Educational Value of Experiments on Life Support Systems with Ground-Based Aquatic Habitats

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On April 10th 2010, at the Kennedy Space Center, President Barack Obama pronounced his "Remarks on Space Exploration in the 21st Century." The President included closed-loop life support systems (LSS) as a technology that "can help improve daily lives of people here on Earth, as well as testing and improving upon capabilities in space." A challenge to enable research on LSS is the need for educational capacities that may open up opportunities for teachers and students to teach, learn, and experiment with a small-scale version of these systems. Such is the case in higher-education institutions with programs in life sciences and engineering. These may have educational platforms available in their laboratories to, for example, study attributes of robustness or optimality in controllers driving servomechanisms and electric motors, but there is no small-scale platform available to study the ecophysiological performance of higher plants in an isolated artificial ecosystem. This paper presents aquatic habitats as educational platforms for experiments in closed-loop LSS, and the lessons learned while working with undergraduate students at the Human-Automation Systems Lab of the Georgia Institute of Technology. It presents the challenges that these systems pose to students in engineering and sciences, and highlights the opportunities to support higher-education-level teaching and learning of concepts in science, technology, engineering, and mathematics (STEM) fields.

I. Introduction

A challenge in long-duration spaceflight is the capability of habitation systems to regenerate life support consumables, such as oxygen and water.[1] *Regenerative* life support systems (RLSS) offer various options to recycle metabolic byproducts, such as urine, and to achieve an incremental closure of gaseous and liquid material cycles. Such *material closure* increases the autonomy of space habitats and helps reduce the frequency of resupply missions and their overall cost. In fact, on April 10th 2010 in his speech on the "Remarks on Space Exploration in the 21st Century," President Barack Obama challenged:

> "*And we will extend the life of the International Space Station likely by more than five years, while actually using it for its intended purpose: conducting advanced research that can help improve the daily lives of people here on Earth, as well as testing and improving upon our capabilities in space. This includes technologies like more efficient life support systems that will help reduce the cost of future missions.*"

An example of current regenerative LSS is the Water Recovery System (WRS) commissioned in the U.S. segment of the International Space Station (ISS), which recycles waste liquids back into potable (drinking) water. But there is an educational dimension to this challenge that consists in the ability to conduct research on LSS with small-scale versions of these systems that may open up opportunities for teachers and students to teach, learn, experiment, and propose solutions to the problems posed by future human spaceflight missions. Traditional research platforms used in engineering education include inverted pendulum, ball and beam, flexible articulations, and water tanks. These kind of platforms exhibit relatively fast temporal responses

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that enable students to conduct experiments in a controlled fashion. Such platforms are useful to explore concepts of optimality and robustness, for example, but there is no current small-scale platform available for a lab-bench that may enable students to perform experiments involving various biological elements, *i.e.* consumer and producer organisms. The aquatic habitat presented in this paper aims to innovate in that direction.

A. Background

Larger-scale proof of concept projects have been undertaken by public and private organizations to study the sustainability problems and issues that arise from integrating human participants within a variety of life support processes. The main challenge has been the development of subsystems and their integration in a single ecosystem. While some projects have tested single regenerative processes to recycle byproduct into consumables, others have established entire biomes and attempted their integration. Such is the case of the project *Biosphere 2* that with a volume of 204,000 [m^3] attempted to integrate six biomes and a human habitat for a crew of seven or eight participants. A series of experiments were performed in Biosphere 2 during 1991-1994.[1] Figure 1 shows some of the facilities that have been built for this purpose, including Biosphere 2.

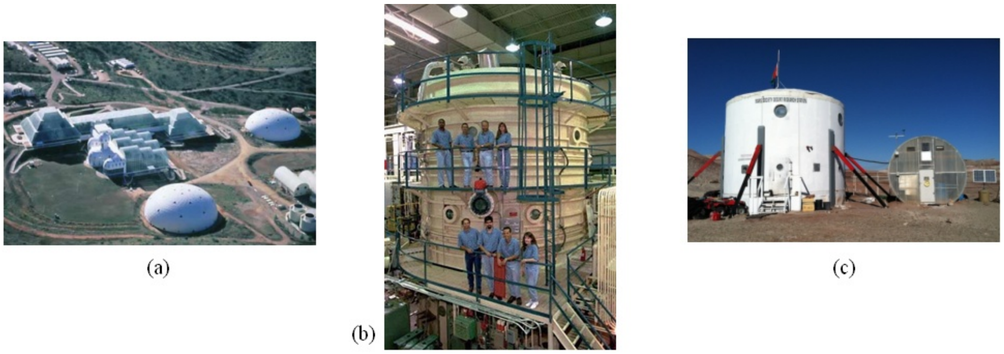

(a)
(b)
(c)

Figure 1. (a) Biosphere 2, (b) Life Support Systems Integration Facility, and (c) Mars Desert Research Station.

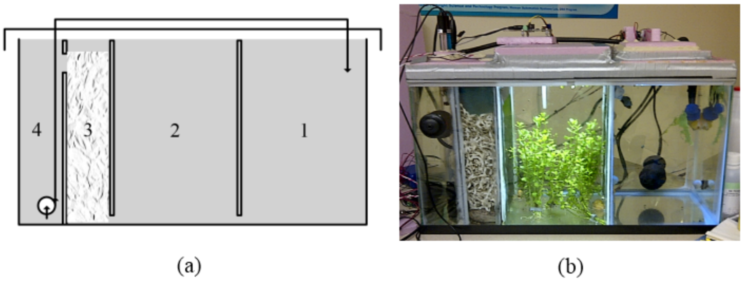
They vary in scale and in the reach of the activities they support. The Life Support Systems Integration Facility (LSSIF), displayed in Figure 1(b), contained a volume of 226.5 [m^3] in which it was able to support crews of four participants.[2] This facility performed various experiments during 1995-1997 in support of what has come to be known as BIOPlex at Johnson Space Center in Houston, Texas. Yet volunteer-driven organizations have also pursued initiatives in this direction. Figure 1(C) shows the Mars Desert Research Station operated in Utah by the Mars Society. But there are alternatives to the use of large-scale facilities for closed-loop LSS research. This paper presents aquatic habitats as educational platforms for experiments in closed-loop LSS. Past projects have made use of aquatic habitats for experiments in zoology and physiology in low Earth orbit (LEO),[3–7] and for ecotoxicological studies in ground-based hardware.[8, 9] Results obtained with the *Closed Equilibrated Biological Aquatic System* (CEBAS) minimodule in Space Shuttle missions STS-89 and STS-90 show that microgravity does not affect aquatic habitats considerably for exposure periods of up to 16 days.[4] This module also flew in STS-107,[6] but no results were reported due to the accident of the Space Shuttle Columbia. Researchers from the Chinese Academy of Sciences have employed a *Closed Aquatic Ecosystem*[10, 11] (CAES) as well for experiments relevant to ecophysiology, a discipline that “seeks to clarify the role and importance of physiological processes in ecological relations of species.[12]” A recent initiative by the Japanese Aerospace Exploration Agency (JAXA) plans to include an aquatic habitat in their International Space Station module, Kibo.[13]

B. Organization

The paper is divided in three additional Sections. Section II describes the small-scale aquatic habitat used, Section III presents the educational challenges and opportunities, and Section IV elaborates on lessons learned. Finally, Section V presents concluding remarks.

II. Description of the Small-Scale Aquatic Habitat

The model of the aquatic habitat[14] focuses on the process of respiration. Dissolved oxygen is consumed by the aquatic organisms at the same time they exhale CO_2 as a by-product. The photosynthesis of plants help to regulate the concentration of CO_2, generating the oxygen needed by all consumers, aiming to maintain "nominal" concentration levels in the habitat. The life support compounds are stored (dissolved) in the water, medium through which they are exchanged between the organisms. The habitat is a 10-gallon tank divided in four compartments by three separators that allow the water to flow, as shown in Fig. 2.



(a) (b)

Figure 2. (a) Recirculation diagram of the habitat; (b) Physical realization of the habitat.

The first compartment houses the animals (consumers) while the second one contains plants (producers) of the *Bacopa Monnierii* species. The third compartment serves the purpose of a mechanical, biological and chemical filter, and the fourth compartment holds the volume of water where the measurements are taken with sensors. The sensors used include dissolved oxygen (DO), pH, oxidation reduction potential (ORP), and water temperature, among others. The water flows through the four compartments; a water pump recirculates it from the fourth back into the first compartment. The first compartment also has a motorized hatch and an aerator that makes the system open (volatile) or closed (non-volatile) to the exchange of gases with the atmosphere; this mechanism can triggered as a fail-safe mechanism when the DO levels reach a minimum of 2.0 [mg/l]. An neutral-white spectrum LED-lamp is installed in the second compartment to irradiate the plants and thus regulate their photosynthesis process. This compartment also gives access to a dosifier pump that increases the carbonate hardness (kH) of the water; the changes in kH are monitored through variations of the pH measurements. The readings from the sensors are processed by a computer/controller. The controller and a pulse width modulation board (PWM) drive LED-lamp power. The computer also positions the hatch, and controls the air and dosifier pumps. The control signals can be the product of control laws or be manipulated through a graphical user interface (GUI).

III. Educational Challenges and Opportunities

During two years, six undergraduate students worked at the HumAnS Lab (three each year) through the Opportunity Research Scholars (ORS) Program of the School of ECE at Georgia Tech. During this time, the students gained hands-on experience in the construction and simulation of the HumAnS Lab Habitat. This Section describes some of the educational challenges and opportunities observed from this experience. The most important challenges to report so far are presented in Table 1, together with the opportunities to enhance the educational potential aquatic habitats for education and research initiatives in support of RLSS. The following Subsections elaborate in each one of these before summarizing the lessons learned in Section IV.

A. Challenges

This Subsection briefly describes the challenges presented in the left-side column of Table 1.

1. Ethics in RLSS research

Working with aquatic habitats, one would assume the possibility to work with fish and other vertebrate models of *consumers*. However, the Georgia Tech *Institutional Animal Care and Use Committee* (IACUC)

	Challenges	Opportunities
1:	Ethics in life science research	Use of invertebrate models (snails) and simulations.
2:	Ecophysiology	Learning about stress, adaptation, homeostasis, and sustainability.
3:	Closed-loop systems	Mathematical modeling, physics, chemistry, biology, and control.
4:	Slow-time response	Simulation tools and approaches.
5:	Human-system interaction	Psychology, cognitive engineering, and user-centered design.
6:	Science communication	Work in multidisciplinary teams.

Table 1. Challenges and opportunities for education and research with aquatic habitats

encourages the replacement of these animal models with invertebrate species or other means of experimentation, such as computer simulations, due to the risk of stress that vertebrates may unnecessary develop during tests, or the possibility of fatalities. This is one of the three-R's policy in support of the *replacement*, *reduction*, and *refinement* in experimental design to address ethical issues in life science research. Therefore, experiments performed with the HumAnS Lab Habitat make use of snails instead of fish as the consumer model. Furthermore, the physical platform is only used to develop mathematical models for simulation in MATLAB Simulink® and for validation of parameters.

2. Ecophysiology

Ecophysiology is the field of knowledge that "seeks to clarify the role and importance of physiological processes in ecological relations of species."[12] In this direction, the challenge consists of deciding which species should be included in the aquatic habitat, and which should not. For example, one may choose to work with a certain species of higher plant to generate oxygen that exhibits a faster growth rate than others. Depending on the experiment to be performed, this may be an advantage or a disadvantage. Such plants may need to be trimmed too often, requiring human intervention and interruption of system closure. Another example can be offered about consumers: a certain kind of shrimp species may not produce enough CO_2 for the plants, hindering the success of experiments that focus on the process of respiration. Therefore, from the ecophysiological perspective, the selection of species is a challenge for experiments with aquatic habitats.

3. Closed-loop Systems

A goal of RLSS is to achieve a high degree of material closure by recycling metabolic byproducts and regenerating life support consumables. For ground-based experiments, aquatic habitats offer the advantage of enclosing a volume of water that serves as a medium in which aquatic regenerative processes take place. Another advantage is the availability of mature technology and commercial products to support such research platforms. However, a challenge of system closure goes beyond the possibility of building a habitat that operates in isolation. The experience of Biosphere 2,[1] and the recent anomaly on the Water Recovery System on ISS,[15] have shed light on an additional challenge for future space habitats: system closure promotes unintended chemical interactions that may result in the depletion of life support consumables, deterioration of regenerative processes, or the accumulation of unknown or unidentified chemical compounds. This challenge alone poses questions that will require multidisciplinary efforts to find answers, and thus enable the safe and autonomous operation of future space habitats.

4. Slow-time Response

Life support processes generally take considerable time, i.e. they have relatively large time constants and slow responses. An example is shown in Figure 3 in which a simulation similar to experiments performed with the CEBAS minimodule are validated in the research platform during a period of time of seven days. The Figure shows the evolution of the dissolved oxygen and the pH in the aquatic habitat (in colors) compared to the computer simulation (in black).

The slow-time response of the aquatic habitat, as well as other regenerative systems, sets limitations to the amount of time and attention that investigators may dedicate to real-time experiments in an educational setting. Although one of the goals is to understand how RLSS will work in conjunction with human operators, educational activities need to take place in shorter and controlled period of time. Therefore, there is the

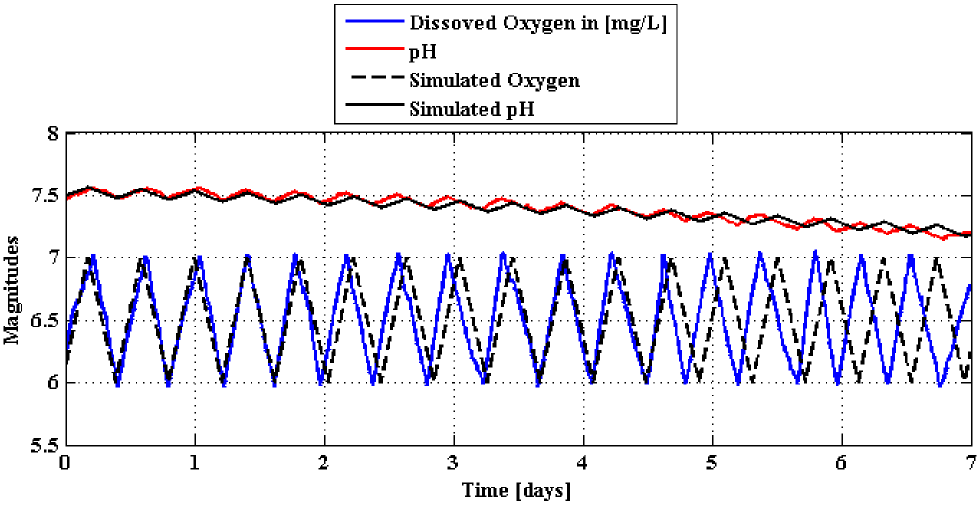


Figure 3. Validation of a Blüm-type experiment.

need to accelerate experiences through other means, which still may make use of the real-time platform to validate approaches and results.

5. Human-System Interaction

In the same direction as in the previous challenge, experiments relevant to the performance of humans interacting with the system may be considerably expensive in terms of time, attention, and cost. Although such interaction may raise questions about how attention may affect the performance of RLSS, other human performance indicators may be tested without such expense, such as perception, situation awareness, decision making, and action selection.

6. Science Communication

As noted in Subsection 3, issues such as material closure in future space habitats requires the attention of specialists in various fields of knowledge to address problems in a multidisciplinary fashion. One challenge for team building is good communication. This is especially the case in teams with members of various disciplines, who may use jargon from their own field. Because such endeavors may involve a variety of fields of knowledge, communication may also require additional efforts in order to enable a successful exchange of ideas. Such challenge is evident in discussions that make use of different terminology to express similar concepts. Such exchanges result in additional resources invested to ensure clarity and consistency in communication. In an educational setting, where students may not have experience addressing this problem, communication may become a challenge as well and the source of frustration.

B. Opportunities

1. Use of invertebrate models (snails) and simulations

In response to the ethical challenge of using non-invertebrate models in research with the aquatic habitat, snails have become the primary animal model for experiments on respiration. They were able to replace invertebrates and exhibited attributes useful for experiments in LSS automation and control. Snails are relatively inexpensive and may feed from growing algae. Algae tablets are commercially available as well.

2. Learning about stress, adaptation, homeostasis, and sustainability

As a non-expert in biology, when faced with the need to make use of snails as the animal model, it was apparent that snails did more than eating and breathing. They undergo periods of aestivation, i.e. periods of metabolic depression in which they reduce their rate of oxygen consumption. This phenomena introduced disturbances in the accumulation and depletion of dissolved oxygen in the water, and provided the opportunity to approximate the animal model as an stochastic system.

3. Mathematical modeling, physics, chemistry, biology, and control

Plants and snails in the aquatic habitat exhibit varying performances depending on environmental factors and availability of food and nutrients. These variations introduce disturbances, non-linearities and time-varying characteristics into the system that, if modeled, open up opportunities for experiments relevant to control and automation. However, this requires the ability to integrate knowledge from various domains, and opens the opportunity to use mathematical tools, such as differential equations and integral transforms, to describe the dynamic behavior of physico-chemical and biological phenomena. The ability to obtain a mathematical model of these systems also allows the design of controllers and fail-safe/fail-operational mechanisms to ensure proper performance and management of anomalies, all these also necessary in larger-scale LSS. Figure 4 shows the comparison of the simulated and real-time accumulation of dissolved oxygen in the aquatic habitat. Disturbances in the real-time data are due to the metabolic changes in snails.

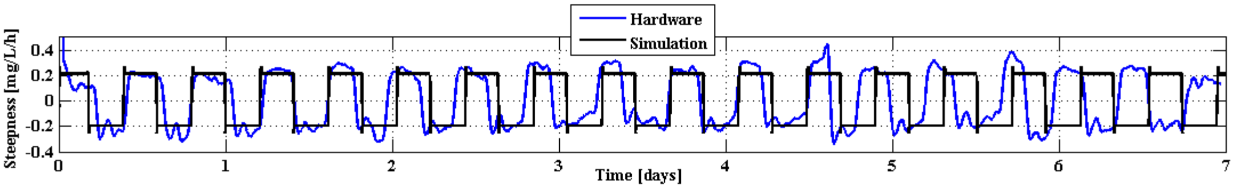


Figure 4. Rate of accumulation/depletion of dissolved oxygen in the aquatic habitat.

4. Simulation tools and approaches

Having mathematical models of physico-chemical and biological elements opens then the opportunity to overcome the slow-time response challenge of the aquatic habitat. Simulations make use of such models to predict the behavior of the system and the performance of controllers and protection systems. Students have the opportunity to implement the model in simulation software and learn how to implement, interpret, and communicate experiments, predictions, and results. Figure 5 shows an example of the simulation prepared for the aquatic habitat described in this paper.

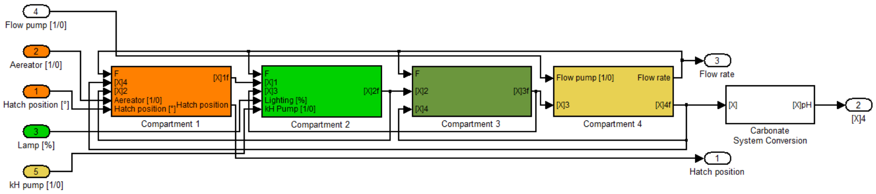


Figure 5. Simplified block diagram of the simulation of the aquatic habitat

5. Psychology, cognitive engineering, and user-centered design

Simulation software also offers the opportunity to design user interfaces to study and explore the interaction of human operators, either experts or non-experts, with the aquatic habitat. Such opportunity, highlights the problems and issues that need to be solved in order to enable human operators to gain awareness about the situation of systems from the cognitive psychology and cognitive engineering perspectives. It also enables students and researchers to evaluate and explore solutions to the anomalies that emerge in the operation of LSS, such as the dimethylsilanediol (DMSD) anomaly experienced on the International Space Station.[15]

6. Work in multidisciplinary teams

By working with a system that involves chemistry, biology, electronics, computing, sensing, and automation, students from a variety of fields may contribute to the multidisciplinary understanding, approach, and solution of problems relevant to the operation and challenges of closed-loop LSS.

IV. Lessons Learned

Making use of an aquatic habitat for education and research on RLSS poses challenges for students, both graduate and undergraduate, who are faced with the need to independently and simultaneously learn and integrate concepts from various fields of knowledge. This may require guidance and mentoring by experts in those fields, together with training in multidisciplinary communication to promote a successful exchange of ideas. If teams of undergraduate students are involved, communication will be especially important in order to define the research problem in such a complex domain. As students and young researchers, their priority should be to understand the research questions first, so that they may brainstorm and propose alternative approaches and solutions to specific problems. Beyond this, good teamwork and team ethics are *essential* as in any other multidisciplinary endeavor in higher-education.

V. Conclusion

Although there is no small-scale educational platform available to perform undergraduate and graduate level research on closed-loop LSS, aquatic habitats show promise to enable educators and students to teach, learn, and experiment with a small-scale version of larger-scale environmental systems. This paper presented the educational challenges and opportunities posed by the use of such platforms, and highlighted concepts and principles that may be taught. The intention of this paper focused in enabling educational capacities that may open up opportunities to conduct research with a small-scale and low-cost version of these systems.

Acknowledgments

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References

[1] Eckart, P., *Spaceflight Life Support and Biospherics*, Microcosm Press and Kluwer Academic Publishers, USA, 2nd ed., 2010.

[2] Williams, D. R., *Isolation: NASA experiments in Closed Environment Living*, Vol. 104 of *Science and Technology*, final report 1, American Astronautical Society, San Diego, California, 2002, pp. 1–5.

[3] Blüm, V. and Paris, F., “Possible applications of aquatic bioregenerative life support modules for food production in a Martian base,” *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 77–86.

[4] Blüm, V. and Paris, F., “Novel aquatic modules for bioregenerative life-support systems based on the closed equilibrated biological aquatic system (CEBAS),” *Acta Astronautica*, Vol. 50, No. 12, 2002, pp. 775–785.

[5] Blüm, V., Andriske, M., Ludwig, C., Paassen, U., and Voeste, D., “The CEBAS mini-module: A self-sustaining closed aquatic ecosystem for spaceflight experimentation,” *Advances in Space Research*, Vol. 31, No. 1, 2003, pp. 201–210.

[6] Blüm, V., “Aquatic modules for bioregenerative life support systems: Developmental aspects based on the space flight results of the CEBAS mini-module,” *Advances in Space Research*, Vol. 31, No. 7, 2003, pp. 1683–1691.

[7] Blüm, V., “Aquatic Modules for Bioregenerative Life Support Systems: Developmental Aspects based on the Space Flight Results of the C.E.B.A.S. Mini-Module,” *Advances in Space Research*, Vol. 31, 2003, pp. 1683–1691.

[8] Slenzka, K., Dünne, M., and Jastorff, B., “Biomonitoring and risk assessment on earth and during exploratory missions using AquaHab,” *Advances in Space Research*, Vol. 42, No. 12, 2008, pp. 1944 – 1950.

[9] Stan, I. A., *Bioavailability and biological properties of several selected ionic liquids*, Ph.D. thesis, Fachbereich Biologie/Chemie, Universität Bremen, September 2009.

[10] Wang, G., Liu, Y., Li, G., Hu, C., Zhang, D., and Li, X., “A simple closed aquatic ecosystem (CAES) for space,” *Advances in Space Research*, Vol. 41, No. 5, 2008, pp. 684 – 690.

[11] Wang, G.-H., Li, G.-B., Hu, C.-X., Liu, Y.-D., Song, L.-R., Tong, G.-H., Liu, X.-M., and Cheng, E.-T., “Performance of a simple closed aquatic ecosystem (CAES) in space,” *Advances in Space Research*, Vol. 34, No. 6, 2004, pp. 1455 – 1460.

[12] Bradshaw, D., *Vertebrate Ecophysiology: An Introduction to its Principles and Applications*, Cambridge University Press, June 2003.

[13] Watanabe-Asaka, T., Mukai, C., and Mitani, H., “Technologies and Analyses Using Medaka to Evaluate Effects of Space on Health,” *Biological Sciences in Space*, Vol. 24, 2010, pp. 3–9.

[14] Drayer, G. and Howard, A., “Design, Modeling and Simulation of a Reconfigurable Aquatic Habitat for Life Support Control Research,” *41st International Conference on Environmental Systems*, AIAA, Portland, Oregon, July 2011.

[15] McCoy, T., Flint, S., Straub, J., Gazda, D., and Schultz, J., “The Story Behind the Numbers: Lessons Learned from the Integration of Monitoring Resources in Addressing an ISS Water Quality Anomaly,” *41st International Conference on Environmental Systems*, 2011.