International Space Station U.S. National Laboratory Initiatives to Address Plastic Pollution

Workshop Report

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Workshop conducted by the International Space Station U.S. National Laboratory in conjunction with the 2019 ISS Research and Development Conference

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ABOUT THE ORGANIZER

About the ISS National Lab: In 2005, Congress designated the U.S. portion of the ISS as the nation's newest national laboratory to optimize its use for improving quality of life on Earth, promoting collaboration among diverse users, and advancing science, technology, engineering, and mathematics (STEM) education. This unique laboratory environment is available for use by non-NASA U.S. government agencies, academic institutions, and the private sector. The ISS National Lab manages access to the permanent microgravity research environment, a powerful vantage point in low Earth orbit, and the extreme and varied conditions of space. To learn more about the ISS National Lab, visit *www.ISSNationalLab.org*.

SUMMARY

The International Space Station (ISS) U.S. National Laboratory held its second annual sustainability workshop during the July 2019 ISSR&D Conference in Atlanta. The objective was to discuss how technology development on the ISS can uniquely contribute to industry actions addressing plastic pollution in the environment. Participants from 13 invited organizations attended, representing several economic sectors: sports, aerospace, technology, agricultural sciences, retail, advanced computing, environmental, space, government research, and technology innovation. Ideas discussed focused on remote sensing applications and the use of microgravity to study the production of environmentally friendly biopolymers that offer the potential of an alternative to nondegradable plastics. This report highlights and expands on the ideas presented and the options discussed for further action.

Just prior to the workshop, data collected using the DLR Earth Sensing Imaging Spectrometer (DESIS), a hyperspectral sensor hosted on the ISS, indicated that the sensor may be capable of indicating the presence of marine debris in the open ocean by detection and analysis of specific spectral signatures. Participants expressed support for considering further work on advanced sensor development, which supported efforts for additional capabilities and use cases. From an ISS National Lab point of view, the objective for an advanced sensor would be to detect near-surface waterborne plastic debris from space, over wide and remote areas, and to use this capability to assist with plastic pollution prevention and cleanup. Broadly, the recommended tasks are as follows:

- Using capable ISS sensors, collect additional data for debris accumulation targets in the ocean and along coastlines to further demonstrate detection capability.
- Where possible, coordinate ISS sensor data collection efforts with the National Oceanic and Atmospheric Administration (NOAA) Hazard Mapping Team and organizations involved with ocean cleanup for field verification.
- Combine and analyze ISS sensor data along with data from other space- and Earth-based sensors in order to more fully identify data gaps, develop marine plastic detection algorithms, and improve ocean circulation models for prediction of the transport paths of floating marine debris.
- Use insights from the data analysis to assist with the design, development, and ISS-based testing of next-generation sensors that can detect and differentiate plastic debris.

Research focused on the production and degradation of biopolymers in microgravity is recommended because it builds upon prior investigations demonstrating bacterial and fungal responses to reduced gravity that alter gene expression and physiological responses that may benefit the synthesis of desirable metabolites. Some biopolymers are superior to plastics not only because their mechanical properties are similar to those of conventional petroleum-based polymers such as polyethylene but also because they biodegrade in ambient environments, even in the ocean, leaving behind only nontoxic residual chemicals. Biopolymers could serve as an attractive alternative to petroleum-based plastics; however, the current economics of biopolymer production must be significantly improved in order to realize this potential. The next steps identified for the exploration of beneficial biopolymers in space are as follows:

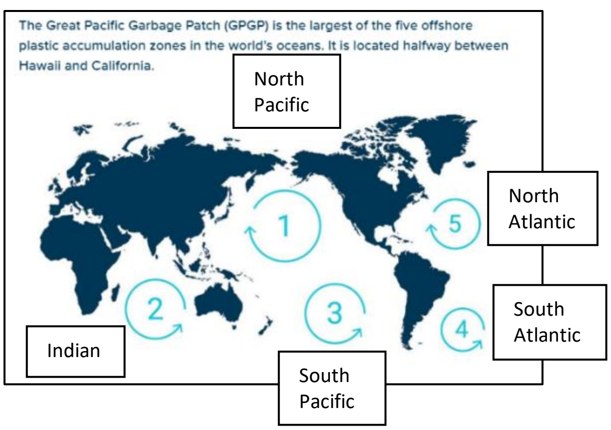
- First, successfully demonstrate production of polyhydroxyalkanoate (PHA) biopolymers on the ISS.
- Then, outline a research program to understand the mechanisms of PHA production and translate the knowledge gained to improve the production and scale-up of commercial terrestrial facilities. This includes examining the use of novel microbes to produce tailored biopolymers for specific applications.

Success with the initial biopolymer production work may open the opportunity for projects investigating the production, use, and recycle of these biopolymers in orbit.

INTRODUCTION

Among the general global population today, there is undoubtedly a high degree of awareness of the widespread pollution of Earth's oceans by anthropogenic debris (1), also called marine debris. The major component of marine debris is synthetic, petrochemical-derived plastic in various forms (2-5). The ever-growing public concern with plastic pollution has intensified efforts aimed at responsible and reduced plastic use and recycling (6-8) and has further motivated research to seek alternatives to plastic. This report highlights and expands on the ideas presented by the International Space Station (ISS) U.S. National Laboratory at its second annual sustainability workshop in July 2019. The workshop focused on how remote sensing and the microgravity environment on the ISS can be uniquely leveraged in the efforts to address the global challenge of plastic pollution.

The origins and impacts of marine debris on marine and other ecosystems have long been studied. In 1997, Captain Charles Moore (9) first discovered and reported on the existence of what is known today as the Eastern Pacific Garbage Patch, a large stretch of floating debris situated between Hawaii and California. Several major garbage patches are now known to exist (10-14), as shown in Figure 1. These garbage patches result from the actions of the major oceanic gyres-systems of circular ocean currents formed by the Earth's wind patterns and the forces created by Earth's rotation. The Great Pacific Garbage Patch is comprised of two distinct accumulations of floating debris within the North Pacific Subtropical Gyre; the larger of the two accumulations is the Eastern Pacific Garbage Patch (the smaller Western Pacific Garbage Patch lies closer to the Eastern Japanese coast).



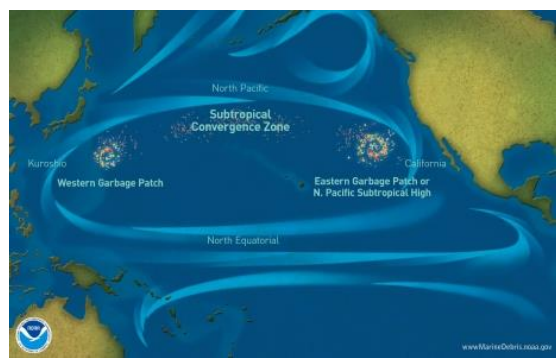


Figure 1: Major marine debris accumulation zones (left) and the Great Pacific Garbage Patch (right). Courtesy of The Ocean Cleanup (2) and NOAA (11)

Marine debris originates from both land- and marine-based human activities. Land-sourced plastic debris enters the environment at all stages in the cycle of production, use, and disposal, enters into watersheds in proximity to densely populated coastlines, and is eventually transported into the ocean (15). Marine-sourced debris includes discarded fishing equipment such as nets, traps, and floats and debris from cargo ships and oil and gas platforms that may be deliberately or accidentally discharged into the oceans. The visible floating debris accumulations are only an indicator of the enormous scale of the pollution. Microscale and nanoscale plastic debris, which results from the breakdown of larger pieces, is now found in the most remote parts of the ocean, throughout the marine food chain, in the global biosphere, and even in geological formations (16). Yet, increases are projected in global demand and production of synthetic, nondegradable petroleum-based plastics (15). If a sustainable alternative is not found, plastic and other debris will continue to accumulate in human habitats everywhere, even outer space (18).

The ISS National Lab held its second annual sustainability workshop during the 2019 International Space Station Research and Development (ISSR&D) Conference in Atlanta in July to gain industry perspectives and gauge interest in an ISS-based technology development effort to address plastic pollution. Participants from 13 large and small organizations attended, representing the following sectors: sports, aerospace, technology, agricultural sciences, retail, advanced computing, environmental, government research, and technology innovation. The two areas discussed by the ISS National Lab and invited presenters were remote sensing for detection and monitoring of marine debris, and the use of the microgravity environment on the ISS for research that may accelerate the development of environmentally friendly alternatives to petroleum-based plastic. At the conclusion of discussions, all participants expressed interest in advancing ISS research in these areas. Some participants also expressed a desire to focus on work that may assist with the prevention of the inflow of plastic waste into waterways and oceans. The remaining sections of this report expand on the workshop discussion and broadly outline research objectives for both areas.

REMOTE SENSING: DETECTION, MONITORING, AND CLEANUP SUPPORT

Space-based, remote sensing data can be applied to provide parameters for ocean circulation models used to predict the paths of marine debris throughout the oceans (19). Modeling studies after the Shoe Spill in the North Pacific (10) and after the 2011 Fukushima earthquake and tsunami showed that marine debris movement can be simulated and mapped using satellite imaging (20, 21). Models like the General NOAA Oceanographic Modeling Environment (GNOME) can be refined with additional, high-quality satellite data. Modeling results can be coupled with the deployment of active or emerging passive technologies (2) for remediation, or in the future, for prevention of debris inflow into waterways and oceans. Prevention work may be performed in concert with governmental, private, and nonprofit organizations for regulation and enforcement. Another important and related potential application of satellite remote sensing data is the study and mitigation of the global spread of invasive species (22) that are able to drift across the oceans on rafts of indestructible plastic debris.

There is global interest in remote sensing technology development for marine debris applications. Space-based remote sensing is identified as a key part of the development and operation of an integrated marine debris observation system proposed in the recent detailed review by Maximenko and co-authors from the global marine science community (23). Imaging spectroscopy was also identified as one of the areas of promise during a session on remote sensing of marine debris in the open ocean at the Sixth International Marine Debris Conference (24). The European Space Agency (ESA) sponsored two parallel ongoing projects, OptiMAL (Optical Methods for Marine Litter Detection) and ReSMaLi (Remote Sensing of Marine Litter), focusing on passive optical spectro-radiometric remote sensing to identify the characteristics of orbiting optical sensors optimal for detection of plastic marine debris. At the University of the Aegean, the Marine Remote Sensing Group has been testing the detection of plastic using multispectral satellite imagery from Sentinel-2 (25). Clearly, there are opportunities for global collaboration that may be facilitated by the ISS National Lab (particularly with ESA member countries that are also ISS partners) in order to accelerate remote sensing technology development for practical marine debris mitigation applications.

The ISS has an inclined orbit of 51.6^{o}, which permits remote sensing of about 90% of the populated Earth and significant portions of the Earth's oceans with a three- to five-day average revisit time. Exterior facilities on the ISS, such as Teledyne Brown Engineering's (TBE) Multi-User System for Earth Sensing (MUSES) precision pointing platform, are available for testing prototype sensors. MUSES currently hosts the DLR Earth Sensing Imaging Spectrometer (DESIS), a hyperspectral sensor able to precisely scan the land surface, the atmosphere, and the oceans (26). The "equatorial" orbit of the ISS may permit tropical ocean sections often obscured by clouds to receive some cloud-free collections at high enough revisit times. Table 1 provides a summary of DESIS key specifications.

Table 1: DESIS features. Source: TBE (26)

DESIS Design Parameters	
Ground Sampling Distance @ Nadir	30 m @ 400 km (reference height)
Ground Swath @ Nadir	~30 km @ 400 km flight altitude
Spectral Range, nm	400 – 1000 nm
Spectral Sampling	2.55 nm for 235 bands

Just prior to the workshop, TBE tested the capability of DESIS to detect marine debris in the Eastern Pacific Garbage Patch by targeting coordinates around 32°N and 145°W. The high spectral resolution and visible to near-infrared (VNIR) spectral range of DESIS are highly desirable features that improve the chances of successful detection of marine debris. A collect with four scenes was acquired with the above coordinate center points on June 29, 2019. These scenes contained a number of clouds, covered 3,600 km^2 of area, and included more than 4 million pixels (the entire Great Pacific Garbage Patch is estimated to cover an area up to 1.6 million km^2).

Using the ENVI™ software from L3Harris Geospatial solution, the data volume was reduced by highlighting only pixels found to be "anomalous." Once pixels were identified as anomalous, they were inspected to see if they were water, clouds, or marine debris. Pixels that included cloud edges and what appeared to be brownish mats in true color images were routinely flagged as the most anomalous. Cloud edges are pixels that mix clouds and water, and while there are fewer of these pixels than of clouds or pure water, the cloud fringes were easily identified by visual inspection. Other anomalies had a uniquely different spectral signature than the other scene contents and often appeared as clumps of brownish pixels in the water. Using these pixels, other areas were found throughout the 3,600 km^2 swath that show high likelihood of containing the debris content signature.

The following images show the data obtained from DESIS. Figure 2 shows the DESIS detection of the Eastern Pacific Garbage Patch.

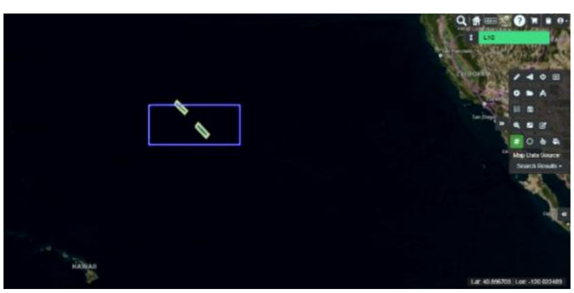


Figure 2: View of location of Eastern Pacific Garbage Patch. Courtesy of TBE

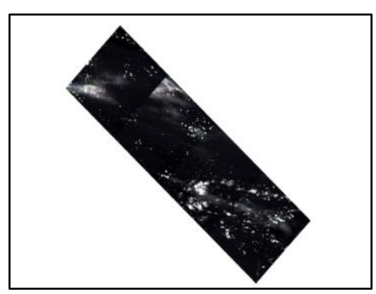


Figure 3: DESIS mosaic from July 9, 2019. Courtesy of TBE

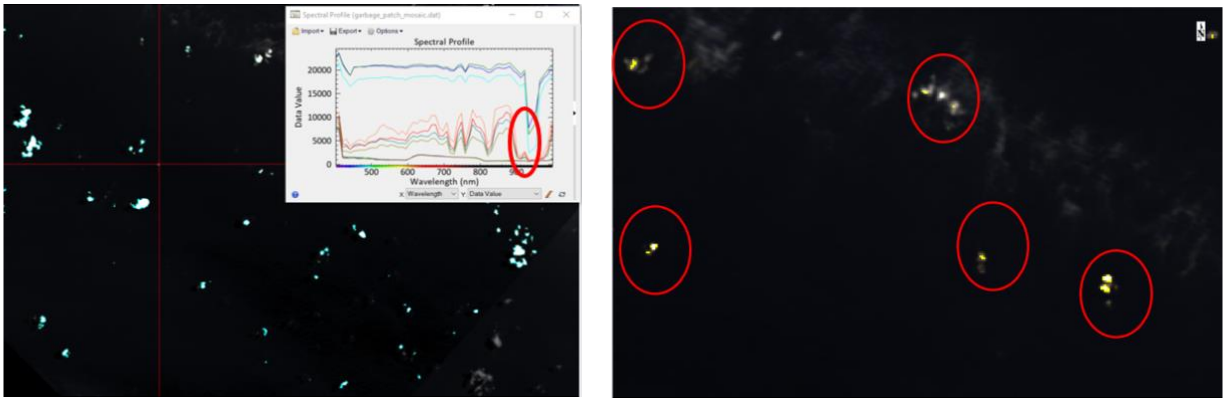


Figure 4: ENVI analysis of DESIS data. Courtesy of TBE

Workshop participants concurred that this analysis of DESIS hyperspectral data seemed to be a step forward in detecting marine debris, and all expressed support for additional work to further develop remote sensing capability for ocean plastics using the ISS. The Eastern Pacific Garbage Patch is too remote and dynamic for independent field verification of these identified pixels as positively plastic or other debris types. However, such data verification could be part of a comprehensive study with easily accessible plastic debris accumulations using Earth-based sensors and sampling in conjunction with satellite remote sensing. For example, ongoing and future TBE efforts with the NOAA Hazard Mapping Team will target coordination of DESIS imaging with field work for locating derelict fishing supplies in the Hawaiian Atolls. The lack of reference spectral data also limits the ability of satellites to identify marine plastic debris. Studies are needed to develop large spectral libraries representative of different types of plastic and other debris that have been subjected to ocean conditions (23, 27, 28) in order to classify debris components. In the future, advanced satellites capable of onboard or cloud-based processing could quickly infer and transmit the location, composition and characteristics of marine debris.

Two complementary areas for further study and development using the ISS were discussed with workshop participants: (1) additional data acquisition for analysis and (2) advanced sensor hardware development. Data analysis consists of obtaining imagery for additional locations of accumulated marine debris from the open ocean and coastlines in the Indian and Pacific Ocean to further test the capabilities of DESIS. Due to the broad diversity of types, sizes, shapes, chemical composition, and buoyancy of marine debris, multiple types of sensors are needed to meet the challenge of observation using satellites (23, 24, 27). Other previous, existing, or planned ISS sensors, such as the Hyperspectral Imager for the Coastal Ocean (HICO), the Hyperspectral Imager Suite (HISUI), or the Global Ecosystem Dynamics Investigation (GEDI) lidar sensor could be included in an analytics study in order to more fully identify data gaps and to develop and improve marine plastic detection algorithms.

Sensor hardware development would involve next-generation hyperspectral or multispectral sensors specifically designed to detect and differentiate plastic debris. Such sensors could provide complementary data to DESIS and expand the results of fusion and analysis to obtain actionable information. For example, a high spatial resolution multispectral or hyperspectral Short-Wave Infrared (SWIR) sensor could be combined with DESIS to complete coverage of the optical spectrum. DESIS data can also provide information to determine the best bands and satellite orbits for identifying and characterizing marine debris.

ENVIRONMENTALLY FRIENDLY BIOPOLYMERS PRODUCED IN MICROGRAVITY

The production of biodegradable polymers from renewable feedstocks has been extensively investigated in recent years due the great potential they offer as an alternative to petroleum-based polymers (29, 30). Polyhydroxyalkanoates (PHAs) are a family of naturally occurring polymers that are synthesized by microbial fermentation of sugars, alkanes, alkanoic acids, and lipids. They are biodegradable, biocompatible, nontoxic, and recyclable. Because the mechanical properties of PHAs are similar to those of conventional petroleum-based polymers such as polyethylene, PHAs have been developed and tested for use in a wide variety of applications such as packaging, cosmetics, drug delivery, agriculture, and as precursors to biofuels. However, the current economics of PHA production have to be significantly improved in order to realize their potential as an attractive alternative to petroleum-based plastics. Technological breakthroughs are needed in utilization of the feed substrate, polymer yield, microbial culture productivity, and PHA recovery from the bacterial cell (30, 31)—all areas that may be uniquely studied in the microgravity environment of the ISS.

The microgravity environment alters the fundamental behavior of living systems because the gravity-induced stressors of weight and motion are not dominant. A recent study of poly(b-hydroxybutyrate) in simulated microgravity indicated that the biopolymer was produced with enhanced bioactivity of the microbes and with no lag time (32). This is consistent with reports from the earliest days of spaceflight that have indicated a stimulating effect of reduced gravity on microbial growth (33, 34). If the specific molecular mechanisms responsible for the stimulation in productivity can be understood, it may lead to PHA production efficiency improvements in terrestrial facilities. A systematic research program on the ISS could examine the use of novel microbes, as well as the production of tailored PHA biopolymers for specific applications. Ultimately, the goal is to accelerate the development of pathways to large-scale in-space or terrestrial production of plastic alternatives. The ISS is currently the only platform that offers a long-term microgravity environment for such studies.

Mango Materials, a San Francisco-based startup, participated in the sustainability workshop and highlighted their innovative closed-loop process that converts methane gas into PHA biopolymers using bacterial fermentation. Methane is readily and relatively cheaply available not only from renewable sources such as anaerobic digesters, but also from other sources such as landfills, coal mines, and other hydrocarbon production facilities. Methane is a prime feedstock for PHA production, as it converts a potent greenhouse gas and inexpensive feedstock into a beneficial material that mitigates plastic pollution (35). PHA-based products can be anaerobically degraded back into methane at the end of their useful lives, and the resulting methane may be used as feedstock to produce additional polymer (35). Mango Materials has successfully scaled its technology from the bench scale to a 500-L pilot unit that has operated continuously since 2015, generating years of data in a field environment. Figure 5 shows samples of articles produced from Mango's in-house, 3D-printed PHA polymers that were presented at the workshop: filaments, finger splints, tweezers, and pliers. Engineering plans have been completed for a larger demonstration facility.

Figure 5: Articles produced from Mango's in-house, 3D-printed PHA polymers. Courtesy of Mango Materials

In addition to the terrestrial benefits of ISS research previously described, a successful first demonstration of microgravity-produced PHA in conjunction with the ISS National Lab will be the first step toward understanding the possibilities of in-space manufacturing of PHA for space use. The Environmental Control and Life Support System (ECLSS) on the ISS is a possible methane source (36), or methane could be produced by other means such as an onboard anaerobic digestion system. These methane sources would enable in-situ resource utilization for the production of PHA for additive manufacturing in space. This is important, as NASA, Blue Origin, SpaceX, and other international actors work toward human interplanetary travel, exploration, and habitation. Additive manufacturing of products using a 3D printer in microgravity has been demonstrated by Made In Space, and the recently launched Tethers Unlimited ReFabricator is an integrated 3D printer and plastics recycler. The ISS, therefore, has all the facilities necessary to demonstrate a mini-version of the "circular economy"—the sustainable production, use, and recycle of bio-friendly materials and the translation of that knowledge for terrestrial benefit.

In space, it is abundantly clear that sustainable processes are not optional, they are a necessity for survival. On Earth, sustainable processes are also not optional, but they appear that way because the system is larger and acts on a much longer time scale. A collaborative research program on the ISS that includes the ISS National Lab, workshop participants, and other global organizations ready to address plastic pollution offers the opportunity for discovering innovative solutions to this sustainability challenge.

RECOMMENDATIONS

Based on these workshop discussions, the ISS National Lab proposes to develop a programmatic approach to addressing the global challenge of plastic pollution. One area of emphasis will focus on efforts that seek to utilize data from ISS sensors to develop the capability for the detection, monitoring, and cleanup of plastics in the ocean. Another area of emphasis will focus on the optimization of biomaterial precursors for the efficient synthesis of biopolymers in microgravity that may serve as an alternative to petroleum-based plastics. Such biopolymers could be used in a wide range of commercial applications, including single-use products such as food packaging as well as industrial chemicals, coatings, adhesives, and pharmaceuticals.

The ISS National Lab proposes to form an advisory group to identify and obtain resources to conduct research on the space station within these emphasis areas. Initially, the advisory group would consist of the ISS National Lab, the workshop participants, and other organizations from the participants' networks that are actively addressing plastic pollution. The group may also generate additional ideas to leverage the ISS for research and technology development aimed at addressing plastic pollution in the environment.

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