Laboratory Architecture as an Infrastructural Capability to Increase the Science Returned by Ocean World Missions

by

Charles A. Hibbitts, Johns Hopkins University Applied Physics Laboratory, Laurel, MD.

Roger N. Clark, Planetary Science Institute, Tucson, AZ

Murthy S. Gudipati, Jet Propulsion Laboratory, Pasadena, CA

Michael T. Mellon, Cornell Univ., Ithaca, NY

Ujjwal Raut, Southwest Research Institute, San Antonio, TX

Tracy M. Becker, Southwest Research Institute, San Antonio, TX

Kurt Retherford, Southwest Research Institute, San Antonio, TX

Diana Blaney, Jet Propulsion Laboratory, Pasadena, CA

Kevin Hand, Jet Propulsion Laboratory, Pasadena, CA

Melissa McGrath, SETI, Mountain View, CA

Everett Shock, Arizona State Univ., Tempe, AZ

Abstract

The processes responsible for the compositions of ocean worlds are a complex combination of exogenous and endogenous mechanisms that are incredibly difficult to duplicate in the laboratory environment. These processes are often inferred from compositional mapping of their surfaces, which to properly interpret, require laboratory measurements of relevant materials, under appropriate conditions, using laboratory instrumentation that cover the measurement capabilities of space mission payloads. Future missions such as Europa Clipper are also equipped with in-situ mass spectrometer payloads that provide complementary chemical information. The environments of these worlds are extremely foreign, with temperature ranges, materials, and even radiation environments that laboratory facilities cannot easily duplicate on Earth. As a consequence of their unique requirements, laboratory facilities investigating the surface compositions and processes relevant to ocean worlds are complex systems in which measurements are also very time-consuming. The expense of the labor, the equipment, and sheer complexity of developing the laboratory capabilities and subsequently performing the measurements has exceeded the available funding resources through existing R&A programs, institutional funding, and mission funding. As a result, the needed laboratory facilities are not being sufficiently supported (either developed, utilized, or both) and thus measurements are not being made that are needed to understand the processes and materials on ocean worlds to fully interpret upcoming and even existing data. This consequence is to the detriment of interpreting future and even existing missions' observations of these bodies. This will potentially impact the effectiveness of future missions if, as a result of a lack of understanding, appropriate instruments are not recognized as being needed or the significance and implications of obtained measurements are misinterpreted. We consider this an infrastructural problem that should be addressed broadly. Solutions may not be as simple as increasing funding for laboratory work in R&A because of the broad (albeit positive) allocation of resources. Establishing centers of excellence (such as RELAB, but tailored towards the unique needs of ocean worlds laboratory requirements) or a funded research coordination hub following SSERVI/ICAR model could be effective if carefully implemented. Alternatively, specifically funding laboratory investigations as part of long-duration missions, which outer planet ocean world missions tend to be, could be an effective solution because of the clear vested interest in, and knowledge about, the needed measurements. Regardless of the solution, one should consider its impact on the community such as the extent to which it brings in new researchers and likelihood of resulting in a self-sustaining capability after initial funding, or mission support, concludes. Also, a single solution may not fit all needs. Hurdles for some laboratory facilities revolve around equipment or laboratory space, while other institutions are challenged in providing personnel with expertise to ensure continual operation and maintenance.

Motivation

We focus this whitepaper on the need for the development and support of laboratory measurements related to spectral observations of Ocean Worlds with the primary application being the need for measurements relevant Europa and the other Galilean satellites for supporting the interpretation of measurements by the Europa Clipper mission. The Europa Clipper currently has a mission objective and an instrument payload suite for remotely mapping composition and geology of Europa that are representative of past missions to ocean worlds (such as Galileo and Cassini) and are likely representative of instrument payloads on mission objectives relevant to future ocean world missions. One of the main goals for the Clipper mission is to conduct detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life. NASA selected nine science instruments for the mission including cameras and spectrometers to produce high-resolution images of Europa's surface and determine its composition as well as surveying Europa's frozen surface in search of recent eruptions of warmer water at or near the surface.

Space Mission Needs for Relevant Laboratory Data

Spacecraft measurements are useful because we have contextual information with which to interpret the observations. For imaging systems, contextual information is aided by hundreds of years of geologic theory. Contextual information for hyperspectral measurements is much more recent, especially for measurements at non-visible wavelengths, yet provides great insights into fundamental physical and compositional character of a material. Because of this incredible power, spectral measurements are also very dependent on the conditions under which the materials are measured. Below are observations from missions to ocean worlds and other moons in the outer solar system that cannot be interpreted because facilities lack the capability and personnel are not funded sufficiently to obtain laboratory measurements of appropriate materials over the appropriate wavelength range under the appropriate conditions.

Cassini Mission to the Saturnian System: After a 13 year orbital tour of the Saturn system with the Cassini mission, we understand much about the icy satellites of Saturn, including Enceladus and Titan. However, many questions remain and new ones have arisen that cannot be answered without laboratory data that is not feasible with current facilities, or for which, current facilities could obtain but do not have the requisite funding to support the work. Example of unknowns include the lack of a definitive answer as to what the UV absorber is in the ice between 0.2 and 0.6 micron. Identification of the dark material on Iapetus is more definitive (Clark et al., 2012), largely due to Cassini VIMS resolving the dark material spatially, combined with a unique 3-micron absorber that is only seen in nano-phase iron oxide. The origin of a 0.28-micron absorption feature observed in spectra of icy satellites remains unknown. The surface composition of Titan is only partially known, largely due to insufficient lab data on organic molecules at Titan temperatures. Lack of optical constants hinder derivation of abundances.

Galileo and Europa Clipper Missions to the Jovian System: The Jovian system, particularly Europa, is entirely different from any other icy body, for the reason that very-high-energy radiation (electrons, protons, and heavier ions at MeV energies) that penetrates far deeper (up to several tens of centimeters) than the skin depth of the optical spectrometers on board Europa Clipper. A major question that needs laboratory facilities to be able to address is: to what extent does the top few millimeter of a surface characterized by these spectrometers represent a good approximation for the chemical composition of tens of centimeters below the surface? In order to address this question, facilities need to be able to simulate relevant (hydrated) samples bombarded with realistic energetic particles at Europa's surface environment, at appropriate temperatures. These measurements would also constrain the amount of time freshly deposited material (via plumes, fissures, or other mechanisms) can be identified on the surface before being altered by exposure to these energetic processing.

Another uncertainty is what is the composition of the hydrate(s) in the Europa spectrum? Is the hydrate composed of salts, acids, mixtures, or something else—that has been a long term question with much debate for about two decades. There are reasons for the uncertainties: 1) insufficient laboratory reference data, 2) laboratory studies that did not include the wavelength range of the Galileo and Earth-based telescopic data, and 3) insufficient signal-to-noise ratio (S/N) and spectral resolution in the spectra of the Galilean satellites. At wavelengths beyond 1 micron, water absorptions dominate the spectral structure of the Europa spectrum. The water on the leading side of Europa is ordinary water ice, but on the trailing side the water absorptions are shifted, indicative of different hydrogen bonding. Is the water in minerals such as salts, or acids, and what is the role of radiation? Intense scientific debates over the years have not resolved the problem, in large part due to insufficient laboratory studies.

Experiments need to be conducted over the wavelength and mass spectral range of the missions' instrument suites and at relevant temperatures in order to obtain the most precise interpretation of surface composition. This has become increasingly clear over the last decade with the Cassini mission and as shown by recent lab spectra. For example, organic compounds display rich absorption bands in

the near infrared. But when in small abundance in a surface with abundant water present, the strongly absorbing water, whether as ice, adsorbed in minerals, in salts, or acids make it difficult to detect the organics at the lowest levels. But organics can potentially be better detected in the near UV where ice is transparent. Thus, UV laboratory measurements may be able to characterize organics at lower levels. Laboratory data on the spectral signatures of trace organics in ice, salts and acids is greatly lacking, and none that we know of covering the deep UV to 5 micron range of the Europa clipper mission. Also, puzzling is the lack of the ~165nm water absorption edge in the far-ultraviolet spectra as revealed by Hubble observations of Europa and Ganymede (Becker et al., 2018, Molyneux et al., 2020). What unique endogenic/exogenic processes are at play at Europa's top surface veneer that mutes this distinct water ice signature observed for many Saturnian satellites? We have a growing spectral library on the infrared that could help identify spectral features in spectra from ocean world missions, like Clipper (e.g. Kokaly et al., 2017 and references therein). However, these measurements are of pristine materials, unweathered by radiation, which can significantly affect spectra from the UV- TIR. Optical constants of Europa analogs (pristine and weathered) in the far-ultraviolet are sorely lacking. Laboratory experiments in the far-ultraviolet have the added burden of stringent contamination control accomplished through ultrahigh capabilities.

The Current Inadequacy of Laboratory Capabilities

Few laboratories are equipped to measure the spectral characteristics needed to characterize materials for detailed comparison with spacecraft measurements of ocean worlds. For example, researchers at a laboratory may have an infrared spectral capability and be capable of radiation experiments on ice mixtures producing new products, for instance with spectra measured of thin film under transmission in the 4-20 micron range. But in this case, the laboratory data are of limited use because the spectral range measured by Europa Clipper is largely not covered and there is much material on Europa that is not water ice. Other labs may have different capabilities, possibly covering the requisite shorter spectral range, but do not include the longer portion of the IR, or UV, or may not have the capability to fully mimic the relevant portions of the space environment, such as temperature or radiation. Very few labs are capable of in-situ mass spectrometry of Icy Worlds ice analogs. All these incomplete capabilities create data that feed a research community making different, even potentially erroneous, interpretations of planetary spectra because the same fundamental data are not covered for all instruments on the spacecraft or the measurements are not fully appropriate. Consequently, it is difficult for labs to cross-compare and validate spectra of various materials that could be utilized by the broader community. Much of the Europa and ocean worlds spectroscopic facilities are one-of-a-kind labs with highly specific and unique capabilities, which is useful, but through a more systematic, or focused, investment NASA could ensure that laboratory facilities are developed that include the measurement capabilities to generate the appropriate data.

Laboratory Capabilities Needed

The following laboratories capabilities would be enabling to laboratory measurements needed to fully interpret the significance of spectral observations of ocean worlds

1. Either all capabilities available in a single environmental chamber/facility so samples remain exposed only to relevant conditions during the entire experiment, or tight coordination between complementary facilities to conduct a thorough investigation without needless duplication.
2. Spectral range: Ideally ~ 0.1 to 12 microns, to cover electronic and vibrational absorptions due to atoms, molecules, and minerals of inorganic, organic, and radiolytic composition.
3. Spectral resolution ~ a few nm or a few cm⁻¹.
4. Mass range: 1 – 500 amu with mass resolution ranging from 50000 to 1 (m/delta-m)
5. Temperature ranges: cryogenic.
6. Radiation conditions (solar UV, solar wind protons, giant planet magnetospheric particles)

7. High to ultra-high vacuum.
8. Bidirectional reflectance spectra & transmission spectra for derivation of optical constants.
9. Able to handle analog materials unstable at room temperature or under vacuum when not cryogenic.

Examples of Current Facilities.

These examples of currently available facilities are not fully inclusive. There are also state of the art facilities at other institutions including but not limited to Georgia Tech, ASU, Univ. of Arizona, NASA Goddard, etc. These facilities serve as examples and represent the general state of the art. While each is highly capable in specific areas relevant to ocean worlds studies, and has proven capable of conducting high quality research, each is also inadequate in one or multiple ways when compared to the needed capabilities listed above for ocean world research. These examples serve to demonstrate that current laboratory facilities are a disparate and largely uncoordinated, even ad hoc, efforts. Also, while capable of addressing some of the open questions regarding ocean worlds, they are not sufficient either individually or together for answering all the questions we have from missions about ocean worlds' compositions. Each facility has done the best it can to develop the needed capabilities with the resources available to it. Also, many facilities are under-utilized; thus, while each could be making important contributions to the understanding of ocean worlds within their capability limits, this is not being done largely because of lack of resources for funding the work. It is worth noting, these state of the art facilities are also managed by authors of this whitepaper.

- JPL & NIST combined capabilities lab: 0.1 – 20 microns spectroscopy, cryogenic systems, 0.1 MeV – 25 MeV electron source (JPL, NIST), large ice-cores (up to 100 cm) at 100 K, in-situ laser-ablation mass spectrometry of ice and minerals, various VUV irradiation sources.
- JPL Ocean Worlds Lab (OWL) and Icy Worlds Simulation Facility. Two chambers provide visible to Near-IR to Mid-IR reflectance spectroscopy (diffuse and specular geometries) under Europa relevant conditions (10^{-8} torr, 50-180 K) and provide electron and proton irradiation of cryogenic samples while spectroscopic measurements are being collected. Mass spectrometry via an RGA (1-300 amu) runs parallel with spectroscopic measurements. Samples and mixtures can be either vapor deposited or preloaded onto the cryostat cold finger. Other environmental chamber capabilities in the OWL include bulk ice tests of morphologic changes resulting from diurnal variations in solar irradiance.
- JPL Planetary Ice Characterization Laboratory (PICL). The centerpiece of this facility is the Basic Extraterrestrial Environment Simulation Testbed (BEEST), a cryogenic vacuum system capable of replicating planetary surface temperatures and pressures, configured to measure infrared reflectance spectra in the same format measured by flight instruments. Capabilities include: vacuum pumps and a chamber cooling to cryogenic temperatures; interfacing multiple spectrometers to enable wavelength coverage from 0.4 to 12 microns; and sample synthesis and characterization capabilities including the formation of hydrated sulfates and organic/ice mixtures.
- APL Laboratory for Spectroscopy under Planetary Environmental Conditions (LabSPEC). 0.14 to 8 micron bidirectional reflectance spectroscopy, ultra-high vacuum (UHV) environmental chamber with temperatures 100 – 650 K. While in the chamber, a sample is held in a holder equipped with a dosing line enabling the sample to be exposed to controlled amounts of gases. While in the chamber, samples can be irradiated with 1 – 40 keV electrons up to a fluence of 80 microamps. The samples can also be irradiated with mass selected ions of H^+ , O^+ , and other gases up to an energy level of 20 keV and a fluence of a few 10s of microamps. The irradiation can be done while the sample is cryogenic or heated. Spectra can be obtained by pausing the irradiation and rotating the sample to the appropriate port for spectral measurement.
- Planetary Science Institute: 0.1-20 micron spectroscopy (reflectance/transmittance), vacuum to ~2 bar pressure, cryogenic (LN2) to 495 K, Deuterium Vacuum UV (VUV) light source irradiation. Re-

flectance on horizontal samples. The “Brown” chamber can operate 0.18 – 5.1 microns (sapphire windows) and temperatures to 50 Kelvin (current spectrometers go to 2.5 microns) under vacuum. Two additional environment chambers can operate from vacuum to ~2 bars and 77 K to 495 K and measure at various phase angles and reflectance 0.18 – 5.1 microns (sapphire windows) on horizontal samples.

- USGS Denver Spectroscopy Lab (not currently NASA funded): 0.2 – 200 micron spectroscopy (reflectance/transmittance), vacuum to ~2 bar pressure (0.2-5 microns), cryogenic (LN2) to 495 K, UV irradiation. Reflectance on horizontal samples. The USGS lab has produced multiple spectral libraries relevant to the Europa Clipper mission, the most recent, Kokaly et al. (2017a, b).
- SwRI CLASSE (Center for Laboratory Astrophysics and Space Science Experiments): Multiple ultra-high vacuum systems that houses < 10 K cryostats mounted with sample holders that support quartz crystal microbalance (QCM) and transmission substrates, equipped with optical spectrometers (0.1-15 microns), radiation sources (10 keV electron gun, 5 keV mass filtered ion gun). Capability to measure bidirectional reflectance/phase curves of planetary analogs in the far-ultraviolet (Raut et al., 2018).

Broader Laboratory Impact

Aside from spectroscopy and compositional laboratory investigations, there is a host of remote and in situ measurements and physical properties that lack laboratory data. (e.g., dielectric properties; photometric functions at a wide array of wavelengths, reflectance and emission; in situ physical properties both thermal and mechanical, etc.). In addition, experimental simulations of planetary surface processes allow insight into their evolution. Examples include sintering, gardening, chemical weathering, biotic and abiotic organic chemistry. Our understanding of all these properties and processes is hampered by the same infrastructural lack of funding needed to develop, maintain and utilize the needed facilities to simulate the materials and environmental conditions appropriate to each world, each evolutionary process, and each physical property of interest. As for compositional investigations, there are infrastructural problems with the funding mechanisms for supporting facilities to explore and understand these processes with relevant ocean world materials. The issues parallel those that affect compositional focused laboratory efforts. NASA funding is limited to R&A, which is inefficient by limiting the scope and scale of environmental chambers and promoting duplication of small systems (even within a single lab) rather than development of a larger more versatile and cost efficient system. In addition, some types of measurements require larger systems that are outside the scope of R&A programs. These larger mid-range-cost systems lack a funding vehicle.

Inadequacy of Current NASA Funding Mechanism:

Laboratory facilities for conducting spectral experiments relevant to understanding the compositions of ocean worlds require significant resources including adequate space, funding over multiple years to build and optimize the system, and continued funding to support personnel to both

Mission-supported laboratory work both before launch and post-launch has dropped precipitously. Coupled with greater demand and less supply from R&A, laboratory facilities and level of effort in those facilities is dropping, resulting in a piecemeal approach to funding laboratory work relevant to Ocean Worlds.

conduct the measurements and to maintain the facilities. Various institutions will have different strengths, but each will need significant external funding to achieve a stable and productive facility. Insufficient external funding, as in NASA funding, is evidenced by facilities either lacking significant capabilities or are capable in most ways, but are significantly under-utilized. Capabilities can be improved through equipment purchases if institutions have such funds (such as research institutes) or through start-up funds. NASA early career funds are also available. However, these are one-shot injections to get a

facility off the ground, often woefully short for funding the effort needed to refine the system or to operate it. Another factor is that lab facilities which were built over many years as funds became available now have aging equipment, and sometimes that equipment may not be repairable when the equipment breaks. Filling that gap, including funding to conduct measurements, could be expected to come from NASA R&A programs and relevant missions. The primary funding opportunity is Solar System Workings and data analysis programs for recently completed missions. Unfortunately, the R&A program is inadequate. For the Ocean Worlds opportunity in 2019, there was an 11% win rate, with 371 proposal submitted, and 41 accepted. In 2018, there were 336 proposals submitted, and 74 selected (22%). Four of the 74 selected proposals from 2018 included one to use lab data to infer ocean world composition, and three were to take additional data. However, each of the funded efforts is a disparate effort that would address a small portion of the ocean major questions, and incompletely at that, and to some extent duplicate previous works. Duplication can be valuable, but with limited resources, it is important to ensure new findings are likely to result. A typical proposal only funds no more and often less than 25% of an investigator's time. It will be difficult if not impossible to make ground-breaking strides in understanding ocean world compositions without more dedicated funding. Missions have traditionally played a major role in this regard. However, that traditional role appears to be less emphasized with current missions and are no longer a significant source of support for laboratory investigations.

Recommendations

There are multiple possible paths to a solution. Existing laboratories could be funded through increased R&A support to address their current limitation in conducting Ocean World experiments; however, R&A does not provide the required stability in support. Additionally, funding through Ocean World missions to support, maintain, and ensure effective operation of the supported facility or facilities would be enabling. However, because planetary missions are cost constrained, activities not directly supporting the delivery of payload or spacecraft are often reduced or eliminated. Thus, we recommend funding laboratory efforts directly tied to relevant Ocean World mission payloads, but separate from mission funds, to ensure the appropriate laboratory capabilities are efficiently developed and measurements executed. We also recommend requiring explicit collaborations and increased coordination between similar facilities to maximize complementary research and reduce needless duplication.

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