NASA Science Technology Development Programs for Ocean Worlds Exploration

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ABSTRACT

The exploration of ocean worlds such as Europa and Enceladus supports NASA's goal to search for life and potentially habitable regions elsewhere in the universe, and further promises to help us understand the origins, evolution, and limits of life on Earth. Over the past several years, NASA's Planetary Science Division has funded several technology development programs to enable future surface and subsurface missions to ocean worlds. These programs include Instrument Concepts for Europa Exploration (ICEE), Concepts for Ocean Worlds Life Detection Technology (COLDTech), Scientific Exploration Subsurface Access Mechanism for Europa (SESAME), Applied Information Systems Research: Autonomous Robotics Research for Ocean Worlds (AISR:ARROW), and Astrodynamics in Support of Icy Worlds Missions. Tasks selected under these programs include the development of scientific instruments including seismometers, imagers, spectrometers, and organic analyzers, and platform technologies including drills, melt probes, through-ice communications, radiation-hard electronics, and autonomy for surface operations. This paper describes the objectives of each of these programs and provides a summary of the work that has been completed or is underway in each.

INTRODUCTION

As stated in NASA's current science plan (NASA 2020), one of NASA's goals is to search for life elsewhere in the universe. This includes exploring potentially habitable regions, which are characterized by the simultaneous existence of key organic building blocks, an energy source, and liquid water (Neveu et al. 2018). While Earth is the only place in the Solar System known to have liquid water on the surface, exploration of the solar system has found multiple worlds that either possess or are likely to possess vast subsurface liquid water oceans. Geophysical and magnetic measurements of the outer-planet moons Enceladus, Europa, Titan, and Ganymede indicate the presence of these oceans covered by thick layers of ice. Evidence supports the potential presence of similar oceans on four other worlds in our solar system (Callisto, Pluto, Triton, and Ceres), indicating that ocean worlds are common in our solar system and likely in other exoplanetary systems.

Ocean worlds are a primary target for exploration because they may contain all the necessities for life to exist today. Measurements made by the Cassini mission support the presence of hydrothermal activity at the seafloor-ocean interface of Enceladus. Similar activity is likely present on the much larger moon Europa, but confirmation must await measurements to be made by the Europa Clipper mission. Just as on Earth, hydrothermal activity can provide a source of thermal and chemical energy as well as the chemical building blocks required by life. Studying these ocean worlds promises to help us understand the origins, evolution, and limits of life on Earth, but new technologies are needed to explore the surface of these icy moons and access their interior oceans (Hendrix et al. 2019).

Since 2013 NASA's Planetary Science Division (PSD) has created programs to develop scientific instruments and spacecraft platform technologies needed to deliver instruments to the harsh environments of distant ocean worlds. The first instrument program dedicated to ocean world exploration focused on instruments needed to explore Europa from orbit. The Instrument Concepts for Europa Exploration (ICEE-1) program funded 15 instruments, seven of which directly impacted the instruments manifested on the Europa Clipper mission scheduled to launch in 2024. ICEE-2 followed in 2018, this time focusing on instruments for a lander mission to Europa. In 2016 the Concepts for Ocean Worlds Life Detection Technology (COLDTech-16) program solicited both instrument and platform technologies and encompassed both surface and subsurface exploration. The Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) solicitation in 2018 expanded the development of technologies needed to access oceans that lay below a thick layer of ice. Following these investments, specific technology gaps were identified for spacecraft platforms. These gaps were addressed by directed work in radiation-hard electronics, antennas, batteries, planetary protection, and landing systems, as well as competed work in autonomy via the 2019 Applied Information Systems Research: Autonomous Robotics Research for Ocean Worlds (AISR:ARROW) program. Autonomy testbeds representative of a surface mission were built and used to develop and assess the ARROW tasks, and COLDTech-20 is developing technologies to communicate through thick ice sheets and continuing the development of autonomy and radiation-hard electronics technology. In addition, the Astrodynamics program solicited the development of analysis tools to enable new mission designs to the outer planets.

The following sections describe the work conducted under each of these programs to prepare for a future mission to explore enticing ocean worlds. Note there is also extensive work being conducted to expand science knowledge of icy moons under other PSD Research and Analysis programs, but those details are outside of the scope of this paper.

INSTRUMENT CONCEPTS FOR EUROPA EXPLORATION (ICEE-1)

During the first decade of the 21st century NASA sponsored a series of Science Definition Teams composed of experts from the scientific community to determine the highest priority science objectives for Europa. The culmination of this work was the 2012 Europa Study Final Report (NASA 2012). The results of this study were used to solicit proposals to reduce the cost risks of instruments to fly on a potential mission (eventually known as Clipper) to conduct a series of flybys past Europa while in orbit around Jupiter. The 2013 Instrument Concepts for Europa Exploration (ICEE-1) program solicited proposals to mature instruments for a mission such as Clipper. Proposal evaluation factors included the relationship of the proposed measurements to science goals as described by the 2012 study, which included characterizing the icy crust. Spacecraft accommodation was also evaluated since accommodation costs are not insignificant in the overall cost of an instrument.

The 15 instruments listed in Table 1 were selected under ICEE-1. They include imagers and altimeters to characterize surface features; spectrometers, radiometers, mass analyzers and plasma instruments to measure the composition of the moon' tenuous atmosphere and its environment, and ice penetrating radar to determine the ice crust thickness and structure.

Principal Investigator / Institution	Task
Frances Bagenal/ University of Colorado	A Probe for Europa's Plasma Interaction
Joseph Westlake/ Johns Hopkins University Applied Physics Laboratory	Plasma Instrument for Magnetic Sounding (PIMS)
Carol Raymond/ California Institute of Technology	Development and Testing of an Integrated Magnetic Mapping Package for the Europa Clipper Mission
Elizabeth Tuttle/ Applied Physics Laboratory	Topographic and Reconnaissance Imaging for Europa Exploration
David Smith/ Massachusetts Institute of Technology	Extended Range Laser Altimeter (ERLA)
James Bell/ Arizona State University	Technology Development for a Topographic Imager on the NASA Europa Clipper Mission
Shahid Aslam/ NASA Goddard Space Flight Center	Thermal IMager for Europa Reconnaissance (TIMER) - Technology Maturation and Risk Mitigation
Matt Kenyon/ NASA Jet Propulsion Laboratory	Development of Large Format Rad-Hard Focal Plane Arrays and Readouts for Thermal Radiometer for Europa Clipper Mission
Dennis Reuter/ NASA	SIRSE: Spectral ImageR/ Spectrometer for

Goddard Space Flight Center	Europa
Kevin Hand/ NASA Jet Propulsion Laboratory	CIRIS: A near- and mid-infrared Fourier transform spectrometer for investigations of the surface composition and habitability of Europa.
Jack Waite/ Southwest Research Institute	Technical development of the MASPEX instrument for Europa Exploration
Robert Green/ NASA Jet Propulsion Laboratory	Europa Short Wavelength InfraRed Spectrometer - Radiation and Planetary protection Maturation ESWIRS-RPM
Murray Darrach/ NASA Jet Propulsion Laboratory	Mass Analyzer for Real-time Investigation of Neutrals at Europa (MARINE)
Alina Moussessian/ NASA Jet Propulsion Laboratory	Ice Penetrating Radar (IPR) for Europa Exploration
Sascha Kempf/ University of Colorado at Boulder	Maturing the Surface Dust Analyzer (SUDA) for Europa Exploration

Table 1. ICEE-1 Tasks

The Europa Clipper mission did come to fruition and is now scheduled to launch in 2024. Included on the mission will be nine instruments, seven of which were supported by ICEE-1 (NASA 2017): Plasma Instrument for Magnetic Sounding (PIMS), Mass Spectrometer for Planetary Exploration (MASPEX), Surface Dust Analyzer (SUDA), Europa Imaging System (EIS), Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON), Interior Characterization of Europa using Magnetometry (ICEMAG), and Mapping Imaging Spectrometer for Europa (MISE).

INSTRUMENT CONCEPTS FOR EUROPA EXPLORATION (ICEE-2)

Like the first ICEE solicitation, in 2018 ICEE-2 solicited the maturation of instruments for a specific mission concept: this time for a Europa lander. Referencing a 2016 science definition team study (NASA 2016), proposals were evaluated on their relationship to science goals and this time could include sample transfer and processing technology. In addition, spacecraft accommodation was given increased priority and awardees were required to collaborate with the Europa Lander pre-project team and other ICEE-2 awardees to provide the opportunity for co-development of potential instruments, sample acquisition and delivery systems, and the lander itself. This requirement was added in response to lessons learned on Europa Clipper, which experienced resource and cost growth during instrument accommodation, and is expected to reduce compatibility issues between related subsystems being developed by different organizations.

Principal Investigator / Institution	**Task**
Shane Byrne/ University of Arizona	Cold-Lightweight Imagers for Europa (C-LIFE)
Richard Quinn/ NASA Ames Research Center	Europa Luminescence Microscope
Scott Murchie/ Johns Hopkins University	Europa Lander Stereo Spectral Imaging Experiment (ELSSIE)
Ricardo Aravelo/ University of Maryland, College Park	CORALS: Characterization of Ocean Residues and Life Signatures

Christopher Glein/ Southwest Research Institute	MAss Spectrometer for Planetary EXploration-ORganic Composition Analyzer (MASPEX-ORCA) for Europa Lander
Antonio Ricco/ NASA Ames Research Center	MICA: Microfluidic Icy-World Chemistry Analyzer
Richard Mathies/ University of California, Berkeley	Microfluidic Organic Analyzer for Biosignatures (MOAB)
William Brinckerhoff/ NASA Goddard Space Flight Center	Europan Molecular Indicators of Life Investigation (EMILI)
James Lambert/ NASA Jet Propulsion Laboratory	Compact Integrated Raman Spectrometer (CIRS)
Mark Panning/ NASA Jet Propulsion Laboratory	Europa Seismic Package
Samuel Hop Bailey/ University of Arizona	Seismometer to Investigate Ice and Ocean Structure (SIIOS)
Mark Moldwin/ University of Michigan, Ann Arbor	Reduced SWAP+C Radiation Tolerant Magnetometer for Europa Lander
Robert Grimm/ Southwest Research Institute	Europa Magnetotelluric Sounder (EMS)
Charles Malespin/ NASA Goddard Space Flight Center	Collaborative Acceptance and Distribution for Measuring Europan Samples (CADMES) System

Table 2. ICEE-2 Tasks

Table 2 lists the tasks funded by ICEE-2. They include imagers, mass and Raman spectrometers, organic analyzers, seismometers, and magnetometers to characterize the environment of Europa from the surface. The final task listed in Table 2, CADMES, is a sample handling system meant to deliver processed samples to the spectrometers and analyzers. These instruments are currently undergoing accommodation studies with the Europa Lander pre-project.

MATURATION OF INSTRUMENTS FOR SOLAR SYSTEM EXPLORATION (MatISSE)

The MatISSE Program supports the advanced development of spacecraft-based instruments that show promise for use in future planetary missions. The goal of the program is to develop and demonstrate planetary science instruments to the point where they may be proposed in response to future announcements of flight opportunity without additional extensive technology development. Instruments selected under MatISSE have applicability throughout the Solar System; the tasks shown in Table 3 are recent tasks that are particularly relevant for use on icy satellites.

Principal Investigator / Institution	Task
Scot Rafkin/ Southwest Research Institute	Maturation of a Hypertunable IR Laser Spectrometer for In Situ Planetary Exploration
Pablo Sobron/ SETI Institute	In-situ Spectroscopic Europa Explorer (iSEE)
Shouleh Nikzad/ NASA Jet Propulsion Laboratory	Compact, High Dynamic Range Ultraviolet Imaging Spectrometer
Gordon Chin/ NASA Goddard Space Flight Center	Picture this SELFI: A Maturation Project for a Submillimeter Enceladus Life Finder

	Instrument (SELFI)
Purnendu Dasgupta/ University of Texas at Arlington	Ion/Liquid Chromatography for Exploration of Solar System (ILCESS)
Richard Mathies/ University of California, Berkeley	The Enceladus Organic Analyzer (EOA)
Talso Chui/ NASA Jet Propulsion Laboratory	A Planetary Broadband Seismometer for the Lunar Geophysical Network and the Ocean Worlds

Table 3. MatISSE Ocean Worlds-Relevant Tasks

These MatISSE tasks include spectrometers that detect signals ranging from ultraviolet to sub-millimeter wavelengths as well as sample handling and analysis instruments to detect potential biomarkers. In addition, a seismometer is in development to help characterize the potentially habitable surface and subsurface environment.

CONCEPTS FOR OCEAN WORLDS LIFE DETECTION (COLDTech-16)

In contrast to the previous solicitations that were focused exclusively on the development of instrument and sample handling technology, the COLDTech-16 solicitation also included spacecraft technology development for subsurface exploration. Specifically, COLDTech-16 sought to develop and advance the maturity of a) science instruments, especially those focused on the detection of evidence of life, especially extant life, in the ocean worlds of the outer Solar System; b) sample acquisition, delivery and analysis systems for such missions, and c) spacecraft technologies required to access their subsurface oceans. Emphasis was placed on technologies required to safely land on a poorly characterized or unknown surface, low power/mass/volume tools to melt or drill through an icy surface, high-radiation environment electronics, and low temperature power systems.

Principal Investigator / Institution	**Task**
Shane Byrne/ University of Arizona	Cold-Lightweight Imagers for Europa (C-LIFE)
Justin Maki/ California Institute of Technology	Ocean Worlds Lander Imager
Richard Quinn/ NASA Ames Research Center	LIfE: Luminescence Imager for Exploration
Samuel Kounaves/ Tufts University	Microfluidic Wet Chemistry Laboratory (mWCL) for Assessing Habitability of Ocean Worlds by Analysis of Surface or Plume Samples
Christopher McKay/ NASA Ames Research Center	Development of Nanopore Sequencing for Automated Ocean World Life Detection
Bryana Henderson/ California Institute of Technology	Supercritical CO2 Extraction and Chiral Supercritical Fluid Chromatography for Ocean Worlds
Bruce Hammer/ University of Minnesota	Nuclear Magnetic Resonance (NMR) Detection of Extant Life
William Brinckerhoff/ NASA Goddard Space Flight Center	Europan Molecular Indicators of Life Investigation (EMILI)

Alison Murray/ Nevada system of higher education	Advancing Nanomotion Sensor Technology to Provide Evidence for Active Life in Ocean Worlds
Dominique Fourgette/ Michigan Aerospace Corporation	Micro Fabricated Optical Seismometer "FROSTY"
Hongyu Yu/ Arizona State University	Seismometers for Exploring the Subsurface of Europa (SESE)
Robert Grimm/ Southwest Research Institute	Plumbing Europa: A magnetotelluric sounder to characterize water layers and habitability within the ice shell of an ocean world
Elena Adams/ Applied Physics Lab	EFun: Plume Sampling System for Enceladus
Antonio Ricco/ NASA Ames Research Center	Sample Processor for Life on Icy Worlds (SPLIce)
Dale Winebrenner/ University of Washington	Autonomous Melt-Probe Penetration of Dirty Ice with Clean Sampling for Life Detection
Kris Zacny/ Honeybee Robotics	Integrated Sample Acquisition Drill and Pneumatic Sample Delivery for Ocean Worlds

Table 4. COLDTech-16 Instrument and Sample Handling Tasks

Table 4 lists the tasks selected to develop instruments and sample acquisition and handling systems for the collection and analysis of samples to potentially detect evidence of life. These include imagers, microfluidics, nanopore sequencers, chromatography, nuclear magnetic resonance spectrometers, motion sensors, seismometers, magnetometers, and sample processors.

The programs described so far all developed science instruments and sample handling systems. Also critically important for the exploration of ocean worlds are the spacecraft technologies needed to safely land on poorly characterized surfaces and access deep subsurface oceans. COLDTech-16 was the first to solicit these technologies, and the subsequent sections in this paper describe additional solicitations for these spacecraft technologies.

Principal Investigator / Institution	**Task**
Larry Matthies/ California Institute of Technology	Precise Landing on Titan
Uland Wong/ NASA Ames Research Center	ICICLES: Intelligence for Choosing Icy Landing and Exploration Sites
Gary Bolotin/ California Institute of Technology	Cold Survivable Distributed Motor Controller
James Longuski/ Purdue University	Advanced Spacecraft Technologies to Explore the Ocean Worlds for the Detection of Extant Life
William Stone/ Stone Aerospace	ARCHIMEDES (A Really Cool High Impact Method for Exploring Down into Europan Subsurface)

Table 5. COLDTech-16 Platform Technology Development Tasks

The tasks listed in Table 5 developed precision landing technologies, a cold-survivable motor for use on cryogenic surfaces, and technologies to traverse multiple kilometers of ice to reach deep oceans.

SCIENTIFIC EXPLORATION SUBSURFACE ACCESS MECHANISM FOR EUROPA (SESAME)

In 2018 the SESAME program supported the formulation and maturation of system concepts and the associated technologies capable of penetrating ice and accessing the subsurface liquid water on ocean worlds such as Europa. The overall goal of this program was to define, and ultimately validate, a realistic architecture for deep (>1 km) subsurface access under flight-like constraints. In addition, proposals were expected to identify, address, and reduce technical risks for the most promising ice penetration systems so that these systems may eventually be infused into potential future flight opportunities.

More specifically, the SESAME technology development solicitation sought to:

a) Identify promising cryogenic ice penetration systems capable of facilitating the detection of life, especially extant life, in the ocean worlds of the outer solar system by providing access to subsurface liquid water bodies that may be located hundreds of meters to tens of kilometers below the surface of the ice.
b) Identify the technology component(s) that represent the greatest technical risk to the overall penetration system.
c) Begin to reduce the key technology risks through an analytical and experimental technology development effort.
d) Develop prototype hardware for cryogenic ice penetration system(s); and
e) Assess the performance of the prototype hardware through analysis and complementary laboratory experiments.

The five activities shown in Table 6 were selected to mature technologies aligned with the program goals.

Principal Investigator / Institution	**Task**
Kris Zacny/ Honeybee Robotics	SLUSH: Search for Life Using Submersible Heated Drill
William Stone/ Stone Aerospace	PROMETHEUS: nuclear-Powered RObotic MEchanism Technology for Hot-water Exploration of Under-ice Space
Kathleen Craft/ Johns Hopkins University	Europa STI - Exploring Communication Techniques and Strategies for Sending Signals Through the Ice (STI) for an Ice-Ocean Probe
Tom Cwik/ NASA Jet Propulsion Laboratory	Cryobot For Ocean Worlds Exploration
Britney Schmidt/ Georgia Institute of Technology	Vertical Entry Robot for Navigating Europa (VERNE)

Table 6. SESAME Tasks

SLUSH is a hybrid thermomechanical drill probe system that combines the most efficient aspects of thermal and mechanical penetration techniques to reach Europa's subsurface ocean. PROMETHEUS advanced a cryobot design that uses closed-cycle hot water drilling as the primary means of penetrating the ice to actively control the descent through the ice shell and into Europa's subsurface ocean. The Europa STI effort tested multiple communication tether designs. The Cryobot task matured a system architecture and associated technologies necessary for accessing Europa's subsurface ocean, including fluidics and thermal modeling, and testing in cryogenic ice chambers and the Arctic. VERNE is a platform that includes a surface station, self-drilling vehicle with a breakable mechanical/data tether that would deploy acoustic communication stations in the ice during descent, and a base station that would remain in the ice to relay communications with the mobile platform to the surface station.

DIRECTED WORK

In addition to the competitively awarded efforts described in this paper, NASA also directed funding to advance development of specific technologies and entire lander subsystems. These consisted of three efforts: the Europa Lander pre-project, radiation-hard electronics, and autonomy testbeds.

The Europa Lander pre-project led by the NASA Jet Propulsion Laboratory (JPL) defined an end-to-end mission concept, identified the necessary technology developments needed to implement it, and began developing some of the critical and/or long-lead technologies. Specific technologies included a high efficiency antenna for communication with Earth, an end-of-mission terminal sterilization system for planetary protection, batteries tolerant to low temperature and high radiation conditions. Extensive work was conducted to address the challenge of autonomously landing on a poorly characterized surface with unknown hazards (i.e. automated terrain analysis and target selection). The De-Orbit, Descent, and Landing (DDL) system was evolved beyond the system used on the Mars Perseverance mission to include greater autonomy, active hazard detection using an onboard LIDAR, and a dynamic landing gear system to accommodate uneven terrain and boulders. In addition, a variety of surface autonomous sampling techniques and tools were investigated. DDL and surface sampling tool development required multiple testbeds of varying fidelity to test and validate the technologies and systems.

The radiation environment in the Jupiter system is the harshest in the Solar system and heavy shielding is required to protect existing flight electronics for long-duration operations there. The development of radiation-hard electronics was funded at the NASA Ames and Glenn Research Centers to reduce – or eliminate – the need for such shielding. Nanoscale vacuum channel transistors that had been developed at Ames for lunar applications, and silicon carbide (SiC) transistors developed at Glenn for long-duration operation on the high temperature Venus surface are also intrinsically tolerant to very high radiation levels. Under PSD funding, both technologies demonstrated excellent radiation tolerance. Nano-vacuum transistors fabricated in both silicon and SiC demonstrated high reliability against gamma and neutron radiation, and 4H-SiC junction field effect transistor integrated circuits demonstrated over 7 Mrad total ionizing dose tolerance, with no destructive single-event effect susceptibility.

Autonomous operations will be critical on future surface and subsurface missions to ocean worlds because the communication lag to the outer planets is long, the mission life of surface assets is expected to be limited by radiation damage, and traversing vertically through ice will not be conducive to Earth-based control. Because autonomy is a system-level technology and therefore is difficult to develop in isolation, NASA developed two testbeds, one virtual and one physical, to support the development and testing of new autonomy technologies for future lander missions to ocean worlds. The testbeds provide simulation in hardware and software of a "generic" planetary lander equipped with a seven degree-of-freedom robotic manipulator and a variety of sensors.

The Ocean Worlds Autonomy Testbed for Exploration Research and Simulation (OceanWATERS), is a software-based simulator at NASA Ames that emulates surface environmental conditions (e.g., lighting and surface material properties), robotic manipulator operation, and high-level lander systems. The simulator supports injection of faults and provides system introspection capabilities. The simulator is modeled on the Europa Lander pre-project, but can be configured for other lander missions and planetary bodies.

The Ocean Worlds Lander Autonomy Testbed (OWLAT), is a hardware-based facility at NASA JPL that emulates planetary bodies with different gravities. The testbed includes a lander deck (with robotic manipulator) mounted on a six degree-of-freedom Stewart platform. The manipulator is equipped with a 6-axis force-torque sensor at its tool interface. Geotechnical instruments and sampling tools are provided as end effectors, which can be attached to the tool interface.

Both testbeds have a common software interface for acquiring sensor data and commanding a manipulator arm, the mast, and the sensor suite. Sensor data available from the testbeds include arm joint and end effector position, measured end-effector forces and torques, and stereo camera images. The virtual testbed allows more complete modeling of the surface environment (such as illumination, topography out to the horizon, and surface albedo) as well as of the lander's external features (in particular a scale model of the complete lander) and its subsystems (such as a power system with onboard battery prognostics). The virtual testbed will also allow rapid and broader modification of environmental and spacecraft parameters. The physical testbed provides higher-fidelity terrain interaction with tools and instruments than the virtual testbed. The physical testbed will also enable more realistic sensing constraints and higher-fidelity dynamics of manipulation / sampling to be studied.

AUTONOMOUS ROBOTICS RESEARCH FOR OCEAN WORLDS (ARROW)

The ARROW solicitation was released in 2019 for the development of functional and system-level autonomous capabilities for the surface exploration of ocean worlds, such as Europa, Enceladus, and Titan. The goal of the program is to develop autonomy software technologies to significantly increase the robustness and productivity of future ocean worlds lander missions including those to destinations with surface conditions and phenomena that may be largely, or completely, unknown a priori at the time of landing. Two projects were funded under this solicitation as shown in Table 7.

The objective of the first task, Raspberry SI, is three-fold: to develop machine learning models to discover mission intent and enable transfer learning and online learning during a mission; to develop a model compression technique to compress large neural networks into an accurate and efficient tiny model for deployment; and to develop a probabilistic planner to enable run-time adaptation based on the state of the spacecraft, environment assumption, and resource availability.

Principal Investigator / Institution	Task
Pooyan Jamshidi/ University of South Carolina	Resource Adaptive Software Purpose-Built for Extraordinary Robotic Research Yields Science Instruments (RASPBERRY SI)
Jonathan Bohren/ Honeybee Robotics	Robust Autonomy for Planetary Sampling

Table 7. AISR:ARROW Autonomy Tasks

The objective of the second task, Robust Autonomy for Planetary Sampling, is to develop a novel extension of NASA's open-source PLEXIL (Plan Execution Interchange Language) execution technology with stochastic decision-making capability to enable dynamic selection of optimal lander procedures.

Both of these tasks will be tested and evaluated on NASA's OCEANWaters virtual testbed at NASA Ames and are scheduled to conclude in 2022. In addition, Raspberry SI will also be evaluated on NASA's OWLAT physical testbed at NASA JPL.

CONCEPTS FOR OCEAN WORLDS LIFE DETECTION (COLDTech-20)

After the successful completion of the SESAME program, specific technology gaps remained. These included technologies to enable communication through many kilometers of ice thickness; radiation-hard digital devices for surface operations and/or an orbiting relay; and autonomy as described in the ARROW section above. The goal of COLDTech-20 is to develop these technologies to acquire samples beneath the surface and process them, including providing access to subsurface oceans or other bodies of liquid water.

Principal Investigator / Institution	Task
Eric Dixon/ Lockheed Martin	Causal and Reinforcement Learning (CARL)
Melkior Ornik/ University of Illinois at Urbana-Champaign	Adaptive, Resilient Learning-Enabled Ocean World Autonomy (DRILLAWAY)
Joel Burdick/ California Institute of Technology	Robust, Explainable Autonomy for Scientific Icy Moon Operations (REASIMO)
Jay McMahon/ University of Colorado	Expert-Informed Autonomous Science Planning for In-situ Observations and Discoveries

Table 8. COLDTech Autonomy Tasks

Four tasks are funded for autonomy as listed in Table 8. The first three listed tasks are developing advanced task planners to automated surface operation in the presence of unexpected errors. The fourth task focuses on the interface between the scientists and the remote autonomous system to maximize science return in the face of unexpected results.

Five tasks were selected to develop through-ice communications technology as shown in Table 9. Both the SLUSH-related and STI Tech tasks are developing tethers to robustly survive the dynamic ice shell on Europa. STI Tech, PARTI Pucks, and the hybrid RF/MI tasks are developing radio frequency transmission concepts, and finally, the hybrid RF/MI task is exploring the use of magneto-inductive transceivers to communicate through ice with unknown and varying conductive properties.

Principal Investigator / Institution	**Task**
Kris Zacny/ Honeybee Robotics	Tether based communication system for the Search for Life Using Submersible Heated drill (SLUSH) Europa probe
William Stone/ Stone Aerospace	Puck-Based Data Transmission Using Adaptive Radio Modems for Through-Ice Communications (PARTI Pucks)
Kathleen Craft/ Johns Hopkins University	Technology for Sending Signals Through the Ice on Ocean Worlds (STI Tech)
Michael Cheng/ NASA Jet Propulsion Laboratory	Hybrid Radio Frequency (RF) and Magneto-Inductive (MI) Transceiver for Europa Sub-Ice Communications
Yoseph Bar-Cohen/ NASA Jet Propulsion Laboratory	Maturation and demonstration of technology to enable through deep-ice communication (CryoComm) on Europa

Table 9. COLDTech Communications Tasks

Two tasks are being funded to develop radiation hardened electronics as shown in Table 10. The first task will develop and demonstrate silicon-germanium electronics to operate robustly under the combined high radiation and low temperatures of ocean worlds, developing device models for circuit design and a full suite of digital, analog, and RF circuit building blocks to create a large-scale integrated circuit prototype. The second task will develop a radiation-hardened-by-design (RHBD) analog-to-digital converter by exploiting a state-of-the-art fabrication technology combined with RHBD mitigation techniques, and applying them to single-chip, low power consumption device.

Principal Investigator / Institution	**Task**
John Cressler/ Georgia Institute of Technology	Environmentally-Invariant Silicon-Germanium Electronics for On-Surface Ocean Worlds Exploration
Tim Holman/ Vanderbilt University	A Radiation-Hardened Analog-to-Digital Converter for Outer Planetary Missions

Table 10. COLDTech Radiation Hard Electronics Tasks

Each of these COLDTech-20 tasks began in the summer of 2021; the autonomy tasks will last for two years and the others will continue for three years.

ASTRODYNAMICS

In addition to the technologies needed for in situ exploration of ocean worlds, it is also challenging to develop mission trajectories to efficiently access the outer planets. To address the shortfalls in our abilities, in 2018 PSD released the Astrodynamics in Support of Icy Worlds Mission solicitation. This program solicited the formulation, maturation, and validation of astrodynamics analysis tools to uncover new mission concepts, motivate entirely new classes of missions that may not have been previously considered, improve the efficiency of missions, and/or extend mission life. The tasks selected under this program are listed in Table 11.

Principal Investigator / Institution	**Task**
Ryan Russell/ University of Texas at Austin	Falcon: Automating the Search and Design Process for Icy World Trajectories
Ossama Abdelkhalik/ Iowa State University	Enhancements to The NASA Evolutionary Mission Trajectory Generator
Rohan Sood/ University of Alabama	ASSET: Astrodynamics Software and Science Enabling Toolkit
Daniel Scheers/ University of Colorado	Quasi-periodic orbit computational tools for mission design

Table 11. Astrodynamics Tasks

CONCLUSION

The exploration of ocean worlds in the outer solar system could provide unprecedented insight into humanity's quest for knowledge of the existence of life beyond Earth. Over the past decade NASA's Planetary Science Division has funded technology development to enable future missions to explore these ocean worlds. These efforts include the development of seismometers, imagers, spectrometers, and organic analyzers, and platform technologies including advanced landing systems, drills, melt probes, through-ice communications, radiation-hard electronics, and autonomy for surface operations. These efforts are establishing a firm foundation to support future missions through advanced technology development that will serve to mitigate risks and enable the exploration of enticing ocean worlds.

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