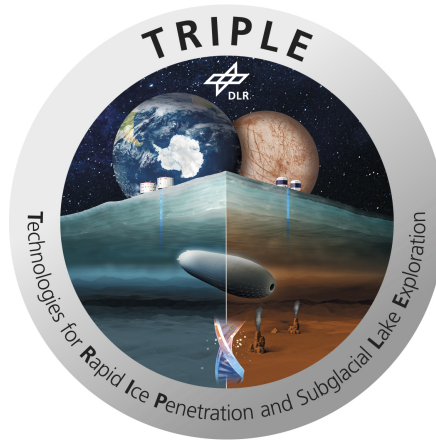


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# TRIPLE - Technologies for Rapid Ice Penetration and Subglacial Lake Exploration

Whitepaper by the TRIPLE Project within the German Space Agency  
Explorer Initiative at DLR



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J. Audehm<sup>1</sup>, R. Bachmayer<sup>2</sup>, M. Bande<sup>17</sup>, R. Bannasch<sup>20</sup>, F. Becker<sup>3</sup>, U. Bestmann<sup>18</sup>, D. Bhattacharya<sup>11</sup>, G. Böck<sup>14</sup>, J. Clemens<sup>12</sup>, M. G. Do<sup>1</sup>, J.-P.P. de Vera<sup>13</sup>, I. Digel<sup>10</sup>, C. Espe<sup>5</sup>, M. Feldmann<sup>5</sup>, O. Funke<sup>4</sup>, G. Francke<sup>5</sup>, K. Frischkorn<sup>15</sup>, K. Geissinger<sup>6</sup>, D. Göpel<sup>10</sup>, C. Günther<sup>1</sup>, D. Gregorek<sup>2</sup>, J. T. Grundmann<sup>16</sup>, F. Joppe<sup>8</sup>, N. Haberberger<sup>7</sup>, D. Heinen<sup>1</sup>, K. Helbing<sup>3</sup>, D. Heutelbeck<sup>9</sup>, P. Höck<sup>15</sup>, G. Höpfner<sup>15</sup>, T. Koch<sup>12</sup>, C. Koch<sup>17</sup>, J. Kowalski<sup>11</sup>, C. Krause<sup>13</sup>, J. Löser<sup>8</sup>, P. Panten<sup>18</sup>, S. Philipp-May<sup>4</sup>, T. Reuscher<sup>8</sup>, H. Rohr<sup>19</sup>, V. Schorbach<sup>9</sup>, F. Schöttler<sup>5</sup>, A. Tepecik<sup>10</sup>, B. Terschanski<sup>11</sup>, M. Vossiek<sup>7</sup>, C. Waldmann<sup>1</sup>, A. Ward<sup>4</sup>, C. Wiebusch<sup>1</sup>, S. Yakovlev<sup>20</sup>, and S. Zierke<sup>1</sup>

<sup>1</sup>III. Physikalisches Institut B, RWTH Aachen University, Otto-Blumenthal-Straße, 52074 Aachen, Germany

<sup>2</sup>MARUM, Zentrum für Marine Umweltwissenschaften Universität Bremen, Leobener Str. 8, 28359 Bremen

<sup>3</sup>Department of Physics, University of Wuppertal, Gaußstr. 20, D-42119 Wuppertal

<sup>4</sup>German Space Agency at DLR (DLR RFA), Königswinterer Str. 522-524, 53227 Bonn, Germany

<sup>5</sup>GSI GmbH, Liebigstraße 26, 52070 Aachen

<sup>6</sup>DSI Aerospace GmbH, Otto-Lilienthal-Straße 1, 28199 Bremen

<sup>7</sup>Institute of Microwaves and Photonics (LHFT), Friedrich-Alexander-Universität Erlangen-Nürnberg, Cauerstraße 9, 91058 Erlangen

<sup>8</sup>Institute of Automatic Control (IRT), RWTH Aachen University, Campus-Boulevard 30, 52074 Aachen

<sup>9</sup>Faculty of Sustainable Engineering, HAW Hamburg, Berliner Tor 21, 20099 Hamburg

<sup>10</sup>Institute for Bioengineering (IfB), FH Aachen University of Applied Sciences, Heinrich-Mußmann-Straße 1, 52428 Jülich

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- <sup>11</sup>Chair of Methods for Model-based Development in Computational Engineering, RWTH Aachen University, Eilfschonsteinstraße 18, 52062 Aachen
- <sup>12</sup>Cognitive Neuroinformatics, Bremen University, Enrique-Schmidt Straße 5, 28359 Bremen
- <sup>13</sup>DLR, Space Operations and Astronaut Training, MUSC, Linder Höhe, 51147 Köln
- <sup>14</sup>GloMic GmbH, Krampnitzer Weg 102, 14089 Berlin
- <sup>15</sup>Institute for Machine Elements and Systems Engineering, RWTH Aachen University, Schinkelstraße 10, 52062 Aachen
- <sup>16</sup>DLR German Aerospace Center, Institute of Space Systems, System Engineering and Project Office, Robert-Hooke-Strasse 7, D-28359 Bremen, Germany
- <sup>17</sup>German Research Center for Artificial Intelligence (DFKI), Robert-Hooke-Straße 1, 28359 Bremen
- <sup>18</sup>Institute of Flight Guidance, Technical University Braunschweig, Hermann-Blenk-Straße 27, 38108 Braunschweig
- <sup>19</sup>TriOS GmbH, Bürgermeister-Brötje-Str. 25, 26180 Rastede
- <sup>20</sup>EvoLogics GmbH, Wagner-Régeny-Str. 4, 12489 Berlin

## Abstract

TRIPLE (Technologies for Rapid Ice Penetration and subglacial Lake Exploration) is a project line initiated by the German Space Agency at DLR (Deutsches Zentrum für Luft- und Raumfahrt - engl. German Aerospace Center) focused on developing, demonstrating and providing an autonomous exploration system for subglacial lakes and ocean environments. The project aims to contribute to future missions searching for extraterrestrial life in the ice-covered ocean worlds of the outer Solar System by demonstrating an integrated system aiming for conducting contamination-free and robust explorations of subglacial lakes, including sample return.

TRIPLE consists of three core components: a melting probe for penetrating the ice, an autonomous underwater vehicle for exploring the water reservoir, and an astrobiological laboratory for in-situ analysis of the collected samples. The operational capability of the technologies will be validated in a test campaign in Antarctica's Dome C region, which serves as an analogous terrestrial scenario for simulating extraterrestrial environments.

In this whitepaper, we present a comprehensive overview of the project line, highlighting its key objectives and the strategies devised to achieve them. Released as the second issue following the initial publication on May 29, 2020, this document serves as an expanded update to its predecessor.



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|                           | Dr. Sabine Philipp-May                                                                     |

Oliver  
Funke

Digital signed by Oliver Funke  
DN: cn=Oliver Funke, o=Deutsches  
Raumfahrtamt, ou=DLR, email=oliver.funke@dlr.de  
Date: 2025.07.28 14:33:35+02'00'  
Reason: Approved

Sabine  
Doris Philipp  
-May

Digital signed by Sabine Doris Philipp-May  
DN: cn=Sabine Doris Philipp-May, o=Deutsches  
Raumfahrtamt, ou=DLR, email=sabine.philipp-may@dlr.de  
Date: 2025.07.28 14:33:35+02'00'  
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## Contents

|          |                                                               |           |
|----------|---------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction and Motivation</b>                            | <b>7</b>  |
| 1.1      | Exploration of Jupiter's Moon Europa                          | 7         |
| 1.2      | Current and Future Missions                                   | 8         |
| 1.3      | Research and Contribution in Germany                          | 10        |
| <b>2</b> | <b>Mission Statement</b>                                      | <b>10</b> |
| <b>3</b> | <b>Project Objectives</b>                                     | <b>11</b> |
| 3.1      | Programmatic and Strategic Objectives                         | 12        |
| 3.2      | Scientific Objectives                                         | 13        |
| 3.3      | Technical Objectives                                          | 14        |
| <b>4</b> | <b>Mission and System Requirements</b>                        | <b>15</b> |
| 4.1      | Mission Requirements                                          | 15        |
| 4.2      | System Requirements                                           | 15        |
| 4.2.1    | Melting Probe                                                 | 15        |
| 4.2.2    | nanoAUV and Launch and Recovery System                        | 16        |
| 4.2.3    | Forefield Reconnaissance System for the Melting Probe         | 16        |
| 4.2.4    | Science Payload in the Melting Probe                          | 16        |
| 4.2.5    | Astrobiological Laboratory                                    | 17        |
| <b>5</b> | <b>Overview TRIPLE</b>                                        | <b>17</b> |
| 5.1      | Overview of the Project Phases                                | 17        |
| 5.2      | Results of Phase 0 + 1                                        | 18        |
| 5.2.1    | Phase 0 - Mission Definition                                  | 18        |
| 5.2.2    | Phase 1 - Requirement Definition and Technology Demonstration | 18        |
| 5.3      | Organization Structure of TRIPLE                              | 21        |
| 5.4      | TRIPLE Schedule                                               | 23        |
| 5.5      | Phase 2 - Current Development                                 | 23        |
| 5.5.1    | The Melting Probe IceCraft                                    | 24        |
| 5.5.2    | nanoAUV and Launch and Recovery System (LRS)                  | 24        |
| 5.5.3    | The Forefield Reconnaissance System (FRS)                     | 25        |
| 5.5.4    | Science Payload Melting Probe (SPI)                           | 25        |
| 5.5.5    | AstroBioLab (ABL)                                             | 25        |
| 5.5.6    | Ground Support Equipment (GSE)                                | 25        |
| <b>6</b> | <b>Realization and Implementation</b>                         | <b>26</b> |
| 6.1      | The Melting Probe IceCraft                                    | 26        |
| 6.2      | nanoAUV                                                       | 26        |
| 6.3      | Launch and Recovery System (LRS)                              | 27        |
| 6.4      | The Forefield Reconnaissance System (FRS)                     | 28        |
| 6.5      | The Science Payload IceCraft (SPI)                            | 29        |
| 6.6      | AstroBioLab                                                   | 29        |
| <b>7</b> | <b>Connectivity Options</b>                                   | <b>30</b> |
| 7.1      | Subglacial Lakes and Other Locations                          | 30        |
| 7.2      | Space                                                         | 30        |



|                              |           |
|------------------------------|-----------|
| <b>8 Summary and Outlook</b> | <b>32</b> |
| <b>List of Figures</b>       | <b>33</b> |
| <b>List of Tables</b>        | <b>33</b> |
| <b>References</b>            | <b>34</b> |

# 1 Introduction and Motivation

To search for potential extraterrestrial habitats and for life, icy moons of the outer Solar System have emerged as promising candidates. Among these, Europa, one of Jupiter's moons, is particularly interesting and one of the most favorable targets for astrobiological exploration. Chapter 1.1 presents the environmental characteristics of Europa, focusing on the features that create suitable conditions for habitability. In chapter 1.2, current and upcoming missions to Europa are highlighted. Finally, chapter 1.3 provides an overview of the contributions of German research efforts to these exploration initiatives.

## 1.1 Exploration of Jupiter's Moon Europa

Our understanding of habitability and the nature of detectable biosignatures is primarily based on astrobiological questions like the origin, the evolution, distribution and future of life in the universe. In order for life to emerge, several minimum conditions must be fulfilled. The essential requirements include [Priscu and Hand (2012), Charles S. Cockell, Bush, et al. (2016), Charles S. Cockell, Simons, et al. (2024)]:

1. The presence of a solvent as a carrier for biochemical reactions: At the current time, liquid water is the only compound known.
2. The existence of biologically essential elements: C, H, N, O, P and S for microorganisms.
3. A source of energy, e.g. chemical energy or electromagnetic energy.
4. The presence of suitable physical and chemical conditions. The limits are as follows:
  - temperature ranging from  $\approx -20^\circ\text{C}$  [Clarke (2014)] to  $120^\circ\text{C}$  [Kashefi and Lovley (2003)]
  - water activity with the current lowest limit being 0.605 [A. Stevenson et al. (2015)]
  - pH-values ranging from 0 (current lowest limit tolerated by acidophiles) to pH 12 - 13 (for alkaliphiles) [Dartnell (2011)]
  - salinity that in liquid environment can reach up to 37 [Jesse P. Harrison et al. (2013)]
  - ionizing radiation from 0 Gy to 6000 Gy [Hand et al. (2009)]

Given the key requirements for habitability, Europa, one of Jupiter's moons, is considered as a promising place in the Solar System to search for signs of extraterrestrial life. The interior of Europa probably consists of a metallic core surrounded by a rocky mantle and a water ice-liquid outer shell [J. Anderson et al. (1998)].

Strong evidence for the existence of a global ocean beneath the visible ice crust was provided by previous observations by the Galileo spacecraft [Pappalardo et al. (1999)]. High-resolution images show surface features that suggest liquid water at shallow depths below the surface [Michael H. Carr et al. (1998)]. Further measurements from the magnetometer support the theory of a salty ocean of planetary proportions that not only formed in the distant past, but is probably still present today [Kivelson et al. (2000), D. Stevenson (2000)]. One explanation for the presence of an ocean lies in the gravitational interaction with Jupiter. The tidal forces acting on Europa during its orbit around Jupiter may produce a tidal heat flow of about  $0.025\text{ W m}^{-2}$  to  $0.050\text{ W m}^{-2}$  [Ruiz (2005)]. This could be sufficient to keep the ocean warm enough for liquid water to exist under the thick ice cover.

Understanding the radiation environment at Europa's surface is crucial for studying its habitability. To date, this environment has only been characterized through models, as no in-situ measurements have been performed yet. The dynamics of particles around Europa are influenced by interactions between Jupiter's magnetic field and Europa's conductive subsurface ocean, along with the influence of Jupiter's corotating magnetospheric plasma. The most comprehensive studies of Jupiter's radiation environment are provided by the Galileo and Juno missions, providing measurements of ions up to hundreds of MeV [Garrett and Jun (2021),



Kollmann et al. (2021)]. Due to the high radiation levels, it can be assumed that the surface of Europa is uninhabitable for life forms and that biosignatures can only be detected below the surface. The ice shell on Europa is estimated to have a thickness ranging from a few kilometers to several tens of kilometers [B. Schmidt et al. (2011), Ashkenazy (2019), Howell S. M. (2021)].

So far, carbon, hydrogen, oxygen, and sulfur have been observed on the surface of Europa [Carlson, M. Anderson, Johnson, et al. (1999), Carlson, M. Anderson, Mehlman, et al. (2005)]. The ocean is believed to be in direct contact with Europa’s rocky mantle and offers similar conditions to the Earth’s biologically rich seabed.

Galileo’s Photopolarimeter-Radiometer measured the diurnal brightness temperatures on Europa, revealing a range from 86 K to 132 K for low-latitudes (up to ~70°) [John R. Spencer et al. (1999)]. Due to the high opacity of water ice, near-blackbody radiation is expected. Taking into account Europa’s obliquity, emissivity, heat capacity, and eclipse, as well as Jupiter’s radiation, internal heating and eccentricity, the annual mean surface temperature has been estimated by Ashkenazy (2019). Assuming a typical internal heating rate of 0.05 W m<sup>-2</sup>, the equator, pole, and global mean annual surface temperatures are 96 K, 46 K, and 90 K, respectively.

Table 1 provides an overview of the existing evidence for the properties of Europa that support its ability to harbor life.

**TABLE 1.** *Essential prerequisites for the habitability and known characteristics of Europa.*

| Key requirements           | Europa’s characteristics                    | Supporting references                                                                                                                                            |
|----------------------------|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Solvent                    | Subsurface water ocean                      | Measurements of introduced magnetic field by Galileo’s magnetometer [D. Stevenson (2000)]                                                                        |
| Essential elements         | C, H, O, S                                  | Observation by Galileo’s Near Infrared Mapping Spectrometer (NIMS) [Carlson, M. Anderson, Mehlman, et al. (2005), Carlson, Calvin, et al. (2009), Dalton (2010)] |
| Energy source              | Hydrothermal processes                      | Observations of the "chaos" region [Goodman et al. (2004)]                                                                                                       |
| Physicochemical conditions | Global mean surface temperature around 90 K | Measurements by the Photopolarimeter-Radiometer (Galileo spacecraft [John R. Spencer et al. (1999), Rathbun, Rodriguez, and John R. Spencer (2010)])             |

### 1.2 Current and Future Missions

For a decisive answer of the habitability, a subsurface exploration might be required. This implies a lander or similar in-situ mission. However, the development of such a mission is currently a challenge, as there are considerable uncertainties. In particular, there is not enough information for the selection of potential landing sites. To pave the way for future missions, NASA and ESA are conducting two major ongoing flyby missions to Europa, which will be introduced in the following sections.

#### NASA’s Europa Clipper Mission

Europa Clipper is the first NASA mission to follow the ocean world exploration pathway outlined in the NASA Roadmap to Ocean Worlds [Amanda R. Hendrix et al. (2019)]. The spacecraft was launched in 2024 and is expected to enter Jupiter’s orbit in 2030.

The main science objectives of Europa Clipper are categorized in the following priority order [Vance et al. (2023)]:

1. Ice shell and ocean: Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties and the surface-ice-ocean exchange.
2. Composition: Characterize Europa's composition, including any non-ice material on the surface and in the atmosphere and any carbon-containing compounds.
3. Geology: Characterize Europa's geology and understand the formation of surface features, including identifying high-science-interest localities.

The mission also aims to search for evidence of recent geological activity on Europa, such as plumes and thermal anomalies, while characterizing these features if found. It will conduct geodetic and radiation measurements, along with high-resolution observations at specific sites. These observations will cover multiple ranges of the electromagnetic spectrum, including ultraviolet, visible, infrared, and thermal infrared. Additionally, ice-penetrating radar will be used to collect data about the subsurface [T. Becker et al. (2024)].

Through the simultaneous collection of data in conjunction with models of Europa's ocean, chemistry, evolution and space environment, Europa Clipper will provide an overall assessment of Europa's habitability. In addition, the Europa Clipper mission is designed to be able to characterize risks for a future potential lander mission.

To achieve the main scientific objectives, Europa Clipper will carry out both in-situ and remote-sensing surveys. Science instruments and engineering sensors are strategically placed on the spacecraft to allow simultaneous data collection at the same surface locations.

## ESA's Jupiter Icy Moons Explorer (JUICE)

The JUICE mission is the first large mission as part of the Cosmic Vision Program 2015 - 2025 [Grasset et al. (2013)]. JUICE was launched in 2023 and is expected to arrive at Jupiter in 2031. The main objective of the mission is to study Jupiter, its extensive magnetosphere, and to conduct a comparative study of Ganymede, Callisto, and Europa.

It was designed to specifically address the following scientific themes [Grasset et al. (2013)]:

1. Life and habitability in the Solar System: To explore the environmental conditions that enable habitability, JUICE will explore the surface and subsurface of Ganymede, and to a lesser extent, Callisto and Europa.
2. From the Sun to the edge of the Solar System: JUICE will study the plasma and magnetic field environment in the Jovian system, as well as Ganymede's magnetosphere. In particular, JUICE will also study the radiation environment at Europa and Ganymede.
3. Gaseous giants and their moons: JUICE will explore the atmosphere and environment of Jupiter as the archetype for giant planet systems.

While JUICE is primarily focused on Ganymede, it will make two flybys of Europa. During these flybys, JUICE's study focuses on the composition of the non-water-ice material, the organic chemistry and the observation of the subsurface, including the determination of the minimum thickness of the ice crust.

## Future Missions to Europa

Europa Clipper and JUICE will provide valuable insights into the environment of Europa and the sites of high scientific interest. Follow-up missions would ideally include a lander on the surface of Europa. A key objective would be to directly sample the composition of near-surface materials and analyze them for organic matter. Of particular interest are buried samples below the surface, which are protected from the Jovian radiation environment. In combination with a lander, the inner structure of Europa and possible geological activities can be determined using

seismic detectors. In addition, electromagnetic soundings would make it possible to determine the local depth of an ice-water interface. To detect and confirm extraterrestrial biosignatures, that may exist near hydrothermal vents on the sea floor, the most difficult challenge would be to melt through the ice and reach the ocean bottom. For this purpose, a robot moving through the ice is required for the ice transit and an autonomous underwater vehicle for the subsurface exploration. That is the mission objective aimed by the TRIPLE project line.

### 1.3 Research and Contribution in Germany

In recent decades, the German space science community has shown significant interest in exploring icy moons and developing key technologies for future space missions [Klenner et al. (2024)]. This is mainly implemented through Germany's contributions to ESA's programs and through the National Program for Space and Innovation from the budget of the Federal Ministry for Economic Affairs and Energy (BMWE).

TRIPLE as part of the DLR Explorer Initiatives belongs to the program line *Innovative Navigation Technologies* of the Navigation Department of the German Space Agency at DLR (DLR RFA). The Explorer Initiatives have been funding universities, research institutions and commercial companies in Germany with project lines for the development of innovative technologies since 2012. The aim is to enable future robotic missions to explore areas of our Solar System that have remained inaccessible. The ability to navigate autonomously plays a key role here, which requires correspondingly highly developed artificial intelligence.

Building on the expertise gained in numerous previous and ongoing projects, e.g. Enceladus Explorer (EnEx) [Kowalski et al. (2016)], Europa Explorer (EurEx) [Hildebrandt et al. (2022)], the TRIPLE project described here aims to develop a contamination-free exploration of subglacial lakes combined with sampling and analysis.

In 2018, the DLR RFA released the mission statement for TRIPLE [Funke and Heupel (2018)]. Experts from the DLR Explorer Initiatives developed a technical concept and initial requirements for a terrestrial test site similar to that expected on Europa. Here, sub-glacial lakes in the Antarctic Dome C region were identified as targets. A Phase 0 study assessed the feasibility of this concept, evaluating and refining it while estimating necessary budgets and timelines. As conclusion, a major test campaign at the Dome C region was planned to demonstrate the technical feasibility of the exploration concept.

## 2 Mission Statement

The DLR RFA defined the mission statement in an internal document in 2018 [Funke and Heupel (2018)]. The following section summarizes this document.

The objectives of TRIPLE are the development, demonstration, and deployment of an autonomous system for the exploration of subglacial lakes and other maritime environments and, as a bonus objective, the recommendation of Germany as a payload-providing partner in a future ESA-, NASA- or other agency's exploration mission to Europa or Enceladus. It is assumed that the exploration of subglacial lakes in the Antarctic will rapidly gain in importance as terrestrial analog scenarios for future space missions to search for extraterrestrial life on the ice-covered water worlds of the outer Solar System.

In the TRIPLE project, a complete system is to be developed that is capable of conducting back- and forward-contamination-free and robust exploration of subglacial lakes, including the retrieval of samples, for the first time. It consists of three main components:

1. a semi-autonomous melting probe with integrated in-situ sensors for ice characterization and forefield reconnaissance (Forefield Reconnaissance System (FRS)),

2. a miniaturized Autonomous Underwater Vehicle (nanoAUV) as the payload of the melting probe,
3. and a Laboratory for astrobiological investigations (AstroBioLab) for highly automated analysis of fluid and sediment samples.

Within these systems, the development of the cable-less nanoAUV with its autonomous navigation capability will be the main focus.

In a field test campaign in the Antarctic, a subglacial lake is to be explored free of contamination, samples taken and brought to the surface for further analysis. The ambition of the technical development is to design a nanoAUV with typical dimensions of 10 cm (or less) in diameter and 50 cm in length. This is necessary, because the nanoAUV is intended to be implemented as a deployable payload in the payload compartment of the melting probe. Its purpose is to transport the nanoAUV through the ice. Thereby, the probe detects obstacles and hazards in the ice (debris, cavities) and navigates safe paths around obstacles. The melting probe detects the ice-water interface and holds its position there. The immediate surroundings are monitored by a camera system, and the images are sent to the surface as a live transmission. Through a dedicated docking system, the nanoAUV is deployed from this position in the subglacial lake. There, the nanoAUV navigates independently through the subglacial lake. For this, the melting probe acts as a base station and will support a navigation network. For navigation and also for docking, the nanoAUV includes a camera system that captures the immediate surroundings. Given the bandwidth-limited data link to the nanoAUV, the images are saved locally. In the vicinity of the melting probe or when docked, data can be transmitted to the surface for further processing. The nanoAUV will autonomously plan and conduct one or multiple missions, from the launch to the return to the melting probe, including docking. The duration of a mission still has to be determined, but is estimated to be about 12 h. The total number of missions still has to be determined. The nanoAUV will detect biochemical anomalies to identify Points of Interest (POI) that may provide evidence of organic materials. Additionally, if possible, the nanoAUV will collect samples from this POI. Such a POI would be, for example, a hydrothermal energy source in the subglacial lake. There, the nanoAUV takes a sample and transports it back to the melting probe while recording important environmental parameters (e.g. pressure, temperature, etc.). After return, the nanoAUV transfers the samples to the melting probe, and prepares for the next mission. Once the exploration of the subglacial lake has concluded, all deployed components will be decontaminated and returned to the ice surface.

The TRIPLE system is designed to minimize the risk of forward-contamination of the subglacial lake to be explored, cross-contamination between different samples, and backward-contamination of the surface or humans. In view of a potential space mission to an icy moon, the technical design of all hardware components, as well as procedures and strategies, will be transferable to space applications. Relevant differences between the terrestrial application developed here (including the use of adequately resistant materials) and a space mission to Europa are to be investigated and described, and appropriate solutions for the space mission are to be identified.

### 3 Project Objectives

The TRIPLE project line includes multiple individual and collaborative projects that run concurrently and are planned in parallel. The project objectives are derived on the basis of the mission statement in section 2. A distinction is made between the programmatic and strategic objectives (section 3.1), the scientific objectives (section 3.2), and the technical objectives (section 3.3).

The primary goal is the development of the overall TRIPLE exploration system. A final test campaign in Antarctica is foreseen to be carried out in the Dome C region with Concordia Station as the base, where an ice layer of around 3.3 km [Siegert (2000)] is expected, with a significant count of subglacial lakes beneath. Thus, Dome C is an ideal region and can be considered as a perfect terrestrial analog scenario with respect to future exploration of Jupiter's ice moon Europa. During this field test, the mission as described in the mission statement (see chapter 2) will be performed according to the guidelines and standard requirements of Planetary Protection [Rummel and Billings (2004)], and the environmental regulations applicable on-site [Antarctic Treaty (1959), Antarctic Treaty (1992)]. Moreover, all components and procedures used for the overall system must be transferable to a future space application.

### 3.1 Programmatic and Strategic Objectives

The programmatic goals of the TRIPLE project are the development, demonstration, and provision of an autonomous system for the exploration of subglacial lakes and marine regions that are permanently or temporarily covered by ice. The development of the exploration system should be viewed as a research and development (R&D) activity with the objective to develop a demonstrator system to support the collection of scientific data in the relevant environment.

A successful demonstration of TRIPLE would position Germany as a preferred partner for the provision of payloads in an agency's future lander mission (e.g. NASA, ESA or others) to Europa. The expertise gained from the DLR Explorer Initiatives will be utilized and further developed to achieve these programmatic objectives.

A major challenge here is the autonomy of the systems, as the respective technology carriers cannot be controlled from Earth in the future space mission. For this purpose, the development of suitable artificial intelligence for robust and accurate navigation and fully autonomous mission execution is essential. This also includes the evaluation and interpretation of sensor data in real time, as well as autonomous decision-making based on this information, in order to ensure the success of the mission.

The TRIPLE project aims to conduct terrestrial exploration of subglacial lakes. Although this focus is on Earth, it also seeks to demonstrate the capabilities of individual TRIPLE components, e.g. the nanoAUV, the FRS and the AstroBioLab, for future exploration of the icy moons in the outer Solar System. To date, no major exploration of such a lake has been carried out without contamination.

A successful completion of the project will further expand on Germany's already existing reputation as a valuable research partner into the fields of complex mobile autonomous systems for space exploration of cryogenic and aquatic environments, making it an even more attractive as a key partner to international space agencies participating in the design and execution of a space mission to Europa and other icy moons. In particular, the nanoAUV and a forefield reconnaissance system for a melting probe can be provided as payloads for such a mission. In addition, technologies from the other subsystems listed below should be considered:

- Miniaturization of underwater vehicles and systems through the systematic utilization of pressure tolerant design.
- Intelligent power management and distribution system
- Guidance, navigation and control solutions including autonomous decision making for uncertain environments
- Autonomous underwater vehicle docking with data and power transfer
- Simultaneous hydroacoustic high-speed communication and navigation methods between the nanoAUV and the melting probe
- A Hazard Avoidance and Target Acquisition System (HATAS) for the nanoAUV and the FRS



- Automated control and trajectory planning, adaptation and monitoring for the melting probe
- Mapping and characterization algorithms for the penetrated ice
- Radar, sonar and permittivity technologies for applications in glacier ice
- Power distribution and data communication in ice over long distances to the surface
- Cable unwinding and rewinding mechanisms
- In-situ decontamination process in ice
- Technology for the automated analysis of samples for biosignatures
- Integrated sensor suite for assessment of environmental conditions for habitability

Another goal is to identify commercial terrestrial spin-off applications that can incorporate parts of the development carried out in TRIPLE (e.g. automated underwater investigation of pipelines and/or offshore installations, autonomous driving, underwater docking approaches).

### 3.2 Scientific Objectives

The primary scientific goal of the TRIPLE project is to observe and interpret environmental processes on extraplanetary oceans of our solar system like on the Jovian moon Europa. The scientific goals can be broken down in three different groups of science objectives of a potential exploration mission:

- Increasing the understanding for the icy body's current state as well as its past evolution by investigating ice and subglacial ocean structure and composition on various scales.
- Investigation of the moon's habitability potential by assessing biogeochemical environmental conditions both within the ice, at the ice-ocean boundary and within the subglacial ocean.
- Search for direct evidence of biosignatures and life either within the ice or at the ice/ocean ocean/seafloor interfaces.

To achieve these objectives the to be developed TRIPLE exploration system has to be able to collect data that allows conclusions to be drawn on geological and biochemical processes in the ice shelf and the underlying water body. Within the ocean environment, POIs can be defined as geographically referenced locations that have been identified for focused study or continuous observation due to their importance for understanding physical, chemical, biological, or geological processes in the ocean. These locations are identified based on the spatiotemporal patterns of the observed variables and the occurrence of anomalies within these distributions. Also, investigating exchange processes between the core of the relevant planetary objects like Europa and the fluid water above is important to assess the potential that this object can harbor life forms or may have harbored them in the past. Besides habitability conditions described by the environmental background parameters, the identification of potential biosignatures is in the foreground of the research activities. As an intermediate step, the Polar regions of the earth are used as templates for the identification of relevant processes and the related observing strategy. Therefore, marine scientists and astrobiologists will be involved in the TRIPLE development phases to ensure that the TRIPLE system is not only a design concept for future planetary applications, but that the system also has specific scientific benefits for terrestrial exploration. To prove its suitability for the planned scientific investigations, the developed technical system is to be used in a terrestrial analogous scenario for a future exploration mission to Europa's ocean.

The exploration of subglacial lakes in Antarctica, most of which are currently still completely unexplored, promises substantial gain in scientific knowledge. These subglacial lakes represent extreme environments that have been isolated from the atmosphere for millions of years, making them ideal for studying the distribution and activity of unique, isolated life forms. To achieve this, direct but minimally invasive entry into the lakes and sample retrieval are necessary, both of which pose significant technical challenges. In this context, the following scientific goals can be achieved with the TRIPLE exploration system:

- Identification and analysis of microorganisms, focusing on their distribution and diversity within the lake; Study the biochemical and physiological processes that help these organisms adapt to isolated conditions.
- Investigation of the interaction between the subglacial lake and the overlying ice sheet, focusing on how subglacial hydrology affects ice sheet dynamics, including its flow and shape.
- Recover climatic information within the ice sheet.
- Investigation of the presence of a subglacial lake network.

### 3.3 Technical Objectives

The primary technical objectives are centered on developing a comprehensive exploration system, with the aim of elevating the technology readiness level (TRL) of all components and subsystems to at least 5. The technology TRL is to be demonstrated in a deployment in Antarctica. Consequently, specific technical objectives for the subsystems are listed below.

The nanoAUV shall carry scientific payloads that support the identification of interesting locations (POI) to take a sample and return to the melting probe. There, for the terrestrial demonstration campaign, the samples are to be handed over and collected in a suitable container for examination and transportation to the surface. For the later space mission, the sample shall be analyzed within the AstroBioLab implemented in the melting probe. Further measured data should be transmitted by the nanoAUV wireless to the melting probe via a hydroacoustic modem. In addition, the nanoAUV is to be charged with energy while being docked at the probe so that multiple successive exploration missions can be carried out.

To fulfill the exploration tasks, a compact integration of scientific instruments, an on-board power management system, a hydroacoustic modem, an on-board computer, navigation sensors, and propulsion is required. Additionally, robust autonomous navigation using decision-making by artificial intelligence (AI) is crucial for effective exploration and sampling. It should also enable the exploration (e.g. mapping, etc.). It must react appropriately to disruptions of any kind, i.e. with decisions and measures that ensure mission success with the highest probability.

The melting probe serves as a central base station for the nanoAUV. The probe should be retrievable and have a payload pick-up device that is suitable for docking and picking up the nanoAUV as a payload. Wireless charging power and datalink are also provided within the docking module during transit and between the subsequent missions. A corresponding docking mechanism must be developed and implemented. When docked, previously collected samples and data are transferred between the underwater vehicle and the probe, while the nanoAUV's batteries are recharged in parallel. The melting probe itself is to be supplied with sufficient energy via a cable connection to the surface in the terrestrial tests in Antarctica. For the future space mission, however, implementation of a Multi Mission Radioisotope Thermoelectric Generator (MMRTG) directly into the melting probe as power supply is inevitable. To maximize scientific benefit from exploration, the possibility of implementing additional suitable payloads (sensors, cameras with lighting, possibly a deployable drilling mechanism for geological investigation of sediment layers in the lake, potentially for stratigraphy) were examined and, if reasonable and technically feasible, these payloads are taken into account for designing the melting probe.

For the navigation and trajectory planning of the melting probe during the ice transit, a forefield reconnaissance system for the direct integration into the tip of the probe is to be developed. The reconnaissance system shall robustly detect obstacles (e.g. ice crevasses) and the ice-water interface.

Developing the TRIPLE system, the Planetary Protection Rules need to be strictly applied. Following the "SCAR's code of conduct for the exploration and research of subglacial aquatic

environments” [I. Alekhina et al. (2011)], it must be ensured that the penetration of the melting probe into the subglacial lake as well as the deployment of payloads, sample containers and samples and the exploration are free of contamination. The technologies deployed must be completely recovered from the lake after completion of the exploration activities. Samples taken must be encapsulated and secured in accordance with and applying appropriate biohazard rules. Automated analysis, possibly a laboratory on the surface, must also be carried out under these safety criteria. Processes and procedures must be developed and tested in advance to enable in-situ decontamination of the shuttle melting probe before it breaks through the ice-water interface. Similarly, when the technical system is retrieved after leaving the water but before reaching the surface, in-situ decontamination must be carried out and a new ice seal of the lake must be ensured.

## 4 Mission and System Requirements

Based on the mission statement (see chapter 2) and the declared objectives (see chapter 3), requirements are derived. The requirements for the mission are presented in section 4.1 and the system requirements for the overall TRIPLE system and its individual subsystems in section 4.2.

### 4.1 Mission Requirements

The complete TRIPLE system, including the melting probe, nanoAUV, and the AstroBioLab, shall undergo pre-testing together in Arctic or Antarctic conditions to validate the functionality and the correct interaction of all components. The main objective of the scientific mission will be to assess the habitability of the investigated environment and identify possible POI in the region around the launch position. The exploration of the subglacial water body shall be carried out autonomously. The TRIPLE project aims to demonstrate that the technical and scientific exploration concept of the system is robust and compatible for exploring unknown oceans on other planets. This will be achieved by successfully melting into an under-ice water body, repeatedly undocking, docking and retrieving the nanoAUV, and acquiring data of scientific interest during a terrestrial analogous demonstration mission.

Following the final demonstration in Antarctica, a comprehensive analysis and evaluation will be conducted to assess the transferability of the TRIPLE system. The design of the TRIPLE mission elements will consider the future transfer and adaptation of the developed technologies to enable space missions.

### 4.2 System Requirements

#### 4.2.1 Melting Probe

The melting probe will be designed for multiple uses with the main purpose of transporting the nanoAUV inside its designated Launch and Recovery System (LRS) from the surface to the targeted subglacial water body and back. It will be engineered to achieve a high melting speed, ensuring that it reaches its planned destination within an acceptable time frame. In addition, the probe will return to the surface by melting once it has completed its task. Differential heating of the melting head provides limited capability of deviating from a vertical melting direction. To ensure stability, the melting probe will be capable keeping a stable position at the exit of its melt channel.

## 4.2.2 nanoAUV and Launch and Recovery System

The nanoAUV is a highly integrated miniaturized Autonomous Underwater Vehicle to explore and sample the unknown environment in the wider vicinity of the melting probe. The vehicle will be able to navigate under-ice autonomously, while following a predetermined mission plan. The nanoAUV will be able to measure, sample and store key scientific parameters, needed for the assessment of the habitability of the subglacial water basin and identifying potential POI within the water column or near the ice-water interfaces. Additionally, the nanoAUV should have the capability to take water samples for identifying possible biosignatures. At the end of each mission the vehicle will return to the Launch and Recovery System (LRS), where it can download the collected information and samples, recharge its batteries, get new mission plans or where it could be safely stored inside the LRS for a return to the surface.

The LRS is an integral part of the melting probe that acts as a safe transport and storage system for the nanoAUV until the melting probe has melted through the ice and detected the ice-liquid interface. Once safe and stable conditions below the ice have been established, the LRS will move the nanoAUV outside of its containment vessel and position it for deployment. While the nanoAUV is being deployed and running its mission, the LRS is supporting navigation and communication to and from the nanoAUV via its hydroacoustic navigation and communication system. For retrieval, the LRS is going to safely capture and lock the nanoAUV. As described above, while captive in the LRS, the nanoAUV is able to upload data to the melting probe via the LRS, while the vehicle's batteries are going to be recharged for a new mission. At the end of a mission sequence the LRS should store the nanoAUV back in the safe transport mode, to be ready to transported back to the surface.

## 4.2.3 Forefield Reconnaissance System for the Melting Probe

The forefield reconnaissance system is an integral part of the melting probe. It will be able to detect obstacles on the melting path to ensure the safe navigation of the probe throughout the mission. In addition, it will be able to detect the ice-water boundary and measure the distance to it in time to help the probe maintain its position in the melt channel.

## 4.2.4 Science Payload in the Melting Probe

The melting probe will be equipped with sensors to characterize the ice shell structure, focusing on internal features like cracks, phase transitions, and near-surface water bodies. These sensors allow indirect measurements of the local water layers, including melt water during the melting phase, fluctuations within the ice layer, ice-water heterogeneity and further characterization of ice and non-ice grains. The science payload enables the melting probe assessing meltwater in real time during the melting phase. By analyzing environmental parameters, it supports critical insights into the habitability of the surrounding environment and guides the mission's scientific objectives.

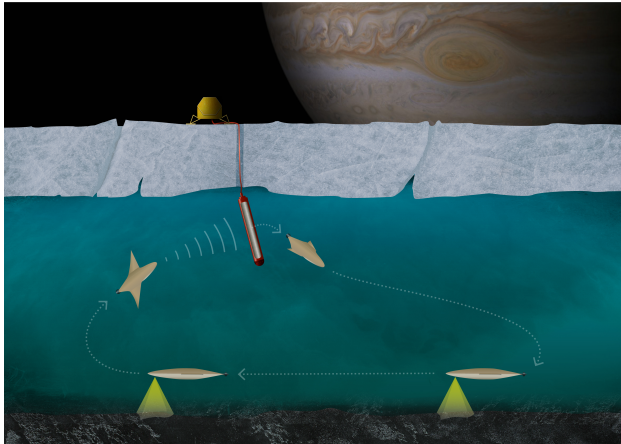
Indirect observations help to determine the ductile-to-brittle transition within the ice shell, affecting global heterogeneity distribution. External pressure measurements on the melting probe will be utilized to assess phase changes (melting vs. sublimation) during the early melting phase, evaluate ice porosity in later stages, and detect melt channel closure through pressure build-up. The sensors will also measure the water in the subglacial lake and provide redundant data to complement the scientific measurements of the nanoAUV.

#### 4.2.5 Astrobiological Laboratory

The automated analysis and transfer of samples from the melting probe and nanoAUV to the astrobiological laboratory will adhere to safety requirements for handling potentially hazardous substances (biohazards). The astrobiological laboratory will be capable of receiving samples from the nanoAUV while ensuring the prevention of contamination. It should be able to analyze multiple samples (at least three) delivered by the sampler and detect the presence of unique biological signatures. Additionally, the astrobiological laboratory should be capable of performing DNA sequencing.

## 5 Overview TRIPLE

A concept was made to meet the project objectives and the mission, and the technical requirements. An overview of the TRIPLE mission with the key components, as mentioned in the mission statement (see chapter 2) is illustrated in Figure 1.



**FIGURE 1.** *Illustrative overview of the TRIPLE mission, highlighting three key components for the exploration of subglacial lakes.*

The following section presents an overview of the project phases, organizational structure, and systems currently under development.

### 5.1 Overview of the Project Phases

An overview of the TRIPLE project with an assignment to the corresponding European Cooperation for Space Standardization (ECSS) phases is provided in Table 2.

Phase 2 of TRIPLE corresponds to the ECSS phases B to D, with the target being a demonstration campaign on the Ekström Ice Shelf, near the German research station - the Neumayer Station III (NM-III) in Antarctica. This test campaign marks the first full TRIPLE system demonstration in a polar environment and serves as an intermediate milestone towards Dome C. This will be a combined scientific and technical field test to demonstrate the technical feasibility and scientific possibilities of the TRIPLE system.



Phase 3 will aim for a demonstration at Dome C. For Dome C, phases A to D will need to be reiterated to accommodate the specific requirements. The ECSS Phase E is not part of the TRIPLE project.

**TABLE 2.** Overview of the schedule of the TRIPLE project line. To specify the targets Neumayer Station III and Dome C, the indices NM3 and DC were introduced respectively as extensions to the project phases.

| Phase<br>(TRIPLE naming)                                                       | Phase<br>(ECSS naming)                                             | Date              |
|--------------------------------------------------------------------------------|--------------------------------------------------------------------|-------------------|
| Initial presentation of the nanoAUV idea                                       |                                                                    | 12/2017           |
| Expansion to the TRIPLE Project idea                                           |                                                                    | 2018              |
| Phase 0 Study                                                                  | 0                                                                  | 11/2018 - 06/2019 |
| Phase 1                                                                        | A/B1                                                               | 2019 - 06/2023    |
| Phase 2 (NM-III)                                                               | B1 <sub>NM3</sub> /C <sub>NM3</sub> /D <sub>NM3</sub>              | 06/2023 - 06/2027 |
| Phase 3 (Dome C)                                                               | A <sub>DC</sub> /B <sub>DC</sub> /C <sub>DC</sub> /D <sub>DC</sub> | TBD               |
| Transfer to German scientific community for utilization in research activities | E <sub>DC</sub>                                                    |                   |
| Space Mission                                                                  |                                                                    | TBD               |

5.2 Results of Phase 0 + 1

Over the duration of the development, several milestones were completed and multiple demonstrations and field tests were conducted to test different segments of the TRIPLE system separately.

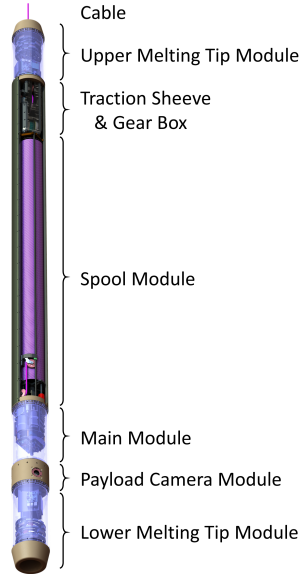
5.2.1 Phase 0 - Mission Definition

In the phase 0 study, the general feasibility, schedule, and cost estimate were examined and completed with the Mission Definition Review (MDR). The exploration of the subglacial lake Lake Concordia in the Dome C region of Antarctica, outlined in the mission statement, was shown to be feasible and financially viable. The resulting schedule and work breakdown structure were used as a baseline for projects funded during phase 1.

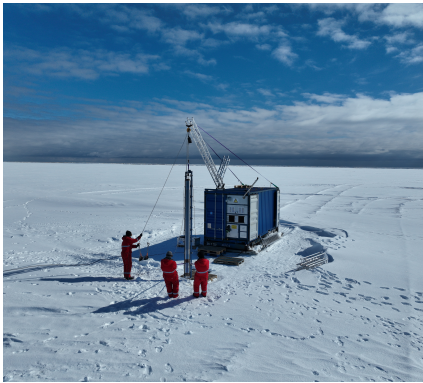
5.2.2 Phase 1 - Requirement Definition and Technology Demonstration

During phase 1, the requirements for the TRIPLE mission on the system level were defined and assessed in a System Requirements Review (SRR). During this phase, a first concept of the TRIPLE systems for the Dome C mission was developed within the TRIPLE-nanoAUV 1 project. In parallel, several projects aimed at the development of critical technologies for individual TRIPLE components.

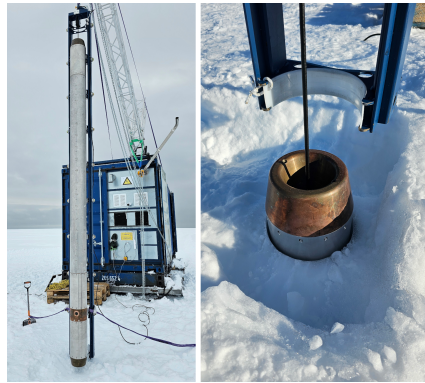
A first recoverable melting probe demonstrator, the TRIPLE-IceCraft (Figure 2), was developed in the project of the same name (2019 - 2024) and tested on the ice shelf in the vicinity of Neumayer Station III (Figure 3) [Regnery et al. (2024)].



**FIGURE 2.** *Technical drawing of the TRIPLE-IceCraft melting probe  
(Total length excl. payload 3.5 m).*



**(a)** *Setup*



**(b)** *Operation*

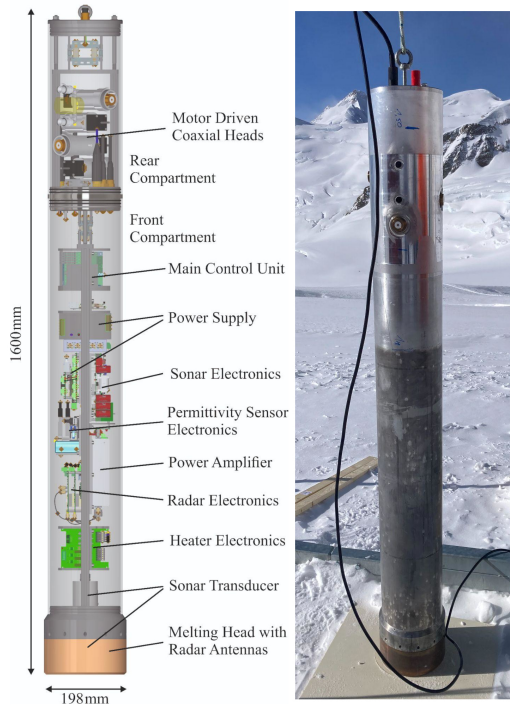
**FIGURE 3.** *The TRIPLE-IceCraft melting probe and the ground support system during a test campaign on the Ekström Ice Shelf, Antarctica 2023/24.*

A ground support system was built for the power supply and operation of the IceCraft melting probe. It houses a generator to produce electrical power, an AC/DC converter to produce operating DC power for the melting probe, and supplies all other equipment with standard 230 V AC power. It also provides a communications interface for the operator to monitor and operate the melting probe.

Within the project TRIPLE-FRS (2020 - 2023), a hybrid radar and sonar-based FRS was



developed and integrated into the head of a melting probe [Stelzig et al. (2024)].



**FIGURE 4.** *Carrier system with an integrated FRS: Technical drawing (left) and integrated system during a test campaign on an alpine glacier (right). Both radar and sonar are integrated into the melting head, while the permittivity module is built at the rear.*

This hybrid approach was chosen to combine the complementary advantages of both sensor systems, thereby enabling a robust detection. Both radar and sonar are integrated into the melting head. To determine the propagation speed of the electromagnetic waves and to further provide scientific data about the ice stratification, the system further includes a permittivity sensor. Figure 4 presents a technical drawing of the FRS, which has been integrated into a carrier system that is capable of melting. With this carrier system, the FRS was used at the Jungfrau firn glacier in Switzerland and successfully tested for its functionality [Stelzig et al. (2024)]. The system was specifically designed to meet the requirements to detect obstacles in the melting path as well as the ice-water boundary, ensuring safe melting through the ice.

The AstroBioLab was developed as part of the project TRIPLE-SciDecABL (2020 - 2023). In the initial development phase, system requirements were defined with environmental constraints and integration with other TRIPLE systems in mind, particularly the nanoAUV sampler. A feasibility study evaluated the overall concept, leading to early tests of microfluidic functionality and DNA sequencing components. Analytical pipelines – centered on fluorescence spectroscopy and microscopy – were selected for their scientific value and suitability for compact, semi-automated operations. Well established methods for the detection of biosignatures such as Raman and UV/VIS spectroscopy, of which miniaturized, space-qualified versions already exist, should at least be used to study the ice crust/glacier itself during the melting phase and



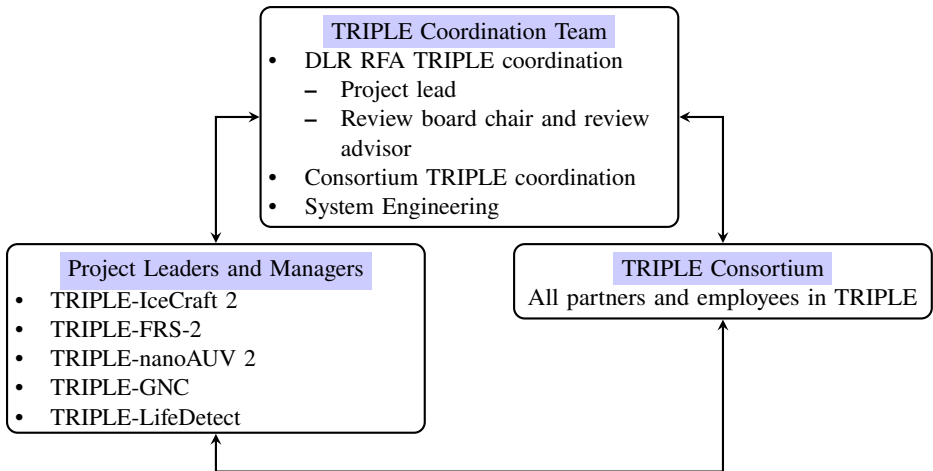
possibly in the future with the nanoAUV to study the liquid water phase under the ice cover. Mass spectrometry was also elected as an analytical pipeline to achieve a more comprehensive understanding of the investigated environment.

Within phase 1, the design of the nanoAUV was mostly completed within the project TRIPLE-nanoAUV 1 (2020 - 2023). Major decisions on technology and design (especially actuation, navigation and miniaturization) were derived from literature and preliminary tests. Different options for the propulsive and steering system were explored with the most promising in a proof-of-concept approach.

Similarly, the LRS concept was developed with its robotic vehicle handling system. A software framework was generated to validate critical functionalities and design decisions. Furthermore, engineering models of various components were also created to test for potential design issues. The project will culminate in a proof of concept for a miniaturized autonomous underwater vehicle.

### 5.3 Organization Structure of TRIPLE

The project management structure is depicted in Figure 5. Due to the complexity of the project, a TRIPLE coordination team was formed to coordinate the activities within the consortium and ensure a proper flow of information. The coordination team includes internal coordination from DLR RFA, which is responsible for leading the project as well as serving as the chair of the review board and acting as a review advisor. Additionally, there is a coordination team from the TRIPLE consortium, currently chaired by the III. Physikalisches Institut B of the RWTH Aachen University. This coordination team ensures that all individual project activities are coordinated consistently in view of the overall objectives. It also acts as a point of contact between the consortium and the project coordination by the DLR RFA. A dedicated system engineering team from the Institute for Machine Elements and Systems Engineering at the RWTH Aachen University is also part of this structure. It is tasked with integrating subsystems, ensuring that technical requirements are met, conducting risk assessments, and facilitating communication between different teams. The leaders and managers of each project serve as contacts for the coordination team.



**FIGURE 5.** Actual organization structure of TRIPLE.

A core element of the overall management scheme has been the close interaction between the involved partners. As a matter of fact, regular telephone conferences and submitting contributions to conferences to outline the planned project activities are carried out. In the current phase (Phase 2), the TRIPLE project line includes five projects, each targeting a specific system or subsystems. The list of all funded projects and associated partners is provided in Table 3. The TRIPLE project also benefits significantly from the support of the DLR’s Space Operation and Astronaut Training Center (MUSC), which will play an important role in the tests in Antarctica.

**TABLE 3.** Overview of the Phase 2 funded TRIPLE projects. The coordinating partner is highlighted in bold face.

| Project, Duration                       | Objectives                                                                                                                                                                                                                                                                                                                        | Consortium Partners                                                                                                                                                                                                                     |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| TRIPLE-GNC,<br>06/2023 - 09/2026        | Development and integration of the nanoAUV and LRS Software, planning and implementation of the NM-III campaign                                                                                                                                                                                                                   | <b>Institute of Automatic Control, RWTH Aachen University</b><br>Cognitive Neuroinformatics, Bremen University<br>German Research Center for Artificial Intelligence<br>Institute of Flight Guidance, Technical University Braunschweig |
| TRIPLE-LifeDetect,<br>06/2023 - 08/2026 | Planning of the NM-III test campaign, development, and application of the scientific payload for the NM-III TRIPLE system (SPI, AstroBioLab, nanoAUV MSP, nanoAUV Sampler) for habitability assessment of under-ice habitats and the sustainable use of the data obtained (CryoTwin, RDM), also with regard to the Dome C mission | <b>Alfred Wegener Institute</b><br>University of Applied Science, Aachen<br>Chair of Methods for Modelbased Development in Computational Engineering, RWTH Aachen University<br>TriOS GmbH                                              |
| TRIPLE-nanoAUV 2,<br>06/2023 - 09/2026  | Construction of the nanoAUV and LRS for the NM-III and partly for Dome C deployment, planning and implementation of the NM-III campaign                                                                                                                                                                                           | <b>MARUM, University Bremen</b><br>DSI Aerospace GmbH<br>EvoLogics GmbH                                                                                                                                                                 |
| TRIPLE-FRS-2,<br>07/2023 - 08/2026      | Development of a hybrid radar and sonar-based FRS for glacier applications, especially for the Dome C mission                                                                                                                                                                                                                     | <b>GloMic GmbH</b><br>III. Physikalisches Institut B, RWTH Aachen University<br>Institute of Microwaves and Photonics, Friedrich-Alexander-Universität Erlangen-Nürnberg<br>Department of Physics, University of Wuppertal              |
| TRIPLE-IceCraft 2,<br>08/2024 - 10/2027 | Technology development of a TRIPLE-IceCraft 2 Melting Probe for the preparation of the Dome C mission                                                                                                                                                                                                                             | <b>GSI GmbH</b><br>III. Physikalisches Institut B, RWTH Aachen University<br>Department of Mechanical Engineering and Production Management, HAW Hamburg                                                                                |

## 5.4 TRIPLE Schedule

A first TRIPLE work breakdown structure (WBS) for all activities within the TRIPLE Project has been developed within the prior project phase 0 and phase 1. In the current phase, the WBS has been updated, focusing on the NM-III test campaign and the work packages for the connection to Dome C and space. All main elements of the TRIPLE exploration system are broken down into the main development tasks and activities in accordance with the schedule (see Figure 6).

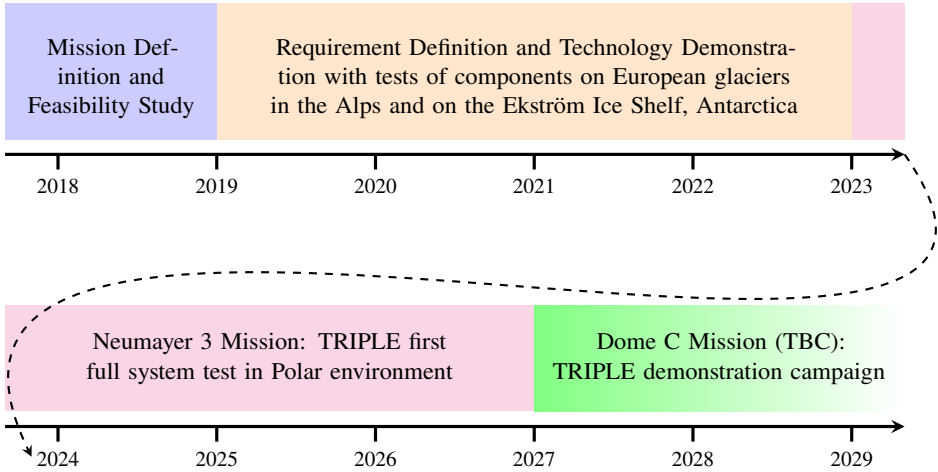


FIGURE 6. *TRIPLE schedule*

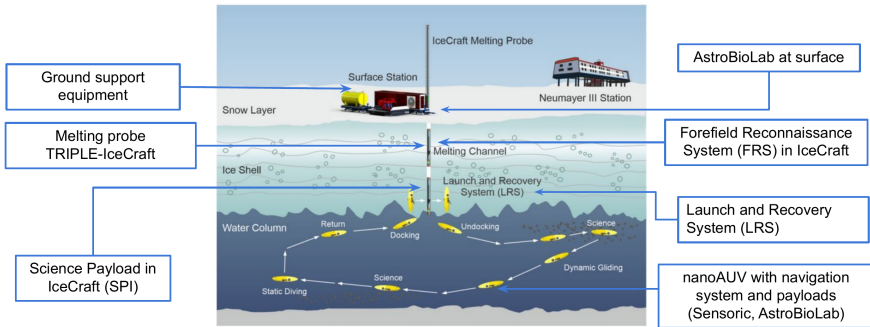
## 5.5 Phase 2 - Current Development

Based on the results from phase 1, a concept was developed to integrate all subsystems into a comprehensive mission scenario (see Figure 7). The mission involves several key phases: melting through the ice sheet, exploring the water body, collecting scientific data, and returning to the surface. Scientific process studies during the NM-III demonstration will focus on the characterization of the sub-glacial ocean regarding temperature and flow structure and gradients, to assess the availability of salt and organic compounds at the ice-ocean interface and in the subglacial ocean. The mission begins with transporting all exploration systems through the ice by downward melting using the IceCraft probe (see chapter 5.5.1). During this phase, the Forefield Reconnaissance System FRS will operate alongside all scientific instruments within IceCraft (see chapter 5.5.3 and 5.5.4). During the ice transit, data indicating ice heterogeneities will be collected. Reference measurements of the ice thickness from the surface will also be conducted. Additionally, permittivity data will be gathered to develop mathematical and numerical methods for geoscience and glaciology applications.

Upon reaching the ice-water interface, the modular Launch and Recovery System LRS inside IceCraft will deploy the nanoAUV into the water. The nanoAUV will carry out its exploration before being recovered by the LRS (see chapter 5.5.2). It will investigate the transition area from sea to shelf by conducting in situ measurements of conductivity, temperature, and depth (CTD),

chlorophyll A (ChlA), turbidity (Turb), and dissolved oxygen (DO), along with collecting samples. Thereafter, IceCraft will ascend by upward melting. On the surface, an AstroBioLab for sample analysis will be ready for operation (see chapter 5.5.5).

Further details on the realization and implementation of the subsystems will be provided in chapter 6.



**FIGURE 7.** System overview for the demonstration campaign on the Ekström Ice Shelf.

### 5.5.1 The Melting Probe IceCraft

The purpose of the electrically powered melting probe IceCraft is to transport a payload, in particular the nanoAUV and its LRS and an in-situ water analysis system (Science Payload IceCraft (SPI)), vertically through a large body of ice to a subglacial lake or ocean, allow the payload to perform its purpose, relay the data to the surface and transport the payloads back to the surface. During this time span, the IceCraft will supply the payload with electrical power, relay the communication to the surface and ensure that the temperature of the outer shell of the payload segment is high enough at all times to counter refreezing of the water.

### 5.5.2 nanoAUV and Launch and Recovery System (LRS)

The nanoAUV is a miniaturized 6 Degrees of Freedom AUV that is developed to carry out the autonomous exploration tasks in subglacial aquatic environments. It is designed to be transported as a payload inside the melting probe through the ice column and carrying scientific sensors. The AUV should also be able to locate and target biochemical anomalies in the water column, known as areas of interest, which are favorable for microorganisms. Such areas of interest would be, for example, regions of significant geothermal heat fluxes in subglacial lakes.

The nanoAUV incorporates autonomous navigation and exploration capabilities that enable to navigate to POIs, take samples and return to the melting probe. These operations are performed using onboard sensing capabilities, such as the miniaturized on-board hydroacoustic Ultra Short Base Line System (USBL) in conjunction with an integrated inertial measurement unit (IMU) and scientific sensors. In order to allow for multiple missions under-ice while maintaining a small size and manage the risk of data loss, the nanoAUV can be recharged and the recorded data can be transferred via the launch and recovery system (LRS) to the melting probe via an inductive link.

The LRS itself is a modular element integrated into the melting probe serving as the subglacial operational hub for the nanoAUV. The LRS provides safe transport of the nanoAUV to-and-from the deployment site and is equipped with a robotic deployment and recovery system.

Moreover, the LRS is equipped with the miniaturized counterpart of the nanoAUV mounted USBL system - enabling not only accurate position but also acoustic communication between LRS and nanoAUV.

### **5.5.3 The Forefield Reconnaissance System (FRS)**

The FRS is used to detect obstacles and crevasses along the trajectory of the probe, as well as to identify the transition between ice and water when reaching a subglacial water body. The FRS is integrated into the tip of the melting probe and is essential for safe melting through the ice. By measuring the distance to obstacles or the ice-water interface, appropriate mechanisms can be triggered to stop the melting probe in time. A hybrid system is employed to conduct sonar and radar measurements. A permittivity sensor is integrated as an additional component to calibrate the propagation speed of the radar waves in the ice.

### **5.5.4 Science Payload Melting Probe (SPI)**

A system for in-situ validating the nanoAUV sensors and time-series measurements is also to be developed for the melting probe, which will be based on the existing IceCraft melting probe.

### **5.5.5 AstroBioLab (ABL)**

AstroBioLab is a compact and resilient field laboratory designed to conduct automated bio-analytical measurements, while currently still requiring human assistance for sample delivery and maintenance. Its analytical processes are built around microfluidics, allowing precise manipulation of minute sample volumes and enabling efficient mixing and separation of chemical components. The system employs fluorescence spectroscopy to analyze chromophoric dissolved organic matter (CDOM) and microscopy for morphological assessments, providing an efficient approach to identify potential biosignatures in subglacial environments. Additionally, AstroBioLab incorporates DNA sequencing and mass spectrometry to achieve a more comprehensive understanding of both the microbial life and the environment that encompasses it.

To maintain analytical precision and prevent cross-contamination, AstroBioLab is equipped with a comprehensive self-decontamination system utilizing ultraviolet (UV) and chemical sterilization. Between samples, the system undergoes a chemical flushing process to eliminate residual contaminants, ensuring the integrity of subsequent analyzes. These decontamination strategies are essential to preserve sample purity, particularly in environments where microbial life is scarce.

### **5.5.6 Ground Support Equipment (GSE)**

The ground station comprises all necessary systems and components to enable a demonstration on the shelf ice in the vicinity of the Neumayer Station III and the transport to and from this location, as well as associated off-site support equipment. Everything is fitted into a 20 ft overseas shipping container including the power generator, a workspace, a crane to launch the IceCraft, the control system of the IceCraft and the ground support equipment for the payloads nanoAUV, LRS and LifeDetect and additional surface equipment, i.e. AstroBioLab. This ground station is in itself not yet suitable for the final demonstration under extreme conditions at Dome C, but acts as a base for this development.

## 6 Realization and Implementation

This chapter focuses on the key components and outlines their technical benchmarks. It details the design and implementation processes for the deployment on the Ekström Ice Shelf.

### 6.1 The Melting Probe IceCraft

The melting probe IceCraft is designed as a modular melting probe for transporting the TRIPLE payloads through ice [Heinen et al. (2021)]. The development for this system aims for a fully functional and retrievable melting probe that provides a standardized cargo area for the other TRIPLE systems and other scientific payloads. For this purpose, the melting probe is thermally controlled from the head over the side walls to the back by heating elements. For now, it allows a melting depth of several hundred meters and a melting speed of up to 5 m/h. One key challenge is the full retrievability of the system and therefore a cable management system, which is a combination of internal storage of the cable and an electric-motor-powered winch for uncoiling and recoiling of the cable.

The probe's structure is divided into several compartments contained within watertight pressure vessels. These vessels are designed to withstand high pressure even during refreezing of the melting channel. The interfaces between modules are designed for easy combination of different scientific payloads and module exchange.

The cable has a coaxial structure and an aramid mesh. It bears the weight of the probe and is used for power transmission and communication. The winch module can uncoil and recoil the cable and consists of a traction sheave, gearbox, spring-loaded tensioner pulley, cable spool, and several guide rollers. The length of the uncoiled cable is determined by counting the rotations of the motor that drives the gear and the traction sheave.

The command and data handling system (CDHS) is a commercial single-board computer with a breakout board. It hosts the slow control and implements the sensor fusion. Data from subsystems and auxiliary sensors, including an IMU, a magnetometer, humidity and pressure sensors, power sensors, and temperature sensors, are provided for fault detection, isolation, recovery (FDIR), and navigation purposes. Communication between the TRIPLE-IceCraft and the surface is facilitated using a power-line module.

The TRIPLE-IceCraft was tested over two Antarctic field seasons at Neumayer Station III, under realistic conditions. During the first season (2022/2023), the main focus was on hardware functions. During the second season (2023/2024), the system was mainly tested for software stability and FDIR functions. Throughout the testing, the TRIPLE-IceCraft melted more than 5 holes with a total length of about 125 m. The deepest hole was 52 m deep, and the cable management system spooled more than 400 m up and down.

### 6.2 nanoAUV

The nanoAUV is designed as a miniaturized and autonomous underwater vehicle with additional gliding capabilities. This design allows to achieve flexibility and usability in unknown environments under the ice. The nanoAUV (Figure 8) features a rear thruster with a vector nozzle for baseline maneuvering and will be enhanced by a buoyancy engine for static buoyancy changes and gliding functionality. The current design is fine-tuned to a terrestrial demonstration but can easily be adapted towards a future space mission, by using space grade components, which are available for all critical parts (refer to section 7).

The required autonomy is achieved using an array of sensors. The AUV is equipped with an IMU, a pressure sensor, and a magnetometer for environment independent localization. The IMU based localization is augmented and improved by acoustic odometry provided by a

doppler velocity log (DVL). The DVL uses the under-ice surface as reference to provide velocity measurement. Positioning is completed using an Ultra-short baseline acoustic positioning system (USBL), which relies on a base station integrated into the LRS and a receiver as part of the AUV. Side scan sonars are planned to allow perception and mapping of the AUV's surroundings.

The integrated on-board computer is geared towards a space grade multi-core microprocessor capable of handling the requirements of the software stack.

The software stack is designed to achieve autonomy under water. The most relevant modules implemented are the Guidance, Navigation and Control (GNC) stack, higher level autonomy, perception, as well as communication. In combination, the modules achieve autonomous execution of a mission consisting of undocking, detection of POI, decision making, exploration, homing, and docking. All modules are designed to fulfill the requirements of a space mission, where external communication is only possible with significant delays and all systems must be recoverable after hard- or software failure.



FIGURE 8. TRIPLE LRS and nanoAUV (Credits: Sebastian Meckel, MARUM).

### 6.3 Launch and Recovery System (LRS)

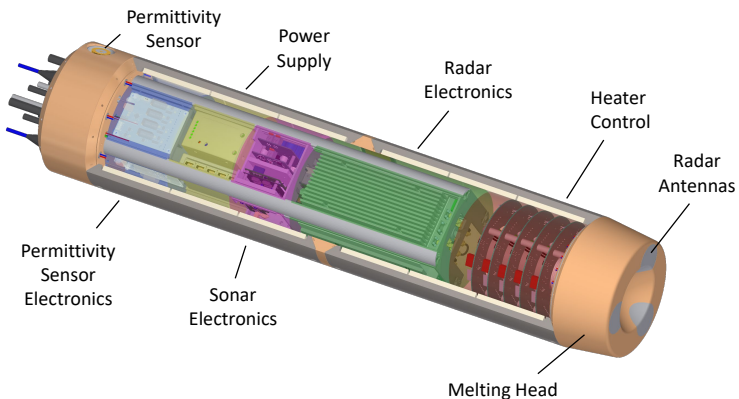
The design concept of the LRS is that of a robotic arm, which can be folded into and out of an extension to the TRIPLE-IceCraft. The arm is equipped with a gripper to safely release and recover the nanoAUV. The LRS kinematics allow for the gripper to recover the nanoAUV from a defined region around the piercing point of the TRIPLE-IceCraft. This way, the recovery system can adapt to disturbances acting on the nanoAUV and cancel out any limitations arising due to the limited maneuverability of the nanoAUV. The LRS incorporates its own power management system, providing necessary power for dedicated system's parts on demand along with continuous monitoring crucial electrical parameters of the running system. The hydroacoustic communication and positioning system is an important part of LRS, enabling communication with the AUV during its autonomous mission while simultaneously obtaining the vehicle's position.

## 6.4 The Forefield Reconnaissance System (FRS)

The FRS features a hybrid radar and sonar system for enhanced robustness, leveraging both technologies' strengths. Radar is ideally suited for measurements in dry ice, but experiences high attenuation in wet environments, such as at the boundary layer to water or in water-filled crevasses. Conversely, sonar is effective in wet environments, making it a complementary technology for these conditions. To optimize the efficiency in the forward direction, it is essential that both sensor systems are integrated into the tip of the melting probe. This design challenge requires a compact configuration due to the limited space available. It must also be ensured that the melting efficiency of the melting probe remains undisturbed.

The radar system is a sequential sampling impulse radar equipped with a high-power impulse amplifier capable of up to 1 kW. It also employs correlation techniques using pseudo-random noise coding to enhance the signal-to-noise ratio. The integration of radar antennas into the melting head is a key challenge. To address this, the antennas are made of aluminum nitride, a material chosen for its high thermal conductivity. The radar operates at 1.35 GHz, which optimizes both the penetration depth and the antenna size.

The FRS sonar is an active system that transmits acoustic signals into the ice and records the reflected waves. A Tonpilz-style piezoelectric transducer is utilized for providing high power output. This transducer comprises a stack of piezoelectric disks clamped between two masses, with the melting head serving as the front mass. The FRS sonar can be operated using a wide variety of signal shapes such as sine bursts, Barker codes, and chirp signals. To counteract high attenuation at increased frequencies, low-frequency signals in the kHz range are employed, with an emitting voltage of up to 600 Vpp, to achieve extended range detection. The permittivity sensor features motor-driven coaxial heads integrated into the side of the melting probe, which can be extended and pressed against the melting channel. The permittivity is derived from a reflection coefficient measurement. This permittivity data is then used to calibrate the radar's propagation speed.



**FIGURE 9.** Technical drawing of the the Forefield Reconnaissance System for the TRIPLE test campaign on the Ekström Ice Shelf.

Figure 9 showcases a technical drawing of the FRS system, designed as a compact modular unit for integration into the NM-III test scenario. The module has a length of ~1 m and is



equipped with all necessary compatible interfaces for connection to the IceCraft and additional adjoining payloads.

## 6.5 The Science Payload IceCraft (SPI)

The SPI is an analytic instrument suite integrated into the TRIPLE-IceCraft system. In its current iteration, it provides stationary time-series measurements at the ice-water interface, which supports nanoAUV sensor validation and environmental monitoring. SPI is equipped with CTD (conductivity, temperature, depth), dissolved oxygen (DO), Chlorophyll-a (ChlA), and turbidity (Turb) sensors, mirroring key parameters measured by the nanoAUV, at the entrance point under the ice.

Due to size and weight limitations with the IceCraft setup used for initial tests at Neumayer Station III, the current SPI setup is intended to be used under the shelf ice (~800 m). All sensors are ready to be used at full ocean depth (6000 m) after pressure housing upgrade and can then be used in deeper deployments such as Dome C.

The SPI transmits data through the Ethernet connection of the IceCraft for real-time acquisition at the ground station, but also has onboard storage in case of communication failures. Future versions shall be designed alongside next-generation melting probes for a more streamlined design, allowing for more power, space, and integration of advanced bioanalytical tools, such as miniaturized fluorescence microscopy and fluorescence spectrometry from AstroBioLab, which will require more advanced automation.

## 6.6 AstroBioLab

AstroBioLab is a robust, compact, semi-automated field laboratory designed for bioanalytical investigations in extreme environments. Its high level of automation and adaptability make it a unique tool for detecting potential biosignatures in subglacial and remote settings. The system integrates advanced analytical techniques within a mobile, thermally insulated unit, ensuring stable operation under harsh conditions.

Housed in a portable aluminum expedition box with wheels, AstroBioLab is actively heated to maintain optimal laboratory conditions, preventing freezing and ensuring the reliability of its analytical components. The system consists of two main sections:

- Housekeeping Module – Contains power management, decontamination systems, and maintenance equipment to support extended field operations.
- Analytical Module – Incorporates fluorescence spectroscopy for the detection of chromophoric dissolved organic matter (CDOM) and fluorescence microscopy for morphological observations, in addition to DNA sequencing for the detection of eDNA and metagenomic investigations in samples. Sample handling is performed using microfluidic pumps and components to ensure precise fluid control and minimal sample consumption. Mass spectrometry is another analytic path for AstroBioLab to ensure the environment has the cornerstone elements (mainly C, H, N, O, P, S) to enable life.

AstroBioLab is designed to process water samples collected via Sterivex filters. The transfer of samples follows established standard operating procedures (SOP) to minimize contamination risks. The system employs a self-decontamination process utilizing ultraviolet (UV) and chemical sterilization, ensuring analytical integrity between samples.

For data acquisition, AstroBioLab operates on a fully automated analytical pipeline following manual sample delivery. All collected data are stored with redundancy, allowing post-mission analysis. The calibration of the analytical components is automated, ensuring reliable performance under field conditions.

Beyond its primary scientific mission, AstroBioLab is highly adaptable and can be repurposed for other more challenging terrestrial applications such as Dome C. In addition, its technological structure aligns with future space mission objectives, making it a potential candidate for planetary exploration scenarios.

## 7 Connectivity Options

### 7.1 Subglacial Lakes and Other Locations

There are several types of subglacial lakes, for which the complete TRIPLE system or one or more TRIPLE segments can be used to conduct an exploration mission in the lake:

- Pressure-melting point from a combination of geothermal or frictional heating and the thermal insulation provided by the thick ice cover, similar to Lake Concordia
- Brine rich liquid sub or englacial water at subfreezing temperatures, similar to the subglacial lake at Taylor Glacier, McMurdo Dry Valleys Antarctica
- Liquid water under a glacial due to volcanic activity beneath the ice cover, for example, Grímsvötn lake under the Vatnajökull glacier in Iceland
- Grounding zones: the region where ice transitions from a grounded ice sheet to a freely floating ice shelf, typically over several kilometers
- Underwater caves: not covered with ice, but difficult to access with divers or remotely operated vehicles (ROVs). The TRIPLE segment nanoAUV could be an option for an exploration mission.

Subglacial lakes are interesting for diverse scientific disciplines: microbes living in subglacial lakes under extreme environments are interesting for microbiology and astrobiology and, depending on whether the lakes are disconnected from the oceans, even for evolutionary biologists [Siegert et al. (2001), Bulat et al. (2004), Säwström et al. (2008), and Murray et al. (2012)]. For climate scientists and geophysicists, subglacial lakes are important research objects as they can help to understand how climate has evolved on Earth and how water cycles work [Bell (2008)]. Glaciologists are interested in subglacial lakes as these influence glacier dynamics [Livingstone et al. (2022)]. A further aspect is that subglacial lakes can cause flooding, and their monitoring can be an aspect of hazard prevention [Cook and Swift (2012) and Gao et al. (2021)].

Future developments may include the deployment of ocean floor lander platforms or profiling instruments to expand the area of investigation in ice-covered regions. As bottom-bound systems, landers offer flexible, long-term operation and could represent a logical next step as an addition to current AstroBioLab-SPI modules—potentially extending to larger ocean floor landers as well as future ocean floor micro-lander concepts. Although deployment, automation, data transmission, and payload integration pose challenges, the broad applicability of such systems makes them a valuable consideration for TRIPLE system extensions. Emphasizing modularity, automation, and connectivity will support adaptability in both terrestrial and extraterrestrial exploration scenarios.

### 7.2 Space

The JUICE and Europa Clipper missions will provide valuable insights into Europa, therefore a lander on Europa would be a minimum requirement to substantially enhance our knowledge of this ocean world. TRIPLE addresses the significant challenges associated with such a lander mission by advancing the development of critical components for space environments, thereby increasing their TRL for deployment. These systems must operate autonomously under extreme conditions, including low gravity, vacuum, cryogenic temperatures, and radiation exposure.

The melting probe shall be designed to navigate subsurface ice and reach liquid reservoirs while maintaining scientific payload integrity. The nanoAUV, in combination with the LRS, shall be capable of autonomous exploration in subglacial oceans, transmitting data through ice or relaying it via a surface station.

In addition to Europa, Saturn's moon Enceladus has been identified as a prime target in the study of ocean worlds and is, for example, particularly interesting for the next large-class mission by ESA [Expert Committee for the Large-class mission covering the science theme "Moons of the Giant Planets" (2024)]. This interest is primarily due to the observation of plumes in the south polar region and the likely contact between its ocean and rocky core, which may host potential hydrothermal activities [C. J. Hansen et al. (2006), Hsu et al. (2015)]. In addition, all organic compounds that are essential as building blocks for life as we know it — carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (CHNOPS) — were measured on Enceladus [Morgan L Cable et al. (2021), Postberg et al. (2023)].

Compared to Europa, the plumes of Enceladus offer easier sampling possibilities, as fresh samples are ejected directly into space. While plume particle analysis can be conducted via sampling from flybys or an orbiter, this approach may not suffice for a comprehensive investigation. Given the potentially low concentration of biosignatures and the high risk of false positives, TRIPLE proposes additional in-situ measurement options. Technologies developed within TRIPLE provide solutions for deploying a lander in the South Polar Terrain, enabling direct collection of samples from the surface and plume fallout to characterize local environments. Future development of the AstroBioLab should focus on creating a system that minimizes sampling activities while optimizing the detection and quantification of trace-level biosignatures in situ. This involves the integration of highly sensitive, miniaturized analytical instruments capable of operating under cryogenic conditions and within strict planetary protection protocols. Autonomous systems must be able to analyze plume material or subsurface ocean samples with minimal disturbance to the environment, ensuring both scientific integrity and mission safety. Prioritizing low-disturbance, high-resolution techniques such as fluorescence spectroscopy, mass spectrometry, or lab-on-a-chip microfluidic assays will be essential for detecting organic molecules or potential microbial life in extremely low concentrations.

In addition, a further range of scenarios for planetary research and exploration for which TRIPLE technologies are also applicable are:

- Martian polar ice caps
- Cometary ice drilling
- Ceres cryovolcanic vein

Apart from the current technological development, the operation of this type of mission faces major challenges. An additional major constraint is the long signal travel times. The operational concept has to reflect all the challenges and has to provide the best possible operational flexibility to the mission team and as well has to take care of safe activity execution and system health state. This balance will be in-cooperated into the operational concept by the TRIPLE operations team. Beyond the required high degree of autonomy for the different subsystems, the necessary data for ground control need to be carefully selected in regard to the available bandwidth in space. The activity planning needs to take ground loops and necessary ground correction actions into account. The long-term planning needs to start early to receive an overview on bottlenecks or additional operational system requirements. Operational space constraints should be integrated into the mission as early as possible, with application at Dome C providing realistic insights.

## 8 Summary and Outlook

In the search for potential extraterrestrial habitats, particularly on the icy moons in the outer solar system, there is a growing need for technology to support future exploration missions. Jupiter's moon Europa is a primary target due to substantial evidence suggesting the existence of a global subsurface ocean beneath its icy surface. Following the current ongoing NASA's Europa Clipper and ESA's JUICE missions to Europa, the next logical step involves deploying a lander mission to directly access and analyze the subsurface samples. The challenges of such a mission include penetrating the several-kilometer-thick layer of ice, withstanding Jupiter's harsh radiation environment and ensuring autonomous and contamination-free exploration. This whitepaper presents the TRIPLE project, which aims to develop key technologies to enable such a mission.

The project aims to develop a comprehensive exploration system consisting of a melting probe capable of penetrating the ice layer and an autonomous underwater vehicle for investigating the subsurface ocean. Integrated life-detection instruments will evaluate the potential habitability of both the ice and liquid water environments. While the primary focus is on designing a system suitable for Europa, the project will also identify subsystem-level technologies that could serve as payloads in other planetary research and exploration missions.

In order to demonstrate the functionality of the system and to test its transferability for future space missions, the system will be subjected to an analog terrestrial test campaign in the Dome C region of Antarctica. An important intermediate step towards this goal is the upcoming test campaign in polar environments on the Ekström Ice Shelf. This test will provide a first insight into the performance of the integrated subsystems in the full TRIPLE mission concept.

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List of Figures

|   |                                                                                                                                  |    |
|---|----------------------------------------------------------------------------------------------------------------------------------|----|
| 1 | Illustrative overview of the TRIPLE mission, highlighting three key components for the exploration of subglacial lakes . . . . . | 17 |
| 2 | Technical drawing of the TRIPLE-IceCraft melting probe . . . . .                                                                 | 19 |
| 3 | TRIPLE-IceCraft test campaign on the Ekström Ice Shelf . . . . .                                                                 | 19 |
| 4 | Carrier system with an integrated FRS . . . . .                                                                                  | 20 |
| 5 | Actual organization structure of TRIPLE . . . . .                                                                                | 21 |
| 6 | TRIPLE schedule . . . . .                                                                                                        | 23 |
| 7 | System overview for the demonstration campaign on the Ekström Ice Shelf . .                                                      | 24 |
| 8 | TRIPLE LRS and nanoAUV . . . . .                                                                                                 | 27 |
| 9 | Technical drawing of the the Forefield Reconnaissance System for the TRIPLE test campaign on the Ekström Ice Shelf. . . . .      | 28 |

List of Tables

|   |                                                                                   |    |
|---|-----------------------------------------------------------------------------------|----|
| 1 | Essential prerequisites for the habitability and known characteristics of Europa. | 8  |
| 2 | Overview of the schedule of the TRIPLE project. . . . .                           | 18 |
| 3 | Overview of the Phase 2 funded TRIPLE projects. . . . .                           | 22 |

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## Acronyms

**AstroBioLab** Laboratory for astrobiological investigations.

**AUV** Autonomous Underwater Vehicle.

**CTD** conductivity, temperature, and depth.

**DLR RFA** German Space Agency at DLR.

**ECSS** European Cooperation for Space Standardization.

**FRS** Forefield Reconnaissance System.

**GNC** Guidance, Navigation and Control.

**IMU** inertial measurement unit.

**LRS** Launch and Recovery System.

**NM-III** Neumayer Station III.

**POI** Points of Interest.

**SPI** Science Payload IceCraft.

**TRIPLE** Technologies for Rapid Ice Penetration and subglacial Lake Exploration.