Navigation Technology for Exploration of Glacier Ice With Maneuverable Melting Probes

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Abstract

The Saturnian moon Enceladus with its extensive water bodies underneath a thick ice sheet cover is a potential candidate for extraterrestrial life. Direct ex-

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ploration of such extraterrestrial aquatic ecosystems requires advanced access and sampling technologies with a high level of autonomy. A new technological approach has been developed as part of the collaborative research project Enceladus Explorer (EnEx). The concept is based upon a minimally invasive melting probe called the IceMole. The force-regulated, heater-controlled IceMole is able to travel along a curved trajectory as well as upwards. Hence, it allows maneuvers which may be necessary for obstacle avoidance or target selection. Maneuverability, however, necessitates a sophisticated on-board navigation system capable of autonomous operations. The development of such a navigational system has been the focal part of the EnEx project. The original IceMole has been further developed to include relative positioning based on in-ice attitude determination, acoustic positioning, ultrasonic obstacle and target detection integrated through a high-level sensor fusion. This paper describes the EnEx technology and discusses implications for an actual extraterrestrial mission concept.

Keywords: minimally-invasive melting technology, in-ice dead reckoning, acoustic positioning, acoustic reconnaissance, multi-sensor fusion, clean sampling

1. Introduction

1.1. Subglacial Liquid Water Reservoirs on Enceladus

It is now widely accepted that the presence of liquid water on planets and moons of our Solar System bears some potential for the development of extraterrestrial life. One astrobiologically relevant candidate is the Saturnian moon Enceladus [1, 2, 3]. At Enceladus' South Polar Terrain, ice grains that contain organic compounds are released and ejected into space through fractures, which are informally called Tiger Stripes. Those fractures are located along four parallel valleys, which are about 200 – 250 m deep and about 50 – 100 m wide [4, 5]. Measurements of the Cassini spacecraft imply that those jets or curtains of particles originate from a subsurface salt-water reservoir in contact with rock and that they are transported through the 30 – 40 km thick ice layer via cracks [6, 7]. Within the Tiger Stripe fractures, temperatures up to 167 K have been observed [8], significantly warmer than the expected 68 K for this region. On a smaller scale, modeled temperatures of hot spots approach 200 K [4]. This has most convincingly been attributed to latent heat carried by water from the subglacial ocean, and deposited via water vapor along the walls of the cracks. These locations are considered as promising regions for the search for extraterrestrial life forms.

1.2. Direct Subglacial Exploration

Currently, our ability to detect and characterize living organisms on distant bodies remains a search for biosignatures, such as polynucleotides, cellular structures, and expected metabolic products (e.g. CH₄), in samples observed and probed from space or returned to Earth [5]. Such biosignatures

are extremely difficult to characterize in a reliable way, and much more so once they have been exposed to the vacuum and the radiation of space. To carry out a scientific investigation, we hence seek to directly access and sample subglacial aquatic ecosystems by targeting water-filled cracks at a moderate depth in which liquid water still communicates with large water aquifers at deeper depth, e.g. a subglacial ocean. Direct exploration requires advanced accessing and sampling technologies. Such a technology is provided by the IceMole, a maneuverable, subsurface icecraft for exploration and in-situ analysis within ice [9, 10].

1.3. Joint Research Collaboration Enceladus Explorer

The IceMole combines drilling with an ice screw to control the contact force exerted on the ice with a differential heating system at the melting head and the main body of the probe. This enables the probe to melt along a curved trajectory or even upwards. Such melting maneuvers, however, imply an on-board navigation system capable of monitoring position and attitude and ambient environment of the probe at any point in time. This also is a main prerequisite for autonomous operations. Within the joint research collaboration Enceladus Explorer (EnEx), a sophisticated in-ice navigation system has been developed and integrated with the original IceMole probe into the EnEx system. Furthermore, an integrated clean access protocol has been developed and tested that allows contamination-free deployment and clean sample collection. In this publication, we provide a detailed introduction to the EnEx system, which consists of the IceMole melting probe enhanced by a navigational payload and a surface control module. In particular, we will describe

- 50 1. the general carrier and sampling system,
 - 51 2. the relative positioning based on attitude determination,
 - 52 3. the acoustic based absolute positioning,
 - 53 4. the ultrasonic fore-field exploration technology,
 - 54 5. a sensor fusion approach to consolidate the acquired data,
- 55 and present results from laboratory and field tests both in the European Alps,
56 and in the Dry Valleys, Antarctica.

57 **2. EnEx System**

58 *2.1. General Design*

59 The complete EnEx system consists of the EnEx-IceMole as well as various
60 surface based devices (figure 1). The EnEx-IceMole is a third generation
61 IceMole¹. Its concept is based upon earlier work on the first and second
62 generation IceMole probes [9, 10]. In its current version the probe has a cross
63 section of 0.15 m x 0.15 m and a length of 2.0 m, including a 6 cm ice screw at
64 the front of the melting head. It's mass is approximately 60 kg. Conceptually,
65 the probe consists of two parts:

- 66 1. The EnEx carrier system includes the melting head with the drive and
67 heating systems and a general body structure containing main circuit
68 board, communications and power control.
- 69 2. Modular payload assembled in custom boxes (dead reckoning box, acous-
70 tic box, sample container).

¹In this publication reference to the IceMole or 'the probe' refers to the EnEx-IceMole generation.

Figure 1: The EnEx system consists of the IceMole upgraded with navigational instrumentation and integrated with a surface power and control system. The surface component includes a ruggedized laptop for data integration and communication, a generator, a reference magnetometer and acoustic reference points. The IceMole probe is connected to the surface by a power cable which plugs into the generator and data cables communicating with the computer as well as with a water sampling tube. The IceMole includes the melting head with the drive and heating systems and a general body structure containing main circuit board, communications and power control. It contains a modular payload assembled in custom boxes (dead reckoning box, acoustic box, sample container), which can easily be pulled out for servicing.

71 Within the IceMole, parts of the carrier system are connected via a CAN bus,
 72 whereas the modular payload systems communicate over ethernet with the
 73 main circuit board and the surface control systems. The detailed design of
 74 the copper melting head can be seen in figure 2. Figure 3 shows the interior of
 75 the melting head. The convex head is equipped with two sets of eight heating
 76 cartridges of 200 W and 160 W which add to a maximum forward melting
 77 power of 2.88 kW. A standard mountaineering ice screw is mounted at the

Figure 2: CAD image of the highly integrated melting head. Two motors, (one being redundant to minimize risk), a gearbox and a customized data acquisition system operates the force-regulated ice screw. In order to take the water sample, a hollow proboscis can be deployed through the inside of the screw. Four phased piezo arrays are integrated into the melting head, one being dismantled in this schematic. The arrays are aligned crosswise around the screw leaning 7.2 deg to the outside.

78 center of the melting head. The drive system allows for a maximum power
79 of 25 W. It can be configured to maintain a contact force between 0 and
80 2000 N. Most types of glacier ice are not strong enough for the highest contact
81 forces to be applied, such that realistic values range from 300 N to 800 N.
82 In the nominal melting scenario the operator sets the heating configuration
83 and a maximum contact force. The resulting melting velocity is internally
84 regulated by a feedback control. Side wall heaters with a linear power gradient
85 are integrated along the hull ($0, 5 - 2 \text{ W/cm}^2$). Tests showed that the back
86 plate has to be heated as well to assure retraction capability in curved and
87 twisted channels. The back melting plate has a power output of up to 0.8 kW.
88 The proboscis for water sample acquisition is deployed from the hollow ice

89 screw (figure 2). The picture furthermore shows four ultrasonic phased arrays
90 and indicates the position of acoustic receivers. Both are components of
91 the navigation suite and will be detailed in section 3.2 on acoustic in-ice
92 positioning.

93 *2.2. Operating Interface and Surface Connection*

94 The IceMole has a threefold permanent connection to the surface station.
95 The three lines are all bundled inside a protecting spring wire reinforced
96 polyurethane hose. It has a total length of 40m. The bundled tether is
97 uncoiled from a cable drum at the surface. The single lines are:

- 98 1. A data line connection to the surface computer system: Full-duplex
99 mode communication between the IceMole main computer, the payload
100 systems and the computer at the surface station is realized via ether-
101 net (1000BASE-T). A RS422 time synchronisation line for the acoustic
102 positioning is also provided (section 3.2).
- 103 2. A power cable with 3x2,5mm cross section (eq. AWG13) connecting
104 the probe to the generators (2x 3kVA, 230V line voltage): This cable is
105 additionally used for communication via a power line modem. Hence, a
106 redundant communication method is available to minimize the risk of
107 losing the probe.
- 108 3. A fluid tube connection, which operates in two different modes: (1)
109 upward pumping of meltwater or any other liquid present in the melting
110 channel and (2) downward pumping of a sterilizing hydrogen peroxide
111 solution.

112 The IceMole is operated from within a custom-built EnEx Graphical User
 113 Interface (EnEx GUI) operated on the surface computer. It yields real-time
 114 data and control access to the heating system, the ice screw and the internal
 115 sensors (temperature, pressure, etc.). The EnEx run control software displays
 116 a summary status of the IceMole and is responsible for the surveillance and
 117 control of the EnEx GUI and the navigation subsystems. Communication
 118 with the subsystems is handled by the User Datagram Protocol (UDP).
 119 Besides its surveillance tasks, the EnEx run control initiates automatic stops
 120 of the IceMole to guarantee undisturbed data acquisition for the navigation
 121 subsystems. These stops are referred to as *measurement stops*. First, a stop
 122 command is sent from the EnEx run control to the EnEx GUI. Once the
 123 EnEx GUI receives information about the upcoming measurement stop, it
 124 turns off the heaters, stops the drive and tightens the screw, to bring the
 125 IceMole into a stationary state. Then, the measurement sequence starts.
 126 Afterwards, a data summary is displayed in the EnEx run control software
 127 to verify data quality. Finally, the data is passed onto the high-level sensor
 128 fusion module (section 3.4). Results of the sensor fusion are displayed in the
 129 EnEx navigation GUI and provide operator support for strategic decisions
 130 during mission execution.

131 2.3. Melting Motion of the IceMole

132 A heating power of the forward melting system of 2.88 kW has been
 133 determined in the design phase as the heat flux necessary to maintain a
 134 melting velocity of 1 m/h for the probe cross-section of 0.15 by 0.15 m².
 135 Contingencies account for conductive losses and the fact that the melting
 136 channel will be somewhat larger in area than the IceMole itself. This approach

Figure 3: This image shows the backside of the melting head. The four acoustic receivers are located in the corners, the phased piezo arrays are aligned crosswise around the centered screw. Close to the center the tubing for sample retraction and the warm water emergency system can be seen. Four fluid releases are distributed across the melting head to assure optimal spreading of the sterilizing fluid.

137 is following [11] and assumes a standard atmospheric pressure of 1 bar as
 138 well as an ice temperature of -17°C , such as expected at Taylor Glacier
 139 in Antarctica. This approach is well established for conventional melting
 140 probes [12]. In order to analyze geometry and surface material influence
 141 on the melting performance however, one has to go beyond a bulk energy
 142 balance consideration and set up a spatially realistic close-contact melting
 143 model. Close-contact melting [13] can be observed whenever a heat source,
 144 in our case the melting head, is pressed against a phase-change material, in
 145 our case glacier ice. For the IceMole, this contact force results from probe
 146 weight and the pulling force exerted by the ice screw. Melting in the vicinity
 147 of the probe induces its motion into the glacier. The probe is separated
 148 from ice by a very thin liquid film (figure 4). Characteristic scales in the

Figure 4: Sketch of the microscale liquid film in front of the probe which is generated between the heated probe and the ice. The width of the melting head is indicated by l . The phase-change is assumed to occur along a clearly defined interface (located at δ) which is at melting temperature T_m . Tangential and normal fluid velocity are given by u and v . For a given heater and ice screw configuration, the probe is assumed to descent into the ice at constant melting velocity U . Pressure and temperature of the melt are denoted by p and T .

149 system are the thin-film parameter (aspect ratio of melt film thickness and
 150 width of the probe), the Reynolds Number and the Peclet Number. For
 151 terrestrial conditions, both thin-film parameter, and Reynolds Number will
 152 be very small, and provide a supporting rationale for the solution commonly
 153 chosen in the literature [13]. Namely, melting velocity, melt film thickness
 154 and temperature profile are calculated from incompressible lubrication theory
 155 coupled to an open boundary heat equation, known as a Stefan problem. The
 156 position of the phase-change interface is given implicitly by requiring a local
 157 heat balance at the interface. The mathematical system is numerically solved
 158 in two and three dimensions [14]. Reflecting the heater control, the model
 159 is implemented with a constant temperature at the probe's melting head.

160 For moderate contact forces this boundary condition realistically models the
 161 thermal situation of the IceMole. For a high contact force (higher than the
 162 maximum force of 800 N usually observed in field test), a constant temperature
 163 at the melting head implies heat fluxes exceeding the available power of the
 164 IceMole (2.88 kW) and this boundary condition would not be appropriate.
 165 Results are in good agreement to [15], who state that a paraboloid melting
 166 head is optimal in terms of efficiency. For curvilinear melting we observed
 167 good agreement between simulation results and laboratory experiments [16].
 168 Set up for the IceMole system design, simulations indicate a non-uniform
 169 temperature distribution and the development of cold ice cones in front of the
 170 acoustic phased arrays (figure 2). In accordance to that, melting velocities
 171 observed in field tests have been lower than predicted by the classical theory.
 172 These observations can be attributed to the lower thermal conductivity of the
 173 sensor’s epoxy surface as compared to copper. A copper casing of the phased
 174 arrays improved the situation, as has been observed in both experiment and
 175 simulations. Though this modification in principle assures the IceMole’s
 176 melting capability on terrestrial glacier ice, the application of front-viewing
 177 sensors to much colder ice, e.g. on Enceladus, implies a revision of the current
 178 melting head design.

179 *2.4. Clean Sampling System*

180 Two of the field tests have been conducted in Antarctica. Hence, the
 181 EnEx system had to be in compliance with the Antarctic Treaty that provides
 182 requirements for operating instrumentation in the pristine Antarctic ecosystem
 183 of Blood Falls [17]. Thus, the sampling and instrument operation has to
 184 be conducted in a manner that prevents contamination of the test sites.

185 Cleanliness is also a key aspect for any extraterrestrial mission to avoid
186 contamination of a potential extraterrestrial habitat and to maintain integrity
187 of any detected signs of life. Therefore special procedures for cleaning and
188 sterilizing of the contacting hardware and bioload monitoring during assembly,
189 before launch and during the mission were taken into account. The clean
190 access strategy is introduced in greater detail in [10]. In this paper we restrict
191 ourselves to a description of the technological aspects of the clean sampling
192 system.

193 *2.4.1. In-situ Decontamination and Sample Quality Assurance*

194 The IceMole has an integrated Clean Access and Sampling Subsystem
195 (CASS). In-situ sterilizing is conducted before the probe reaches its target.
196 For this step, any remaining melt water in the melting channel is pumped
197 out through an internal pumping system, which is optionally supported
198 by additional booster pumps towed behind the probe (figure 1). Next,
199 3% hydrogen peroxide is injected into the melting channel through four
200 orifices at the melting head, as well as through the sampling proboscis
201 (figure 2). Injection pressure is powered by an inert gas (argon or nitrogen)
202 that is connected to a pressure vessel filled with 100 dL of 3% H_2O_2 . Both
203 the inert gas cylinder and the tank containing the 3% H_2O_2 solution are
204 located at the surface station and connected to the IceMole by the fluid tube
205 connection (see 2.1). The operating pressure for the decontamination system
206 is approximately 10 bar. After an appropriate reaction time (approximately
207 15 min) the decontamination fluid is no longer traceable and the probe is clean.
208 Now the probe can approach the target and tap the water filled crevasse with
209 the proboscis deployed by a pneumatic system. A first sample is pumped to

210 the surface for testing. This strategy assures that no remaining H_2O_2 solution
211 is in either tubes or melting channel. Once cleanliness has been confirmed,
212 pristine brine samples are collected into two internal, sterile, gas-tight sample
213 bags (5 dl each). The sampling bags are located in two separate gas tight
214 boxes and connected to the proboscis through a series of valves. The bags are
215 filled by producing an under-pressure in the sample bag boxes (approximate
216 filling time is 180 sec). Optionally, the brine can be pumped to the surface
217 directly through a hose and sampled there by the booster pumps. Although
218 the latter seems to be the simpler approach, care has to be taken as the
219 sample alters its biochemical structure immediately after being exposed to
220 oxygen in the air.

221 2.4.2. *Emergency Rescue System*

222 Clean access not only means to avoid contamination of the environment and
223 assurance of a clean sample, but also to minimize the risk of losing the probe in
224 the melting channel since the probe itself represents potential contamination.
225 In addition to its main function, the CASS provides an emergency rescue
226 system for the IceMole in case of a complete system failure and loss of
227 communications. In this case, the pressure vessel of the decontamination
228 system on the surface will be filled up with clean hot water. The hot water
229 will be forced through the fluid tube to the orifices at the melting head and
230 will release the ice screw from the ice, allowing the probe to be extracted
231 through the melting channel and returned to the surface.

232 3. In-ice Navigation

233 Within the EnEx project a sophisticated navigation solution has been
234 developed and integrated into the probe’s navigation suite. It consists of four
235 modules:

- 236 1. Dead Reckoning (DR) based on inertial and magnetic attitude determi-
237 nation,
- 238 2. an Acoustic Positioning System (APS) that yields the absolute position
239 based on trilateration of acoustic signals,
- 240 3. an Acoustic Reconnaissance System (ARS) based on sonography for
241 fore-field exploration, and
- 242 4. a high-level Sensor Fusion (SF) unit to integrate the acquired DR, APS,
243 and ARS data.

244 The four modules are described in detail in the following subsections.

245 3.1. DR for Relative Position and Attitude Determination

246 Dead Reckoning (DR) means to determine the position of the melting
247 probe relative to a given starting point based upon its attitude evolution and
248 information on the distance traveled. The distance traveled is determined
249 by counting the motor-steps and correct them by gear ratio and ice screw
250 thread pitch. The attitude of the IceMole is determined by an Attitude and
251 Heading Reference System (AHRS) which relies on gyroscope readings of
252 an Inertial Measurement Unit (IMU). In a second step the AHRS attitude
253 solution is fused with the magnetic heading determined from differential
254 magnetometry to limit drift and improve accuracy. Both AHRS, and the

255 differential magnetometer system are described in the following subsections.
256 Further details can also be found in [18].

257 3.1.1. Attitude and Heading Reference System

258 Long mission times of up to 100 h and more and slow translational and
259 rotational motion are major challenges for inertial sensors. High angular
260 accuracy is needed to achieve a position accuracy of 1 m for a distance of 60 m.
261 Priority is to control the system drift, while the update rate is of secondary
262 importance. Usage in polar regions limits the accuracy of the independent
263 determination of the north direction. The chosen fiber-optic gyroscopes (FOG)
264 type inertial measurement unit (IMU) Northrop Grumman LN-200 matches
265 both, the performance requirements and additional geometric constraints in
266 the IceMole's DR box (figure 1). Data and power conversion is tailored to the
267 IMU specifications. Integration angles, sensor biases and noise parameters
268 for the Kalman filter have been determined from rate table tests and Allan
269 variance analysis [19]. The AHRS algorithm carries out a quaternion based
270 strap-down attitude calculation. It is corrected by a Kalman filter, which
271 uses gravity aiding by the accelerometers as well as heading updates from the
272 differential magnetometer system. Important steps of the algorithm are:

- 273 1. Initial Alignment: The initial alignment of the IMU with respect to
274 a north-oriented, local navigation frame is a crucial step in order to
275 keep initial errors small. It is performed by measurements of the Earth
276 rotation vector $\omega_{\mathbf{E}}$ and the gravity vector $\mathbf{g}$. At first the east-axis is
277 defined as the cross product of $\mathbf{g}$ and $\omega_{\mathbf{E}}$, and secondly the north-axis is
278 defined as the cross-product of east-axis and $\mathbf{g}$. The alignment procedure

Figure 5: Diurnal magnetic field intensity measured in the Dry Valleys, Antarctica. Long-term variations in total intensity are shown with overlaid short-term variations such as noise. The change of noise level in the intensity plot before 19:00 correlates with the sunset.

- 279 takes at least four minutes. Its duration could be further shortened by
- 280 additional consideration of the magnetic heading and fine alignment
- 281 filtering.
- 282 2. Attitude propagation by gyroscopic readings: Since the IceMole is able
- 283 to operate with steep pitch angles and vertically, the attitude propaga-
- 284 tion algorithm is based on a singularity-free quaternion implementation.
- 285 Differential change of the quaternion is determined using the last avail-
- 286 able attitude, the fraction of the earth rotation in the update interval
- 287 and the rotation rate measured by the gyroscopes [20].
- 288 3. Error state prediction through a Kalman filter: Despite initial calibra-
- 289 tion, small sensor errors cannot be totally avoided and there will be

an offset between true and calculated attitude of the IceMole. The AHRS is very sensitive to errors of the gyroscopic readings, such that a small initial sensor bias will produce large attitude errors eventually. Hence, further error correction is necessary. Updates from the magnetometer system and the APS can be used to correct residual attitude errors, while the prerequisite is that the AHRS filter is robust enough to continue operation with imprecise initial attitude estimation. In this project, a filter based on the Psi-angle error model [21, 22] was adopted to the melting case. The filter uses a nine state design, including attitude and the gyroscope errors biases and scale factor errors. The system noise model is based on the LN-200 gyroscopes random walk, rate random walk and bias stability. The observation model noise uses the accelerometer noise, as well as an estimate of the magnetometer heading accuracy. The approach is further detailed in [18].

4. Filter update based upon gravity and heading updates: The differential magnetometer system provides heading updates during regular measurement stops. In the absence of forward motion, accelerometer readings only contain gravity, sensor errors and noise, but no kinematic acceleration. Collectively, the magnetic heading and stationary gyroscopic readings are used for filter updates. Furthermore, the AHRS algorithm is aided by an error approximation conducted during SF.

3.1.2. Differential Magnetometer System

The magnetometer system yields independent attitude data based on measurements of the surrounding magnetic field by means of scientific fluxgate magnetometers. The sensors have a measuring range of 65.000 nT, a resolution

315 of 7, 75 pT, and a maximum sampling rate of 100 Hz. Sensor noise is low with
 316 20 pT @ 1 Hz. These specifications assure a high resolution and a measuring
 317 range larger than the Earth's magnetic field. To provide magnetic heading,
 318 two magnetometers are used: One is integrated into the DR box aboard the
 319 IceMole, the other one serves as a static magnetic heading reference and is
 320 installed at the glacier surface (figure 1). The use of a reference measurement
 321 (instead of a reference model of the Earth's magnetic field) is advantageous,
 322 when applying the system in regions close to the magnetic pole, or when
 323 significant variations in the magnetic field are expected. For test sites relevant
 324 to the EnEx project, alterations of the magnetic field are significant. Figure
 325 5 shows the variation of the magnetic field intensity at a glacier test site over
 326 a period of about 8 h. It varies in the range of 40 nT, which is about 0.1%
 327 of the total magnetic field. This translates into a maximal heading error of
 328 about 1°.

329 Requirements for the application of the reference magnetometer in the
 330 field are a static position at constant attitude and a location in a magnetically
 331 relatively clean environment with few disturbances. It has to be leveled, such
 332 that its z-value (long axis) corresponds to the z-axis of the navigation frame
 333 (plumb line). Especially when being exerted to intense solar radiation, such
 334 as in the Antarctic summer, it can happen that a slow tilt is induced due
 335 to melting underneath the magnetometer's legs. This tilt translates into a
 336 small deflection of the magnetometer's z-axis with respect to the z-axis of
 337 the navigation frame. Such a deflection can be eliminated during processing
 338 of the recorded data based on an independently available measurement of
 339 the direction of gravitational acceleration (IMU). Hence, this is not critical.

Figure 6: Magnetic heading during motion and measurement stop. Between 18:08 to 18:09 a single, and last rotation of the ice screw is visible after the side heaters were turned off. Single magnetic bursts are cut being too high ($> 5^\circ$) to be taken into consideration.

340 Instead, rotation around the z-axis would be more critical, however, this
 341 would require a z-axis torque acting on the magnetometer, which cannot
 342 easily be induced by melting. Also, short-term disturbances at the reference
 343 are very small and can be neglected. The angle between the z-value and
 344 horizontally measured values is referred to as the local inclination, the angle
 345 between sensor y and x-axis as magnetic heading of the reference.

346 Magnetic measurements have to be corrected for distortion errors due to
 347 secondary magnetic fields induced by magnetic materials, electromagnetic
 348 sources and magnetic reluctance. This is especially true inside the IceMole.
 349 To correct for magnetic disturbances in the acquired data, a magnetic baseline
 350 model of the IceMole has been developed. Generally, the disturbance of a

351 magnetic field is modeled as an ellipsoid, characterized by its eigenvectors
 352 and center. Without any disturbance, the ellipsoid is given by a centered
 353 sphere. The matrix which transforms from a centered sphere to the ellipsoid is
 354 referred to as the correction matrix and corrects for errors associated with this
 355 particular disturbance. The ellipsoid itself is determined by measurements
 356 in a special calibration unit, which is magnetically calibrated beforehand
 357 and assures a clean background. For the IceMole both static, and dynamic
 358 disturbances (and corresponding correction matrices) have been determined.
 359 Static calibration was conducted by acquisition of approximately 150 measure-
 360 ments, while performing various rotations through specific orientations. The
 361 ellipsoid is then given by a best-fit. Corrections have accounted for as much
 362 as 10% of the measurement value per sensor axis. To account for the dynamic
 363 disturbances, each disturber has been considered individually by measuring
 364 its isolated effect on the magnetic field. This yielded a set of correction
 365 matrices each of which is associated to one disturber. A particular IceMole
 366 configuration corresponds to a set of disturbances to be active. In order to
 367 correct for their combined error all correction matrices of the associated set
 368 are applied to the raw magnetometer data.

369 A significant noise level is present in the magnetic field of the IceMole,
 370 which makes data interpretation difficult. Figure 6 shows typical magnetic
 371 heading noise levels during a field test. In this common drive-cycle the
 372 measured heading noise drops significantly during a measurement stop, when
 373 at first heaters and then the motor are turned off. The increase of noise
 374 displayed in figure 7 was a result of turning on the side wall heaters. Although
 375 the induced noise is non-zero and adds a constant aberration to the heading,

Figure 7: Comparison of uncorrelated heading data from AHRS and magnetometer. While AHRS heading drifts over time, the magnetic heading has non-observable modeling errors. The period of increased noise level between 17:45 and 19:30 indicates the use of the side wall heaters.

376 it can be eliminated by using a low-pass filter and an estimate filter to reduce
 377 the error. In addition to that, no significant remanence appears from the
 378 induced magnetic fields. Though an induced magnetic field can be observed
 379 from the stepper motor and heaters, this generates no significant remanent
 380 magnetisation onto the materials used in the IceMole. The induced magnetic
 381 field of the stepper motor or heaters disappears after short time. Based on
 382 the detected noise the covariances for later fusion are adjusted.

383 The magnetometer raw data recorded on-board the IceMole yields a
 384 magnetic field vector that indicates the attitude of the fluxgate sensor relative
 385 to the local magnetic field. To determine the magnetic heading from the
 386 measured magnetic field vector, it is rotated into a North-East-Down (NED)
 387 coordinate system. The transformation matrix (direction-cosine matrix) relies
 388 on an independent measurement of the gravity vector by the IMU. In a
 389 next step, the rotated vector is projected onto the xy-plane of the NED
 390 coordinate system and evaluated as the magnetic heading Ψ . With the

391 local declination and inclination (DI), the magnetic heading Ψ can finally
 392 be converted into geographic north. Prior knowledge of DI can be acquired
 393 by external alignment given by AHRS (standard procedure during EnEx
 394 operations) or SF, or alternatively, by using less precise look-up tables. Any
 395 reoccurring alignments during a mission improves the initially determined
 396 DI and will have a positive effect on the accuracy of the navigation results.
 397 It can also be used to model the surrounding environment of the IceMole
 398 during mission and update the IceMole magnetic model for compensation.
 399 However, reliability of DI data is depending on both external alignment as
 400 well as magnetic sensor variances and should therefore only be acquired once
 401 the local magnetic field is no longer influenced by disturbances, e.g. induced
 402 by the IceMole launch pad.

403 3.1.3. *Collective AHRS and Magnetic Data Processing*

404 Both the attitudes determined from AHRS, and the magnetic heading
 405 have complementary advantages and drawbacks. The error of an AHRS-only-
 406 heading varies depending on its alignment state. Starting from a small error
 407 with a new alignment, the error increases during a mission and suddenly drops
 408 during the realignment. Though in principle, magnetometer-only-headings
 409 would have low noise and negligible ascending errors, there is a significant
 410 distortion of results due to the presence of a-priori unknown magnetic sources
 411 and secondary magnetic fields during run-time. These previously unknown
 412 errors depend on position, attitude and state of the IceMole. The impact
 413 of the heating system on the noise level of the magnetometer sensors is
 414 visible in figure 7. This figure also shows the differences between AHRS and
 415 magnetometer heading. State driven changes of the magnetometer reading

Figure 8: Qualitative comparison of heading variances: The upper left plot indicates the increasing covariance errors of the AHRS heading during mission due to drift between realignments of the system (initial alignment in T1, realignment in T4 and T6). The upper right plot indicates the variance of the magnetometer heading due to system-noise or external disturbers, e.g. the starting ramp between T0 and T1 or low noise at measurement-stops (T5-T6). The lower left plot shows the variance of the magnetometer bias (DI) estimation, which drops to the level of realignment data at T2 and T6 (but not in T4 with non improving correction data) and increases in between corrections due to physical movement into other areas of unknown DI (limited by look-up table values). Finally, the calculated and passed heading variance equals a superposition of the bottom left and top right variances as shown in the bottom-right plot.

416 on a conceptual level are shown in figure 8, upper-right. The increase of
 417 uncertainty due to passing an unknown disturber is shown in figure 8, lower-
 418 left. To provide one attitude result for further processing in the DR algorithm,
 419 AHRS attitude, magnetometer heading and reference corrections are fused
 420 based on variances of the measurements and states of the relevant subsystems.
 421 The full conceptual schematic indicating the qualitative characteristics of the
 422 AHRS and magnetometry fusion (AHRS/MAG) is given in figure 8.

Figure 9: Overview of the navigation data process chain: The white boxes indicate sensor input data, the light grey box indicates output and the dark grey boxes indicate data processing steps. The IMU raw data is processed within the AHRS. It furthermore determines the gravity vector (G), which is used to calculate magnetic heading (MAG heading) from magnetometer data (MAG, reference MAG). Both results are combined yielding the drift stabilized attitude of the IceMole (AHRS/MAG). Next, DR based on the attitude estimate AHRS/MAG and information on the traveled distance yields a predicted state of the IceMole. Subsequently, the predicted state is corrected with APS measurements. The corrected state is both used in the next prediction step, and enables computation of a global 3D map from ARS measurements. State of the IceMole as well as the computed map are visualized for the operator and can be used for trajectory planing and autonomous navigation.

3.1.4. Dead Reckoning Algorithm

The main steps of the DR algorithm and its connection to the global Sensor Fusion (SF) are displayed in figure 9. DR is calculated from AHRS/MAG fusion and the axial speed data generated of the ice screw turn rate. A launchpad odometer yields information on the used rope length and provides additional input. DR is conceptually a part of the relative position and attitude determination (section 3.1). Due to its role as predictor in the calculation of the final IceMole state, however, its effective implementation is integrated into the high-level SF (section 3.4), in which results of the DR are

also further processed. Reliable external updates via the SF from e.g. APS are available only at certain points in time, hence the AHRS/MAG fusion represents the major source for the navigation system in between external updates. Both AHRS/MAG, and DR have been tested successfully under laboratory conditions and in various field campaigns. The system was able to perform initial alignment as well as continuous tracking of the probe's attitude and position. Updates during measurement stops were used successfully for the stabilization of the heading drift. Particular scenario examples are further outlined in the section on field test results.

3.2. Acoustic Positioning System

3.2.1. Principle of the APS

The Acoustic Positioning System (APS) provides data on the absolute position of the IceMole within a volume of glacier ice [23]. Subsets of this data are used by the SF to correct the drift of the position provided by DR (section 3.1). As stand alone system the APS is based on trilateration which is the determination of the unknown position of an object, here the probe within ice, by measuring the distances to at least three other objects of known position [24]. These distances are obtained by measuring the propagation times of pulsed ultrasonic signals between the emitters at the ice surface and the receivers within the probe [23] (figure 10). Given the signal propagation times, the speed of sound in ice and the known emitter positions, the position of the probe can be reconstructed for a specific time. Monitoring the position over time yields the trajectory of the probe.

Figure 10: Principle of the APS: The absolute position of the probe within ice is determined by trilateration. For this purpose the distances between the emitters at the surface and receivers within the probe are determined by measuring the propagation times of pulsed ultrasonic signals.

455 3.2.2. *Acoustic Properties*

456 In order to achieve accurate acoustic in-ice navigation it is essential to
 457 know the physical parameters regarding the speed of sound as well as the
 458 attenuation in ice. This project was focused on the properties of terrestrial ice.
 459 Future missions to Enceladus have to be based on sufficiently autonomous
 460 instruments capable of adopting algorithms to the specific ice structure and
 461 quality and calibrate them with parameters determined at the landing site.

462 Generally, sound waves propagate in solid materials as pressure and shear
 463 waves [25]. Pressure waves travel much faster in ice than shear waves and
 464 are therefore the first to be detected [26]. For pressure waves the speed of
 465 sound in glacier ice is about 3600 m/s^2 . However, due to inhomogeneities

²Measured during the field campaigns carried out within the EnEx project.

466 and density gradients in glacier ice the speed of sound is not constant but
 467 depth dependent [27, 28, 29]. Strength and therefore quality of the received
 468 acoustic signals is influenced by attenuation which is composed of absorption
 469 and scattering. While the first reduces the received amplitudes and limits
 470 the sensitivity, scattering leads to changes in arrival times. Like the speed
 471 of sound, attenuation varies with depth and depends on ice structure and
 472 inhomogeneities. Compact, clear ice as it is found deep below the glacier
 473 surface attenuates less than firn ice, which contains many gas inclusions
 474 [28]. With the South Pole Acoustic Test Setup (SPATS) it was found that
 475 at a depth between 150 m and 500 m the attenuation length is about 300 m
 476 for frequencies between 10 – 30 kHz [30]. However, attenuation in ice is in
 477 general expected to depend on the frequency of the acoustic signal [31]. Low
 478 ultrasonic frequencies show less attenuation compared to higher ultrasonic
 479 frequencies, whereas higher frequencies provide better spatial resolution.

480 *3.2.3. System Design*

481 The APS consists of six ultrasonic emitters, four receivers, a signal genera-
 482 tion system and a data acquisition (DAQ) system [23] (figure 11 for a system
 483 overview). The signal generation system is situated at the glacier surface and
 484 the ultrasonic emitters are inserted into the glacier at a depth of about one
 485 meter. The receivers and the DAQ system are integrated into the IceMole
 486 head (figure 3) and the IceMole payload bay (figure 1), respectively. The
 487 APS is optimized for signal frequencies of about 18 kHz.

488 The acoustic emitters used in the APS are spherical, omnidirectional,
 489 piezoelectric (lead zirconate titanate) sonar pulse transducers. The net of
 490 six emitters is connected and controlled via the Field Programmable Gate

491 Array (FPGA) based Central Transducer Unit (CTU), which generates pulsed
492 signals. The signal from the CTU is amplified by the front end unit and then
493 passed onto the emitter. Additionally, the emitters can be used as receivers
494 which allows measurements from one emitter to another to investigate ice
495 properties, as detailed in the results section 4.4. The CTU also ensures
496 synchronization between the signal generation and the IceMole by a strobe
497 signal distributed via a dedicated cable. The accurate position of each emitter
498 is needed for trilateration and is determined via GNSS RTK ($\sigma = 2.5$ cm).

499 The APS receivers consist of a piezoelectric disk (lead zirconate titanate)
500 and specially dedicated front end electronics. Both, the piezo disk and the
501 front end electronics are encased by a metal housing to reduce electromagnetic
502 noise pick up. Good acoustic coupling of the piezo disk and the IceMole head
503 is achieved by pressing the piezo disk to the melting head. The front end
504 electronics contains two amplification stages including two analog filters, one
505 broad and one narrow passband. Both channels are digitized by analog-to-
506 digital (ADC) converters with 12 bit resolution and a sampling rate up to
507 2 MS/s.

508 Data acquisition is performed by the FPGA (Spartan-6 SLX 16) based
509 APS DAQ system. The DAQ system (figure 12) simultaneously reads the
510 digital outputs from the four receivers, stores the recorded waveforms and
511 then transfers these to an embedded PC (Raspberry Pi). There are two
512 possible digitization modes, one with a lower sampling rate but a higher
513 number of recorded waveforms per emitter and one with a higher sampling
514 rate but less recorded waveforms. The first mode records 64 waveforms per
515 emitter with a sampling rate of 500 kS/s, while the second mode records 32

Figure 11: APS system overview: The signal generation system is situated at the glacier surface and the ultrasonic emitters are situated about one meter below the surface. The receivers are integrated into the IceMole head and the DAQ system is integrated into the IceMole payload bay.

516 waveforms per emitter with a sampling rate of 2000 kS/s. In both cases the
 517 data acquisition window is about 32 ms starting one millisecond before the
 518 acoustic signal is emitted. This ensures that one millisecond of pure noise is
 519 obtained in each waveform. The DAQ system is synchronized with the CTU
 520 with an accuracy of better than $1 \mu\text{s}$.

521 Data preprocessing is performed by an embedded PC. To reduce noise
 522 the waveforms of each receiver are averaged and filtered using a band pass
 523 filter. The signal propagation time is determined by searching for the earliest
 524 point in time, when the noise level is surpassed by a factor of five. The noise
 525 level is defined as the standard deviation of the first millisecond of data. Raw
 526 data as well as signal propagation times are transferred to a central database
 527 at the surface via TCP/IP.

528 The APS is controlled by the operator via the EnEx run control software
 529 (section 2.2). Once a measurement cycle is initiated, signal generation within
 530 the CTU is triggered and simultaneously data acquisition is started.

Figure 12: Overview of the APS DAQ system for acquisition, analog and digital processing of the acoustic waveforms. Piezo disks and custom front end electronics are integrated into the IceMole melting head (box on the right), online processing is conducted in the IceMole’s acoustic box.

At the surface, data quality can be further improved in contrast to online processing by applying advanced de-noising techniques to the recorded data. For this purpose a combined de-noising method based on both wavelet transform and infinite impulse response filters [32, 33] has been developed. To ensure a reliable trilateration only signals are considered, which pass iterative consistency tests with respect to the reconstructed position.

The APS has been successfully tested in the laboratory, in full system swimming pool tests and in several field campaigns within both temperate and non-temperate glaciers. Further details can be found in section 4.

3.3. Acoustic Reconnaissance System

The Acoustic Reconnaissance System (ARS) is designed to detect possible obstacles or regions of interest in front of the probe. This fore-field informa-

Figure 13: Principle of the ARS: Acoustic waves are emitted by piezo transducers. The electronic system is switched to receiver mode and echoes reflected at structural inhomogeneities (e.g. stones, bubbles etc.) are then acquired by the same piezos. The arrangement of several piezo transducers in an array structure allows for steering and focusing of the acoustic lobe due to phase shifted emission of acoustic waves.

tion is acquired by sonography (figure 13), primarily known due to medical applications [34, 35] or material inspection [36, 37]. ARS uses emission of phased acoustic signals and the recording of respective echoes. Any disturbances within the ice like crevasses, stones, water or air filled pockets create echoes of the emitted signals due to the difference in acoustic impedance of the different media. Imaging is based on the amplitudes and time delays of the received echoes. To enable a scanning of the environment, piezo arrays are driven with phase shifted signals. This results in the formation of an acoustic lobe. By variation of the phase shift between the single piezo elements the direction and focal distance of the lobe can be adjusted [38, 39].

As in case of the APS, the performance of the ARS highly depends on the physical properties of the ice. The general dependencies are described in section 3.2.2. Since the ARS uses higher signal frequencies than the APS the increased acoustic attenuation has an even higher impact on signal

557 propagation. Due to the direct contact with ice, the physical properties of
558 ice and the harsh environment in which the phased arrays have to work, e.g.
559 high temperature gradient and high pressure on the active surface, a design
560 had to be developed with specifications differing very much from typical off
561 the shelf products as used in medical and material testing applications.

562 3.3.1. System Design

563 In the melting head four linear phased arrays (Manufacturer: Imasonic,
564 Voray-sur-l'Ognon, France) are integrated crosswise around the ice screw
565 leaning 7.2 deg to the outside (figure 2 and 3). The phased arrays developed
566 for this application consist of 16 elements with a resonance frequency of
567 780 kHz inside a housing made of the same material as the melting head.
568 The active area is made of epoxy resin to adjust the acoustic impedance to
569 ice impedance. This configuration enables a steering of the acoustic lobe of
570 more than ± 45 deg with an overlap of the field of view directly in front of
571 the probe.

572 Pulse pattern generation and data acquisition is performed by one FPGA
573 based electronics per array to achieve phase shifting at very high precision.
574 An output stage transfers these logic pulses into high voltage and addresses
575 each of the 16 piezo elements of each array separately. Immediately after
576 all pulses are sent, the acquisition of acoustic signals arriving at 8 of the 16
577 array elements starts. Sampling is performed by amplification and high speed
578 digitization of 16 kilosamples at 2 MS/s, resulting in a maximum acquired
579 distance of approximately 15 m in water ice. An embedded PC is used to
580 handle the data and communicate with the surface.

581 The ARS system is controlled via the EnEx run control software. A

Figure 14: Left: Laboratory setup with a volume of 3 m^3 . This contains a 50 cm layer of bubble free ice above a 30 cm layer of liquid water. On top of the ice layer a phased ultrasonic array is positioned pointing into the ice. Right: A standard ARS B-scan. The labels A to D represent multiple passages of the wave between the ice surface and the bottom of the container, where index 1 indicates the first reflection from the ice/water interface. Index 2 and 3 are multiple reflections between top and bottom of the ice layer and index 0 indicates the reflection from the bottom of the container superposed with index 3.

582 typical ARS measurement stop performs a scan from -45 deg to $+45 \text{ deg}$ in
 583 1 deg steps for each array. The data is transferred to a central database at
 584 the surface via TCP/IP (section 2.2). The acquired data is phase corrected
 585 and averaged for visualization. Absolute values of the signals are low pass
 586 filtered with a cutoff between 100 kHz to 500 kHz by applying a 3rd order
 587 Butterworth filter to create the envelope and then plotted in a 2D intensity
 588 graph. Finally, the graph is transformed to a polar mapping representing the
 589 scanned sector (B-scan).

590 3.3.2. Laboratory Tests

591 The system was tested in the Aachen Acoustic Laboratory at RWTH
 592 Aachen within a Polyurethane container with bubble-free ice volumes up to

593 3 m^3 (figure 14). Due to the limited volume numerous artifacts are measured,
594 as the acoustic wave travels multiple times back and forth. During the test
595 (figure 14) the volume was not entirely frozen and thus several echoes are
596 visible during each passage of the sound wave between different layers of
597 media. The main echoes visible are the reflection from the ice/water interface
598 and from the bottom of the container. As the speed of sound in bubble-free
599 ice (3838 m/s at 0° C [26]) is more than twice the speed of sound in water
600 (1400 m/s at 0° C [40]), the first reflected signal travels multiple times between
601 the top of the ice layer and the bottom of the ice layer before the echo from
602 the bottom of the container is detected. This pattern can be observed at least
603 four times, meaning that the signal traveled in total through 4 m of ice and
604 2 m of water. Moreover, the signal was attenuated at the ice/water interface
605 (40% loss), the reflection at the bottom of the container (80% loss) and the
606 phase transition from water to ice (40% loss) during each passage through
607 the container.

608 During a second test (figure 15) one phased array was integrated into the
609 IceMole in horizontal position and submerged in a swimming pool. Due to
610 the large volume of the pool, fewer artifacts were induced by wall reflections.
611 Spherical objects with a diameter of 20 cm filled with air or concrete were
612 spread throughout the pool as phantoms. Due to the lower speed of sound
613 compared to ice, the maximal acquirable distance is limited by the acquisition
614 window to about 6 m . All objects can be detected as reflections in the ARS
615 B-scan (figure 15). The difference in acoustic impedance of water as compared
616 to air produces a single, very well defined echo peak (total reflection) of the
617 air filled phantoms whereas the concrete filled phantoms produce two peaks

⁶¹⁸ (front and back side) of lower amplitude.

Figure 15: Top: Test setup in a swimming-pool ($17.7 \times 14.34 \text{ m}^2$) with spherical air (A1, A2) and concrete (C1, C2) obstacles with a diameter of 20 cm. The IceMole contained one phased array with horizontal scanning direction. Bottom: Scanned data (± 45 deg, 6 m sampling window); white circles mark obstacle positions measured at the water surface (± 5 cm). Side-lobe echoes (marked by *) are detected at the same distance and at a fixed angle deviation from the true object. Additionally the side lobe echoes are blurred and much lower in amplitude. Therefore, these side lobe echoes can be identified as ghosts which can be filtered out by advanced signal processing tools.

619 3.4. Multi-sensor Fusion and High-level Postprocessing

620 Multi-sensor fusion and high-level postprocessing enable the use of IMU,
621 MAG, DR, APS and ARS data for IceMole navigation purposes. In particular,
622 this provides an estimate of the current state x_t (position and attitude) of
623 the probe and a global map Y of the environment. An overview of the sensor
624 fusion and the data processing chain is shown in figure 9.

625 3.4.1. Data Handling and Time Reference

626 The data produced by all sensors and subsystems of the navigation suite
627 are stored in and distributed by a central database running on the navigation
628 notebook at the glacier surface. It provides a standardized interface via
629 TCP/IP and allows other subsystems to access not only the current but also
630 past data. This is especially important when systems run with different data
631 acquisition frequencies. In addition, the integrated mechanisms for dumping
632 and restoring the whole database or selected tables are used for backups
633 and post-processing. In practical tests this solution turned out to be fast
634 enough to handle both, small data with a high frequency (e.g. IMU data
635 with 200Hz) as well as large data with a low frequency (e.g. APS and ARS
636 raw data), simultaneous and in real-time. Furthermore it is important that
637 all subsystems share the same time reference. A GPS receiver is used to
638 retrieve the current time. Subsystems are synchronized via NTP (network
639 time protocol). All data packets are time-stamped.

640 3.4.2. Position and Attitude Estimation

641 Because all errors are assumed to be Gaussian, an extended Kalman filter
642 (EKF) is used to estimate the state. For the prediction step, the traveled dis-

643 tance between time $t-1$ and t is computed from the control commands u_t given
 644 to the screw step motor. Since gear transmission ratio and the pitch of the ice
 645 screw are known quantities, distance traveled can be calculated from standard
 646 motion equations. For this calculation the screw is assumed to be nearly
 647 slip-free with additive Gaussian noise. In the correction step, the predicted
 648 state $\bar{x}_t$ is corrected using the preprocessed measurements $z_{t;q}$ resulting from
 649 the AHRS/MAG fusion (section 3.1.1 and 3.1.2) and the measurements $z_{t;p}$ of
 650 the APS (section 3.2). Because $z_{t;q}$ provides an attitude quaternion together
 651 with a covariance matrix describing the underlying uncertainty, it can be
 652 incorporated using the usual Kalman equations. The propagation times $z_{t;p}$
 653 measured by the APS have to be converted into distances by multiplying
 654 them by the speed of sound in ice. In a next step a position estimate based on
 655 trilateration techniques (e.g. Bancroft's method [41] or least-squares) is used
 656 for correction. However, the geometric constellation of the acoustic emitters
 657 is not optimal for trilateration, because they are arranged approximately in a
 658 single plane which results in large positioning errors from small measurement
 659 errors. In addition, trilateration in 3D space needs at least three distance
 660 measurements (if one solution can be excluded as implausible), but it can
 661 happen that only the signals of one or two emitters are received, even when all
 662 emitters are active. To overcome these limitations, a tightly coupled update
 663 [42] is used instead of trilateration. Thereby, the non-linear distance errors
 664 for all received emitter signals are calculated from the measured and expected
 665 distances. Expected distances are given by the Euclidean distance between
 666 the estimated state and the emitters' positions. By means of a first order
 667 Taylor series expansion, the estimated errors are used to correct the relevant

Figure 16: Positioning error for different methods to correct the state estimate with the APS based on simulation data [18]. The different lines show the error without integrating the measurements of the APS (no pinger update), the result for the update with trilateration, and the the error of the tightly coupled update.

668 components of the state vector. This strategy reduces the positioning error
 669 significantly, as shown in figure16. It allows the fusion algorithm to perform
 670 state correction even with a single APS measurement.

671 3.4.3. Mapping of the Environment

672 The environment map is computed from the measurements of the ARS
 673 (section 3.3). The field of view of its four sensors covers two 2D cutting
 674 planes (x/y and x/z) in front of the IceMole. These local maps are fused
 675 over time into a global 3D map. A common approach to solve this task
 676 is grid mapping, which was successfully applied to a wide range of robotic
 677 applications where the map Y is discretized into equal-sized cells Y_i which

678 can be either occupied or empty (denote by o and e). In a probabilistic
 679 grid map, a single probability $P(o)$ is used to model the state of a cell.
 680 The approach used within this project however, relies on an evidential grid
 681 map [43, 44, 45]. It is based on the belief function theory [46] (also called
 682 Dempster-Shafer theory), a generalization of the classical probability calculus,
 683 and uses belief functions to represent the state of each cell. This allows for
 684 probability mass assignments not only to the singletons o and e but also to
 685 the union $\Theta = \{o, e\}$ and the empty set $\emptyset$. This has the practical advantage
 686 that it makes different dimensions of uncertainty explicit [47]. A lack of
 687 measurements for example, can be expressed by assigning mass to the union
 688 Θ and conflicting evidence can be expressed by assigning mass to the empty
 689 set $\emptyset$. In the probability framework, both cases would lead to an uniform
 690 distribution $P(o) = P(e) = 0.5$ and are therefore indistinguishable. Figure 17
 691 shows an evidential grid map and its probabilistic counterpart. Autonomous
 692 navigation as well as a human operator can take advantage of this additional
 693 information during the exploration of an unknown environment.

(a) Probabilistic grid map: $P(o)$

(b) Evidential grid map: $m(o)$

(c) Evidential grid map: $m(e)$

(d) Evidential grid map: $m(\Theta_Y)$

(e) Evidential grid map: $m(\emptyset)$

Figure 17: Comparison between a probabilistic and an evidential grid map computed from the sensors of a simulated robot [47]. Plot (a) shows the probabilistic grid map, where black indicates occupied areas (high probability for o), white empty areas (high probability for e), and gray uncertain areas (probability uniformly distributed between o and e). Plots (b) to (e) shows different mass components of the evidential grid map, whereat (b) shows occupied areas (mass on o), (c) empty areas (mass on e), (d) unobserved areas (ignorance, mass on Θ), and (e) areas with conflicting measurements (mass on $\emptyset$). Black represents a mass value of one and white represents zero.⁴² In the evidential grid map it is thus possible to distinguish between different dimensions of uncertainty and it provides significantly more information.

694 3.4.4. *Simultaneous Localization and Mapping (SLAM)*

695 Although the task of exploring an unknown environment can be viewed as
696 two separate problems (localization and mapping), they are not independent
697 of each other. Rather it is a joint estimation problem commonly known as
698 simultaneous localization and mapping (SLAM) [49]. A successful approach
699 to solve the SLAM problem is the FastSLAM algorithm [50] that uses a Rao-
700 Blackwellized particle filter to estimate the joint distribution. We proposed a
701 generalization for evidential grid maps in [51].

702 In first experiments, the evidential FastSLAM algorithm was successfully
703 applied to the task of navigating a melting probe through deep ice [48] and
704 the results are shown in figure 18. The estimated trajectories for different
705 sensor combinations are shown in figure 19.

(a) Positioning error

(b) Evidential grid map: $m(o)$

(c) Evidential grid map: $m(e)$

(d) Evidential grid map: $m(\Theta_Y)$

(e) Evidential grid map: $m(\emptyset)$

Figure 18: Results of the evidential FastSLAM algorithm during a pool test with the melting probe [48]. Plot (a) shows the localization error for different sensor combinations, where DR stands for dead reckoning using the screw feed only with fixed heading, AHRS/MAG for the fusion of AHRS and magnetometer data, APS for results from the acoustic trilateration, and all for the combination of all sensors including the correction with the map computed from ARS measurements. Plot (b) to (e) show the different mass components of the evidential grid map (cf. figure 17) computed by the algorithm. The four circles in the plots show the ground truth positions of the obstacles (cf. figure 15).

Figure 19: Estimated trajectories during a pool test for different sensor combinations. The dotted line in each plot corresponds to the estimated path and the error bars show the position uncertainty (standard deviation) estimated by the particle filter. (a) shows the result for DR using the screw feed only, (b) shows the result for DR with AHRS/MAG attitude corrections, (c) shows the result for DR with APS position corrections, and (d) shows the result with all available sensors, namely screw feed, AHRS/MAG, APS as well as ARS corrections wrt. the estimated map. DR-only has the highest estimated uncertainty, followed by DR + APS, DR + AHRS/MAG, and the combination of all sensors with the lowest estimated uncertainty. The latter corresponds to the real localization error (cf. figure 18 (a)).

706 4. Field tests

707 The EnEx system has been tested in four field campaigns of increasing
708 system complexity reflecting the different development phases of the project.
709 Two field tests took place on the Morteratsch Glacier in the European Alps and
710 two field tests in the McMurdo Dry Valleys, Antarctica. Relevant differences
711 between both test regions are:

- 712 • Glacier ice temperature: Ice temperature of Morteratsch Glacier is
713 homogeneously close to the melting point of 0°C , whereas ice is much
714 colder at Taylor and Canada Glacier in Antarctica (as low as -17°C).
- 715 • Proximity to the pole: The latitude of Morteratsch Glacier is about
716 $46,4^{\circ}$, whereas it is about $-77,7^{\circ}$ in the Dry Valleys.

717 4.1. Collaboration with the MIDGE Project

718 Tests in Antarctica have been conducted as part of an international
719 collaboration together with the MIDGE (Minimally Invasive Direct Glacial
720 Exploration) project. The goal of this collaboration was to collect a clean
721 brine sample from an Antarctic englacial brine body (e.g. concentrated salt
722 water), located within the Blood Falls crevasse. This location in the McMurdo
723 Dry Valleys, East Antarctica is a unique glacial feature where subglacial liquid
724 is released from a subglacial reservoir approximately 5 km upstream from
725 the glacier [52] and migrates along the glacier bed prior to its release to
726 the surface. The brine is assumed to be of marine origin [53, 54], which is
727 currently further investigated by the US-NSF project MIDGE. Blood Falls is
728 the only known location in Antarctica where significant volumes (thousands
729 of cubic meters per event) of subglacial water are forced to the surface where

730 they can be sampled and investigated without deep drilling, making it an
731 ideal terrestrial test site analog to a potential mission scenario to the Tiger
732 Stripes on Enceladus.

733 4.2. *EnEx Carrier System*

734 The IceMole worked well both on Morteratsch Glacier as well as in
735 Antarctica. The longest melting channel on Morteratsch Glacier had a length
736 of 25 m. A maximal melting velocity of 1.1 m/h and a minimal radius of the
737 melting trajectory of approximately 10 m could be observed. The different
738 modules of the integrated EnEx system have been tested in scenarios including
739 both horizontal melting, and a starting configuration with an oblique angle
740 of attack. The IceMole could successfully be maneuvered into a horizontal
741 melting path to test its ability to level out from an inclined trajectory. In
742 all of the EnEx field tests the melting scenarios were restricted to one major
743 change in melting direction. This was partially due to time limitations in
744 the field, but also due to minimize the risk of losing the IceMole, as the
745 retraction of the probe through a curved and twisted channel turned out
746 to be a challenging task. The mass and the length of the probe hinders its
747 movements to follow the channel and the probe tends to jam into edges within
748 the ice surface of the melting channel. Integration of the ARS module into
749 the melting head led to a significant decrease of the melting velocity, even
750 after certain system design modifications (compare 2.3). As a consequence
751 the ARS module had to be removed for large parts of the field tests.

752 In the final field test at Blood Falls, the IceMole successfully penetrated
753 pressurized brine trapped in the Blood Falls crevasse after melting along an
754 inclined, straight melting path of ≈ 17 m length. In that particular scenario,

Figure 20: Attitude results after AHRS/MAG fusion for the Blood Falls scenario (17 hours). The roll motion of the probe is clearly visible. It corresponds to a rotation about the main probe axis (roll) and is due to the counter-torque action of the IceMole in response to the rotation of the ice screw. During a forward run the roll delta angle is negative, during the run stops (4 – 5 h) the angle stays constant. Positive rotation can be observed at 16.5 h when unscrewing the ice screw.

755 there were difficulties with the CASS. However, the IceMole was still able
756 to retract a large volume of subglacial liquid by means of the redundant
757 booster pumping system. Despite difficulties with the CASS during the Blood
758 Falls scenario, the principle functionality of the CASS (penetration of the
759 crevasse, stopping of the IceMole and deployment of the proboscis) has been
760 demonstrated in earlier field tests, including Canada Glacier.

761 4.3. *Relative Positioning*

762 The DR subsystem has been successfully tested at both test sites. Both
763 IMU, and magnetometer could be used at all temperature conditions, even
764 at harsh Antarctic temperatures and high latitudes. The AHRS was able
765 to perform initial alignment, as well as continuous tracking of the IceMoles
766 attitude. The differential magnetometer system was able to stabilize the
767 attitude drift during run and measurement stops. In most of the melting
768 scenarios data of good quality was acquired. Figure 20 shows the computed
769 attitude angles of the probe for the final melting scenario at the Blood Falls.

770 4.4. *Acoustic Ice Properties*

771 Dependencies of the speed of sound and acoustic signal attenuation on
772 depth and direction in the glacier have been investigated. The attenuation is
773 important for determining the imaging range of the APS. Information about
774 the behavior of the speed of sound is crucial for the acoustic navigation itself.
775 In order to analyze dependencies on depth and distance, additional acoustic
776 transducers have been inserted in holes of greater depth. Also, different
777 transducer combinations have been analyzed. Horizontal distances between
778 the holes have been determined by differential GPS. The propagation time
779 has been determined by the first crossing of a fixed threshold. The resulting
780 speed of sound shows fluctuations of up to 10 % depending on the depth but
781 constant with time. Other test sites show different depth-profiles but also
782 variations of the same order of magnitude. The speed of sound measured
783 within the transducer array shows a directional variation of $< 5\%$. To develop
784 a predictive model for these effects further studies are necessary. Figure 21

Figure 21: Determination of the attenuation length in glacier ice from the width of averaged acoustic pulses for various distances. The fit is done with the parameter A0 for the amplitude of the exponential function and the parameter k for the attenuation coefficient.

785 shows the determination of the attenuation length from the RMS (root-mean-
786 square) of the signals at different distances for the 2013 and 2014 Morteratsch
787 field tests. The determination based on the RMS is more stable than on the
788 amplitude. Losses of acoustic energy due to spherical spreading are taken
789 into account. For these measurements the transducer and the receiver were
790 inserted in different holes in the same depth and the distance of transducer
791 and receiver was varied by using different pairs of holes. From the attenuation

792 coefficient of the exponential fit the attenuation length was determined to be
793 (13.18 ± 0.02) m in 2013 and (11.07 ± 0.12) m in 2014. In 2013 it was possible
794 to receive a signal at a distance of 45m with a signal-to-noise ratio sufficient
795 for a precise measurement of the arrival time. This allowed to deduce on
796 the speed of sound, which was determined to be (3738 ± 18) m/s. In 2014 a
797 significantly increased acoustic range of 130 m has been accomplished through
798 improved power dissipation and frequency matching.

799 *4.4.1. Absolute Positioning*

800 The feasibility of absolute positioning in glacier ice based upon trilateration
801 of acoustic signals has been demonstrated. Figure 22 shows the reconstruction
802 of a sample straight trajectory. Each circle represents the reconstructed
803 position of the IceMole at the time of the corresponding measurement stop.
804 An accuracy of the positioning of better than 17 cm could be achieved. This
805 value denotes the median distance from a straight trajectory. A robust signal
806 detection has been accomplished up to an emitter-receiver distance of about
807 20 m.

808 **5. Conclusions and Outlook**

809 *5.1. Conclusions*

810 In this paper, the EnEx system, consisting of the melting probe IceMole
811 and its navigation system, have been described. The EnEx system integrates
812 an extensive set of sensors like an IMU and magnetometers for attitude deter-
813 mination, an odometer based on ice screw rotation, an acoustic positioning
814 system and an acoustic reconnaissance system. To consolidate all available

Figure 22: Reconstructed trajectory recorded during a field test on the Morteratsch Glacier in 2014. Each reconstructed position is displayed as a colored circle. The time corresponding to a certain reconstructed position is color coded, where red represents early times and blue represents later times. The trajectory is projected to each coordinate plane for reasons of clarity. The positions of the six emitters as well as their projection on the x-y plane are displayed as gray boxes.

815 sensor data, a sophisticated multi-sensor fusion based on evidential SLAM
816 has been developed. Functionality and performance of the system have been
817 demonstrated in laboratory and field tests. In particular,

818 1. the IceMole is capable of melting into temperate and poly-thermal
819 terrestrial glacier ice, both in vertical down direction as well as at an
820 oblique angle. It is capable of changing its melting direction during
821 melting. The integrated pumping system keeps the water column within
822 the channel low. The CASS allows collection of liquid samples. Melting
823 tends to have a lower efficiency as the ambient ice gets colder [55]. This
824 will have to be further studied both experimentally and numerically.

825 2. DR yields reliable attitude and position data for the slow melting
826 motion through terrestrial glacier ice. Updating the IMU data with
827 magnetic measurements compensates for increasing errors of inertial-only
828 attitude determination and improves accuracy of the results. Differential
829 magnetometry based on a magnetic reference system is suitable for
830 correcting local errors and variations. The working principle relies on
831 the presence of any magnetic field. In the case of Enceladus a strong,
832 homogenous and already well described magnetic field ($B_0 = 325 \text{ nT}$) is
833 provided by Saturn. As the baseline magnetic field is constantly tracked
834 via the reference station it is not necessary to know the direction of the
835 field a-priori. Hence, equal results in precision and reliability of relative
836 positioning can be expected for Enceladus, after modifying the sensors
837 according to the local environmental conditions.

838 3. Absolute in-ice positioning based on acoustics is possible, both in
839 temperate and in poly-thermal terrestrial glaciers. The maximal emitter-

840 receiver distance up to which a robust signal detection is possible can be
841 further increased by: a larger signal power, a better frequency matching
842 between the acoustic receivers in the IceMole and the ambient ice
843 properties, a better coupling of the emitters to the ice, and an improved
844 signal processing. Though the principle concept is expected to work
845 also at Enceladus conditions, a real systems set-up for a space mission
846 would require additional knowledge on local ice structure and quality.

- 847 4. The ARS concept enables forward looking acoustical imaging. Initially,
848 specification of the piezo arrays was based on the physical properties of
849 ice and principles of sonography. The acquired beam forming quality
850 and lateral resolution however was better than expected and actually
851 needed. Findings suggest a redesign of the phased arrays with focus
852 on the resonance frequency and the number of elements to reduce the
853 lateral resolution in favor of range. Although the ARS performance is
854 very promising it turned out to be challenging to integrate the sensors
855 into the melting head while maintaining an acceptable melting efficiency.

856 This difficulty has not been solved yet. It is rather one objective of the
857 ongoing research to reduce the thermally inefficient area by applying
858 copper covers or grids and/or reducing of the number of elements.

- 859 5. The multi-sensor fusion combines all available sensor data. It provides
860 an absolute, drift-minimizing position and attitude estimate with higher
861 accuracy than provided by the individual subsystems. Furthermore, a
862 global 3D map is computed from local 2D measurements, while the belief
863 function representation provides an additional dimension of uncertainty
864 useful for operator support and autonomous decision making.

865 5.2. Outlook

866 The development of a fully capable ice-penetrating probe for an astrobi-
867 ological mission to Enceladus or another icy body in the Solar System will
868 be a long, multi-stage process with each phase being aimed at optimizing
869 various aspects of the probe. Within the *EnEx - Enceladus Explorer Initiative*
870 of the DLR Space Administration this challenging and exciting scientific
871 and technical goal will be further pursued. Crucial to a future mission to
872 Enceladus is the level of autonomy of the system. In any extraterrestrial
873 exploration mission, the one-way signal travel time to Earth is several minutes
874 up to hours, depending on the target body. Therefore, the probe must be
875 able to navigate autonomously through the structurally highly uncertain icy
876 body and be able to respond to target and obstacle detection during run time.
877 This is a challenging task for current technical systems. One solution could
878 be to install an acoustic sensor network on the surface and at an appropriate
879 depth within the ice that enables robust positioning. A difficulty of this idea
880 is the initialization of each acoustic sensor with its exact position in order
881 to relate to that information during the motion of the melting probe. This
882 could be overcome by deploying the acoustic sensors with corner reflectors
883 in which case their coordinates could be determined by laser ranging and
884 imaging from an orbiting satellite [56]. Independent knowledge about the
885 sensors initial locations could then also be used to gain further information on
886 the environment and the ice structure. The icy environment itself, however,
887 is another major source of uncertainty, not only for the applicability of an
888 acoustic sensor network but for all technological components of an Enceladus
889 exploration mission. Few experimental studies address heat conduction, ice

890 structure, acoustic wave propagation including scattering and absorption,
891 and generally the nature of water ice metamorphism under very cold ice and
892 low pressure conditions. Around the geologically very active area around
893 Tiger Stripes, Enceladus' surface is covered by precipitated and potentially
894 amorphous ice particles that have previously been ejected into space. Close
895 to the Tiger Stripes, temperatures could be high enough for these particles to
896 bond, which could result in an extreme variability of ice the structure. Both
897 laboratory experiments and ab-initio computer simulations would help to gain
898 a better understanding of very cold icy environments. Further experiments
899 during a preliminary lander mission on either Enceladus or any other of the
900 icy moons in our Solar System could then address the structural uncertainty.
901 The expected large uncertainties in the acquired sensor data requires us to
902 handle uncertain, incomplete and unexpected information. The approach
903 chosen in the project Enceladus Explorer relies on bio-inspired strategies.
904 This approach can be further pursued by developing cognitively motivated
905 strategies for autonomous navigation. Another mandatory requirement fo a
906 future space mission to Enceladus is the miniaturization of the IceMole system
907 to reduce the necessary heating power. A potential mission scenario based
908 on the EnEx-IceMole technology which also discussed power requirements
909 is presented in [5]. Miniaturization will furthermore increase the probe's
910 maneuverability and decrease its mass. Consequently, all components have to
911 be either smaller or replaced by a more light-weight technology with similar
912 functionality. As for the attitude determination, there are miniaturized IMUs
913 based on the so-called MEMS technology, which in principal show a similar
914 level of accuracy and stability, however, have to be strongly supported by

magnetometer measurements, new evaluation algorithms and/or additional observations. Finally, the melting process itself needs to be further investigated as the environmental conditions on the icy moons of our Solar System imply almost vacuum conditions. This translates into the possibility of a phase change below the triple point, hence, within the sublimation regime, and poses a further challenge. Though there is experimental evidence that sublimation does not play an important role even in vacuum [57], we need to conduct further theoretical and experimental studies to gain a better understanding of the dynamic behavior of melting probes under extraterrestrial conditions.

6. Contributions

The EnEx project is based on an idea and initiative of the DLR Space Administration. The EnEx-IceMole carrier system including its sampling system CASS as well as the supporting infrastructure for the field tests, and the simulation model have been developed at the Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences. The DR system has been collaboratively developed by the Institute of Space Technology and Space Applications LRT 9.3, Universität der Bundeswehr München (IMU/AHRS), the Institute of Flight Guidance, Technische Universität Braunschweig (differential magnetometer/attitude update), and the Cognitive Neuroinformatics group at University of Bremen (integration as part of the sensor fusion). The APS has been developed by the III. Physikalisches Institut, RWTH Aachen University and the Department of Physics, Bergische Universität Wuppertal. The ARS has been developed at the Institute of Bioengineering at FH Aachen

939 University of Applied Sciences and the III. Physikalisches Institut, RWTH
940 Aachen University. SF was done by the Cognitive Neuroinformatics group
941 at University of Bremen. The concept for a lander mission to Enceladus
942 was studied by the Institute of Space Technology and Space Applications
943 LRT 9.1, Universität der Bundeswehr München. The clean access strategy
944 has been developed collaboratively between the Institute of Bioengineering,
945 FH Aachen University of Applied Sciences and scientists from the MIDGE
946 project. Field tests in Europe have been organized and logistically supported
947 by FH Aachen University of Applied Sciences. Field tests in Antarctica have
948 been collaboratively organized by FH Aachen University of Applied Sciences
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Graphical Abstract: