipped with an acoustic positioning system, composed of receivers in the probe itself and several emitters (pinger) on the glacier surface. It will determine the position of the IceMole by measuring the signal propagation time and trilateration, which requires a solid knowledge of the propagation of acoustic signals in ice. A method to determine these properties during the operation of the IceMole will be developed.

Here we will give an overview over the goals of the project and the design of the IceMole. We will present the status of the development of the acoustic positioning system and show the results of simulations on the positioning accuracy.

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1. GOALS OF THE ENCELADUS EXPLORER PROJECT

The IceMole (Fig. 2) is a combination of a melting and drilling probe. It is equipped with an ice-screw and several heaters that can be operated separately, which enables it to move in every required direction and even change its direction during an operation.

There are several promising applications for a probe like the IceMole. One of them is the exploration of the so called Blood Falls in Antarctica. The Blood Falls are crevasses through which hyper-saline ferrous water leaks from a nearby sub-glacial lake. When the water reaches the surface it oxidizes and turns red and makes the area look like a bloody waterfall. During the analysis of samples from the surface, autotrophic bacteria with a unique metabolism were found and make the recovery and investigation of samples from that lake an interesting topic for microbiologists.

The acquisition of water samples from one of the crevasses is similar to possible operations on the Saturn moon Enceladus. Enceladus is one of the most promising candidates for the search for extraterrestrial life. It possesses liquid water, which comes from a pressurized pocket underneath the surface and erupts from cryovolcanos (tiger stripes) in the south polar region. In addition to liquid water, an increased temperature compared to the rest of the moon was measured at these tiger stripes (Fig. 1).

In both scenarios the task of the IceMole is to drill and melt its way down to a crevasse, recognize the crevasse early enough and take a sample without falling into the crevasse or contaminating the ecosystem. In order to fulfill this task, the probe needs to be able to decontaminate itself, recognize its environment, determine its exact position and navigate around obstacles. The goal of the Enceladus Explorer project is the development of the technologies necessary for this mission.

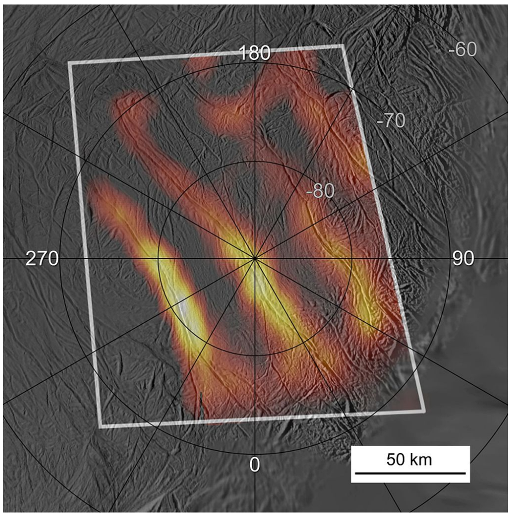

FIGURE 1. Thermal map of the tiger stripes. The temperature varies between 72 and 180 K [1].

Another possible application of the IceMole would be the installation of sensors in acoustic neutrino astronomy. The IceMole could be used to drag a chain of sensors through the ice and place them at well known positions.

2. DESIGN OF ENEX

The Encaldus Explorer (EnEx) is an advancement of the first IceMole (Fig. 2). It will be equipped with 16 heaters in its head and 8 side-heaters. The ice-screw will be used

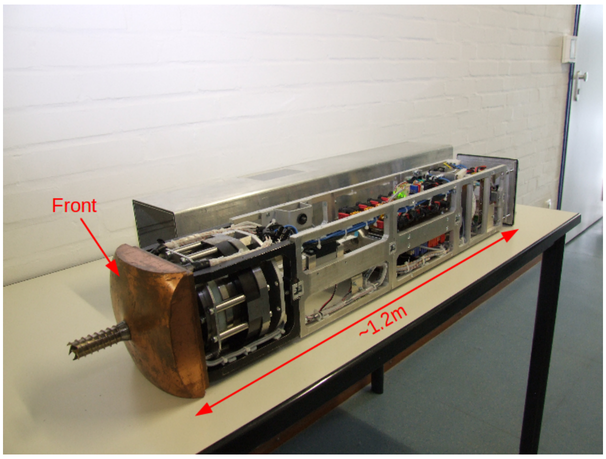

FIGURE 2. Interior view of the first IceMole design [2].

to pull its head against the ice. Compared to conventional meltdown probes, who can only melt downwards with gravity, this enables the IceMole to dig in every required direction. Since the heaters can be operated separately the IceMole can change its direction with a curve radius of ∼ 10 m. The IceMole used for EnEx will be ∼ 1.2 m long and have a quadratic cross section with an edge length of 15 cm. Due to the quadratic profile the rotation of the ice-screw will only lead to a minimal rotation of the whole IceMole around the axis of the ice-screw. This slow rotation will be used by the environment recognition system to do a 360°-scan of the region in front of the IceMole over several hours [3].

2.1. Inertial Navigation

The IceMole will be equipped with three independent positioning systems. The inertial navigation system will consist of a differential magnetometer and an Inertial Measurement Unit (IMU), composed of a gyrocompass and accelerometers. The IMU provides the position and orientation of the IceMole by calculating both from measured parameters in a stepwise procedure, which is why the errors on both add up over time. The magnetometer provides only the orientation of the IceMole. This orientation will be combined with the measurement of the cable length and thereby with the covered distance of the IceMole, which enables it to calculate the path through the glacier.

Since both systems are still under testing, an acoustic positioning system will be developed to have a redundant positioning system.

2.2. Acoustic Positioning

The concept of the Acoustic Positioning System (APS) is shown in Fig. 4. The position of the IceMole will be determined by trilateration algorithms from the measured distances between ASPs and the IceMole. It will consists of three subsystems, the Acoustic Surface Pingers (ASP) developed by the Bergische University of Wuppertal, an Acoustic Data System (ADS) and the acoustic sensors placed in the IceMole-head, both developed by the RWTH Aachen. The signal propagation times will be measured and the distances will be calculated from these times and the speed of sound in ice. This approach comes with a few challenges. A good coupling between the ASP and the ice has to be ensured. The same is necessary for the coupling between the sensors and the head. The quality of the coupling between the head and the ice is ensured due to the tension from the ice-screw and the water in the melting canal. The signal propagation time will be measured with a precision of 1 µs and the positions of all ASP can be measured with an accuracy of ∼ 1 cm. That means that the speed of sound has to be known with an precision of 1 % to achieve a positioning accuracy of below 1 m. The quality of the ice is also very important for a good performance. If there are too many cracks in the ice or the attenuation is too large, the signal from one or more ASPs could get lost. When the number of heard ASPs is reduced to less than four, it becomes impossible to locate the IceMole at all. In addition a speed of sound profile has to be determined for each test site, which also requires a sufficient quality of the ice.

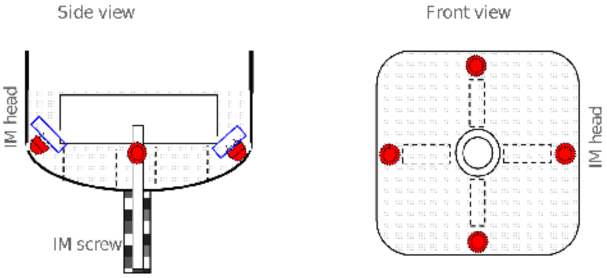

FIGURE 3. Positions of the acoustic sensors integrated in the IceMole-head [4].

For the four acoustic positioning sensors in the IceMole-head PZT-discs with a preamplifier stage are used. Their positions in the IceMole-head can be seen in Fig. 3. In order to optimize the signal-to-noise ratio, the pressure between the sensors and the head shall be tunable and the resonance frequency of the sensors shall meet the resonance frequency of the head.

The frequency of the pingers is flexible (20 – 500 kHz) and can therefore also match the resonance frequency of the IceMole-head. The velocity of the IceMole is about

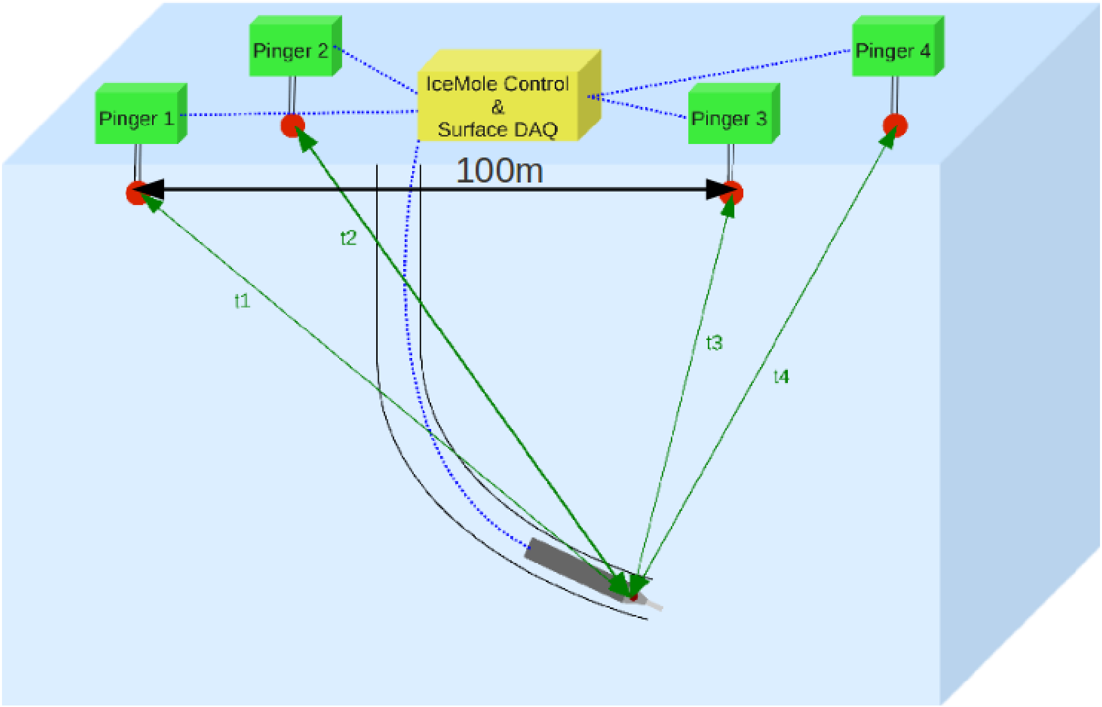

FIGURE 4. Principle of the Acoustic Positioning System.

1 m/h, so that it is sufficient to determine the position of the IceMole at rare intervals (every few minutes). For this reason it is possible to fire one pinger and then wait for the signal to reach the IceMole before pinging the next one. The peak-to-peak voltage per sent pulse will be up to 1 kV. For the coupling between the pinger and solid ice there are two possibilities. One is to couple the pingers through water or another liquid that does not freeze on the glacier, the other option is to freeze the pinger directly on the surface. One idea for the determination of the speed of sound is, to measure the sound waves that are bent backwards in the glacier from one pinger to another. The feasibility of this is still under investigation.

3. FIELD TESTS

In order to build a functional system and to learn more about the propagation of sound waves in glacial ice, several tests on different glaciers are planned during the three years. The first one took place at the end of July 2012 on the Morteratsch glacier in Switzerland. The second one is planned for May 2013 on the Matanuska glacier in Alaska. The remaining two test-sites are both in Antarctica, the first one on the Canada glacier (November 2013) and the second one at the Blood Falls on the Taylor glacier (November 2014).

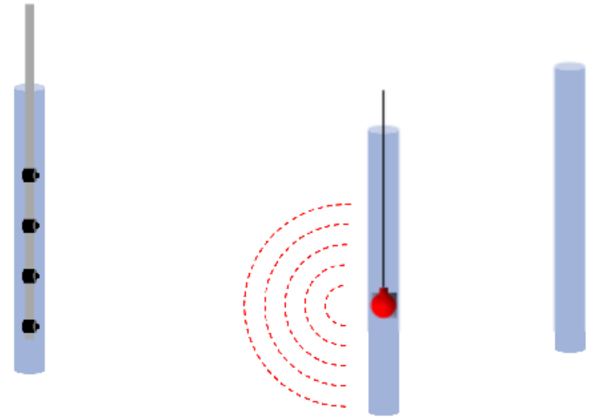

FIGURE 5. Setup of the field test on the Morteratsch glacier [4].

3.1. Measurements on the Morteratsch Glacier

The main goal of the measurements on the Morteratsch glacier was to measure the speed of sound and the attenuation length in dependence of the depth in the glacier and to get an impression of the homogeneity of a real glacier. With this informations a model for the behavior of the sound speed in this glacier shall be derived. A melting down probe was used to drill holes with a di-

TABLE 1. Results of the Simulation.

	Assumed Error	Uncertainty on IceMole position
Time	1 µs	$\sim$ 1 mm
Sound Speed	40 m/s	$\sim$ 1 m
Pinger Position	1 cm	$\sim$ 1 cm

ameter of $\sim$ 15 cm, a depth of up to 5 m and a distance of up to 30 m. The propagation between two holes was measured by inserting 4 receivers mounted on an aluminum bar at distances of 50 cm into one hole and pinging from another one with two commercial pingers (ITC 1001, SQ09) and a Hades-sensor [5] at different depths (Fig. 5).

4. SIMULATIONS ON THE ACCURACY OF THE ACOUSTIC POSITIONING SYSTEM

The purpose of this simulation is to study the influence of possible sources of uncertainty on the precision of the acoustic positioning system. Considered sources are the measurement of the propagation times, the positions of the ASPs and the uncertainty of the speed of sound profile. In the first approach the geometry of the pinger-array and the position of the IceMole were fixed, three pingers at three corners of a square at a distance of 100 m and the IceMole in the center of that square at a depth of 50 m. The real propagation-times between each pinger and the nominal position of the IceMole are calculated from the known geometry assuming a speed of sound of 4000 m/s. Around these times Gaussian distributions are created from which the measured arrival times and their errors are derived. The uncertainties on the speed of sound and the positions of the pingers are also assumed to follow a Gaussian distribution. From each measured distance between one ASP and the IceMole, a sphere around the ASP is derived, on which the IceMole is located. The actual position of the IceMole is calculated from the interception point of the three spheres. The assumed uncertainties and simulation results are summarized in Tab. 1. A time resolution of 1 µs is doable with a sufficient signal-to-noise ratio and the determination of the positions of the ASPs within 1 cm is possible by the use of a tachymeter or GPS. The remaining critical error source is the uncertainty on the speed of sound, which has to be known with an error of 1 % or less for a sufficient spatial resolution of the IceMole Position.
In order to improve the simulation the use of more ASPs and a flexible geometry of the array and the position of the IceMole will be included. Advanced trilateration algorithm will be developed to benefit from the over-constrained measurements. To control and study the varying speed of sound the use of different distances and configurations between the pingers will be tested. A model of the behavior of the speed in a glacier e.g. as a function of depth will be developed and integrated in the positioning algorithms.

5. SUMMARY AND OUTLOOK

A probe like the IceMole offers many different applications, not only for the search of extraterrestrial life, but also for the precise placement of sensor chains in ice. During the development of the acoustic positioning system tests on various glaciers will be performed. The analysis of the data from these tests will lead to a better understanding of the propagation of sound waves in glacier ice and shall be used to develop a model on the depth-dependence of the sound speed in glaciers. This model is needed to reduce the influence of the error of the speed of sound, which was identified as the most crucial error source.
An improved design of the prototype developed by the FH Aachen, the Enceladus Explorer, could be used to explore water filled cracks on the Saturn moon Enceladus some day. Before starting a space mission to Enceladus, the next step will be the exploration of the Taylor Glacier in the Antarctica. The probe will operate in this similar, smaller scale scenario in order to test the functionality of the systems.

ACKNOWLEDGMENTS

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