



Agenda Item:	ATCM 13
Presented by:	SCAR
Original:	English
Submitted:	07/05/2013

Advancing technologies for exploring subglacial Antarctic aquatic ecosystems (SAEs)

Advancing technologies for exploring subglacial Antarctic aquatic ecosystems (SAEs)

1. Summary

This information paper supports the SCAR Lecture to the Antarctic Treaty and responds to a request from parties for further information on the topic of technological development and deployment to subglacial aquatic environments (SAEs) in Antarctica.

The paper is drafted by the SCAR ATHENA Expert Group (Advancing TechNologies and ENvironmental stewardship in Antarctica) led by Professor Jemma Wadham (University of Bristol, UK) and Professor Peter Doran (University of Illinois, Chicago, USA). The paper outlines the scientific arguments for future technology development and deployment to subglacial aquatic environments in Antarctica, followed by an assessment of the current status and application of available technologies. It concludes with a discussion of what is required technologically and environmentally for the future exploration of SAEs, and summarises the activities of the ATHENA group to date.

2. Background

Antarctic Subglacial Aquatic Environments (SAEs) are recognized as central to many processes that have shaped the polar ice sheets both today and in the past. They include a range of features that differ in geologic setting, age, evolutionary history, hydrological conditions and size, and include subglacial lakes, ponds, swamps, intermittently flowing rivers and thick sediments [1]. These environments are “natural” earth-bound macrocosms that in some instances trace their origins to a time before Antarctica became encased in ice. In contrast to other habitats, which are strongly influenced by atmospheric processes, processes in SAEs are affected by the flow of the overlying ice, the ice-water boundary layer, basal heat flux and potential thermal or non-thermal fluid transfers, depending on the tectonic conditions. Antarctic SAEs remain the least explored sector of the cold biosphere, yet are now known to be viable habitats for microbial life despite the harsh environmental conditions [2-7]. Understanding biogeochemical processes in Antarctic SAEs features highly on the international science agenda [8]. Within these sub-surface aquatic environments, microbial life drives chemical weathering, which in turn exports dissolved nutrients and carbon to downstream ecosystems [9-13] and greenhouse gases to the atmosphere [14]. The full spectrum of sub-ice environments present beneath the Antarctic continent provides an unparalleled opportunity to explore and study one of Earth’s last frontiers and decipher fundamental clues to the planet’s history, climate and biology.

To date, there have been four funded international campaigns to access and directly sample Antarctic SAEs: the Lake Vostok Drilling Programme; WISSARD: Whillans Ice Stream Subglacial Access Research Drilling Programme; the Lake Ellsworth Exploration Programme and the BEAMISH project: Basal conditions on Rutford Ice Stream; BEd Access, Monitoring and Ice Sheet History. The former programmes have been executed. These sub-ice missions will result in a dramatic shift in the current understanding of Antarctic SAEs via the generation of first time data on subglacial physical, chemical and biological processes. They revolve largely around sample collection and return with very limited *in situ* sensing of physical and chemical parameters. However, there is a strong scientific rationale to being able to survey Antarctic SAEs in a more spatially and temporally extensive manner. This requires the development of new clean technologies, which form the subject of this information paper.

3. Rationale for technology development

Antarctic SAEs include a diverse suite of different hydrological environments, incorporating physical, chemical and biological processes with temporal and spatial variability operating at different scales. This dynamic variability may not be revealed by spot sampling in a few locations, limiting the scientific understanding of SAEs. SAEs range from the deeper, more hydrologically isolated porewaters within

sedimentary basins some tens of kilometres below the ice-bed interface to shallow, dynamic networks of lakes and rivers, which export solute and nutrient to the coastal ocean. The arguments for study are compelling and diverse, likely to be refined and augmented as new data emerges from recent and planned drilling campaigns. In many respects, the next phase of SAE exploration in Antarctica requires dedicated effort and financial backing into the development and validation of new technologies that are commensurate with a desire to acquire data with spatial and temporal complexity. Two end member examples of this data requirement are outlined as follows.

Deep sediments, including sedimentary basins and sediments within subglacial lakes, may contain clues to the previous glaciation history of the continent. Many are thought to contain overridden marine sediments deposited prior to glaciation in Antarctica [15]. They may also constitute favourable habitats for micro-organisms, in a similar manner to sub sea floor sediments within the oceans. The micro-organisms may include anaerobes such as methanogens, capable of driving the accumulation of methane hydrate over million year time scales, with potential to be released to the atmosphere during deglaciation [14]. Within such sedimentary basins, biogeochemical reactions may occur slowly but spatial heterogeneity may be large (e.g. greater methane hydrate accumulation in frozen bed areas [14]), thus, identifying a need for spatially extensive datasets. Deep sedimentary basins are also challenging to access by available drilling technology, due to the need to drill into deep sediments beneath thick moving ice, and additionally, to remove sediments in a sterile manner and without permitting loss of biogenic gases. Drilling to deep sediments beneath thick glacial ice cover in this manner still remains an elusive goal and would require coupling of ice sheet drilling techniques and sediment/rock drilling (e.g. ANDRILL).

Challenges to couple ice sheet drilling with deep sediment sampling include, 1) The challenge associated with recovering sedimentary cores and or samples at depth beneath some kilometres of glacial ice cover, 2) The need for drill fluid circulation to enable deep drilling into sediments and 3) Issues associated with the potential for contamination of the SAE (e.g. overlying subglacial lake or subglacial water system) with drill fluid. In this instance, the physical separation of lake and ice sheet “drilling” fluids may maintain lake sterility. Adaption of newly developing remotely operated sea floor drills may be a viable option for drilling into deep lake sediment or sedimentary basins. Drilling through ice into a frozen basal environment beneath the ice sheet may be less problematic and a single drill fluid may be suitable for both ice and deep sediment drilling. There may be some requirement to establish the nature and temperature regime at the frozen bed to ensure that coring through the transition is feasible especially under thick ice where temperatures might approach pressure melting. There are significant gains to be made in this area also by geophysical surveys, including new methods [16], to widen data availability and to inform selection of drilling sites.

At shallower depths beneath the ice sheet, the dynamic exchange of water via rivers and subglacial lake drainage events has the potential to drive the export of nutrient and solute to the coastal ocean. Long time series of *in situ* recorded data at more than one location are desirable for capturing processes that exhibit high temporal and spatial variability. In these shallow environments change over time is likely, and single snap shots of a SAE may miss fundamental processes or evolutionary behaviour. This calls for the development of autonomous or tethered (where ice flow rates are low) sensor platforms and networks of observatories such as those that are routinely employed within the marine sciences. However, the remote nature of these SAEs generates challenges for their future access and study using conventional technologies. As for all SAEs, reliance upon sample collection and return (as employed in subglacial lake drilling campaigns) has disadvantages and is associated with the risk of non-recovery of samples. The capacity to acquire complex data sets *in situ* via a suite of autonomous or remotely operable sensors is a desirable goal for future SAE exploration.

4. Technologies for Antarctic subglacial exploration

SAEs have been observed for some time using remote sensing [17-19] and geophysical techniques [20-24] but only very recently have plans been devised and implemented to sample and study these environments directly. The long lead in times for the sampling of SAEs is largely related to the technological difficulty of penetrating the overlying ice sheet, but also reflects the cautious approach warranted by the pristine nature of these environments, and their poorly understood capacity to sustain viable ecosystems. This is particularly true of Antarctic subglacial lakes. SCAR (via the Scientific Research Programme, SALE: Subglacial Aquatic Lake Environments) played a fundamental role in shaping the science priorities and international

partnerships in the nascent field of subglacial aquatic research, more recently succeeded by the Action Group devising the recent Code of Conduct for the Exploration and Research of Subglacial Aquatic Environments (AG-CCER-SAE) and the ATHENA Expert Group (2010-2012). The latter was established in recognition of an important need for a new path forward that focuses international exchange on the appropriate technology and methodologies required to carry out the science in an environmentally responsible way.

The study of subglacial environments requires a diverse set of technologies that include those required for SAE entry, sample collection and return, *in situ* sensing during short deployment missions, observatories for longer (potentially one way) deployment missions and methodologies tailored to the environmental conditions of subglacial environments. It is notable that while current subglacial drilling targets in Antarctica are largely focused around subglacial lakes and sub-ice stream sediments, there is also mounting scientific motivation to enable the deep access of sedimentary basins buried beneath the ice sheet, which requires the development of new drilling and sample recovery methods.

There are two specific technological issues that are paramount as we move into a new era of Antarctic SAE exploration. The first regards the development of SAE entry and sampling protocols, which are commensurate with the need to protect these pristine and remote habitats. The second regards the technological developments that are required to ensure that there is maximum data return from future Antarctic subglacial missions. This information paper focuses upon the latter of these issues. Many of the challenges for SAE exploration are technological. Current operational lake access campaigns are largely oriented towards sample collection and return (Vostok, WISSARD, Lake Ellsworth, BEAMISH), with limited *in situ* analyses and no long-term monitoring of chemical and physical conditions. Part of this approach stems from concerns over environmental protection and the impact of deploying permanent instruments in Antarctic SAEs. An equally limiting factor is the current dearth of sensing technologies of sufficient maturity for deployment to the bed of the Antarctic Ice Sheet, via single sensors or via observatories/sensing platforms. Beneath the ice sheet, perennial cold, high pressure, low levels of target analytes, remote location and the need to deploy sensors via a borehole create severe challenges for instrumentation.

5. Technology Challenges: sensors and platforms

a) Sensors

While the first phase of funded lake access programmes will generate highly novel datasets and a revised understanding of SAEs, a significant output from these campaigns will be the generation of new scientific questions and hypotheses that require a second phase of carefully targeted lake exploration. These follow-on drilling campaigns are already at the planning stage in some countries, but are limited in scope by the immature status of many technologies for *in situ* monitoring or the difficulty of deploying these technologies in a clean and sterile manner.

Sensor technology for sub-ice applications is in its infancy and the measurement of most parameters remains intractable, particularly in the area of chemical sensing and biological/biosensing. While chemical sensor deployments in marine environments are approaching routine for some parameters (e.g. dissolved oxygen, H₂S, nutrients), these tools require design modification and rigorous testing before becoming real candidates for glacial field science. In comparison sensors which measure physical parameters (pressure, temperature, electrical conductivity) have been widely employed in glacial systems [25-27]. The lack of chemical and biological sensor maturity, therefore, creates a divergence between the science ambitions to better understand life and life mediated processes in SAEs and what is possible via current technology. Glacial environments are challenging for *in situ* chemical sensors because of the combination of low concentrations of analytes (often nanomolar), low temperatures/high pressure, freeze/thaw and, in subglacial sedimentary environments, high sediment loading, complex stresses and abrasion. Size is also often an issue either because of limited available space (e.g. down-borehole deployments) or because processes of interest occur on the micro-scale.

Biogeochemical parameters that may be important to measure via sensors within SAEs include: major and trace ions, dissolved oxygen, pH/Eh, dissolved nutrients and dissolved gases such as hydrogen sulphide and methane. The greatest advances in chemical sensor development and deployment in glacial systems have been achieved for a very narrow range of target analytes, such as dissolved oxygen. Gradients in oxygen

concentration within SAEs may arise from biological processes, also indicating whether there is the potential for the development of anoxia in waters of sediments. Fibre optic dissolved oxygen probes have been employed successfully in artificial sea-ice mesocosms ([28, 29] and more recently in glaciers [30]. Microelectrode-based oxygen sensors [31, 32] also offer promising solutions where additional robustness is required, and incorporate simple interrogation electronics. Tractable reagent based techniques exist for nutrients such as nitrate, nitrite, ammonia, phosphate, iron and manganese. A flexible modular fluidic colorimetric/fluorometric system could access many of the major nutrients with common technology elements. Systems based on this principle are available commercially (e.g. Envirotech Instruments LLC, WetLabs), but are too large (>5L) and complex for use in many subglacial applications. Recent advances in microfluidic reagent based analyser technology have demonstrated performance (~100nM resolution) and robustness in oceanographic for nitrate and nitrite [33, 34]. This technology has the potential for modification for sub-ice applications, developing a generic platform technology based on marine lab-on-chip systems, operable with any colorimetric or fluorometric reagent based detection protocol. For dissolved gas sensing, the technology status for a glacial application is still highly immature. The same is true of biological sensors and biosensors.

b) *Sensor platforms:*

There are few sensor platforms with the potential for operation either as observatories (long-term missions) or sampling probes (short term missions) within Antarctic SAEs. For tethered, remotely operable systems and autonomous systems, significant challenges are presented by the need for a small size to enable down-borehole deployment and a suite of sensors which are capable of operation under difficult *in situ* conditions (See Section 4a) and which do not impact the study environment. Additional unique development challenges for autonomous sensor platforms are substantial and include the need for a) wireless data transmission through water, sediment and glacial ice, b) autonomous operation, c) potential for long-term deployment and associated issues associated with power and sensor life time and d) robustness when deployed to ice/bed interface environments. The issues of environmental protection for sensor deployments to the ice sheet bed become even more paramount given the likely non recoverability of autonomous instrumentation from within Antarctic SAEs post-mission.

The last 5 years has witnessed large scale international effort in the development of new sensor technologies and sensing platforms for SAEs, resulting in a recent dramatic increase in the number and diversity of prototype systems available. Tethered systems include down-borehole deployable probes such as the NASA-JPL Micro-Submersible Lake Exploration Device (WISSARD) which was deployed to Subglacial Lake Whillans in January 2013. Also under development or deployed on smaller glacier systems include autonomous submersible vehicles for subglacial lake access such as ENDURANCE (<http://www.stoneaerospace.com>), miniaturised wireless probes (CRYOEGG [35], GLACSWEB [36]) and ice-melting probes such as Ice Mole [37] and the VALKYRIE probe (<http://www.stoneaerospace.com>). However, all have specific issues associated with access and deployment to Antarctic SAEs, to include large size, limits on data transmission path through ice, sediment and water, restricted sensor suite and issues associated with long-term non recoverable deployment (e.g. sensor life time). Few of these systems house biogeochemical sensors and most are unsuitable for long-term non-recoverable deployments at present. There is huge potential for such technologies to advance the next phase of SAE exploration in Antarctica as clearly defined by the science goals. However, the environmental implications of such deployments must be well thought through and integrated into sensor development plans. Beyond SAEs, the potential reward is similarly high since technologies will be applicable across a wide range of remote/extreme and non-extreme environments where *in situ* measurements are desirable.

6. Activity of the ATHENA Group

The SCAR ATHENA Expert Group (<http://seis.bris.ac.uk/~chgpl/Athena/home.htm>) was formed in the wake of the SCAR SALE Scientific Research Programme. The goals of the group and achievements in relation to these goals are listed as follows,

- a) To help establish the critical environmental and technological infrastructure for the future access, sampling and monitoring of Antarctic subglacial aquatic environments (SAE)

The founding of the ATHENA group in 2010 brought together a diverse range of scientists and technologists who are active in the exploration of Antarctic SAEs. Over this time period, several members of the group have initiated collaborations or acquired funding for projects focussed upon technology development for SAEs (the UK NERC-funded “DELVE: Development and Validation of Chemical Sensors for Icy Ecosystems” programme (Wadham, Mowlem, UK), the NASA JPL Micro-Submersible Lake Exploration Device (Behar, US) and the elemental speciation programme (Barbante, Italy). The ATHENA group convened a very successful session at the SCAR Open Science Conference in Portland in July 2012, where the Vostok drilling programme field report was presented for the first time. The ATHENA Co-chairs (Peter Doran and Jemma Wadham) are now assembling a special issue for *Annals of Glaciology* focussed up on the development of clean technologies for SAE exploration. This will include the publication of drilling methodologies for international drilling campaigns such as WISSARD.

- b) To work with SCAR Action Groups, Expert Groups and Research Projects to promote interdisciplinary science on Antarctic SAEs, and specifically by developing linkages with research on Antarctic climate (via ACE), Biodiversity (via EBA) and sub-ice geological exploration (via SieGE).

Several of the ATHENA group members also serve on the Code of Conduct Action Group for the Exploration and Research of Subglacial Aquatic Environments (AG-CCER-SAE) (Alekhina, Doran, Vincent, Wadham), and have proposed to SCAR that the ATHENA group be awarded a zero cost extension in order that this Code of Conduct might be revised following the findings of the Vostok and WISSARD drilling campaigns, which have now been executed.

- c) To provide an independent and international forum for the sharing of information and data during the run up to and execution of funded lake access drilling campaigns (e.g. Russia-Lake Vostok and US-WISSARD, UK-Lake Ellsworth).

The group has successfully provided an independent forum for the sharing of information and data during the run up to the recent implementation of funded lake access drilling campaigns. It has hosted 5 steering committee meetings and has included a website which has served as a central portal for the dissemination of documentation regarding the clean technologies and environmental stewardship of SAEs.

7. Conclusions

The last 10 years has witnessed a dramatic increase in the profile of Antarctic SAEs and the impetus for their study, linked to their potential to reveal clues to Antarctic Ice Sheet history, hydrology and Antarctica's role in global biogeochemical cycles and biodiversity. This raised profile was linked strongly to the activity of SCAR via SALE, AG-CCER-SAE and ATHENA. It culminated in the funding of four campaigns to access and directly sample SAEs (Vostok, WISSARD, Ellsworth, BEAMISH), which will shortly result in new datasets and insights. The next phase of Antarctic SAE exploration is very likely to be shaped by the availability of technology for addressing core science goals. The development of new clean technologies for the future exploration of SAEs in Antarctica must be tailored to the specific environmental protocols of each different SAE. Central to science objectives for sub-Antarctic drilling programmes is the establishment of protocols for environmental stewardship and standards to minimize contamination of these unique environments. These protocols must be tailored to be compatible with a wide range of scientific investigations. Environmental stewardship aspects are two-fold: 1) protecting the environment by minimizing alterations and; 2) retrieving uncompromised samples for scientific investigations. Given the potentially low biomass and dilute chemistries expected in these many sub-Antarctic ice sheet environments, both aspects pose challenges for current technologies. Provided these environmental and technical challenges can be overcome, there is the potential for the next phase of SAE exploration to drive a step change in our understanding of climate history, life and glaciological processes within Antarctica.

8. References

1. Priscu, J., et al., *Antarctic subglacial water: origin, evolution and ecology*, in *Polar Lakes and Rivers*, W.F. Vincent and J. Laybourn-Parry, Editors. 2009, Oxford University Press: Oxford. p. 320.

2. Lanoil, B., et al., *Bacteria beneath the West Antarctic Ice Sheet*. Environmental Microbiology, 2009. **11**(3): p. 609-615.
3. Mikucki, J.A., et al., *A Contemporary Microbially Maintained Subglacial Ferrous "Ocean"*. Science, 2009. **324**(5925): p. 397-400.
4. Priscu, J.C., et al., *Geomicrobiology of subglacial ice above Lake Vostok, Antarctica*. Science, 1999. **286**(5447): p. 2141-2144.
5. Karl, D.M., et al., *Microorganisms in the accreted ice of Lake Vostok, Antarctica*. Science, 1999. **286**(5447): p. 2144-2147.
6. Bulat, S., et al., *Microbial life in extreme subglacial Antarctic lake environments: Lake Vostok*. International Journal of Astrobiology, 2008. **7**(1): p. 69-69.
7. Bulat, S.A., et al., *DNA signature of thermophilic bacteria from the aged accretion ice of Lake Vostok, Antarctica: implications for searching for life in extreme icy environments*. International Journal of Astrobiology, 2004. **3**(01): p. 1-12.
8. Priscu, J., et al., *Exploring Subglacial Antarctic Lake Environments* EOS, 2005. **86**(20): p. 193-197.
9. Wadham, J.L., et al., *Biogeochemical weathering under ice: Size matters*. Global Biogeochem. Cycles, 2010. **24**(3): p. GB3025.
10. Raiswell, R., et al., *Bioavailable iron in the Southern Ocean: the significance of the iceberg conveyor belt*. Geochemical Transactions, 2008. **9**: p. -.
11. Statham, P.J., M. Skidmore, and M. Tranter, *Inputs of glacially derived dissolved and colloidal iron to the coastal ocean and implications for primary productivity*. Global Biogeochemical Cycles, 2008. **22**(3): p. -.
12. Wadham, J., et al., *The role of the Antarctic Ice Sheet in Global Biogeochemical Cycles*. Royal Transactions of the Society of Edinburgh (ISAES proceedings), 2013. **104**: p. 1-12.
13. Raiswell, R. and D. Canfield, *The iron biogeochemical cycle Past and Present*. Geochemical Perspectives, 2012. **1**(1): p. 1-220.
14. Wadham, J.L., et al., *Potential methane reservoirs beneath Antarctica*. Nature, 2012. **488**(7413): p. 633-637.
15. King, E.C., J. Woodward, and A.M. Smith, *Seismic and radar observations of subglacial bed forms beneath the onset zone of Rutford Ice Stream Antarctica*. Journal of Glaciology, 2007. **53**(183): p. 665-672.
16. Eisen, O., et al., *A New Approach for Exploring Ice Sheets and Sub-Ice Geology*. Eos, Transactions American Geophysical Union, 2010. **91**(46): p. 429-430.
17. Fricker, H.A., et al., *An active subglacial water system in West Antarctica mapped from space*. Science, 2007. **315**(5818): p. 1544-1548.
18. Wingham, D.J., et al., *Rapid discharge connects Antarctic subglacial lakes*. Nature, 2006. **440**(7087): p. 1033-1036.
19. Smith, B.E., et al., *An inventory of active subglacial lakes in Antarctica detected by ICESat (2003-2008)*. Journal of Glaciology, 2009. **55**(192): p. 573-595.
20. Ferraccioli, F., et al., *Aeromagnetic exploration over the East Antarctic Ice Sheet: A new view of the Wilkes Subglacial Basin*. Tectonophysics, 2009. **478**(1-2): p. 62-77.
21. Anandakrishnan, S. and J.P. Winberry, *Antarctic subglacial sedimentary layer thickness from receiver function analysis*. Global and Planetary Change, 2004. **42**(1-4): p. 167-176.
22. Bamber, J.L., et al., *East Antarctic ice stream tributary underlain by major sedimentary basin*. Geology, 2006. **34**(1): p. 33-36.
23. Dowdeswell, J.A. and M.J. Siegert, *The dimensions and topographic setting of Antarctic subglacial lakes and implications for large-scale water storage beneath continental ice sheets*. Geological Society of America Bulletin, 1999. **111**(2): p. 254-263.
24. Bell, R.E., et al., *Influence of subglacial geology on the onset of a West Antarctic ice stream from aerogeophysical observations*. Nature, 1998. **394**(6688): p. 58-62.
25. Engelhardt, H., et al., *Physical Conditions at the Base of a Fast Moving Antarctic Ice Stream*. Science, 1990. **248**(4951): p. 57-59.
26. Engelhardt, H. and B. Kamb, *Basal hydraulic system of a West Antarctic ice stream: Constraints from borehole observations*. Journal of Glaciology, 1997. **43**(144): p. 207-230.
27. Hubbard, B.P., et al., *Borehole Water-Level Variations and the Structure of the Subglacial Hydrological System of Haut Glacier Darolla, Valais, Switzerland*. Journal of Glaciology, 1995. **41**(139): p. 572-583.

28. Mock, T., et al., *Micro-optodes in sea ice: a new approach to investigate oxygen dynamics during sea ice formation*. Aquatic Microbial Ecology, 2002. **29**(3): p. 297-306.
29. Mock, T., M. Kruse, and G.S. Dieckmann, *A new microcosm to investigate oxygen dynamics at the sea ice water interface*. Aquatic Microbial Ecology, 2003. **30**(2): p. 197-205.
30. Bagshaw, E.A., et al., *Determination of Dissolved Oxygen in the Cryosphere: A Comprehensive Laboratory and Field Evaluation of Fiber Optic Sensors*. Environmental Science & Technology, 2011. **45**(2): p. 700-705.
31. Sosna, M., et al., *Development of a reliable microelectrode dissolved oxygen sensor*. Sensors and Actuators B: Chemical, 2007. **123**(1): p. 344-351.
32. Sosna, M., et al., *Field assessment of a new membrane-free microelectrode dissolved oxygen sensor for water column profiling*. Limnology and Oceanography-Methods, 2008. **6**: p. 180-189.
33. Beaton, A.D., et al., *An automated microfluidic colourimetric sensor applied in situ to determine nitrite concentration*. Sensors and Actuators B-Chemical, 2011. **156**(2): p. 1009-1014.
34. Beaton, A.D., et al., *Lab-on-Chip Measurement of Nitrate and Nitrite for In Situ Analysis of Natural Waters*. Environmental Science & Technology, 2012. **46**(17): p. 9548-9556.
35. Bagshaw, E., et al., *Novel wireless sensing methods for sub-ice applications*. AGU Abstracts, San Francisco, 2012.
36. Martinez, K., R. Ong, and J. Hart, *Glacsweb: a sensor network for hostile environments*. 2004 First Annual Ieee Communications Society Conference on Sensor and Ad Hoc Communications and Networks, 2004: p. 81-87.
37. Dachwald, B., et al., *Development of a novel subsurface ice probe and testing of the first prototype on the Morteratsch glacier*. Geophysical Research Abstracts, 2011. **13**(EGU2011-4943.).