National Aeronautics and Space Administration

Ocean Worlds (4x)

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Project Objective:

At the highest level, our objective is to enable the detection of life, if it exists, on and within ice-covered ocean worlds. Derived from that high level objective, our goals were to develop, test, and demonstrate techniques, instruments, and platforms for future competed Ocean Worlds missions. To be competitive will require both scientific and technical expertise. Over the past three years we have achieved scientific expertise by coupling JPL planetary scientists with JPL earth scientists (8x/32x), and with external earth ocean and cryosphere scientists. We achieved technical expertise by bridging JPL roboticists with engineers at premier Earth ocean and cryosphere exploration institutions (specifically Woods Hole Oceanographic Institution [WHOI]). These cross-directorate and cross-institutional links form 'Strategic Ocean Worlds partnerships' that will help position JPL as NASA's 'Ocean Worlds' leader.

Our work had two primary tasks: Task 1 was focused on the ice-water interface and Task 2 was focused on the exploration of the oceans' 'Deep Refuge', or hadal depths. As part of Task 1 we developed ice-water interface robotic vehicles for in situ chemical and biological analyses of sea ice and lake ice in the Arctic. As part of Task 2 we designed and deployed deep ocean robotic landers, or 'Cubesats for the Sea', in partnership with WHOI, and b) Analyze deep ocean and arctic samples for the study of life and biosignatures in extreme environments relevant to ocean worlds.

The quantitative capability goals of the proposed work were, by the end of the 3rd year, to 1) map the underside of Arctic permafrost lake ice for methane seeps, 2) demonstrate long term untethered data acquisition beneath Arctic lake ice, 3) demonstrate deployment of the BRUIE vehicle through sea ice, and operations for 2 days under sea ice, 4) deployment a prototype jointly designed JPL/WHOI hadal vehicle to an ocean depth of at least 4 km and collect 1 panoramic image, 10 cubic centimeters of water from depth, and 5) generate an online database of spectra and imagery for use by the broader ocean worlds science community.

Publications:

1. **Hand, K. P., Bartlett, D., Fryer, P., Peoples, L., Williford, K., Hofmann, A, & Cameron, J. (in revision, 2019). Discovery of novel structures at 10.7 km depth in the Mariana Trench may reveal chemolithoautotrophic microbial communities. Deep Sea Research I.**
2. **Hand, K. P., & German, C. R. (2018). Exploring ocean worlds on Earth and beyond. Nature Geoscience, 11(1), 2.**
3. **Santibáñez, P. A., Michaud, A. B., Vick-Majors, T. J., D'Andrilli, J., Chiuchiolo, A., Hand, K. P., & Priscu, J. C. (2019). Differential Incorporation of Bacteria, Organic Matter, and Inorganic Ions into Lake Ice during Ice Formation. Journal of Geophysical Research: Biogeosciences.**
4. **Carnevali, P. B. M., Herbold, C. W., Hand, K.P., Priscu, J. C., & Murray, A. E. (2018). Distinct Microbial Assemblage Structure And Archaeal Diversity In Sediments Of Arctic Thermokarst Lakes Differing In Methane Sources. Frontiers in Microbiology, 9.**
5. **Matheus Carnevali, P., Rohrssen, M., Williams, M.R., Michaud, B., Adams, H., Berisford, D., Love, G.D., Priscu, J.C., Rassuchine, O., Hand, K.P., Muray, A.E. (2015) Methane sources in arctic thermokarst lake sediments on the North Slope of Alaska. Geobiology. doi: 10.1111/gbi.12124.**
6. **Jakuba, M.V., German, C.R., Bowen, A.D., Whitcomb, L.L., Hand, K., Branch, A., Chien, S. and McFarland, C., 2018, March. IEEE Teleoperation and robotics under ice: Implications for planetary exploration. In 2018 IEEE Aerospace Conference. pp. 1-14.**

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FY18/19 Results:

For Task 1 in year 3 we continued development and deployment our instrumented buoyant rover for under-ice exploration (BRUIE), and continued analyses of the ice-water interface in Arctic lake and sea-ice environments. The BRUIE platform was developed by JPL and represents a unique and innovative platform for studying the ice-water interface; no other institution has such a vehicle, or any vehicle of comparable size and mass. The rover was previously operated remotely via Iridium satellite link from a Quonset hut in Barrow, Alaska and from a robotics lab at JPL. The approach for this past year was to further develop the rover for short and long term, untethered, satellite- or cell-phone controlled deployments with improved instrumentation, mobility, and sample collection for studying the chemistry and biology of the ice-water interface (Figure 1). Critical to our approach has been the development of a robust mobility platform for science. To that end, we have also an instrumented tail on BRUIE that positions sensors as close as possible to the ice-water interface.

Our approach for Task 2 has evolved over the past three years, as WHOI has invested more and more money and FTE in the collaboration. Following on our initial design sessions, in the early stages of this R&TD, the 'CubeSats for the Sea' concept has transformed into the team producing the smallest full-ocean-depth-rated autonomous explorers ever deployed. These vehicles define the new state-of-the-art for exploring our ocean below 6 km, because there is currently very little work being done on access to such regions of the ocean. These 'Cubesats for the Sea' bring JPL's innovative systems engineering skills together with Woods Hole Oceanographic Institute. Below we provide details on results for each Task:

Results for Task 1: Ice-water interface

- Tested traverse capability and vehicle endurance in an Arctic sea ice in May '19. BRUIE was driven on a safety tether under sea ice for 3 days, providing tether-streamed video and acoustic telemetry/positioning, operated both locally in the field and from remote sites. Deployment was located between two ice pressure ridges, presenting acoustic and navigation challenges. Demonstrated acoustic navigation and communication in rough ice terrain.
- Designed, built, and integrated ground equipment (including iridium modems and wind turbines, building on remote operations from Year 2. In Nov '18, BRUIE was deployed to a thermokarst lake in Alaska. Ground stations provided hourly telemetry updates and the vehicle was collected in late December.
- Integrated MarCO-derived flight operations software, including multiple sequence engines, remote sequence upload capability, onboard extended Kalman filter for real-time navigation. Tested data collection over multi-week deployment. (Apr '18).
- From Fall 2017 deployment: Completed 1.7 km traverse untethered under ice in Alaskan permafrost lake. Completed 5 days of contiguous, untethered, remote under ice operations (duration limited only by field test ending). Completed remote operation controlled from JPL and from Barrow hut via acoustic modem relay.
- Fall 2018, deployed BRUIE under lake ice for full season test (Nov-May). Lost signal from the rover in early Dec. Conducted 'rescue' mission to recover vehicle in mid-December. Vehicle, and dual-ground station equipment, recovered successfully.
- Redesigned the BRUIE tail to integrate high-fidelity science instruments: dissolved methane, dissolved oxygen, and conductivity/temperature. New design provides a more flexible platform for adding future instruments, and allows all instruments and electronics to be contained in the tail structure, which can be removed/swapped with a single panel. Redesigned tail provides greater mechanical robustness by integrating all electrical wire penetrators into a single part, with a secondary seal interface between the tail volume and the BRUIE main body. Tail also adds a magnetic compass near the tip (far from the rover motor magnets) for redundant navigation capability in the event of lost acoustic communications.
- Demonstrated ability of BRUIE to deploy science instruments at the ice-water interface with precision and minimal disturbance to the local environment. Inserted BRUIE tail instrument package into a delicate brinicle growing on the ice underside, which is a unique achievement for an underwater robot, and demonstrates the usefulness of BRUIE for studying the ice-water interface.

Results for Task 2 Deep Refuge

- Developed new underwater camera, rated for full-ocean-depth, and incorporated JPL's terrain relative navigation software into Hadal vehicle.
- Within 7 months of whiteboard drawings, the JPL/WHOI Orpheus vehicle was deployed off of Cape Cod (Sept-Oct '18). Limited to water just a few hundred meters depth due bad weather, but the vehicle was tested/validated at depth. The vehicle performed 100m traverses along the sea bottom for later terrain reconstruction.
- Release of ballast successful; deployment and recovery proved easy relative to standard vehicles.
- JPL/WHOI Hadal vehicle science definition and incorporation of Hadal community science objectives and measurements complete (Science Trace Matrix).
- Ocean Worlds online database structure complete. Currently populated with lab spectra of samples and analog materials. Not yet accessible external to JPL.
- Orpheus vehicle deployed 3 times to 1600+ meters in Sept 2019 cruise. The vehicle performed multiple transects with square and lawn-mower patterns to obtain visual data for odometry reconstruction. Detected plume with chemical sensors on last dive.
- While on 1600m cruise, altitude hold controllers successfully followed terrain even during canyon descent.
- Tested endurance of vehicle, including autonomous recovery upon battery depletion, from depth.
- Visual inertial odometry tested and worked successfully in JPL test tank. Utilized vehicle processor for post-processed odometry for comparison against USBL data. Validated processor can perform visual odometry in real-time.

Benefits to NASA and JPL (or significance of results):

Our research and technical development has been motivated by the following overarching question: What are the chemical and physical characteristics of geobiological processes at the ice-water interface and the deepest seafloor-ocean interface, and how can we build robust robotic platforms to enable the investigation of these processes? The scientific significance is that we have developed robotic platforms (BRUIE and Orpheus) that can obtain in situ chemical, geological, and biological measurements (e.g., conductivity, pH, temperature, pressure, methane, and dissolved oxygen) in extreme environments on Earth that can inform our understanding of how to search for signs of life on ocean worlds. These measurements, coupled with sampling of ice and water for subsequent cell counts and bioload, will help us constrain the chemical dynamics at the ice water interface that could power biology. This is of particular interest in the context of Europa because the chemistry of Europa's ice shell may be a critical source of oxidants and other nutrients that help maintain a habitable subsurface ocean. Our measurements constitute a set of integrated, interdisciplinary field experiments that pave the way for future robotic missions.

Technologically, our work is significant in that we are working to change the way ocean exploration is conducted on Earth, and through that change build toward exploring oceans beyond Earth. The existing state of the art for robotic platforms and instruments for in situ exploration of ocean worlds are large, cumbersome, power-hungry systems that are often expensive and difficult to deploy. The state of the art has been somewhat limited by the lack of strong forcing functions to push the technologies to smaller more reliable systems; in Earth's ocean it has been less expensive to use a big boat to deploy and recover a large, unreliable system, than to invest heavily in smaller, easier to deploy, and more reliable systems. By bringing together JPL's expertise in the latter, with the expertise of WHOI in the former, we have developed BRUIE and Orpheus, which are small, easy-to-deploy, low power, and inexpensive systems that can transform our ability to explore Earth as an ocean world, and eventually ocean worlds elsewhere in the solar system.

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