DEVELOPMENT AND TESTING OF A MANEUVERABLE SUBSURFACE PROBE THAT CAN NAVIGATE AUTONOMOUSLY THROUGH DEEP ICE

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ABSTRACT

The "IceMole" is a novel maneuverable subsurface ice melting probe for clean sampling and in-situ analysis of ice and subglacial liquids. In 2010, a first prototype was successfully tested on a Swiss glacier and demonstrated successful horizontal, upward, and downward melting capabilities. The probe also drove a curve and penetrated layers of "dirt". Within project "Enceladus Explorer" – or "EnEx"– a more ambitious IceMole probe is currently under development. The main objective of EnEx is to develop and test the technology that is required to navigate in deep ice, in preparation of the IceMole and the associated navigation technologies for extraterrestrial targets.

Key words: Ice melting probe; IceMole; Ice research; Mars; Icy moons; Europa; Enceladus.

1. INTRODUCTION

After the discovery that life can thrive in the most extreme icy environments on Earth [1, 2], it is now widely discussed that extraterrestrial life may also exist in environmental niches in the ice or in aquatic environments beneath the ice of other Solar System bodies [3, 4]. The objects which are considered to have the highest potential to harbor life are Mars [5], Europa [6], and Enceladus [7, 8]. Although their subsurface environments are scientifically extremely interesting, they are also extremely difficult to access. The required technology is developed and tested since 2009 at FH Aachen University of Applied Sciences' Astronautical Laboratory. "IceMole" is a maneuverable subsurface ice melting probe for clean sampling of ice and subglacial liquids and for clean in-situ measurements [9, 10].

Funded by the DLR Space Administration, a university research consortium[1], led by FH Aachen, currently develops a more advanced IceMole probe that includes a sophisticated system for obstacle avoidance, target detection, and navigation in deep ice. The main objective of this project, which is termed "Enceladus Explorer" – or "EnEx" – is to advance and test the technology that is required to navigate in deep ice.

In this paper, we **(1)** describe the IceMole design and report the field test results of the first prototype on the Swiss Morteratsch glacier, **(2)** discuss the main technological issues for the in-situ subsurface exploration of icy environments in the solar system, and **(3)** describe the Enceladus Explorer mission concept, including the developed probe and navigation solutions.

2. ICEMOLE

Ice melting probes have been used since the 1960's for terrestrial research in deep ice [13]. Those "pure" melting probes, however, have three major drawbacks: **(1)** they penetrate only vertically downwards and it is difficult to (intentionally) change their direction, **(2)** they cannot penetrate dust/sand/grit layers, and **(3)** they cannot be recovered from greater depths. The IceMole remedies these drawbacks of traditional ice melting probes. Its design is based on the novel concept of combined melting and drilling (or – more precisely – screwing) with a hollow ice screw – as it is used in mountaineering – and a max. 3-kW melting head at the tip of the probe (Fig. 1).

Figure 1. IceMole 1 melting head with hollow ice screw.

[1]The Enceladus Explorer Collaboration.

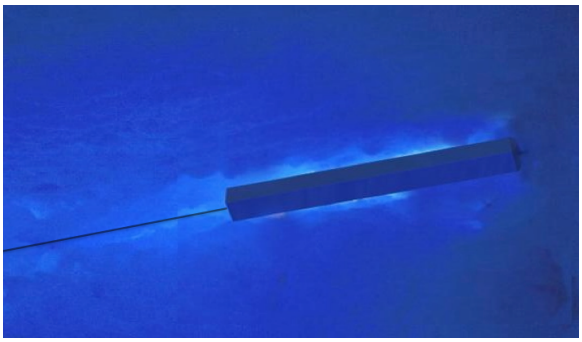

Figure 2. IceMole operations in deep ice (artist impression).

This design has three major advantages: **(1)** The ice screw provides a driving force that presses the melting head firmly against the ice. This guarantees good conductive heat transfer into the ice and allows to melt into any desired direction (Fig. 2), even upwards, against gravity. It even drags the probe through moderately thick[2] layers of dust/sand/grit. **(2)** The hollow ice screw, when being thermally isolated from the melting head, feeds clean ice into the probe, where it can be analyzed. **(3)** Uneven differential heating of the melting head generates a torque that forces the probe into a curve.

The IceMole probe has the shape of a rectangular tube with $15\,\mathrm{cm} \times 15\,\mathrm{cm}$ cross section (Fig. 3). The length of the probe is only constrained by the desired maneuverability. The quadratic cross section is required to counter the torque of the ice screw. The required electric power is generated by a surface aggregate and transmitted via cable (Fig. 4). In cold ice, the cable must be uncoiled from the probe because the meltwater re-freezes behind the probe[3]. The power cable is also used for communications and data transfer to the surface via a powerline modem. Although the IceMole design is currently adapted to the subsurface investigation of terrestrial glaciers and ice shields (mass $\approx 30\,\mathrm{kg}$), it will also be adapted for extraterrestrial ice research. A first miniaturized IceMole, called "MarsMole" (mass $< 5\,\mathrm{kg}$), will be tested by end of 2012 under simulated Mars conditions.

3. MAIN TECHNOLOGICAL ISSUES FOR THE IN-SITU SUBSURFACE EXPLORATION OF ICY ENVIRONMENTS IN THE SOLAR SYSTEM

The design and operations of any human-made robotic exploration device that has to work at (and below) the icy environments in the Solar System raises several technological challenges, especially for the remote icy moons of the giant planets. Their large distance from the Sun has implications for power supply and their large distance from the Earth has implications for the communications architecture and the required autonomy of the subsurface probe. Communications between the subsurface probe and the Earth requires a surface station and probably also an orbiter. After its deployment, the probe encounters a largely unknown environment that may contain areas with obstacles, which should be bypassed. This is only possible if the probe is steerable and able to sense obstacles in its closer environment. To navigate in the ice, a steerable probe also has to know its position and orientation without external references. Another key driver for the engineering of the probe is the pressure that is acting on it in deep ice.

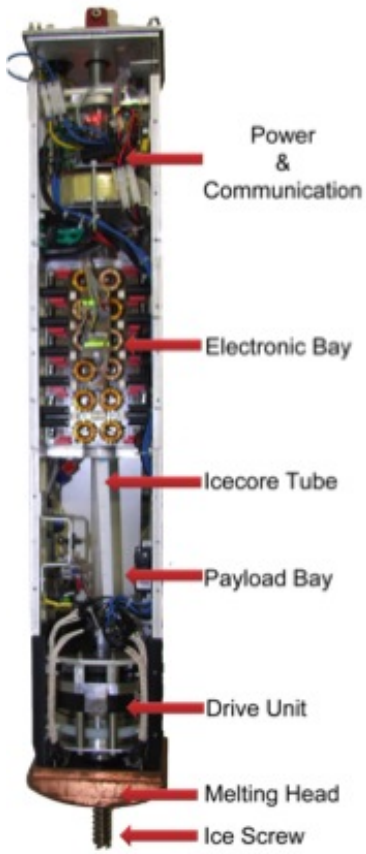

Figure 3. IceMole 1 assembly view.

Power Supply: Due to the large distance from the Sun, the solar radiation flux in the outer Solar System is very low. This has fundamental implications for the power supply of the surface station and the subsurface probe. For Europa and Enceladus, it seems impossible to avoid radioisotope heater units (RHUs) or even small nuclear reactors for several-kW ice melting probes. For a *small* Mars polar ice cap probe, however, power supply from

[2] It can probably not cope, however, with layers that are thicker than the length of the screw and with obstacles that are larger than the diameter of the screw.

[3] This is not necessary in temperate glaciers, where the ice temperature is $0°\mathrm{C}$, because the meltwater in the melting channel remains liquid. It is also not necessary in snow/firn, because the meltwater percolates downward.

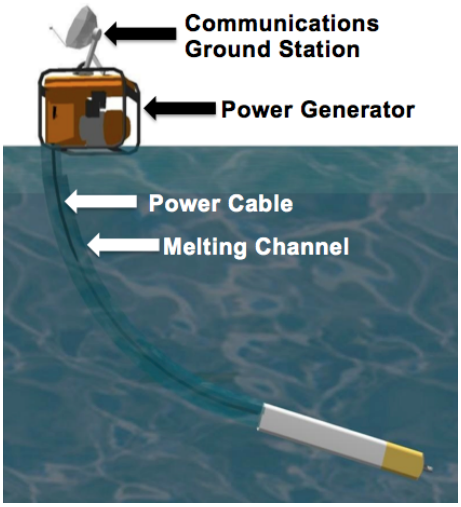

Figure 4. IceMole operations concept.

a surface solar generator may be feasible (during polar summer) because a heating power of ≈ 30 W may be sufficient [13, 14]. Because both RHUs and nuclear reactors generate direct heating power and because the conversion efficiency to electric power is limited, they should be located inside the subsurface probe. For terrestrial ice melting probes, the traditional power transmission between the surface station and the probe is by cable, paid out from a coil in the probe [13]. The delivery of heating power to greater depths, however, is challenging due to both mechanical and electrical constraints. High voltages (up to several kV DC) must be considered for the power supply of several kW to minimize resistive losses in the cable. The thickness of the cable, along with the available total volume for its storage, is the limiting factor for the achievable penetration depth. The IceMole concept foresees a "train" of cable containers that do not restrain the maneuverability of the probe and remain at their current location in the ice, when their part of the cable is completely uncoiled. Because the empty containers are still powered, they may be equipped with repeaters and sensors, so that a supplementary sensor chain can be deployed within the ice. While the IceMole may be recovered from the ice (because it can melt upwards), this is not possible for the cable and the cable containers.

Prevention of Blocking: Great care has to be taken, particularly in cold ice, to ensure that the re-freezing of ice alongside and behind the probe is slow compared to the melting velocity, in order not to jam the probe. While this is not an issue for moderately cold terrestrial glaciers, it is critical for very cold ice [15]. Therefore, low-temperature melting probes must foresee heating elements distributed along the side walls of the probe. Another problem with natural ices is the emplacement of components that cannot be molten, like dust or salts, because the dust concentrates underneath the melting tip, building up an insulating layer and increasing the friction. To solve this problem, JPL's Cryobot foresees an active water jet system that splashes and pumps away the debris that accumulates at the melting head [16]. An ice screw at the tip of the probe, however, as used by the IceMole, that drags the probe through such layers seems to be a more robust solution.

Gravity Dependence and Attitude Control: Traditional melting probes require the force of gravity to set the direction of penetration, which is only vertically downwards. Therefore, they would not work in microgravity environments. Such probes are also inherently unstable, so that the slightest deviation from the vertical direction results in an increasing tendency to "lean" and finally to "topple over" [13], which is almost inevitable in inhomogeneous ice (with voids, cracks, dust layers, etc.). Therefore, they require some means of attitude control, even if their vertical orientation is only to be maintained. Using an ice screw at the tip, as in the IceMole, neither the direction of penetration nor the contact pressure between the melting head and the ice depends on gravity. The ice screw stabilizes the direction of penetration and active attitude control can be based on differential melting, i.e., by controlling the heating power in the head and along the side walls of the probe, which drives the probe into a curve. This allows gravity-independent operations under zero gravity conditions, e.g., on comets.

Obstacle Avoidance, Steerability, Autonomy, and Navigation: The large distances from the Earth to Jupiter and Saturn yield signal round trip times of $\approx 2-3$ hours, which require any robotic exploration system to operate as autonomously as possible. Autonomy is especially challenging for the exploration of extraterrestrial subsurface environments: in the ice, the probe encounters a largely unknown environment that may contain obstacles, such as inclusions of rocks and liquids, layers of dust, and cracks, crevasses, and voids, especially close to the surface. Therefore, the probe should be steerable and able to sense and bypass potential obstacles in its close environment. Depending on the mission objective, it should also be able to sense potential targets for scientific investigation, e.g., liquid-filled pockets and/or crevasses. To navigate in the ice, a steerable probe also has to know its position and orientation without external references. Therefore, the probe requires a sophisticated attitude control system and an attitude determination system that is based on inertial navigation.

Communications: Having a probe that is able to melt upwards, it may considered to return the probe to the surface and thus to avoid communications between the subsurface probe until it has returned. This would require, however, a very large degree of autonomy and would be associated with a high risk. It would also be very disappointing to loose the probe without knowing the reason for it and without having gained some data before. Therefore, we consider a communications link between the probe and the surface station as essential. Using a powerline modem, the power cable (with intermediate repeaters) can be used for data transmission. From the surface station, all data (science and housekeeping telemetry) will then be transmitted to Earth, probably via an orbiting spacecraft. The link between the surface station and the Earth can be based on standard space communications technology.

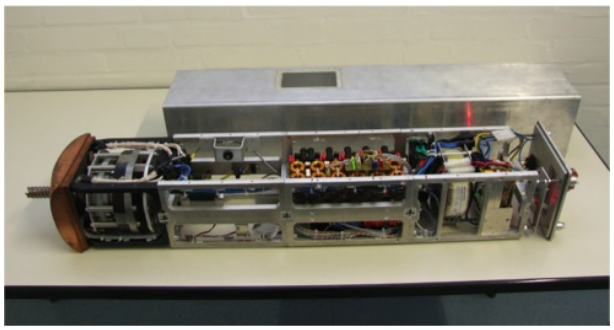

Figure 5. IceMole 1 (with casing removed).

Pressure: Subsurface ice probes must be able to sustain the ambient hydrostatic pressure as well as pressure transients from re-freezing and when reaching the ice/water interface of subglacial water/brine reservoirs. Two basic system architectures may be considered [13]: **(1)** a "dry" system architecture, based on a pressure-tight vessel, capable of structurally withstanding the maximum external pressures and housing all system components with sealed windows and openings, or **(2)** a "wet" system architecture, where at least parts of the probe can either be flooded with meltwater or are immersed in, e.g., silicone oil.

4. ICEMOLE 1 FIELD TESTS

A first IceMole prototype, "IceMole 1" (Fig. 5), was successfully tested on the Swiss Morteratsch glacier in September 2010 (Fig. 6). Three penetration tests have been made: **(1)** melting $45°$ upwards for $\approx 1.5\,\mathrm{m}$, against gravity (Fig. 7). **(2)** melting horizontally sidewards for $\approx 5\,\mathrm{m}$ (Fig. 8). **(3)** melting $45°$ downwards for $\approx 3\,\mathrm{m}$, thereby penetrating three obstructing non-ice layers (made from material found on the glacier) and driving a curve with a radius of $\approx 10\,\mathrm{m}$ (Figs. 9 and 10). The penetration velocity was $\approx 0.3\,\mathrm{m/hr}$ (but is planned to be increased to $\approx 1\,\mathrm{m/hr}$ for the next prototype).

5. ICEMOLE POTENTIAL FOR CLEAN IN-SITU ANALYSIS AND SAMPLING

Up to now, the test results show that the IceMole concept is a viable approach for the clean delivery of scientific instruments into deep ice (and recovering them afterwards), as well as for clean sampling. Contrary to conventional ice-core drilling methods, the IceMole does not utilize any drilling fluid and may by sterilized according to planetary protection standards before its subglacial deployment (additionally, an optional module for in-situ chemical decontamination of the probe during its melting through the ice is under development). In any case, the material sampled by the hollow ice screw at the tip of the probe does not come into contact with the exterior

Figure 6. Deployment of IceMole 1 on the Morteratsch glacier, Switzerland. Image credits: FH Aachen, www.forschungsfotos.de.

Figure 7. First channel, $45°$ upwards, $\approx 1.5\,\mathrm{m}$.

of the IceMole. Because the ice screw is thermally isolated from the melting head, the ice is fed into the probe's interior, where it may be analyzed in-situ. For the alternative clean sampling of subglacial liquids instead of ice, the liquids may be pumped through the hollow ice screw into sterile bags, from where they can be recovered after the probe has returned to the surface. Additionally, the direct pumping of water to the surface is an option.

6. ICEMOLE 2

Between 2010 and 2012, an advanced IceMole prototype, named "IceMole 2" (Fig. 11), was developed at FH

Figure 8. Second channel, horizontal, $\approx 5\,\mathrm{m}$.

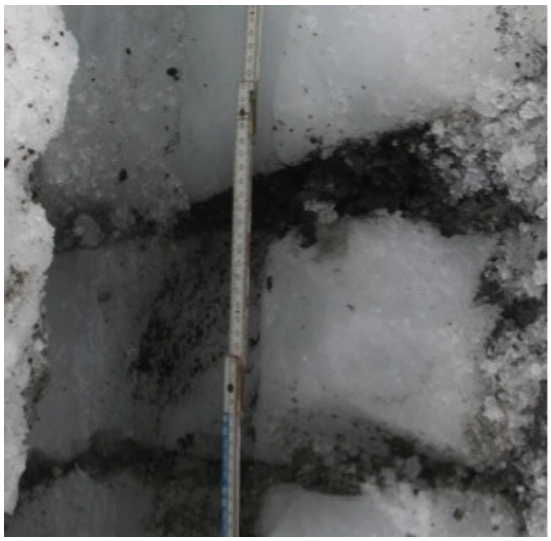

Figure 9. Third channel, $45°$ downwards, $\approx 3\,\mathrm{m}$, penetration of $\approx 4\,\mathrm{cm}$ of material found on the glacier.

Figure 10. Third channel, $45°$ downwards, $\approx 3\,\mathrm{m}$, curve with a radius of $\approx 10\,\mathrm{m}$ (channel was opened afterwards).

Aachen University of Applied Sciences. IceMole 2 has a better heater control system and thus better steering capabilities than IceMole 1. It contains an attitude determination system and should achieve an increased melting velocity of $\approx 1\,\mathrm{m/hr}$. In September 2012, IceMole 2 will be tested on the Icelandic Hofsjökull glacier and should demonstrate the recoverability of the probe by melting a "standing U" with a curvature radius of $< 10\,\mathrm{m}$ and a max. depth of $\approx 13\,\mathrm{m}$ (Fig. 12).

7. ENCELADUS EXPLORER

Although Europa is probably most interesting from the astrobiological perspective, access to subsurface material is easier on Enceladus. Recent analyses of Cassini measurements imply a subsurface salt-water reservoir on

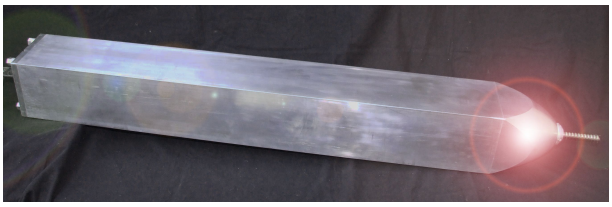

Figure 11. IceMole 2.

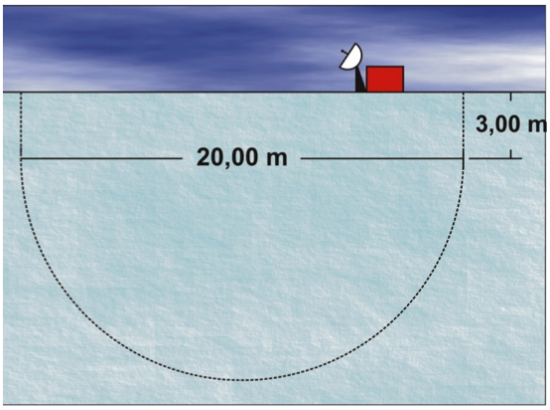

Figure 12. IceMole 2 field test scenario.

Enceladus, where ice grains containing organic compounds escape via cryvolcanism from "warm" fractures in the ice, known as "Tiger Stripes" [17]. Because landing in close vicinity to a water-bearing fracture is too risky, we propose to land at a safe distance and use a maneuverable IceMole probe to navigate to the fracture at a depth of $\approx 200\,\mathrm{m}$ below the surface (Fig. 13). Once there, the probe can sample and analyze the materials in the fracture.

Between 2012 and 2015, a university research consortium funded by the DLR Space Administration and led by FH Aachen University of Applied Sciences will develop an advanced IceMole probe, which includes a sophisticated system for obstacle avoidance, target detection, and navigation in deep ice. The main technical objective of

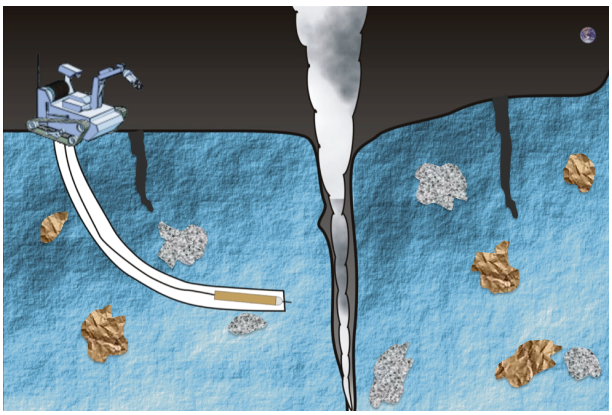

Figure 13. Enceladus Explorer operations concept.

the Enceladus Explorer or EnEx project is to develop and test navigation in deep ice, in preparation of the IceMole and its navigation technology for extraterrestrial applications. The EnEx probe will have an inertial measurement unit (IMU) and two magnetometers, one in the probe and one on the surface, to measure its attitude, which will then be used together with the advance of the ice screw to calculate the probe's position. An ultrasound sensor in the melting head should detect the targeted crevasse as well as obstacles in the ice. Additionally, acoustic pingers on the surface will measure the probe's position independently via triangulation. An intelligent multi-sensor fusion system will generate a consistent scenario from the raw data of the navigation sensors for the operator, and maybe later for autonomous control. It will also optimize the probe's trajectory in the ice with respect to available resources, time, and risk. The EnEx probe will also feature a clean mechanism for sampling of subglacial brine from a crevasse. EnEx shall demonstrate the suitability of the developed technologies for navigation in a terrestrial analog test environment and not yet in the real Enceladus environment. Nevertheless, the operational requirements at Enceladus and a mission scenario will already be investigated within the EnEx project.

To validate the EnEx technology, it is intended to use the EnEx probe, in co-operation with a US team, in the Antarctic 2014/15 season for taking clean samples of a unique subglacial aquatic environment and extraterrestrial analog in the McMurdo Dry Valleys, Antarctica, known as Blood Falls, with subsequent chemical and microbiological analysis [11, 12]. Before the deployment of the probe at the Blood Falls, two intermediate field tests are foreseen to validate the cleanliness of the sampling method for the deployment at Blood Falls.

8. SUMMARY AND CONCLUSIONS

The IceMole technology, which was already successfully tested on a glacier, is a viable approach for clean sampling and analysis of deep ice and subglacial aquatic environments. More advanced probes are currently under development and will be tested in the coming three years in Iceland and Antarctica.

ACKNOWLEDGMENTS

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